Sixth Edition

Modern Construction Handbook

ANDREW WATTS

Birkhäuser newtecnic

MODERN CONSTRUCTION HANDBOOK

SIXTH EDITION

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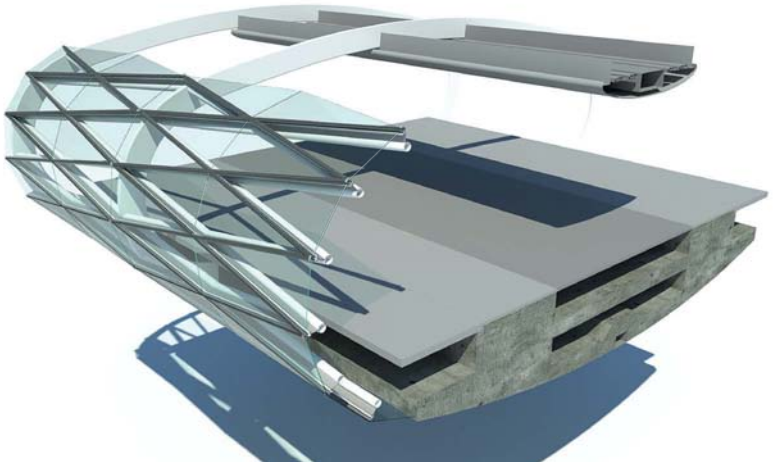
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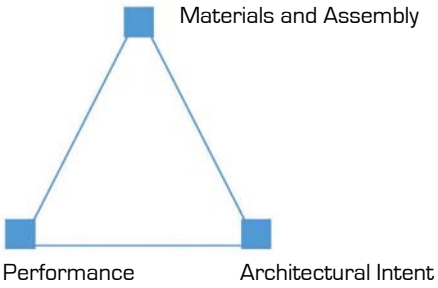
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a | Example of curved glazed facade system supported on steel tubes

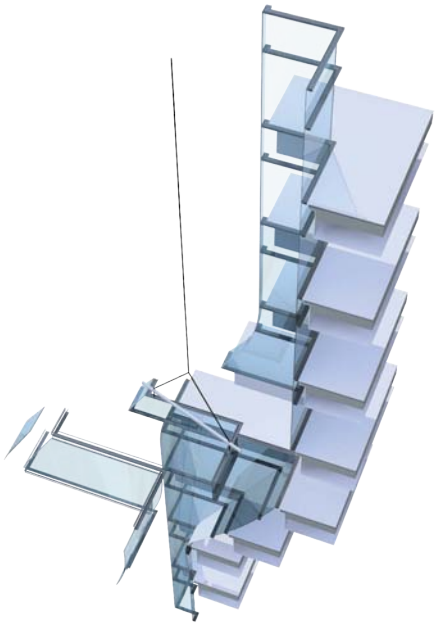


b | Relation of governing aspects of design

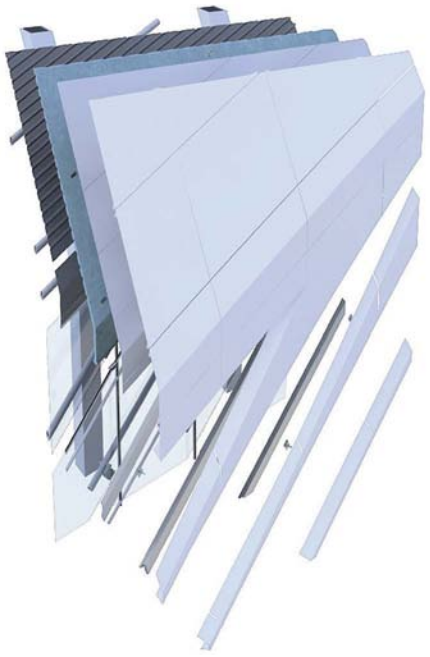
This book presents building and envelope technologies as entities independent of previous application; the technologies are instead presented according to their principle material and key characteristics. This is contrary to the traditional method of building component presentation found in existing technical manuals and manufacturer specifications, which commonly focus on the traditional application of each technology. The current available publications focus on the specific application of building technologies for rectilinear buildings; grouping technologies in terms of building type rather than the basic principles which govern them. This approach allows the corresponding current technologies for standard systems to be compared easily. However, it is often not possible to extract the driving principles behind the technology from an examination of its application in buildings alone. Also, the principles and generalised guidelines which made the technology applicable for a certain application may not be applicable to another building technology: therefore, the design of alternative system types incorporating these technologies is restricted.

The materials-based approach specific to this book allows parallels to be drawn between building technologies that are based on the same primary material. The development and use of building technologies are informed mainly by the physical properties specific to each material and the way the material is processed, manufactured or formed for use as a building material. Arranging with respect to material also provides greater freedom for the designer in how the technology is applied in a system. The design is then formed based on the individual technology's characteristics and performance. The approach allows innovative applications of current technologies to be designed and implemented. To further this book's intent, detailed applications of the technologies in building projects are not provided. Some suggestions are given as to potential applications, but the aim of these example systems is to inspire new designs rather than provide a set method of application. Therefore, the text provides the information required to select and apply the technologies in a way that is flexible; it does not explicitly guide or restrict the designers' use of them. The skill of combining and applying the technologies to a building design project remains with the individual designer, as this requires creativity which is inspired but can not be taught. This and the other books in the Modern Construction Series therefore facilitate the continuation of an innovative design process, enabling complex buildings to be achieved through an economically feasible and sustainable design.

Technical publications of building technologies are most commonly used during the detailed design phase of a building system. The basis for detailed calculations and system design, the early stage designs for a given system are consequently less specific in the choice of materials and systems for structures and facades. This late introduction of the specific facade technology into the design process creates a large disadvantage in terms of maximising system efficiency. A key fact which has been presented in multiple research publications highlights that the value of building performance and associated construction costs are both determined by the early stage design. The design process for buildings usually involves the production of interim reports which provide a snapshot of drawings, calculations and evolving specifications at a given point in time. The integration of technical design early in the design



c | Example of curved and folded glass corner detail



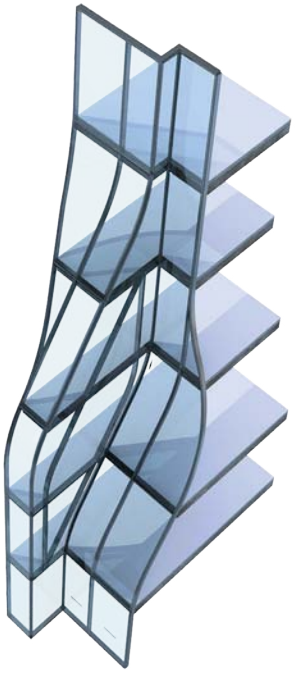
d | Example of GRC-clad steel tube secondary facade structure and GRP external shading louvres fixed to curved glazing

process provides opportunities for the technologies used to inform the design process as well as to inform the design 'product'. The linking of building systems so that they can interface more easily has long been an aspiration of manufacturers; the current situation is one where few systems coordinate easily with each another (a). Interfaces between different building systems can be extremely complex and difficult to design prior to construction, resulting in laborious onsite fabrication to resolve the interfaces, which restricts the ability to achieve continuous high performance across the whole building and envelope. This suggests that the taxonomy of building systems incorporated in this book should be based on a robust set of genuinely different generic types: these would have to be identified independently of current systems of classification, such as those described in designers' specifications. The structure of architecture-based specifications identifies components and assemblies in interrelated sections, where each sub-item in the assembly is identified independently: such as 'curtain walling', which itself comprises several generic external wall types set out in this book. Specifications then link items such as 'curtain walling' to their constituent materials of glass, seals, paint finishes and so on under quite different headings. While the system is useful in describing a building for use by a contractor, particularly with regard to national standards including those for performance testing, specifications do not relate to the parts in a way that can be easily used at the design stage in order to understand generic facade assemblies. Therefore, the approach taken in the classification system of the Modern Construction Handbook is to group items in a way known to building design teams: structure, walls, roofs, and environment.

Governing aspects of design

Building system constructions can be thought of as having three governing aspects; the materials and assembly, the system performance and the architectural intent or integration of strategies. All three are interlinked (b) with factors of one aspect often affecting factors in one or both of the other aspects; considering all three aspects is key to a successful design as they form the foundation for the building systems. All aspects can be considered in parallel; due to the interlinked nature, the different constraints and opportunities for the design related to each aspect can have an impact on the constraints and opportunities of the other two aspects. Given the nature of the design process, with the greatest impact on the system design achieved in the initial phase and a potential for design influence that then exponentially decays over the duration of the project, the described approach can be adopted from the initial design stage. This will provide the required impact on the design, allowing the required level of performance and sustainability to be achieved.

This book aims to present current construction technologies and trends, highlighting characteristics relating to the three governing aspects for each topic or system. This is in order to enable the existing technologies to be integrated to form a feasible building system design, which is achieved through the interpretation of the designer. Technologies can be assessed and compared independently of traditional application to allow an advantageous application to be determined, which may not correlate with the traditional applications of the technology. The integration of technologies should be based on the key aspects of materials



a | Envelope with curved and folded glass corner detail



b | Example of solar insolation analysis of complex forms



c | Section through double skin facade with plants in cavity

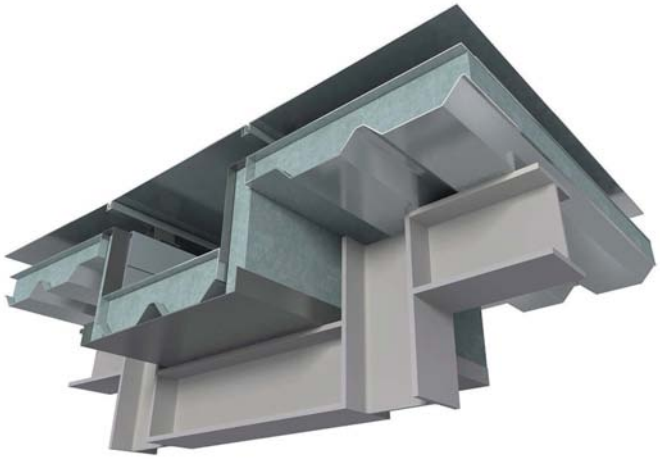
and assembly, performance and architectural intent, rather than previous project applications. This text also demonstrates the shift and continuity between traditionally constructed pre-industrial buildings and the current technologies which can be used to form the mass customised complex geometry buildings of the 21st century. The word 'complex' is used to denote geometries which are not rectilinear, and therefore cannot be described by plans and sections which can be extruded in a straight line through the form of the building.

Information layout

The construction of buildings has, historically, been based on a varying relationship between loadbearing structure, walls and roofs, and this forms the basis of classification in this book. In some buildings, the walls, roofs and structure are a single entity, as they are in medieval cathedrals – with the exception of their additional timber roofs, used to protect the structural ceiling. In framed construction, the walls and roofs can be continuous over a single supporting structure: while in many cases of 20th century construction, walls, roofs and structure are quite separate, and are then subdivided within each category to provide a 'collage' form of construction where systems are overlaid in the manner of a visual collage.

The current technologies used in the design of contemporary buildings are presented, grouping the technology systems in distinct chapters covering walls, roofs, structure and environment. The book begins with a chapter on building materials, providing knowledge of the initial processes of forming the materials that comprise the building technologies, and ends with advanced applications of the systems described in the intermediate chapters, providing insight into the complex systems which can be achieved through the integration of current technologies. The category of materials precedes the technology specific chapters, since an understanding of the physical nature of materials is essential in construction-led architecture. The material properties and characteristics are given in a comparative form to allow the potential materials for a specific technology to be compared and evaluated, based on the key performance factors and required characteristics for a system. The current manufacturing methods for producing construction materials are also detailed, allowing the stages of the manufacturing process to be understood and considered when selecting materials for an assembly with regards to sustainability. The chapter presents how the tectonics of material systems have been used historically and how digital tools are bringing flexibility back into building construction, something which was considered to be too expensive until the arrival of CAD/CAM (computer aided design/computer aided manufacturing). This return to an almost pre-industrial approach to design allows new buildings to develop a much closer empathy with existing buildings, even if the technologies used are very different. The non-rectilinear nature of some of the material systems allows them to engage more robustly and elegantly with the existing fabric, both pre-industrial and that of 20th century Modernism in architecture.

In the current technology sections, the relevant characteristics of each technology are described, covering a wide range of elements from material performance to assembly method; these elements



d | Example of composite panel arrangement with metal rainscreen



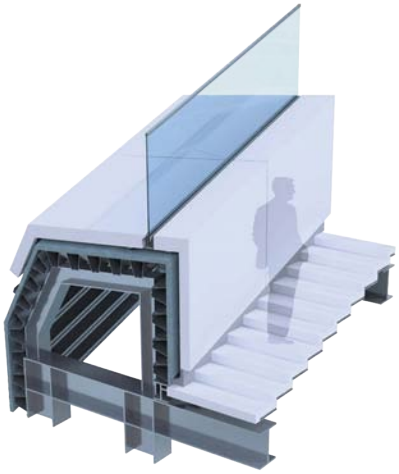
e | Example of typical loadbearing brick wall configuration with masonry piers

can all be mapped back to the three key aspects mentioned in earlier sections. The three aspects of materials and assembly, performance and architectural intent are themes which run throughout the book; these details are presented in each current technology section. The paragraphs on 'system design' show how the generic example works. Generic system examples of the technology are discussed in the text, providing information on their assembly and the mechanical performance as a primary structure or enclosure. The method for applying the system to different geometries is explained in 'system details'. The geometries show how the system can be set out on different mathematically based surfaces, and how it can meet at corners and junctions. The information is simply presented without additional analysis or guidance, so as to provide flexibility for application in design projects. The technologies can then be compared and selected based purely on their characteristics and performance for use in building and facade systems, with system examples used to inspire potential design solutions.

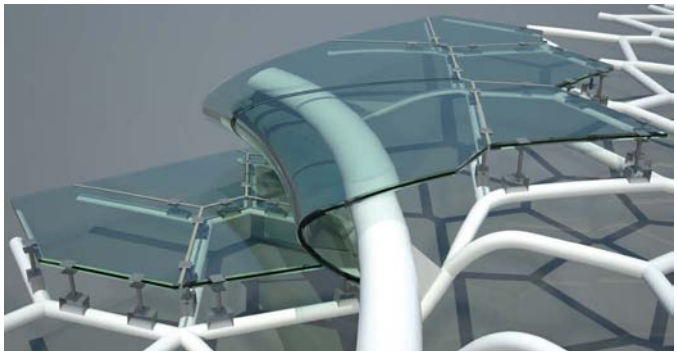
The environmental chapter provides an overview of building physics and its influence on a facade system design. The environmental elements have a large impact on all three key aspects; for example the material properties will influence thermal transmission through the envelope, therefore impacting the performance of the envelope and the conditions of the internal spaces. In order to meet the architectural intent in terms of structural form, the integration of the technologies in the system influences environmental factors of the occupied spaces such as the airflow and temperature, which will affect occupant comfort and energy consumption. In environmental terms, the use of several layers of envelope and structure in a single building can create a much richer set of internal spaces than those provided by the single-skin envelope. The outer wall can be made of a double skin, or even as a deep zone within the building, which is an inhabitable equivalent of the 'twin wall' or 'double skin' facade. This has helped to inform both material systems – not all of which need to be sealed – as well as the environment chapter where passive cooling, heating and ventilation can be used to reduce overall energy consumption as well as create a stronger link between the built environment of the city and the building itself. The information laid out in this section aims to assist this aim.

Lifts/elevators are described within the environment chapter since they are usually considered to be part of the mechanical systems, the layout of which is designed by a specialist consultant. As a result of this last decision it can be seen that the environment section could include both systems that reduce energy consumption by using low-energy passive strategies, as well as high-energy active strategies such as mechanical ventilation, and lifts/elevators can be seen as part of this strategy to make tall buildings usable.

The final chapter gives illustrations of possible applications of the technologies. This is intended to provide inspiration to the designer as to what can be achieved through the combination of these current technologies, rather than giving explicit guidance on how they should be used. This chapter also adds a parametric component to some of the examples, thus highlighting the range of possibilities that might exist for some of the examples shown.



a | Detail fragment showing GRC rainscreen cladding interface with roof surface build up



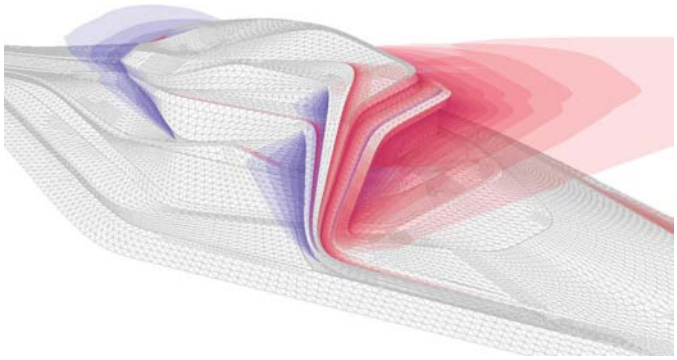
b | Example of complex curved glazed roof supported on steel tubes

Design motivation

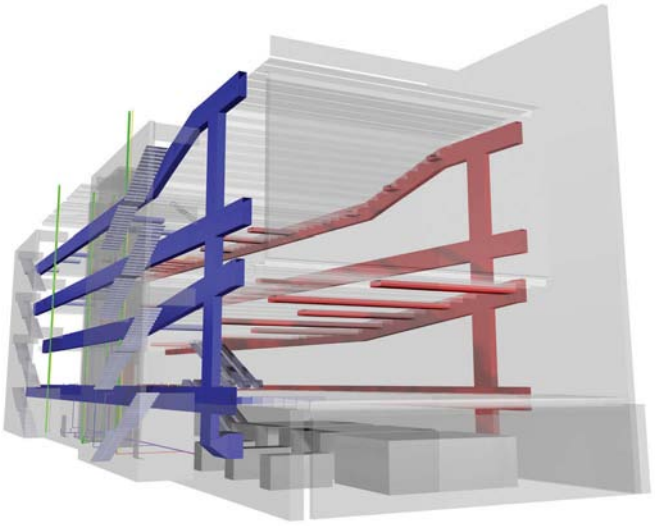
The effect of building construction on the environment has been of concern since at least the 1960s. There is now a need for sustainable design; more than just reducing energy consumption. The effect in building construction is firstly a growing awareness of the energy required to construct buildings, or 'embodied energy', and secondly the energy required to operate the building when in use. The embodied energy part of the equation is concerned with the combined amount of energy needed to manufacture the materials, to transport them to site, then install them on site. One method of reducing this is to make system designs and assemblies simple in order to allow for local production with non-specialised equipment, limiting the transport-related carbon impact. Sustainability should not limit the creativity of the design but fuel it; ambitious building designs should be realised not by simplifying the concept or geometry but by simplifying the systems used to make the complex design achievable. Striving for increased simplicity in system assembly also provides honesty in the construction, along with advantages in structural and material efficiency.

An example of simplification can be seen in the development of the ceiling void, which was originally designed to provide a contained airflow route to expel air from the internal space without creating uncomfortable airflows in the occupied space. With increased mechanical and technological servicing, the function of this space shifted to one of concealing servicing. The trend is now moving towards exposed servicing in the ceiling space. This development has been driven by the creation of flat slabs which resist punching shear, eliminating the requirement for slab down-stands which increase the ceiling zone depth and require services and ducts to be redirected to accommodate them. With the elimination of these non-uniform servicing and duct routings, it is considered acceptable to have services exposed, removing the need for a suspended ceiling as its original function of directing air has been replaced by ductwork. This leads to a reduction in floor height as the ceiling void depth is effectively eliminated, producing benefits mainly in reducing the material required for the building. The overall height of the building is reduced, decreasing the primary structure mass and the area of facade required.

20th century Modernist architecture can be considered in terms of its response to mass production techniques through the use of the structural frame. Building components and assemblies were used as repeated identical elements in building compositions. The use of steel or concrete frames led to building envelopes being enclosed in non-loadbearing cladding. The use of repeated, rectilinear bays can be seen as a response to manufacture, including the straight lines of cut timber and plywood used for concrete formwork. Consequently, as a result of the widespread use of the structural frame in much of 20th century Modernist architecture, the separation of structure and external wall has dominated where the facade is reduced to non-loadbearing walls. This trend is now being reversed as new materials and manufacturing techniques provide the ability to easily create non-rectilinear forms. This provides opportunities for increased integration of the envelope system back into the primary structure, as the method of using rectilinear bays as an assembly is no longer a necessity. The integration of skin and structure into loadbearing facades can also allow much



c | Example of environmetal analysis: Cumulative shadow projection for a complex form



d | Example of model showing mechanical ventilation system

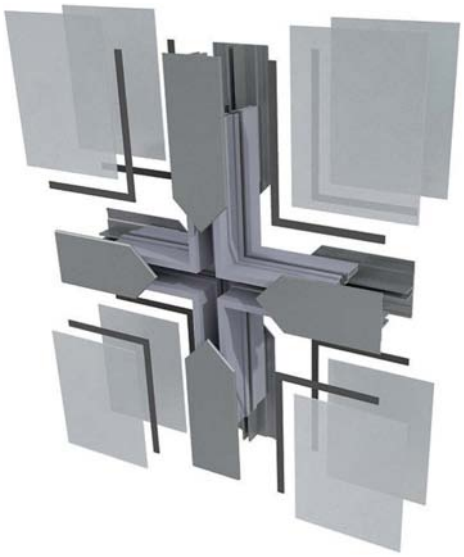
greater freedom in the design of the external envelope to suit the requirements of the spaces immediately behind. Both loadbearing and deep rainscreens are possible solutions for this approach.

The recent introduction of computer-controlled tools has taken away the imperative of mass production, offering instead possibilities of 'mass customisation' where many components of different size can be produced quickly to the required quality. In terms of the relationship between structure and external envelope, the introduction of mass customisation suggests that systems for both facades and structures could become more complex and interdependent, while remaining economical by the standards of contemporary building construction.

As previously mentioned, there are three key aspects which should be considered when creating a building system design: materials and assembly, performance, and the integration of strategies to realise the architectural intent. These underpin the design of high-performance building systems, regardless of geometric complexity or external constraints. The three aspects are highly interdependent; they can be evaluated separately but must be balanced and considered in parallel to achieve an optimised design. During the course of this book, each current technology is presented with text describing the relevant characteristics, constraints and opportunities which can be linked to the three key aspects of design. These aspects, explained in the following sections, can be mapped and compared to inform design decisions for the creation of a building system design.

Materials and assembly

Materials and assembly forms the tangible element of the design; it is often considered as the more straightforward aspect. This category encompasses: the materials used and their properties, the manufacturing methods and the physical assembly. The materials chapter provides fundamental material data to inform material choice for a specific technology or system. Additional information is given with regard to manufacture and typical applications based on historic and current trends. For each material there are certain inherent constraints, but also opportunities relating to the properties and the methods for manufacture: these are discussed in each section. The information provided should be taken as knowledge to fuel the design of building systems of any geometry or complexity. Current trends include the increased use of insulation in envelope build-ups in order to increase the thermal performance leading to a reduction in heating and cooling loads. The way in which materials are used is evolving, with increased use of metal and concrete panels as a rain screen. The method of fixing elements is also evolving, with a trend towards simplified connections; for example connections in glazing are moving increasingly towards glued and clamped connections with a gradual reduction in the number of metal fixings. There is also an increased use of composite materials, such as fibre-reinforced concretes and polymers for both cladding and structural applications. The materials chapter will provide the relevant information to aid in the design of building structures and envelope systems. For each material there are certain inherent constraints but also opportunities relating to the properties and the methods for manufacture. These are discussed in each section.



a | Exploded detail view showng polycarbonate composite panel joint construction



b | Example of polycarbonate composite panel construction

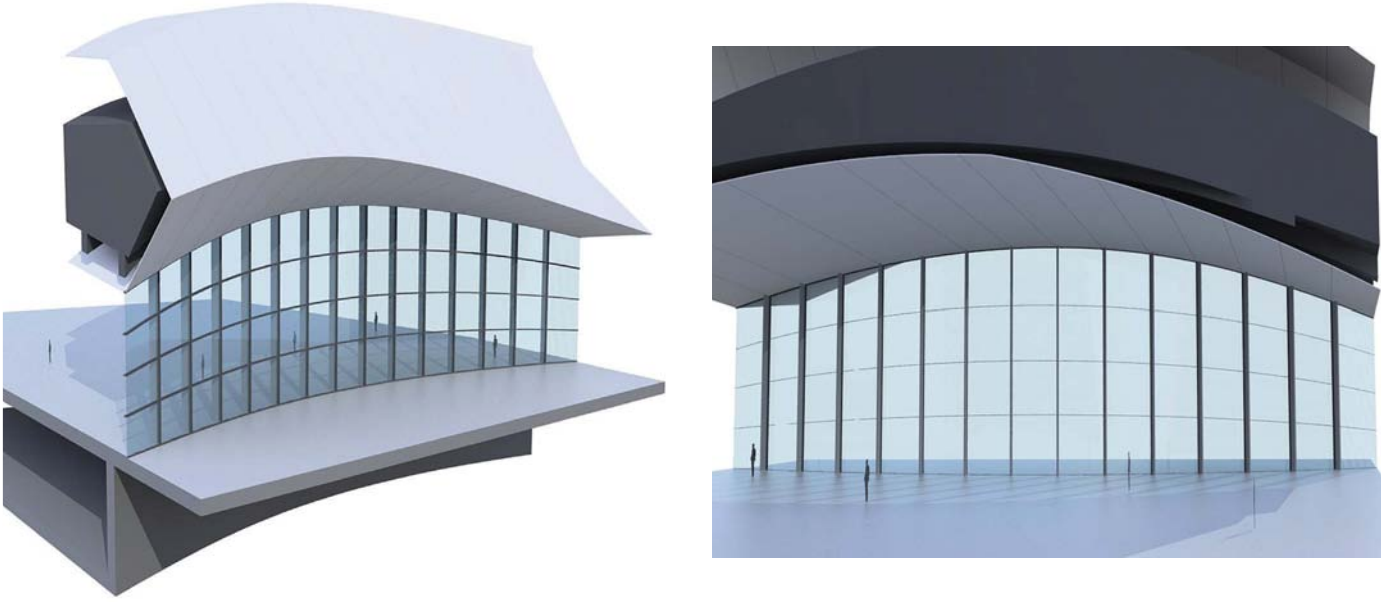
The information provided should be taken as knowledge to fuel the design of building systems of any geometry or complexity.

Current architectural design has a preference for rectilinear spaces linked in a spatial organisation which is also primarily rectilinear, though dependent upon site conditions, based around the use of rectilinear structural frames. The design generated is then given an outward facade expression of materials formed with openings or wraps as an interface between the internal arrangement of the building and its immediate site context. An alternative design methodology is to add the material systems to that mix, using integration methods as an additional driving factor. This leads the design into a direct connection with traditional loadbearing construction but moves it forward with changing methods of industrial production. Digital tools allow the performance of a design to be explored and optimised (MCH_14, b), and be developed to enable the fabrication of a component which has not been made in a particular way before. Alternatively, a design may use historical models, either to endorse the construction methods of existing buildings, to mix old and new to create something new, or even to advance what is already constructed by physically adjusting it using the same material but a different material system.

From the point of view of construction, the highly integrated and also geometrically complex system could be achieved with digital tools for design and fabrication; the tools of mass customisation. The possibility of mass customisation of components allows a departure from the repeated rectilinear component so that components can be more geometrically complex, either as individual components or as complete building assemblies. Recent developments in building forms have been seen in both twisted and folded geometries.

The approach of folded and twisted building forms is a way of introducing complex geometry while maintaining contemporary principles of 'repeatability' in order to make them economical to build using a conventional approach to construction. In this sense, the approach of twisted and folded forms is an intermediary one between the rectilinear repetition of Modernist construction and the emerging construction methods described here. The current approach to folded and twisted facades requires geometric discipline in order to maintain the repeatability of components, mainly facade panels, used in conventional construction techniques. With the greater introduction of digital fabrication tools, the need to maintain a geometric discipline will slowly disappear, perhaps making design choices more dependent on the principles of design performance that is imperative in buildings.

In terms of manufacture and assembly, there is a balance to be determined between on- and off-site production; both have certain advantages and there is commonly a combination of the two, because in modern construction it is not practical to use purely one form of production. Details are given in each section relating to the construction and assembly sequence for each technology. These can be compared and collated when designing a system to ensure its construction is feasible.



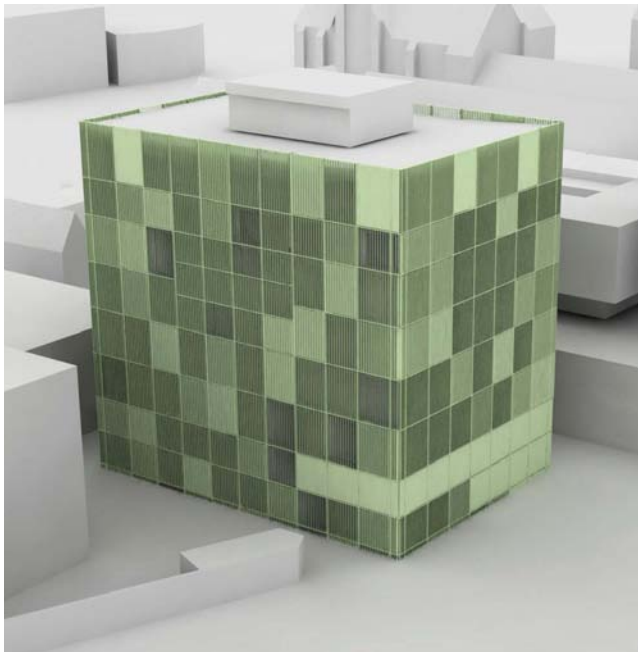
c | Case example of GRC rainscreen facade

One example of the opportunity in material and assembly aspects is found in FRP composite cladding, which utilises the high strength-to-weight ratio properties of the composite material in addition to the composite action of the panel assembly. The panels consist of two thin sheets of FRP separated by rigid thermal insulation and clamp-fixed on all sides (a). This separation of the sheets provides a greater bending resistance resulting in a stiffer panel. The FRP material used has a high strength-to-weight ratio, particularly in tension, allowing the sheet thickness and weight to be reduced. The buckling failure, which would also be common for a thin sheet of FRP in compression, is restricted by the internal thermal insulation which prevents the sheets from buckling inwards, enabling the sheet thickness to be reduced further. The assembly allows for a decreased panel thickness, but the inclusion of a thermal insulation filling and thermal breaks in the extruded frame means a good thermal performance of the wall can still be achieved. The system elements are simple to manufacture and combined into unitised panels which can be manufactured off-site and then assembled on-site to create the desired structure, creating a straightforward and quick assembly process (b). Further information on this system can be found in the section of fibre reinforced polymers as wall systems (MCH_178).

Performance

The performance of an envelope or structural system is another critical element which underpins the whole design; a successful building system cannot be achieved without consideration of the performance aspects from the beginning of the design. The envelope has the function of providing weather resistance for the building structure and internal space, it is the interface between the internal and external spaces of the building. This system must function at a high level to be structurally stable and create the desired internal environment while minimising the energy consumption of services. An essential factor of environmental concern is the energy consumed by the building in use. Natural ventilation, thermal mass and associated issues of night-time cooling have become primary tools in reducing energy consumption for heating and cooling buildings. This has resulted in the reintroduction of opening windows and cross ventilation in building envelope systems. Where spaces are required to have a high level of technical performance, or a specific daylight provision, these aims can be achieved without immediate reference to the external envelope, but instead to the building structure. An interstitial zone between internal spaces and external facade structures creates an opportunity for a buffer zone between them (MCH_8, c), which could be used as an inhabited space or for circulation around the building.

The performance aspects of technologies are detailed throughout the chapters. Information is provided regarding methods for providing effective waterproofing and thermal performance both for the main area and for joints within each system. When combining technologies, this information must be collated and compared in order to inform the integration of technologies to a high-performing envelope system. The integration of skin and structure into a loadbearing facade has obvious difficulties. The conventional 'layered' approach of cladding applied to structural forms in Modernist construction has the advantage of superimposing



a | Example of environmental analysis: Adapted shading system design based on solar radiation analysis



b | Example shading layout construction, where the density of shading can be varied

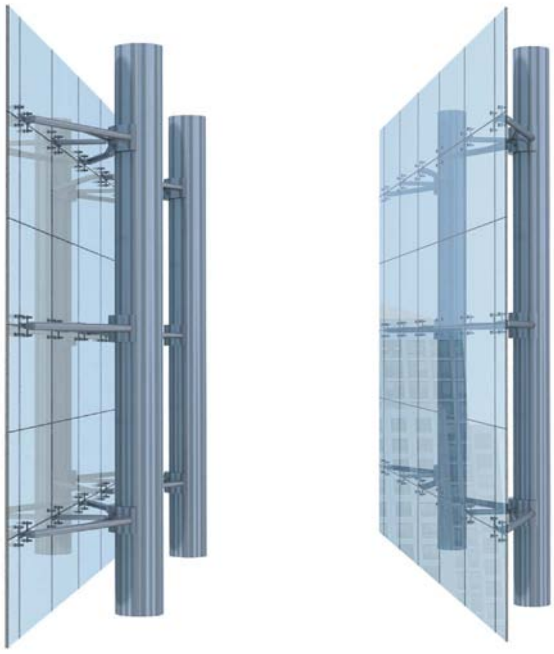
waterproofing, thermal insulation and vapour barriers to form a sequential wall build-up. In loadbearing facades, it is more difficult to integrate these different functions into a single structural wall. In combining current technologies to form an emerging technology, the technical performance of the new technology is dependent upon the successful integration of the existing technologies.

An example of the consideration of performance aspects can be seen in the inclusion of customised solar shading technologies to create a comfortable internal environment. The overall performance of the envelope is increased by using targeted shading design, which customises the shading level to the specific facade area, based on a solar radiation study of the proposed building form and orientation (a). Shading in general is used to improve the performance to create a comfortable internal environment; this is taken to another level of increased performance by customising the shading based on the incident solar radiation of each envelope area (b). The result is that an increased level of shading is used in areas of high-incident solar radiation to reduce the thermal gains in the internal spaces corresponding to those areas, reducing the cooling load of the building. Further information on this system can be found in the section on solar shading as an environmental system (MCH_364).

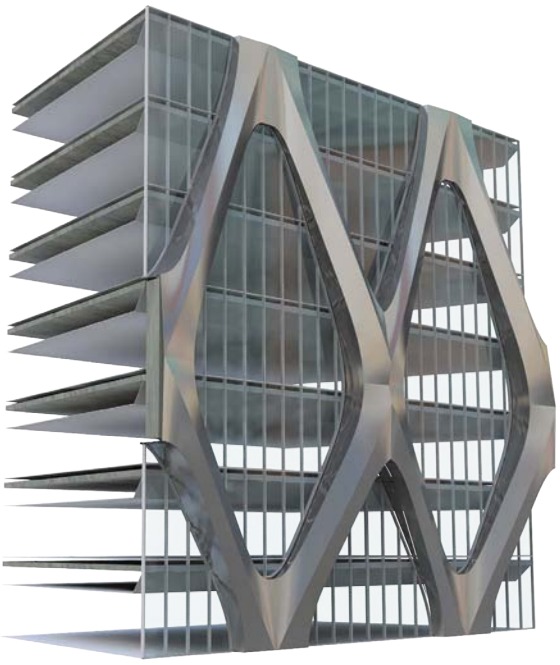
Realisation of architectural intent through integration of strategies

The elements integrated to form a facade system impact the overall system design, and vice versa. The existing technologies are selected to meet the envelope design and architectural intent, but also to enhance it. To achieve this, a high level of integration is required from the initial facade concept, an approach which provides a high level of flexibility in the overall design of the building. This integration results from the geometric 'behaviour' of the being better controlled than would be the case if components did not have 'rules' set for their combination in a facade assembly.

The tendency is to avoid interfaces; these arise from the combinations of different systems – typically walls and roofs. Interfaces can have a lower performance than the body of the facade system and therefore reduce the performance of the envelope as a whole. These can be avoided by providing a single material system using the technologies detailed in this book. A single material system, however, is not always suitable as there is a balance to be found between the function of the envelope and the level of integration reflected through the extent of interfaces. In certain circumstances, it is more beneficial to create a higher performing system through the combination of a range of material systems. The option of flexibility provided by multiple material systems of higher integration is beneficial for projects with certain site, structure and design constraints. The example of a completely self-contained unit in a rural site with no infrastructure allows for complete integration of both the envelope systems and the building structure, as there are no governing external constraints. However, this is rarely the case; the majority of building projects have to be designed to fit into the existing infrastructure landscape and constraints. In this case, a more flexible and therefore slightly less integrated envelope system can be advantageous. For example, for a building to be constructed in a large city where the site area is highly constricted, a more flexible modular system could be preferable. This would allow the system to be fabricated off site, providing a certain degree of system integration of assemblies which can then be transported to site, in small units, for installation.



c | Overviews showing bolt fixed glazing supported by branching steel framework



d | Example of metal-clad steel exoskeleton and unitised glazing facade

Some building designs for complex forms evolve as a result of more information being known about the building, allowing more of the design to be fixed. Consequently, the different criteria of the design can be set as 'parameters' which can be related as a matrix in the form of a spreadsheet. The spreadsheet can be linked to the process of modelling the building forms digitally in a parametric design software. Working parametrically allows the design to establish what is 'fixed' and what will be 'variable' in the design development. This approach allows a digital design method to evolve. In facade design, the behaviour of the model as a set of surfaces can be understood by number, size, geometry and so on. The relationship of the parameters in the design allows the digital model to evolve through an engineering-based method of iteration, rather than starting the digital design model again each time a new option is explored. This approach requires some discipline and clarity in the design approach at the outset, which often makes the parametric design method more suited to design development than initial design research. However, parametric plug-ins are becoming available for early stage design software, ensuring that the parametric approach is gaining influence throughout the design process.

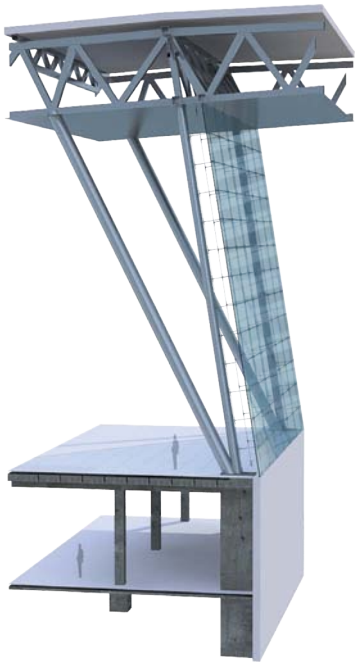
Different assemblies and component sizing and arrangements can be explored through parametric modelling, which allows for the optimisation of complex system arrangements. This variation in more complex arrangements of linked spaces is tackled in projects where design is informed by an interest in parametric design, where spaces can be linked by rhythm and links achieved through the assistance of computer software. Parametric modelling provides an interrelationship between parts of the building as well as the urban space surrounding it. Through this method, many more iterations can be investigated and explored than are possible by hand using conventional 2D CAD, or even by conventional physical modelling.

Bolt fixed glazing is an example of a technology which has opportunities related to architectural intent aspects and the integration of strategies. The structure and glazing system can be integrated to form a single slimline system. This can be advantageous both in terms of reducing the structural weight and complexity, and in realising an architectural intent of high visibility throughout the envelope if desired. Lateral stability can be provided by wide lateral bracket fixing arms which increase the structural stability of the system, enabling it to be used to form large spans of glazed facade (c). Further information on this system can be found in the section on bolt fixed glazing as a wall system (MCH_126).

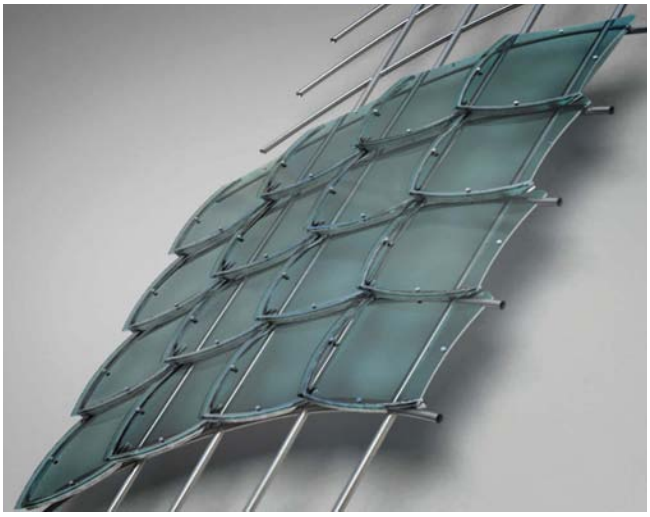
Relation to other design industries

The building industry moves at a considerably slower pace than that of technology or transport design industries in terms of its rate of technological development. This is in part due to the scale, which is considerably larger for building technologies, meaning that full-scale prototyping of a complete building system is impractical. This means the system must be physically tested in small sections of around one or two storeys. The design is then validated through predictive modelling and interpretation of small scale testing; the complete performance of the building technology as part of a building system can only be determined after it is built into a new building construction. Because of this, the drive to develop building technologies is often project-driven.

Building technologies also have very different requirements; there is a need for certain movements, durability and flexibility



a | Case example of a large-scale unitised glazing system supported by double cable system and interfacing with metal-clad steel structural trusses



b | Example of shingled glazing system supported on steel tubes

of the system and an increased lifespan with the ability to adapt and update the system at a later point. There is also a need to be able to respond to change without creating inefficiency in the initial design. The system may need to respond to changes in load paths, cladding and glazing elements and architectural intent, for example.

Development within the building industry is usually project-based and therefore emerging technologies are developed based on the demands/intent of a specific project. However, emerging technologies can be taken from other industries, such as the use of polymer seals, providing opportunities for envelope system design. The use of parametric design in architecture has been centred around the use of software that was originally developed for other industries.

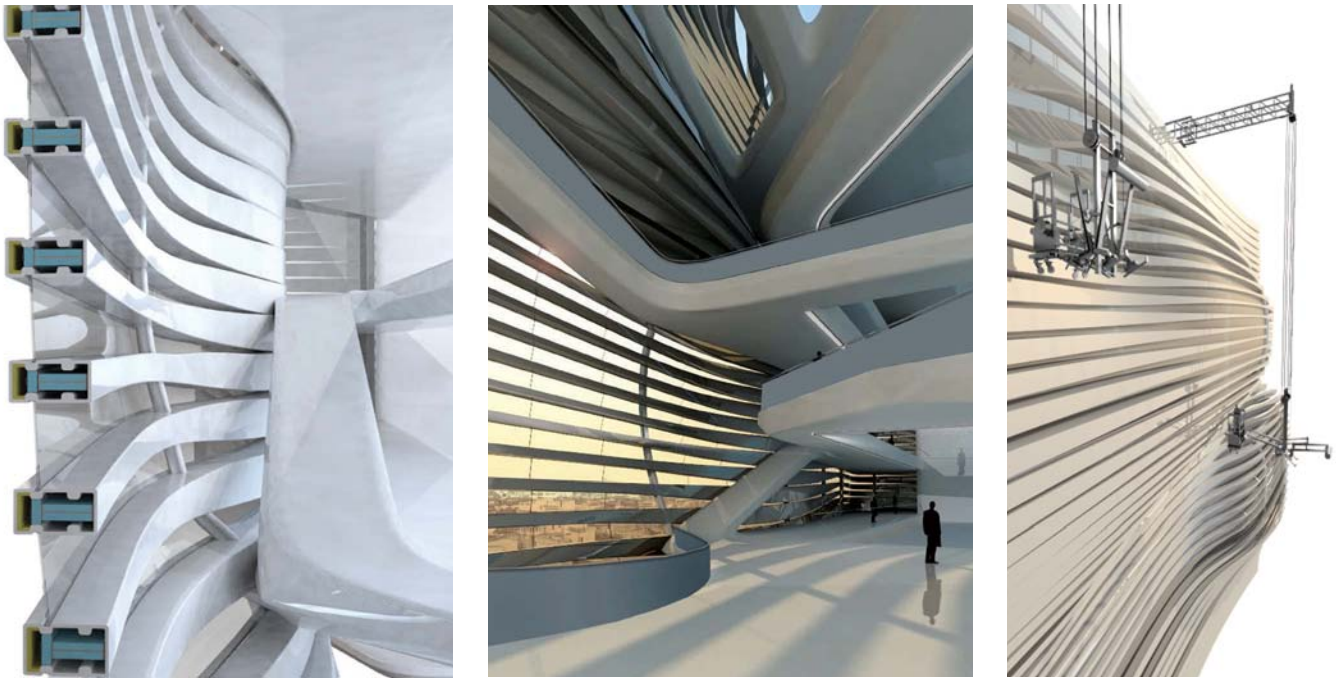
Application cases

Considering the three aspects as described in previous sections, a firm basis is provided for creating an integrated high-performance system design. This can be advantageous when simplifying the system and reducing the material weight used, which has numerous benefits including increasing the sustainability of the design and reducing the system cost. Example cases are presented in the following paragraphs to provide inspiration for routes in which the technologies presented in this book can be taken forward using different approaches to inform building design projects.

The first case is an example of a current technology: this is where an existing technology is utilised with a focus on optimising the current technology to create a higher-performing system. An example of this can be found in Applications 12: large-scale glazing facades (MCH_454). This case is one of clamped glazing enabling a full-glazed facade across numerous storeys with a minimal visible intermediate supporting structure (a). This design pushes a current system to reach increased performance in order to allow the architectural intent of a large facade span with a high level of visibility, which is achieved through increased performance in terms of structural efficiency, waterproofing and thermal performance. This approach of maximising the performance of an existing technology is a relatively low-risk method of achieving increased performance with an integrated system, enabling the desired architectural intent to be created.

Another case is a building design which points to a new technology but is constructed using existing technologies. These projects provide inspiration and direction for the development of new technologies. The designs are bold, and push the boundaries of existing facade technologies, creating an opportunity for the development of an emerging technology. An example of this is in Applications 11: complex curved glazed roofs (MCH_452), This case shows a complex curved glazed roof consisting of small, geometrically identical panels (b). This points to the development of a panelisation tool to enable a complex geometry glazed envelope formed from unitised panels. This tool would allow the system seen in this case to be transformed into a uniform watertight envelope, formed of unitised glazed panels which are optimised in terms of geometry and assembly.

The final case is one in which the development of an emerging technology is used to meet the requirements of a particular project, as previously mentioned, which typically is how the development of new technologies is produced. This can be a material, construction method or a design tool that adds value to the system. This final case is generally higher risk, as a larger initial investment is required



c | Case example of full height glazing with integrated GRP-clad structural frame

for the development of the new technology in order to cover the design, analysis and testing required to prove the feasibility and performance of a new technology. An example of this case type can be seen in Applications 15: full height glazing with GRP-clad structural frame (MCH_462). In this project the structure has been fully integrated into the glazed wall system, significantly reducing the depth of the combined envelope and structure (c). This is achieved by coordinating the design of the envelope and the structure to ensure both are high-performing and easy to fit when combined to form the final system. In this case, the architectural intent can be realised in a way that also provides greater structural and material efficiency.

The three different cases show that development can either occur incrementally or in large steps; each method of development carries a certain level of risk, with the final case of developing and implementing emerging technologies carrying the greatest risk. All the application cases, however, follow the same approach intended by this book, of forming building systems from a collection of technologies which are evaluated based on their characteristics and performance capabilities.

The Modern Construction Series

The Modern Construction Handbook forms part of a series of modern construction books aimed at providing information for the design of high-performing building systems. The series consists of: Modern Construction Handbook, Modern Construction Envelopes, Modern Structural Design, Modern Environmental Design and Modern Construction Case Studies. This book in particular provides an overview of current technologies and their relevant materials relating to building structures and envelopes. Modern Construction Envelopes provides increased detail of envelope systems, to enable a detailed system design to be formed for an envelope system. Modern Construction Case Studies then gives project-based examples of the application of current technologies presented in the series, and emerging technologies. The other two books provide a greater basis for understanding the factors which need to be considered to accommodate complex geometries within the building system design. Modern Structural Design and Modern Environmental Design set out strategies for the integration of site context, spatial arrangement and internal circulation with structural and environmental deign considerations.

Qualifying comments

The building techniques discussed and the built examples shown are designed to last for an extended period with a relatively high performance. Consequently, buildings for exhibitions and for temporary use are excluded. In addressing an international readership, references to national legislation, building regulations, codes of practice and national standards have specifically not been included. This book explains the principles of accepted building techniques currently in use. Building codes throughout the world are undergoing increased harmonisation because of increased economic and intellectual globalisation. Building components and assemblies from many different countries are often used in a single building. Since building codes are written to protect users of buildings by providing for their health and safety, good construction practice will always uphold these codes as well as assist in their advancement. The components, assemblies and details shown in this book describe many of the building techniques used by the building industry today, but this book does not necessarily endorse or justify their use since techniques in building are in a continual state of change and development.

01
MATERIALS

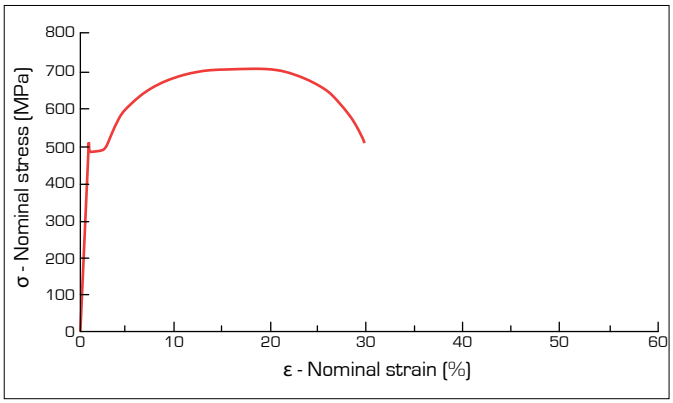
1	**Steel**
	Production
	Performance
	Applications
2	**Aluminium**
	Production
	Performance
	Applications
3	**Copper, zinc, lead**
	Production
	Performance
	Applications
4	**Stone**
	Production
	Performance
	Applications
5	**Glass**
	Production
	Performance
6	**Concrete**
	Production
	Performance
	Applications
7	**Fibre reinforced concrete**
	Production
	Performance
	Applications
8	**Ceramics**
	Production
	Performance
	Applications
9	**Timber**
	Production
	Performance
	Applications
10	**Polymers**
	Production
	Performance
11	**Material testing**



a | Steel hollow profiles

Density mild steel	7840 kg/m^3 (490 lb/ft^3)
Design strength	from 275 N/mm^2 to 900 N/mm^2 (from 5.7 x 10^6 to 18.8 x 10^6 lbf/ft^2)
Young's modulus	210 kN/mm^2 (4.4 x 10^9 lbf/ft^2)
Coefficient of thermal expansion	11 x 10^{-6} K^{-1} (6.1 x 10^{-6} ^{0}F^{-1})
Thermal conductivity	45 W/m$^\circ$C (26 BTU/hr.ft.^{0}F)
Specific heat capacity	480 J/kg$^\circ$C (0.11 BTU/lb^{0}F)

b | Properties and data of structural carbon steels



c | Medium carbon steel stress-strain graph

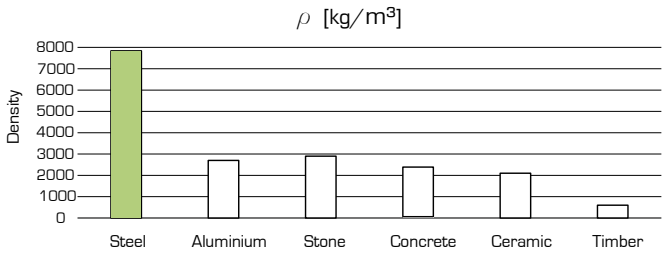
Overview

Cast iron and wrought iron were the forerunners of steel. Cast iron, a brittle material with high compressive strength, came into general use as a building material at the end of the 18th century, while wrought iron was developed some 50 years later. Wrought iron is a more ductile material and has greater tensile strength, making it less susceptible to shock damage. By the end of the 19th century, both materials had been superseded by steel (a)(b)(c). Steel was first produced around 1740, but was not available in large quantities until Bessemer invented his converter in 1856. This device introduced a method of blasting air into the furnace (hence 'blast furnace') to burn away the impurities that inhibited the extraction of a purer iron. By 1840, standard shapes in wrought iron, mainly rolled flat sections, tees and angles were available which could be fabricated into structural components, which are then assembled by riveting them together.

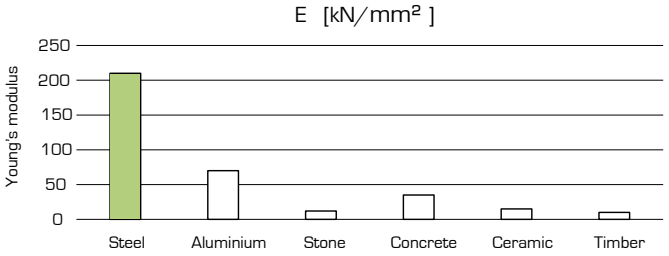
Comparison with other materials; general properties

In comparison with other materials, steels have the following general properties:

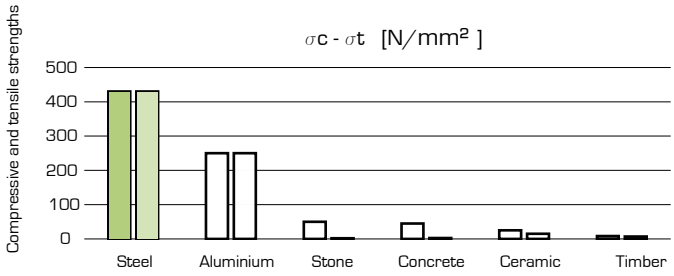
- High ductility (c), deforming long before they fail.
- Lighter than an equivalent structural member in reinforced concrete (d).
- High stiffness (e). High rigidity in both tension and compression.
- High strength in both tension and compression (f)(k).
- Appearance is smooth in sheet form; rougher of texture in rolled sections and castings, even with paint applied.
- High impact resistance.
- Thermal expansion approximately half that of aluminium (g).
- High thermal conductivity (h).
- High electrical conductivity.
- Susceptibility to continuous rusting, excluding weathering steels.
- Low fire resistance.
- Low specific heat (j).



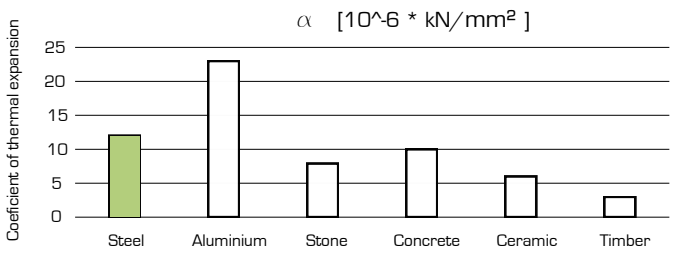
d | Materials density comparison



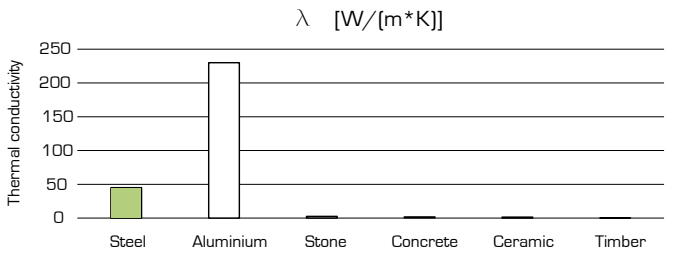
e | Materials Young's modulus comparison



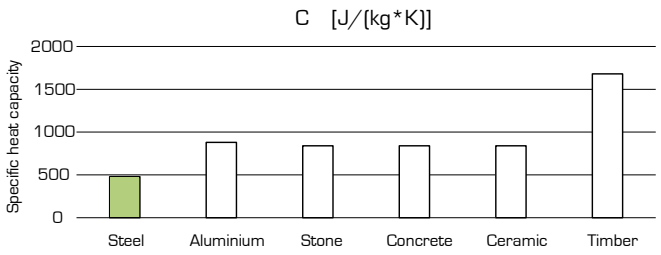
f | Materials tensile and compressive strength comparison



g | Materials coefficient of thermal expansion comparison



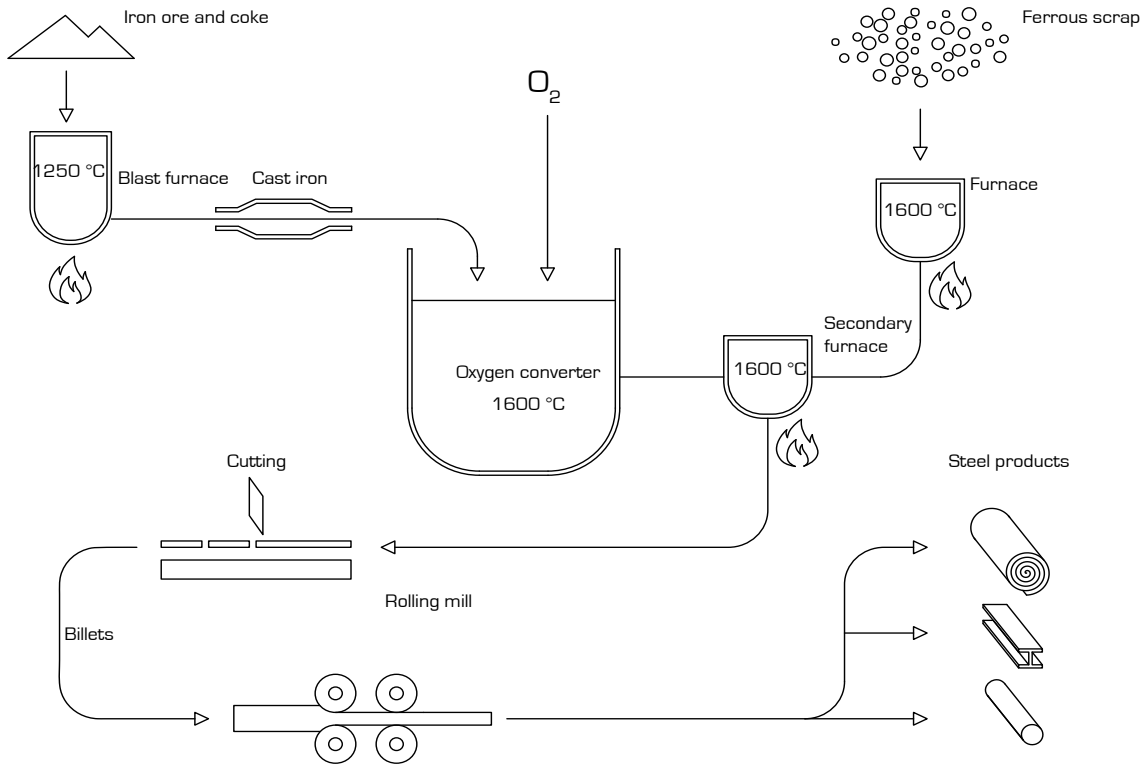
h | Materials thermal conductivity comparison



j | Materials specific heat comparison

Standard	Steel grade	Nominal thickness of element t [mm]			
		t ≤ 40 mm		40 mm < t ≤ 80 mm	
		fy [N/mm²]	fu [N/mm²]	fy [N/mm²]	fu [N/mm²]
EN 10025-2	S 235	235	360	215	360
	S 275	275	430	255	410
	S 355	355	490	335	470
	S 450	440	550	410	550
EN 10025-3	S 275 N/NL	275	390	255	370
	S 355 N/NL	355	490	335	470
	S 420 N/NL	420	520	390	520
	S 460 N/NL	460	540	430	540
EN 10025-4	S 275 M/ML	275	370	255	360
	S 355 M/ML	355	470	335	450
	S 420 M/ML	420	520	390	500
	S 460 M/ML	460	540	430	530
EN 10025-5	S 235 W	235	360	215	340
	S 355 W	355	490	335	490
EN 10025-6	S 460 Q/QL/QL1	460	570	440	550

k | Characteristic values for medium carbon steel



a | Steel production process

Production

Steel is an iron-based metal alloyed with small amounts of other elements, the most important being carbon. The three main forms of steel used in the building industry are sections, sheets and castings. First, iron is refined from ores containing iron oxide. The iron oxide is heated in a blast furnace until it is molten, using carbon as a reducing agent. The molten material is poured into moulds to produce pig iron. It is then re-heated to remove impurities, including carbon, to make cast iron that has a carbon content of 2.4 to 4 percent. Steel is produced by reducing the carbon content to approximately 0.2 percent, with materials such as manganese and silicon added to halt the oxidation process and stabilise the carbon content. It can be poured when molten to make castings or formed into ingots for later processing of steel elements (a).

Uses and Limitations

Structural mild steels are made in three types called 'grades', increasing in design strength from 275N/mm² to 400N/mm² (5.7 x 106 lbf/ft² to 8.3 x 106 lbf/ft²), varying slightly in different regions of the world. High strength steels can reach design strengths of 800N/mm² (17.6 x 106 lbf/ft²). Since the Young's Modulus is constant for all these types, the strength of the material increases but the stiffness remains constant. Steel also increases in cost with higher levels of strength, both in the cost of the raw material and in the working of the material. In addition, as strength increases in the material, welding becomes more difficult and consequently more specialised. In some high-strength steels, which undergo heating and quenching during their manufacture, the effects of welding could potentially undo the work of manufacture if sufficient care is not taken. Standard rolled sections are manufactured in the low-to-medium-strength grades, but higher strength steels are made mostly in the form of plate (b), due to lower demand for their use. Consequently, compound shapes for structural components, such as beams and columns, must be specially fabricated.

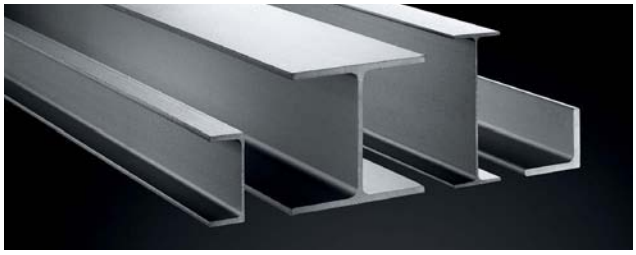
Hot rolled process

Hot rolling is a mill process which involves rolling (c) the steel at a high temperature (typically over 920° C (1700° F), which is above the recrystallization temperature of steel. When the material is heated beyond the recrystallization temperature, steel can be shaped and formed easily, allowing the material to be formed as large-scale components. Hot rolled sections, such as H, I, L or U profiles (d), are formed using caliber rolls in order to obtain the same cross-sectional shape as that of the rolls. After producing a near cross section such as an H-shape by caliber rolling, the product is finished by a universal mill and an edging mill (e). For example, an H-shaped cross section is formed when the material passes through four rolls, making the universal mill, which is equipped with a pair of vertical rolls and a pair of horizontal rolls, suitable for rolling H-beams. The edging mill is equipped with caliber rolls as shown in the diagram above, and has the ability to adjust the flange widths of individual products. The arrangement of rolls varies with requirements for the specific cross-section of the material, but the process for each profile is very similar.

Hot rolled steel is typically cheaper than its cold rolled equivalent due to the fact that products are often manufactured at source, avoiding the need for steel to be reheated, which is the case with cold rolled steel. As hot rolled steel cools, it shrinks slightly, allowing less control over the size and shape of the finished product when compared with comparable



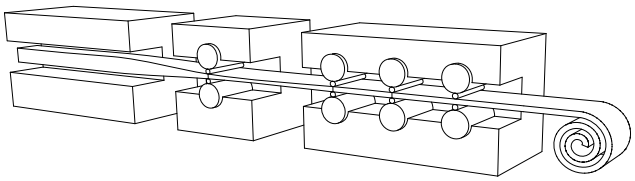
b | Steel coil



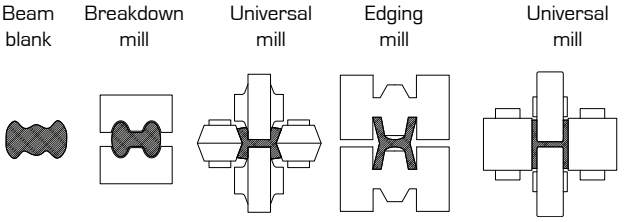
d | Steel open section beams



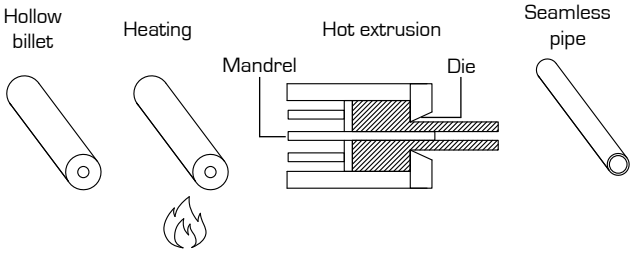
f | Steel hollow section beams



c | Steel rolling process



e | Rolled steel open section beam process



g | Hot extruded steel seamless pipe production

cold rolled products. Hot rolled products, such as steel bars, are used to make large-scale structural components such as I-beams, box sections and tubes. These are used in situations where precise shapes and tolerances are not a primary requirement.

Cold rolled process

Cold rolled steel is essentially hot rolled steel that has undergone further processing. The steel is processed further in cold reduction mills, where the material is cooled (to room temperature) followed by annealing and/or tempered rolling. This process produces steel with closer dimensional tolerances and a wider range of surface finishes than hot rolled steel. When referring to bar products, the term used is 'cold finishing', which usually consists of cold drawing and/or turning, grinding and polishing. This process results in a higher-strength material with four main advantages over hot rolled steel: cold drawing increases the yield and tensile strengths, often eliminating further costly thermal treatments; turning removes surface imperfections; grinding narrows the original size tolerance range; polishing improves surface finish.

All cold-formed products provide a superior surface finish to those which are hot rolled. Their application suits conditions where tolerances, surface condition, concentricity, and straightness are the major factors. Cold-worked mild steels are also used for much smaller-scale structural components such as lightweight structural framing in metal framed housing and low-rise commercial buildings, as well as in drywall partitioning and in backing walls to facade systems.

Processing

Production of tubes and pipes

There are two primary types of steel pipe (f); one is seamless and the other has a single welded seam along its length. Each type has a different use. Seamless tubes are typically more light in weight, and have thinner walls. Seamed tubes are heavier and more rigid, with greater consistency in their physical properties, and are typically straighter. Typically, seamed tubes are used in instances where the pipe is not put under a high degree of stress. Characteristics of pipe size can be varied during manufacture, such as diameter, as can the wall thickness of the pipe also be varied during production. The specific steel grade used will affect the strength and flexibility of a pipe. Other controllable characteristics include length, coating material, and finish.

Extrusion

It is possible to extrude steel to form complex sections (g), but this currently has only limited applications due to the high pressure needed to extrude the material. Aluminium is a much softer material, making it easier to extrude. Even when aluminium is alloyed with other materials such as bronze, the extrudable size of sections drops dramatically. Extrusions in steel cannot exceed shapes that fit into a circle approximately 150mm (6") in diameter. This is too small for structural sections, but their smooth appearance makes them suitable for components such as stiffeners in curtain walling, to provide a fin that is visually more refined than an I-section or a tee. Currently, it is still far easier to roll steel sections than to extrude them.



a | Galvanized dipping process



c | Fire protection coating



b | Paint coating



d | Manufacture of curved stainless steel panels

Performance

Degradation of the material

The effects of corrosion, oxidation and degradation both change the appearance of steel and can reduce the performance of the material, even leading to its failure if maintenance is not carried out as scheduled. Where steel components are coated with plastics or paint coatings, steel can undergo surface discolouration, paint delamination, solvent swelling and embrittlement of the material itself. Steel can be attacked as a result of water-based corrosion or be oxidised at higher temperatures.

Protections

Galvanising is a zinc coating that is corrosion-resistant, applied to the steel in a hot dip bath or as a flame spray (a). Galvanising occurs after fabrication of steel components to cover all the welding and drilling. This process can cause distortion of smaller steel components, so may not suit all types of fabrication. The appearance of galvanising when new is a mottled shiny grey, turning to a dull grey with weathering as the zinc oxidizes. Its visual appearance is often not suitable for exposed structural steelwork or cladding in buildings, where paint coatings are more common.

Paint coatings

Paint coatings are applied in layers, typically as follows:
The first coat, the primer, is applied directly onto the cleaned steel surface (b). This coating helps to create a better surface finish in the final layer by providing a high amount of adhesion for coats applied subsequently. Primers are applied directly to steel to provide resistance to corrosion.

Intermediate coats are applied in order to build up the overall film thickness of the paint coating. Thicker coatings provide a longer life in the service of a steel component, particularly when exposed to the atmosphere. Intermediate coats are specially designed to enhance overall protection and, when highly pigmented, decrease permeability to oxygen and water.

The finish coat provides the final appearance and surface resistance of the paint system. Depending on the conditions of exposure, the paint build-up provides the first line of defence against the effects of weather, sunlight, exposure and condensation.

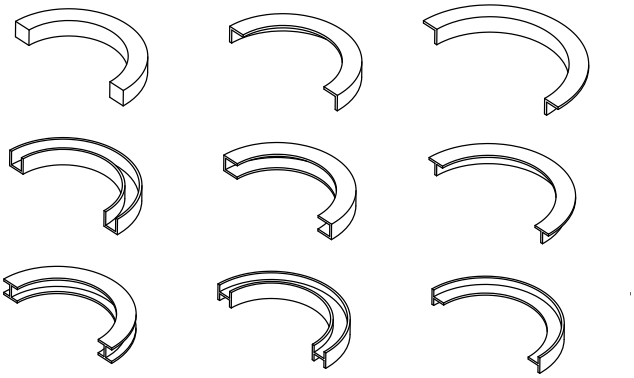
Stripe coats are coats of paint that are applied locally to welds, fasteners and external corners. Their purpose is to create an increased thickness of coating at edges and corners, where paint has a tendency to contract and thin upon drying. Paint coatings can also provide fire protection through the use of intumescent paint (c).

Stainless steel

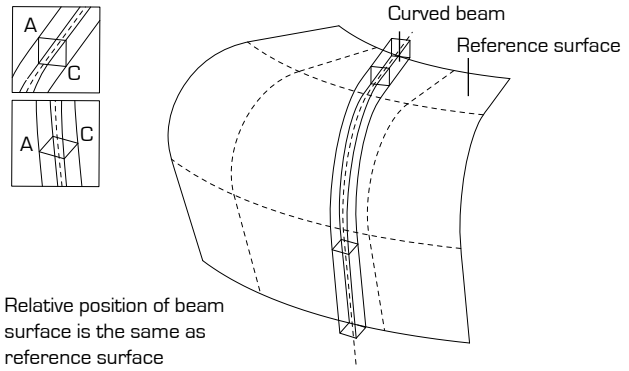
Stainless steel is an alloy of steel which contains between approximately 11 and 25 % chromium, together with nickel in some types, giving it properties that are distinct from carbon steels; the main one being a high resistance to corrosion without the need for an additional coating. Since the material is considerably more expensive than carbon steels, stainless steel is most commonly used in small building components and in cladding panels where durability is a primary requirement (d).



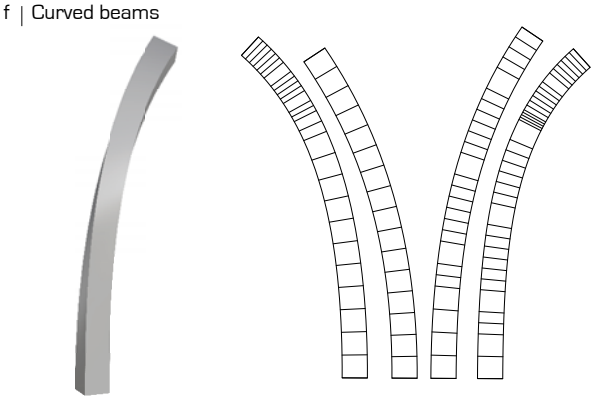
e | Mandrel tube bending machine



f | Curved beams



g | Design of bespoke twisted beam elements



h | Fabrication of bespoke twisted beam elements

Applications

Standard steel beam elements

Sizes of standard beam and hollow sections range in depth from between 21.3mm and 1036.3mm, and in width from 21.3mm to 508mm, as shown in Eurocode design tables. These standard sizes vary slightly between countries as a result of the requirements of each market. The length of a beam element will depend on the cross section, thickness of steel, transportation and factory limitation, but standard steel sections can be manufactured in lengths from 12 metres to 20 metres.

Stainless steel

For conditions where the environment is highly corrosive, the use of stainless steel is extremely suitable, as the material is highly resistant to corrosion and usually requires no coatings. Stainless steels have higher fire resistance than carbon steels. Although the material develops a thin oxide layer that protects it from further corrosion, different grades of stainless steel are available to suit the severity of exposure from polluted urban to maritime to rural environments. When using stainless steel there is the risk of bimetallic corrosion at the junction of stainless steel and carbon steel when they are used together.

Working with the material

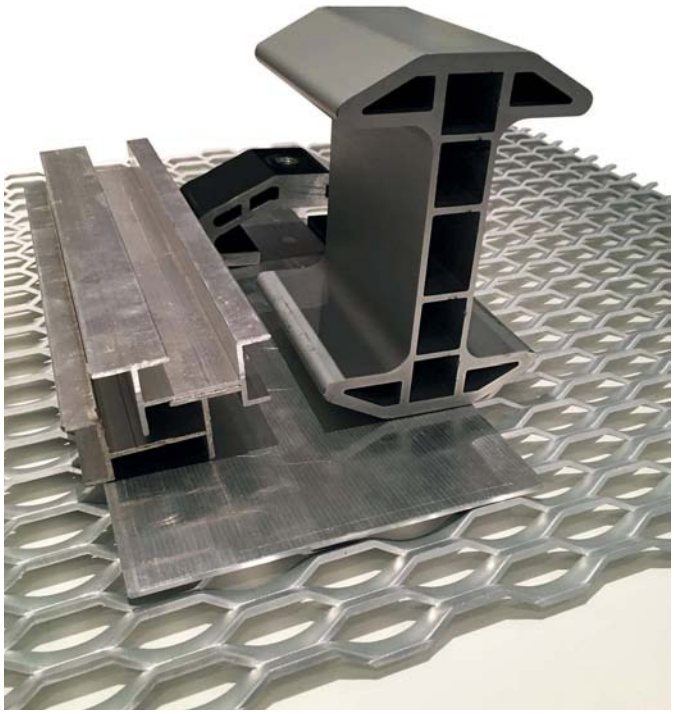
Sections and sheets can be curved to small radii (f). Bolting and welding are the most common methods of joining sections, sheets and castings. Steel can also be sawn and drilled. An essential characteristic of steelwork is that it will continue to rust if surface protection is not provided. When drilling or cutting the material, the newly-exposed surface requires protection, which is particularly important if the material has already been factory coated.

Cold bending of steel sections

Tubes, angle sections, channels, I-sections, channels and box sections can be curved by the process of cold bending. This method uses mechanical force to push a steel section against a die, forcing the element to take the shape of the die (e). An alternative method is induction bending, which is used mainly for large section tubes. This technique uses induction to heat up a short length of pipe quickly, resulting in minimal deformation of the profile of the curved section.

Specially fabricated steel components

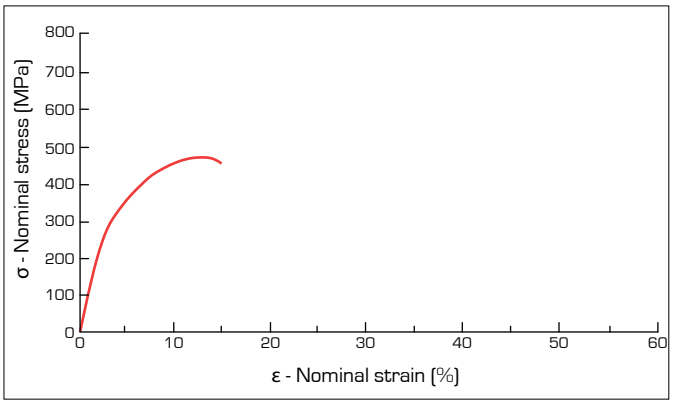
Some shapes of steel section can be difficult to achieve with conventional processing methods. Specially fabricated steel components are made using advanced computational modelling and digital fabrication tools. A recent example of the application of this method is the structural frame of the Beijing National Stadium, designed by architects Herzog and de Meuron. A significant challenge, from the point of view of fabrication, was to use steel box sections for structural beams of varying cross-sectional shape, which also resulted in complex geometries at the junctions between the structural members. The outer faces of the steel box sections were maintained as always being parallel to the base surface, which resulted in twisting box sections (g), made from flat steel plate which was curved to form each box section. Consequently, all surfaces of those box sections remained developable, that is to say that they were made from flat sheet. The individual faces of the box sections were curved to shape, then assembled and welded together to form complex structural sections that could not be made by conventional means (h).



a | Aluminium products

Density mild steel	2700 kg/m^3 (169 lb/ft^3)
Design strength: heat treated	Extrusion: 255 N/mm^2 (5.3 x 10^6 lbf/ft^2) Plate:185 N/mm^2 (3.9 x 10^6 lbf/ft^2)
Design strength: fully softened	Plate: 105 N/mm^2 (2.2 x 10^6 lbf/ft^2)
Young's modulus	70 kN/mm^2 (1.5 x 10^9 lbf/ft^2)
Coefficient of thermal expansion	23 x 10^{-6} K^{-1} (12.8 x 10^{-6} ^{0}F^{-1})
Thermal conductivity	200 W/m^{o}C (116 BTU/hr.ft.^{0}F)
Specific heat capacity	880 J/kg^{o}C (0.21 BTU/lb ^{0}F)

b | Properties and data of aluminium alloys



c | Aluminium stress-strain graph

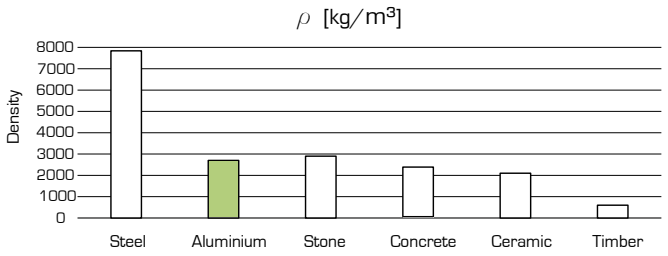
Overview

Aluminium is extracted from bauxite, a hard, red clay containing up to 50% aluminium oxide. Alumina, or aluminium oxide, is extracted from the bauxite ore. Bauxite is the most important ore of aluminium, containing approximately 30–50% alumina. Pure aluminium was first produced in 1825, and by the late 19th century a method was found to mass produce the material by the electrolysis of alumina and cryolite (a).

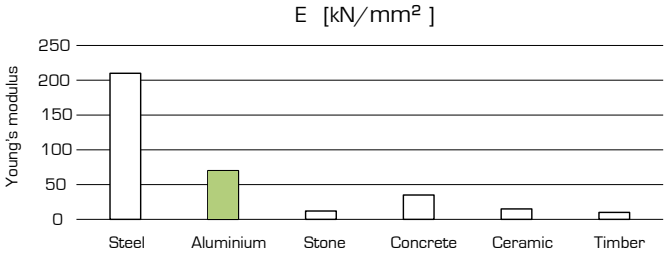
Comparison with other materials, general properties

For comparison with other materials, aluminium alloys have the following general properties (b):

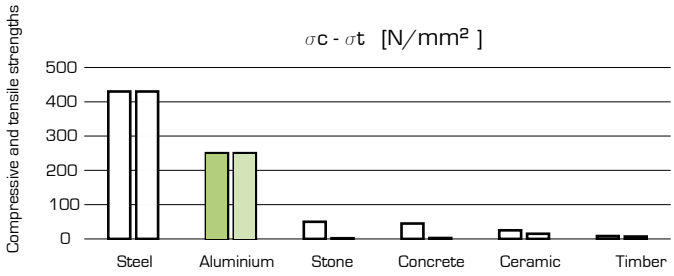
- Lightness, weighing about a third that of steel (d).
- High tensile strength, similar to that of steel (f)(k).
- High impact resistance.
- High corrosion resistance, but aluminium requires protective coating in very polluted or severe atmospheric conditions. Coatings are not applied solely for appearance.
- Thermal expansion approximately twice that of steel (g).
- High thermal conduction (h).
- High electrical conduction.
- Poor stiffness (c)(e).
- Low resistance to soft impact, but absorbs impact energy which localises damage. Whereas a soft or low level impact, such as a kick, would not damage a steel panel, it will dent one in aluminium.
- A high impact, such as a car reversing into a panel, would cause a large steel panel to buckle across its entire height and length, but one made of aluminium will again dent only around the impact area.
- Poor fire resistance



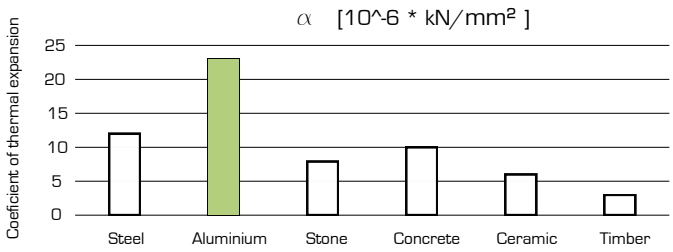
d | Materials density comparison



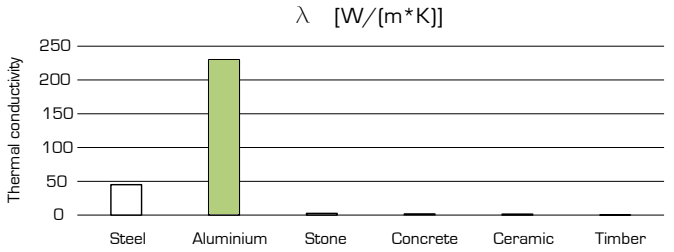
e | Materials Young's modulus comparison



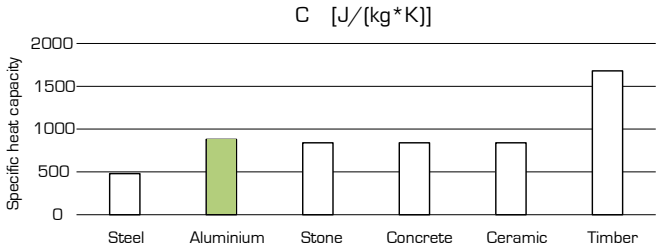
f | Materials tensile and compressive strength comparison



g | Materials coefficient of thermal expansion comparison



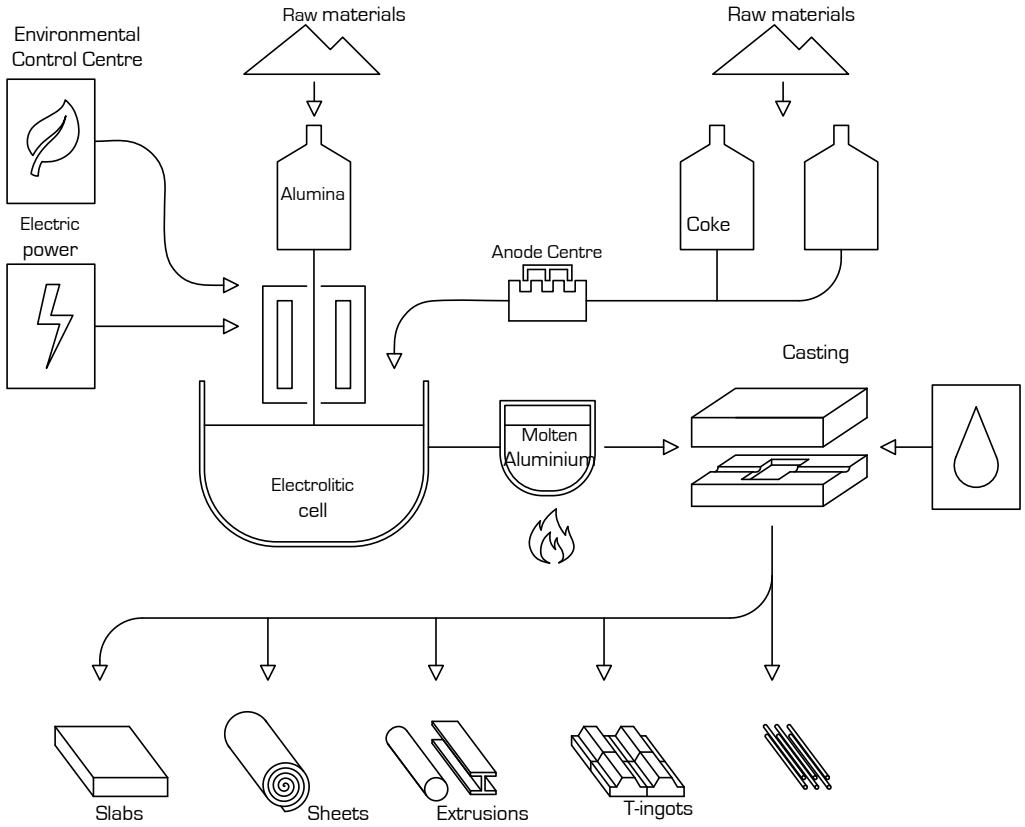
h | Materials thermal conductivity comparison



j | Materials specific heat comparison

Alloy EN-AW	Temper	Thickness mm	0.2% proof strength f_o, N/mm²	Ultimate tensile strength f_u, N/mm²
3004	H14 | H24/H34	≤6 | 3	180 | 170	220
	H16 | H26/H36	≤ 4 | 3	200 | 190	240
3005	H14 | H24	≤ 6 | 3	150 | 130	170
	H16 | H26	≤4 | 3	175 | 160	195
3103	H14 | H24	≤ 25 | 12,5	120 | 110	140
	H16 | H26	≤4	145 | 135	160
5005/5005A	O/H111	≤50	35	100
	H12 | H22/H32	≤12.5	95 | 80	125
	H14 | H24/H34	≤12.5	120 | 110	145
5052	H12 | H22/H32	≤40	160 | 130	210
	H14 | H24/H34	≤25	180 | 150	230
5049	O / H111	≤100	80	190
	H14 | H24/H34	≤25	190 | 160	240
5454	O/H111	≤80	85	215
	H14 | H24/H34	≤25	220 | 200	270
5754	O/H111	≤100	80	190
	H14 | H24/H34	≤25	190 | 160	240
5083	O/H111	≤50	125	275
		50< t ≤80	115	270
	H12 | H22/H32	≤40	250 | 215	305
	H14 | H24/H34	≤25	280 | 250	340
6061	T4 / T451	≤12,5	110	205
	T6 / T651	≤12,5	240	290
	T651	12,5< t ≤80	240	290
6082	T4 / T451	≤12,5	110	205
	T61/T6151	≤12,5	205	280
	T6151	12,5< t ≤100	200	275
	T6/T651	≤6	260	310
		6< t ≤12,5	255	300
	T651	12.5< t ≤100	240	295
7020	T6	≤12.5	280	350
	T651	≤40		
8011A	H14 | H24	≤12.5	110 | 100	125
	H16 | H26	≤ 4	130 | 120	145

k | Characteristic values for wrought aluminium alloys - sheet, strip and plate



a | Aluminium production process

Production

Aluminium is made from bauxite, which is essentially an hydrated alumina, or aluminium oxide. Mined bauxite is treated chemically to remove impurities and obtain alumina, which is aluminium oxide. This is then reduced to aluminium by electrolysis. Because aluminium has a very high melting point (2450^{0}C) it cannot be electrolysed on its own, and so it is dissolved in molten cryolite. A high electric current is passed through the alumina-cryolite mixture at around 1000^{0}C, and the molten aluminium is tapped off (a).

Aluminium alloys are either formed directly, followed by continuous casting, or are cast into solid ingots. The metal is then cast into ingots which form the basis for producing aluminium alloys. Pure aluminium is too soft for structural use and is therefore combined with other metals to form alloys to increase its strength and hardness, though reducing its ductility. Magnesium, silicon and manganese are the most common additives. Aluminium alloys make strong, lightweight structural components. In common with steel, aluminium is a material that can be extruded, rolled and cast into complex shapes: plates, sheets, extrusions and castings.

Uses and limitations

Pure aluminium and its alloys come in two broad groups: the non heat-treated alloys, also called fully softened alloys, whose strength is produced from being cold worked, and the heat-treated alloys whose strength is produced by heat treatment. The non heat-treated types are generally not as strong, but have better corrosive resistance.

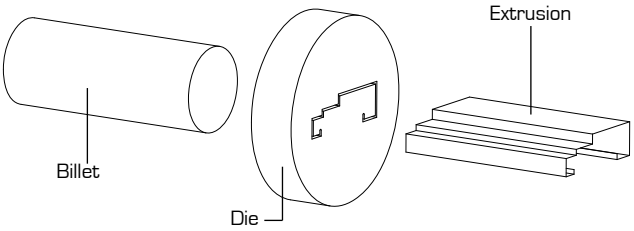
Structural use of aluminium alloys is limited by two significant disadvantages: they are more expensive to manufacture than steel and they deform more easily under load. Aluminium alloys are more elastic than steel, restricting their use to components and assemblies where this is not a constraint. Since the Young's Modulus of aluminium is one third that of steel, buckling is an important issue in its structural use. The potential of this material as a full structural material in buildings is beginning to be recognised. The Media Centre at Lord's Cricket Ground, London, England, is a recent notable example because of the full structural use of aluminium in a large-scale building frame.

Extruded profiles

The extrusion process starts with an aluminium billet in various lengths of up to 7 metres, supplied in a wide range of alloys (b). The billet is pre-heated in the billet heater to around 400-500^{0}C, but the specific temperature will vary primarily in accordance with both the alloy type and the required shape. The extrusion process is carried out by applying high pressures, between 1600 and 6500 tonnes, depending on the size of the equipment used, forcing it through a die opening shaped with the specific cross-section required for the extrusion (c). The rate of the extrusion process can be between approximately 5 metres and 80 metres per minute, depending on the type of alloy used and the complexity of the cross-section.



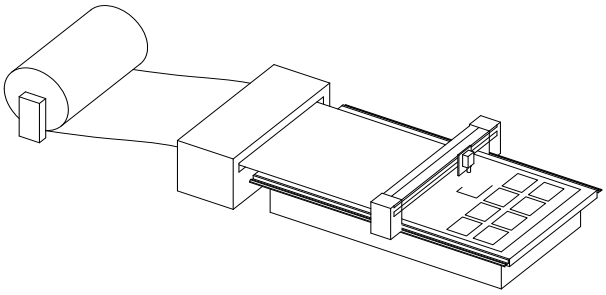
b | Aluminium billets



c | Aluminium extrusion process



d | Aluminium roll



e | Laser cutting of an aluminium sheet



f | Aluminium block



g | Close-up of CNC milling an aluminium block

Working with the material

Aluminium can be cut and drilled, riveted, bolted, screwed and glued. The material can also be welded. However, welding is usually done using the fully softened alloys, since this process can undo the work of the heat treatment in the other alloy types. Since the design strength of the fully softened alloys is half that of the heat-treated types, the section sizes used in welded aluminium structures can often be similar to those of comparable steel structures, but with considerably less weight.

The design strength of the heat-treated alloys, which is similar to the bottom end of the design strength of steel, can be exploited in extrusions, which require no welding in their manufacture. Extrusions can be used to form complex profiles, such as those needed in window sections or walkway decking, and be much lighter than an equivalent member in steel. The material can also be cast to form complex shapes that are more economic in large quantities than an equivalent fabricated component.

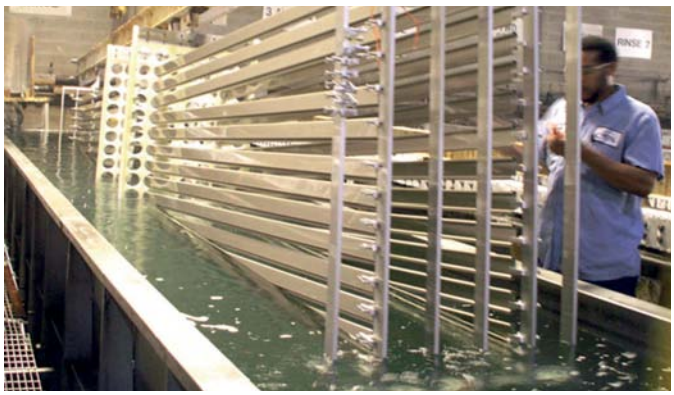
Machining

Aluminium alloys can be machined much more quickly than equivalent steel sections due to their lower hardness. The most common techniques for machining include sawing, turning, tapping, laser cutting and computer numerical controlled (CNC) milling.

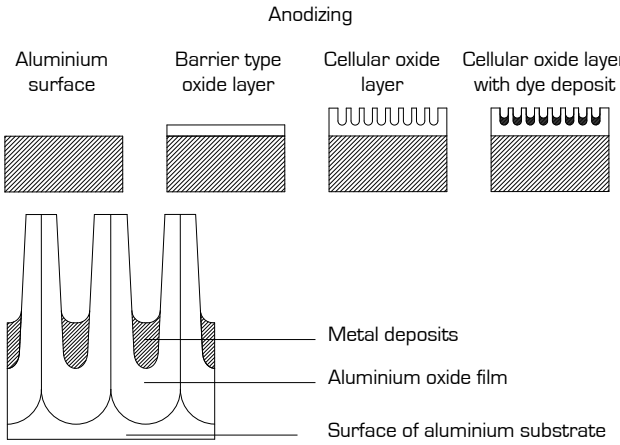
Aluminium extrusions can be sawn accurately with the appropriate rotating blade and rotations per minute. The choice of blade is driven by the alloy used and the thickness of the extrusion. Aluminium can also be easily threaded or drilled. Turning aluminium can be undertaken with standard, special or automatic lathes and requires a high speed of rotation.

Aluminium can be laser-cut (e), but the process is difficult to achieve due to the high reflectivity of the material, which can cause the beam to go back through the lens and damage the optics of the machine. In addition, molten pool, which can be highly reflective, is formed when a laser beam strikes the surface of an aluminium sheet. Consequently, considerable precision is needed in the use of such tools.

For milling, a block of aluminium is placed on a CNC table (f). A tool head with rotating bit is steered by computer, following a specified path to achieve the required shape (g). Milling bits for aluminium have larger teeth pitches than equivalent tools for steel. Power and stability are required to achieve a high quality surface and a high speed is required, just like for other aluminium machining processes.



a | Aluminium anodizing unit



b | Microstructure of anodized aluminium surface



c | Examples of anodized aluminium products



d | Fire-retardant aluminium composite panel

Performance

Degradation of the material

On exposure to the atmosphere, aluminium forms a protective coating of aluminium oxide. Under adverse conditions, the oxide film can break down locally, but it usually reforms to a greater thickness preventing further attack. Aluminium can be exposed to the weather, in non-polluted environments and away from maritime conditions, without the need for additional treatment, provided the surface is maintained. Over time, it loses its initial bright appearance and assumes a dull grey sheen. Aluminium should be cleaned regularly to avoid pits forming in the material surface. However, one way to avoid this is to anodise or paint the material with a proprietary coating. Aluminium is susceptible to electrolytic corrosion in contact with certain materials such as copper. Therefore direct contact with copper and copper-rich alloys, such as brass and bronze is avoided and the material should be used in a way that water does not flow onto it from copper. However, water flowing from aluminium to copper or lead is not harmful. There is no corrosive action between aluminium and zinc or zinc coatings and galvanised surfaces. Some timber preservatives contain compounds harmful to aluminium. Untreated timber affects the material to a much lesser extent.

Protections

Anodising: anodising produces a fine translucent film over the surface of aluminium (a). The anodising process results in the replacement, by electrochemical means, of the metal's naturally formed oxide film by a dense chemically resistant artificial film many times the thickness of its natural equivalent. This film is extremely hard, gives added protection against abrasion, and reduces the adhesion of dirt particles. Anodising is carried out by immersing the aluminium in an electrolyte and applying an electrical current, creating an oxide layer integral with the underlying metal (b). The anodic film is porous and must be sealed. This is done by immersing the anodised aluminium in boiling water or steam. The anodised coating can be dyed; the sealing then assists its colour-fastness. Anodising should be carried out after welding. The process of welding would otherwise break down the anodising process at heat-affected locations. Broken-down anodising could result in weld impurities that would impair its structural effectiveness. Aluminium's natural finish, often referred to as mill finish, can be worked to produce a polished, ground or brush-grained finish. Etching gives a matt and non-directional finish with no direct reflections. Anodising generally follows these processes, increasing durability and enhancing long-term appearance (c). Brightening is not suitable for architectural alloys, which are only 99.5% aluminium because the brightening is not uniform. Chemical brightening on other alloys dissolves and flattens surface irregularities found in extruded or sheet aluminium surfaces, and produces a mirror finish with a very high reflectivity. It can be anodised without dulling the surface.

Coatings

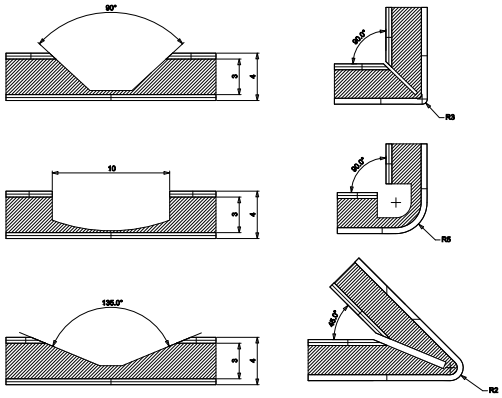
Aluminium can be coated in a wide range of colours through the use of proprietary processes. Plastic coatings provide a durable paint surface; polyester powder coating is one of the most common finishes. Plastic coatings are dip-coated, sprayed or electrophoretically deposited underwater. The electrostatically applied finish ensures that an even coat is built-up on the metal. These paints fade and lose their shine with time, though the change is slow and even. PVDF (polyvinylidene di-fluoride), also called PVF2 in Europe, and powder coatings are most



e | Aluminium extrusion



f | Cold rolled aluminum coil



g | Folding techniques for aluminium panels



h | Aluminium extrusions

commonly used. PVDF is a spray-applied finish which is highly resistant to fading in sunlight, making it very suitable for external use where colour stability is an important consideration, such as in wall cladding. Powder coating is applied in an electrolytic process that provides a softer and less expensive coating than PVDF. It is not as resistant to fading in sunlight, but is a harder finish and less expensive, making it suitable for both an economic external finish and excellent for internal use.

Recycling

Aluminium is a fully recyclable material. Recycling not only retains the scrap value of aluminium but also eliminates possible adverse effects on the environment of the discarted metal. Moreover, production of aluminium from a recycled material requires just 5% of the energy needed to produce aluminium from bauxite.

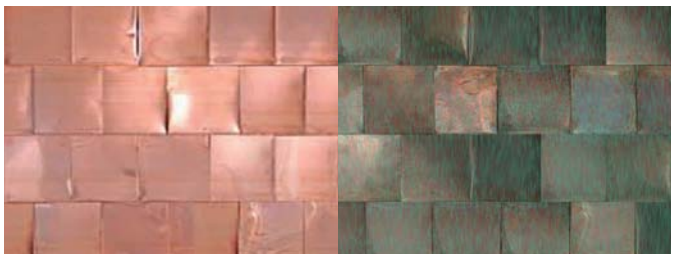
Applications

Aluminium alloys are well suited to applications which require properties of lightness, resistance to corrosion and structural strength. The material is commonly used for the following applications:

- Temporary structures, like stages and pavilions, for which low transportation costs and speed of installation are priorities.
- Structures with limited access for maintenance.
- Long-span roof structures such as space frames and geodesic domes that are required to be light in weight.
- Structures exposed to humid and corrosive environmental conditions.

Aluminium alloys can be extruded to a very wide range of cross-sectional shapes of varying complexity (e). This ability provides a high level of control over the dimensional accuracy and the fit of assemblies, such as aluminium window frames. Extrusions can be made as strong and light sections, making the application of extrusions particularly suitable for framing to glazed curtain wall assemblies (h). Grooves for joints, thermal breaks and glazing beads can be incorporated into a window frame due to the material's ability to be processed and to achieve complex shapes which can fit together in a single assembly.

Aluminium alloys can also be used to form cladding panels which are either flat or curved (d)(f). The ability of the material to be folded or rolled to form profiled sheets allows the work to be conducted on site (g). Aluminium panels can be further processed either in a workshop or on a building site, without any specialised tools.



a | Natural and with patina copper cladding



b | Zinc cladding



c | Lead preformed cladding panel

Density	Copper = 8900 kg/m^3 (556 lb/ft^3) Zinc = 7000 kg/m^3 (437 lb/ft^3) Lead = 11,400 kg/m^3 (712 lb/ft^3)
Tensile strength	Copper = 216–355 N/mm^2 (4.5 x 10^6 to 7.4 x 10^6 lbf/ft^2) Zinc = 139–216 N/mm^2 (2.9 x 10^6 to 4.5 x 10^6 lbf/ft^2) Lead = 15–18 N/mm^2 (3.1 x 10^5 to 3.8 x 10^5 lbf/ft^2)
Young's modulus	Copper = 112–148 kN/mm^2 (2.4 x 10^9 to 3.1 x 10^9 lbf/ft^2) Zinc = 68 - 95 kN/mm^2 (pure) (1.4 x 10^9 to 2.0 x 10^9 lbf/ft^2) Lead = 13–15 kN/mm^2 (2.7 x 10^8 to 3.1 x 10^8 lbf/ft^2)
Coefficient of thermal expansion	Copper =17 x 10^{-6} K^{-1} (9.4 x 10^{-6} ^{0}F^{-1}) Zinc =23 to 40 x 10^{-6} K^{-1} (12.8 x 10^{-6} to 22.2 x 10^{-6} ^{0}F^{-1}) Lead 29.5 x 10^{-6} K^{-1} (16.4 x 10^{-6} ^{0}F^{-1})
Thermal conductivity	Copper = 368 W/mK (213 BTU/hr.ft.^{0}F) Zinc:= 115 W/mK (67 BTU/hr.ft.^{0}F) Lead: = 35 W/mK (20 BTU/hr.ft.^{0}F)
Specific heat capacity	Copper = 390 J/kg°C (0.093 BTU/lb ^{0}F) Zinc = 380 J/kg°C (0.090 BTU/lb ^{0}F) Lead = 130 J/kg°C (0.031 BTU/lb ^{0}F)

d | Properties and data of copper, zinc and lead

Overview

Copper, zinc and lead are durable, ductile metals that provide a longer design life than metals with painted finishes. Their ability to resist the effects of air pollution, and the low maintenance requirement of the metal surfaces, assure their use for facades and roofs of buildings where a longer design life is a priority. The design life is also dependent upon the thickness of the metal and its location within a given facade assembly. These metals are fully recyclable.

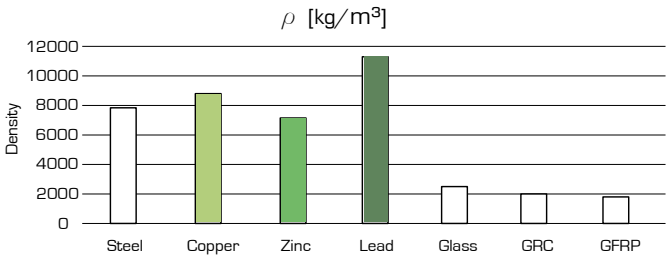
Their use in traditional construction has ensured that there are well-evolved techniques for the use of all three metals for durable weather-tight finishes to roofs, facades, rainwater gutters and associated downpipes. These metals today are manufactured to a more consistent purity than was historically the case, ensuring a greater level of consistent performance in use. A mix of on-site and prefabrication techniques has greatly advanced their use in recent years, with seaming and fixing technology having greatly improved productivity. The folded or profiled sheets required for roofs and walls can be formed direcly to the required shape, on site, from metal coil directly from the factory using mobile machines. The economic nature of this mixture of site-based and prefabricated techniques has allowed these metals to be used on a wide range of building types.

Weathering

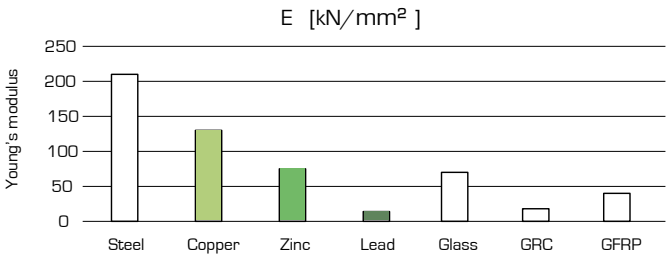
All three metals have a characteristic appearance after a prolonged period of exposure to the effects of the atmosphere. Weathering can be uneven, so copper, zinc and lead are manufactured with different pre-weathered finishes to provide the long-term appearance from the beginning of a building's design life. For example, copper can be pre-weathered to different intensities from brown to green (a). Zinc can be pre-weathered to different shades, from light grey to black (b). All metals can be lacquered to maintain their natural appearance as seen immediately after manufacture.

Production

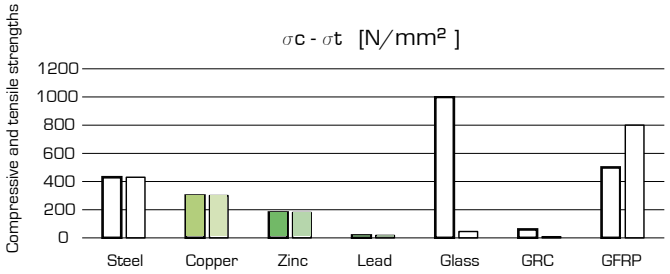
Copper, zinc and lead occur naturally as ores in which the metals are combined with other chemical compounds. Copper is mined from open pits, where it is scooped out by large excavators and transported directly by road for processing. Zinc and lead are taken from underground mines with conventional mining techniques. Copper, zinc and lead are all obtained from their ores by a process of extraction, which varies according to the type of ore and its target purity. Removing the other constituents of the ores is called 'concentrating' and is typically undertaken using a process of flotation. First, the ore is ground into small particles, then water is added to the mixture together with various chemicals, which react with metal particles and create a thick



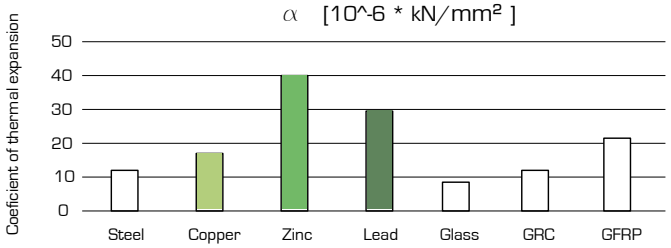
e | Materials density comparison



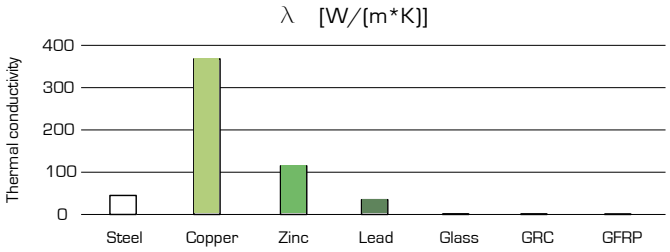
f | Materials Young's modulus comparison



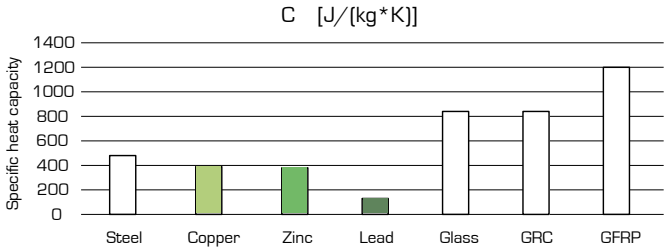
g | Materials tensile and compressive strength comparison



h | Materials coefficient of thermal expansion comparison



j | Materials thermal conductivity comparison



k | Materials specific heat comparison

layer of foam on top of the mixture. Up to this point, the processing of the ores is similar for copper, zinc and lead. After this point, the further processing of these three metals varies significantly.

Copper

After concentration, the material is put into a furnace with the addition of silica flux. The copper concentrate and flux melt, and iron particles combine with the flux, while sulphur combines with oxygen. The remaining material, called 'matte', is then transferred to another furnace called a converter, where the process is repeated. Following this stage, the copper is moulded to form electrical anodes, and each of these is then placed in a separate tank with a copper cathode at the opposite end. Acidic copper sulphate solution is used as an electrical conductor. An electrical current is applied to each tank, and the pure copper is stripped from the anode and deposited on the cathode. It takes up to fifteen days to produce pure copper. The material is now melted and cast into ingots, cakes, billets, or rods.

Zinc

After flotation, zinc is filtered and mixed with lime, then put into a furnace where it is fused with other minerals, then converted to zinc oxide. The material is then smelted, a process of melting the zinc oxide and adding molten lead, which dissolves the zinc and carries it to another chamber where it is separated upon cooling, leaving lime in the first chamber. Zinc is further refined by maintaining the molten state of the material for several hours longer. This allows the contaminants to settle to the bottom of the tank. Finally, the molten zinc is cast into ingots.

Lead

When lead has been concentrated in the flotation process, the material is filtered and 'roasted'. The lead concentrate is further refined to remove the sulphur content. The concentrate then passes to a sinter plant, where it is mixed with minerals while heated air, at a temperature of 1,400°C (2,550°F), is blown through the grate. Then the ore fuses into a brittle material called sinter. The lead concentrate is then passed through a blast furnace. The coke burns at 2,200°F (1,200°C) and produces carbon monoxide, which reacts with the material resulting in molten lead.

To refine the bullion, it is kept in a 'drossing kettle' at a temperature just above its melting point, about 330°C (626°F). At this temperature, impurities rise to the top of the kettle and form a scum which is skimmed off. When the lead has been sufficiently refined, it is cooled and cast into blocks, which can then be formed into the required elements (c).



a | Copper coil

Copper							
Coil Thickness (mm)	0.40	0.5	0.6-0.7	0.8	0.9	1	1.50-3.00
Most common application		Min. thickness for self-supporting and for fully supported	Typical roofing grade				Usually for curtain walling

b | Data according to BS EN 1172: 2011/BS EN 14782: 2006/ BS EN 14783: 2013



c | Zinc coil

Zinc							
Coil Thickness (mm)	0.60	0.65	0.7	0.8	1.00	1.20	1.50
Most common application	Min. thickness for self-supporting and for fully supported		Minimum recommended for standing seam system	Minimum recommended for batten system			

d | Data according to BS EN 501: 1994/BS EN 14782: 2006/ BS EN 14783: 2013



e | Lead Rolls

Lead							
Roll Thickness (mm)	1.25 Green	1.50 Yellow	1.75 Blue	2.00 Red	2.50 Black	3.00 White	3.25 Orange
Most common application				Flat Roofing, Pitched roofing, Vertical cladding	Flat Roofing, Pitched roofing	Flat Roofing, Pitched roofing	Flat Roofing, Pitched roofing

f | Data according to BS EN 12588: 2006

Performance

Copper

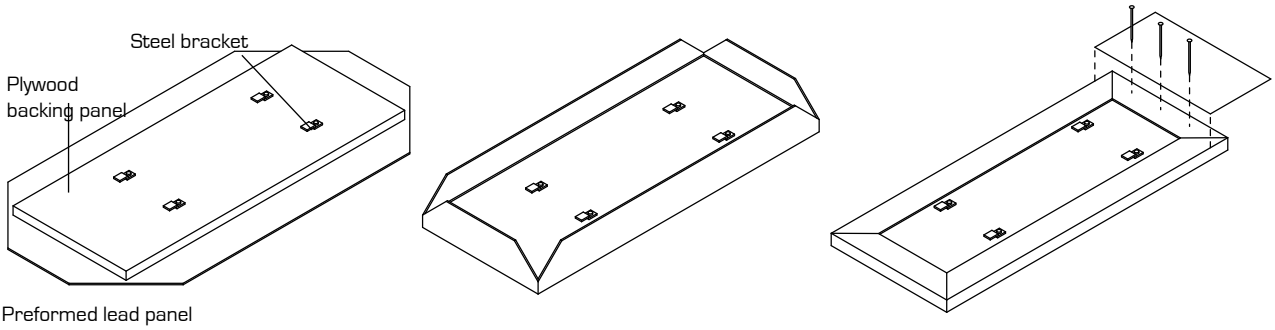
Copper is strong in tension, tough and ductile, but is not as malleable as lead. The material has a shiny red/yellow colour when new (a), slowly developing a protective sulphate layer on its surface when exposed to the atmosphere. This patina has a characteristic shade of green which has a fairly consistent colour and texture. Copper is available with a pre-weathered, or pre-patinated finish which is chemically induced. This finish varies slightly from naturally weathered cladding. Well-maintained copper cladding which has oxidised atmospherically will last from thirty to fifty years. There is a variety of copper types available, each of which is suitable for a particular task (b). For instance, deoxidised copper is suitable for welding, while fire-refined tough-pitch copper, with its tougher resistance to corrosion, is used for cladding. Otherwise, both have similar properties. Copper forms a high proportion of metal in alloys such as bronze, which is primarily a mixture of copper and tin. Brass is primarily a mixture of copper and zinc, and aluminium bronze is primarily a mixture of copper and aluminium. Copper can be cut, drilled, nailed, welded and soldered with hand power tools, making it versatile for site-intensive work. When used as cladding, joints between sheets are made by folding the edges together. This method takes advantage of the fact that copper can be bent along an edge fairly easily, but is rigid enough to remain folded.

Zinc

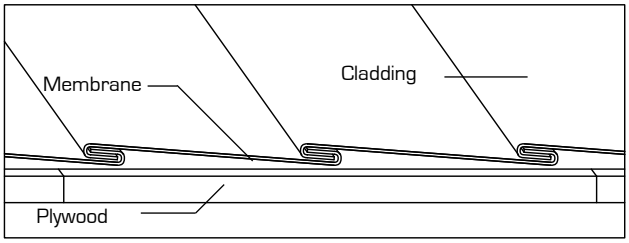
Zinc sheet for cladding is made from either commercial zinc or from an alloy of zinc with small amounts of copper and titanium added. The properties of the two types are similar, but zinc alloy has better tensile strength and resistance to creep, which is long-term plastic deformation under load. Zinc is a durable material, although it is more brittle than copper. It is manufactured as a white-coloured metal (c), but when exposed to the atmosphere a carbonate is slowly formed which produces a protective coating that is grey-white in colour. The material has a linear thermal expansion that is similar to lead and higher than copper. Zinc can be cut, drilled, nailed, welded and soldered with hand power tools, making it reasonably versatile for use on site. Its rigidity makes it well suited to standing seam joints (d). Well-maintained zinc cladding can last for between thirty and fifty years. Zinc is liable to attack from copper alloys, so that rainwater running off copper should be avoided. Apart from its use in alloys, zinc is used as a protective coating to steel, applied through a process of galvanising and sherardising.

Lead

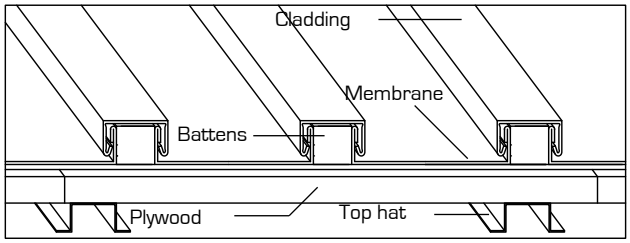
Lead is an extremely durable, ductile and malleable material, making it extremely useful for roof coverings and flashings in traditional roof construction (e)(f). However, while its relative softness allows lead to be formed into complex shapes, its lack of rigidity means that a supporting material must be provided beneath it. Timber boards are most commonly used for this. Lead has low resistance to creep. On exposure to the atmosphere, a protective coating of lead carbonate is slowly formed on its surface. This gives weathered lead a dull grey appearance. Lead is a poisonous material, leading to increased awareness of the dangers of water run off from lead cladding reaching the water supply. Lead can be cut, drilled, nailed, welded in a process called leadburning, and soldered with hand power tools. Due to its lack of rigidity, lead sheet is most commonly jointed by dressing it over rounded timber battens or rolls.



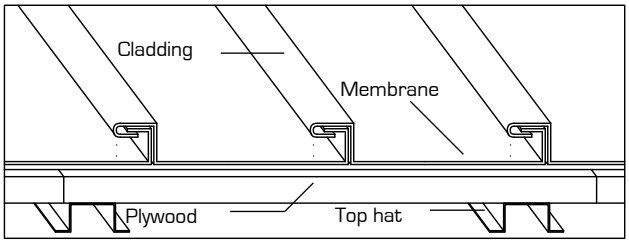
g | Preformed lead panel



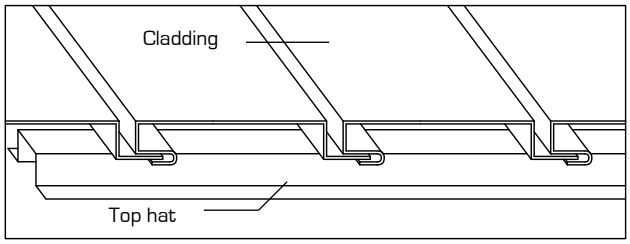
h | Flat lock panels system



k | Batten system



j | Standing seams panels system



l | Interlocking panels system

Applications

All three metals have a characteristic appearance after a prolonged period of exposure to the effects of the atmosphere. Weathering can be uneven, so copper, zinc and lead are manufactured with different pre-weathered finishes to provide a long-term appearance from the beginning of a building's design life. For example, zinc can be pre-weathered to different shades, from light grey to black. Copper can be pre-weathered to different intensities from brown to green. All metals can be lacquered to maintain their natural appearance as seen immediately after manufacture.

The ductile nature of copper, zinc and lead allows them to be folded with relative ease to allow individual metal sheets, or rolls, to be cut and joined together, to form folded joints (g). The durable nature of these three metals, combined with the oxidising layer that produces their individual characteristic appearance, allows the materials to be used as weather-resistant layers. Consequently, all three metals have long been used as coverings to roofs. In recent years, the visual quality of their natural finishes have led to their use in facades, as alternatives to the paint-based coatings of steel or aluminium sheet. The most common methods common to copper, zinc and lead are described here: standing seam joints, batten joints, flat lock panels and intrerlocking panels.

Flat lock panels

This joint is used where rainwater is expected to run over the joint in a downward direction without the risk of water building up on the surface, which makes it suitable for facades and for areas of roof which are nearly vertical. The flat lock is like a standing seam joint, but with the upstand folded down to allow rainwater to run freely across the joint (h).

Standing seam joints

Metal sheet is folded outwards at the edges of the sheet, where the sheets meet. The folded edges are lapped over one another to form a sealed joint between the sheets (j). Although traditional in its origin, the technique of the standing seam joint is used on large-scale projects, where profiling machines and seaming machines are used to form the sheet on site, then to seal the joints between the sheets when they have been installed. The use of these machines allows large areas of roof to be enclosed quickly and economically.

Batten joints

This is a traditional jointing technique in which continuous timber sections, called battens, typically in the order of 25mm x 25mm, are used to form the profile of the joint between metal sheets (k). The timber sections are held in place by clips, secured to the supporting structure or substrate onto which the metal sheet is laid. The edges of the metal sheet are lapped are folded over the timber battens to form a watertight joint.

Interlocking panels

Metal sheets are formed at their edge to form a projecting 'male' edge on one side, and a recessed 'female' joint on the other side of the sheet (l). A male joint is fitted to a corresponding female joint. This joint is formed on all four sides of each metal sheet, but the joint cannot be considered to be fully water tight. The technique is used mainly on building facades to form shadow gap joints that provide a corresponding visual sharpness.



a | Marble milling with KUKA robot



b | Marble wall feature, Citco gallery, Zaha Hadid Architects

Density	Natural stone: 2200 to 3000 kg/m^3 (137 to 187 lb/ft^3) wet Cast stone: 2100 kg/m^3 (131 lb/ft^3)
Characteristic compressive strength	Granite = 30 - 75 N/mm^2 (6.3 x 105 to 1.5 x 106 lbf/ft^2) Sandstone = 10 - 30 N/mm^2 (2.1 x 105 to 6.3 x 105 lbf/ft^2)
Young's modulus	6.9 N/mm^2 to 21N/mm^2 (144 x 106 to 439 x 106 lbf/ft^2)
Coefficient of thermal expansion	7.9 x 10^{-6} K^{-1} (4.4 x 10^{-6} $^0F^{-1}$)
Thermal conductivity	1.7- 4.0 W/m°C (0.98 - 2.3 BTU/hr.ft.^{0}F)
Specific heat capacity	840 J/kg°C (0.19 BTU/lb ^{0}F)

c | Properties and data of aluminium alloys

Overview

Stone is a natural material which is generally durable, allowing it to be used for conditions where low maintenance is a high priority, such as paving, and facades which might suffer accidental damage. Natural stone can be cut to almost any shape (a), in sizes up to a maximum of around 1.5 metres x 1.5 metres, depending on stone type. Stones are used primarily as finishes for floors and walls, both externally and internally (b). Most stones can be recycled easily for other uses within building construction.

Comparison with other materials; general properties

Natural stone has the following properties (c) common to most types:

- A heavy material, weighing as much as reinforced concrete (d).
- High compressive strength (f). Natural stone is a brittle material that is strong in compression but is weak in tension.
- Low tensile strength.
- Brittle, but high impact resistance improving with thickness.

Reconstituted stone has the following properties:

- A heavy material, weighing as much as reinforced concrete.
- High tensile and compressive strength.
- High impact resistance.
- Susceptible to shrinkage like concrete.

Production

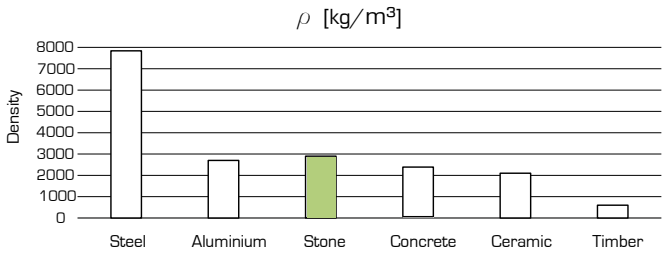
Stone is cut or hewn from large blocks which have been cut, blasted or split from the bedrock. Being a natural material, the appearance and durability of stone, even from the same block, can vary enormously. To control quality, it is sometimes best to select cut stone at the quarry. Since no two cuts produce the same appearance, when defining the required quality it is advisable to define a limited band between the most veined and least veined stone acceptable. As stone is a naturally occurring material, the properties are not as controlled as man-made materials such as steel. Stone from a particular quarry is usually tested before sale in order that its physical and mechanical properties are known. When stone is used in structural applications, the material undergoes rigorous testing to determine its performance in the intended application.

Uses and limitations

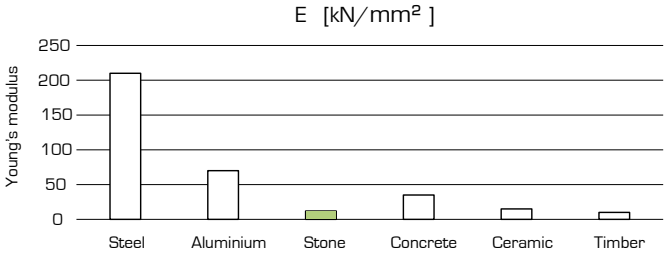
Stone is used in two essential applications: where it is supported on a continuous substrate, as in paving, and secondly where it is point-fixed to a backing wall, as in its use as a facing material in a facade. When the material is point-fixed, its ability to span between fixings becomes an essential physical property, measured mainly by its flexural strength.

Performance

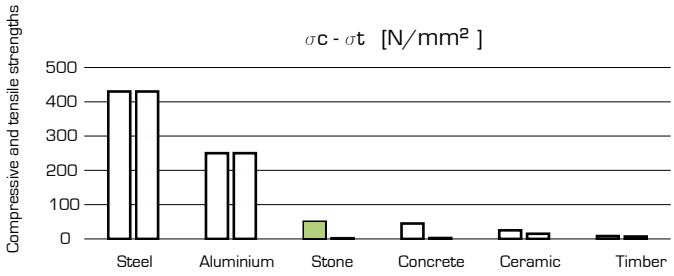
Natural stone is a brittle material that is strong in compression but is weak in tension. It is used mostly for wall facings and pavings, although the high unit cost means that it is rarely used in a traditional loadbearing capacity. Most stone has the strength and durability of block and brickwork. The most widely used types are granite, limestone, sandstone, marble and slate (k). Igneous rocks, such as granite, are formed directly from molten magma. Sedimentary rocks, such as limestone and sandstone, are made up from the eroded elements of earlier rocks laid down in beds near the earth's surface, and are often composed of loose material bound together by cement-like materials. Metamorphic rocks, such as slate and marble, are igneous or sedimentary rocks which have undergone a chemical transformation due to high temperature and pressure.



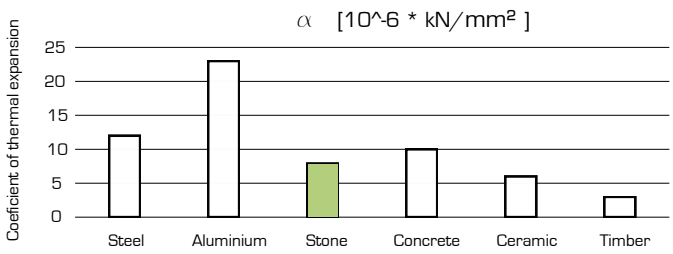
d | Materials density comparison



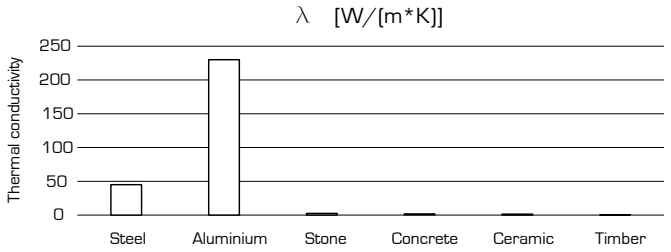
e | Materials Young's modulus comparison



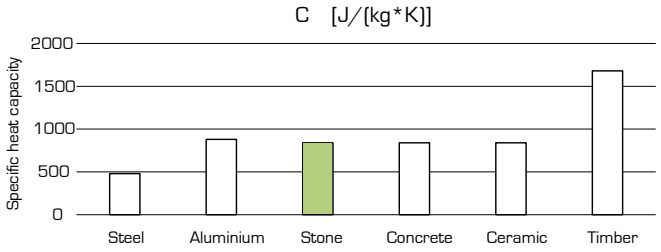
f | Materials tensile and compressive strength comparison



g | Materials coefficient of thermal expansion comparison



h | Materials thermal conductivity comparison



j | Materials specific heat comparison

Class	Hardness	Colour	Texture	Main uses
Sandstone	Fairly hard if well cemented	Light buff to light chocolate or brick red	Granular, with sand grains visible	General, walls, buildings
Limestone	Fairly soft, easily scratched	White, light gray or light buff	Fine to crystalline, sometimes with fossils	All building uses
Marble	Slightly harder than limestone	Various - white to black, often pinkish, blue-grey or olive green	Finely granular to coarsely crystalline	Usually decorative, non-structural
Granite	Harder than marble	From very light grey to grey, sometimes pink	Coarsely crystalline, sometimes fine grained	Structural and cladding
Dark igneous rock	About as hard as granite	Grey, dark green to black	Coarsely crystalline, sometimes fine grained	Structural and cladding
Lavas	About as hard as granite	Various, pink, purple, black	Fine grained, might have pores	Foundation and building stone
Quartzite	Very hard	Variable, white, buff, red or dark brown	Dense, glassy	Building stone
Slate	Softer than granite	Grey, dark brown, or brick red	Finely crystalline	Roofing and paving tiles
Gneiss	About as hard as granite	Grey, sometimes with pink or white bands	Coarsely crystalline, sometimes fine grained	Building stone, sometimes decorative

k | Properties of stones most commonly used in construction



a | Stone quarry



c | Storing of stone slabs



b | Stone cutting



d | Stone block cutting with wirecutter

Granite, within the building industry, refers to coarse-grained igneous rocks. It has a wide range of colours, and is extremely hardwearing. Most granites are grey or pink, with mixtures of white/grey and pink/grey depending upon their geographical source.

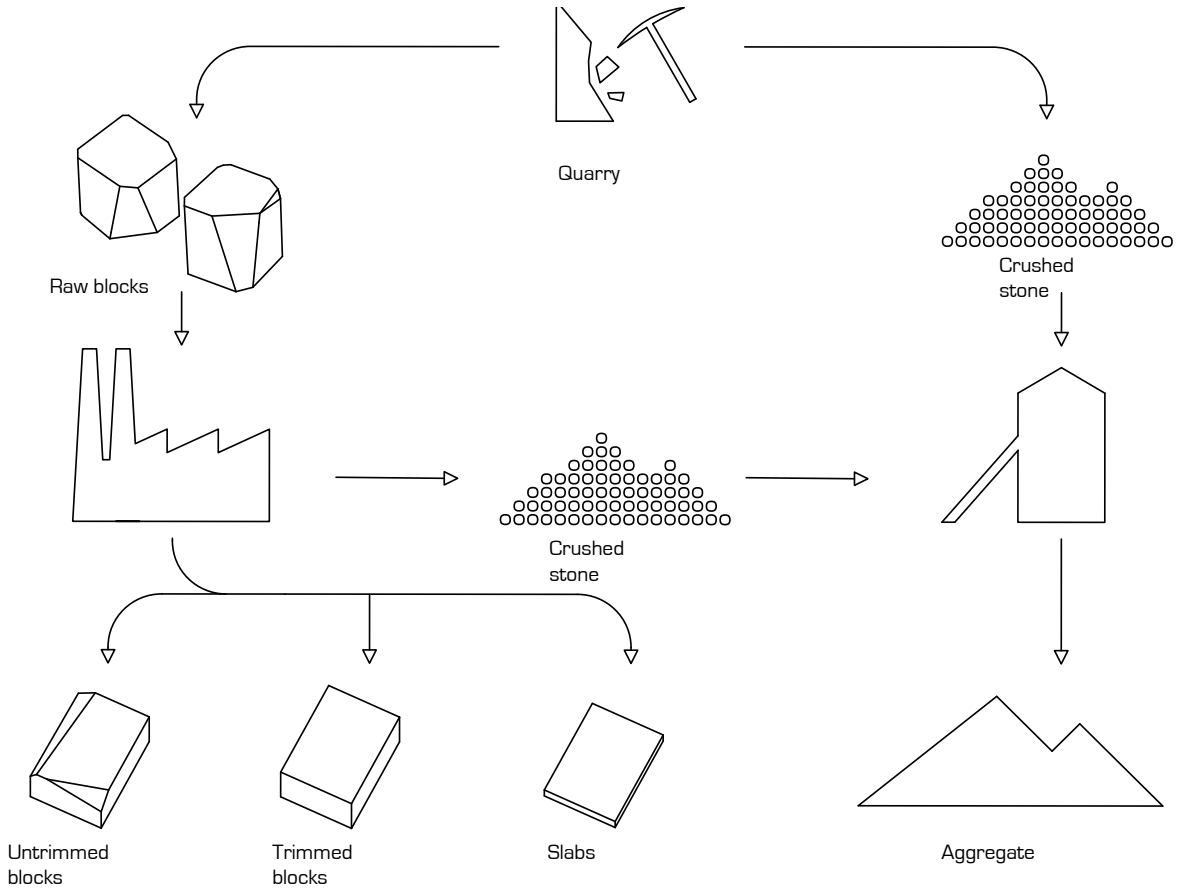
Limestone is made up from rock material bound together by calcium carbonate, in the form of the mineral calcite. Many limestones contain a proportion of the mineral dolomite. The colour is generally light, ranging from near white through to brown and grey. Chemical impurities can cause a darkening of the colour. Limestones vary in texture and can range from a sand-textured and coarse material to one that is so fine-grained as to lack visible particles. Limestones such as Portland Stone (Indiana Limestone in the USA) are strong and durable.

Most sandstones consist mainly of quartz grains cemented together by mineral solutions. Calcareous, dolomitic, ferruginous and siliceous cements are common. Small amounts of other minerals, often iron compounds, give the stone its colour. Sandstones vary in colour from dull crimson to pink or green/brown mixtures to blue/grey. Sandstones vary enormously in durability from soft, easy-to-work types with low strength and high porosity, to relatively durable types with strengths approaching those of granites, with lower porosity.

Marble is a metamorphic rock formed by the recrystallisation of limestone or dolomite through a combination of heat and pressure. The crystalline structure is seen in a fractured surface, which gives it a sparkling appearance. During metamorphism, impurities in the original limestone, such as different minerals, are incorporated into the rock and appear as bands or as discrete inclusions scattered through the calcite mix. No true marble shows fossils. Veined marbles are the result of minerals deposited from solutions penetrating cracks and fissures. Some marbles contain fragments of earlier crushed rocks. A wide range of colours and textures may be found. The presence of iron gives rise to shades of yellow, brown and red as a result of oxidation.
Slate is a crystalline rock produced by dynamic metamorphism of clays and shales, causing it to be orientated along a single grain or 'slaty cleavage' which allows the rock to be split into sheets. It is used mainly for roof slates and for durable surface finishes such as floors. The colour of slate varies from grey to green to black to red.

Working with the material

Stones are extracted typically by quarrying from ground level downwards (a). Stone is removed by drilling and splitting using diamond saws or iron wedges, extracting the material as blocks (b). The blocks are then cut into slabs, then cut further to the sizes required (c). The work is often slow and can yield unexpected visual results in the slabs which are cut (d). Machines are used to cut stones to specific shapes, with water jet cutting techniques being used for complex shapes, such as that used for curved paving. Stone can be finished to provide very diffferent finishes, from flamed to matt honed, to polished. Polishing does not change the structure or weathering of stone and is typically applied where stone is used as a flooring material. Additional finishes include etching and needle gunning, but stone used externally usually has no additional treatment after being cut to size (e). Metal fixings in the



e | Processing of stone

form of brackets and dowels are used where the mortar joints do not provide sufficient stability for lintels and copings. These fixings are used extensively in stone cladding panels where the material is supported by a structural frame.

Reconstituted stone

Reconstituted stone, also referred to as cast or 'reconstructed' stone, is made from cement and crushed stone that is cast in a mould. It is used either as a structural material or as a facing to a concrete component. Steel reinforcement is used if the casting has a structural function.

Applications

Cladding

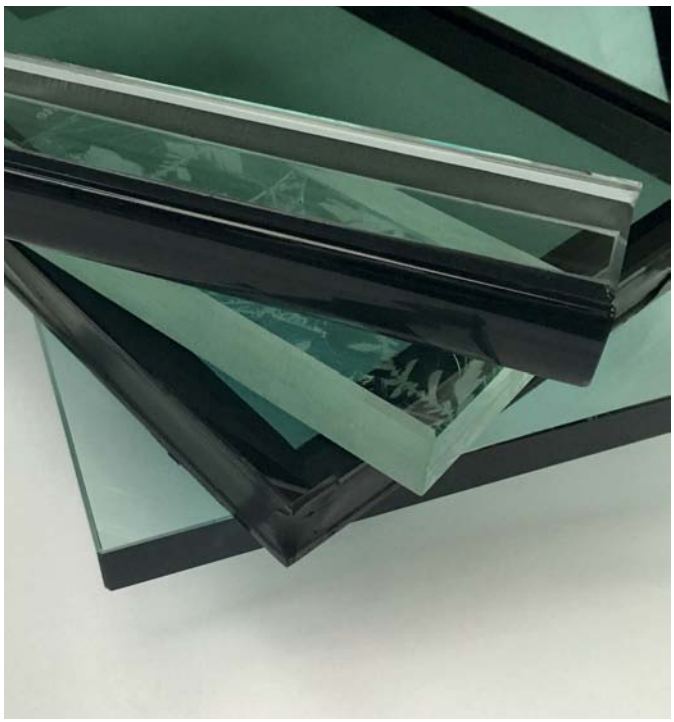
Stone facade panels are fixed with metal fixings, typically as brackets and dowels with open joints between panels. Sealed joints are still used to provide the more 'traditional' appearance associated with loadbearing stone. These fixings are secured to a continuous substrate or metal frame. The size of stone panels is limited to approximately 1.0 metre x 1.5 metres, depending on stone type. Even though stone is considered to weather well, some types of stone can be adversely affected by weathering due to exfoliation as a result of a freeze/thaw cycle, pollution and salts.

Flooring

Because of its high durability, stone is ideal for exterior applications. Some of the most common exterior uses of stone include paving for areas of hard landscaping, roads and curbs to roads. The finish for stone paving is generally made to provide sufficient slip resistance to ensure that users can walk without slipping, even when wet from rain. For external use, a rough finish is chosen, typically, in order to achieve the non-slip surface needed during periods of wet weather. In contrast, many interior applications of floor paving choose a smooth finish, primarily for ease of cleaning. Some common stone finishes are: flaming, sandblasted finish, brushing, honed finishing, polished, sawing, terma effect finish and satin finish.

The use of digital tools for stone processing

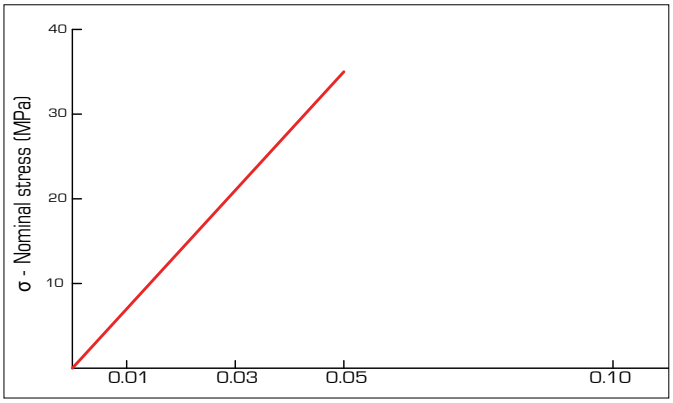
Sagrada Familia Basilica in Barcelona is a high-profile example of the use of digial cutting tools in the production of stone blocks. Computational design and building information modelling (BIM) were used to achieve the required complex geometry of stone elements. Loadbearing stone blocks were carved with the use of cutting tools with multi-axis robotic arms that have a computer-controlled ability to undertake cutting, milling and polishing tools. Significant advances in stone cutting technology were experienced during both the design and construction of the project as a result of surface modelling and solid modelling digital design tools. Stone pieces were cut to provide a set of 3D forms that would fit together as a 'kit of parts' able to take into account the gap for mortar jointing while maintaining the overall geometric forms required for the project.



a | Architectural glass products

Density	2500 kg/m^3 (156 lb/ft^3)
Tensile strength	45 N/mm^2 (9.4 x 10^5 lbf/ft^2)
Compressive strength	130–250 N/mm^2 (2.7 x 10^6 to 5.2 x 10^6 lbf/ft^2)
Young's modulus	70 kN/mm^2 (1.4 x 109 lbf/ft^2)
Coefficient of thermal expansion	9 x 10^{-6} K^{-1} (5 x 10^{-6} F^{-1})
Thermal conductivity	1.1 W/m°C (0.64 BTU/hr.ft.°F)
Specific heat capacity	840 J/kg°C (0.20 BTU/lb °F)

b | Properties and data of float glass



c | Glass stress-strain graph

Overview

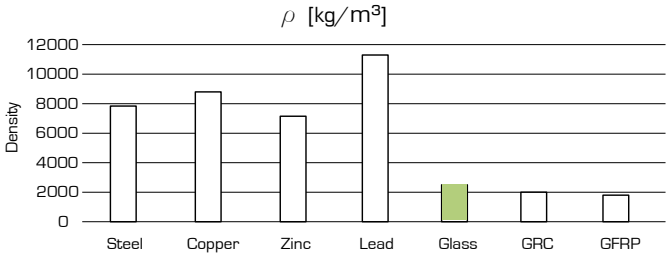
An essential use of glass in buildings is in the double-glazed units of glazed facades and curtain wall (a). With the increasing importance of thermal insulation and the need for a marked reduction in energy consumed to temper the internal environment of buildings, the use of single glazing with thin supporting frames without thermal breaks is no longer used in most new buildings except where, for example, the spaces enclosed by the glass are considered to be external and serve only as canopies, or in the outer screens to double facades. An exception to this principle is glazed walls in very temperate climates, where neither heating nor mechanical cooling is needed during the year.

Properties

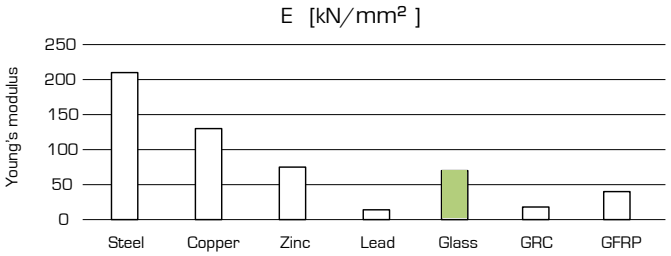
The characteristics common to different glass types are:

- Variable tensile strength.
- Prone to fracture resulting from tiny cracks or imperfections.
- Variable impact resistance.
- Non-corrosive.
- Non-combustible.
- High heat conduction (b).
- Low thermal expansion.

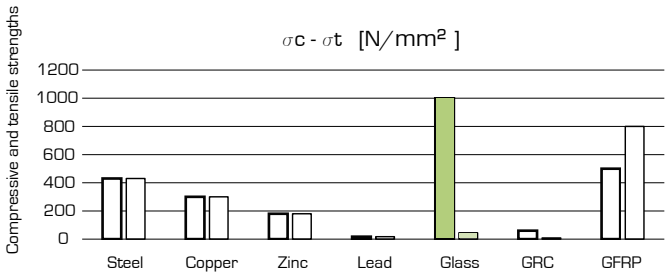
Glass is an elastic material: it does not exhibit permanent deformation until breakage (c). However the material is fragile, and will fail suddenly if subjected to very high stresses. When glass is deflected, it has one face in compression and the other in tension. Whilst the resistance of glass to compressive stress is extremely high, its resistance to tensile stress is significantly lower (f). The resistance to breakage on deflection is of the order of 40 MPa for annealed glass and 120 – 200 MPa for toughened glass, depending on thickness, edgework, holes and notches (k).



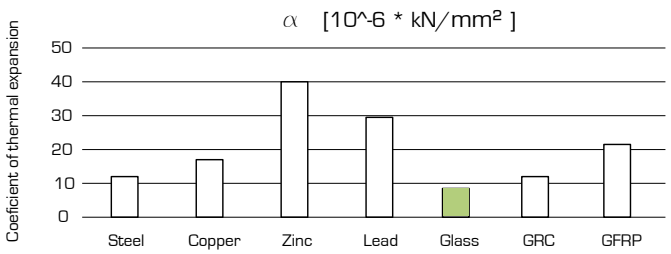
d | Materials density comparison



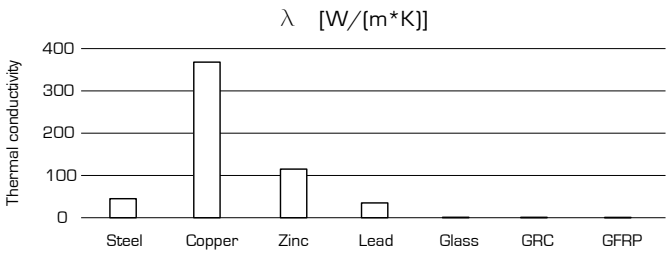
e | Materials Young's modulus comparison



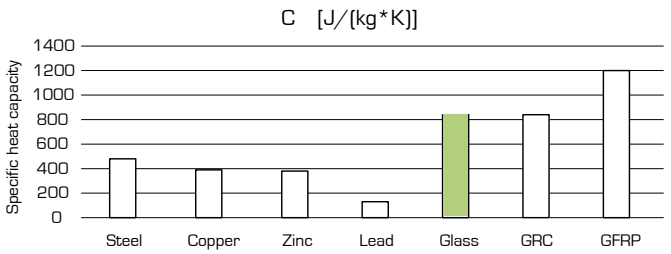
f | Materials tensile and compressive strength comparison



g | Materials coefficient of thermal expansion comparison



h | Materials thermal conductivity comparison



j | Materials specific heat comparison

Location	Glass type					
	Fully Toughened Glass		Heat Strengthened Glass		Annealed Glass	
	f_{rh} (MPa)	γmv	f_{rh} (MPa)	γmv	f_{rh} (MPa)	γmv
Far field surface	90	1.2	40	1.2	45[b]	1.8[b]
Edge	67.5[d]	1.2	30[d]	1.2	21[c]	1.8
Hole	58.5[e]	1.2	26[e]	1.2	21[c]	1.8

[a] f_{rk} for t_f =5s

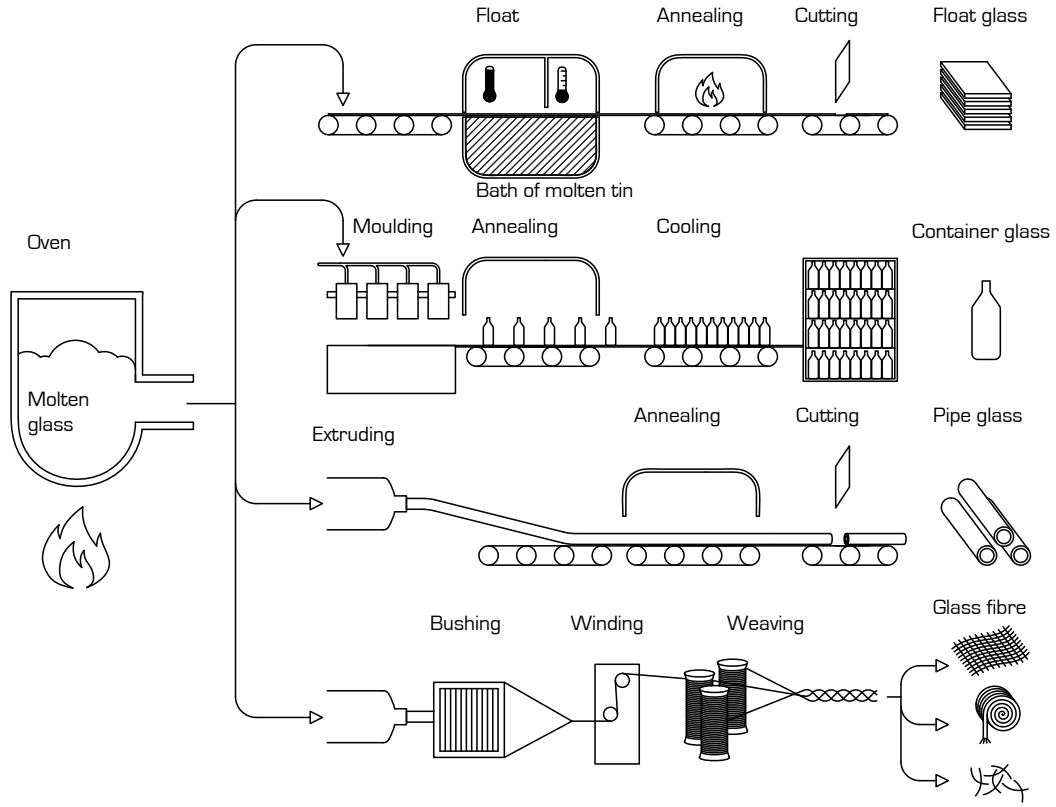
[b] f_{rk}/ γmv = 45/1.8 corresponds to P_f =1/2000 for new or uniformly weathered glass. A larger value of γmv should be used for naturally weathered glass and a lower value of $f_{rk.}$

[c] f_{rk}/γmv = 21/1.8 corresponds to ground glass edges with flaws ≤ 1 mm long and ≤ 0.5mm deep. For highly polished glass or float glass, higher / lower values should be used respectively.

[d] corresponding to 75% of far-field surface stress by meeting edge distance recommendations in EN12150:1.

[e] corresponding to 65% of far-field surface stress by meeting edge distance recommendations in EN12150:1.

k | Characteristic values of toughened and annealed glass and corresponding material partial factors for ultimate limit state



a | Glass production process

Production

The manufacture of float glass is the first stage of production. Float glass is made by pouring molten glass onto a bath of molten tin. The glass floats on top and is drawn off as it solidifies (a). The material is available in thicknesses ranging from 2mm to 25mm (1/8in to 1in). Most float glass has a green tint caused by small amounts of iron oxide in the glass. Adding different oxides to the mix during the manufacturing stage can alter the tint of the glass.

Glass is manufactured in sheets of float glass approximately 6000mm x 3000mm, which is typically much larger than can be used as single sheets in buildings. Some glass manufacturers are able to temper and laminate glass at this size, providing more opportunities for designers to use large glazed panels in facades. However, since most glazing is made in double-glazed units, glass panels do not often achieve these sizes, primarily due to issues of deflection under wind load and the dead weight of the glass. A 3000mm wide double-glazed unit, storey height, weighs around 650kg, making it difficult to lift into place using conventional lifting systems for glazed units and even more difficult to consider moving it around by hand. Double-glazed units of half their size can be difficult to manhandle on site. In addition to the weight of glass, its size is an important consideration when designing with the material. The six-metre by three-metre sheets, called 'jumbo' sheets, are required to be cut economically to avoid waste. This makes glass economical for the 1500mm wide panels preferred in office buildings, but does not restrict their cutting to rectilinear panels. Triangular panels can also be economical if cut without significant waste, as can other shapes which fit the jumbo sheet format.

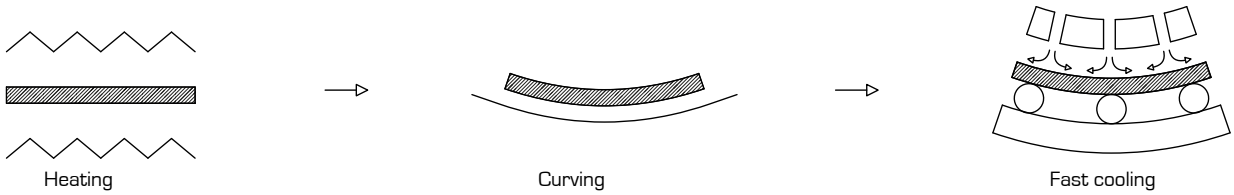
Glass curving

The curving of glass has undergone some development, at least in the quality of production, in recent years (b). Specialist companies around Europe now offer single-curved glass panels in both tempered and laminated glass (c). Some companies around the world will now provide double-curved panels. The ability of glass to be curved, coated and tempered is making it more of a sculptural material again (d), following the tradition of the Guimard Metro Entrances.

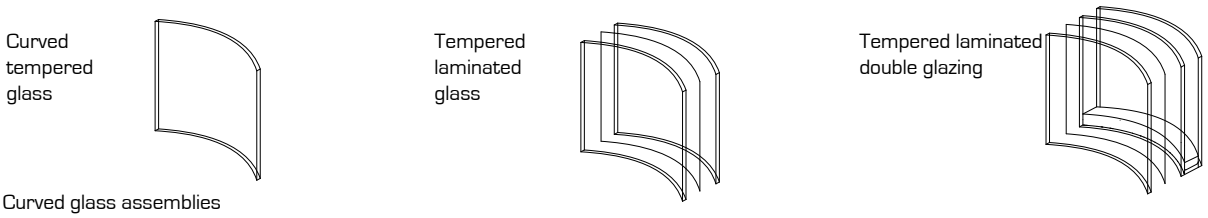
Material selection

Heat-soaked glass is made by reheating float glass then cooling it quickly, which puts the surface of the glass into compression and removes impurities such as nickel sulphide. When broken, fully toughened glass disintegrates into tiny, comparatively harmless pieces. Its strength, measured in terms of impact resistance, is up to five times that of float glass. The toughening process can produce minor distortions in the glass, usually caused by roller marks. Heat-soaked glass is a partially toughened glass for use where full toughening is not required, or as part of a laminated glass construction.

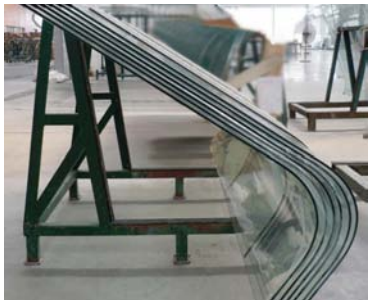
Laminated glass is made by bonding two or more sheets of glass together with a film of plastic in between, called the interlayer. The interlayer can be clear or translucent, and is available in a wide range of colours to create effects of colour in the glass that are translucent in a way which is different from the screen printing of glass. When broken, laminated glass stays together in a single piece due to this bonding between the layers. This makes it very useful for glazed roofs and for glazed screens which are set in front of glazed facades. However, after the initial impact,



b | Glass curving process



c | Curved glass assemblies



d | Curved glass



e | Curved glass

laminated glass will eventually fall away as dangerous fragments of glass, so it is required to be replaced as soon as possible, with the floor area beneath the broken panels typically being secured to avoid the risk of injury to those below. Combining several laminates together in one sheet can make anti-vandal and even bullet-resistant glass.

Wired glass is made by sandwiching a steel wire mesh between two layers of glass, which are then rolled flat. The wire holds the glass together for a period of time during a fire and so prevents the passage of smoke from one side to the other. The roughcast product can be polished to provide a more transparent finish. Wired glasses cannot be toughened and are not regarded as safety products.

Fire resistant glass is formed by glass sandwich panels containing an intumescent layer. In a fire the layer of gel, or salts, reacts to the rise in temperature to provide a degree of insulation against radiant heat.

Variable or switchable transmission glass is a new form of treated glass. Though expensive, it aims to reduce internal heat loss from inside as well as reduce solar gain. It is able to change its own thermal and light transmission performance by means of an electrical signal. In many applications, it turns from transparent to an opaque white when an electric signal is introduced. Applications include glazed partitions in office buildings.

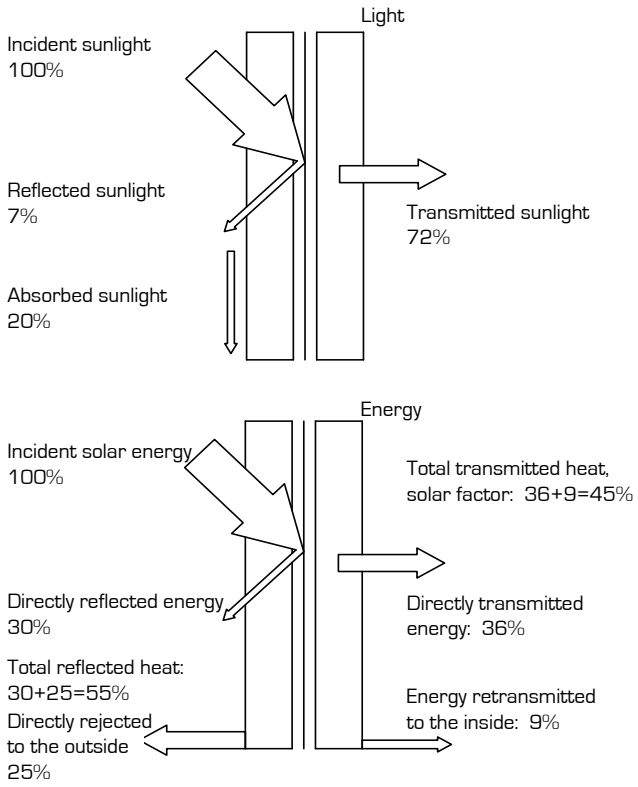
Glass blocks can be solid or hollow. Solid blocks are used as paving for floors. The hollow type is used for walls and consists of two half-bricks fused together to give a smooth appearance on both faces. Glass can be mounted in double- and triple-glazed units to provide greater thermal insulation and sound insulation than is achieved by an equivalent single sheet of glass. An insulated unit can be a mix of float, laminated or other glasses. To improve thermal performance, the air gap between the layers can be evacuated to create a vacuum or be replaced with a low conductivity gas such as argon. The maximum size of double-glazed units is determined by the maximum sizes of glass types used. However, the size of unit is usually determined by windloading rather than maximum glass sizes.

Working with the material

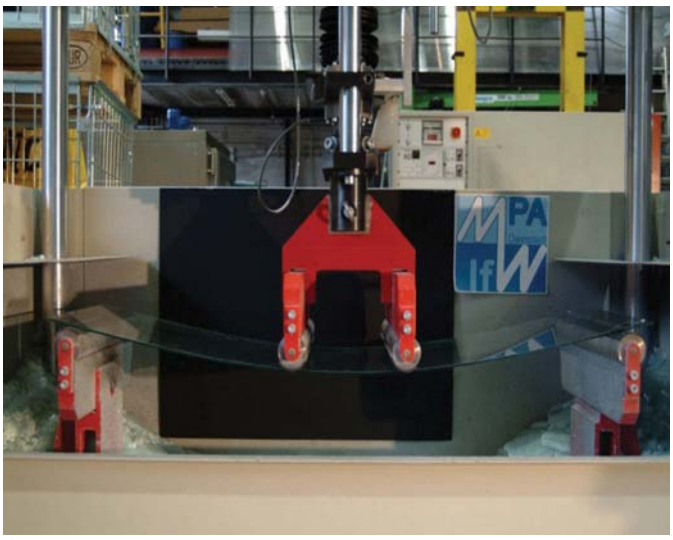
Float, toughened and laminated glass can be curved. Flat glass is heated and moulded to shape in either one or two directions (e). Float glass can be cut, drilled, screwed and glued. It can also be bolted using proprietary systems. Toughened glass cannot be cut, drilled or surface worked after manufacture, but laminated glass can be drilled with specialist equipment.

Surface and body treatments

Float, toughened and laminated glass can be further treated to allow varying levels of light transmission and thermal insulation. Sometimes this is done during the manufacturing process. These treatments are body tinting, screen-printing, sand blasting and acid etching, coatings, including low-E, fritting, and curving. Body-tinted glass is produced by small additions of metal oxides to the glass, reducing solar gain. A limited range of tints is available, including shades of green, grey, bronze and blue.



a | Light and energy performance of glass



b | Four-point bending test for fully toughened glass

Performance

Architectural glass can be described by its physical properties, as follows:

Visible Light Transmittance is the percentage of visible light directly transmitted through the glass.

Solar Factor is the percentage of total solar energy (or heat from the sun) able to pass through the glass.

UV Transmission describes how much sun-damaging UV rays are transmitted through the glass. The lower the value, the bigger the reflection of UV radiation, allowing greater protection of interior fittings and fabrics against the effects of fading colour.

U-Value is used to measure internal heat loss or heat gain through glazed assemblies in the external wall. The lower the U-value number, the greater the level of thermal insulation. In glazed areas of the external envelope of a building, the U-value of the construction must be evaluated in conjunction with the potential for heat transfer through solar gain to understand its overall thermal performance. When calculating U-values of glazed assemblies, an average value is taken that accounts for the thermal transmittance of each element. An average U-value of a glazed assembly would include the individual values for the glass, the frame and any insulated spandrel panels that may be present.

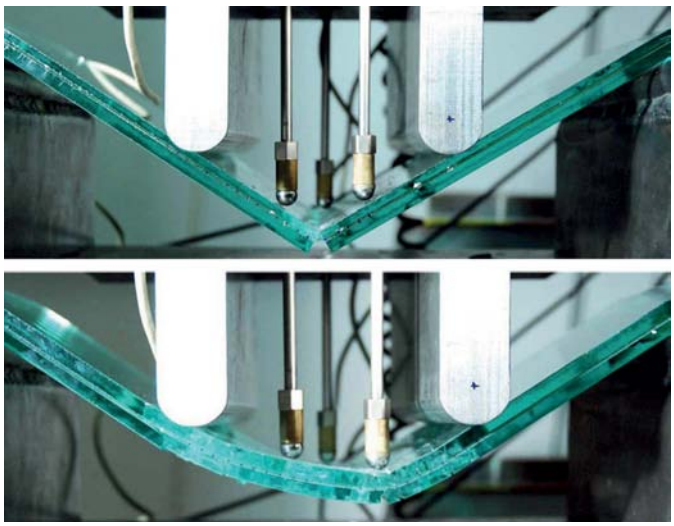
G-value is the coefficient used to measure the solar energy transmittance of glass. It is expressed as a value between 0 and 1 where low values represent low thermal transmittance. The G-value is sometimes referred to as the Solar Factor and is expressed as a percentage (for example a g-value of 0.35 is equivalent to a Solar Factor of 35%).

Solar Heat Gain Coefficient (SHGC) is the solar energy transmittance of a complete glazing assembly including glass, frame, opaque inserts and external shading.

Shading Coefficient is the ratio of the solar energy transmitted by a particular glass combination to that transmitted by a reference glass, usually 3 mm- or 4 mm-thick clear glass.

Light Transmission is the percentage of light that passes from the outside of the glass assembly to the inside. It is often expressed as a percentage with lower values representing lower levels of light transmission (a).

The use of glass in double-glazed units allows the encapsulated inner faces of the glass to have coatings applied to them to reduce their U-value and to reduce solar gain. This makes double-glazed units increasingly energy efficient, and the introduction of argon gas into the void between the glass panels further increases their thermal performance. When used in curtain walling, the framing is typically much poorer in thermal performance, bringing the U-value from a typical 1.1 W/m2K up to a typical 2.0W/m2K, depending on the framing type. The thermal break in curtain wall systems is a structural component at present, so finding a much higher-performing thermal break is not without its difficulties. In very cold climates, triple-glazed units are being introduced, though there is still a limited condensation risk at the edges of the unit where the perimeter spacer conducts greater amounts of heat energy. A development over the past 10 years has been in the introduction of so-called 'super neutral' glasses in double-glazed units which have high solar control performance combined with higher levels of transparency



c | Laminated glass post-failure behaviour



d | Impact test of a fully toughened glass panel

than was formerly the case with so-called 'body tinted' glasses. Super neutral glasses have a colour which is visually not as strong as the older generation of body-tinted types, though these are still available. Super neutrals allow more daylight transmission than their forerunners, but in locations where there is considerable exposure to the effects of the sun an additional outer screen of solar shading panels might be used. A recent development in glass design has been the introduction of all-glass structures, where glass components are connected together by silicone bonds. The silicone serves as both adhesive and sealant, providing weathertight enclosures. The scale of use to date has been modest, with single-storey conservatories, walkways, canopies and glass floors as the primary examples of their use. Most applications have additional mechanical fixings to overcome concerns about the long-term durability of all-glass structures, but this varies from project to project. An alternative to the all-glass structure is the cladding of conventional structures or walls in opaque rainscreens. This method uses screen-printed glass, which is typically silicone bonded to a backing frame then hooked onto or fixed back to, a carrier frame behind. This use of glass as an external rainscreen allows the void between the glass and the external face of the backing wall to have lighting, creating a glow to an otherwise opaque or utilitarian facade, with the benefit of creating some lighting for the safety of users around the building.

One of the main changes in the use of glass in facades and roofs is a gradual move away from entirely rectilinear glass panels to those that deviate slightly from it. These can range from parallelogram shapes to triangular to diamond patterns in glazed facades, but all are based on the need for repeatability of glass unit size in order to make the glass economical to manufacture. In addition, glazed walls are required to move in relation to their supporting structure, and must be able to move from one panel to the next. This further encourages the panels to be of the same size in order to ensure that the movements have a consistent 'behaviour' of movement across the extent of the walls. Some projects, particularly for glazed roofs, have used a large number of glass panel sizes in order to suit the structural geometry of the roof form, but these are typically quantified in detail by the design team in order to control cost. A recent alternative to the curving of glass as part of the manufacturing process has been to 'cold bend' glass sheets on site, typically as part of a stick (site assembly based) glazing system. The extent to which the glass can be pushed at the corners to take up a curved form across its surface is limited (b)(c), but curves in glazed walls and roofs are often modest, making the idea of cold bending more attractive to contractors.

Approximate and easily available maximum glass sheet sizes:
1) Float glass. Maximum size 3180 x 6000mm (125in x 235in) for thicknesses from 2 .5mm to over 25mm (3/32in to 1in)
2) Clear toughened glass. Maximum size 4200 x 2000mm (165in x 80in) for thicknesses from 6mm to 12mm (1/4in x 1/2in)
3) Laminated glass. Maximum size 3180 x 4200mm (125in x 165in) for thicknesses from 4mm to over 25mm (5/32in to 1in)
4) Rough cast wired glass. Maximum size 3700 x 1840mm (145in x 72in) for thickness 7mm (1/4in)

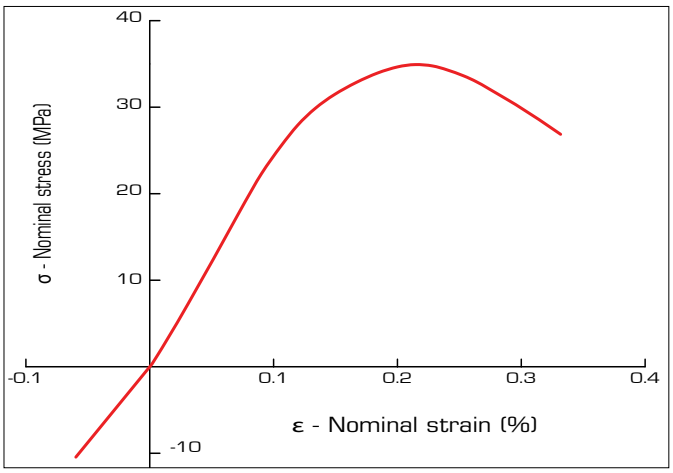
Glass is one of the easiest materials to recycle and is economically viable. Enormous energy savings in glass manufacture can be made by recycling the material.



a | Concrete products

Density of concrete with dense aggregate	2200 to 2600 kg/m^3 (137 to 162 lb/ft^3)
Density of concrete with lightweight aggregate	320 to 2000 kg/m^3 (20 to 125 lb/ft^3)
Design strength	35 N/mm^2 (2.2 x 10^5 lbf/ft^2)
Young's modulus	70 kN/mm^2 (1.5 x 109 lbf/ft^2)
Coefficient of thermal expansion	12.0 x 10^{-6} K^{-1} to 7.0 x 10^{-6} K^{-1}(6.7 x 10^{-6} to 3.9 x 10^{-6} F^{-1}) reducing with age
Thermal conductivity concrete with dense aggregate	1.0-1.8 W/m°C (0.58 to 1.04 BTU/hr.ft.°F)
Thermal conductivity concrete with dense aggregate	0.4-0.7 W/m°C (0.23 to 0.4 BTU/hr.ft.°F)
Specific heat capacity	840 J/kg°C (0.20 BTU/lb °F)

b | Properties and data of concrete



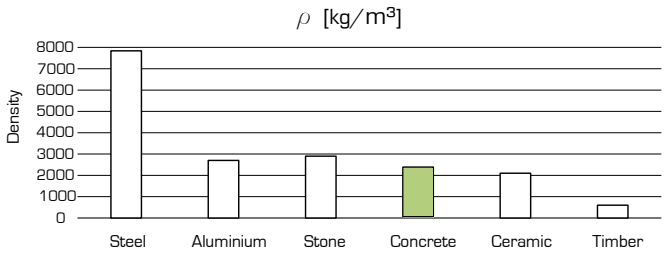
c | Concrete stress-strain graph

Overview

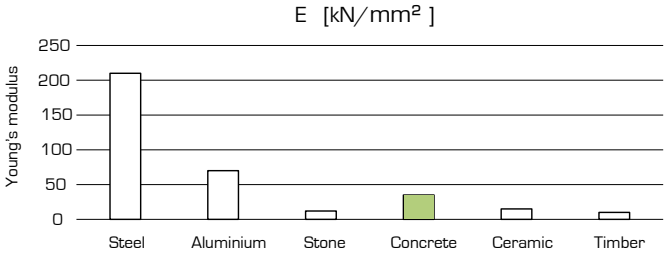
Concrete is a dense material, composed of cement and aggregate mixed with water (a). It sets to form a hard, brittle material, strong in compression but weak in tension (b)(c). Portland cement is the most widely used binding agent for concrete and consists of lime and clay mixed together at high temperature, which is then crushed to form a fine powder. In reinforced concrete, steel and concrete are combined to take advantage of the compressive strength of concrete and the tensile strength of the steel used. Two types are used; mild steel reinforcement is used to form complex elements and has a yield strength of around 250N/mm^2, and high-yield reinforcement is used elsewhere with a yield strength of around 460N/mm^2. As the concrete sets it shrinks, gripping the steel bars thus producing a monolithic structural material for use as frames, walls and floors. These can be cast in place at the site, or off site as precast elements.

Properties

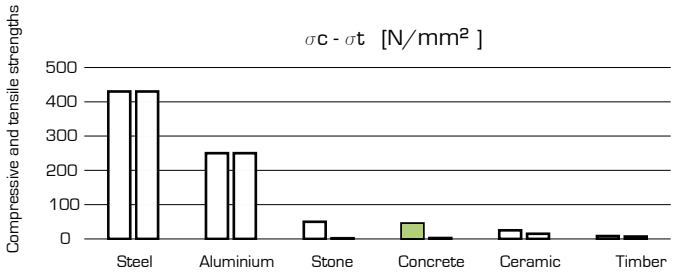
- Easily moulded.
- High strength in compression (f).
- High acoustic insulation for both airborne and structure-borne sound.
- Concrete has higher fire resistance than steel or timber, but appropriate cover to steel reinforcement is needed.
- Most shrinkage of the material occurs as creep during the first year after casting.
- Moisture movement occurs, but is less significant than with timber.
- Slightly permeable to water.
- It will not set properly if the air temperature approaches freezing point. If the air temperature is too high, it will set too quickly, causing cracking.



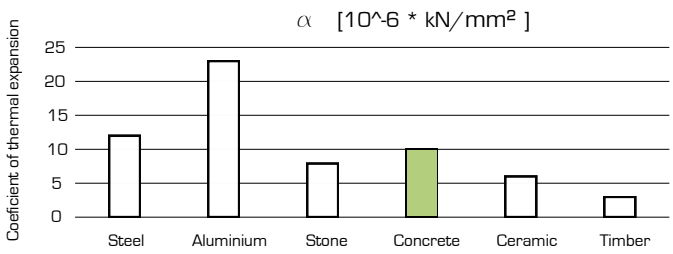
d | Materials density comparison



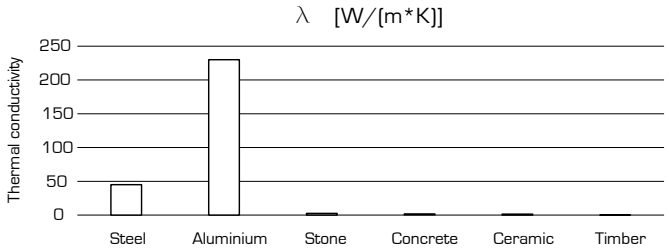
e | Materials Young's modulus comparison



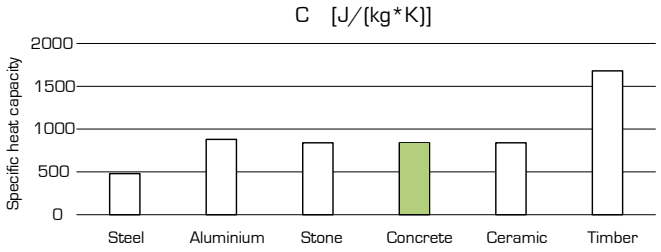
f | Materials tensile and compressive strength comparison



g | Materials coefficient of thermal expansion comparison



h | Materials thermal conductivity comparison



j | Materials specific heat comparison

Class of Concrete	f_{ck}	$f_{ck,\ cube}$
C8/10	8	10
C12/15	12	15
C16/20	16	20
C20/25	20	25
C25/30	25	30
C30/37	30	37
C35/45	35	45
C40/50	40	50
C45/55	45	55
C50/60	50	60
C55/67	55	67
C60/75	60	75
C70/85	70	85
C80/95	80	95
C90/105	90	105
C100/115	100	115

k | Concrete classes according to BS EN 1992-1-1, 2004, Design of Concrete Structures, General rules



a | Setting reinforcement



b | Setting up formwork



c | Setting up formwork

Production

Mix and workability

Essential properties of concrete, such as its ability to be poured, its strength and its durability, all depend on the proportions of the constituent parts of the mix. When designing a concrete mix, a primary consideration is the ratio of the weight of water to the weight of cement, known as the water - cement ratio. In general, the less water is used, the higher the strength of the concrete as a result of water leaving pores in the concrete. However the more water is added to the ratio, the easier it becomes to pour the concrete in place, which also has an influence over the ability to obtain a higher level of visual finish. For the most common applications of concrete, the water-cement ratio is around 0.4 to 0.5.

In addition to water and cement, the aggregate content of concrete has an effect on the behaviour of the material. Aggregate is granular material such as sand, gravel and crushed stone. The main effect of aggregate is to lower the shrinkage of the concrete. To further control the mix, the proportion of aggregate to fluid cement is considered, as is the maximum size of aggregate, in order to achieve the desired performance and behaviour of the concrete mix. In general terms, the largest aggregate size does not exceed 1/3 of the thickness of a concrete component. In addition to aggregate size, the mix generally consists of differing sizes of aggregate.

There is also a wide range of admixtures that can be added to a concrete mix. One of the most common types is an air-entraining admixture. Air content improves the workability of concrete in its liquid form, so can be a benefit to many different mix ratios. An admixture of this type is required for concrete that is exposed to freeze-thaw action, in order to avoid cracking and spalling of the concrete. Other useful admixtures are water reducers that help control the consistency of a mix, as well as retarders and accelerators which are used to affect the time required for concrete to harden. Sometimes supplementary cementitious materials or pozzolans are added to the mix; they are used as a replacement for cement and they reduce permeability. This group of materials include fly ash, slag cement, silica fume, and metakaolin.

Steel reinforcement

In reinforced concrete, reinforcement usually takes the form of steel bars; however sometimes different materials are used. The reinforcement works in tension while the concrete works in compression. The amount of reinforcement bars used in concrete structures depends on the forces applied to the element, and is usually about 1% of the weight for beams and about 6% for columns. Beams and slabs, for example, are sometimes reinforced only on the side when it is in tension (a). The cost of steel is significantly higher than that of concrete, so reinforced concrete design aims to minimise the amount of reinforcing bar used. Reinforcing bars are protected from moisture and chemical corrosion by the concrete cover, so reinforcing bars are set typically at a minimum distance of 50mm from the outside face. In case of fire, the reinforcing bars are able to maintain their structural integrity for the required period with an adequate concrete cover, which also provides thermal insulation from the high temperatures experienced during a fire.

Cast-in-situ concrete

Cast-in-situ is a method of construction that involves pouring wet concrete into formwork to form the concrete in its required position in the building. Cast-in-place reinforced concrete is usually delivered ready-mixed to site and is poured either by pumping or by crane bucket (d).



d | Cast-in-situ method with use of a concrete pump



f | Precast concrete elements



e | Pouring water on curing concrete slab



g | Production of prestressed element

The steel reinforcing rods for cast-in-place reinforced concrete are set in place, often in the form of a cage, between formwork.

Formwork is usually a temporary structure supporting and providing a form to wet concrete, and is made from plywood or steel sheet, but other materials are also used to give a specific appearance to the finished concrete (b). Formwork can take up complex shapes, but since the cost of formwork can be up to half of the total cost of the concrete, the efficient use and re-use of formwork is essential (c).

After the concrete is poured in place, it is left to cure. Concrete shrinks as it cures and can take more than a year to reach its final size, though it continues to shrink indefinitely by tiny amounts. The rate of shrinkage is considerable in the period immediately following the pouring, but slows down by the end of the first year. After approximately twenty-eight days, the concrete approaches its design strength. It is important that the concrete does not dry too quickly in order to avoid cracking (e). The long-term movement of concrete, or 'creep', occurs during the lifetime of the building. Typically, around half the amount of creep occurs in the first three months of the concrete being poured in place.

Precast concrete

Precast techniques have two main advantages over cast-in-place construction. The first is that quality can be easier to control in a workshop, and the second is that precast elements can be assembled rapidly on site. Cast-in-place concrete needs time to gain strength before it can support another element, and this slows down construction activities on-site. Precast concrete is usually more expensive than cast-in-place due to additional transport costs. To be economic, and comparable in cost with cast-in-place construction, the number of different components is minimized in order to reduce the number of moulds, prototypes and trial panels that would be required. Precast concrete systems are manufactured as proprietary systems for both structural frames and wall-cladding panels (f). There is a significant move towards reusing the formwork from one application to the next. Components are cast in moulds which are usually made from glass reinforced polyester, steel or concrete.

Prestressed concrete

In prestressing, reinforcement in the form of high-strength steel wires, rods or cables are passed through the concrete and tensioned at the ends (g). This can occur before pouring the concrete into the formwork, as pre-tensioning, or after the concrete is cured, as post-tensioning.

When an ordinary reinforced concrete beam is loaded, compression is created in the top half of the beam and tension in the bottom part. The compressive stresses in the concrete created by the tension wires must be overcome before the beam bends. However, when a prestressed beam or similar component is loaded, the concrete is in compression throughout its depth, allowing it to be shallower in depth than a reinforced concrete equivalent. Prestressed concrete is more suitable for large spans than ordinary reinforced concrete because components can be shallower and as a consequence lighter, reducing the dead load. Prestressing increases resistance to shear forces compared to a reinforced concrete beam, making it possible to achieve a more slender section than using cast-in-place techniques.



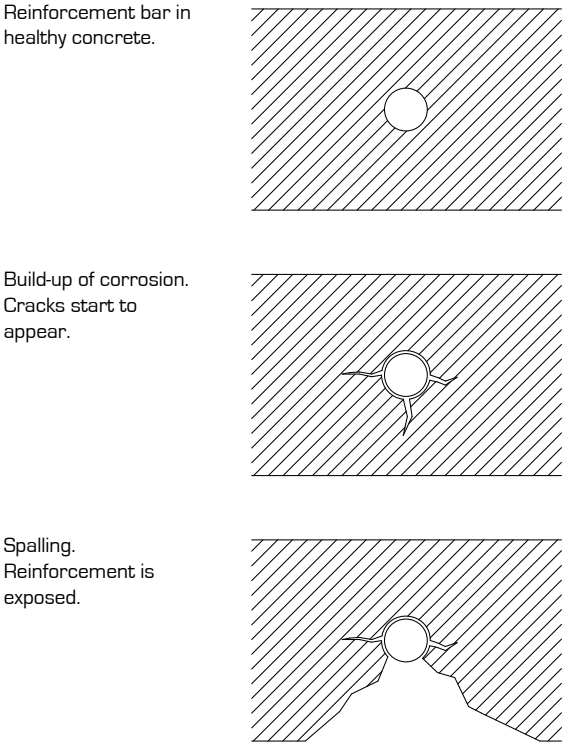
a | Crack pattern resulting from the alkali-silica reaction



b | Deterioration of concrete as a result of carbonatation



c | Example of efflorescence on concrete



d | Rebar corrosion and concrete spalling

Performance

Durability

In addition to the design parameters for concrete which have already been set out, the concrete mix is further adjusted to suit the specific site condition. This includes exposure to elements during the construction, as well as long-term exposure during the life of the building. However, various factors can potentially cause degradation of the concrete. Aggregate expansion may happen if the aggregate contains reactive silica. In certain conditions it leads to an alkali-silica reaction followed by cracking of the material (a). Another factor is the minimum cover of concrete over reinforcing bars, which might lead to the corrosion of the reinforcement bars. Corrosion of reinforcing bars can result in expansion of the steel, which can cause the concrete to crack (d). There are also chemical causes that can lead to concrete damage such as carbonation, leaching, exposure to sulphates, chlorides or sea water (b) (c). Thermal damage might occur when concrete is exposed to very high temperatures, as is experienced during a fire.

Fire resistance

Concrete is non-combustible and has a slow rate of heat transfer, making it suitable as a fire-resisting material when compared with other structural building materials.

Recycling

Concrete can be recycled by crushing the material and using it as an aggregate in new concrete. Although the use of recycled concrete is new, it has been successfully used in new reinforced concrete structures.

Finishes

Concrete adopts the texture of the formwork. Steel formwork leaves a smooth appearance, while softwood boards leave an imprint ranging from fairly smooth plywood to rougher finishes of planks. Boarded formwork produces a pattern of joints across the concrete face. Other finishes include tamping, where a board is moved in a tapping action across the surface of the concrete to form a directional texture; trowelling, where concrete is smoothed with a hand tool; and power floating, where a poured slab is smoothed with a machine to provide a finish that avoids the need for an additional layer of smooth screed.

The fine aggregate and cement determine the colour of the concrete. Changing the attributes of the fine aggregate has a dramatic effect on the appearance of the concrete, whereas large aggregate has little effect unless retardants are used and the large aggregate is exposed. Colour additives can also be added to the mix. Unfortunately, slight variations in the proportions of additives have a dramatic impact on the appearance of the concrete, making it hard to achieve consistent colour between batches.

Paint provides a thin decorative layer, but is prone to flaking and requires re-coating at regular intervals. Colour stains are an alternative as they are absorbed by the top surface of the concrete, forming a permanent coloured finish. Sand blasting and acid etching, processes more commonly associated with glass, can also be used. Bush-hammering the material exposes the large aggregate and provides a rough texture to the surface. Conversely, polishing provides a smooth, shiny surface. However, both of these surface treatments are very labour intensive. Unpolished concrete has a dusty surface and it may be appropriate to seal the surface.



e | Robotic casting of complex concrete form



g | Complex concrete form



f | Pouring of concrete mix into steel formwork



h | Self-levelling concrete

Applications

Complex shapes

One of the biggest advantages of using concrete is its ability to be cast in virtually any shape (g), but geometrically more straightforward solutions and rectilinear elements are more cost effective. Complex geometries require complex formwork, which increases the overall cost and the time needed to position both the reinforcing bars and the formwork, as the layout of the reinforcement becomes more complicated. The use of advanced computational tools and digital fabrication methods (e), such as laser-cutting or CNC-milling, can reduce cost and time, making unique concrete structures feasible. Specially formed concrete elements can be cast-in-situ or fabricated as precast components, but the maximum size of elements that can be transported is a limiting factor in the case of precast concrete components.

Concrete pumps

One of the difficulties of working with concrete is transferring the liquid material to various locations on the site. This issue was addressed with the invention of the concrete pump in the 1920s. There are two main types of concrete pumps in common use: the boom pump and the line pump. Boom pumps are mounted on trucks, and have a robotic arm that enables precise placement at the point of delivery of the concrete (f). They are mostly used on large-scale projects where there is a need to place the liquid concrete in locations remote from the point of delivery to site. These pumps are capable of pumping material at a high delivery rate, with the largest boom pumps reaching up to 70 meters in a vertical direction. Line pumps are more modest devices, and are mounted both on trucks and on trailers. They require a steel or rubber hose attached to the nozzle, and they work at lower volumes than boom pumps. Concrete pumps are also used to spray concrete onto a surface that may be the substrate to a concrete wall. This method, called shotcrete, originates from civil engineering projects, where it is used in the construction of tunnels and earth-retaining structures. It requires the concrete to be sufficiently liquid to be pumped through a nozzle, but it is also required to be sufficiently dense to remain in place. The density of the material is varied to suit both its application and the angle of the base surface in relation to a horizontal plane. This method does not require traditional formwork, as a base surface is used. This technique is not yet widely used in building construction, but there are a growing number of projects that have taken advantage of its potential.

Other uses of concrete

Lightweight concrete is used primarily for toppings in profiled steel/concrete composite construction. It is also used for non-loadbearing components such as precast wall panels. It is not used for high strength applications, but is suitable for most structural applications where weight is an important consideration. The material is typically made from crushed pumice or clinker, giving it better properties of heat and sound insulation than cladding panels made from other materials.

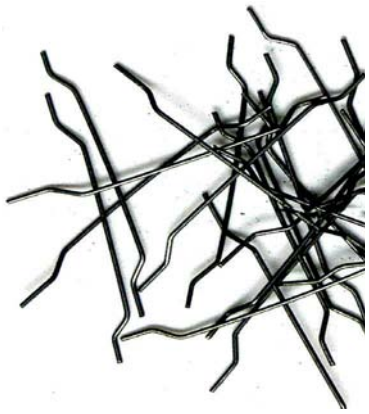
Ferro-cement is a concrete-based material which is typically used to make yacht hulls. This material is beginning to be used as a structural material in buildings, and is suited to complex shapes with a high quality smooth finish. A recent example is the curved roof trusses of the Menil Museum in Houston, Texas, USA. Ferro-cement consists of a cement mortar-based mix with a high degree of steel reinforcement. It has good tensile strength in thin sections. Complex shapes can be formed by applying the wet mix onto a steel mesh by hand without the need for formwork.



a | Glass fibre reinforced concrete



b | Glass fibres



c | Steel fibres

Density	1600-2200 kg/m^3 (99-137 lb/ft^3)
Tensile strength	35 N/mm^2 to 52 N/mm^2 (7.3 x 10^5 to 1.1 x 10^6 lbf/ft^2)
Young's modulus	2.1 to 4.1 kN/mm^2 (43 x 10^6 to 85 x 10^6 lbf/ft^2)
Coefficient of thermal expansion	50 x 10^{-6} K^{-1} (28 x 10^{-6} ^{0}F^{-1})
Thermal conductivity	0.19 W/m°C (0.11 BTU/hr.ft.^{0}F)
Specific heat capacity	1300 J/kg°C (0.31 BTU/lb ^{0}F)

Density	2300 - 3000 kg/m^3 (143-187 lb/ft^3)
Compressive strength	150 N/mm^2 to 250 N/mm^2 (3.1 x 10^6 to 5.2 x 10^6 lbf/ft^2)
Tensile strength	< 7 N/mm^2 (1.5 x 10^5 lbf/ft^2)
Young's modulus	40 to 100 kN/mm^2 (835 x 10^6 to 2088 x 10^6 lbf/ft^2)

d | Properties and data of GRC (right) and UHPC (top)

An overview of GFRC

Glass fibre reinforced concrete, called GRC or GFRC, is a composite material comprising reinforcing glass fibres set in an aggregate and cement-based matrix (a). The first examples of incorporating glass fibres (b) into concrete appeared in the 1940s, but they were not durable due to the erosion of fibres in the alkaline environment of concrete. Alkaline-resistant fibres were invented in 1967 by The Great Britain Building Research Establishment, allowing further development of GRC in architectural applications. The performance of a GRC component loaded in bending is defined by three main characteristics: limit of proportionality (LOP), modulus of rupture (MOR) and ultimate failure strain (e_u). These characteristics can be determined from the stress-strain relationship which is established through flexural testing.

Properties of GFRC:

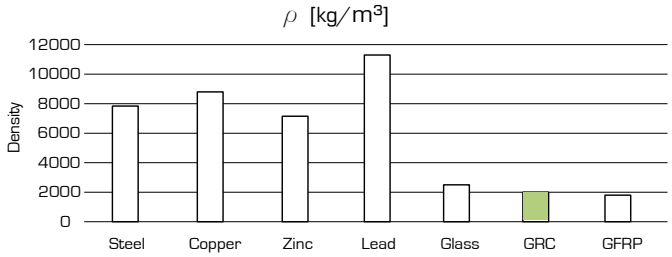
- Performs better in compression than in tension, like concrete, but is stronger (d).
- Fibres are the principal load-carrying members,
- Fibres provide reinforcement for the matrix in fibre-reinforced composite materials.
- Weathers well but is susceptible to fading, particularly with brighter colours.
- Recyclable.
- Non-combustible.

An overview of UHPC

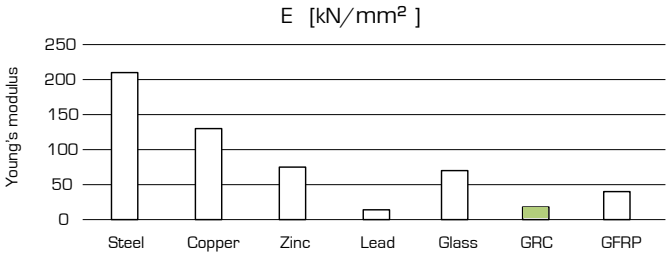
Ultra high performance fibre reinforced concrete, called UHPC, or UHPFRC, is a composite material using a cement matrix with steel (c), glass or organic fibres. The material was developed around 20 years ago and is considered to be a major breakthrough in concrete technology. UHPC has the capacity to deform and support flexural and tensile loads, even after initial cracking, so it can be used as a structural material. In some applications, reinforced concrete has been replaced with UHPC, with the benefit of reducing construction time by eliminating the need for traditional reinforcement. The high percentage of steel fibres, ranging from 6 to 30% in weight, allows the material to achieve a high post-cracking tensile strength, which increases the ductility of the material. UHPC typically has a lower water-cement ratio when compared with GRC, ranging from 0.20 to 0.25.

Properties of UHPC

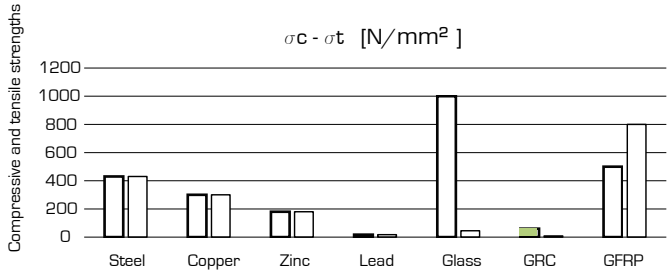
- Performs better in compression than in tension, like concrete, but is stronger (d).
- Fibres are the principal load-carrying members
- Fibres are steel or organic
- Higher durability in comparison to concrete or GFRC.
- Non-combustible
- Can be reinforced with steel-reinforcing bars or can be pre-stressed.



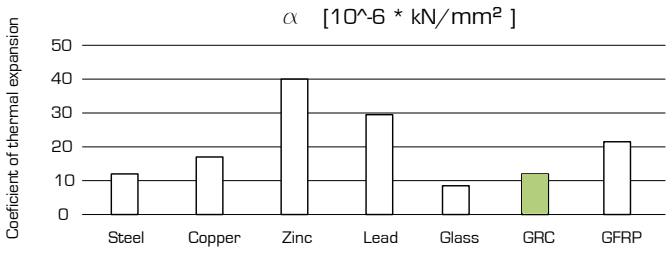
e | Materials density comparison



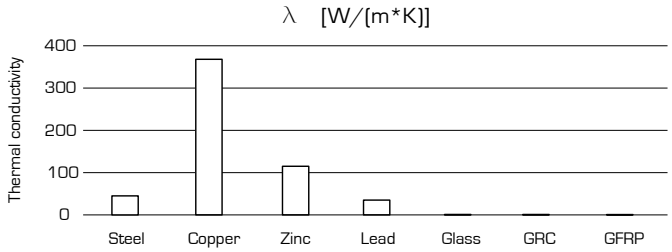
h | Materials Young's modulus comparison



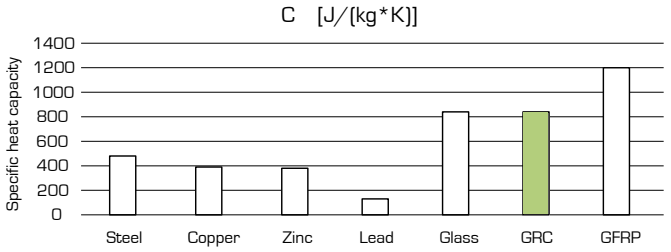
f | Materials tensile and compressive strength comparison



j | Materials coefficient of thermal expansion comparison



g | Materials thermal conductivity comparison



k | Materials specific heat comparison

Production

While manufacturing methods for GFRC and UHPC are very similar, the main difference is in the mix and material used for reinforcing fibres. A typical mix for GRC consists of 2 - 6% chopped glass fibres, a cementitious binder, sand, pozzolan as 10 - 25% cement replacement, 5% acrylic polymer emulsion, and admixtures. UHPC is made up of steel or organic fibres (ranging from 6 - 30% in weight), cementitious binder, silica fume, quartz flour, fine silica sand, and high-range water reducer. UHPC typically has a lower water-cement ratio when compared to GRC, ranging from 0.20 - 0.25.

In both cases the material needs to be cast in moulds, which are usually made of steel or plywood sheets, or CNC milled from a foam polymer block (MCH_54, a). The choice of fabrication method for a mould depends upon the geometry of the element to be formed, and can significantly affect the cost. If the 3D geometry of the element to be formed is developable, that is to say its curved surface can be unrolled to form a flat surface, the finished component is usually cheaper; while non-developable objects require an expensive CNC-milled foam mould. The difference in cost is a result of CNC milling usually taking longer than other moulding methods, with the milled form requiring further work to make it smooth enough for use as a mould. While plywood and steel can be reused, foam moulds are usually used only once, due to their lack of durability.

The casting of GFRC and UHPC can be undertaken with spraying or pouring techniques. In the pouring method, the fibres are mixed with concrete slurry prior to casting, resulting in an isotropic structure in terms of fibre orientation. The packing density of fibres limits the possible fibre content in this case, typically determining a lower mechanical performance.

The mix is poured into moulds which are vibrated in order to distribute the material equally and remove air bubbles. The poured material is covered to prevent moisture loss and left to set. The element is demoulded the next day and cured under polythene sheets to maintain moisture content.

In the spray manufacturing of GFRC, the concrete slurry and the fibre are fed separately into the spray nozzle (MCH_54, d). Fibres, in the form of roving, are chopped to a specified length in the spray gun, before being added to the slurry. Then the slurry is projected onto the mould surface using pressurised air (MCH_54, c).

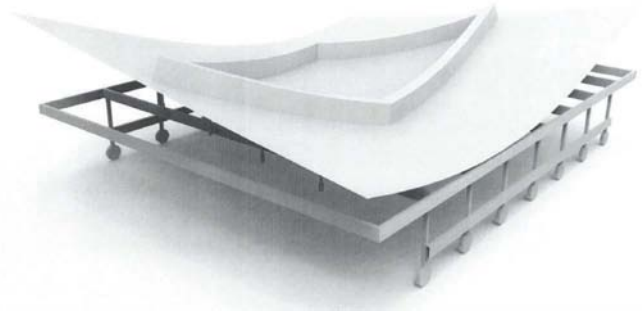
For UHPC the process is very similar; however the fibres can also be pre-mixed into the slurry. In order to achieve doubly curved elements, the preferred technique is spraying. The slurry is sprayed from a gun and built up in thin layers on the mould surface until it achieves the required thickness. The material is then compacted by use of hand rollers, and left to set under a protective polythene sheet to prevent moisture loss. After demoulding, the piece is covered and left to cure.



a | CNC milling of a foam mould



c | Application of GRC with spray-guns



b | Mould based on developable surface



d | GRC Spray-gun

The curing of both GRC and UHPC takes approximately seven days unless a polymer curing compound is used to reduce the time. It is important that the moisture content is controlled during this process, so usually the units are covered with polythene sheets. However, there is no need for the material to be covered if a curing compound is used. There is another variation of UHPC, called HRUHPC, or heavy reinforced ultra high performance concrete, that uses the same principles as UHPC but has enhanced structural properties. The main difference in the physical properties between these two materials is in the cementitious mix used, though both materials are prestressed to maximise their respective performance.

Performance

Durability

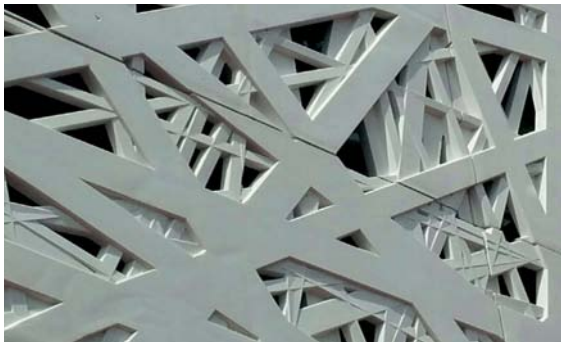
GRC is a composite material rich in cement, with a water-cement ratio less than 0.40, and with a low water permeability grade; factors which determine a high degree of durability. The main effect of the exposure of GFRC to the external environment is in its ductility. The hydration of cement in GFRC continues for several months after casting. This can cause calcium hydroxide crystals to build up around the fibres, which are both highly alkaline and also abrasive, and their buildup locks the fibres into the matrix, preventing fibres from slipping after the GRC cracks. The surface coating on glass fibres helps to prevent the buildup of calcium hydroxide crystals around the fibres.

UHPC has higher performance in durability than its equivalent in GFRC. The higher durability of UHPC is a result of the cement in the mix, combined with the use of aggregate with a small diameter of only a few millimetres. This mix results in a highly homogeneous concrete. The water-cement ratio is less than 0.25, and ultra-fine particles which are added, such as silica fume and ultra-fine synthetic silica, result in a high degree of compactness. These characteristics result in a material of overall durability that is very high. UHPC has high resistance to chloride ion penetration due to its low capillary porosity, making it extremely resistant to corrosion, even with the inclusion of a large proportion of steel fibres in the mixture.

Fire

Both GFRC and UHPC are fire resistant and non-combustible, and have a fire resistance higher than that of concrete. The rating achieved according to European and American Standards is as follows:

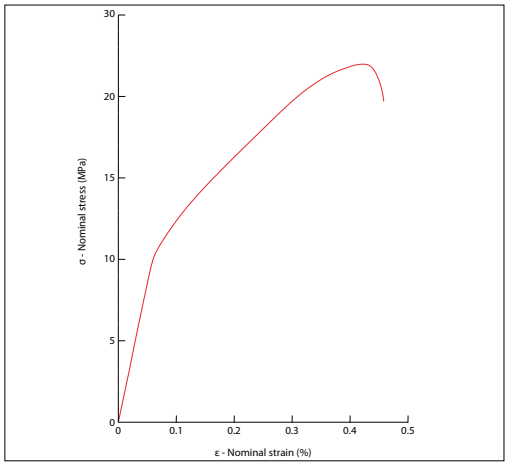
- Reaction to fire classification: A1 according to EN 13501-1:2007: Fire classification of construction products and building elements.
- Class 0 according to BS 476: Fire tests on building materials and structures. Classification and method of test for external fire exposure to roofs.
- Class A according to NFPA 255: Standard method of test of surface-burning characteristics of building materials.
- Class 1 according to ASTM E84: Standard method of test of surface-burning characteristics of building materials.



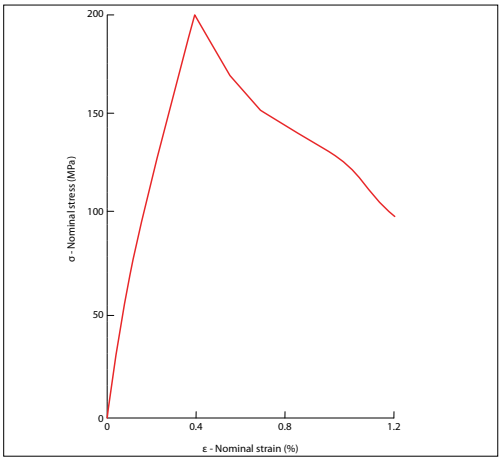
e | GRC facade panels



g | FRC facade panels



f | GRC stress-strain diagram



h | UHPC stress-strain diagram

Applications

As a result of their physical properties, UHPC and GFRC are very suitable for use as facade cladding panels. Both materials can be moulded easily to form a wide range of forms in widely varying sizes and forms as (e) (g). The size of panels in these materials is limited by fabrication, but developing technologies have resulted in large-scale CNC machines that are able to maximize the size of the moulds (a). However, the transportation capabilities also need to be taken into account when considering large-scale casting.

Both materials are relatively lightweight when compared to natural stone or precast concrete products; however UHPC has a higher structural performance than GFRC (f)(h). This generally results in panels of the same size having approximately the same weight, as the reduction in material with UHPC is balanced by its higher material density. Even though UHPC is more expensive than GFRC as a material, the reduced quantity required for a panel in UHPC, when compared with GFRC, should be taken into account.

One of the advantages of UHPC over GRC is that UHPC can be used as a structural material. The higher tensile and compressive strength of UHPC allows it to be used for columns and other loadbearing elements. Reinforcing bars can be cast into UHPC structural elements. When pre-stressed, a UHPC beam can achieve sizes comparable to that of steel, while maintaining the advantages of the complex forms and fire resistance associated with concrete.

There are many similarities between GFRC and UHPC. Both GFRC and UHPC can be used to provide relatively lightweight cladding panel when compared with an equivalent in either natural stone or cast stone products. Steel connection components, such as channels or sockets, can be pre-cast into the panels to facilitate the connections to the primary structure. For this reason the installation process is easy and cost-effective. Furthermore, because of the cementious durable finish, GFRC and UHPC panels are straightforward to maintain and clean.

Both GFRC and UHPC panels can achieve a high level of visual finish. The external surface can be modified to suit a range of visual expressions and surface finishes.

Due to low permeability combined with the use of acrylic polymers within mixes, both absorption of water and carbonation are reduced, allowing components to retain their original appearance for longer. As a result of the matrix mix, UHPC can achieve a design life of up to 60 years. The material can also achieve a low level of discolouration due to the combination of small concrete particles and a high density of mix. For these reasons UHPC is particularly suitable for applications in highly polluted environments. GFRC and UHPC facade panels have been used in different locations around the world as a locally sourced material, since their transportation time is required to be relatively short for the materials to remain economical.



a | Extruded ceramic products

Density average brickwork	1900-2100 kg/m^3 (118 to 131 lb/ft^3)
Design strength	5.0 to 25 N/mm^2 (1.0 x 10^5 to 5.2 x 10^5 lbf/ft^2)
Coefficient of thermal expansion	5.0 x 10^{-6} K^{-1} to 8.0 x 10^{-6} K^{-1} (2.8 x 10^{-6} to 4.5 x 10^{-6} $^0F^{-1}$)
Thermal conductivity	1.3 W/m^0C at 5% moisture content (0.75 BTU/hr.ft.^{0}F)
Specific heat capacity	800 J/kg^{0}C (0.19 BTU/lb ^{0}F)

b | Properties and data of ceramic

Overview

Ceramics used in the construction of buildings are usually clay-based products. The most common applications are building bricks, extruded terracotta facade panels and paving (a).

Properties

- A heavy and durable material (c).
- High compressive strength (e).
- Very low tensile strength.
- High resistance to weathering.
- High thermal mass.
- High acoustic mass.
- High impact resistance.
- High fire resistance.
- Susceptible to thermal and moisture movement.
- Low seismic resistance.
- High resistance to corrosion.
- Brittle (d).
- Usually low coefficient of thermal expansion (f).

Production of bricks

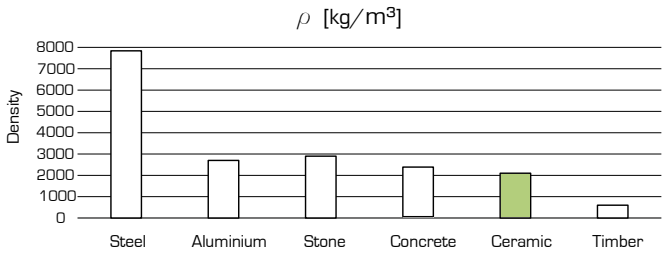
Bricks are made by cutting or moulding clay. They are then baked in a kiln to form a hard, brittle unit (MCH_58, a). A very wide range of colours and textures is available, from the precisely dimensioned, evenly coloured types which are wire cut from a clay extrusion to the less regular handmade bricks which are individually formed in moulds. Extruded wirecut bricks are sometimes made with holes running through them to reduce their weight or to allow reinforcing rods to link them together (a). Hand-made bricks often have an uneven appearance which provides a rich visual texture as a completed wall.

Production of extruded terracotta panels

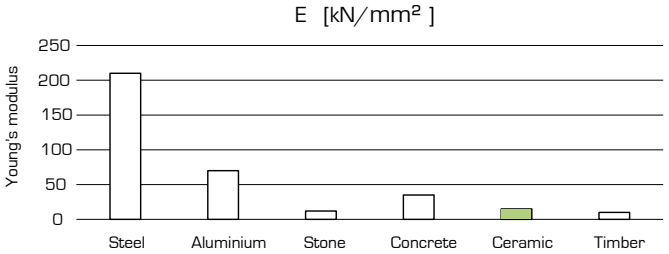
In recent years, terracotta has become an alternative material to brick for use in building facades. Rather than stacking bricks to make a wall of rainscreen configuration, as in cavity wall construction, extruded tarracotta is used to make large-scale panels which are supported on metal brackets and rails. The use of terracotta extrusions has developed from the more traditional use of terracotta tiles that are hung from timber battens to form a tiled wall. Extruded terracotta is made by pouring a clay-based mix into a hopper, then forcing it through metal dies to form the chosen extrusion. The continuous extruded strip is cut to the required length to form the basis of a panel or tile, usually with a wire. The extruded strip is then passed through a kiln, where it is fired to form the terracotta product. The extruded strips may be glazed or left in a natural condition.

Specially made terracotta components, such as L-shaped corner panels, are made by hand, with assistance from smaller-scale presses, then fired.

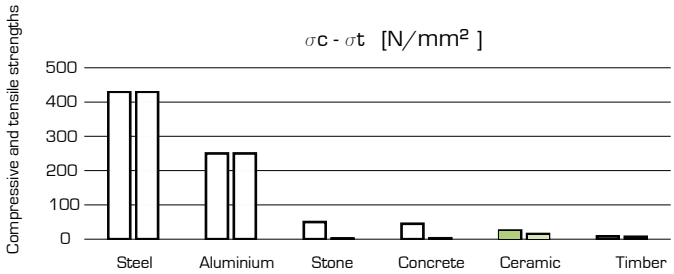
Ceramics can be both glazed to a wide range of colours and textures for visual reasons, as well as being used to reduce water absorption (j)



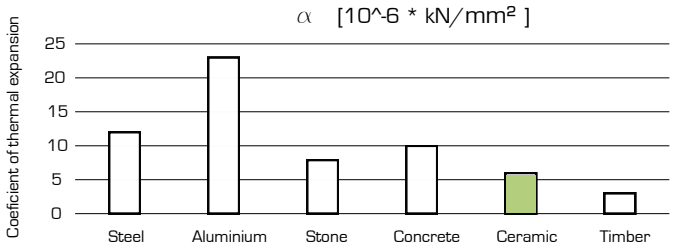
c | Materials density comparison



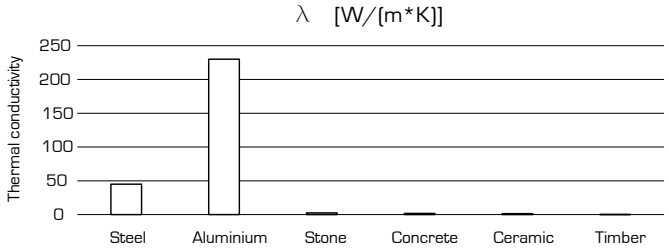
d | Materials Young's modulus comparison



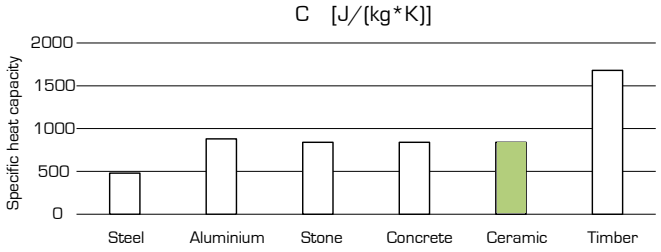
e | Materials tensile and compressive strength comparison



f | Materials coefficient of thermal expansion comparison



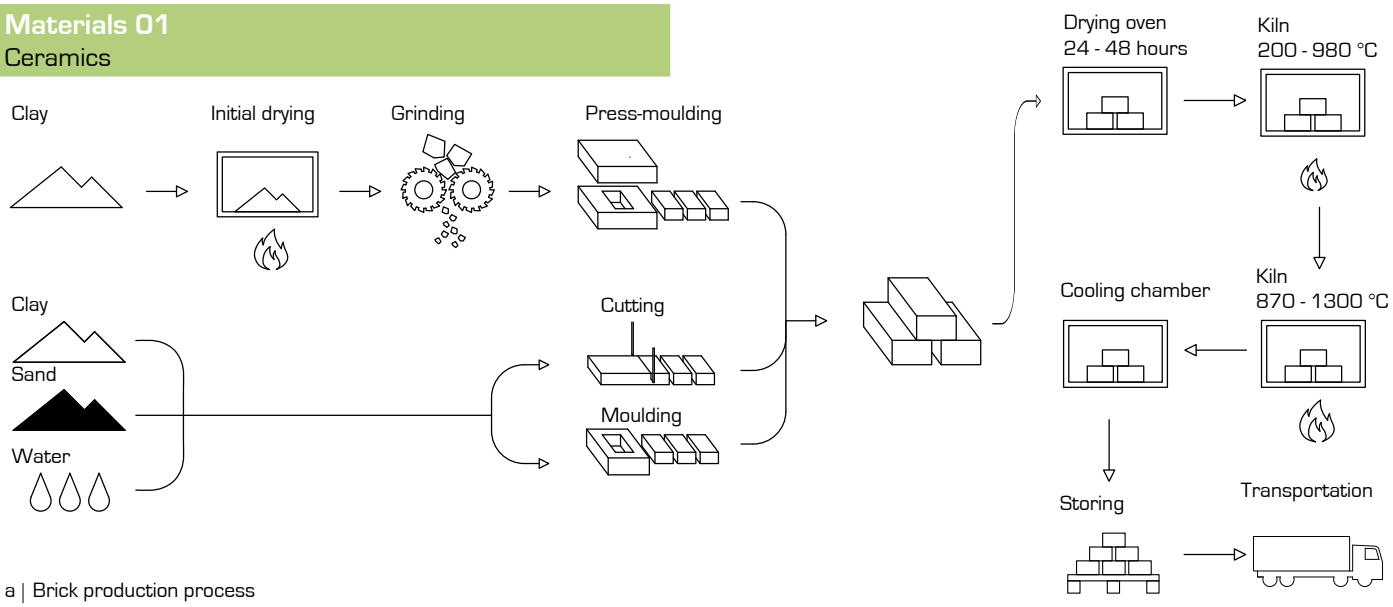
g | Materials thermal conductivity comparison



h | Materials specific heat comparison

		Minimum Compressive Strength Gross Area psi (MPA)		Maximum cold water absorption %		Maximum five-hour boiling absorption %		Maximum saturation coefficient	
ASTM Standard		Average of 5 blocks	Individual	Average of 5 blocks	Individual	Average of 5 blocks	Individual	Average of 5 blocks	Individual
C62 Grade	SW	3000 (20.7)	2500 (17.2)	-	-	17.0	20.0	0.78	0.80
	MW	2500 (17.2)	2200 (15.2)	-	-	22.0	25.0	0.88	0.90
	NW	1500 (10.3)	1250 (8.6)	-	-	No limit	No limit	No limit	No limit
C216 Grade	SW	3000 (20.7)	2500 (17.2)	-	-	17.0	20.0	0.78	0.80
	MW	2500 (17.2)	2200 (15.2)	-	-	22.0	25.0	0.88	0.90
C652 Grade	SW	3000 (20.7)	2500 (17.2)	-	-	17.0	20.0	0.78	0.80
	MW	2500 (17.2)	2200 (15.2)	-	-	22.0	25.0	0.88	0.90
C1088 Grade	Ext.	-	-	-	-	17.0	20.0	0.78	0.80
	Int.	-	-	-	-	22.0	25.0	0.88	0.90
C902 Class	SX	8000 [4000] [2] (55.2) [[27.6]][2]	7000 [3500][2] (48.3) [[24.1]][2]	8.0 [16.0][2]	11.0 (18.0)[2]	-	-	0.78	0.80
	MX	3000 (20.7)	2500 (17.2)	14.0	17.0	-	-	No limit	No limit
	NX	3000 (20.7)	2500 (17.2)	No limit	No limit	-	-	No limit	No limit
C1272 Type	F	10,000 (69.0)	8800 (60.7)	6.0	7.0	-	-	-	-
	R	8000 (55.2)	7000 (48.3)	6.0	7.0	-	-	-	-

j | ASTM brick classification



a | Brick production process

on the outside face of terracotta facade panels. A primary constituent of the glaze is silica, which is melted and then fused with the ceramic surface as a result of high temperature. Metal oxides can be added to the glaze mix in order to accelerate melting, while alumina is used to keep the molten glaze on the surface of the terracotta component. Different colours can be achieved by adding colourants; traditionally iron oxide, cooper carbonate or cobalt carbonate.

One method of applying the glaze is to dip the terrcotta component into a mixture of metal oxides, together with powdered minerals and water. Another method is to pour the glaze onto the ceramic element, applying the mix with either a brush or spraying the wet glaze onto the surface of the component. Yet another method is to use a dry powdered glaze that is dusted onto the terracotta component. Specific additives can also be applied in the kiln to create a mist of glaze that is rich in sodium, and which reacts with the chemical compounds already existing in the extruded clay component. This method provides a finish known as salt glaze.

Performance

Durability

The mix of the raw material has a great effect on the durability of the manufactured ceramic component, for both bricks and extruded terracotta. If the clay contains soluble salts, then efflorescence might appear on the surface of the manufactured brick – usually as a white stain – but some minerals cause yellow, red or green discolourations in clay-based products. In the case of bricks, calcium carbonate content can reduce their durability. The calcium carbonate content can transform into quicklime during the kiln processing (a), and may cause expansion as soon as water is absorbed by the brick. This can result in the spalling of fragments of material, resulting in circular pits left on the surface of a brick.

Salt attack is one of the most common causes of degradation of non-glazed ceramics, affecting bricks specifically. Because of the high water absorption of some bricks, salt can saturate the brick in the form of a solution. When water evaporates from the brick, salt is drawn near the outer face, forming crystals just below the surface. As the crystals grow, the pressure on the matrix increases, and eventually cracks can appear. These effects do not apply to higher quality bricks, but serve to inform an understanding of the visible appearance of historic examples.

Acoustic properties

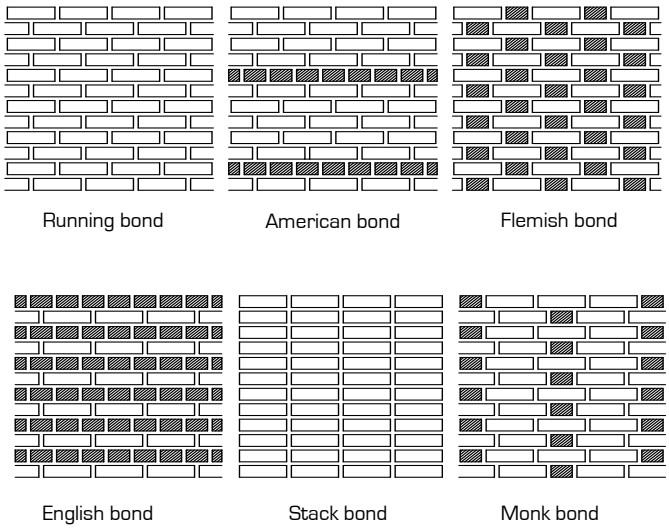
Brick walls provide high levels of acoustic insulation, when compared to a similar wall in other common building materials. The attenuation of airborne sounds can be further increased by the use of the cavity wall, where the inner skin of the the wall is made from brick or concrete block.

Fire resistance

Ceramic materials are non-combustible and have high resistance to the surface spread of flame. Bricks have a lower rate of transfer of heat during a fire than many other building materials, though terracotta panels are usually fixed to a metal supporting frame in rainscreen configuration which makes them less high performing than brick in this regard.

Recycling

Bricks and pavers are commonly reclaimed and are typically either reused for brick wall construction, or are crushed for use as a filler or base for other forms of construction. They can also be used in landscaping conditions around buildings.



b | Most common brick bonds



c | Ceramic louvres

Applications

Typically ceramic building materials are used as bricks to provide a self-supporting construction, or as extruded terracotta panels which are held in place by a secondary fixing system. Bricks vary in size between countries; bricks in the UK are generally made in a single size: 215mm long x 102.5mm wide x 65mm high, (7 5/8" l x 3 5/8" w x 2 3/8" h). When constructing brickwork, a 10mm joint is typically used throughout, resulting in vertical courses 75mm high and 225mm long. Two bricks laid side by side with a 10mm joint are equal to a brick length.

Construction in brick

Bricks are bonded with mortar, a material applied in a paste form, made from sand, binder and water. Portland cement is commonly used as a binder, but sometimes it is replaced with lime mortar. An individual brick is given a classification based on how brick is laid and oriented inside a wall. The most typical orientations are where the brick is laid flat and forms a 'stretcher' when its long, narrow side is exposed. When the short side of the brick is exposed horizontally, it is called a 'header'. Much less commonly, bricks can be laid vertically, forming a 'soldier' course with the long narrow side exposed; typically when they form an arch or flat lintel course above window and door openings. Bricks can also be set in a 'sailor' course, with the broad face of the brick exposed while set vertically. Alternatively, they can be set with the short end of the brick exposed and set vertically – called a 'rowlock' – or be turned to expose the broad face of the brick, still set vertically on edge, which is called a 'shiner'.

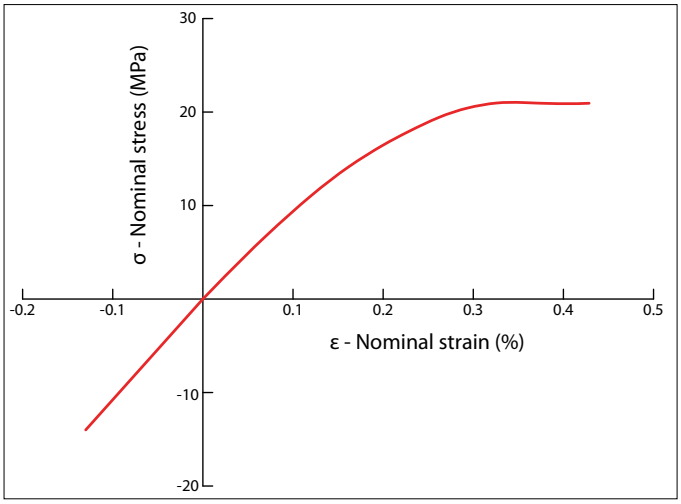
Consequently, bricks can be set together in many different combinations, which offer different amounts of stiffness and watertightness, each with a distinct pattern visible on the outside face of a wall. These combinations of brick are called 'bonds'; some of the most commonly used being running, English, Flemish and American bonds (b). Bricks can be easily cut and drilled. Metal fixings, in the form of brackets and dowels, are used to provide additional support for walls, and these are easy to integrate due to the ease of working with brick as a material. These fixings are used extensively in brick cladding, which is supported by a structural frame (c). Bricks are made in a wide range of colours from reds to blues to yellows. The colour of a brick is determined largely by the type of constituent clay, how that clay is fired, and which pigments are added.

The most widely used types are common, facing, engineering and calcium silicate bricks. 'Fair faced' bricks are usually used on the external face, while rougher-faced bricks are used within the depth of the wall. Engineering bricks are used for their high strength and are almost impervious to water, so are often used below ground in addition to structural applications where brick is used as a primary loadbearing element. Calcium silicate bricks are made from a mixture of sand and lime, and are compressed under steam pressure in a mould. They are low to medium strength, and their water absorption is comparable to that of clay bricks. They are mainly used in internal walls, where their light appearance can be exploited.

The modular nature of brickwork imposes a certain discipline on the detailing of openings and corners. Specially shaped bricks, called 'specials', are usually kept to a minimum in order to reduce costs associated with their use. Bricks can be transported in large or small quantities, with relative economy, over short distances. The modular nature of brick limits the spectrum of achievable shapes; however there are some examples of unconventional formal use of this material. An example of this approach can be found in the work of Eladio Dieste, an Uruguayan engineer and architect. He developed a technique of building single thickness brick shell structures, based on curved and arched forms. A current development is the research into building brick structures using robotic devices.



a | Timber products



b | Timber stress-strain graph

Overview

Timber is probably the oldest building material (a). Due to its structural strength and wide availability, it can compete even with the most innovative materials. It is fully recyclable, safe and easy to work with. It has a cellular micro-structure that gives its unique properties.

Properties

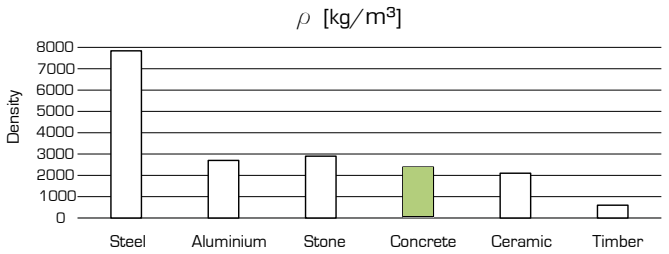
Timber has the following general properties:

- It is fibrous and elastic, making it strong in tension and compression (b). Like metals, it performs better in tension than in compression (e).
- Undergoes varying degrees of moisture movement.
- Straight grain is stronger than an irregular grain and is easier to work with.

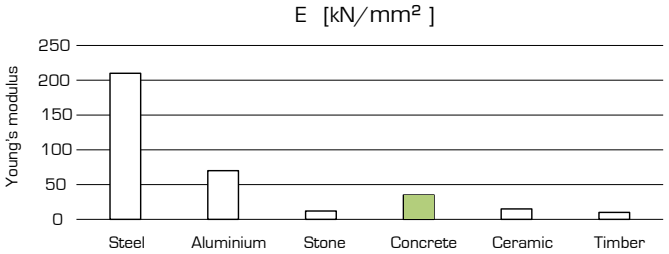
Material classification

Commercial timber is classified as either softwood, from conifers, or hardwood, from broad-leaf trees (k). Softwood is used for most structural timber (j), as it is easily worked due to its softness and straightness of grain, though oak is common for exposed structural timber frames. Typical types are cedar, douglas fir, western hemlock, pine, redwood (scots pine), spruce, whitewood and yew. Most softwood comes from the coniferous forests of the northern hemisphere. Hardwoods have high strength and durability, a rich grain and varied colour. They are more expensive than softwoods which make them too expensive for most current structural use, but suitable for joinery and finishes. Typical varieties of hardwood are ash, beech, birch, cedar, iroko, mahogany, maple, oak, teak and walnut. Hardwood occurs in most parts of the world but is obtained mainly from both northern temperate forests and tropical rainforests. Since hardwoods constitute a large proportion of the rainforests, and take much longer to grow than softwoods, the world's supply is depleting at an alarming rate. As a result, the use of certain tropical hardwoods has come under considerable scrutiny in recent years.

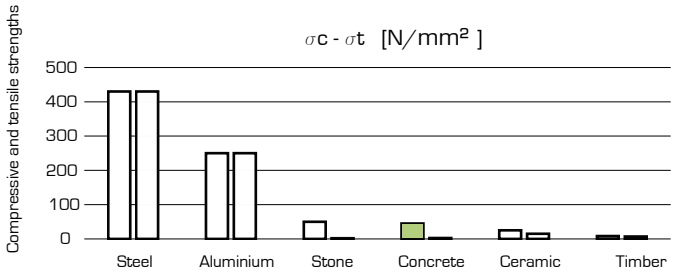
Another commercial product is the glued laminated timber, also known as 'glulam'. Glulam is manufactured by bonding together individual laminations of solid timber. This produces members of rectangular cross-section that are larger and longer than may be obtained simply by sawing a normal log. Glulam is readily available, extremely reliable and very adaptable in design. Glulam is a type of material classified in North America as engineered wood, but in Europe, the term "wood" is not used for its purpose as a structural material. As indicated by the structural codes of practice and their supporting standards, these always deal with structural timber, of which glulam forms a vital part. Both softwood and hardwood are laminated to produce glulam; for the former the main species used are larch and douglas fir, while for the latter European oak, sweet chestnut and American white oak are mainly used.



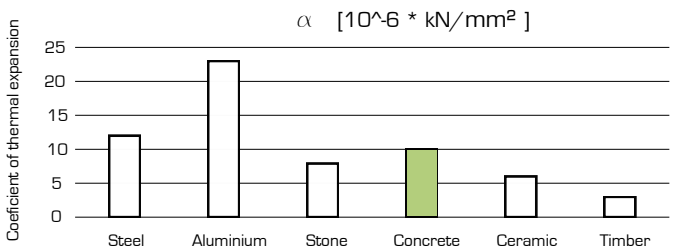
c | Materials density comparison



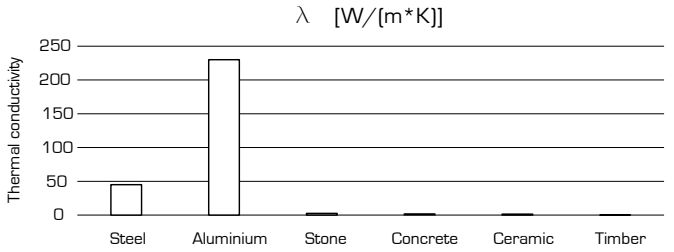
d | Materials Young's modulus comparison



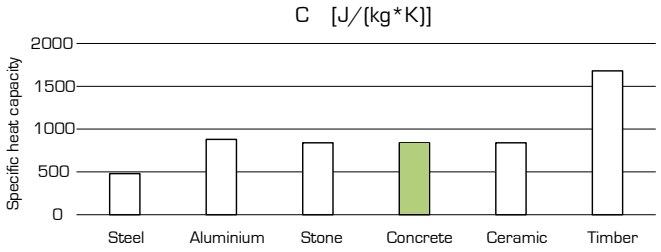
e | Materials tensile and compressive strength comparison



f | Materials coefficient of thermal expansion comparison



g | Materials thermal conductivity comparison

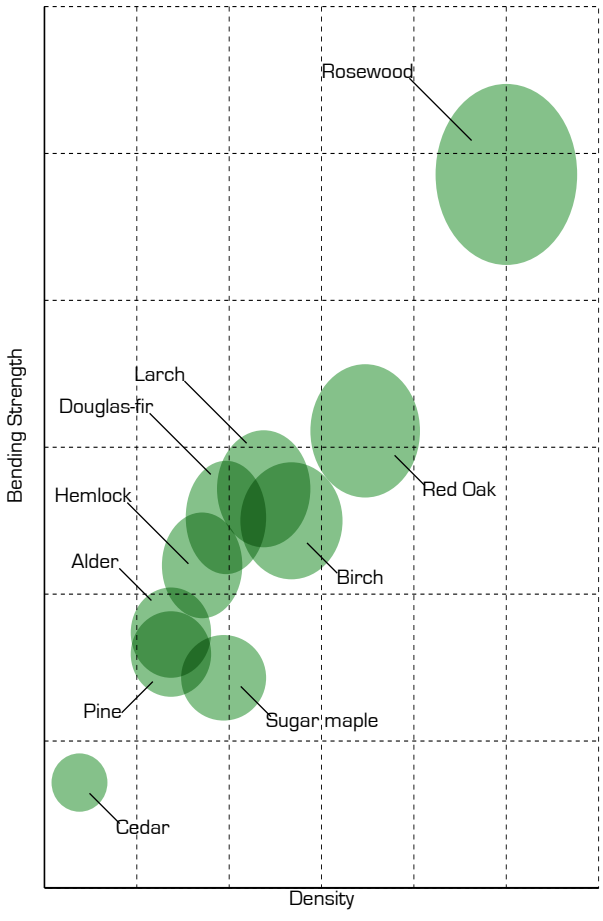


h | Materials specific heat comparison

Softwood (C22)	
Density	340 kg/m^3 (21.2 lb/ft^3)
Design strength	6.8 N/mm^2 (1.4 x 10^5 lbf/ft^2) bending
Young's modulus	9.7 kN/mm^2 (2.0 x 10^8 lbf/ft^2)
Coefficient of thermal expansion	34 x 10^{-6} K^{-1} (18.8 x 10^{-6} F^{-1}) across grain 3.5 x 10^{-6} K^{-1} (1.9 x 10^{-6} F^{-1}) along grain
Thermal conductivity	0.14 W/m^{0}C (8.1 x 10^{-2} BTU/hr.ft.^{0}F) across grain
Specific heat capacity	3.0 J/kg^{0}C (7.2 x 10^{-4} BTU/lb ^{0}F)

Hardwood (D40)	
Density	590 kg/m^3 (36.8 lb/ft^3)
Design strength	12.5 N/mm^2 (2.6 x 10^5 lbf/ft^2) bending
Young's modulus	10.9 kN/mm^2 (2.3 x 10^8 lbf/ft^2)
Coefficient of thermal expansion	40 x 10^{-6} K^{-1} (22.2 x 10^{-6} F^{-1}) across grain 4.0 x 10^{-6} K^{-1} (2.2 x 10^{-6} F^{-1}) along grain
Thermal conductivity	0.21 W/m^{0}C (12.1 x 10^{-2} BTU/hr.ft.^{0}F) across grain
Specific heat capacity	3.0 J/kg^{0s}C (7.2 x 10^{-4} BTU/lb ^{0}F)

j | Properties and data of softwood and hardwood



k | Comparison of bending strength of different timber species



a | Timber conversion



b | Timber convertion - plain sawing



c | Timber drying



d | Curing of a glued, laminated timber beam

Production

Plantation

Trees for timber production are sourced either from natural forest or from industrial tree plantations; the latter accounting for 5% of global forests. Timber production can be up to ten times higher per unit area on tree plantations than that of natural forests.

The growth cycle on plantation

In the first year the ground is prepared, after which the saplings are planted. The distance between sapling trees in a plantation is dependent upon on each tree species. When the canopy above closes, and when the trees' crowns are touching, the forest becomes too dense and the trees are thinned in order not to slow down their growth. About one third of the trees is cut down at this stage, but because of their young age, the trees might still be too small for timber, so they are used in the production of paper or particle board. Usually the canopy closes again and the thinning process needs to be repeated. After a period of between 10 years and up to 60 years, the trees are mature and ready for harvesting, depending on species and growth rate. Once the trees have been cut down for timber production, the ground is cleared and the cycle is repeated.

Conversion

After a tree has been cut down, the trunk is transported to the sawmill, where it is converted into boards with the use of circular saws and bandsaws (a). This process consists of two steps, 'breaking down', which is essentially a rough sawing task, and 'resawing' which is a series of tasks of finishing, planing and further machining the timber. There are several different methods of undertaking this process, but the aim is the same with each: to reduce waste to a miniumum, and to produce the highest quality cut timber. The most common methods are plain sawing and flat sawing (b). They produce less waste but the quality of the wood can be less regular. Other methods, such as rift or quarter sawing, result in a higher quality of the final product and minimise the consequences of shrinkage, though more material is wasted. The orientation of the grain is an important facor is processing the raw lumber of the tree.

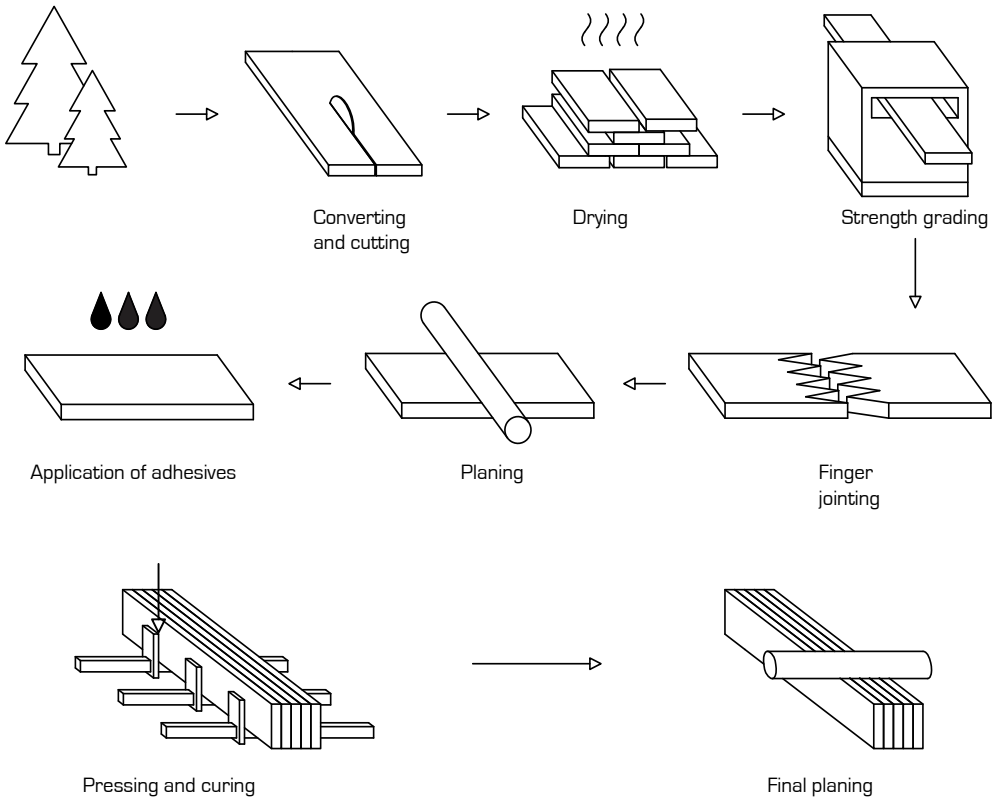
Seasoning and drying of timber

Because of its micro-structure, wood will absorb moisture and expand accordingly, either as a result of rain or humidity; shrinking when moisture content is lost. When a tree is cut down for timber production, it starts to lose its moisture immediately, and continues to do so until it reaches an equilibrium with air humidity. Cut timber is dried further before it can be used in building construction (c). There are two methods of drying: natural and artificial. The choice of method depends upon the required moisture in the timber and the environmental conditions in which it is to be used. The moisture content of timber is the weight of water in a given timber sample as a percentage of the weight of its equivalent when fully dried in an oven. The moisture content is typically reduced to 18 - 22% before it is ready to be used in building construction.

Derivative products

Plywood

Plywood sheet was invented in the USA in the 1930s, and is made by bonding together veneers peeled from logs. Both softwoods and hardwoods are used. They are layered so that the grain of each veneer is set at right angles to the one either side, providing strength in both directions as well as minimising thermal movement. Good quality



e | Glulam production process

plywood has very little thermal movement. Plywood is graded according to its resistance to moisture penetration, which is determined mainly by the glue used. The most common types are interior grade, exterior grade and marine grade. The face veneers vary from a rough finish, such as douglas fir, to a smooth one like birch. The different veneers have little influence on either moisture penetration or strength. Because plywood performs well in shear, it is used as sheathing to timber wall panels. Plywood also has high impact resistance. It can be bent to small radii, sometimes using a steam treatment.

Chipboard

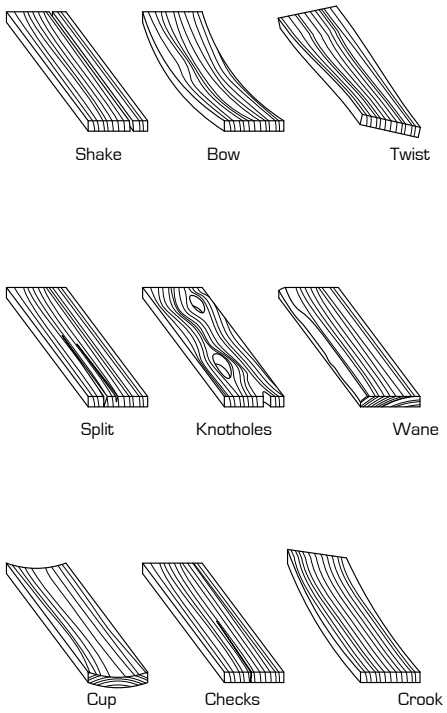
Chipboard, medium density fibreboard (MDF), and hardboard are the most common particle boards. All are made from mixing wood particles, normally wood waste, with an additive to form a sheet material that is cured between heated plates. Chipboard was developed primarily for the furniture industry in the 1960s. However, it is also used as a flooring material in wood construction as a cheaper alternative to plywood or timber boards. Chipboard is not as strong, or as rigid, as an equivalent plywood sheet, since the wood fibres are shorter. Like plywoods, it resists shear forces but is less capable of withstanding impact damage and is harder to fix with screws and nails. Also, it cannot be curved except in a pre-formed process. Chipboard is also more prone to creep under prolonged loading than plywood and timber. MDF has smooth faces and a uniform cross-section. This gives it a great advantage over other boards of having smooth exposed edges that require no lipping or trim when cut. For this reason it is often used for built-in furniture and interior panel systems.

Glued laminated timber

Laminated timber, or glulam, performs well in both tension and compression. When used in its natural form, the growth defects of timber tend to reduce the structural strength of the raw material, limiting the use of timber in building construction. Glued laminated timber components are able to overcome this limitation by bonding together individual timber boards to form timber components of larger size, such as beams and arches (d).

In the production of glued laminated timber, timbers are chosen for both their quality and their ability to be bonded. The more commonly used timber species are European whitewood and redwood, larch, Douglas fir, Caribbean pine, European oak, and sweet chestnut. After the wood is converted into boards and dried, its water content might still be too high for lamination, so the timber is often dried further in a kiln. The raw timber is then graded for strength, and any defective timber is removed. The material is connected by 'finger jointing' to form long laminated timber sections which retain similar structural properties to an equivalent smaller-scale component in natural timber.

The laminated sections are then planed and glued. The adhesive used is spread evenly across the material, the laminated sections being stacked, bonded together, then pressed to take up their final form (e). Clamps are used to press the timber to the required shape, and to apply the correct pressure to the individual laminated sections. The laminated timber section is left to cure for about eight hours at a temperature of around 25°C, after which it is planed to the final shape, following this it is stored for a further 24 hours before being ready for use.



a | Timber defects



b | Impregnation in a vacuum chamber

Performance

Defects

Timber is dried carefully in order to avoid the effects of crook, split, twist, cup, or bow that may result from the drying out process being uneven (a).

Naturally occurring defects appearing in wood consist mainly of shakes and knots. Knots occur where branches were located in the tree from which the timber was cut, and leave a distinct pattern in the cut timber. They can weaken the timber structurally, and when dried, they may fall out, leaving a knot hole. Other defects, like wane, may result from errors in the cutting or processing of the raw material.

When timber is exposed to moist conditions, it is usually ventilated naturally in order to avoid degradation by rot.

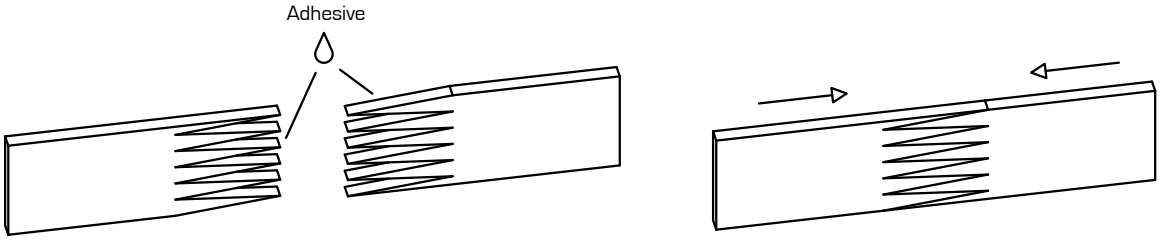
Protection

There is a big variety of protective products for timber. Impregnating the outer zones of timber with preservative chemicals will prevent the wood from rotting or infestation, but some of the chemicals used for this purpose can harm the natural environment if they are allowed to leach into the ground. Impregnation is typically done in a vacuum pressure process (b). Timber with a moisture content of less than 30% is placed in a vacuum chamber. The air is pumped out of the chamber and the preservative solution under huge pressure is forced deep into the wood. Glued laminated timber is very durable. The oldest, still-standing documented examples were constructed 150 years ago. There are also many examples from around 1950 of glulam structures in their modern form, using synthetic resin adhesives.

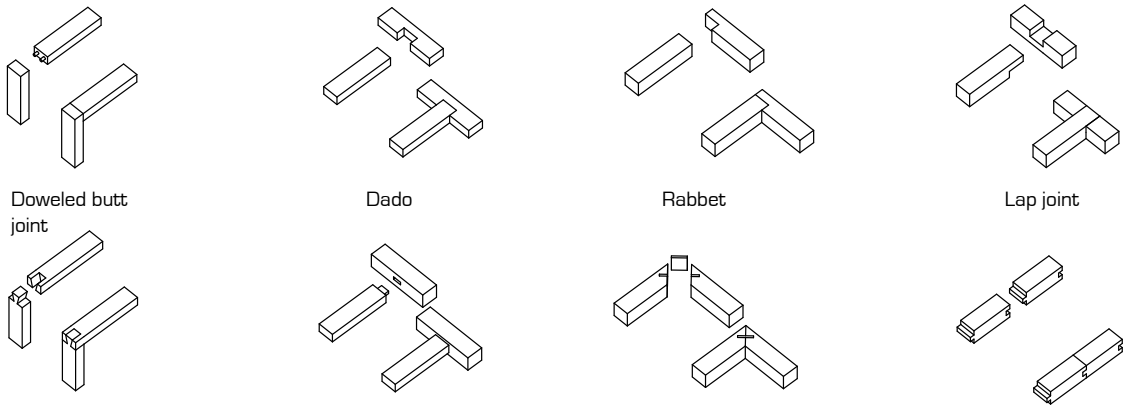
Fire resistance

Although timber is combustible, it burns relatively slowly and is often able to retain its structural properties during fire for longer than an equivalent steel structure. When a heavy timber element is exposed to high temperatures, it ignites as it reaches the burning point, which is usually about 300°C, depending mostly on the timber species. When the timber is on fire, a layer of char forms on the surface and protects the core of a member, since char has low conductivity. Underneath the char, there is a pyrolysis zone, which is a layer of heated wood that has been affected by heat. In this shallow layer, the wood is irreversibly decomposed in a chemical sense. The core of the timber member is affected, reducing its structural strength as a result of moisture loss,.

Lighter timber structures are protected with fire retardants, since the thickness of their constituent members is not usually sufficient to resist the effects of fire. Fire retardants are applied directly onto the surface or in a vacuum pressure process. Their main purpose is to create a physical barrier to the flame spread. There are also intumescent coatings used which react to temperature increase, forming an expanded layer of insulation around the timber in the event of fire.



c | Finger joint



d | Glulam production process

Applications

Before the 20th century most connections in structural timber assemblies were designed to function in compression, rather than tension, as connections were difficult to form without adding significant amounts of iron to the structure. However, the development of modern glues and metal connectors which are light in weight has resulted in a wide range of contemporary tension and compression joints (d). The most common joints in timber that perform well in tension and compression are the bolted metal connector, split ring connector and the nail-plate connector. The bolted connector is a thin plate of galvanised steel with projecting teeth. The connector is set between the timber sections being joined, and is embedded into both sections as the bolt fixing is tightened. The split ring connector works in a similar way to the bolted connector; both fixings transmit shear forces at the joint across the bolted connection. A different connection device, the nail-plate, is a metal plate which is pressed, during manufacture, to form a series of nail-like projections on one side. The plate is pressed into the timber sections being joined to form a patch connection on either side. The complete timber assembly is fabricated under factory-controlled conditions, and is most commonly used in prefabricated floor and roof trusses.

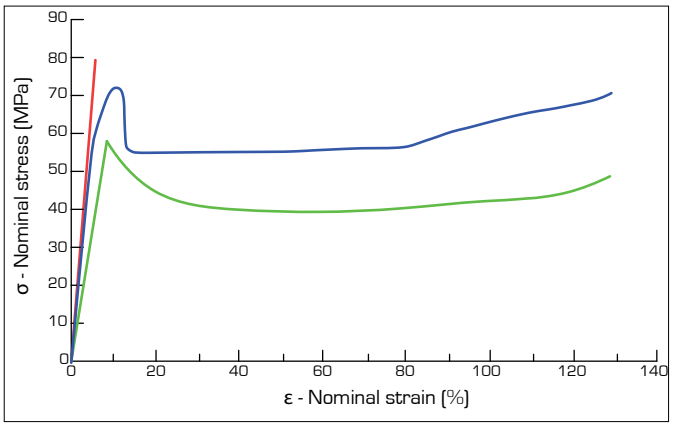
Bonded connections in timber are glue-welded joints that are almost as strong as the wood itself. Widely used types are urea-formaldehyde, phenol-formaldehyde and resorcinol. Glued connections provide structural continuity at the joint. They do not break down when exposed to the weather or changes in temperature. The finger joint is a type of glued connection, that is extensively used, particularly in the production of glulam. In joinery, particularly for built-in items, simple jointing techniques that allow parts to be made quickly and efficiently tend to be used. Most joints are designed to be manufactured easily using machinery, which has led to the reduced application of traditional techniques such as dovetailing. However, the availability of adhesives has enabled simple mitred and butt joints to be used.

Bending

The cellular structure of timber makes it strong in tension, but this is true only when the direction of the grain is along the vertical axis of the element. That means that to achieve solid wood arches or other curving elements, the timber must be bent. It is done with a steam-bending process. The member is placed in a steam box, where it is exposed to hot steam, which makes the wood pliable. After the heat and moisture is applied to the timber, the element can be bent around the mould. Usually it is clamped to a positive mould in order to achieve the desired shape. Steam bending is a traditional method used in various applications, from furniture to ship building. It weakens the timber slightly and it might leave residual stress that can result in the breaking of the material. Moreover, not all wood species are suited for this process.



a | Polymer material



b | Polymer (red) PCV-U (green) polycarbonate (blue) stress-strain graphs

Rigid polymers

An overview of acrylic

Acrylic, or poly-methyl methacrylate (PMMA), is a thermoplastic of a transparent appearance most commonly used as an alternative to glass due to its lightweight or shatter-resistant properties (a). Acrylic sheet, developed as Perspex in the 1930s, is a plastic based on polymers of acrylic acid. PMMA is made by polymerising an MMA monomer with a catalyst to form a powder which can then be extruded, moulded or cast.

Acrylic has the following general properties:

- High transparency and optical clarity.
- Weathers well with high resistance to yellowing.
- Hard but brittle when under load, especially under an impact force (b).
- Prone to scratching.
- Easily recycled.
- Combustible.

An overview of PVC-U

The term PVC-U, or UPVC, denotes the unplasticised form of polyvinyl chloride, or PVC. This rigid form of PVC is used for a wide range of building components from guttering and ground drainage pipes to window frames. The material can be easily extruded or moulded to complex shapes and is available in a range of colours. The low thermal conductivity and flexibility of the material, combined with its ability to be extruded, makes it very suitable for window frames where the material is, in effect, its own thermal break, minimising the risk of condensation on the face of the frame inside the building.

PVC-U has the following general properties:

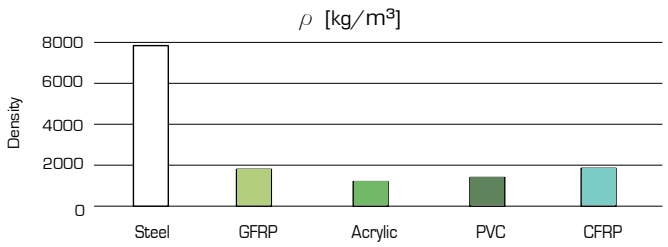
- Available in a range of colours.
- Weathers well but is susceptible to fading, particularly with brighter colours.
- Tough but flexible (b).
- Recyclable.
- Combustible.

An overview of glass reinforced polyester (GFRP)

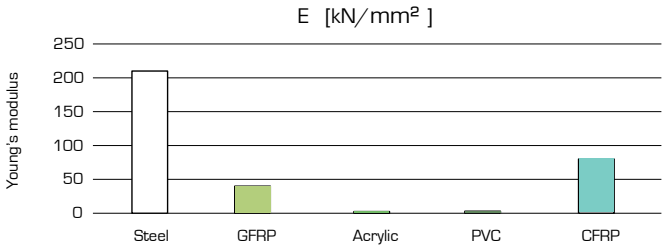
Its main use is in specially fabricated wall cladding panels. Glass reinforced polyester, or GFRP, is made from a combination of glass fibre mat and polyester resin. It is a thermosetting composite which has high tensile, shear and compressive strength combined with lightness and resistance to corrosion. However, like aluminium, it deflects considerably under high loads and requires stiffening.

GFRP has the following general properties:

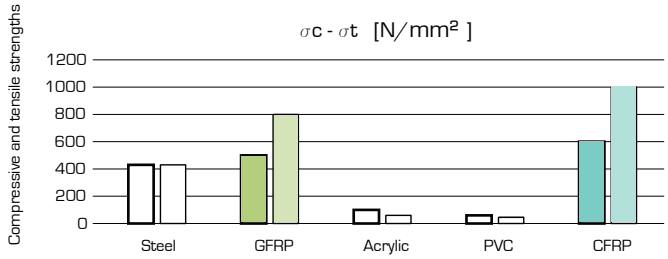
- Strong but light (c)(e).
- High stiffness compared with plastics (d).
- High impact resistance.



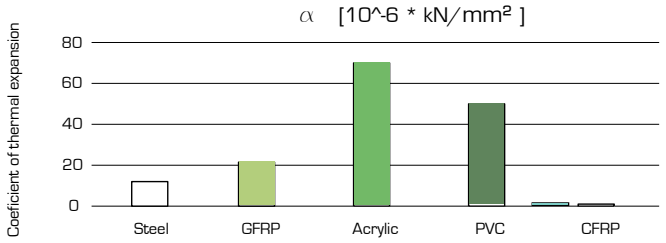
c | Materials density comparison



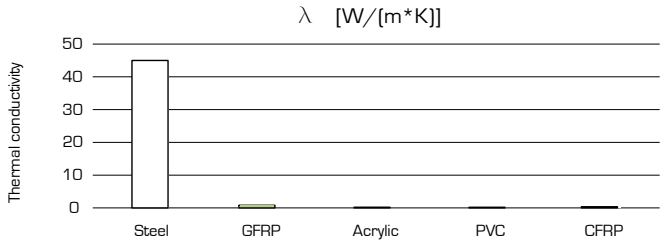
d | Materials Young's modulus comparison



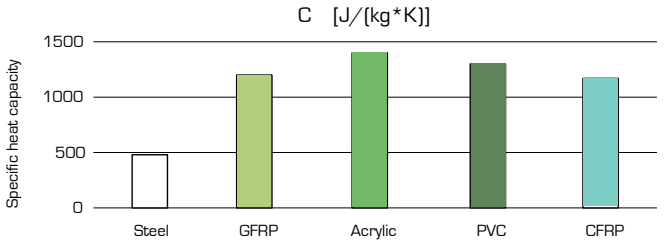
e | Materials tensile and compressive strength comparison



f | Materials coefficient of thermal expansion comparison



g | Materials thermal conductivity comparison



h | Materials specific heat comparison

An overview of carbon fibre reinforced polyester (CFRP)

CFRP is a very strong and light fiber-reinforced polymer which contains carbon fibres. Structural properties of carbon fibre depend on the orientation of the fibres in the layers, and vary between applications.

CFRP has the following general properties:

- High strength to weight ratio (c)(e).
- High rigidity.
- High resistance to corrosion.
- High electrical conductivity.
- High resistance to fatigue.
- High tensile strength but brittle.
- High thermal conductivity in some forms (g).

Fabrics and membranes

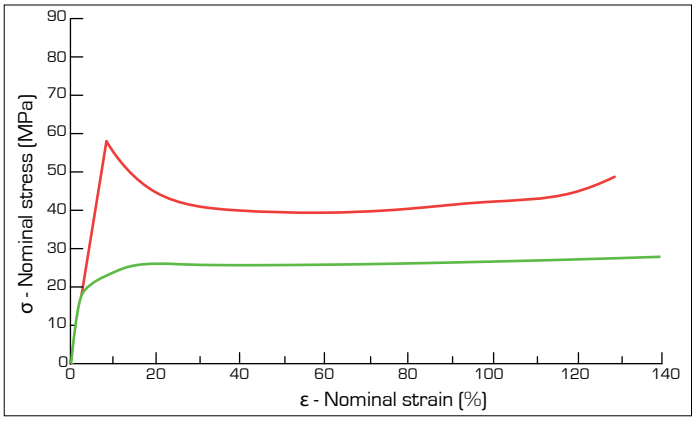
An overview of ETFE

ETFE, or ethylene tetrafluoroethylene, is a polymer similar to PTFE, (marketed as Teflon). ETFE is made by extrusion to form a sheet material. Thicknesses vary but 0.2mm is a common thickness of material for ETFE cushions, allowing them to be very light in weight at around 350g/m² for this thickness of sheet. Heavier gauge sheet at 0.5mm thickness weighs around 1000g/m². Inner layers of ETFE sheet that provide separate chambers within the cushion are often made from 0.1mm thick sheet.

The material is also used for its high level of transparency, with 95% light transmission, and its durability when compared to other fabric materials, with a life expectancy of 25-35 years based on visual criteria. In order to provide translucent areas of roof (or facade) using the same material, a white coloured translucent sheet is manufactured which allows around 40% light transmission. ETFE does not provide a barrier to the passage of UV light, making it ideal for use in buildings where extensive planting is displayed, though the translucent white sheet has greatly reduced UV light transmission. Solar shading can be provided by a pattern of dots printed onto the surface of the ETFE cushion, with a reflective silver colour being a popular choice, though other colours and patterns can be developed for individual projects. The sound absorption of ETFE cushions is low, so that sound travels easily through the material. The toughness of ETFE sheet is combined with a high resistance to tear. Damage by sharp objects puncturing an outer membrane does not spread easily into a larger tear. The material has fairly high resistance to surface fading from UV light where there is a gradual loss of surface reflectivity. ETFE sheet is also highly resistant to attack from chemicals and from airborne pollution in urban areas. Its low level of surface friction ensures that cushions do not hold dirt and dust easily, making cushion roofs relatively easy to maintain. ETFE roofs are usually cleaned as a result of rain in temperate climates, though access for maintenance is required, usually provided by walking along the external clamping plates with cable assistance or from external structure. Cushions are repaired by the



a | PVC/Polyester fabric



b | PVC-U (red) ETFE (green) stress-strain graphs

use of ETFE tape, which is visible, or by complete replacement of the panel, depending largely on the visual requirements of the roof design.

An overview of PVC fabrics

PVC, or polyvinyl chloride roof membranes have been in use since the 1960s as a very lightweight and relatively economic roofing material, and have become widely used in recent years (a). Membranes in this material were first developed in Europe in the late 1960s and were used in the USA from the 1970s onwards. PVC sheet material is usually reinforced with glass fibre to give it increased rigidity that is easier to bond to the substrate (d).

The PVC used in membranes is plasticised (PVC-P), unlike the unplasticised PVC (PVC-U, or uPVC) used to make window frames and rainwater drainage components. PVC-P is rigid at normal external temperatures, but softens when heated, making it flexible and allowing strips or sheets to be welded together to form a continuous membrane without the need for standing seams or visible joints. Plasticisers and filler material in PVC-P is added to give the material greater flexibility. The material has very low levels of shrinkage, is dimensionally stable and does not creep visibly with age. The material experiences very small amounts of movement under full wind load.

The main properties of PVC and polyester fabrics are:

- High dimensional stability
- High colorfastness
- High cleanability
- High seam strength and stability
- High abrasion resistance, easy to fold
- Varies in translucency from 7% to 15%
- Reflects between 68%-75% of incident sunlight
- Quality of light transmitted is colour balanced, diffused and free of shadows and glare

PVC fabrics are made from polyester cloth which is coated on both sides with a layer of PVC. The coating protects the fabric against the effects of rain and of UV light. The PVC coating is a mixture of PVC powder, softeners and plasticisers, UV stabilisers, pigments and fire retardants (c). An additional outer coat of lacquer slows down the effect in the PVC coating of becoming increasingly brittle with age, which results from the softeners within the material gradually moving to the surface of the PVC coating. The lacquer coating also slows down the fading effects of the colour pigments. A PVDF lacquer (a fluorinated polymer) is typically used, which also ensures that the surface has low surface friction so that it will attract little dust and dirt, and allows the membrane to be cleaned easily. Acrylic lacquers are also used. The typical weight of a roof using this material is 500 - 800g/m^2. A PVC/polyester membrane roof will last around 15-25 years.

	Rigid Polymers		Fibre Reinforced Polymers		Fabrics	
	Acrylic	PVC-u	GRP	CFRP	ETFE	PVC/polyester fabric
Extrusion	X	X			X	
Pultrusion			X	X		
Injection moulding	X	X				
Compression Moulding			X	X		
Calendering					X	
Manual Lamination			X	X		
Doctor Blade						X
Dip Coating						X
Vacuum Moulding	X	X	X	X		

c | Examples of polymer fabrication methods

Acrylic	
Density	1150-1220 kg/m^3 (72 to 76 lb/ft^3)
Tensile strength	38 N/mm^2 to 80 N/mm^2 (7.9 x 10^5 to 1.7 x 10^6 lbf/ft^2)
Compressive strength	83 N/mm^2 to 124 N/mm^2 (1.7 x 10^6 to 2.6 x 10^6 lbf/ft^2)
Young's modulus	1.8 to 3.8 kN/mm^2 (38 x 10^6 to 79 x 10^6 lbf/ft^2)
Coefficient of thermal expansion	50-90 x 10^{-6} K^{-1} (28-50 x 10^{-6} $^0F^{-1}$)
Thermal conductivity	0.20 W/m°C (0.12 BTU/hr.ft.^{0}F)
Specific heat capacity	1280-1500 J/kg°C (0.3-0.36 BTU/lb ^{0}F)

GRP	
Density	1600-1950 kg/m^3 (100 to 121 lb/ft^3)
Tensile strength	300 N/mm^2 to 1100 N/mm^2 (6.3 x 10^6 to 23 x 10^6 lbf/ft^2)
Compressive strength	360 N/mm^2 to 880 N/mm^2 (7.5 x 10^6 to 18 x 10^6 lbf/ft^2)
Young's modulus	35 to 45 kN/mm^2 (7.3 x 10^8 to 9.4 x 10^8 lbf/ft^2)
Coefficient of thermal expansion	21.5 x 10^{-6} K^{-1} (11.9 x 10^{-6} $^0F^{-1}$)
Thermal conductivity	0.4-1.2 W/m°C (0.23 to 0.7 BTU/hr.ft.^{0}F)
Specific heat capacity	1000-1400 J/kg°C (0.23-0.34 BTU/lb^{0}F)

PVC U	
Density	1400 kg/m^3 (87 lb/ft^3)
Tensile strength	35 N/mm^2 to 52 N/mm^2 (7.3 x 10^5 to 1.1 x 10^6 lbf/ft^2)
Young's modulus	2.1 to 4.1 kN/mm^2 (43 x 10^6 to 85 x 10^6 lbf/ft^2)
Coefficient of thermal expansion	50 x 10^{-6} K^{-1} (28 x 10^{-6} $^0F^{-1}$)
Thermal conductivity	0.19 W/m°C (0.11 BTU/hr.ft.^{0}F)
Specific heat capacity	1300 J/kg°C (0.31 BTU/lb ^{0}F)

ETFE	
Density	1700 kg/m^3 (109 lb/ft^3)
Tensile strength	38 N/mm^2 to 48 N/mm^2 (7.9 x 10^5 to 1 x 10^6 lbf/ft^2)
Compressive strength	10.3 N/mm^2 (2.2 x 10^5 lbf/ft^2)
Young's modulus	1.5 kN/mm^2 (8.3 x 10^7 lbf/ft^2)
Coefficient of thermal expansion	9 x 10^{-5} K^{-1} (5 x 10^{-6} $^0F^{-1}$)
Thermal conductivity	0.238 W/m°C (0.14 BTU/hr.ft.^{0}F)
Specific heat capacity	1900-2000 J/kg°C (0.44-0.46 BTU/lb ^{0}F)

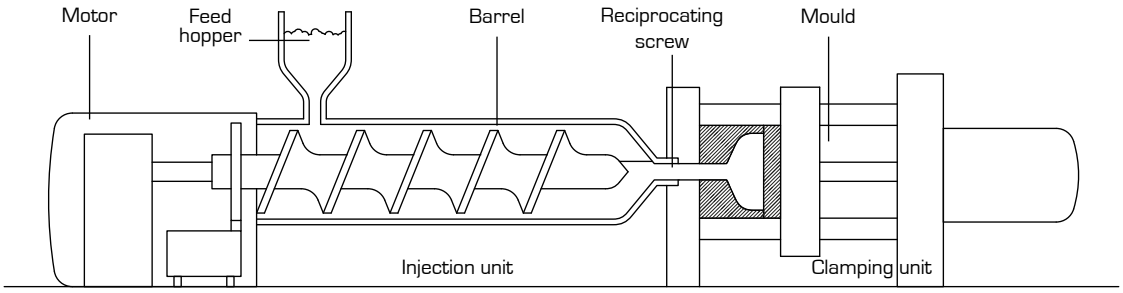
d | Polymer sheets



a | FRP panels



b | Fabrication of FRP panels



c | Injection moulding machine

Production

The chosen method of production of polymers is dependent upon the required shape, size and finishing of the component to be made.

Extrusion

Extrusion is a manufacturing process used to create objects of a fixed cross-sectional profile. The polymer is pushed through a die of the desired cross-section. This method allows the creation of very complex cross-sections, with an excellent surface finish. This process is very economic for thermoplastic components made in large quantities. Extrusion also allows the combination of different polymers by co-extrusion or hollow chambers, but the cross-section must remain constant.

A polymer, usually in the form of granulate, is fed into the extruder, where it melts. Then it is forced through a die, a hollow metal form, that gives shape to the material in cross section. The extruded material emerging from the die is cut to length.

Pultrusion

This method is particularly useful for manufacturing GFRP structural sections and sheets. Long fibres that are soaked in resin are pulled through a heated mould for a few minutes. During this time, the heat of the mould cures the polymer. The manufacturing tolerances are less than concrete ones but greater than that expected for steel. The process is similar to extrusion, the method requiring the pultruded component to have a constant cross-sectional profile.

Injection moulding

Injection moulding is a common method of manufacturing polymer components, including elastomers, but is most commonly applied to the manufacture of thermoplastic and thermosetting polymers. Injection moulded products are characterised by a high quality surface finish and dimensional stability. The polymer mix is put into an extruder, similar to that used in a full extrusion process, made molten then forced through a nozzle into a mould, which is secured by clamps (c). The mould is made of metal, either steel or aluminium, so injection moulding is most viable for big production runs, due to costs associated with fabricating the mould. Currently some lower temperature thermoplastics can be injected into moulds made from 3D printing with photopolymers, which do not melt during the process. This makes the process more economic, but the selection of materials is still limited.

Compression moulding and transfer moulding

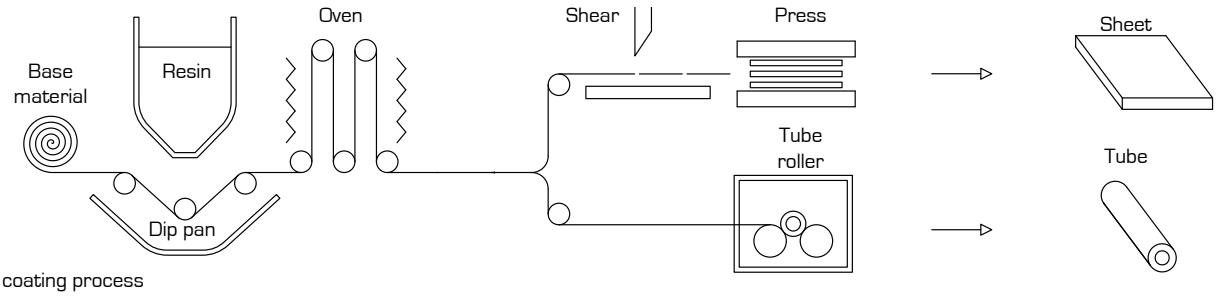
These manufacturing methods are used mainly for large volume manufacturing tasks, due to the high cost of moulds and associated tools. Moulds are typically made of metal, but for compression moulding resin moulds are also used. Usually resins are used, sometimes reinforced with fibres. In such cases, fibres are already impregnated within the resin, and such a mixture is called 'prepreg'. The impregnation is therefore a separate process that takes place before moulding, unlike the other methods presented here.



d | Test of FRP panel



e | Compression test of a sample of CFRP sandwich panel



f | Dip coating process

Calendering

This method uses polymer powder as a raw material and is used for the production of polymer foil, mainly PVC. Powder is melted and compacted under pressure, then rolled into a thin layer through the use of heated rollers. Then the material is cooled down with chill rollers. This method allows the surface of the product to be embossed by using rollers with an integral pattern.

Manual lamination

FRP elements are usually manufactured with manual lamination, or 'hand lay-up' method. Components to be manufactured require a mould, which gives the shape to the material, which can be made from plywood, sheet metal, or be milled from polyurethane foam to suit more complex shapes. The mould is coated with a release agent, then a layer of gel resin is applied. This will be the outer surface of an object, so resins with high impact resistance and hardness are often used. Fibres most often in form of textile or chopped strand mats, are put on top of it and impregnated with liquid resin. The material is then pressed with a hand roller in order to remove air bubbles and to ensure good bonding with the layer beneath. The process is repeated until the desired thickness is achieved.

Doctor blade

This is a method used for PVC and silicone coatings for fabric. The main material is a premixed polymer coating paste, consisting of PVC powder, plasticiser, and additional additives. The fabric is first coated with a bond enhancer, than the PVC paste is spread out across a flat surface. The excess material is scraped off with a fixed blade called a 'doctor blade'. The materials are bonded together in an oven at a temperature of around 180°C. The coating is normally applied on both sides, which requires the process to be repeated, unless a vertical coating plant is used, which can coat both sides at the same time. The last step is the application of a top coat, which prevents adverse effect of UV radiation on plasticisers.

Dip coating

A fabric is dipped into a liquid material, typically PTFE or PVC. The fabric then undergoes a drying process where the moisture evaporates and sintering occurs when the temperature is raised to around 330°C. At this temperature the wetting agent decomposes and the polymer particles sinter (f). The process is repeated until the material reaches the desired thickness.

Vacuum resin transfer moulding

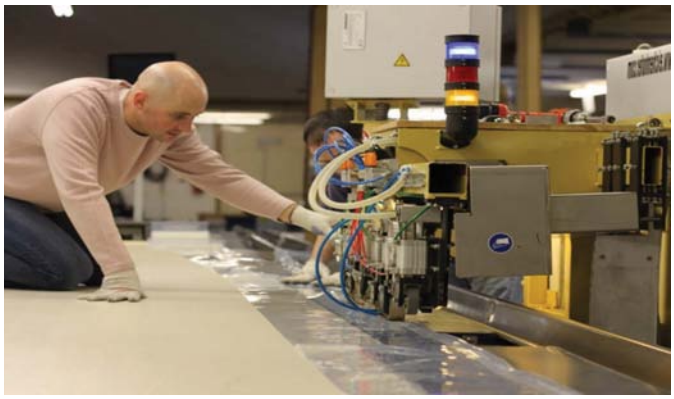
This method is a further development of a hand lay-up method that provides a smooth finish on both sides. First the fibrous layers are placed in the mould, and put into an airtight porous release film and breather cloth. Then air is pumped out, and resin is forced under pressure into the mould. The material is cured in an autoclave, where conditions of pressure and temperature can be controlled, resulting in a high quality product. The pressure during the curing process ranges from 2 to 25 bar, and the temperature is usually about 180°C.



a | Manufacture of curved acrylic polymer panel



b | Manufacturing of curved acrylic polymer panels



c | Manufacture of fabric panels



d | Manufacture of fabric panels

Performance

Mechanical properties of membranes:

- Tensile, compressive and flexural strength.
- Elongation and impact resistance.

Physical properties:

- Hardness and density.
- Dielectric strength.
- Volume resistivity and arc resistance.
- Thermal conductivity.
- Heat distortion and heat resistance.
- Flammability and thermal expansion coefficient.

Chemical properties:

- Durability.
- Degradation of the material.
- Resistance to acids, alkalies and organic solvents.
- Water absorption.
- Resistance to ozone.
- Ultraviolet radiation and weathering.

General characteristics:

- Surface quality and cosmetic appearance.
- Dimensional stability.
- Fabrication and end-use tolerancing.

Performance in fire

The performance of a membrane during a fire depends on both the fabric used and the stitching at the seams, where this joining method is used (d). Membranes lose their tensile stregth at high temperatures, with PVC starting to stretch at temperatures above 70-80°C, and PVC seams starting to peel at around 100°C. At 250°C the PVC melts, leaving holes in the membrane. PVC has fire retardants in the coating so that it self-extinguishes when the flame source is removed which results in few, if any, burning fragments dropping down from the roof. PTFE/glass fibre fabrics fail at around 1000°C, but seams will fail at a much lower temperature of around 270°C. With both materials, the failure of the membrane forms holes in the roof which allow heat and smoke to escape.

A major concern in the use of polymer materials for single layer and multiple layer fabric roofs is their performance in fire. ETFE sheet is not easily inflammable and will self-extinguish quickly under direct flame. Few burning fragments will fall below during a fire, since the material melts rather than burns, with most of the burnt material being carried away in the rising hot air of a fire. ETFE sheet melts at around 275°C, forming holes in the fabric which allows the heat and smoke of a fire to escape. However, some roofs still require smoke vents, since this may not always occur during a fire if the smoke and heat is being generated in an area away from the roof, where the ETFE cushions are not affected by the fire. The small amounts of material used in ETFE cushions, with an average wall thickness of 0.2mm, result in little material being deposited during a fire.



e | Fibre glass pultrusion profiles



f | Process of FRP pultrusion



g | Fibre glass mould for curved FRP panels



h | Manufacture of curved FRP panels

Generally, FRP achieves a high degree of durability which allows long-term external use of the material. If FRP is exposed to a humid environment, the matrix can absorb fluids which can break the chemical bonds between polymer chains which can result in a reduction of the mechanical properties of this composite material. FRP can be protected against moisture absorption by the use of protective coatings on its outer surface, such as a resin-rich epoxy.

Direct exposure to UV light can determine the degradation of polymer constituent which results in discoloration of the surface and micro-cracking of the matrix. UV radiation can penetrate only the outer surface and the degradation is confined to a thin layer near the surface. The protection of FRP from UV radiation is commonly accomplished through the use of UV resistant paints, coating or a sacrificial surface coating.
The adequate selection of additives, such as fire retardants or inorganic fillers, enable the material to achieve a high fire resistance. Durable intumescent paints can also be used with non fire-retardant resins as a cheaper solution.

If properly designed for fire resistance, FRP elements can achieve the highest rating in accordance with both European and American Standards:

- Reaction to fire classification: A1 according to EN 13501-1:2007: Fire classification of construction products and building elements.
- Class A according to NFPA 255: Standard method of test of surface-burning characteristics of building materials.
- Class 0 according to BS 476: Fire tests on building materials and structures. Classification and method of test for external fire exposure to roofs.
- Class 1 according to ASTM E84: Standard method of test of surface-burning characteristics of building materials.

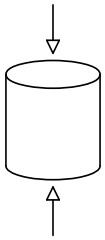
Fire protection

Some polymers are resistant to degradation at high temperatures, while others can be produced with an addition of fire-resistant additives and fillers.

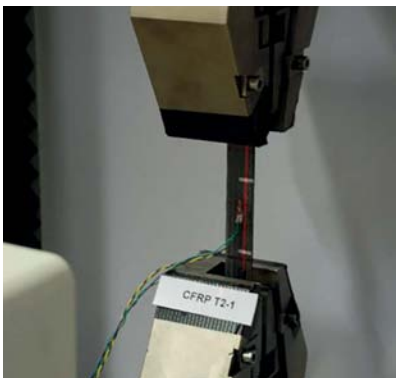
Membranes

A single layer membrane fabric roof in either PVC or PTFE/glass fibre typically has a U-value of around 6.0W/m2K. Where two layered membranes are used, with a minimum air gap of 200mm between the membranes, the U-value can be reduced to around 3.0 W/m2K. Double layer membranes are less commonly used as they have a severely reduced light transmission; the translucency of the material being one of its main advantages. Thermal insulation can be added to a double layer membrane by using a translucent fibre-based insulation, as used in fibre glass cladding panels discussed in the previous chapter. The insulation can be fixed to the inner face of either membrane, depending on how the roof void is ventilated.



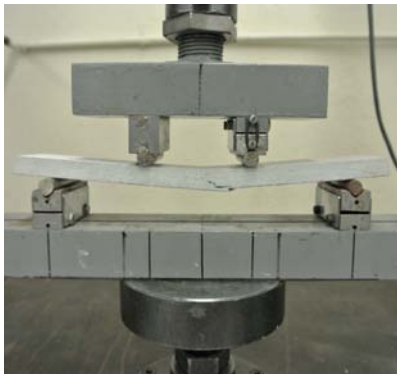


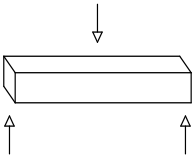
a | Compression test



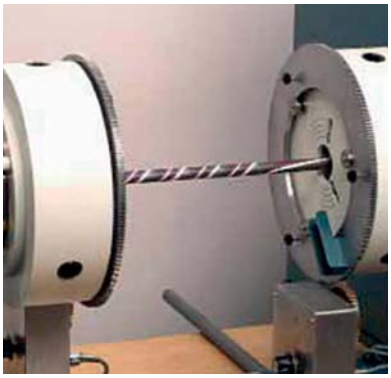


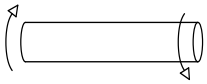
b | Tensile test





c | Four-point bending test





d | Torsion test

Testing of building materials

Compression

Compressive tests are conducted in order to measure the compressive strength and compressive modulus of a material. For example, compressive tests of concrete specimens are undertaken during construction to determine that the delivered concrete mixture meets the requirements of the strength specified in the design (g). Standards and codes give specific indications about the shape and the number of specimens to be tested. In a laboratory, a uniaxial compressive force is applied uniformily to one face of the specimen until it breaks (a).

Compressive strength is calculated mathematically by dividing the failure load by the cross-sectional area resisting the load. For innovative composite materials such as FRP, compressive tests are usually undertaken during the design process in order to identify the expected compressive strength for specific products. The physical size of specimens is regulated by specific standards. To determine both the load-compression diagram and the compressive modulus, the test set up includes a laser extensometer to record compression of the specimen.

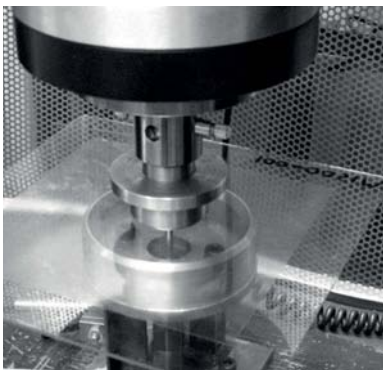
Tension

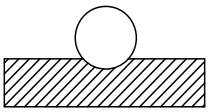
The tensile test is conducted to define three key physical properties of a given material: maximum tensile strength, tensile modulus of elasticity and the resulting tension stress-strain diagram. For innovative composite materials such as FRP, tensile testing is usually carried out during the design process, in order to identify the expected tensile strength for the specified fibre configuration. Sizes of specimens are determined by recommended standards.

Grips, which are shapes formed at the end of each specimen, are clamped into an instrument which applies a tensile load at a certain speed (b). The sample elongation is measured with a laser extensometer. From the data measured, it is possible to define the force–elongation diagram which evaluates the elastic and plastic behaviour of the material being tested, as well as determing the rupture load. By dividing, mathematically, the forces by the initial area of the specimen and dividing the elongations by the initial length, it is possible to define the stress-strain diagram of the specimen, as well as the maximum tensile strength of the material, and finally the tensile modulus of elasticity.

Bending

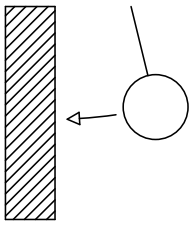
Testing is conducted to evaluate three key physical properties of a given material related to bending: the flexural stress-strain response of the material in order to measure shear stiffness, flexural stiffness and strength. The test is carried out during the design process for specimens of non-standard material such as composite materials to define the mechanical properties that can be specified for the project. Two types of flexural test are distinguished: the three-point bending test and the four-point bending test (c). The test type to be performed for each material is specified in reference standards. The size and number of specimens to be used are defined by standards. The specimen is supported at two points while a testing machine imposes a load concentrated at one point, for three-point bending, or is spread to two points for four-point bending. Displacement transducers are





e | Indentation hardness test





f | Impact test

	Compression	Tension	Bending	Torsion	Indentation hardness	Impact
Metals and alloys	x	x	x	x	x	
Glass	x	x	x	x		x
Concrete	x	x	x	x		x
Ridgid Polymers	x	x	x	x	x	x
Fabrics membranes		x	x			
Timber	x	x	x	x		
Stone	x	x	x			x
Ceramics	x	x	x		x	x

g | Table of materials and test data

used to record central displacements. Loads versus displacements are recorded. From the resulting graph it is possible to calculate flexural and shear stiffness and, from the maximum load, it is possible to evaluate the flexural strength using formulae in the codes.

Torsion

Torsion testing is carried out to determine the behaviour of a given material when twisted. Four different mechanical properties are measured: the modulus of elasticity in shear, yield strength and ultimate shear strength, torsion yield strength and the modulus of rupture in torsion. The test is often performed for material specimens but it is mainly conducted to check the behaviour of full-sized components which are subjected to torsional loads in service. Three types of torsional testing are undertaken: failure testing (the specimen is twisted until failure), proof testing (a torsional load is applied for a fixed amount of time) and operational testing (the final designed elements are tested under the service loads). Torsion-testing equipment consists of a twisting head which grips the specimen and applies the twisting moment and a weight head which grips the other end of the specimen and measures the twisting moment of torque (d). The angular displacements and twisting moments are measured and from them, the mechanical properties mentioned above can be calculated through empirical formulae.

Indentation hardness

The indentation hardness test is conducted to determine the hardness of a material, defined as its resistance to plastic (permanent) deformation. A precisely shaped tool is driven into the surface of a test specimen applying known forces (e). The size of the resulting indentation is measured and used to calculate a hardness value for the material. Different hardness scales can be found in literature differing in the shape and material of the indenter used, and in the applied forces.

Impact

The impact test is conducted to measure the ability of a specimen to resist high-rate loading. The test is usually performed in order to check the resistance to impact for specific conditions in use, such as an impact test for a given material used as a facade panel. In this case, two types of tests are undertaken: a soft body impact test to represent impact from a person falling, and a hard body impact test to represent impact from tools and equipment (f). Standards and codes specify the test procedures for specific materials and associated applications. In general, the impact test is undertaken by dropping an impactor from a certain height or imposing the load using a pendulum impactor. Depending on the shape and weight of the impactor, a given impact energy is transferred to the specimen. Depending on the level of damage of the specimen for a specific impact energy, the impact resistance is determined.

02
WALLS

	Trends in facade design
	Generic wall types
	Metal
1	Sheet metal
2	Profiled cladding
3	Composite panels
4	Metal rainscreens
5	Mesh screens
6	Louvre screens
	Glass systems
1	Stick systems
2	Unitised glazing
3	Clamped glazing
4	Bolt fixed glazing
5	Glass blocks and channels
6	Steel windows
7	Aluminium windows
8	Timber windows
	Concrete
1	Cast in situ
2	Storey height panels
3	Small precast panels
	Masonry
1	Loadbearing walls
2	Cavity walls
	Brick
	Stone and block
3	Cladding
4	Rainscreens
	Fibre reinforced polymers
1	FRP cladding
2	FRP rainscreens
	Timber
1	Timber frame
2	Cladding panels



a | Metal sheet: Jewish Museum Berlin, Germany. Architect: Daniel Libeskind



b | Metal composite panel: Usera Public Library, Madrid, Spain. Architect: Ábalos & Herreros



c | Metal rainscreen: Lock-keeper's Centre, University of London, U.K. Architect: Surface Architects



d | Metal sheet: Falmouth School's Design and Technology Block, Falmouth, U.K. Architect: Urban Salon

Significant changes in the design of external walls in recent years have increased thermal performance and solar control, provided greater water tightness and demonstrated a reduction in air infiltration rates through wall assemblies, and a limited return to natural ventilation where possible as a partial alternative to mechanical ventilation in larger scale buildings. These changes have led to a shift in design priorities. During the late 1980s, the increased use of thermal insulation brought with it an increased risk of condensation occurring in cladding assemblies. This condensation can occur both inside the panel and on the inner face of wall assemblies. A result of technical development has been the avoidance of condensation. The increased use of natural ventilation, both as air supply and as a means of cooling buildings at night, has had an effect on cladding design, particularly in the integration of opening lights and louvered slots in panels. The arrival of the deep plan building, with distances of up to 18 metres between external walls, has led to a need for greater levels of daylight entering a building. This, in turn, has increased the need for both solar shading and glare control. In addition, the cost of photovoltaic cells, which can generate electricity when exposed to sunlight, has reduced considerably over the past 15 years. As a result, these are increasingly used in large-scale applications for buildings. These energy-led changes in wall design have generated a range of technical developments which have changed the emphasis of facade design. The architectural interest in the expression of structure in buildings has been replaced by an interest in energy conservation. This is largely because the effect of additional layers of external insulation, blinds, shading and so on often renders the structure almost invisible.

Thermal insulation

The use of thermal insulation has increased dramatically over the past 15 years, with wall assemblies achieving a U-value of 0.25 W/m²K as a minimum standard. This compares with a typical level of 0.6 W/m²K in the early 1980s. There is an accompanying risk of interstitial condensation occurring within a wall assembly from damp air that penetrates a wall assembly where it may condense and cause damage. In addition to dew point calculations undertaken at the design stage to assess risk, vapour barriers are added to halt the passage of damp air into wall assemblies where interstitial condensation can occur, typically on the warm (in winter) side of the insulation. Alternatively, the internal construction can be ventilated in order to draw away damp air.

Condensation can also occur on the inner face of a wall in temperate climates, typically where there is continuity in a material from the outside to the inside of a building that allows a direct passage of heat or cold through the external envelope. When this 'thermal bridging' occurs, condensation can form on the inner face of the wall where it can drip down, resulting in inconvenience to building users and damage to the construction. Thermal bridges are avoided by providing a separating component in a low conductivity material, called a 'thermal break', that prevents heat or cold from being transmitted between the inside and outside. An example of its use is in glazed walling, where the construction of a frame of mullions and transoms requires some continuity of metal from outside to inside. Plastic spacers of low thermal conductivity are positioned to provide a thermal break that also enhances the structural integrity of the construction.

Two generic types of thermal insulation have emerged for use in wall systems: rigid foam and flexible quilt types. The rigid foam type is made typically from either a polymer-based board such as polyurethane foam. Since both are non-hygroscopic or 'closed cell', they can be used in situations where the thermal insulation can become wet without any significant reduction in its performance. Closed cell insulation is also used to form the structural core of metal-faced composite panels (b) as well as in facing the inner leaf of cavity walls. In contrast, flexible quilt is made typically from a mineral fibre quilt, cut to fit voids in panel frames more easily than board, but its lack of rigidity makes it unsuitable for use externally. While heavier insulation helps to provide a more rigid, water resistant material, the lighter, less rigid types provide better thermal insulation. As a result, the choice of core is a balance between the needs of rigidity and thermal performance.



e | Metal screen: Sun Tower Office Building, Seoul, South Korea. Architect: Morphosis Architecture



f | Metal louvre screen: Nordic Embassy, Berlin, Germany. Architect: Berger + Parkkinen



g | Metal profiled cladding: Vacheron Headquarters, Geneva, Switzerland. Architect: Bernard Tschumi



h | Metal screen: St Andrews Beach, Victoria, Australia. Architect: Sean Godsell

Rainscreens

Rainscreen cladding is a development of the rainscreen for pressure-equalised walls researched during the 1960s. It was found that water commonly penetrates joints in walling because of the outside air pressure being greater than that inside the joint. Water arriving by a variety of means, mainly gravity, wind and capillary action, was able to penetrate the outer seals of joints. The introduction of rainscreen framing systems and panel systems overcame this problem by creating an outer 'screen' layer or seal that stops most of the water entering the joint, but ensures that the air pressure in the void behind the panel or joint is the same as that outside it (c). Rainscreen systems have three essential functions:

- To protect joints in the cladding assembly from the worst effects of windblown rain.
- To provide a decorative screen for a waterproofing system whose appearance is not suitable for an external wall. The same principle applies to roof cladding.
- To provide an outer protective layer to thermal insulation fixed on the external face of a high thermal mass construction such as concrete.

Drained and ventilated systems

There has been a move away from 'hermetically' sealed systems, which rely entirely on a single weatherproof outer skin, towards 'drained' systems. This is common to virtually all sealed facade types. Drained systems accept that the air pressure differences between the outside of the wall and the inside will allow small amounts of rainwater to penetrate the outer seal. This effect can be countered through two means; the water can be drained away within the metal framing that supports the cladding panels, and the pressure differences can be equalised by ventilating the system by providing slots at drainage points, usually set at the base of the wall. This ensures that water is not trapped within the panel framing, nor is the water discharged at vulnerable points in the construction where staining and damage can occur on the face of the panel. The use of ventilation within an assembly, on the external side of a thermal insulation layer, allows cladding systems to dry out once water has penetrated. Wherever water or water vapour penetrates a material in a wall or roof, it is stopped from travelling further by the vapour barrier or waterproof membrane. At this point, it can be difficult for the water to dry out. A void is sometimes formed at the vapour barrier to allow the water to evaporate and prevent the adjacent material from being damaged. This is particularly important in the case of timber, where eventual rot can occur. The development of drained systems accepts that externally applied seals will leak small amounts of water and that it is better to design for that eventuality. Even systems with a single outer seal can be designed to drain away water within their construction.

Use of materials in facade systems

The different material systems for facades are very much influenced by the particular material chosen. The essential issues in working with each material in facade assemblies are described in the following paragraphs.

Metals

Metals used in facade systems are based mainly on sheets, extrusions and castings. Thin sheet metal is made in narrow strips up to 1000mm wide, making it necessary to form simple, reliable joints at close centres when joining the material together to form a weather-tight surface (d). This is done by folding the metal together at the edges to form a continuous seam that projects from the wall surface, making it difficult for water to penetrate from outside. Standing seams are economic to make, but need to be done with care to avoid uneven joint lines (g). Because it is difficult to achieve crisp lines with this method, which relies on site-based workmanship rather than the use of workshop-based machines, the uneven 'oil canning' appearance can be accepted as an uneven texture forming part of the design. Because sheet metal used in facades is thin in order to fold it and work it, it requires support from underneath. The support surface conveniently forms a base for a backing waterproof layer which is needed behind sheet metal since it is unable to exclude rainwater. Sheet metal can be welded



a | Unitised glazing system: IAC Headquarters, New York, U.S.A. Architect: Frank Gehry & Studios Architecture



b | Clamped glazing system: Rheinisches Landesmuseum, Bonn, Germany. Architect: Archtektengruppe Stuttgart



c | Bolt fixed glazing system: Tower Bridge House, London, U.K. Architect: Rogers Stirk Harbour + Partners



d | Glass blocks: Maison Hermes, Tokyo, Japan. Architect: Renzo Piano Building Workshop

together to form a continuous waterproof sheet material, but thermal expansion needs to be allowed for standing seam joints that prevent the material from deforming as the metal expands. The number of joints on a facade can be reduced by increasing the size of the metal sheet being used. Profiled metal sheet can be formed into very long lengths, and into widths of up to around 1500mm. Joints between sheets are formed by lapping sheets both horizontally and vertically with sealant set between adjacent sheets to provide a waterproof joint. This allows the sheet material to span between the supports of a framed supporting structure behind, rather than needing continuous support. Fixing profiled sheet to the supporting structure requires fixings that penetrate through the outside of the sheet to the inside, which presents a potentially weak point for waterproofing. This penetration through the material by fixings is avoided in standing seam sheet metal. Fixings for profiled sheet are made to be fixed easily, using a self-tapping screw, which has a waterproof washer on the outside and a drill bit on the front of the screw to make a hole. The self-tapping sealed screw is essential to the success of profiled metal sheeting, and corner trims and folded copings in the same material ensure the watertightness of junctions.

Sheet metal has been developed in recent years to be bonded to closed cell insulation, since both materials are used very economically in combination, so that the stiffness of insulation is combined with the watertightness and durability of metal. The successful bonding of rigid insulation to thin metal has been essential to the success of composite metal panels. These panels are joined with tongue-and-groove joints, usually on two sides. While this is a reliable joint, the joint on the opposite two sides is usually less accomplished, normally being a butt joint sealed with silicone, with an additional top hat metal profile to enhance the seal. Four sided tongue-and-groove jointed panels are more difficult to fix and more difficult to remove if damaged. The tongue-and-groove joint incorporates a void in the centre that allows water to drain down. The basic principle with sealing joints between composite panels is to ensure that any water entering the joint will drain down an internal cavity that drains water away to the outside at the bottom of the panels.

Glass

Glass in facades is supported either by edge frames or by fixing it at points. Glass facades are beginning to be glued together without any metal fixings, but the design of such structures is in its early stages. Frames supporting the glass must both hold the glass in place and prevent rainwater from penetrating the seals. Difficulties in providing reliable rubber-based seals have led to the 'pressure equalised' or 'drained and ventilated' frames discussed earlier in this section. Water penetration in frames has traditionally been caused by capillary action where the air pressure inside the frame becomes higher than the outside atmospheric pressure, drawing water into the frame and potentially causing leaks. The problem of capillary action has been overcome, not by increasing the pressure on the seal between frame and glass, but by ventilating the void inside the frame so that any water that penetrates the outer seal is drained away safely down the cavity to the outside. The drained and ventilated cavity provides a second line of defence against rainwater penetration through the outer seal. The principle of pressure equalisation, with an inner chamber behind an outer seal, is essential to current framed glazing systems (a). An alternative method of glazing is to avoid a frame entirely in order to increase the effect of transparency given by the glass. In point fixed glazing, the glass is only held at at a few points by small brackets or bolts. Glass is clamped together with plates, and bolted together through the joints between the glass (b). Alternatively, holes are drilled in the glass and the sheets are held by bolts secured directly through the holes in the glass without plates, using discs or a countersunk profile to the bolt connector (c). Joints are sealed with silicone in a single line of defence. While the material does not suffer problems of water being drawn through, it as happens with clamped rubber seals, good workmanship is essential to the success of these single seals.

Walls built in glass blocks are constructed by bonding the blocks together with either a cement-based mortar or silicone (d). Because blocks are set with continuous vertical and horizontal joints, giving them their characteristic appearance, panels are structurally inherently



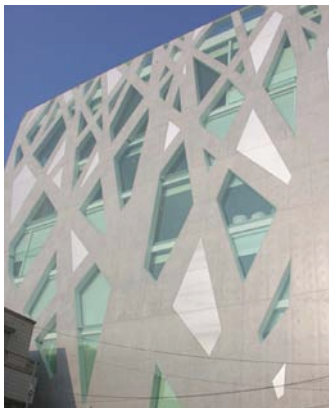
e | Stick glazing system: ING Headquarters, Budapest, Hungary. Architect: Erick van Egeraat



f | Metal windows: Matsunoyama Museum of Natural Science, Matsunoyama, Japan. Architect: Tezuka Architects



g | Timber windows: Old Nichol Street, London, U.K. Architect: Maccreanor Lavington Architects



h | Concrete: Tod's building Architect: Toyo Ito & Associates

weak, and this is dealt with by introducing steel or aluminium reinforcing strips or rods into both vertical and horizontal joints as reinforcement. However, this limits glass block panel sizes to modest dimensions when compared to other glass wall systems. The principle of stack bonding limits panel sizes but is usually overcome by making the supporting structure lightweight, yet rigid in order to minimise its visual effect. More heavyweight supporting structures make the blocks appear more like individual panels set into a visual grid.

Concrete

An essential aspect of concrete is that it is a material formed in a mould, leaving a surface finish which is the mirror image of that mould or formwork. Consequently, an important aspect of concrete detailing is understanding how formwork and moulds are fitted together. Formwork can be made into almost any shape, from plywood or GRP (glass reinforced polyester), though specially-made formwork can be expensive to make. Joints between formwork panels are visible in the finished concrete, and if this is not to be overclad with another material, then joints need to be arranged to suit the architectural concept for the facades. Complex shapes for facade panels can be made more easily in precast concrete where, in a workshop, concrete is poured into a mould which is laid flat, making it much easier to take up complex shapes and textures which would be much harder to form vertically (h). Ferro-cement is capable of a high degree of surface modelling, being made as a cement mortar-based mix with a high proportion of steel reinforcement. This material ensures very smooth finishes, but is more commonly used for yacht hulls.

In-situ cast concrete is a monolithic material that provides an almost continuous waterproof surface. Rainwater penetrates only a few centimetres into the depth of the material, but in temperate climates this leads to visible surface staining. This can be overcome by colouring the concrete, adding textures, or ensuring that rainwater does not wash off surfaces where dirt can collect, which would cause staining on an area of wall beneath. Movement joints with in-situ concrete require careful attention so that they are waterproof but do not leave strong lines that are at odds with the overall concept of the facade. The facade designer must always be aware of where joints occur and how wide they will be in order to avoid disappointment during construction.

Precast concrete panels are jointed with pressure equalised drainage chambers behind vertical joints, which drain out of horizontal joints. Like in-situ cast concrete, the general areas of concrete are waterproof, but the joints require careful attention to avoid their becoming too wide as a result of wanting to achieve a consistent joint width both vertically and horizontally across the facade. Horizontal joints have to accommodate deflections and movement from the supporting structure if the panels are supported from floor slabs, as is usually the case due to their self-weight. Vertical joints are usually required to be thinner in order to exclude rainwater. The visual balance of joint widths, although a seemingly small issue, is critical to the visual success of precast panels (j). Notching and grooves are introduced around openings to ensure that windows and doors can be inserted in a way that provides weather protection as well as concealing part of the frame to avoid visible seals around the edge of the openings. Highly visible seals can also lead to very disappointing visual results.

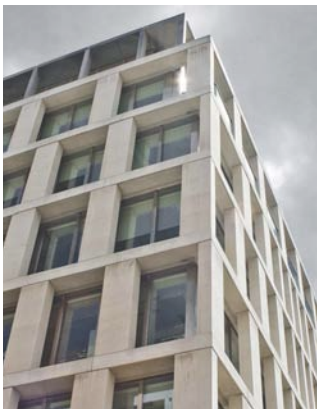
Masonry

Loadbearing walls in brick, stone and concrete block have the advantage of being able to avoid the visible movement joints associated with non-loadbearing cladding, which can enhance the massive visual quality of traditionally built walls (k). An essential issue in loadbearing construction is to ensure that the wall is sufficiently thick to avoid rainwater penetration as well as being able to provide thermal insulation, either in the wall construction or on the inner face. The sealing of windows and doors into openings follows the principles of reinforced concrete discussed in the previous paragraph.

In masonry cavity walls, two masonry skins are tied together to form a single wall, and here the detailing of openings in walls is undergoing



j | Concrete panels:
Housing Villaverde, Madrid, Spain.
Architect: Chipperfield Architects



k | Masonry loadbearing walls:
30 Finsbury Square, London, U.K.
Architect: Eric Parry Architects



m | Masonry loadbearing walls:
Bluecoat Art Gallery, Liverpool, U.K.
Architect: BIQ Architects



n | Masonry cavity walls:
Private residence, Dublin, Ireland.
Architect: Boyd Cody Architects

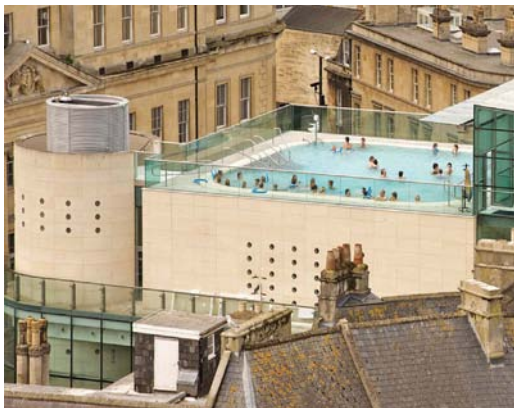
continual refinement in order to reduce thermal bridges (d). The top of an opening is supported with a lintel that both closes the opening and ties the two skins together while forming as small a thermal bridge as possible. Proprietary cavity closers and insulated lintels are used, but these tend to match the shorter life-cycle of the windows rather than that of the supporting structure, which is usually longer. Providing a continuity between the thermal insulation in the cavity, fixed to the inner skin in the case of blockwork or masonry units, can lead to wide joints around windows, which needs careful attention to avoid visual clumsiness. This issue is easier to resolve if the thermal insulation forms part of the inner skin, as is the case with inner skins in timber framing or light gauge steel frames.

In stone cladding, panels are mortared together and supported on fixings at each floor level, where each stone is individually restrained back to an inner wall that provides lateral restraint from wind loads (p). Windows and doors are typically fixed to, and supported by, the inner wall. The gap between the outer thin stone and the windows fixed to the inner walls is usually achieved by either putting a trim around the reveal in the same material as the window (usually metal) or by adding stone panels around the opening (q). When stone panels are used around the opening there is always the choice of either revealing the edge of the stone of the reveal trim (or the edge of the adjacent stone in the facade), or alternatively mitring the junction between the two stones. Since the thickness of stone cladding is seen only at external corners, the choice of revealing or concealing its actual thickness, rather than the massive stone quality the facade may aim to convey, is an essential design consideration. Thin stone cladding is often used for its surface texture rather than conveying an idea of massiveness (r). The choice of easily commercially available stones has increased dramatically in recent years, widening the choice to thinner sandstones and limestones which have physical properties closer to those of weak granites. Masonry rainscreens are a recent development and comprise extruded terracotta panels that are fixed in a variety of ways depending on their size. Since they are completely independent of backing walls they present enormous freedom in design.

Plastics

Plastic-based cladding achieved a certain popularity in the 1960s and 1970s, presenting a fresh approach in building construction based on lightness in weight and a craft-based working method in economic materials that appealed to designers. Since then its use has been more modest, with concerns about durability and colour fading which have largely been overcome with the plastic-based materials available today. Sealed plastic-based cladding uses mainly polycarbonate and GRP sheet that is either fixed into frames generally used for glazed curtain walling, or is fixed together as self-supporting panels in a way similar to metal composite panels. Most types are available as proprietary systems, with manufacturers having their own details for window openings, parapets, cills and corners.

When polycarbonate sheet is used, the material often has up to five layers within the material that provides a high level of thermal insulation. Some manufacturers use thermally broken sections, but the more visually appealing sections have no thermal breaks. Since these sections are made from aluminium extrusions, the opportunity continually exists to improve the system in conjunction with manufacturers. An essential aspect of working with proprietary systems is that some have standard window and door sections which have an appearance that may not suit other design approaches. The challenge here is to be able to modify the windows, doors and trims to suit the overall design for the facade. Other polycarbonate sheet systems have little provision for windows and doors and usually have no standard method of interacting with the supporting structure. These have to be developed with the manufacturer to suit a particular design. Because polycarbonate is used for its qualities of transparency and translucency, the supporting framework is very visible, even with translucent wall panels, so trims to support framing should be designed as carefully as those for glazed curtain walling. In common with glazed walls, polycarbonate panels can be either fixed into frames or fixed at points with bolts and brackets. Silicone-based sealants are commonly used to seal between panels as is used in bolt fixed glazing.



p | Masonry stone and block cavity walls:
Thermae Spa, Bath, U.K. Architect: Grimshaw Architects



q | Masonry stone and block cavity walls:
NoLi Housing, Philadelphia, U.S.A.
Architect: Erdy McHenry Architecture



r | Masonry cladding:
Archaeology museum Almeria, Spain.
Architect: Paredes/Pedrosa

GRP panels are also fixed into glazing systems, but can be fixed together as sealed cladding units with pre-formed standing seams like some proprietary systems for profiled metal sheet. They can also be formed into flat rainscreen panels with visible or concealed fixings. An important aspect of detailing in this material is its relatively high thermal expansion which leads to larger gaps between components than is the case with other materials. The economic nature of plastic-based cladding is beginning to be recognised in new buildings, particularly with the ability of plastics to be coated in different colours economically, unlike the dominant use of pre-coated coil in metal panels; however the prejudice against the material due to its discoloration in older examples has yet to be overcome in architectural applications.

Timber

Timber is susceptible to more movement than the other materials described, mostly as a result of changes in moisture level within the material. Consequently, timber used in facade cladding is allowed to accommodate movement as well as being ventilated to ensure that bowing, twisting and warping of timber components is minimised. In detailing timber, it is difficult to form joints that perform well in tension without the need to introduce another material, usually metal. Metal pin connections, nail plates, cleats and angles are an integral part of the language of timber joints.

Although timber can be used as both cladding panels and as rainscreen panels over a different background wall, the timber boards in both cases are set clear of the backing wall to ensure that both sides are well-ventilated. When timber boards are used to clad a platform frame, the same general principles apply as for the construction of individual timber cladding panels, except for the vertical joints. Vertical joints between boards in the platform frame can have timber trims and fillets added that protect the end grain of the timber from rainwater, where the timber is particularly vulnerable. Joints between timber cladding panels use a mixture of metal trims and rubber-based seals in the manner of unitised glazed walls, with a drained and ventilated chamber behind the outer timber cladding.

An important consideration in the detailing of timber is that the thermal conductivity of both softwoods and hardwoods is very low, from 0.14 – 0.21 W/m²K, compared to 45 W/m²K for steel and 2000 W/m²K for aluminium. Thermal breaks are not a significant issue in timber construction, which considerably eases any issues of thermal bridging around openings. This allows enormous flexibility in timber detailing, with a reduced risk of condensation occurring either within the construction or on the inside face of the wall in temperate climates. Openings in timber walls increasingly use metal trims to enhance the visual refinement of details. Metal trims can also support fly screens, awnings and related metal attachments to window and door openings. Timber wall construction is relatively thin at around 150mm overall, compared to 300mm for concrete and masonry-based facades, resulting in smaller window reveals which are easy to detail with modest trims and cills. Window frames are sometimes set on the outside face of the wall to reduce any risk of rainwater penetration as well as providing internal window cills.

Timber rainscreens vary enormously, from big timber sections fixed back individually to a backing wall, in the manner of an open-jointed timber deck set vertically, to timber panels with louvres and sliding slatted panels. The positioning of metal fixings is critical to the visual success of all these timber cladding methods. Corner brackets and fixings have a tendency to be large in order to give a secure fixing, so attention to detail of brackets and fixings is essential in achieving an elegant appearance. Traditional techniques used lapping of timber boards, with concealed nails and screws to protect fixings from corrosion, but contemporary detailing puts much less emphasis on lapping in order to give greater visual precision to the construction.



a | Small precast concrete panels: St Albans Pavillion, St Albans, U.K. Architect: MUF Architects



b | Plastic-based cladding: Dance Studio, Tooting & Mitcham Football Club, U.K. Architect: Clash Associates



c | Plastic rainscreen: Reiss store, London, U.K. Architect: Squire & Partners

This section discusses changes over the past ten years in the 17 generic non-loadbearing cladding types set out in this chapter, and further identifies a smaller set of six generic types from this list. The application of this set of cladding types in 'thin' and 'layered' facades is discussed, as well as how these facades are slowly developing with the use of technology from other industries.

The generic types are as follows:

1. Fully supported sheet metal
2. Profiled cladding
3. Composite metal panels
4. Metal rainscreens
5. Metal mesh screens
6. Glass stick systems
7. Glass unitised systems
8. Point fixed glazing (clamped and bolt fixed)
9. Glass blocks
10. Steel framed glazing
11. Precast concrete panels (a)
12. Masonry facings to cavity walls (brick, block, stone)
13. Stone cladding
14. Terracotta rainscreen
15. Polycarbonate insulated systems (b)
16. Timber cladding to platform frame (f)
17. Timber rainscreens

All these systems still in use have undergone technical development to improve performance, largely concerned with energy conservation. Reports over the past ten years have suggested that no clear pattern of use has emerged in the use of cladding systems. The choice of cladding system is very much affected by building type and the number of a particular type built in a given year. The full range of cladding systems in this book is in full use. The preference for one system over another is very much driven by the building type and particular performance criteria and budgets of individual projects. A clear pattern that is emerging is that the choice of cladding systems available has not affected the move towards the emergence of a new set of generic types which are common to all the 17 cladding types. From these generic types, it is clear that the different types are supported by either a monolithic structure or a backing wall to a frame, or alternatively to an open structural frame. Each generic type is rarely supported by both structural types. Since framed construction is more recent, the more recently-developed techniques of glazing are used in conjunction with frames. Traditional loadbearing structures continue to be used in conjunction with traditionally-based techniques. Structurally, the traditionally-based cladding is characterised by techniques that use materials in short spans.

From the list, these short span generic types for monolithic structures (and backing walls to frames) are as follows:

Fully supported sheet metal
- Metal rainscreens
- Masonry facings to cavity walls (brick, block, stone)
- Stone cladding
- Terracotta rainscreens
- Timber cladding to platform frame
- Timber rainscreens

Also from the list, generic types for open framed structures are as follows:
- Metal profiled cladding
- Metal composite panels
- Metal mesh screens
- Glass stick systems
- Glass unitised systems
- Point fixed glazing (clamped and bolt fixed)
- Glass blocks
- Steel framed glazing
- Precast concrete panels
- Polycarbonate insulated systems



d | Masonry rainscreen:
Walsall Art Gallery, U.K.
Architect: Caruso St John Architects



e | Timber frame:
Harmood Children's Centre, London, U.K.
Architect: Greenhill Jenner Architects



f | Timber cladding panels: Carmarthen Place, London, U.K.
Architect: Architects in Residence

Generic forms

Six generic cladding types are identified below which are common to both non-glazed and glazed cladding systems. The first three types are used for small span applications with a backing wall. The second three types are used for large span applications without a backing wall.

Three types for small span applications with a backing wall:

1. Fully supported sheet with sealed joints
2. Facings with sealed joints: facings to masonry cavity walls, glass blocks, masonry cladding, timber boarding
3. Rainscreens with open joints: masonry, timber boarding, metal, mesh screens

Three types for large span applications without a backing wall:
4. Self-supporting profiled sheet
5. Stick systems: metal, glass, point fixed glazing, insulated polycarbonate
6. Panel systems: Precast concrete, timber, metal composite, glass unitised

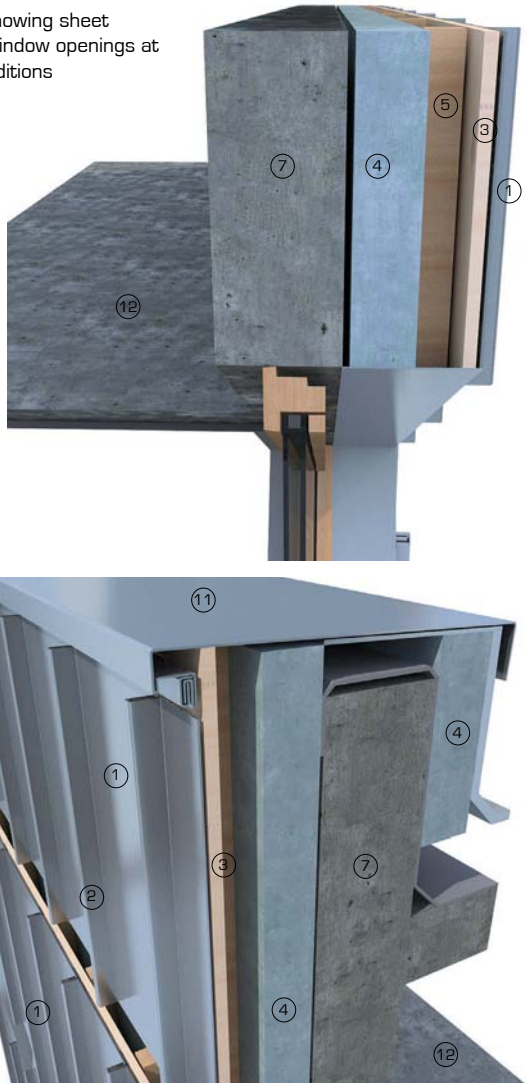
The application of these generic types in 'thin' and 'layered' facades

Modern single-sealed glass framing systems used in building construction, which rely on silicone bonding and rubber-based pressure seals, together with tempered, body-tinted glasses, are based on techniques developed by glass manufacturers for the car industry. Car manufacturers are relatively few in number, but they place very large orders for a restricted range of specially designed glass products such as windscreens. The building industry, in contrast, generates relatively small orders from a huge number of customers all of whom have quite different requirements. The current custom-built nature of building construction does not in itself encourage, glass manufacturers to invest significantly in new systems. As a result, most recent developments in glazing for buildings have followed in the wake of those developed for use in cars. Performance specifications for car glazing systems apply a complex set of criteria to a single very narrow 'wall' thickness. The use of glass with a structural capability, coupled with controlled light and heat transmission, is a strong influence in the design of facades. It reduces the thickness of external walls, allowing floor areas to be maximised. It allows a single, competitively priced product, such as body tinted tempered glass, to fulfil a range of functions. In these 'thin' or 'compressed' facades, functions of weatherproofing, thermal insulation, air handling and glare control are compressed into a very thin wall.

Over the past 15 years, this principle has been developed to incorporate other components within a narrow depth. Louvred blinds and mechanical ventilation can now be incorporated. Heat from solar radiation can be partially absorbed by blinds set within the depth of a 100mm to 300mm deep double-glazed unit. Air passes through the unit, drawing away heat from the blinds, providing a thin external wall whose performance is a balance between different, and sometimes conflicting, criteria. In these thin facades, the integrated blind will absorb heat during periods of high solar gain when blinds must be orientated to act as a radiator of heat. This can conflict with occupants' requirements for daylight. Each facade will respond differently to the changing weather conditions, by either manual or electrical means.

An alternative approach for external walls is the separation and layering of the functions of weatherproofing, ventilation, thermal insulation, and daylight/glare control. With this 'layered' approach, specific layers in the envelope system are created to deal with the specific tasks of excluding rainwater and controlling heat loss and heat gain, glare and ventilation. To achieve this, a layered system superimposes generic types. A current disadvantage of this system is that a layered facade requires considerably more depth of 'wall'; from around one metre where external solar shading is provided, to about three metres where the zone between the inner and outer wall becomes a usable space in a building, in the manner of a conservatory or winter garden.

b | (Right) 3D detail views showing sheet metal wall system with window openings at window and parapet conditions





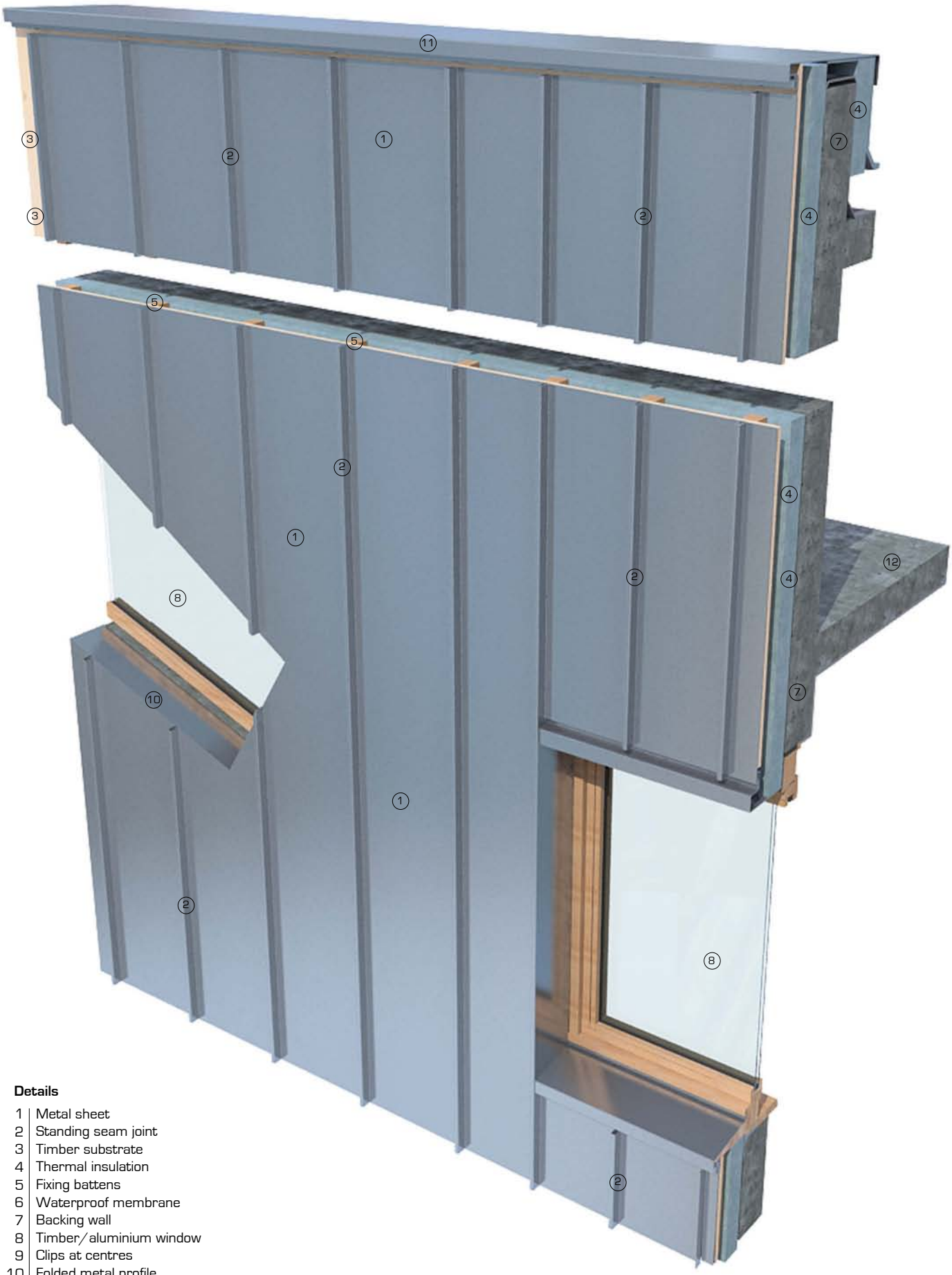
a | 3D view of sheet metal wall system with window openings

System design

Sheet metal is typically supported directly on a substrate (3), providing a system formed from thin sheet (1) which can closely follow a complex geometry with relative ease, making it very suitable as a covering for a highly modelled facade. This material system has developed from its traditional use in roofing, where the standing seam technique is well established (2), to a facade material that can cover projecting windows (8), externally set structure and areas of flat facade with equal ease. In recent years, sheet metal has been used to enclose forms of complex geometry on either folded or curved facades. Consequently, this system also provides an economic outer covering in projects where wall and roof are combined in a single form, or where the external envelope is highly modelled in a single form where one material is required for the complete envelope. The principles of rainwater exclusion used on roofs can be applied for use on facades with continuous joint lines, to form a complete envelope from a (nominally) flat roof to a vertical wall, to inverted soffit conditions.

The two generic methods for supporting sheet metal facades that suit different conditions are continuous standing seams and tiled shingles. Standing seams are suited where long, straight or continuous joint lines are required or where the facade has gentle curves which can be picked out by the joint lines (2). Tiled shingles are suited to complex geometries and smaller-scale applications where a high degree of surface modelling is required. Metal sheet can also be laid onto a timber-based substrate as an outer covering to a complex form. Both methods set the thermal insulation behind the substrate (4), typically creating a ventilated void between substrate and insulation, but this is dependent on the construction of the backing wall rather than on the sheet metal layer.

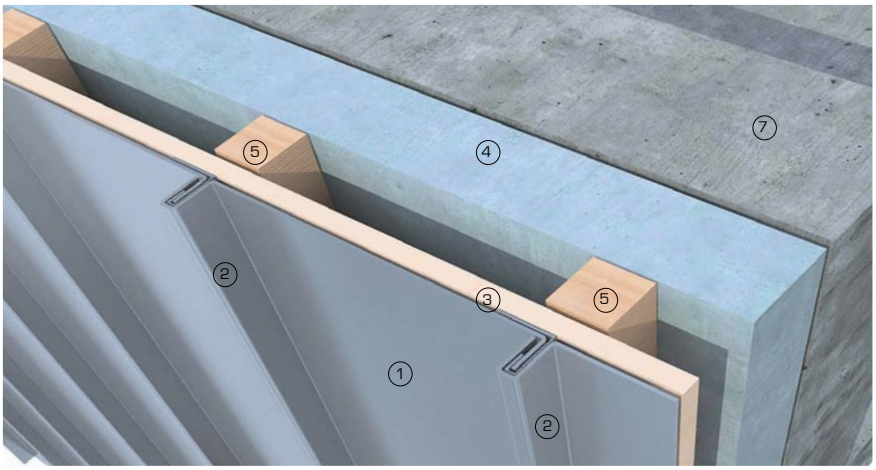
Standing seam roofs have traditionally had a slightly uneven appearance due to the softer, more ductile metals used; mainly lead, zinc and copper, the ductility of which allows them to be formed more easily when used in traditional, site-based installations. The 'oil canning' effects of sheet metals, which are visible immediately after installation when used in facades, tend to diminish visually as the surface weathers to the characteristic patina of the metal used. The texture remains with weathering, giving a hand-crafted appearance which suits visually vibrant facades. Some recent buildings have even slightly exaggerated this effect before installation to create a highly textured surface finish to the metal. Standing seam metal facades have the essential visual characteristic of highly visible joints at relatively close centres of between 450 - 600mm. This construction method, used traditionally as a roofing system, is used increasingly in facades as an economic system that is easy to combine with other facade elements such as glazing without the need for reveals and visible flashings (11).



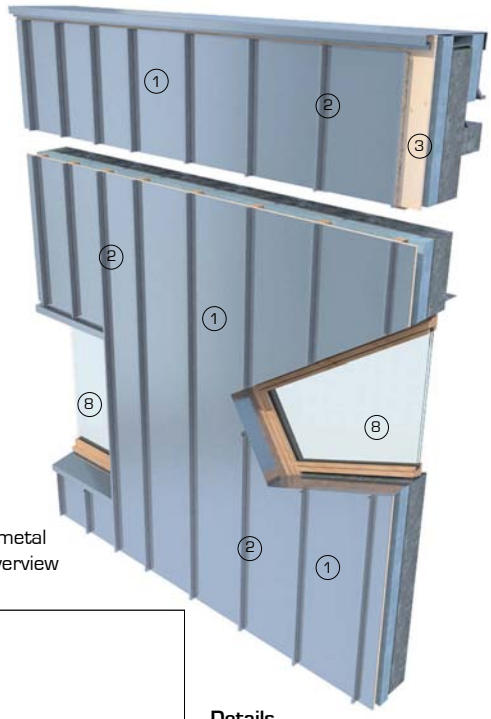
Details

1 | Metal sheet
2 | Standing seam joint
3 | Timber substrate
4 | Thermal insulation
5 | Fixing battens
6 | Waterproof membrane
7 | Backing wall
8 | Timber/aluminium window
9 | Clips at centres
10 | Folded metal profile
11 | Metal flashing
12 | Concrete floor slab

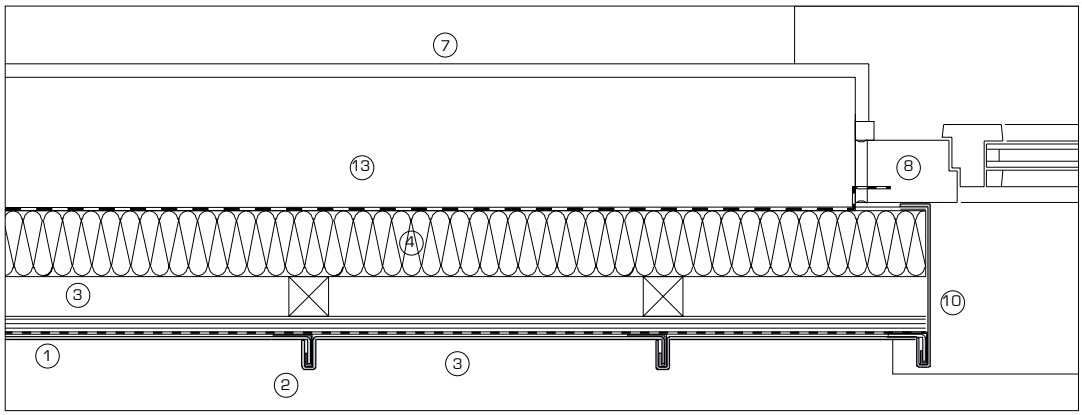
c | 3D view of wall system with window opening and parapet detail



d | 3D detail view showing profiled metal sheet wall construction



e | 3D view showing profiled metal sheet wall construction overview



f | Horizontal section 1:10. Profiled metal sheet fixed to concrete backing wall

Details

1	Metal sheet
2	Standing seam joint
3	Timber substrate
4	Thermal insulation
5	Fixing battens
6	Waterproof membrane
7	Backing wall
8	Timber/aluminium window
9	Clips at centres
10	Folded metal profile
11	Metal flashing
12	Concrete floor slab

System details

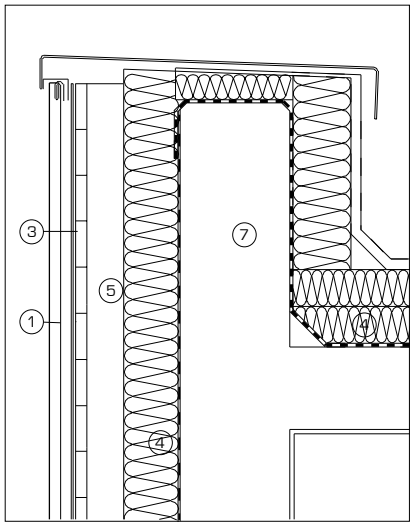
Continuously supported sheet metal provides a rhythm of standing seams that do not need to be visually coordinated with openings and junctions in the facade (e). Flashings can be formed at window and door openings without modular co-ordination and are not required to be specifically aligned with an adjacent standing seam or shingle edge for a reliable joint to be formed (11). When joints are at visually close centres, at around 400mm, the joint pattern provides an overall texture for a facade rather than defining rows of joints. When used in long lengths from rolls, the material allows horizontal joints to be avoided in smaller scale applications, up to around 12 metres in length, but curved or highly modelled facade/roof combinations require shorter distances between horizontal joints to accommodate the curvature. In such situations tapered joints are often used, sometimes with staggers set into them as are used at the centre of traditional circular metal roofs.

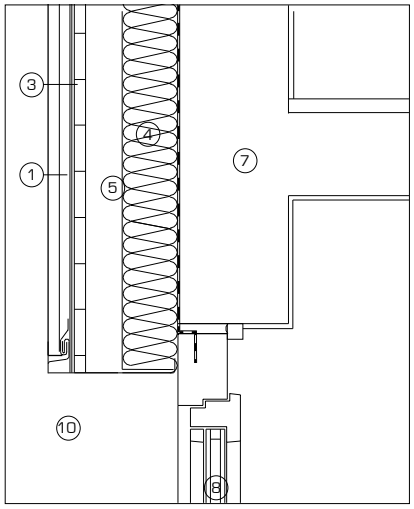
Where crisp, straight lines are required in the design, the standing seam method is used on vertical joints in a variety of configurations to suit visual requirements. The choice of seam is primarily visual, ranging from the wide-rolled seam of traditional lead roofing to the thin folded projecting seam of traditional zinc and copper roofing. Horizontal joints are folded to form a flattened seam that allows rainwater to run off it without finding its way into a joint.

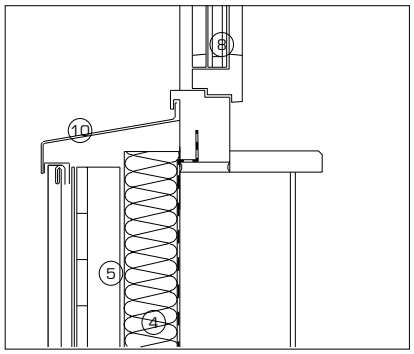
Tiled or 'shingled' standing seam metal facades use flattened, folded seams on all sides of the panel (2). Since the same source material of metal strip is used, metal tiles usually come in widths of around 450-600mm depending on the metal used. The jointing system also performs well when the tiles are set diagonally, with 45° being most commonly used in practice.

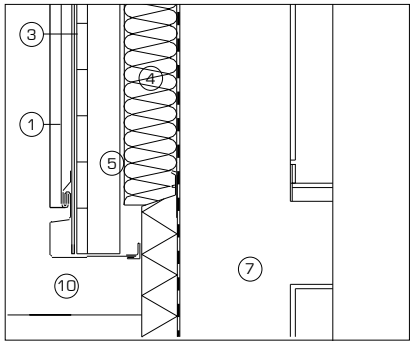
Both methods use a continuous supporting material, typically plywood sheet for its ability to form complex surfaces with ease (3). Timber boards are also used, but mainly in an open-jointed configuration to support zinc sheet, which requires ventilation on its internal face to avoid corrosion. Timber substrates are usually ventilated on their internal face in order to reduce the possibility of damage associated with trapped moisture (5).

For both standing seam joints and shingled tiles, openings and edge flashings, including parapets, are formed with folded metal flashings in the same material (11). Flashings can be set below the material at junctions which reduces their visibility, enhancing the texture of the facade material where required. Flashings are typically of two visual types: those that formed a visible strip that laps over the face of the adjacent area of metal sheet, and those that form a shadow gap between the flashing and the surface of the adjacent metal. Since sheet metal surfaces are formed by folding over edges of narrow sheets to form a continuous metal surface, they do not have a natural link into windows and doors set into a typical facade. Windows are often sealed against the backing wall in which they are held rather than being sealed against the sheet metal wall (8).





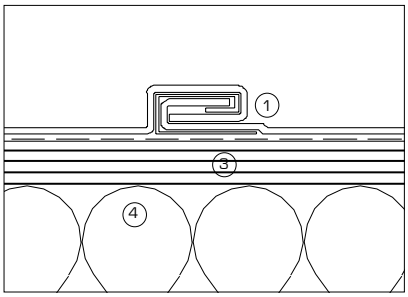


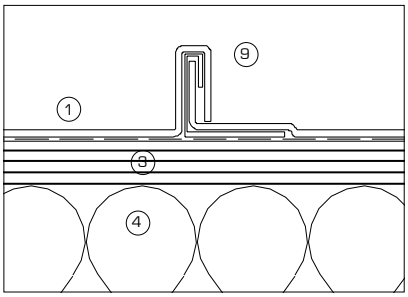


g | Vertical section 1:10. Typical wall system



h | 3D detail view showing window head detail within profiled metal sheet system





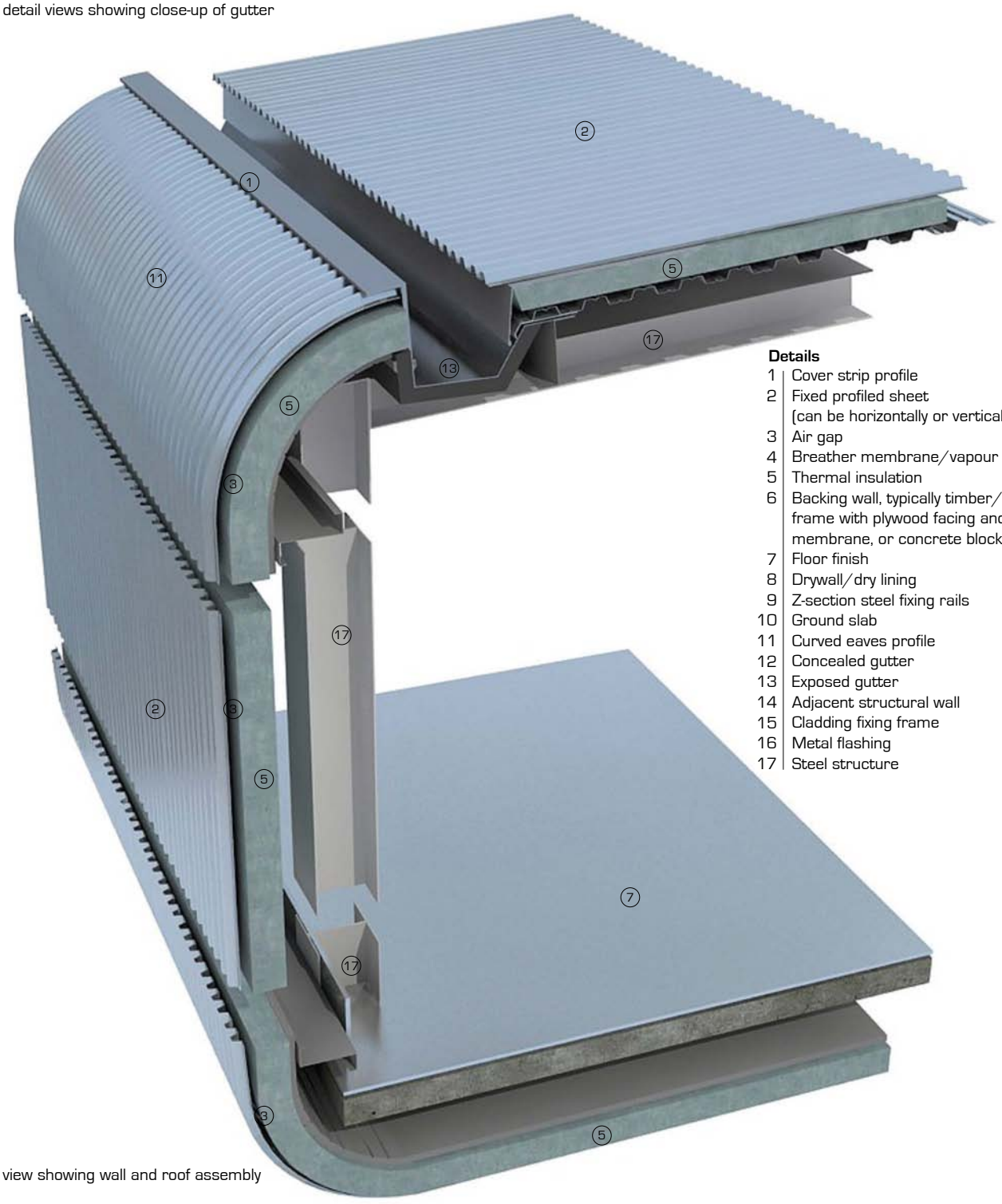
j | Plan 1:5. Standing seam profiles



k | 3D detail view showing window cill detail within profiled metal sheet system



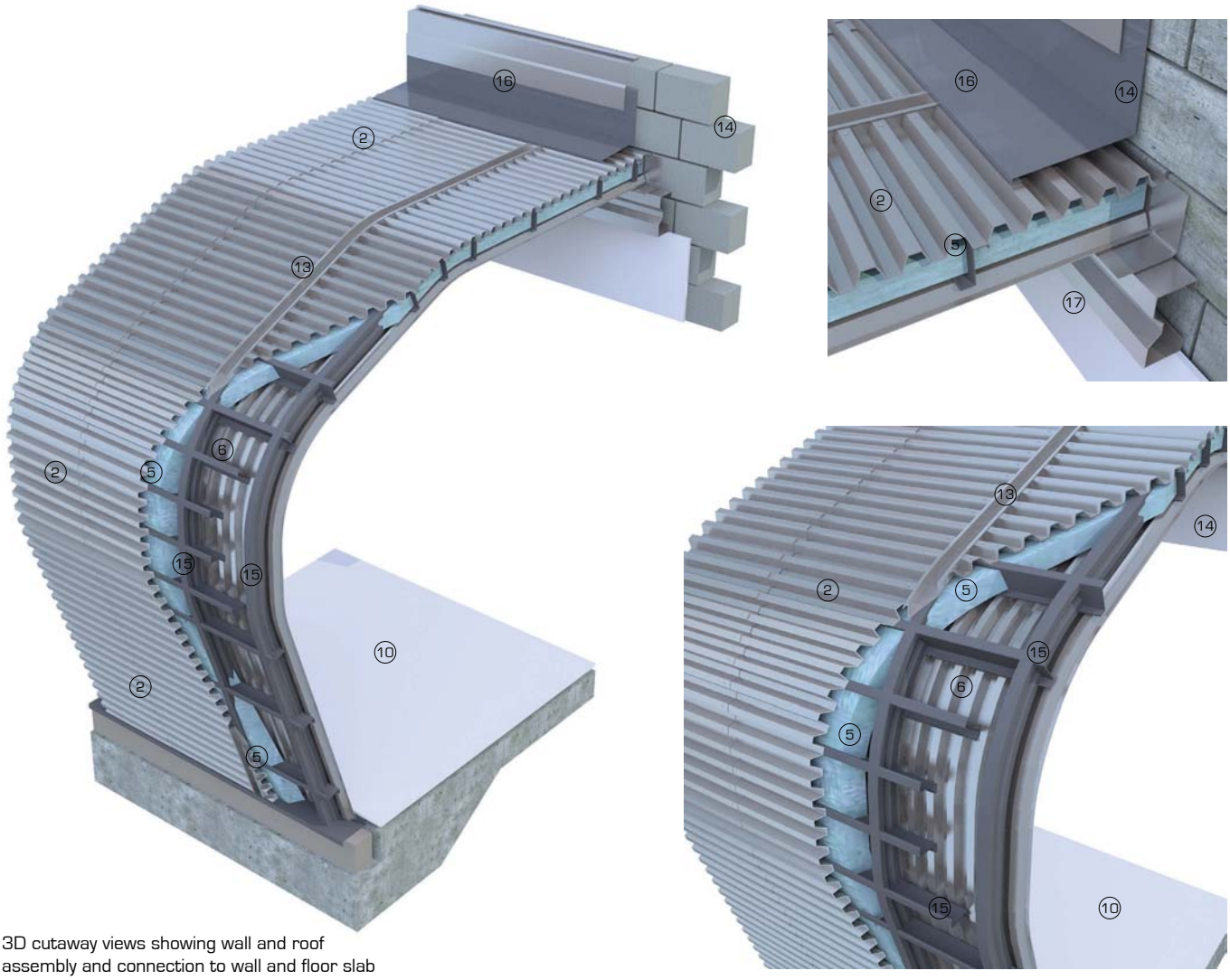
a | 3D detail views showing close-up of gutter



Details

1	Cover strip profile
2	Fixed profiled sheet (can be horizontally or vertically fixed)
3	Air gap
4	Breather membrane/vapour barrier
5	Thermal insulation
6	Backing wall, typically timber/metal frame with plywood facing and waterproof membrane, or concrete block
7	Floor finish
8	Drywall/dry lining
9	Z-section steel fixing rails
10	Ground slab
11	Curved eaves profile
12	Concealed gutter
13	Exposed gutter
14	Adjacent structural wall
15	Cladding fixing frame
16	Metal flashing
17	Steel structure

b | 3D view showing wall and roof assembly



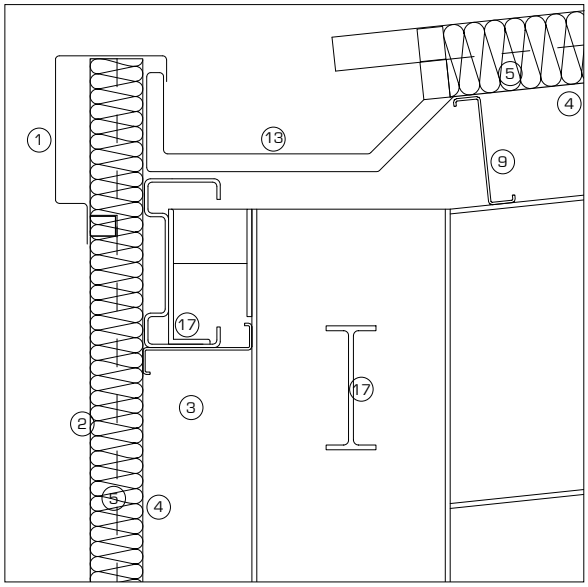
c | 3D cutaway views showing wall and roof assembly and connection to wall and floor slab

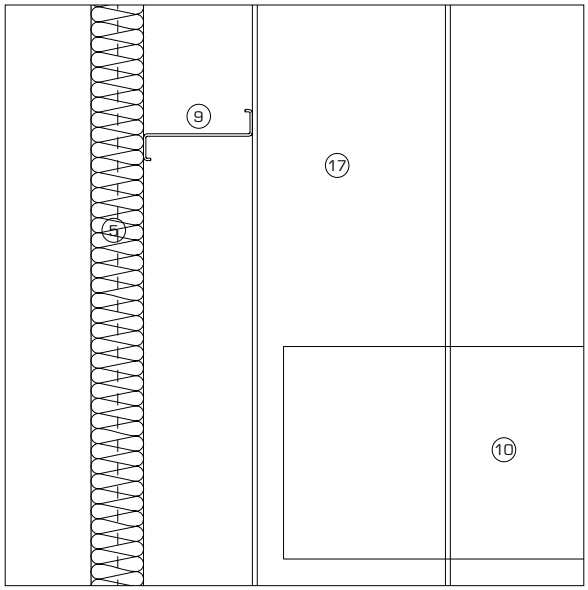
System design

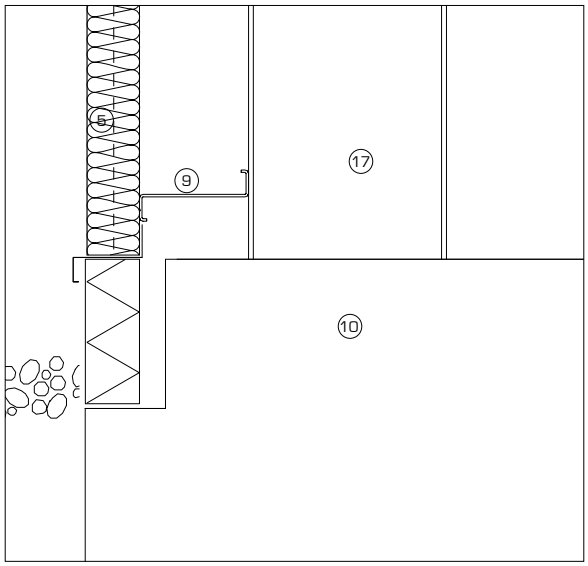
The main difference between profiled metal cladding and the continuously supported type is that profiled sheet can span 3-5 metres between supports, depending on the (sectional) profile used (2). The profile depth provides the material with rigidity in one direction, allowing it to be fixed directly to a structural frame rather than requiring the continuous support of an additional substrate. Its profile allows the sheet to be gently curved in one direction during installation on site , with the material still lapped on all edges regardless of its orientation. Profiled sheet can be curved along its rigid length by crimping in the factory, usually to form curved corner pieces for horizontally-set cladding, or curved eaves pieces for vertically-set cladding (11). Proprietary systems offer a range of curved components as well as 90° corners where short lengths of sheet are welded to form a crisp corner panel. The wide range of profiles available, from small wave profiles to deep profiled sections, gives a wide range of visual effects.

Profiled metal cladding has developed from its initial application in industrial buildings in the 1970s to wider architectural applications. This material system uses a single metal, either steel or aluminium, for the complete cladding of, typically, manufacturing or storage buildings which have large shallow-pitched roofs and a relatively small facade area in relation to that of the roof. The all-metal envelope evolved, in an architectural sense, with the introduction of curved eaves and a concealed gutter (12) with walls and roof appearing to be a continuous form. The profiled metal sheet was set with the ribs running from top to bottom of the roof and continued down the facades in the same alignment. As its use in facades developed, profiled metal cladding was used horizontally rather than vertically, in order to curve the wall profile when seen in section (c), and at different angles in order to introduce an expression of complex geometry.

As a material system, the profiled nature of the material requires continuity of the profile from sheet to sheet, making it difficult to create visual offsets in the setting out of the material. Where a change of orientation or direction is needed by the design, a projecting cover strip or recessed shadow gap joint is needed which creates a break in the system. Since the shape of the profile cannot be varied in regular manufacture, the lines of the sheet and visible joints at geometric changes in the system dominate its appearance. In common with standing seam metal, profiled metal sheet does not have windows and doors that form part of the material system, though these items can be made in the same material and finish. Because windows and doors are made by different manufacturers, it is important to ensure either colour matching at the fabrication stage, or contrasting colours/finishes that work together visually. Where the inner lining of the wall is also formed in profiled metal sheet (typically flatter, and sometimes perforated for acoustic performance), a similar approach is taken.







d | Vertical section 1:10. Profiled cladding wall construction

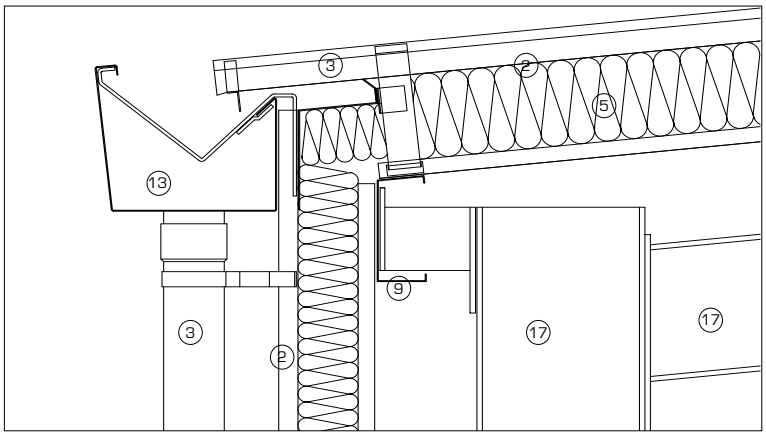
e | (Right) Vertical section 1:10. Gutter

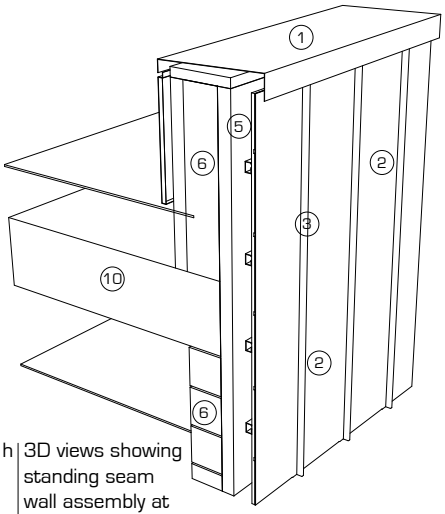


f | 3D view showing wall and roof assembly

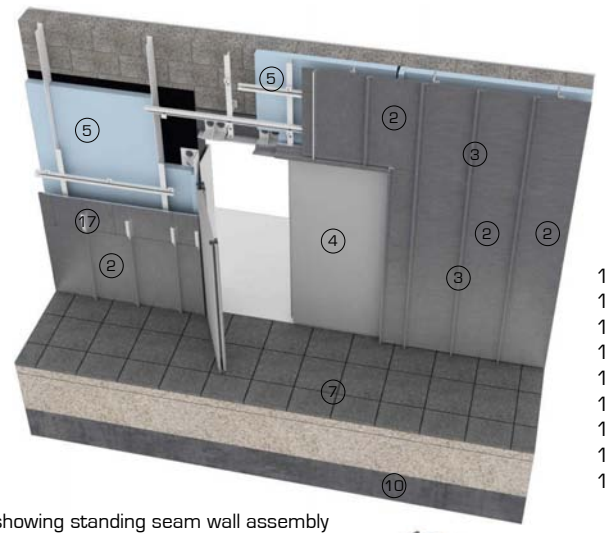
g | (Below) 3D view showing gutter detail in profiled cladding wall construction







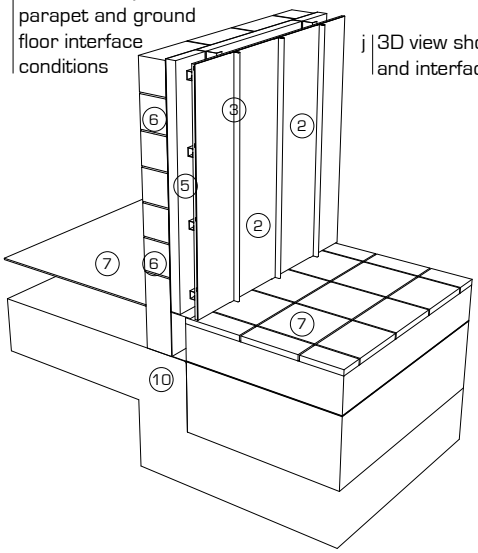
h | 3D views showing standing seam wall assembly at parapet and ground floor interface conditions

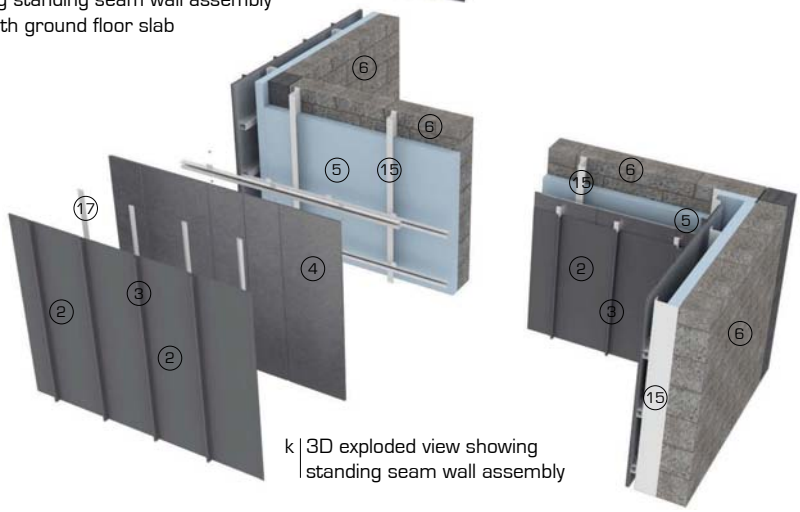


j | 3D view showing standing seam wall assembly and interface with ground floor slab

Details

1 | Cover strip profile
2 | Metal sheet
3 | Metal standing seam
4 | Breather membrane/vapour barrier
5 | Thermal insulation
6 | Blockwork backing wall
7 | Floor finish
8 | Drywall/dry lining
9 | Z-section steel fixing rails
10 | Floor slab
11 | Curved eaves profile
12 | Concealed gutter
13 | Exposed gutter
14 | Adjacent structural wall
15 | Cladding fixing frame
16 | Metal flashing
17 | Steel structure
18 | Standing seam clips





k | 3D exploded view showing standing seam wall assembly

System details

Vertically-set sheeting requires folded metal flashings at the top and bottom of the wall to form parapets and cills (1), as well as corners, usually made from flat sheet. Some manufacturers provide crimped flashings for corners in order to provide visual continuity between adjacent facades. Where flat sheet is used at corners, plastic or foam-based filler pieces form part of the system to close the gaps between the profiled sheet and the flat metal flashings that are usually set onto the face of the profiled sheet. The visual impact of these filler pieces needs to be assessed within the design. Horizontally-set sheeting can be formed as continuous cladding with barely visible joints resulting from lapping the sheets (3). Alternatively, the profiled sheet can be divided into bays, formed with vertical joints closed with cover strips or with recessed pressed (top hat) sections.

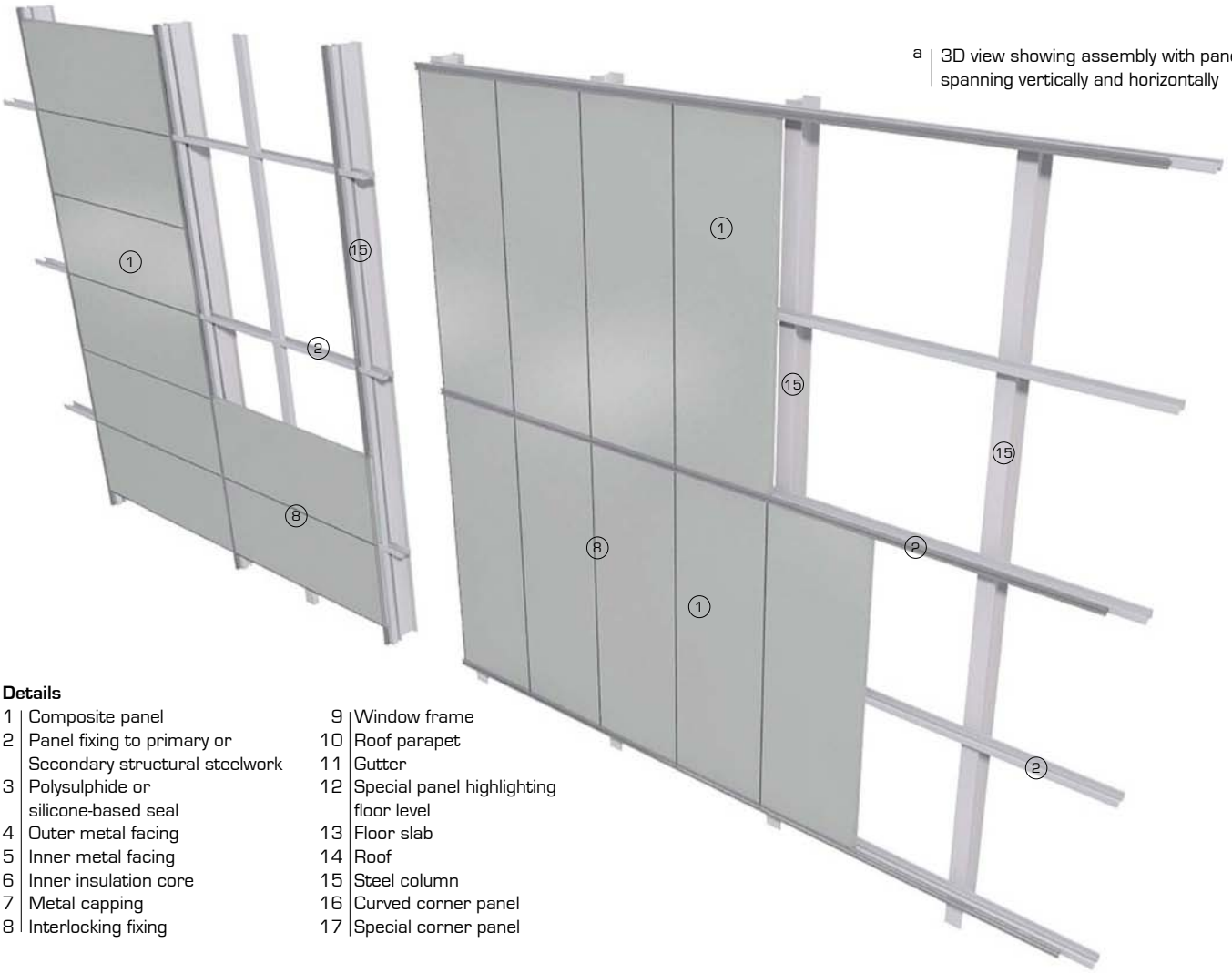
At roof level, parapets are formed with a pressed metal coping with another flashing beneath (h). A metal flashing is used to close the gap between the roof deck and the parapet upstand where the roof is also clad in profiled metal sheet. Where only a low upstand is required, as at the gable, a folded flashing is fixed to the roof surface to form a sealed edge. A metal coping flashing is then fixed to the upstand and is folded down the face of the external wall. Although the thermal insulation forming part of the wall construction is made continuous with that of the roof, the void in the parapet is usually filled with thermal insulation to avoid high temperature variations between the outside and inside of the construction (5).

The void behind the sheet is filled with thermal insulation which requires a vapour barrier on its internal (warm in winter) face (4). The internal lining of the wall can be in any material, though dry lining or an additional layer of profiled metal sheet is typical (8). Some manufacturers have proprietary lining sheets in metal which are flatter than the external profiled sheet to suit the typical requirements of internal finishes.

Openings for windows and doors are sealed with metal flashings that can be determined as much by visual requirements as by the needs of weatherproofing. Window openings often have wide cover strips around the edges of the opening to provide a full weather-tight seal which forms a highly visible part of the design.

Corners can be made from either externally set cover strips or by recessed corner flashings to suit the design. The recessed version requires careful installation of the cladding sheets on site in order to achieve the relatively narrow corner joint widths. Cover strips usually have their edge folded back to provide a crisp line around the profile. Folded flashings are usually in two parts, with an inner seal between cladding and window, and an additional outer flashing which is sealed with silicone back to the profiled metal.

Although proprietary systems are available, it is easy to adapt these systems where the facade fabricator makes flashings to suit individual requirements. Principles of details are well understood by fabricators and complete proprietary systems are not always required.



a | 3D view showing assembly with panels spanning vertically and horizontally

Details

1	Composite panel
2	Panel fixing to primary or Secondary structural steelwork
3	Polysulphide or silicone-based seal
4	Outer metal facing
5	Inner metal facing
6	Inner insulation core
7	Metal capping
8	Interlocking fixing
9	Window frame
10	Roof parapet
11	Gutter
12	Special panel highlighting floor level
13	Floor slab
14	Roof
15	Steel column
16	Curved corner panel
17	Special corner panel

System design

This material system provides a complete wall assembly in a single panel form, sometimes with integral windows and doors that interlock with the regular panels (a). Panels consist of an inner core of rigid thermal insulation (6) onto which a thin metal sheet is bonded to each side (4)(5), with a specially formed profile around the edges of the panel that forms a weathertight connection with adjacent panels (c). This material system is made as a complete proprietary system, each with varying levels of interchangeability and surface finish in relation to their cost. Their main visual advantage is the smoothness of the panel faces that form a complete system with integral panels for corners, parapets and window openings. Their main technical advantage is in providing a complete wall construction in a thin panel which is also highly thermally insulated. Panels are typically made in widths of 1100mm to 1400mm to suit the manufactured width of metal coil (7), but are long; up to around 15 metres, where transportation of the panels becomes a primary consideration of their size.

Panels typically have interlocking joints on two sides, forming an integral part of their fabrication, with panels being set either vertically or horizontally (8). Joints are typically formed to avoid a thermal bridge from inside to outside by creating a small break between inside and outside layers of metal, and are shaped to ensure that rainwater runs back out of the panel. Joints between panels at their short ends, where there is no interlocking joint, are butt jointed and sealed with cover strips. Panel systems are also used with interlocking joints on all four sides, and these are usually made in sizes that can easily integrate doors and windows which also form part of proprietary systems.

Vertically-set panels that interlock on two sides are usually storey height. Where panels are stacked over more than one storey, the horizontal joints between panels are usually sealed with metal flashings. Panels are supported on horizontal rails (2), typically at floor level to allow a floor-to-ceiling panel arrangement without intermediary structure that would be visible from inside the building. Horizontally-set panels that interlock on two sides are stacked one above the other, with tongue and groove horizontal joints which usually contrast visually with the vertical joints, which have wider sight lines in order to accommodate a metal cover strip, a rubber-based gasket, or a combination of them (b). Since vertically set panels are typically separated by the flashings, vertical joints can be discontinuous, allowing windows to be set in specific locations on a floor-by-floor basis, with each floor having its own arrangement of composite panels that is not aligned with those on the floor below. This has given rise to the use of mixed panels, set both vertically and horizontally, in a tiled arrangement rather than the exclusive use of the rectilinear grid seen until recently.

In four-sided interlocking panels, joints usually incorporate an inner chamber set between an inner and outer seal in order that the system



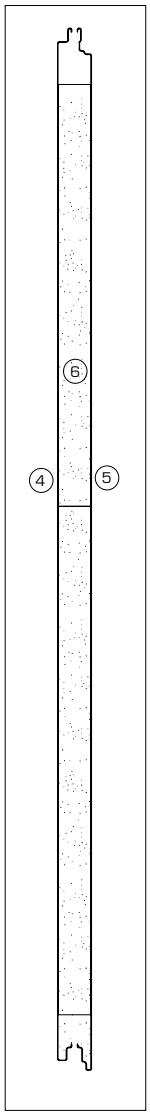
c | 3D detail view showing connection profile for vertical two-way interlocking profiled panels

b | 3D view showing composite panel with vertical capping and interlocking horizontal joints

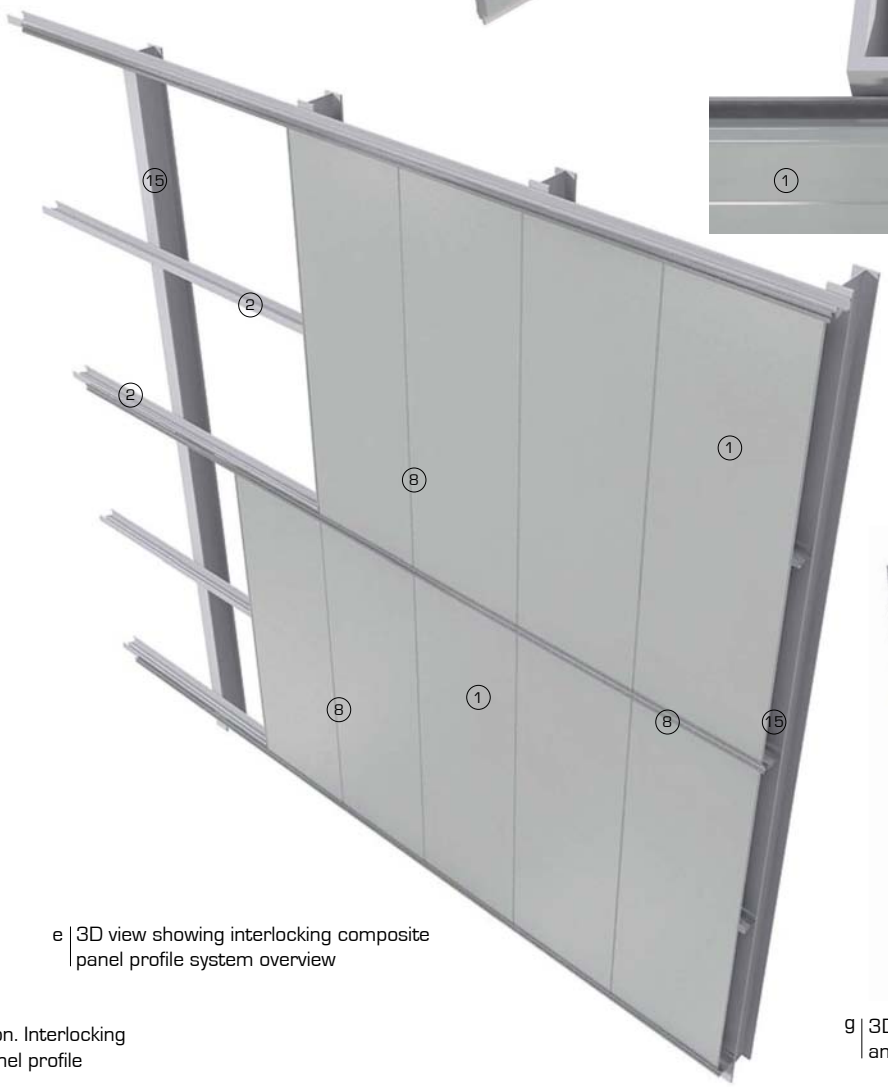




d | 3D detail view showing metal bracket and capping fixed to structural frame



f | Vertical section. Interlocking composite panel profile



e | 3D view showing interlocking composite panel profile system overview



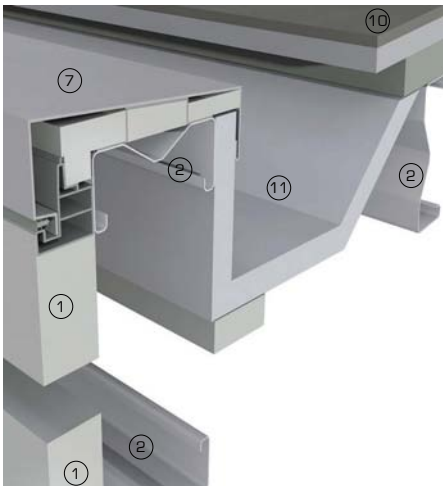
g | 3D detail view showing metal bracket and capping supporting panels

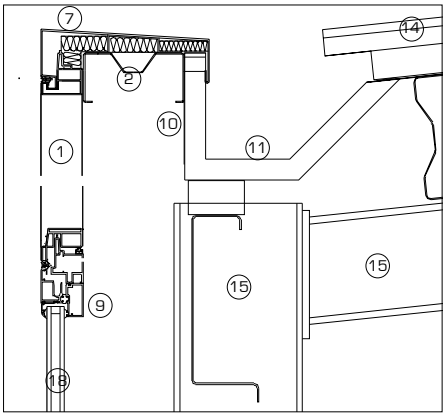


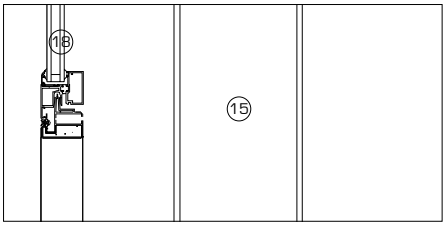
Details

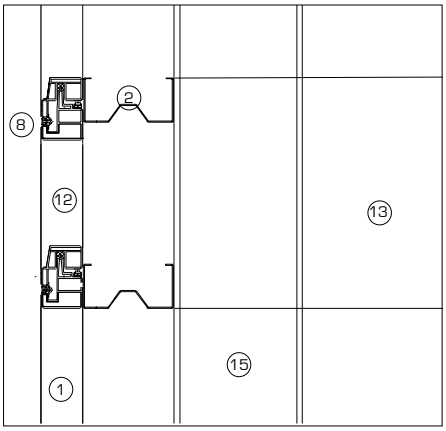
1 | Composite panel
2 | Panel fixing to primary or secondary structural steelwork
3 | Polysulphide or silicone-based seal
4 | Outer metal facing
5 | Inner metal facing
6 | Inner insulation core
7 | Metal capping
8 | Interlocking fixing
9 | Window frame
10 | Roof parapet
11 | Gutter
12 | Special panel highlighting floor level
13 | Floor slab
14 | Roof
15 | Steel column
16 | Curved corner panel
17 | Special corner panel
18 | Double glazing

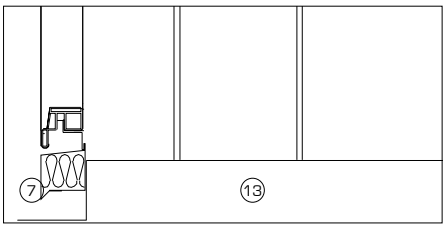
h | 3D views showing vertical section through typical wall system



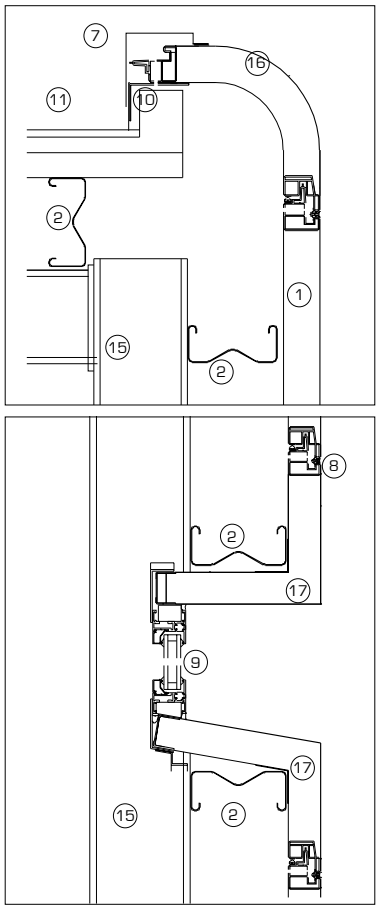




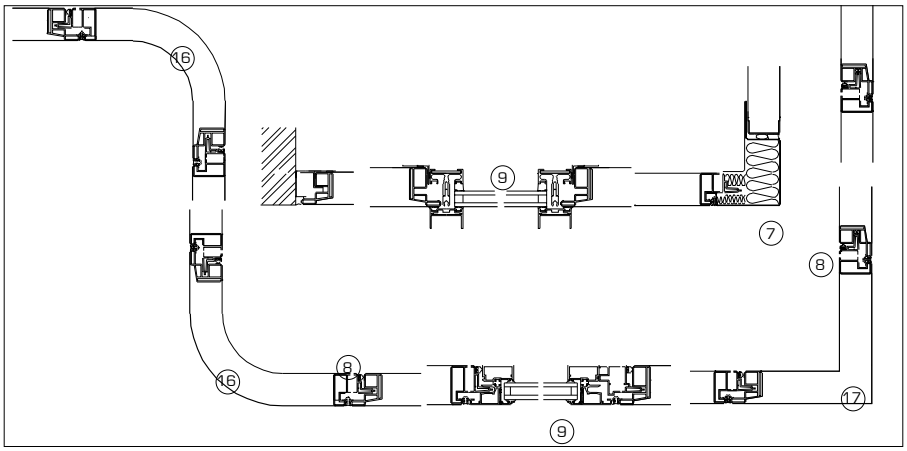




j | Vertical section 1:10. Wall build-up showing typical details



k | Vertical section 1:10. Corner details and special application panels



l | Horizontal section 1:10. Corner details and special application panels

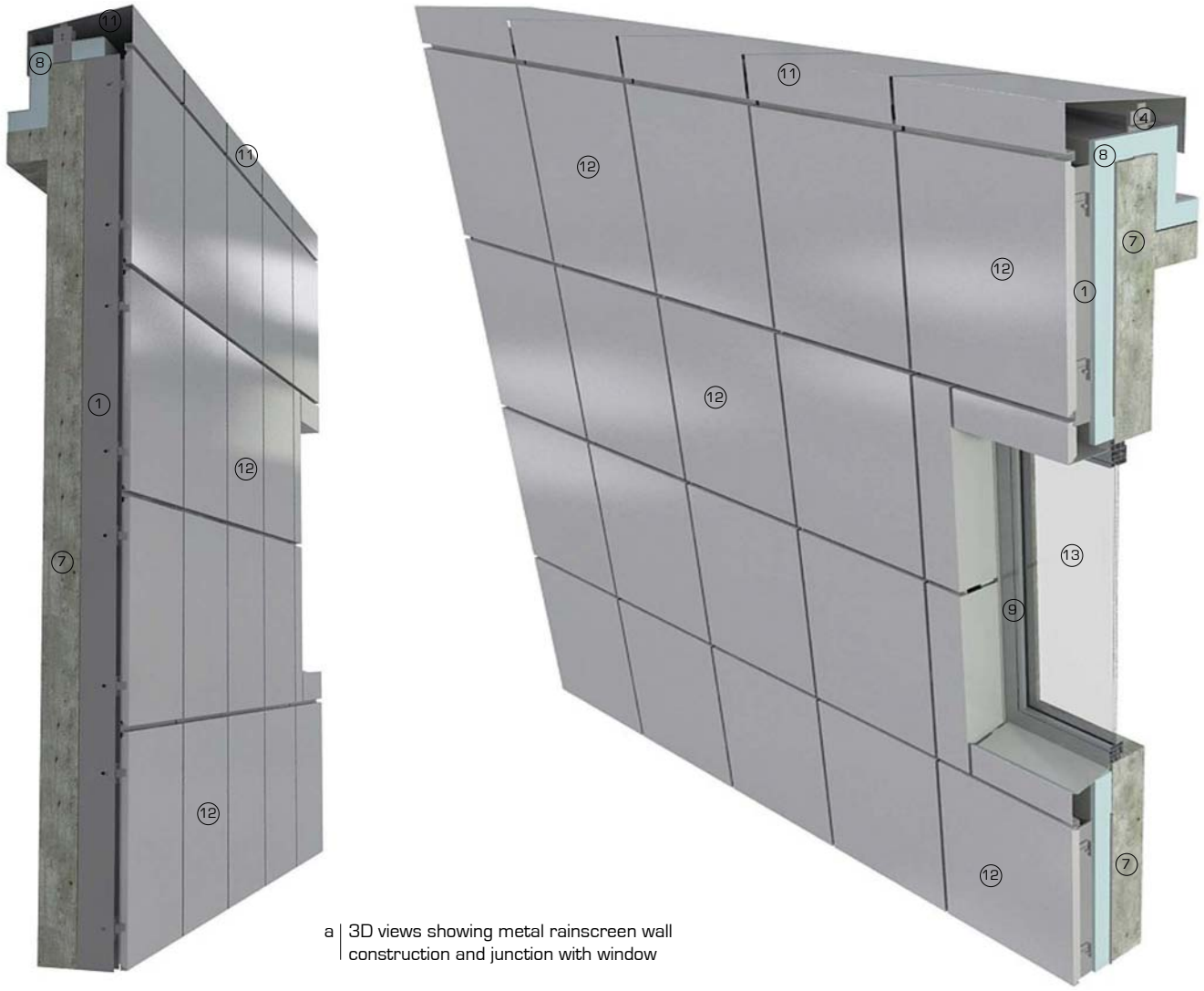


m | 3D view showing special corner panels

be internally drained and pressure equalised. Window and door frames interlock into the surrounding panels and are of a depth equal to that of the composite panels. Interlocking joints are usually made sufficiently rigid to allow two or three panels to be used at a storey height without a visible supporting structure. For both the vertical and horizontal orientation of panels, this material system requires a supporting metal frame, typically in mild steel but sometimes in aluminium. This frame is arranged in a way that will support the edges of the composite panels, and is fixed back to the primary structure of the building (k). The visual characteristics of the supporting frame are usually secondary as they are often concealed behind the interior finishes of the building. Where visible, they form an essential part of the material system, and are often formed from rectangular hollow sections.

System details

Both two-sided and four-sided interlocking panels have windows and doors as separate components which are coordinated with the material system to varying degrees, with four-sided interlocking systems being the more closely integrated. Windows and doors are fitted in a such a way so that they are either flush with the external face of the composite panels in order for the same panel to panel flashings to be used to seal the door/window, or alternatively windows/doors are recessed (h). In recessed window and door openings, flat metal panels are used to close the gap between the face of the composite panels and the window or door frame (9). Some manufacturers of composite panels offer special corner panels for window reveals which are also used at internal and external corners of the facade, and others have a range of preformed panels for cills, corners and parapet copings as part of their systems (m). This avoids the need for visible metal flashings which lap down over the face of adjacent composite panels to provide a lapped joint, and have a flatter, smoother appearance when compared to pressed metal flashing panels. A wider range of interface components is usually available on four-edge interlocking panels to add to the seamless clipped-together appearance of these systems. Parapets are typically formed with a pressed metal flashing (7) that folds down the face of the facade, but can also be created with a parapet panel which can be flat or curved to suit the design. Where a pressed metal flashing is used, a layer of thermal insulation is set beneath, with a vapour barrier on the internal (warm in winter) face of the insulation in order to provide continuity of insulation between wall and roof (j). Colour matching between metal flashing and composite panel is essential to the success of this method, unless a completely different colour is used for folded metal items. Four-edge interlocking systems allow the possibility of a thin parapet coping of around 100mm that forms a visual continuity with the panels beneath. Any water that penetrates the outer seal is drained away to the base of the wall within the drained and ventilated framing to the panels. Windows are often given the same colour and finish in order to provide a visual continuity between window frame and composite panel, giving the facade the visual crispness previously associated with fully glazed walls.

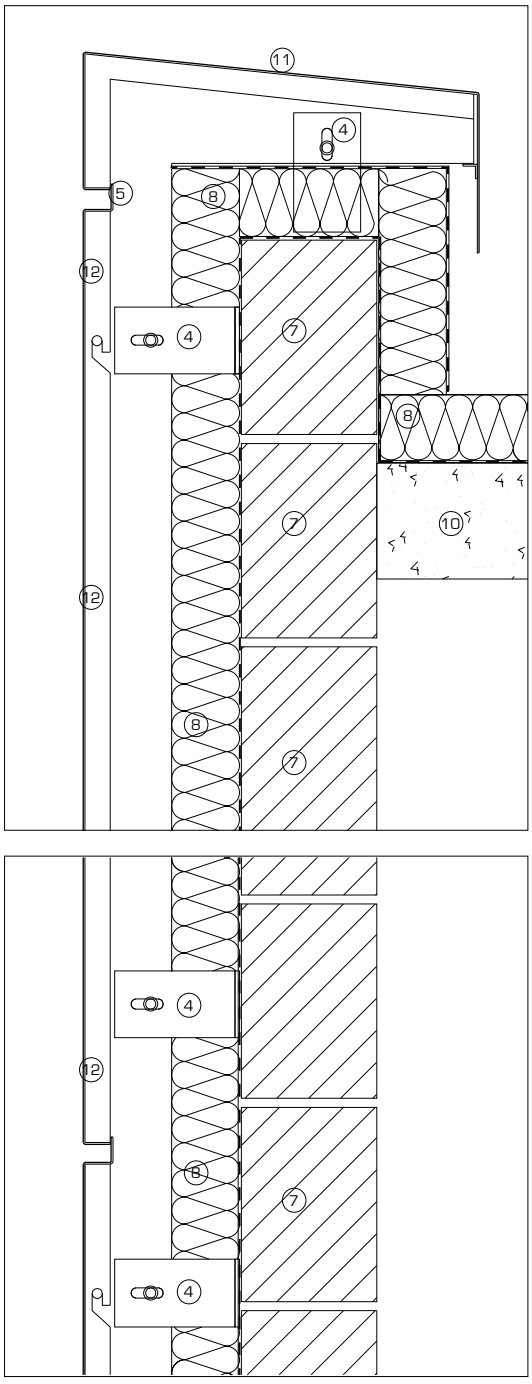


a | 3D views showing metal rainscreen wall construction and junction with window

This material system uses the rainscreen principle of allowing rainwater to pass through open joints, or partially open joints, where the water is drained away back to the outside of the building. Panels are set typically forward of a waterproofed and thermally insulated backing wall. Wind driven rain that passes through the outer open joints is drained away down the cavity between the back of the rainscreen panel and the outer face of the backing wall. The backing wall is typically of economic type as it is not visible if interior finishes are applied within the building. Metal rainscreen panels are typically given either a completely open joint with framing positioned in a way that conceals views into the joint, or have folded edges on the panel to close the joint visually, but not to seal it (a). Small amounts of rainwater that pass through the outer joint are drained away in the ventilated void behind. Visually, this material system provides visually crisp joints with strong shadow lines to the metal panels. The use of narrow joints between panels can give the metal panels a more monolithic appearance as the joints are less visible. Rainscreen panels can provide a flatness or consistency of texture across a facade that is independent of the backing wall behind. Most panels are internally fixed so as to avoid visible fixings. Face fixings on the metal sheet are usually not preferred since, at around 3mm thick, point fixings on a thin sheet can produce visible distortions across the panel surface. Panels are usually formed as trays or 'cassettes' with folded edges (12) that provide rigidity to the panel as well as a depth to the joint that both reduces rainwater penetration and obscures views into the void behind.

Most panels are fixed with either a hook-on fixing or with slotted grooves in the manner of composite metal panels that avoid the need for any visible fixings. With hook-on supports, panels have brackets that are fixed to the sides of the panels that form the tray (b). Panels are fixed onto vertical rails which are usually aligned with the joints where they serve as a screen to the void behind. Continuous rails are preferred to individual fixings, except in small-scale applications, since rails are much faster to fix than individual brackets.

Sizes of rainscreen panels are determined by available metal sheet sizes. Metal coil is supplied typically in 1200mm and 1500mm widths, with metal plate in greater widths and in varying lengths. Metal-faced composite materials are also used, comprising either a thin metal sheet, such as aluminium, bonded to both sides of a rigid plastic core, or alternatively a single sheet of metal bonded to one side of a honeycomb panel. Composite materials that use a thin (3-5mm thick) inner plastic-based core can be folded to form trays, but honeycomb panels require either an edge strip to conceal the joints, or are set close enough together for the inner core not to be visible. An alternative method of fixing panels is to form a folded tongue and groove joint on the long edges of the panel where panels slot together. An advantage of this method is that the support framing behind can be simplified with vertically-set or horizontally-set rails to suit the pressed metal panels where concealed fixings can be used.



b | Vertical section 1:10. Parapet showing typical details

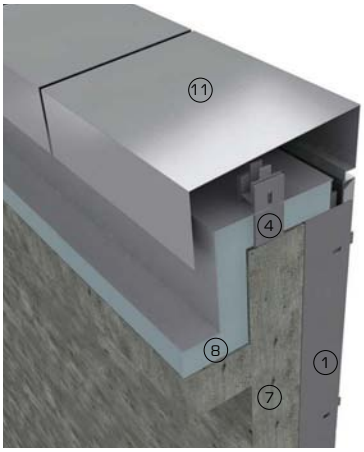


c | 3D detail views showing window and parapet detail in rainscreen wall system



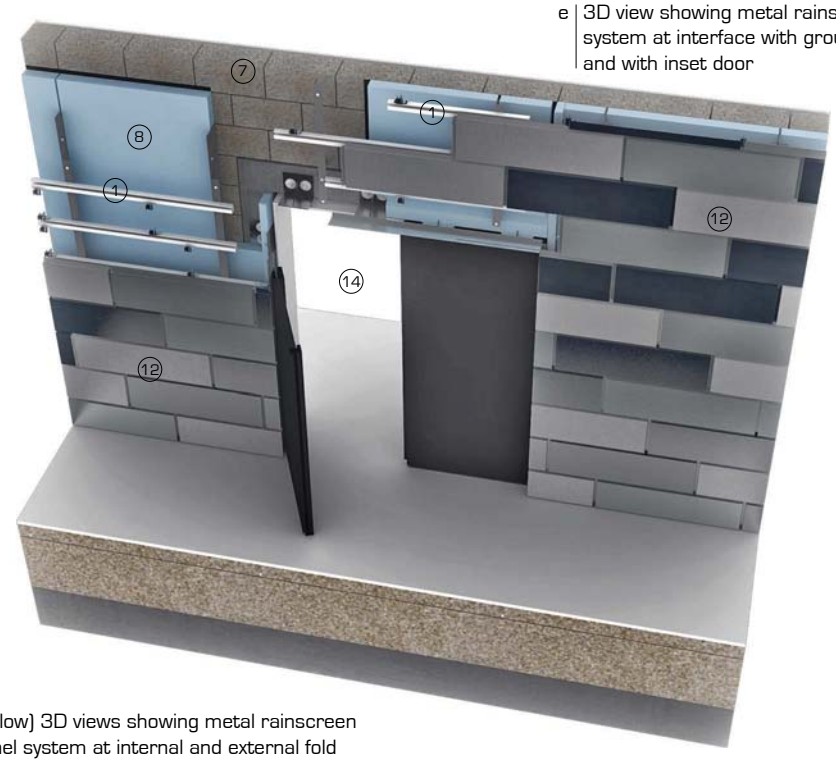
Details

1 | Metal support frame
2 | Stainless steel mesh
3 | Stainless steel spring
4 | Metal fixing bracket
5 | Fixing bolt
6 | Framed perforated metal sheet
7 | Backing wall
8 | Insulation
9 | Window frame
10 | Floor slab
11 | Pressed metal parapet coping
12 | Metal rainscreen cladding panel
13 | Double glazing

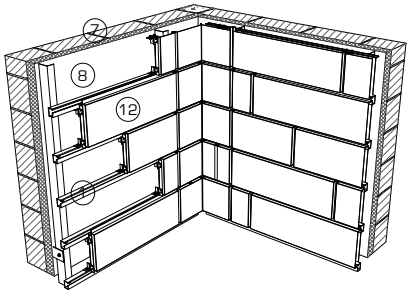


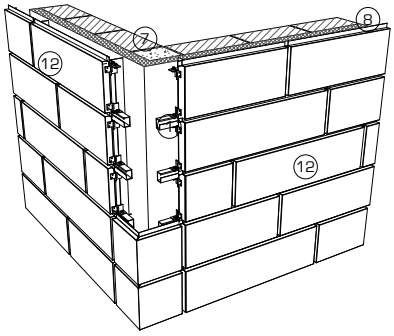
d | 3D detail view showing typical parapet details

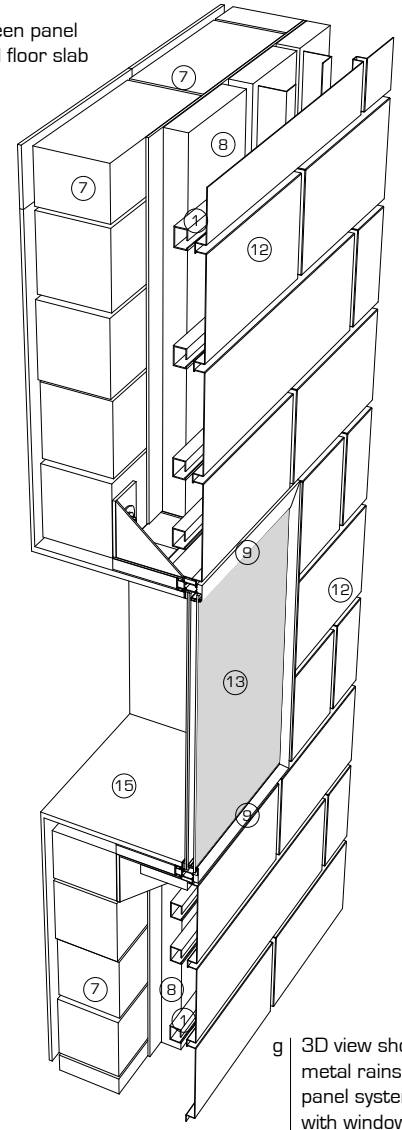
e | 3D view showing metal rainscreen panel system at interface with ground floor slab and with inset door



f | (Below) 3D views showing metal rainscreen panel system at internal and external fold in facade







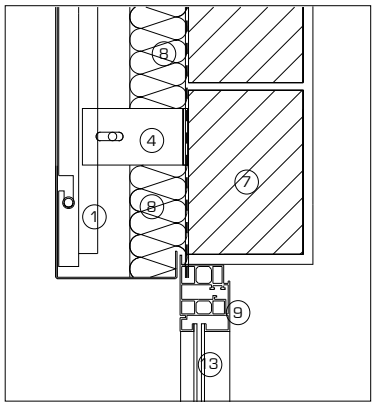
g | 3D view showing metal rainscreen panel system with window opening

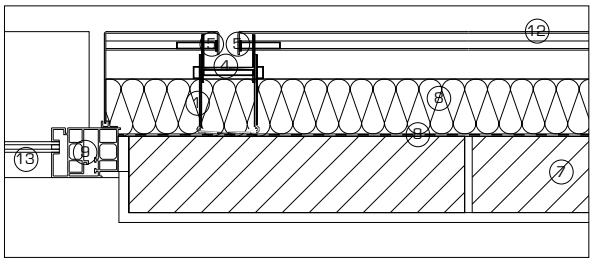
System details

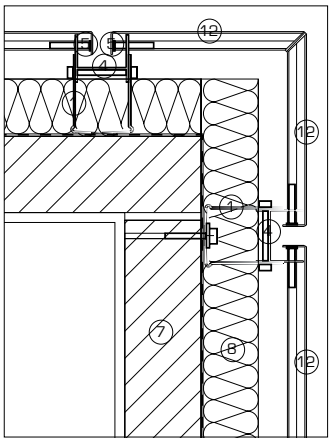
An essential aspect in the design of metal rainscreen systems is the layout and fixing of the framing that supports the rainscreen cladding (e). Although panels can be set out independently of the backing wall behind, which is one of their primary advantages, the need to fix panels economically makes it essential to engage with the idea of their fixing during the detailed design stage. This is of particular importance where rainscreen panels are set out to coordinate visually with window openings (g). The open-jointed nature of the rainscreen panels allows the junction with windows to be straightforward and visually driven, as windows and doors are sealed to the backing wall with which they form a continuity. At facade corners, panels are formed typically either from folded sheet or thin composite sheet, or alternatively with mitred panels that meet at the corner, particularly where honeycomb panels are used. Internal corners are formed in the same way, but their geometry allows panels to meet without any special panels with two panels butting up to one another (f). The corner condition is an important junction, from a visual point of view, as the thin nature of rainscreen panels can be either exposed or concealed at this point. Butting panels together with an open joint on the corner can make it difficult to create a visually sharp edge to the facade (j), with any imperfections in the setting out of panels being apparent.

Parapets are formed in a similar way to corners, with panels fabricated to suit particular project conditions as a part of manufactured systems. Since the coping is sealed between panels on its horizontal face to avoid rainwater falling directly through the joint between panels, the joint is often recessed to match with the open joint on its external vertical face. The coping usually has a little gap between the coping panel and the inner face of the parapet upstand in order to ventilate the cavity where the joints between the facade panels do not admit sufficient air for ventilation (j).

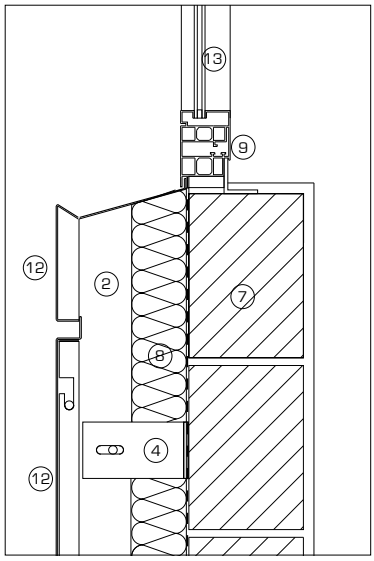
Because windows in openings are sealed directly against the waterproof layer of the backing wall, the visual treatment of the junction of panel and window requires attention during design to avoid an uncoordinated alignment. The rainscreen panels are terminated adjacent to the window in order to conceal the seal between window and backing wall (m). In order to avoid staining from dust and dirt, cills are usually formed in a way that directs rainwater to the sides of the opening and down joints between panels rather than directly down the face of the panels below. Drips at ground level are formed as pressed metal flashings, with the gap between the panels and the backing wall being closed with metal mesh that allows the passage of air for ventilation but avoids the ingress of insects into the ventilated void. Although manufacturers offer metal rainscreen panel systems, their design can be modified to suit individual projects and fabricated economically.







n | Horizontal section 1:10. Typical details through wall and junction with window



h | Vertical section 1:10. Typical window details



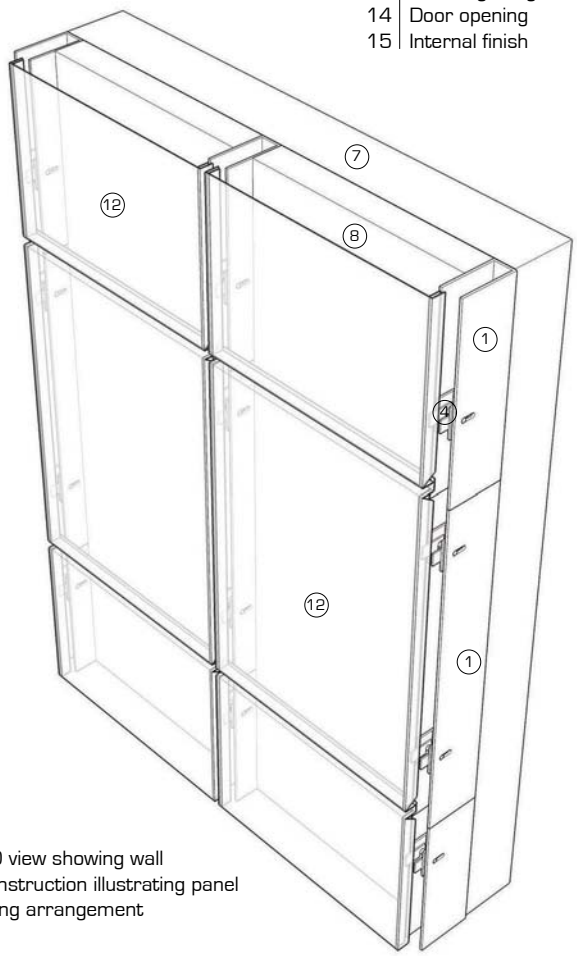
k | 3D view showing basic rainscreen panel system

Details

1	Metal support frame
2	Stainless steel mesh
3	Stainless steel spring
4	Metal fixing bracket
5	Fixing bolt
6	Framed perforated metal sheet
7	Backing wall
8	Insulation
9	Window frame
10	Floor slab
11	Pressed metal parapet coping
12	Metal rainscreen cladding panel
13	Double glazing
14	Door opening
15	Internal finish



j | 3D view showing basic rainscreen panel system at window opening



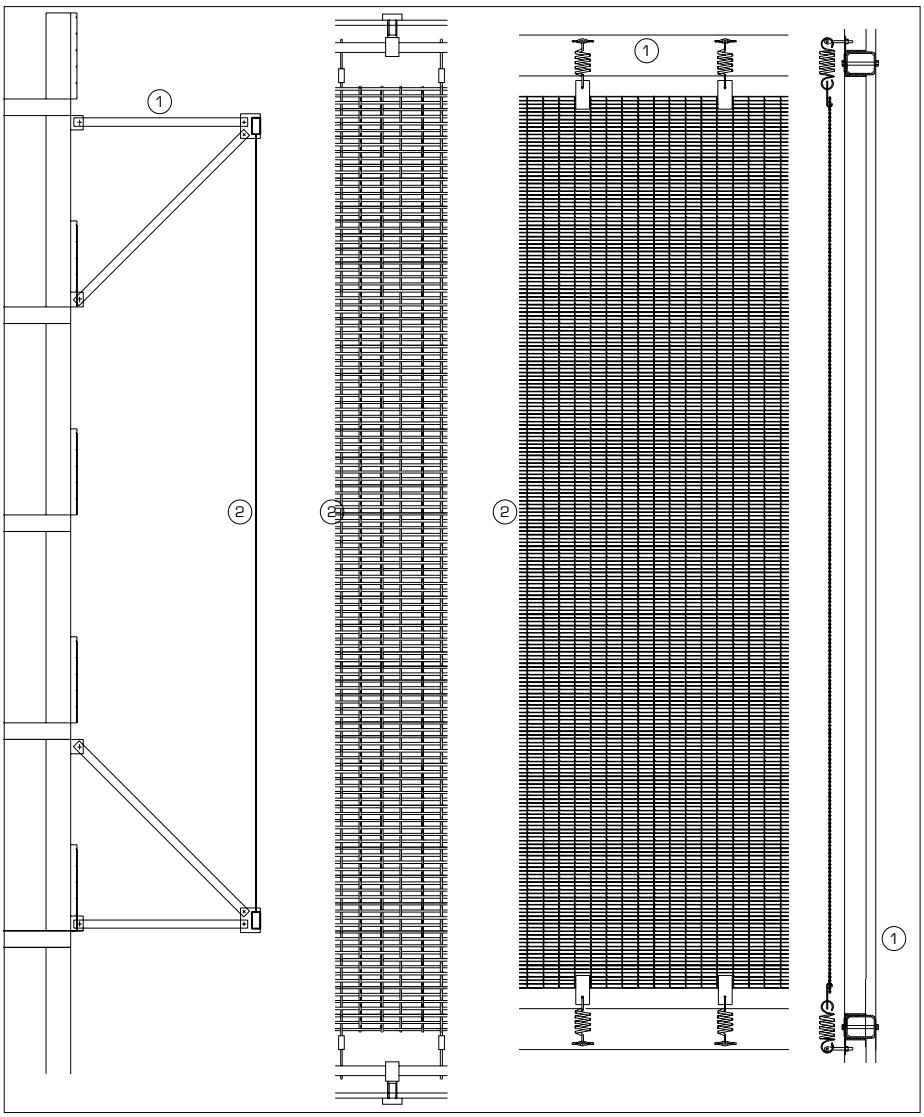
m | 3D view showing wall construction illustrating panel fixing arrangement



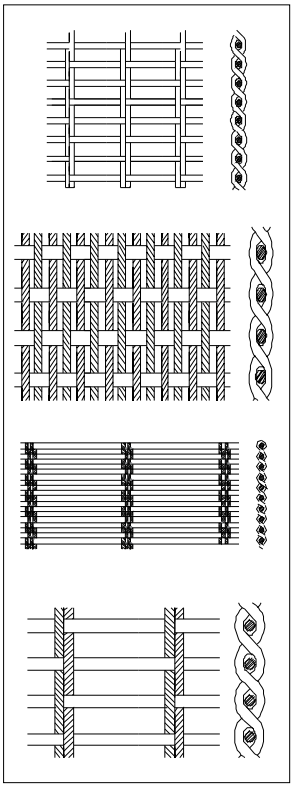




b | 3D views showing various mesh screens



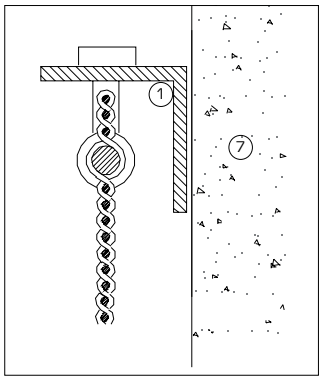
a | Elevation and vertical section 1:25. Typical screen arrangement



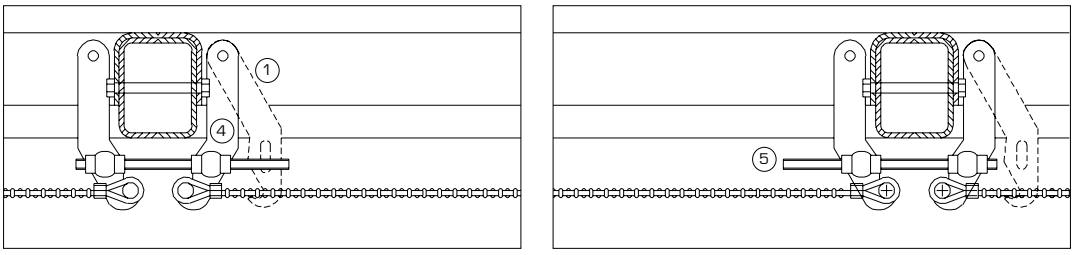
c | Examples of mesh weave patterns

Details

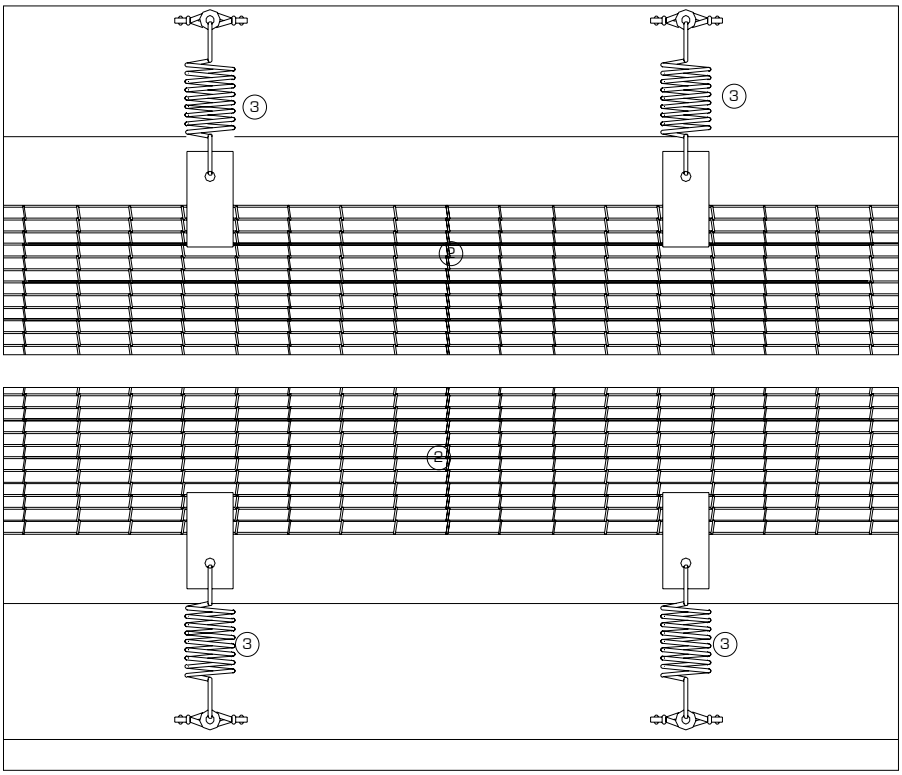
1 | Metal support frame
2 | Stainless steel mesh
3 | Stainless steel spring
4 | Metal fixing bracket
5 | Fixing bolt
6 | Framed perforated metal sheet
7 | Backing wall
8 | Insulation
9 | Window frame
10 | Floor slab
11 | Pressed metal parapet coping



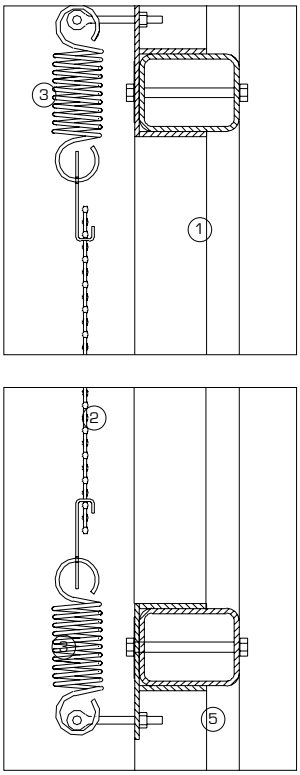
d | Vertical section 1:2. Woven mesh fixed to wall



e | Horizontal section 1:2



f | Elevation 1:2



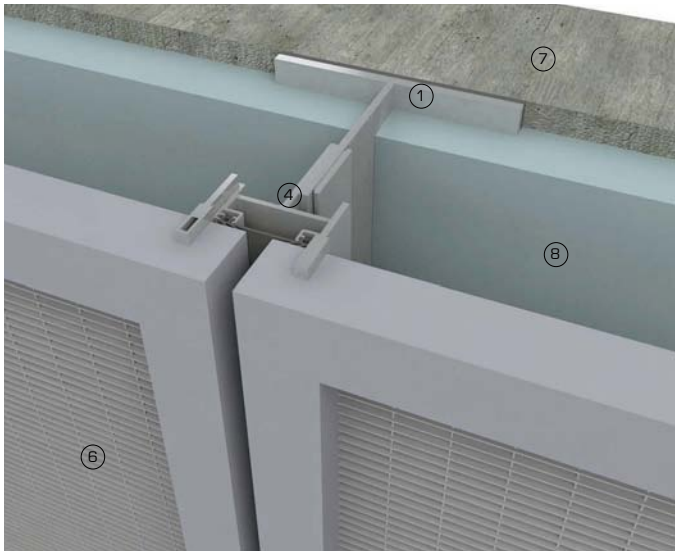
g | Vertical section 1:2

System design

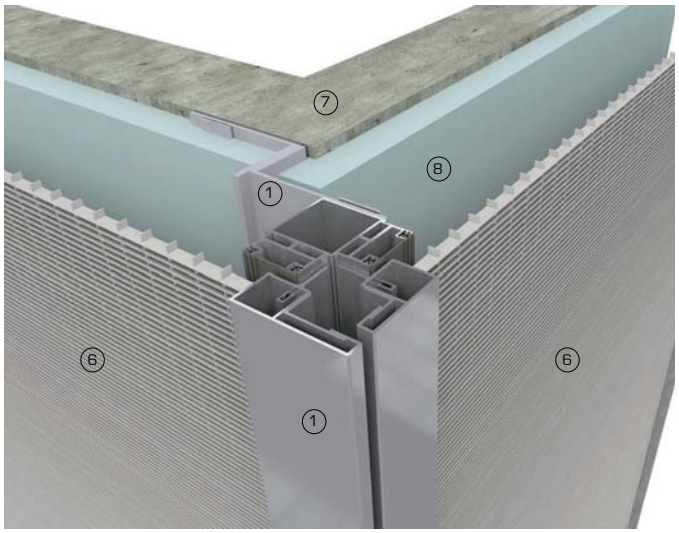
Metal mesh in facades has been developed as a material system from the early 1990s with the introduction of woven stainless steel and woven copper to provide lightweight screens, typically as screens (b). From its origins in industrial applications, such as woven metal conveyor belts, stainless steel mesh is used in facades for a variety of functions: solar shading to glass walls, guarding to full height balustrades, and as visual screen to backing walls. Woven stainless steel has cables set in one direction, which can be tensioned at points or along its edges to provide a rigid, lightweight screen that has little visible supporting structure, while metal rods set perpendicular to the direction of the cables provide rigidity in one direction (c). Stainless steel is preferred to mild steel for its greater durability and resistance to corrosion. Copper and bronze are being introduced, but the lower tensile strength of these materials currently limits their use to smaller-scale applications. Because the cables require tensioning, their supporting structure can be visually prominent (a), which has led to a greater interest in using more rigid meshes made from rod woven in both directions, where the material is set into a frame at its edges (b). Consequently, there are three generic types of varying rigidity: rigid mesh, mesh flexible in one direction and fully flexible mesh.

Rigid mesh is made from rods which are woven in two directions that can use very similar patterns to those where cable is used in one direction. The material is made in relatively small panels of around 1800mm x 1500mm, and is fixed by clamping the materials into a continuous edge frame or by point fixing, since the material cannot be tensioned. The diameter of the rod is typically around 2mm, set into a grid of 6mm x 2mm. Mesh sheets are joined to form a continuous wall of mesh panels where the grid of the frame can dominate visually. Because no cable is used, the material can be colour-coated or etched to create specific visual effects. Where aluminium is used (not as rigid as stainless steel), the material can be anodised in addition to these finishes, though panels are made from either greater diameter rods or smaller panel sizes.

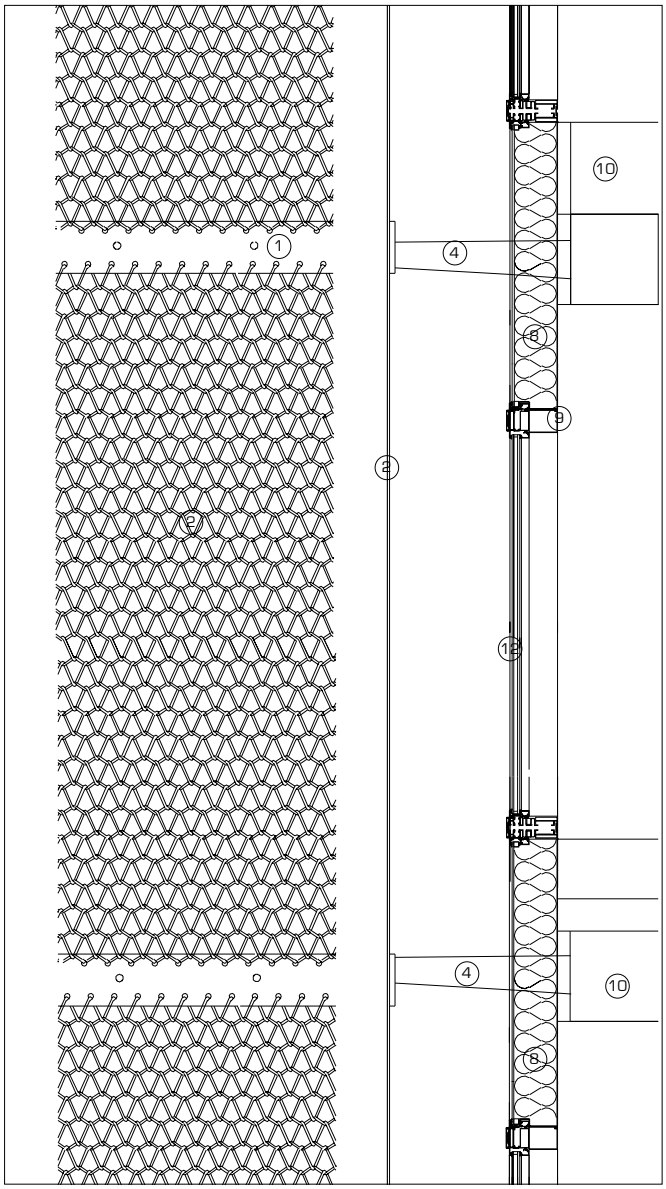
Mesh which is flexible in one direction is sometimes woven in groups of cable running the length of the material, with thin rods woven into these cables in the opposite direction across the width of the material, creating a visually textured surface. The material is manufactured in long lengths, allowing it to be used as a continuous facade 'wrapping' material, either tensioned horizontally across the facade or hung from top to bottom (f). Meshes are typically hung to reduce the sagging that can occur when used horizontally, but cables are beginning to be set at different angles, even 45° from the vertical direction. These meshes are usually made in widths up to around 7500mm, but they require restraint at close centres if used as guarding as their deflections can be high. A wide variety of weave pattern is used to suit different amounts of transparency, rigidity and weave. Light transmissions range from 25% to 65%, making them very suitable for solar shading where a specific percentage of shading is required. Light transmission can be reduced



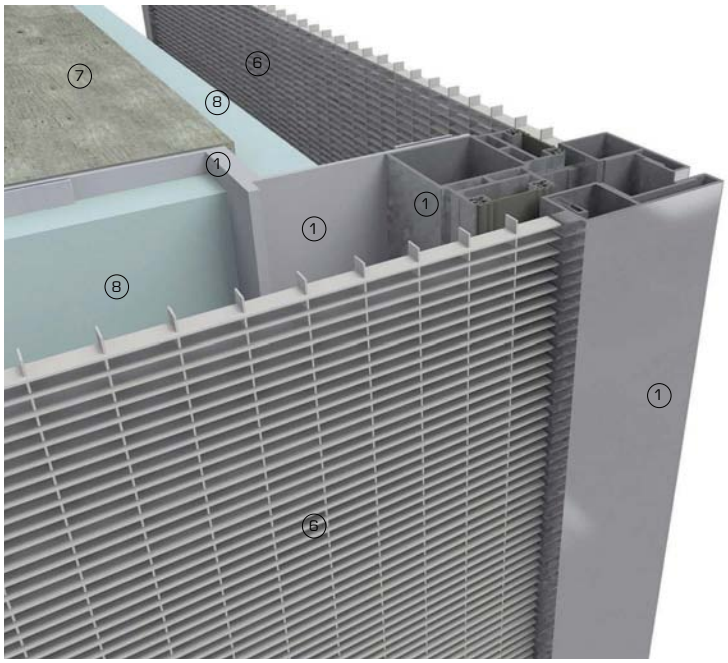
h | 3D detail view showing panel junction of perforated metal screen



j | 3D detail view showing external corner of perforated metal screen



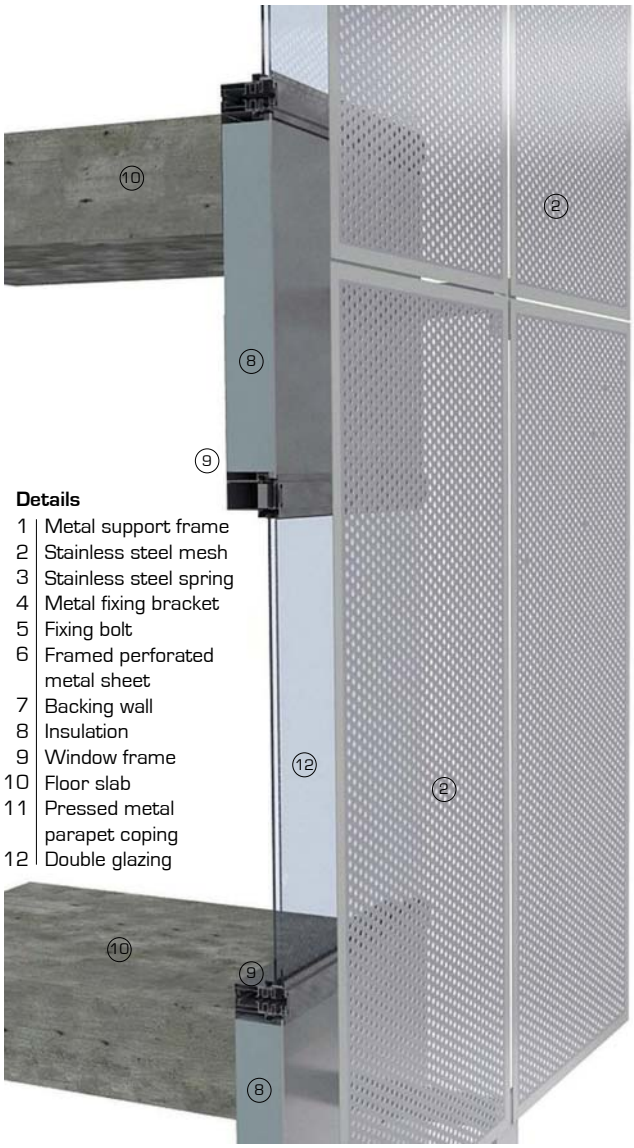
k | Vertical section and elevation 1:25. Mesh flexible in one direction fixed to brackets supported on adjacent wall



l | 3D detail view showing external corner of perforated metal screen



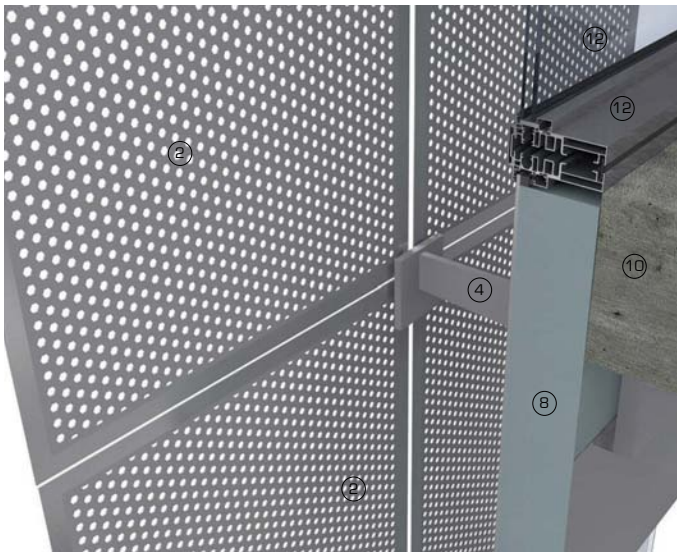
m | 3D detail view showing mesh panel in front of curtain wall glazing



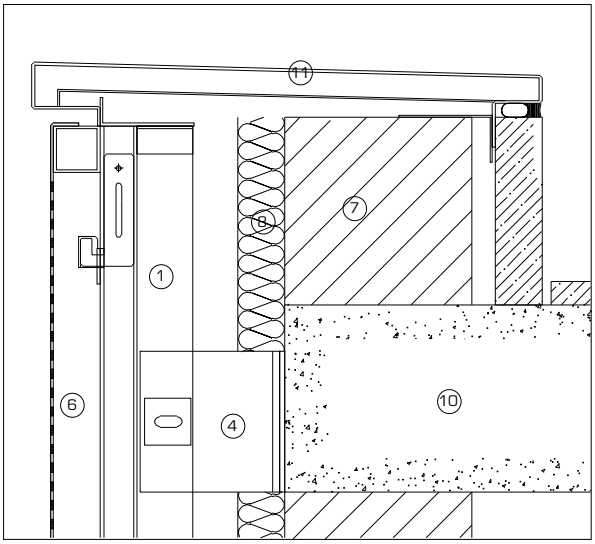
Details

1	Metal support frame
2	Stainless steel mesh
3	Stainless steel spring
4	Metal fixing bracket
5	Fixing bolt
6	Framed perforated metal sheet
7	Backing wall
8	Insulation
9	Window frame
10	Floor slab
11	Pressed metal parapet coping
12	Double glazing

n | 3D detail view showing mesh panel in front of curtain wall glazing



p | 3D detail view showing mesh panel in front of curtain wall glazing



q | Vertical section 1:10. Parapet of perforated metal screen

by reducing the distance between cables, between rods, or a combination of both, depending on the visual effect required. Cable thicknesses vary from 2mm to 6mm, with rod diameters ranging from around 2mm to 4mm. Weave patterns can be as dense as 4mm x 10mm for low light transmission to 4mm x 10mm for high light transmission. Meshes can also incorporate a varying weave within a single length of material to suit varying light transmission requirements.

Fully flexible mesh is less commonly used in facades, but has a visually rich appearance as a result of its non-rectilinear open weave (k). Metal widths range from around 1800mm to 2400mm and are manufactured in long lengths. More open weave versions are available, which resemble thin cable woven in two directions. These are manufactured in widths of around 6000mm, requiring restraint at around 1500mm centres. The material is held in place by tensioning the material in two directions, typically in an edge frame, but where panels can be as wide as the material as manufactured, subject to its deflections being within the limits of its prescribed use.

System details

Where rigid mesh is fixed into a frame around its edge, the material is usually clamped between flat bars, or angles of the same material (p). The plates are clamped with bolts, which can be countersunk to avoid highly visible fixing bolts. The frames are then fixed back to the facade on support brackets. An alternative edge frame uses a C-shaped folded section into which the rigid mesh is fixed (h). Rigid mesh can be curved in either one direction or two directions to give a highly modelled surface. The form of the curves is typically influenced by its supporting structure, which needs to be a balanced blend of structure and mesh to avoid the supporting structure from becoming visually dominant.

Mesh which is flexible in one direction avoids the need for a highly visible supporting frame, but typically requires substantial mild steel brackets projecting from the facade that can absorb the tension in the cables at each end (k). Panels can be set side by side to create a continuous texture of material across a facade, which is one of its preferred visual characteristics (n). Whether the material is set vertically or horizontally, a similar variety of support methods can be used at the ends of the cable. Cables can be turned over a continuous rod at its ends to form a loop, with the rod being supported on individual brackets to suit the design rather than being aligned with each cable. Alternatively, the continuous rod can be woven into the mesh, usually during manufacture, with the rod being supported in the same way.

Details

1 | Extruded aluminium frame
2 | Curtain wall carrier system
3 | Extruded aluminium louvre blades
4 | Floor slab



a | 3D view showing metal louvre screen in front of curtain wall system

System design

Metal louvres are used typically in facades either to provide weather resistance to the ends of ducts for mechanical equipment or as acoustic screens (a). Glass blade louvres with metal frames are used to provide ventilation to daylit spaces such as semi-open circulation spaces where high levels of thermal insulation are not required. The orientation of metal louvres is as much a visual consideration as one of technical performance, with the blades used to conceal views through as well as to allow the free passage of air through the panel (b). For this reason, metal louvre blades can be set either vertically or horizontally with an orientation that avoids views through the blades. At ground/street level, horizontal blades usually conceal views through the void behind, but above ground floor level, the 45° orientation of the blades allows views through unless an additional bank of blades is added, which both improves weather protection and conceals views through the panel. Vertically set blades provide a screen that conceals views through when seen at an oblique angle, but allows views through a small part of the facade when directly facing the facade. Deeper vertically-set blades increase the screening effect for views at close proximity to the louvres. Where more than a single row of inclined blades is needed in horizontally-set louvres, typically to improve their weather resistance, rainwater is drained by forming a groove along the bottom edge of each blade to drain away water through the sides of the louvre frame, then down the base of the frame and back to the outside (c). The perimeter of the frame is sealed against the surrounding waterproofed wall, where a different material is used for the surrounding area of facade.

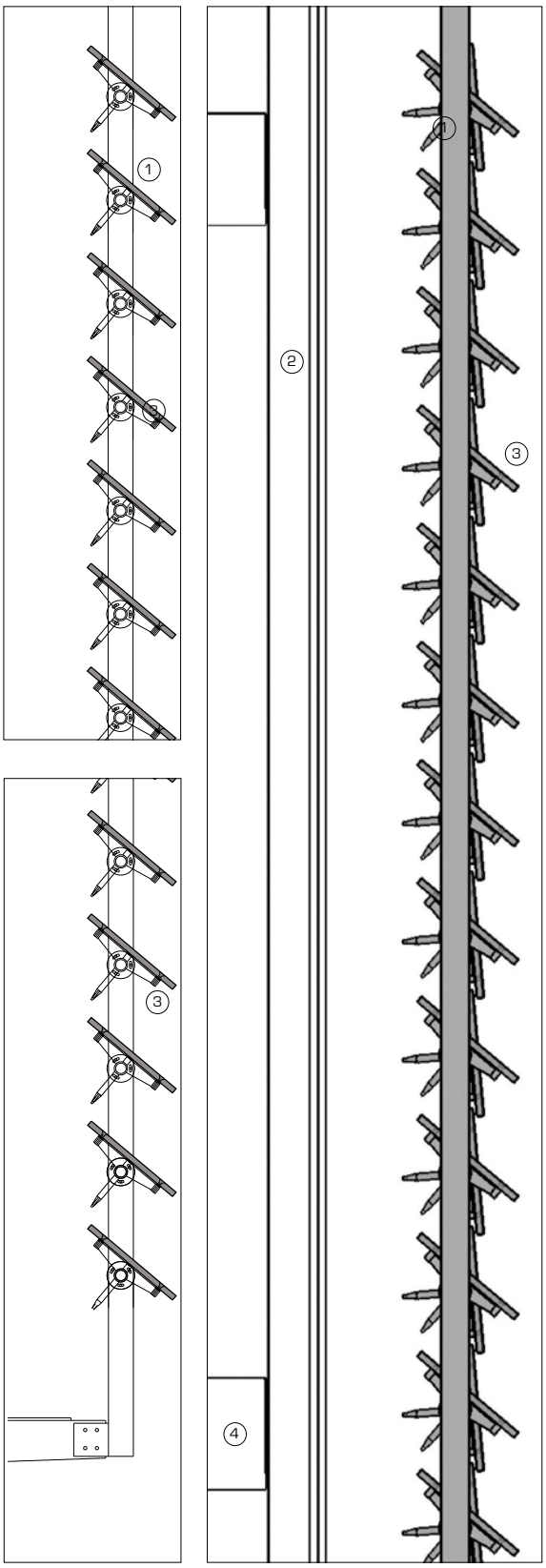
Where metal louvres are set into a curtain walling system, blades are placed in a perimeter frame to form a complete panel which is then fixed into curtain walling framing in the same manner as a glazed unit or metal panel would be fixed (d). This is particularly useful where a glazed wall has a few louvre panels that form part of the facade. The louvres can be introduced without the need for changing the system to accommodate the louvres, simplifying the interfaces between glass/metal units and the open louvre panels. Water that penetrates the glazing system is drained away through the drained and ventilated cavity of the curtain walling system. Metal louvre blades are usually made from extruded aluminium or mild steel. Aluminium is typically polyester powder coated, while mild steel is galvanised and painted. The use of aluminium provides precisely formed sections that can both encourage the passage of air through the panel and minimise rainwater penetration. The blades are fixed into a perimeter frame also formed from extrusions or angle sections to suit the frame size and method of drainage. Mild steel is often used where greater resistance to accidental damage is needed, as the material better withstands the effects of local impacts than aluminium, and can also be accommodated within curtain walling systems.



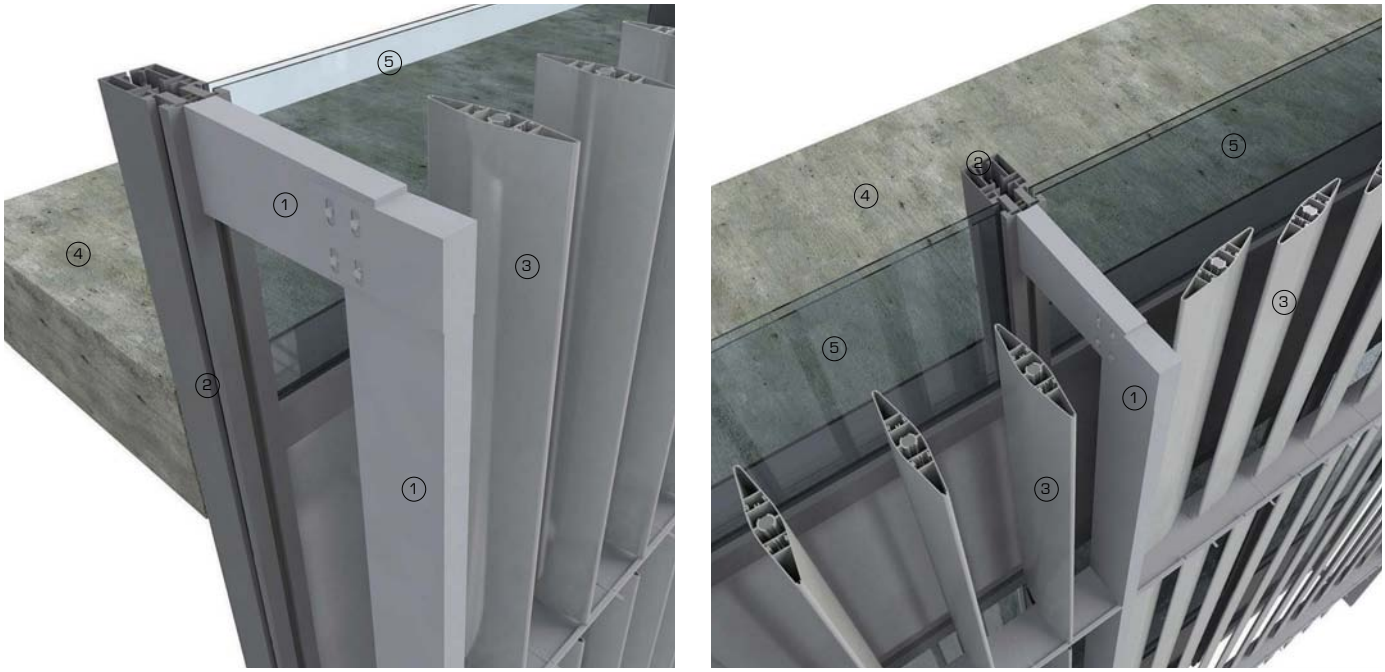
b | 3D detail views showing louvre panel fixing details



c | 3D view showing metal louvre screen in front of curtain wall system



d | Vertical section 1:25. Metal louvre system and fixing elements



e | 3D detail views showing profiled aluminium louvres and fixing system



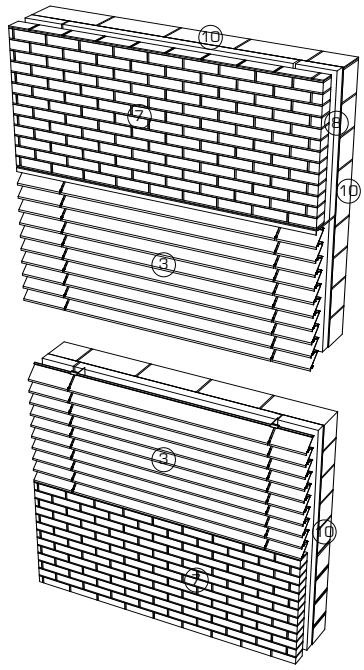
f | 3D view showing profiled aluminium louvres and fixing system overview



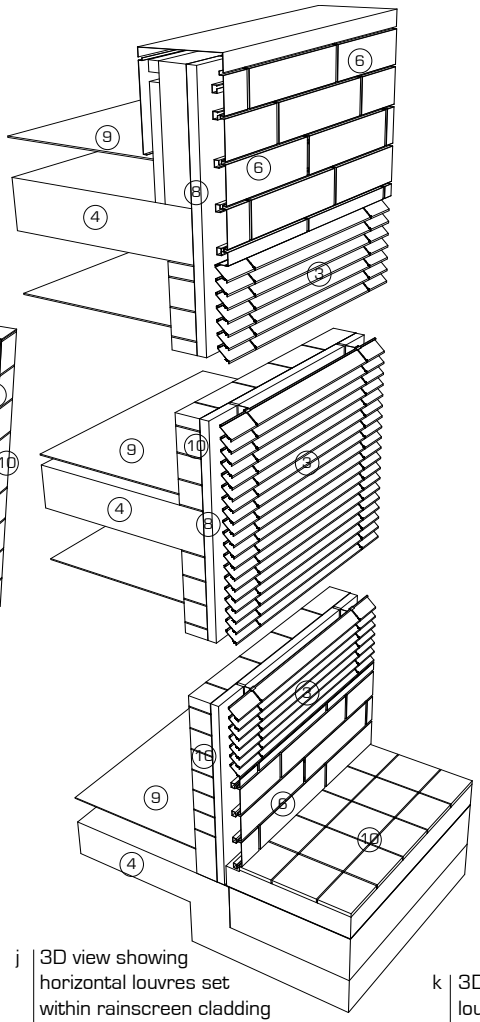
g | 3D detail views showing profiled aluminium louvres and fixing system

Details

1 | Extruded aluminium frame
2 | Curtain wall carrier system
3 | Extruded aluminium louvre blades
4 | Floor slab
5 | Glazing
6 | Masonry rainscreen cladding
7 | Brickwork outer leaf
8 | Thermal insulation
9 | Floor finish
10 | Blockwork backing wall



h | 3D view showing horizontal louvres set within loadbearing masonry facade system



j | 3D view showing horizontal louvres set within rainscreen cladding facade system



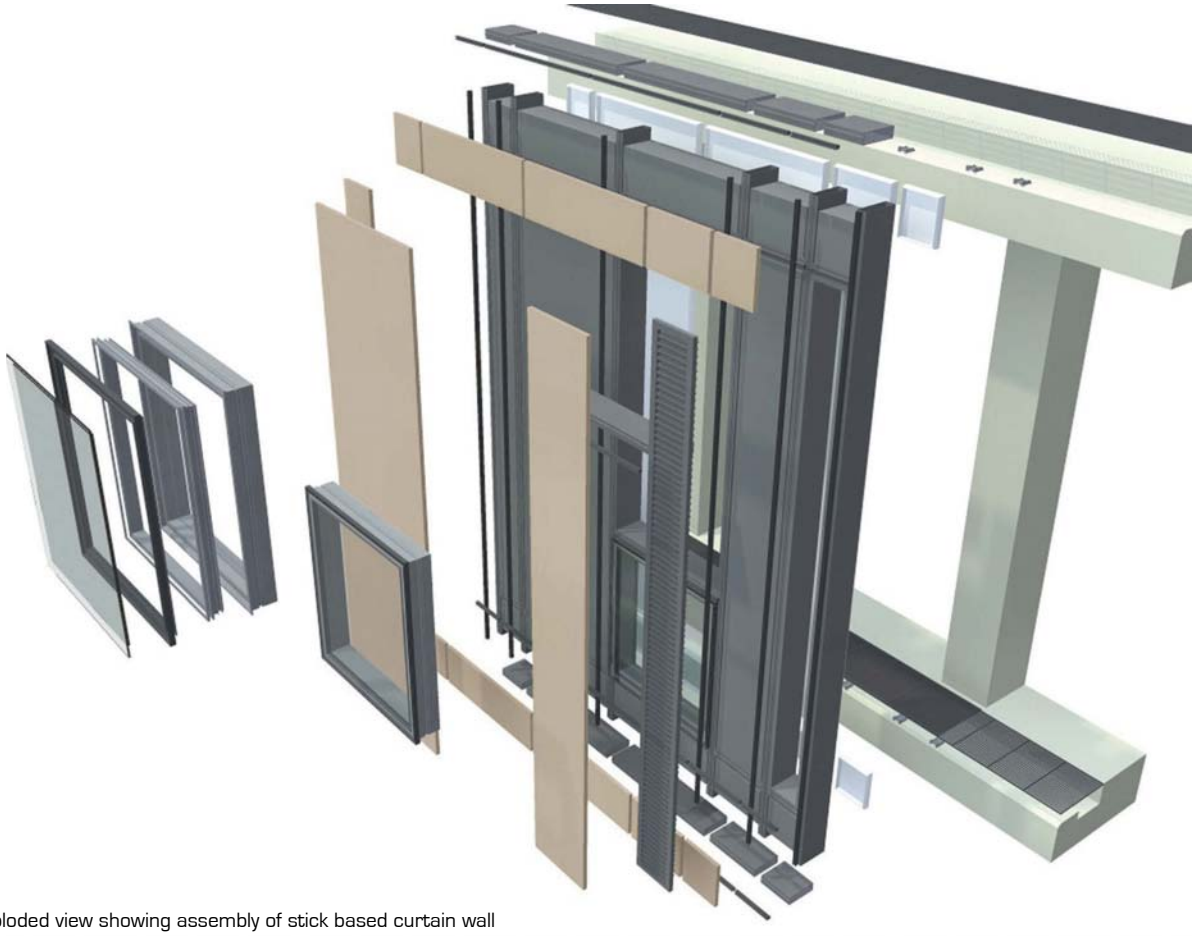
k | 3D view showing horizontal louvres set within rainscreen cladding facade system

System details

Metal louvre panels are made in widths of 1500mm to around 3000mm to suit the facades into which they are set. Individual blades are supported by vertical or horizontal framing members along the length of the blades in order to provide the required stiffness in addition to the perimeter frame required for each panel (e). Because of the required technical performance and visual criteria required of louvres, they are made as proprietary systems which are adapted to the requirements of individual projects. Doors in louvre panels are usually formed in a similar way to fixed panels to avoid them being highly visible, but usually have larger frames to provide the required door panel stiffness.

Metal louvres are also used for solar shading as part of double skin facades, typically set 750mm to 1000mm in front of a glazed outer wall (f). This application of metal louvres has led to them being required in much larger sizes, set vertically or horizontally to suit the incident sun angles for which shading is provided. Since aluminium is extruded economically in widths of up to around 300mm, depending on the profile design, metal louvres used for solar shading are often made in combinations of curved sheet and extrusions linked together to form a complete shape (e). The resulting forms of these blades are also finding an application as regular louvre blades in facades (j) where the increase in scale makes them a more integrated part of the language of metal panel facade design (k). Larger scale louvre panels allow them to be used as both fixed or adjustable types on a single facade, where the louvres are a less visually obvious part of the design. Mechanisms for moving louvres typically comprise pivots set on top and bottom with a sliding arm at the bottom, to which the blades are connected to provide louvre movement (g). These can be hand or electrically operated. Aerofoil-type sections can span up to around 3000mm.

Glass louvre blades are held by metal clips, usually made in cast or extruded aluminium, that provide structural support to the blades. Clips are linked to rods that form part of the supporting frame to the louvres. The rods move up and down, allowing the louvre blades to be moved to opened and closed positions to suit both ventilation and solar shading requirements. Movement of the blades is controlled either manually with a winding mechanism, or electrically, with louvres operated in groups of panels. Panel sizes are around a maximum of 1500mm high x 1200mm wide. Glass blade louvres provide around 70% free area when fully open. Thermal insulation and lower rates of air infiltration can be achieved with double-glazed units. The maximum length of panel is also 1200mm, with blade widths of around 150mm to 200mm. The high air infiltration rates associated with glass blade louvres have improved in recent years, but do not significantly affect their performance for the semi-external applications with which they are usually associated.



a | Exploded view showing assembly of stick based curtain wall

System design

An essential difference between glazed walls and those built in other materials is that the seals in glass construction form a continuity that usually requires the installation to be continuous, starting at one point in the wall and setting glazed panels next to each other to continue the assembly. This is different from other material systems, which often allow for much more flexibility in their methods of construction, and which do not have any significant influence on the design of the building.

The main types of glazing system that use primarily double-glazed units are stick glazing (a), unitised panels, point-fixed glazing and window walls. In addition, the principles of these systems can be made as small-scale windows set into openings of walls made in a different material. Glass blocks can also be considered as glazed walls, but follow none of these principles, using a stack bonded version of masonry construction. All these types are set out in this chapter.

For all glazed wall types the first operation on site is usually to fix the brackets that will carry the facade system to the floor slabs (r). These are usually made of stainless steel, though mild steel and aluminium can be used depending on the specific application. Brackets are fixed either onto the floor itself, or onto the vertical face of the slab at its edge. Fixing brackets directly onto the floor slab suits situations in taller buildings, where access to the edge would require scaffolding or moving platforms called 'mast climbers', which can be slow to use and suit straight facades in simple arrangements. Floor-mounted brackets are sometimes set into a pocket in the floor slab in order that they can be covered by screed and floor finishes. Office buildings typically have raised floors, so the brackets can be fixed directly on the floor slab. If brackets are set on the side of the slab, then this is done usually to avoid conflicting requirements at floor level, such as a thin floor build-up, or where brackets cannot be accommodated in pockets set into the slab. It can also be easier to fix brackets on the edge of the slab if scaffolding is used.

Once brackets are in place, framing members or panels are fixed to them. In the case of stick glazing, mullions (verticals) are fixed first, then transoms (horizontals), then glazing and capping (h). The glass is fixed with temporary short clamps first, until it is all properly aligned, then the full pressure plates are applied with their rubber-based seals (c). This makes stick glazing slower to install than unitised types, but has the advantage of flexibility of installation on site. Some glazed walls, such as those used for full height glazed walls, may be fixed back to full height steel frame rather than floor slabs (d). If the steel frame is designed as a single structure that does not have the structural movements associated with slab edge deflections, this provides the opportunity to omit the aluminium structural box section on the back of the glazed wall assembly and fix the glazing assembly directly to the supporting steelwork.

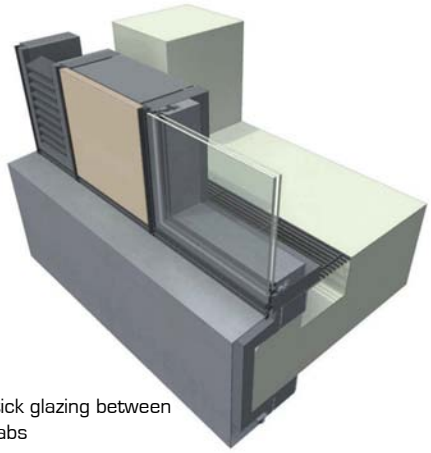
With unitised glazing, panels are typically hung from brackets and are fixed side by side on a single floor until the floor is complete (j), or as

b | (Below) Exploded view of unitised, double skin system with opening windows

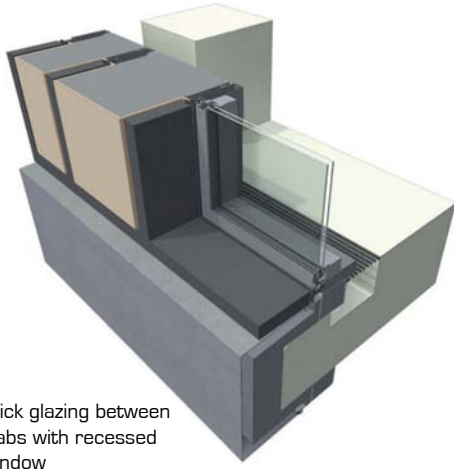




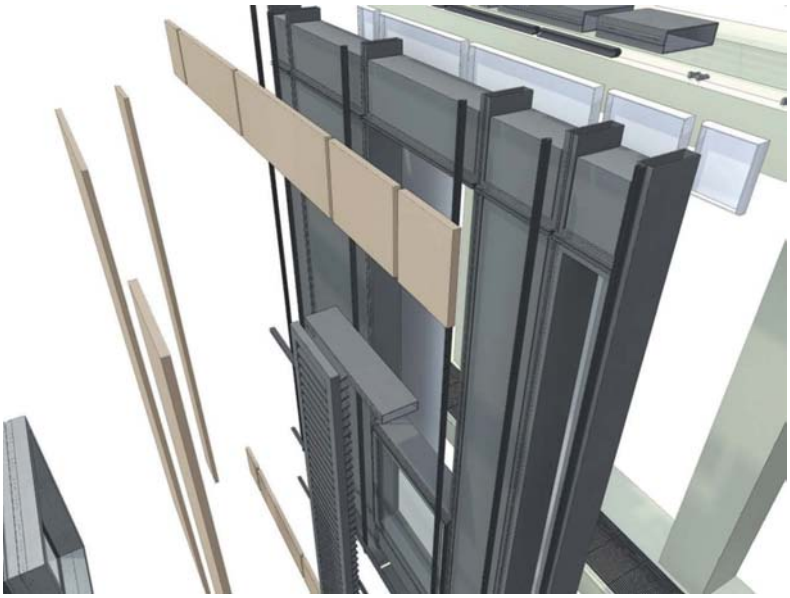
c | Exploded view showing window assembly within stick based curtain wall



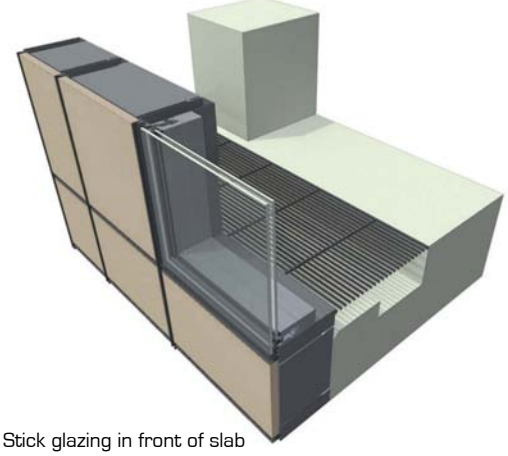
e | Stick glazing between slabs



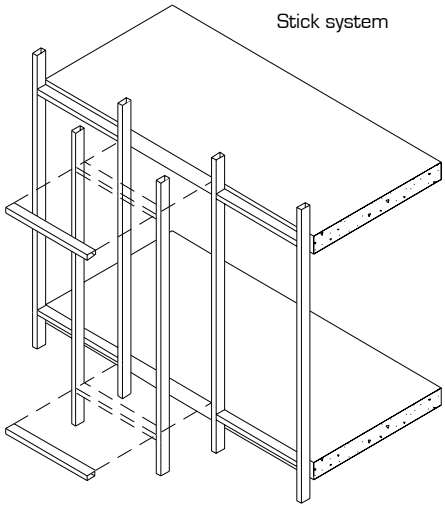
f | Stick glazing between slabs with recessed window



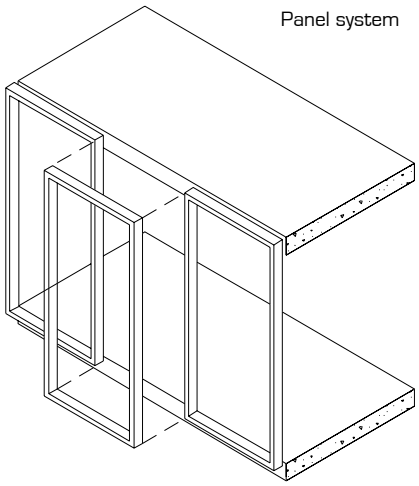
d | Exploded view showing arrangement of opaque infill panel within stick based curtain wall



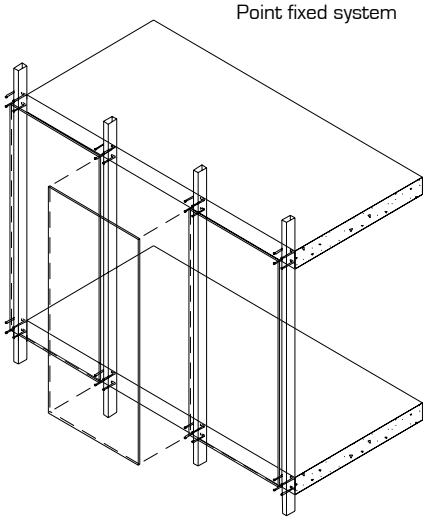
g | Stick glazing in front of slab



h | Glass stick system assembly



j | Glass panel system assembly



k | Glass point fixed system assembly

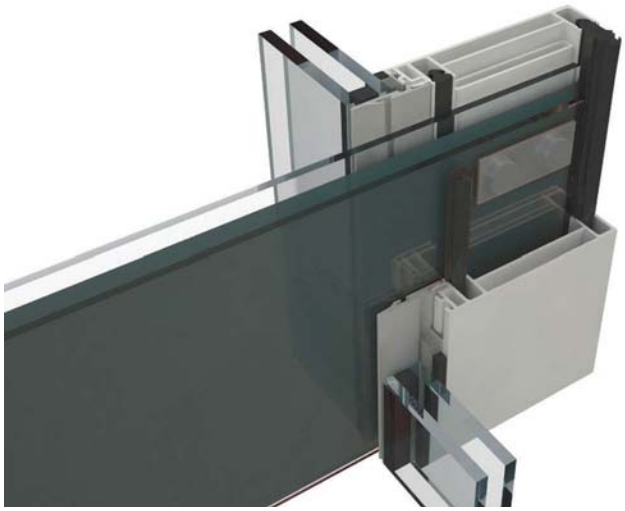




m | Detail of unitised connection for double skin mullion



n | Unitised, double skin glazed panel

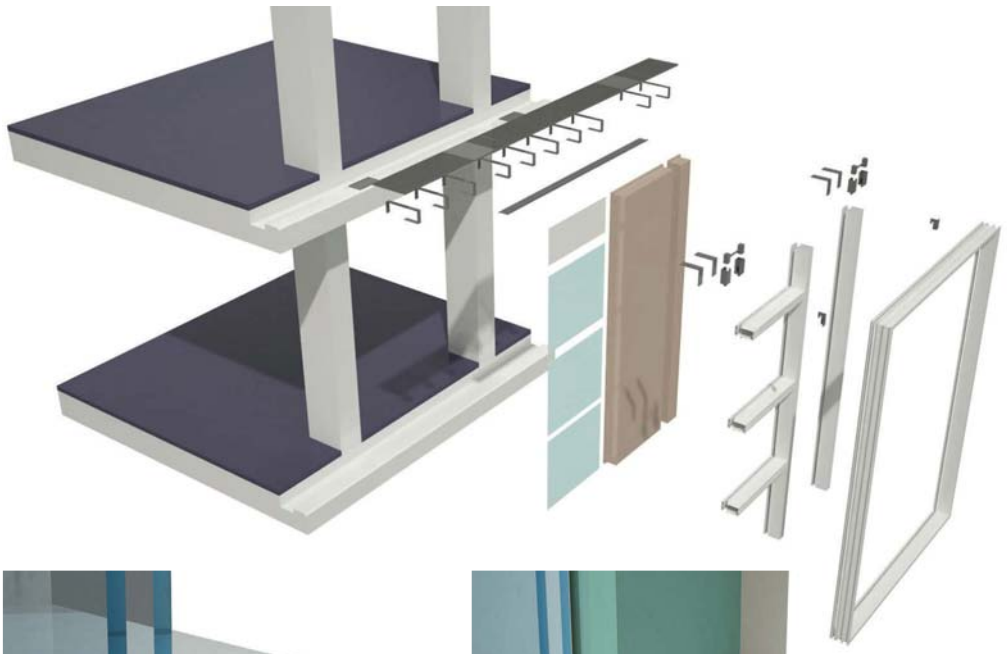


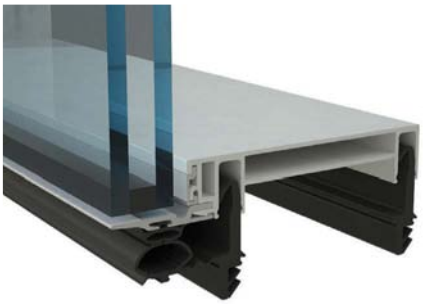
p | 3D views of glazed vertical louvre set into unitised glazing system



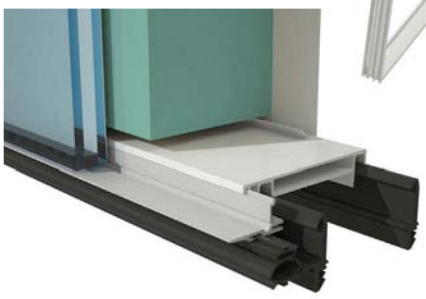
q | Unitised, double skin panel with opaque infill

r | Exploded view of unitised glazing panel with framing for additional opaque inserts





s | Frame detail for unitised system



t | Frame detail for unitised system with opaque glazing



u | 3D section showing unitised panel hung from floor slab

much of it as can be closed off. Sometimes gaps are left in glazed wall installations on site in order to allow access directly from outside for building materials used for work inside the building, depending on climate and site location. Unitised installations typically start at the bottom of the building and work upwards, slotting panels in one above the other, lifted in place by crane. This makes it a fast method of closing the external wall, allowing work to progress inside the building at an earlier stage than would be possible with a comparable stick glazed installation.

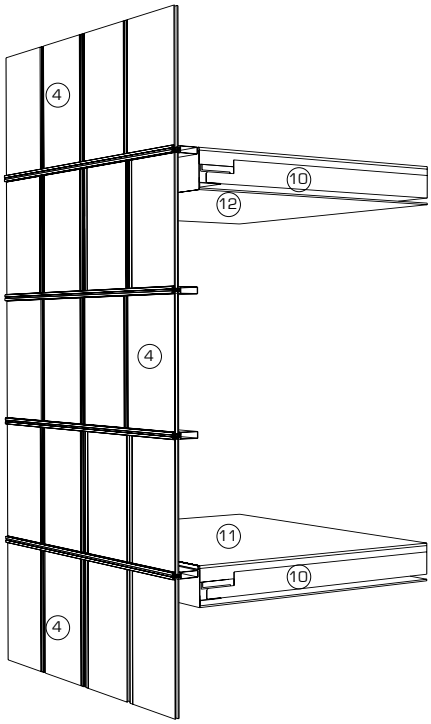
Point fixed glazing is fixed in a variety of ways, depending on the size of installation and the method of support. Small scale clamped glazing over one or two floors may be supported at its base, with clamps used to transmit loads down from the top panel to the floor below (k). This method of installation starts by fixing clamps at floor level and setting the glass in place from the bottom upward, with either scaffolding or temporary supports to hold the glass in place. If glass mullions are used rather than a steel frame, then the glass mullions are installed along with the glass panels. If a steel frame is used, then this is installed before the glazing. Larger scale bolt fixed glazing is installed with glass panels being craned into place with bolts or clamps often already fixed to the glass, making it easier to install. These larger installations are typically supported from a steel frame which is built either by installing large prefabricated sections, sometimes pre-finished, or by using steel sections which are first set in place and levelled, then have prefabricated supports for the glazing fixed in place, which may also be pre-painted.

Clamped glazing is used typically for glazed walls which do not need to interface with internal walls, as an edge frame to the glazing is typically needed in such situations.

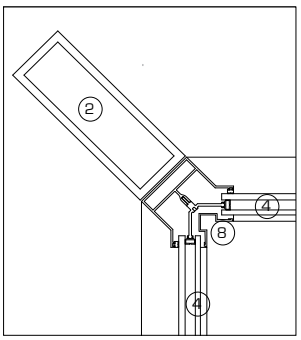
Where a glazed roof forms part of the same design, the roof elements are sometimes installed before the glazed wall in order to provide a shelter to spaces below, allowing the work to proceed from the top down, away from materials and equipment being moved in and out of the building below. The sequence of installation can influence the detailed design of glazed walls and enclosures, so this should be taken into account during the stages of design development.

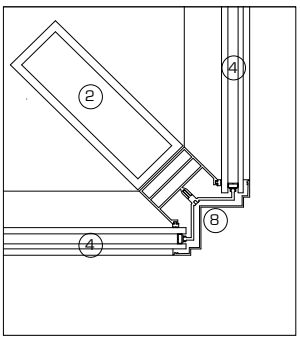
Window walls are installed either as independent sets of windows and fixed panels fixed together to form a single frame (e), or are fixed back to a structural backing wall. Where installed as large-scale window assemblies, the glazing can be installed as complete window panels, sometimes of considerable size. This makes the system surprisingly quick to install, though the weight associated with large panels requires the use of a substantial crane. Windows fitted to a backing wall often have the brackets fixed to the wall in advance, either at the sides for narrow windows, or on the bottom of the window assembly for wider assemblies. The windows are then sealed against adjoining construction in order to provide a weathertight envelope. The infill glass panels are then installed afterwards, allowing work to proceed inside the building, while this installation work is conducted in parallel.



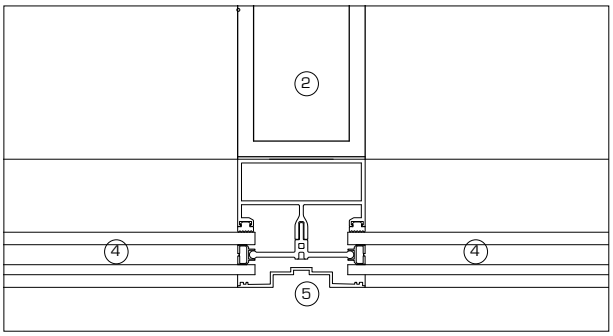


b | 3D overview of basic stick system





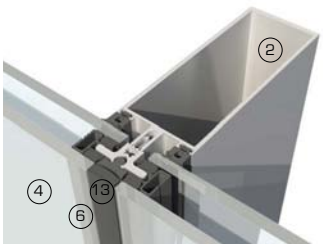
c | Horizontal sections 1:10. Toggle-fixed unitised glazing system frame at internal and external corners



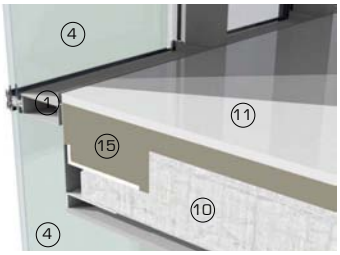
d | Horizontal section 1:2. Unitised glazing system



a | 3D detail views showing basic stick glazing systems



e | 3D detail view showing uncapped unitised glazing detail



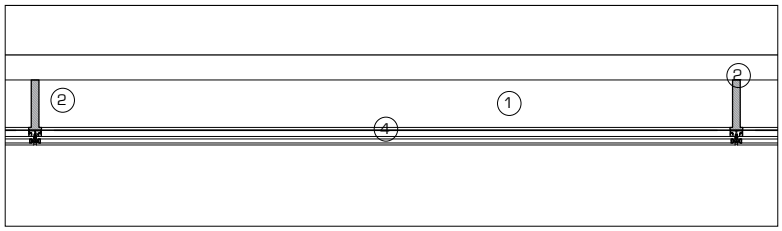
f | 3D detail view showing unitised glazing connection to slab

System design

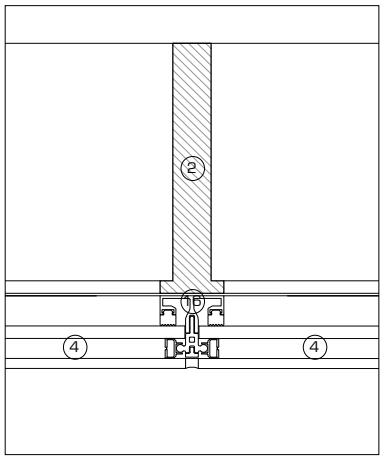
This material system is essentially a site-based method of forming glazed walls, with mullions (vertical framing members) and transoms (horizontal framing members) prepared in the factory with the slots and holes required for assembly and installation on site (a). Stick systems are suitable for glazed walls with either a wide variety of conditions or complex geometry which makes the use of prefabricated glazed panels uneconomic. This method also has the advantage of permitting a discontinuity of mullion and transom to give an ungridded appearance, while maintaining the internally drained and ventilated principles of the system; an essential aspect of this form of glazed wall. This principle accepts that small amounts of water will penetrate the outer seal of the curtain wall, but this water is drained away into a chamber immediately behind this seal, and returned to the outside at the base of the wall. The overall continuity of framing required in stick glazing ensures that the internal chamber in the transom can drain into an adjacent mullion and that any moisture is drained (a) , typically immediately above movement joints.

Stick glazing systems comprise extruded aluminium sections (3) onto which glazed panels are set, held in place with extruded aluminium pressure plates which secure the panel to the carrier frame with screw type fixings (d). A synthetic rubber-based outer seal is set between the glass and the pressure plate (6). A gasket of the same material is also set between the inner face of the panel and the carrier frame to provide an inner air seal. The pressure plate (5) is secured with visible fixings at around 300mm centres, which are usually concealed with a continuous cover capping in extruded aluminium clips onto the pressure plate (9). The cover cap is sometimes omitted where a more utilitarian appearance is required, but the installation of the fixing screws needs to be done with additional care, and holes need to be planned to avoid visually unexpected results. The capping profile can be made in a variety of flat, projecting or recessed profiles to suit visual requirements (k). Similarly, the supporting aluminium grid of mullions and transoms can be formed in a variety of structural-based sections that can vary from a rectangular box section to an I-section to a T-section with a blade-like appearance.

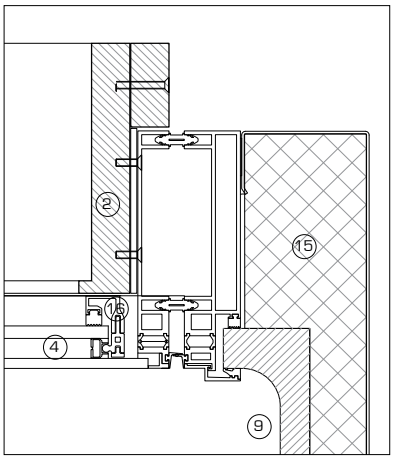
In terms of panels set into the framing, double-glazed units are the most typical panel used, though insulated opaque panels are used for spandrel conditions at floor level, typically faced in metal or opaque glass. Spandrel panels are made either as single sealed panels or as panels with a separate decorative front panel. Single panels have the insulation bonded to the inner face of the glass, with a vapour barrier set on the inside face of the panel. Alternatively, the spandrel panel is formed with an air gap between the outer panel and an insulated panel behind. The insulated panel is typically faced in metal on both sides. Where opaque glass is used as the outer panel, care must be taken to avoid dust entering the air gap from becoming visible on the outer face, if the outer panel is required to be ventilated to avoid a build-up of heat in the cavity.



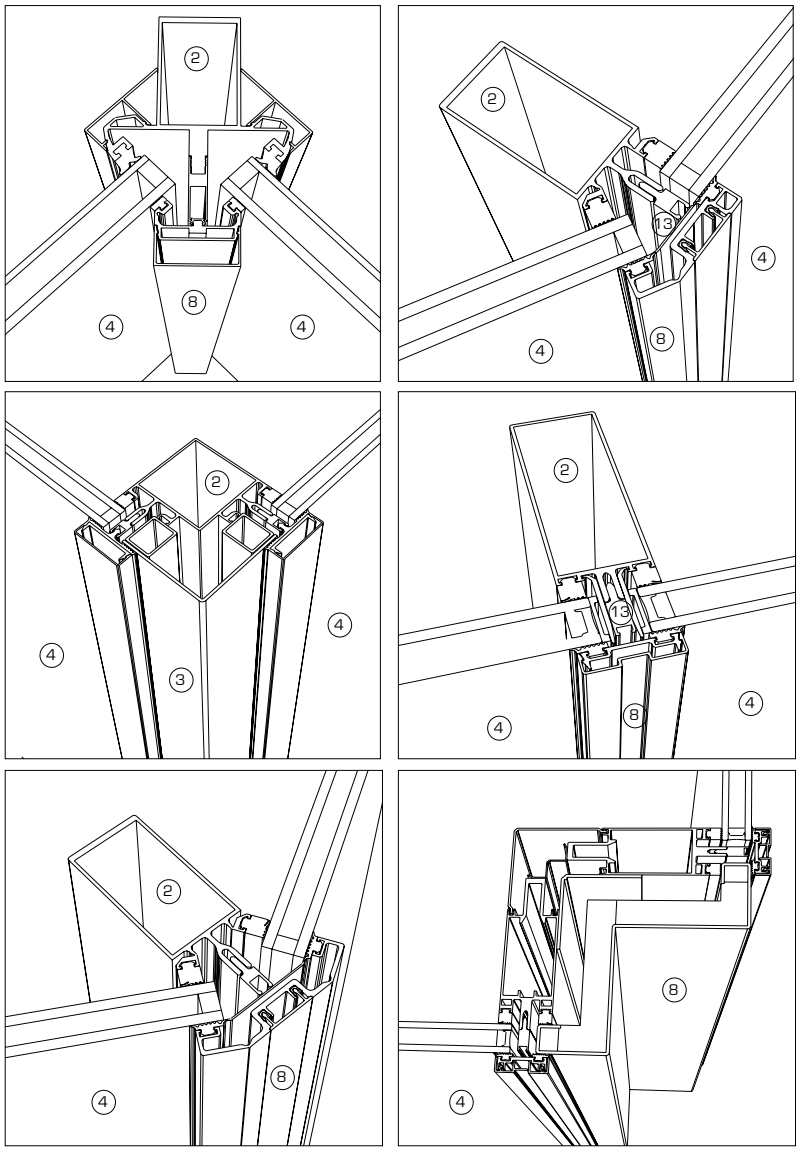
g | Horizontal section 1:10. Unitised glazing system and typical unitised glazing system corner condition



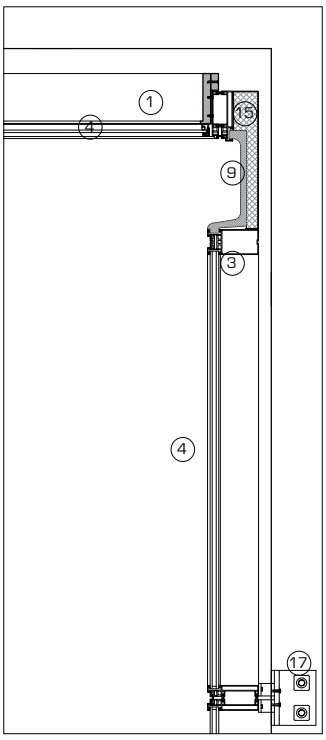
h | Horizontal section 1:2. Unitised glazing system frame



j | Horizontal section 1:2. Unitised glazing system at junction with insulated panel



m | 3D views showing corner and angled glazing panel connections



Details

1 | Extruded aluminium transom
2 | Extruded aluminium mullion
3 | Extruded aluminium section
4 | Single-glazed or double-glazed unit
5 | Pressure plate
6 | Rubber-based seal
7 | Metal honeycomb panel
8 | Capping piece
9 | Metal-faced or opaque glass-faced insulated panel
10 | Floor slab
11 | Floor finish
12 | Ceiling finish
13 | Thermal break
14 | Projecting bracket to support external screen
15 | Thermal insulation
16 | Toggle-fixing
17 | Fixing bracket

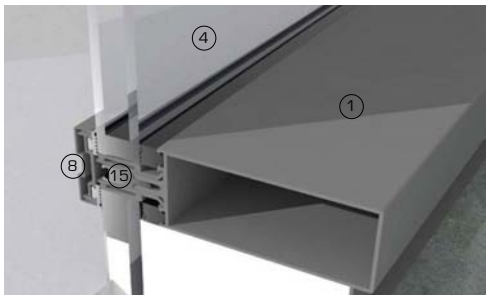


k | 3D views showing flexibility of stick glazing to allow discontinuity of capping pieces

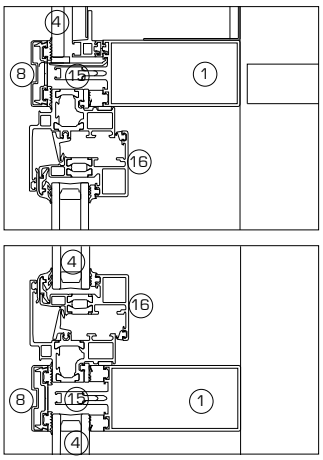




n | 3D view of stick glazed wall with outer glazed screen



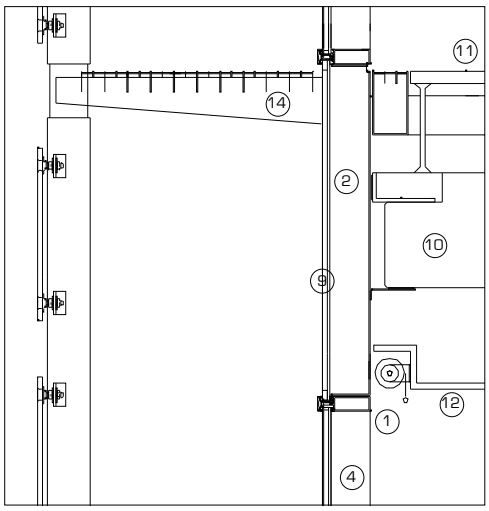
p | 3D view of stick glazed wall with outer glazed screen

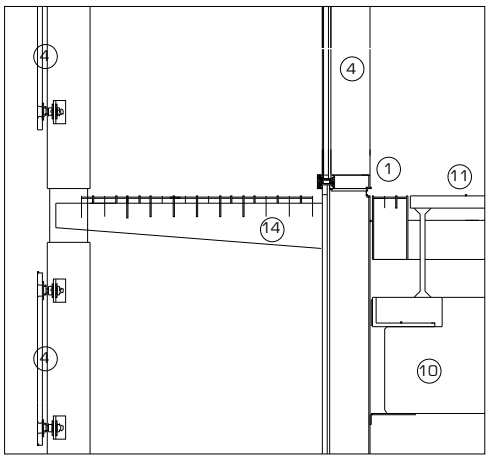


q | Vertical section 1:5. Opening window within stick glazed wall

Details

1 | Extruded aluminium transom
2 | Extruded aluminium mullion
3 | Extruded aluminium section
4 | Single-glazed or double-glazed unit
5 | Pressure plate
6 | Rubber-based seal
7 | Metal honeycomb panel
8 | Capping piece
9 | Metal-faced or opaque glass-faced insulated panel
10 | Floor slab
11 | Floor finish
12 | Ceiling finish
13 | Thermal break
14 | Projecting bracket to support external screen
15 | Toggle fixing
16 | Glazing frame





r | Vertical section 1:5. Stick glazing system with additional outer glazed screen to provide solar shading or as part of a twin face wall

Stick curtain walling is constructed by spanning mullions vertically from floor to floor from brackets fixed at each floor level, by either hanging each mullion and restraining it at the floor level below, or by supporting the mullion at floor level and restraining it at the floor slab above (n). The hanging mullion option usually allows a smaller mullion to be used, but this depends on the specific application. Mullion sections are joined from floor to floor with a sliding connection that allows the glazing between each floor level to move independently, while maintaining the overall continuity of the system. The movement joint is visible in the facade and is accommodated either at the junction of the mullion and the transom above, or within the length of the transom, usually within the spandrel panel. Brackets supporting the framing are fixed either onto the floor at the edge of the slab, or on the vertical edge of the slab (q).

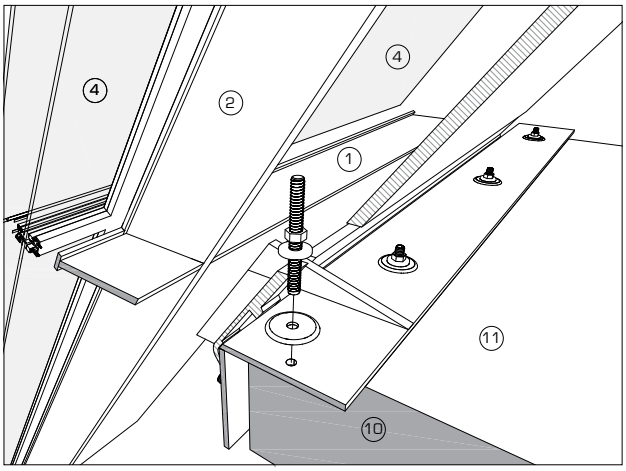
System details

Interfaces with openings, edges and different adjacent materials are formed either by the use of metal flashings or by special components that form part of proprietary systems, such as synthetic rubber strips that are glazed into the system on one side of the strip, and are bonded directly to the face of adjacent concrete or masonry surfaces on their projecting face. This provides a continuity of waterproofing across the interface of two systems, with thermal insulation and a vapour barrier set behind to form a continuity of the complete construction.

Windows are fitted into stick glazing by applying an additional sub frame (q) within the main framing against which the opening light is closed. The overall width of the window frame is usually of similar width to that of the main framing of mullions and transoms. Both outward or inward opening windows and doors are used, some with their frames silicone bonded to the glass to reduce their visual impact externally, though the frames look similar from within the building. Electrically operated windows, such as those at high level, usually have a motor in a box that fits within the height of the window frame. With the wiring concealed within the framing, the visual impact of motors and window opening arms has been reduced significantly in recent years. Junctions at floors are closed by bringing floor finishes up to the transom, which is also set at floor level to close off the gap between floors (u)(y). The spandrel panel has a smoke seal between separated floors, but a full fire barrier is required in some countries where the spandrel panel is required to be fire-resistant and to provide a barrier that stops flames from passing from floor to floor. Corners are formed, typically either with a special extrusion (m) that allows a glass-to-glass junction at the corner, or has two mullions meeting at a corner and an insulated metal flashing turning the corner. Parapet copings are formed by glazing the bottom edge of the metal flashing into the top transom and folding the flashing over the top of the parapet. Junctions between mullions and adjacent areas of wall in a different material are made in the same way.



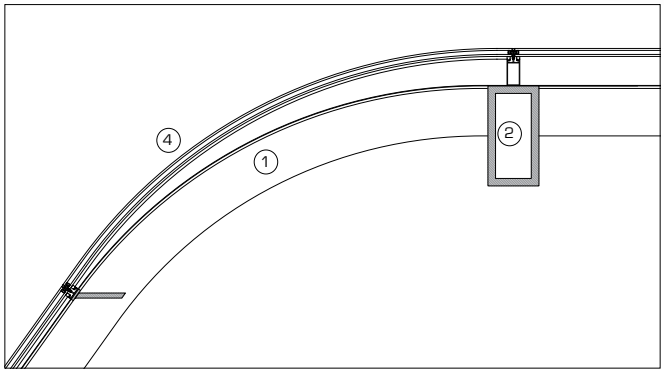
s | 3D view of inclined and curved stick glazing system

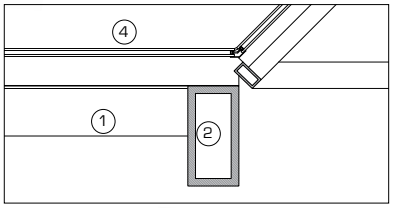


t | 3D exploded view of typical restrained connection to steel



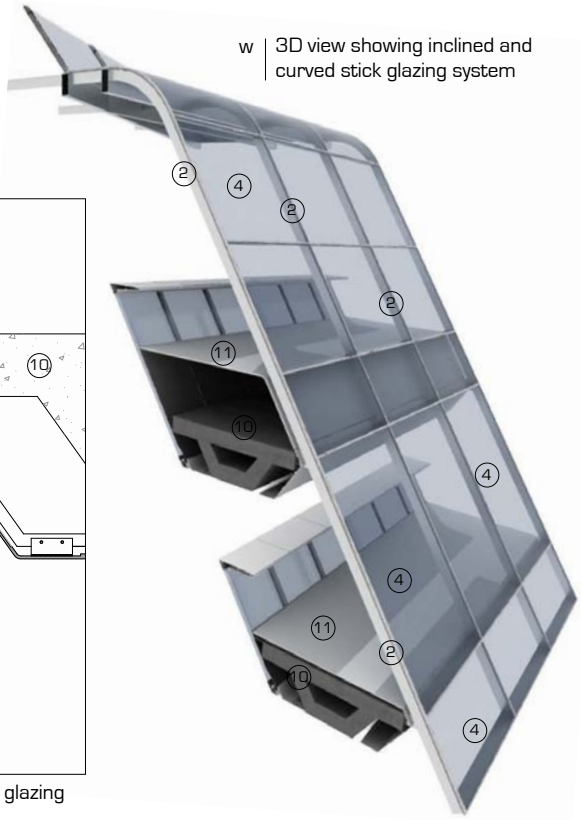
u | 3D detail view showing inclined stick glazing system connection to floor slab

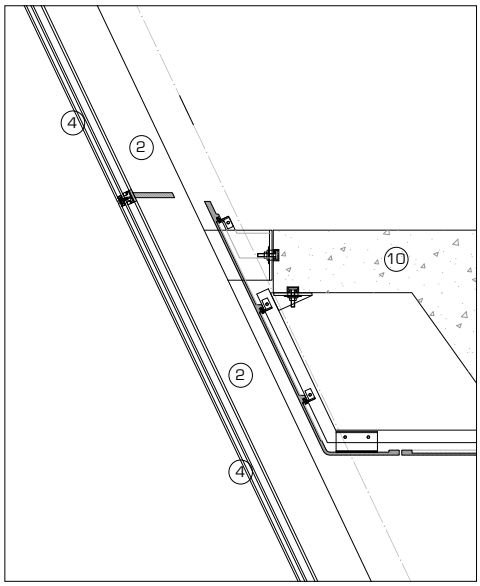




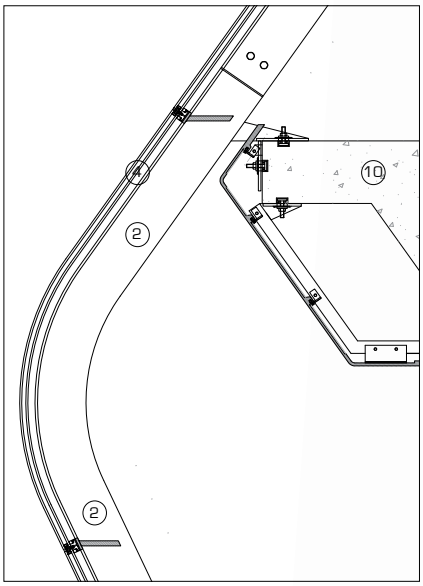
v | (Left) Horizontal section 1:10. Curved stick glazing system

w | 3D view showing inclined and curved stick glazing system

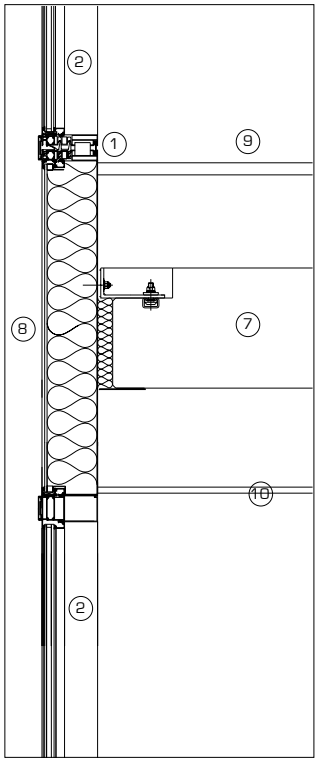


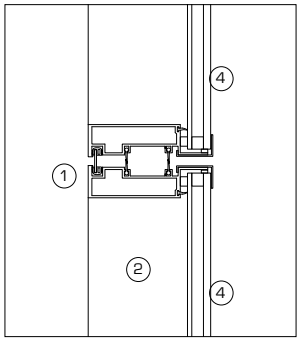


x | Vertical section 1:10. Inclined stick glazing system at floor junction

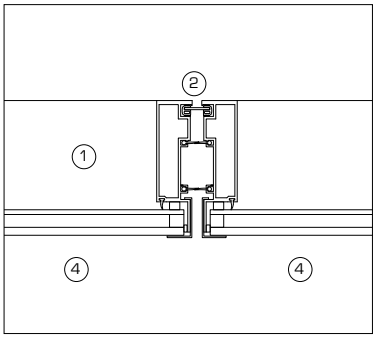


y | Vertical section 1:10. Curved stick glazing system

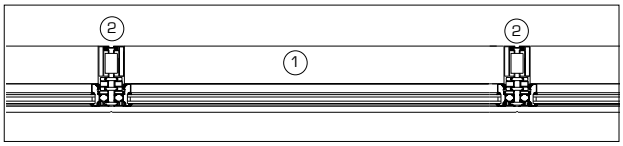




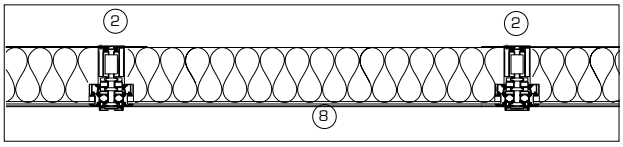
a | Vertical section 1:5. Unitised transom



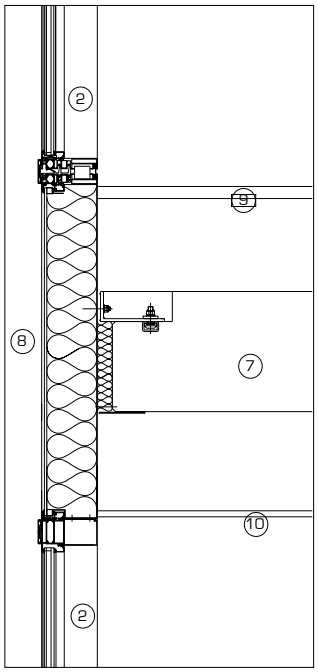
b | Horizontal section 1:5. Unitised mullion



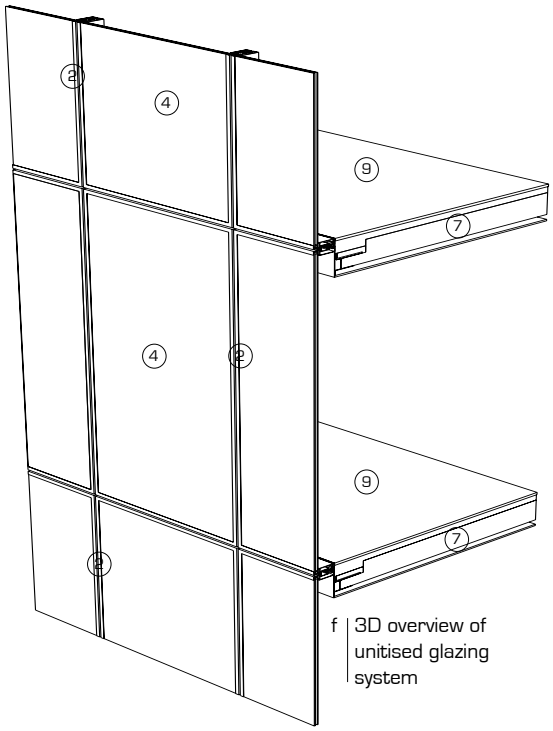
c | Horizontal section 1:25. Transparent unitised panel



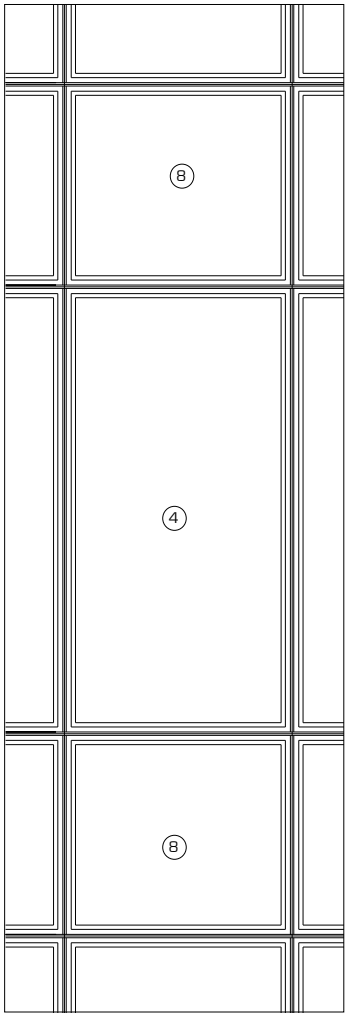
d | Horizontal section w 1:25. Opaque unitised panel



e | Vertical section 1:25. Typical unitised glazing system



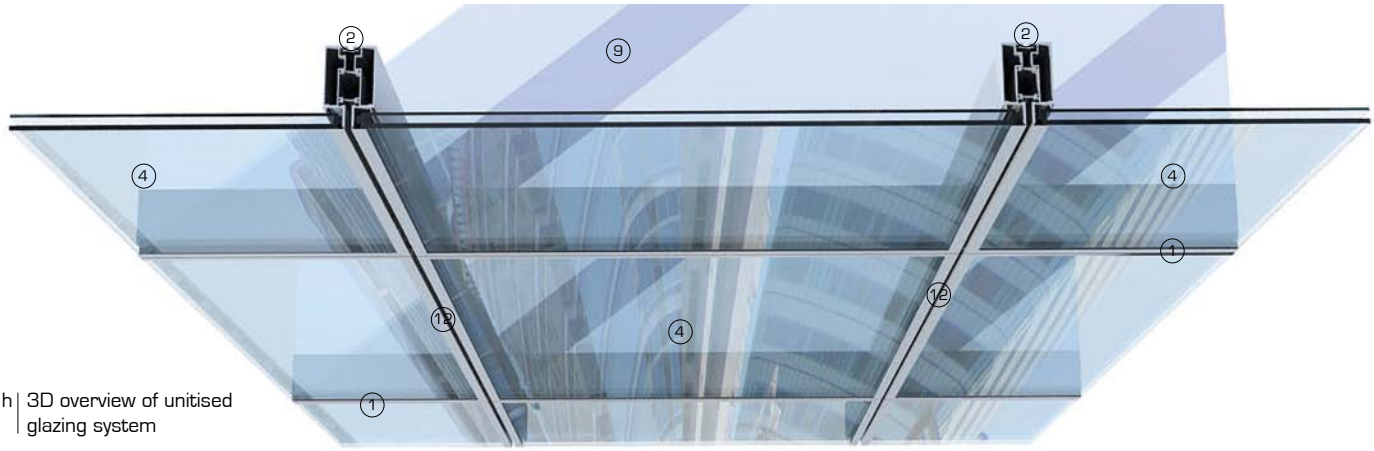
f | 3D overview of unitised glazing system



g | Elevation of typical unitised glazing system

Details

1 | Extruded aluminium transom
2 | Extruded aluminium mullion
3 | Extruded aluminium section
4 | Single-glazed or double-glazed unit
5 | Rubber-based weather seal
6 | Rubber-based air seal
7 | Floor slab
8 | Metal-faced or opaque glass-faced insulated panel
9 | Floor finish
10 | Ceiling finish
11 | Silicone seal with optional aluminium corner extrusion
12 | Capping piece



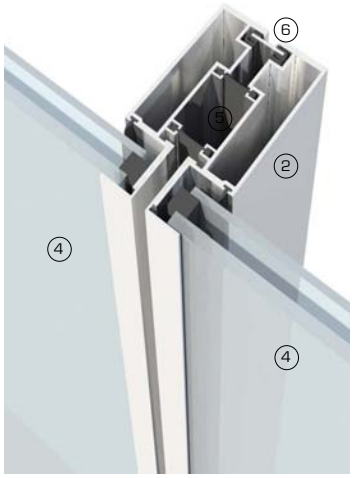
h | 3D overview of unitised glazing system



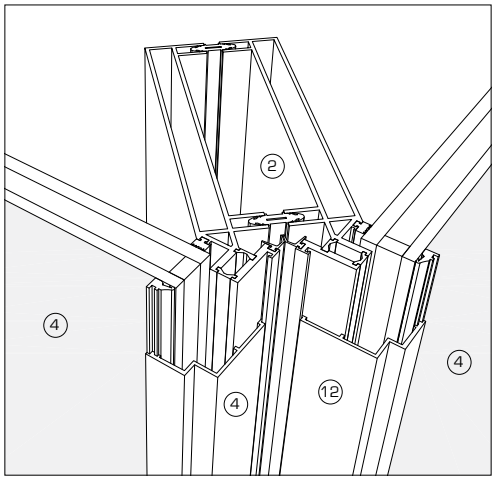
j | 3D detail view showing framed corner connection



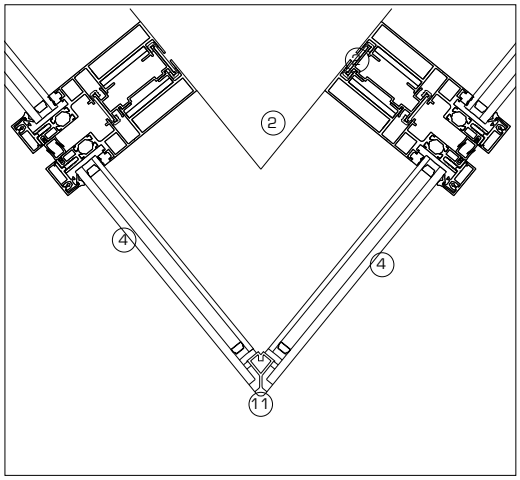
k | 3D detail view showing unframed corner connection



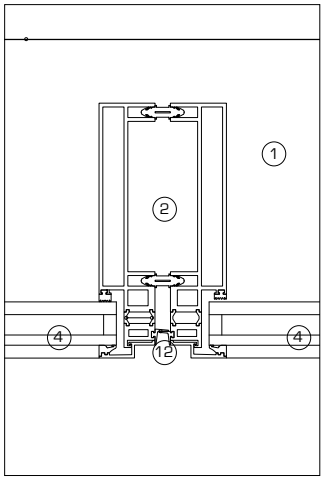
l | 3D detail view showing frame assembly



m | 3D detail view showing framed corner connection



n | Horizontal section 1:5. Unframed corner connection



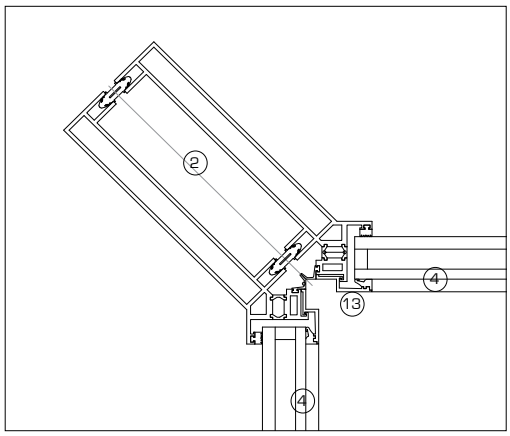
p | Horizontal section 1:5. Unitised mullion

System design

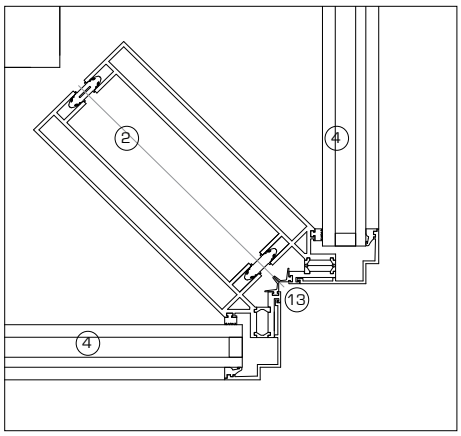
Unitised glazing is essentially a method of using prefabricated panels which are fixed together on site to form a complete glazed wall (h). Like stick glazing, unitised glazing uses aluminium framing to support the glazing (f); but where stick glazing is secured to a continuous supporting frame, all of which is fixed on site, unitised glazing is put together in the factory. Panels are delivered to site, lifted into place and set next to one another; the gaps between each panel being sealed with synthetic rubber gaskets. These gaskets interlock from panel to panel vertically, but are typically separated at each floor level with a continuous horizontal gasket that follows the horizontal joint between panels. Some systems have panels which are completely separate structurally from the adjacent panels, allowing a damaged panel to be removed if damages occur, either during construction or later, but the junction between vertical and horizontal joints requires special attention. Other systems are semi-interlocking on horizontal joints in order to combine the structural capacity of members as well as to assist in internal drainage. This type of horizontal joint is also used for stick systems where large-scale frames, covering several bays both vertically and horizontally, are pre-assembled in the factory and then lifted into place on site. The glass units and pressure plates are then fixed on site as per regular stick glazing methods.

The double-glazed units in unitised glazing are fixed to the supporting frame either from the outside of the panel or the inside (c), to suit the strategy for glass replacement in the event of accidental damage. The double-glazed units are secured with pressure plates which are either mechanically fixed to the main frame, or form part of the frame itself. An alternative method of fixing glass is to bond the glass units to a sub frame which is then mechanically fixed to the aluminium frame. This method provides an all-glass appearance on the outside, usually with a recessed joint between panels giving a shadow gap appearance between panels.

Vertical joints between panels have an outer seal which is usually formed by two gaskets which are pressed together (d). These are made from synthetic rubber, typically EPDM. Behind this outer seal is a drained and pressure equalised chamber closed off by an inner seal, also formed typically in EPDM. At the internal face of the panel is an air seal. In hot and humid climates, typically in South East Asia, it is assumed that moisture will find its way to the back of the supporting aluminium frame. Consequently, seals are in horizontal joints to drain moisture from the back of the system to the front face of the panel, where it is released to the outside. In more temperate climates, unitised panels are sealed in the mid-depth of the framing, with the inner joint visible from within the building serving as an air seal only. Any rainwater that penetrates the outer seal is drained down through the inner chamber and is expelled at the base of each unitised panel, typically at floor level. Horizontal joints between the transoms formed by the top of one panel and the bottom



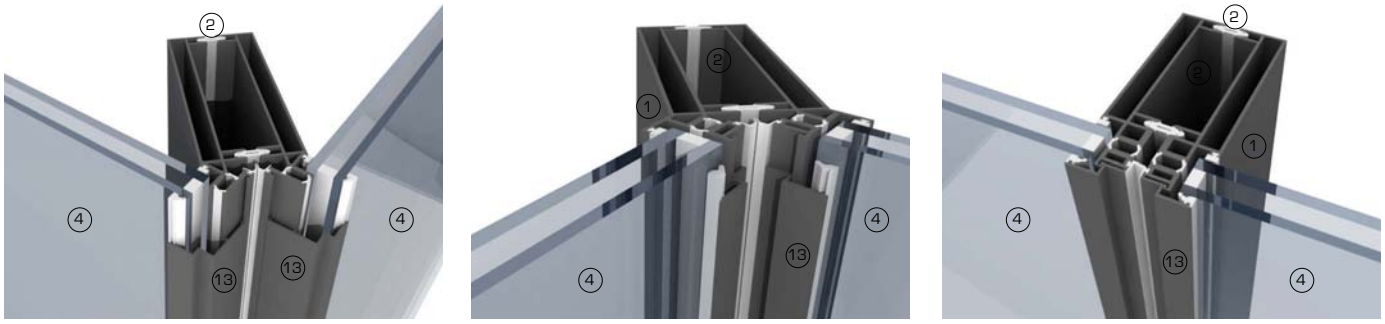
q | Horizontal section 1:5. Unitised glazing internal corner connection



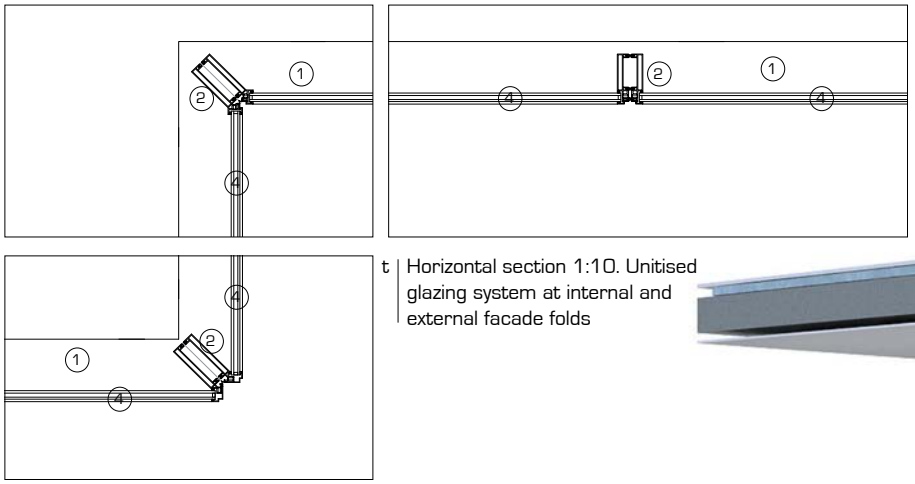
r | Horizontal section 1:5. Unitised glazing external corner connection

Details

1 | Extruded aluminium transom
2 | Extruded aluminium mullion
3 | Extruded aluminium section
4 | Single-glazed or double-glazed unit
5 | Rubber-based weather seal
6 | Rubber-based air seal
7 | Floor slab
8 | Metal-faced or opaque glass-faced insulated panel
9 | Floor finish
10 | Ceiling finish
11 | Silicone seal with optional aluminium corner extrusion
12 | Thermal insulation
13 | Capping piece
14 | Concrete structure



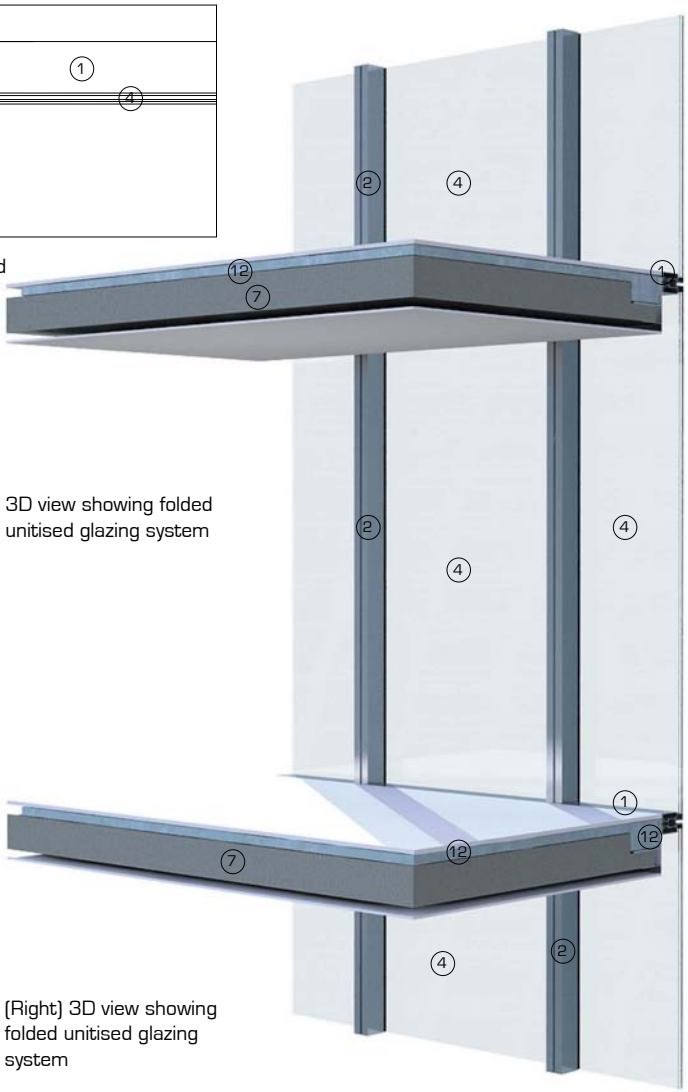
s | 3D detail views showing unitised glazing frame



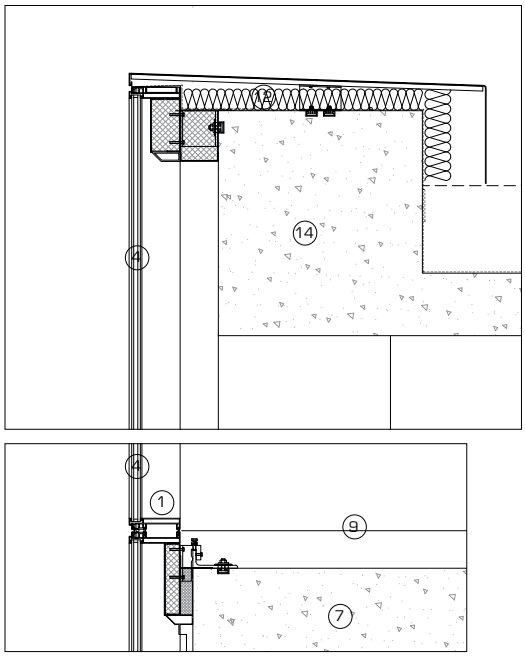
t | Horizontal section 1:10. Unitised glazing system at internal and external facade folds



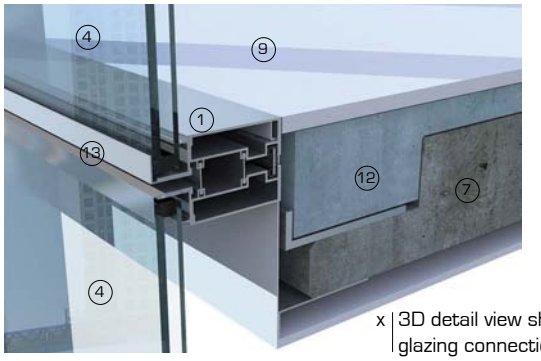
u | 3D view showing folded unitised glazing system



v | (Right) 3D view showing folded unitised glazing system



w | Vertical section 1:10. Unitised glazing at parapet level and floor-slab level and (below) 3D view of typical floor-level connection



x | 3D detail view showing unitised glazing connection to floor slab



y | 3D overview showing unitised glazing connection to floor slab

of the panel above are formed in the same way, with seals aligned with those in the vertical joints to ensure that rainwater is drained to the outside. Unitised panels typically include at least one additional transom to provide a spandrel zone at floor level, for example, though some systems incorporate an additional transom set against the inside face of the glass only, so that it is not visible externally but provides a horizontal edge against which internal ceiling finishes can be set.

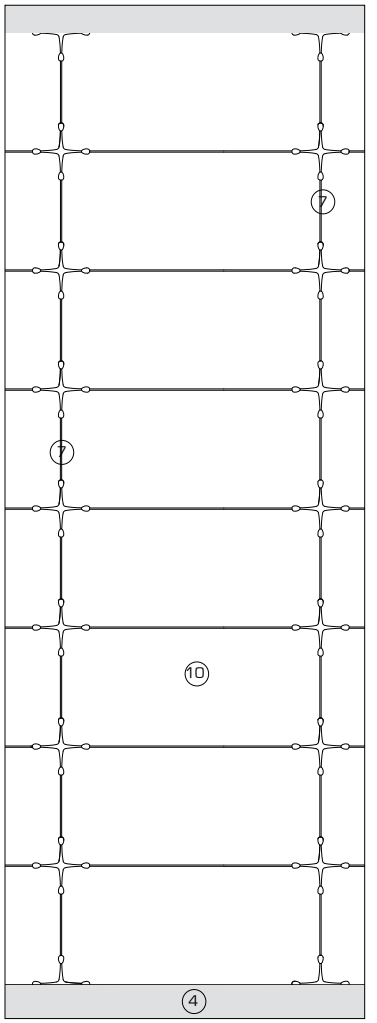
Panels are set so that they span from floor slab to floor slab, and like stick glazing, are either hung from a floor slab and restrained on the floor below, or are supported on a floor slab and are restrained on the floor above (v). Like stick glazing, movement between panels is provided by a sliding spigot joint set into the vertical joint between mullions. This movement is taken out horizontally in the horizontal joint, typically at floor level.

In common with stick glazing, unitised panels have thermal breaks set within the framing in order to reduce the transmission of heat or cold from the outside of the frame to the inside, or vice versa. Since the inner ventilated chamber is typically deeper than that used in stick glazing (s), the thermal break is positioned accordingly in order that the thermal break and double-glazed unit are aligned. The overall width, or sight line, of the unitised panels is greater than those used for stick glazing, from around 80mm to 120mm depending on the application. The greater width often suits the needs of internal partitions which are required to intersect with the framing members of the facade.

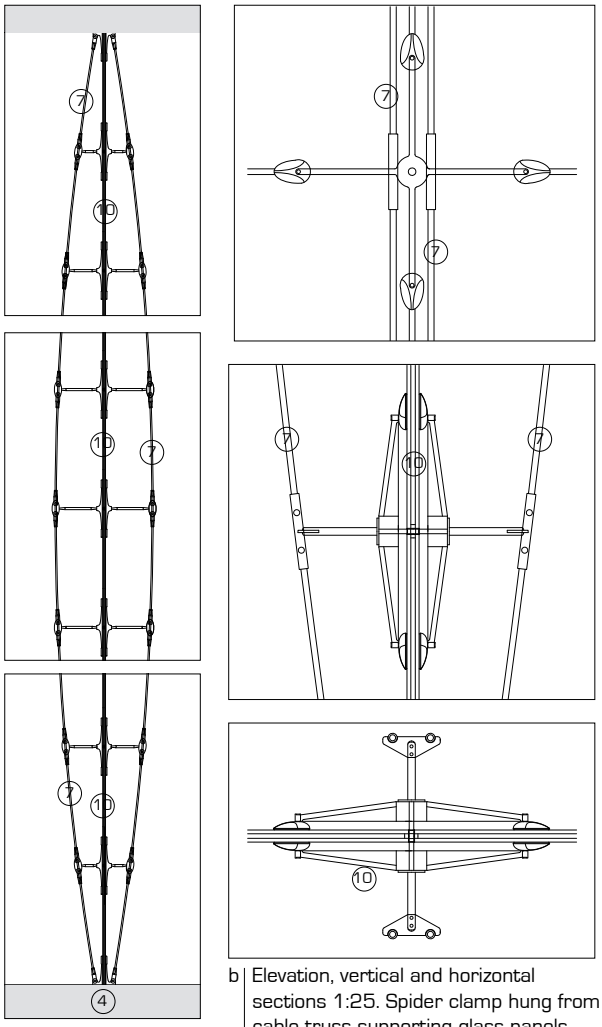
System details

An essential aspect of unitised glazing is that the panels use the same perimeter framing, which can however be of different shape and have different materials set within them. Corner panels are the most common of the atypical panels, and are often the most complex to construct in the factory (t). In common with stick glazing, unitised panels can have vertical glass-to-glass joints rather than setting a mullion at the corner, providing a visual crispness of the frameless corner. The unitised frame is stiffened internally to compensate for the loss of structural stability of the corner. Regular framed corners are usually made with a 45° angled mullion to reduce the visual impact and sight lines of the mullion (s).

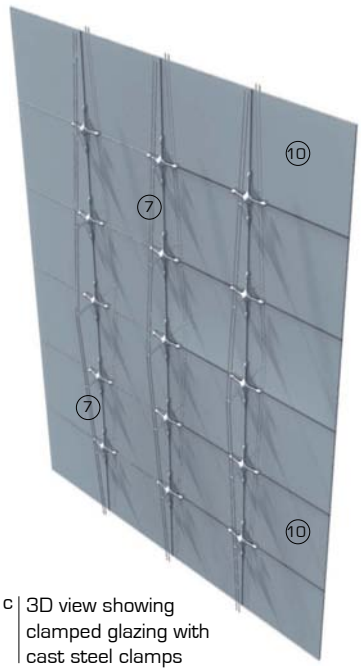
Parapet copings are formed by sealing and waterproofing the gap between the top of the panel and the parapet wall behind with a synthetic rubber seal that is integral with the panel (w). Thermal insulation is used to provide a complete continuity of insulation from wall to roof (12). A metal coping is set on top of the panel to provide protection to the membrane beneath. Elsewhere, most interfaces follow the principles of stick glazing, with an integral EPDM strip that can be fixed to project out beyond the edges of the panels (13), allowing the strip to be bonded to an adjacent construction.



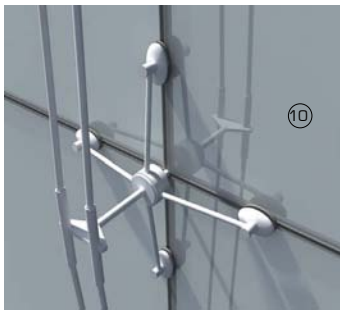
a | Elevation and vertical section 1:50. Clamped glazing with cast steel clamps held in place by forming part of a continuous truss



b | Elevation, vertical and horizontal sections 1:25. Spider clamp hung from cable truss supporting glass panels



c | 3D view showing clamped glazing with cast steel clamps



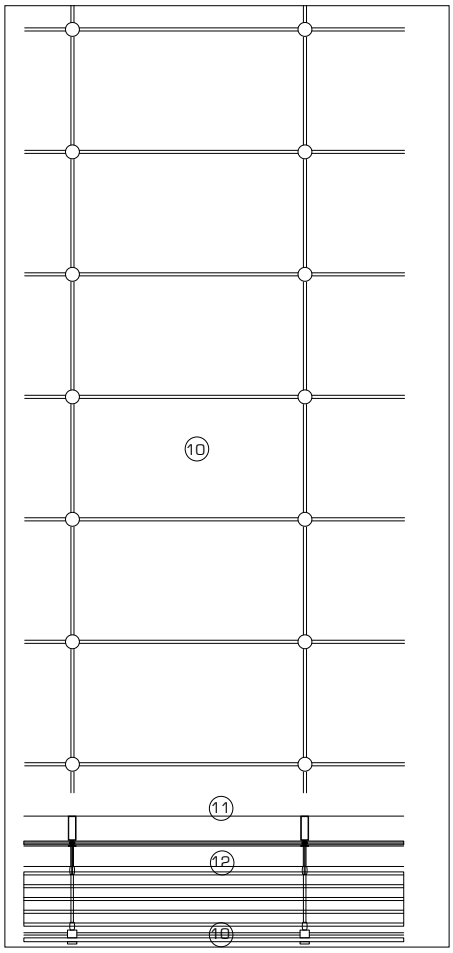
d | 3D detail view showing clamped glazing fixing method

System design

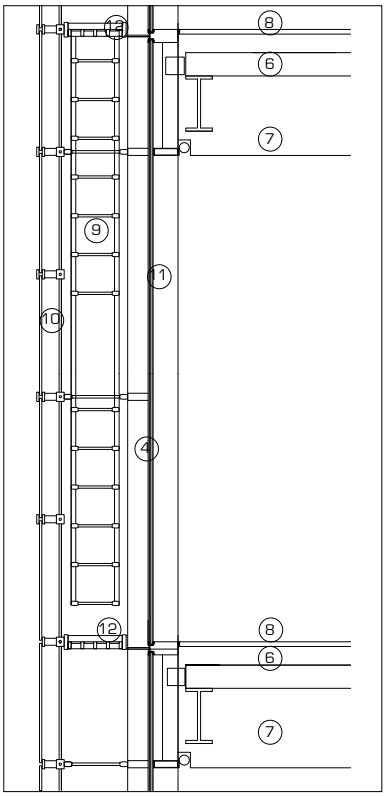
There are two types of 'point fixed' glazing used for facades: clamped glazing (a) and bolt fixed glazing. Both systems are used to increase the transparency of a facade, and this is particularly successful in open jointed single glazing as is used in double skin facades. Where double-glazed units are used with their black edge band and joints between units, the width is usually equal to that of framed glazing, but the omission of framing provides a visual continuity of glass where transparency is required. The all-glass appearance has visual benefits to oblique views across a facade, where the double-glazed units are seen as a continuous uninterrupted surface made all the more dramatic by changes in direction provided by corners, as well as increasingly by folds in the glass surface. Where a sealed facade is required, joints are sealed with silicone through the full thickness of the joint, typically with a polymer-based backing rod in the mid-depth of the joint (b). Clamped glazing was the first point fixed glazing system used commercially and developed in the 1960s, using metal plates called 'patch plates' set on either side of glass sheets at their corners. This technique is still used, though with increasing geometric complexity.

The clamped glazing system positions the fixings holding the plates in place such that they pass through the joints between the glass to avoid the additional complexity and cost of drilling the glass (d). Because fixings are positioned at the glass edges, rather than within the glass itself, the span between fixings is higher than for an equivalent bolt fixed solution, and glass thicknesses may be higher for a clamped glazing solution as a result. When used in a single-glazed configuration in double skin facades (g), the glass is joined with clamps, plates and brackets (f), and the preferred material is stainless steel due to its resistance to corrosion. The use of plates allows a more complex geometry of glass to be used, such as in a shingled arrangement of lapped glass panels, where air can pass up through gaps between lapped glass sheets while admitting only small amounts of rainwater into the buffer zone behind (w). Glass can be supported either at the corners or along its edges to suit the supporting structure for the glass, which is usually visually lightweight in order to maximise transparency. Clamps are formed by setting a synthetic rubber gasket, typically EPDM, between the stainless steel plate and the glass sheet. A bolt is passed through one side of the plate and is secured into the other plate, usually with a countersunk type.

Clamped glazing often uses glass fins to provide structural stability, set at 90º to the plane of the glass and typically supported at its base on the floor slab. Glass fins usually come in lengths equal to the height of each panel (r), with a patch plate connection occurring at each horizontal joint of the glass, to form a single structural section with the dead load of each panel transferred to the glass panel below in the case of single glazing, or alternatively to the glass fin behind. Installations have been known to reach up to around 15 metres in height, though these are flat glass walls or those forming vertical walls which are curved in plan. Glass



e | Horizontal section 1:100. Cable hung clamped glass facade



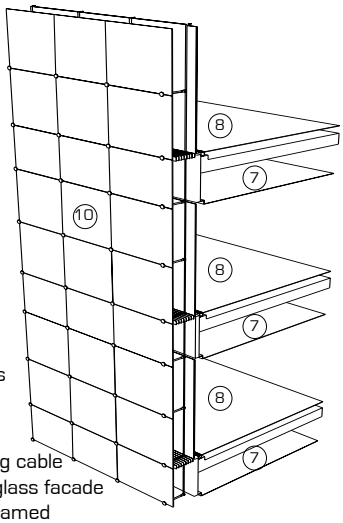
f | Vertical section 1:100. Cable hung clamped glass facade



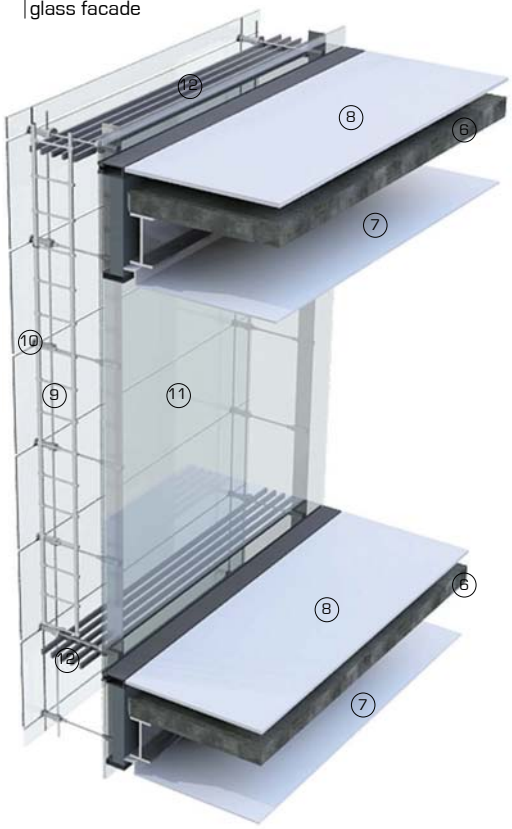
g | 3D views showing cable hung clamped glass facade

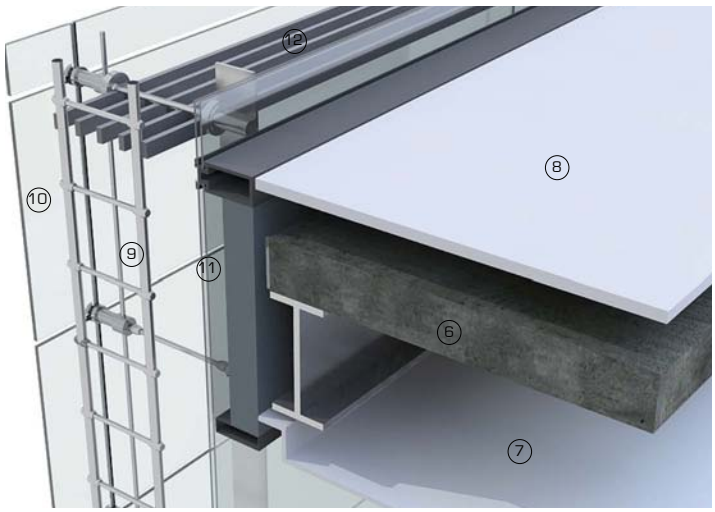
Details

1 | Stainless steel patch plate
2 | Single-glazed or double-glazed unit to suit application
3 | Silicone seal
4 | Glass fin
5 | Support bracket
6 | Floor slab
7 | Ceiling finish
8 | Floor finish
9 | Access ladder
10 | Clamped glazed wall
11 | Inner curtain walling
12 | Maintenance access deck

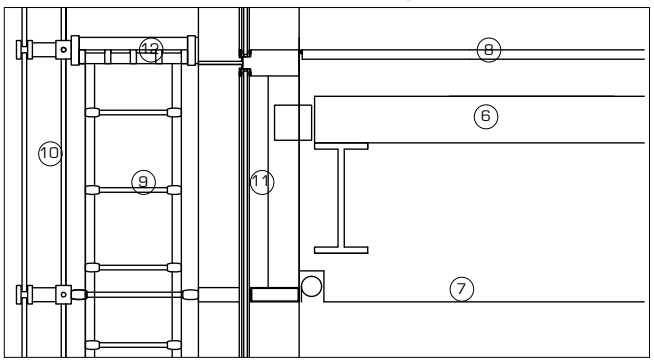


h | 3D view showing cable hung clamped glass facade with vertically framed supporting system





j | 3D detail view showing cable hung clamped glass facade



k | Vertical section 1:50. Cable hung clamped glass facade

Details

1 | Fixing bracket
2 | Extruded aluminium mullions
3 | Opaque glazing
4 | Ground slab
5 | Backing wall
6 | Inclined and lapped glass
7 | Cable support
8 | Corner clamp
9 | Cast metal fixing bracket
10 | Clamp bracket
11 | Metal parapet coping
12 | Thermal insulation
13 | Single or double-glazed unit
14 | Concrete slab

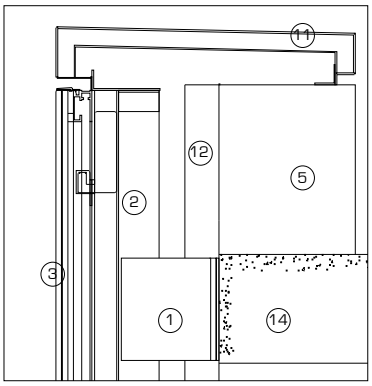


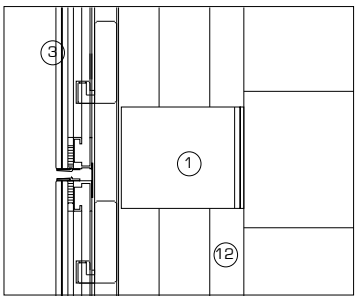


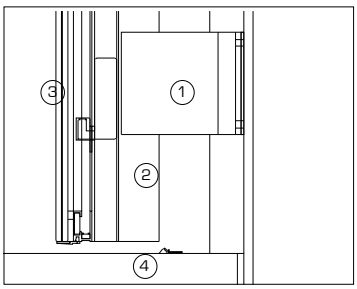
m | 3D views showing opaque clamped glazing panel system at panel-to-panel and movement joint conditions



n | 3D overview showing opaque clamped glazing panel system







p | Vertical section 1:10. Opaque clamped glazed panels. Junctions at ground level, movement joint and panel-to-panel conditions



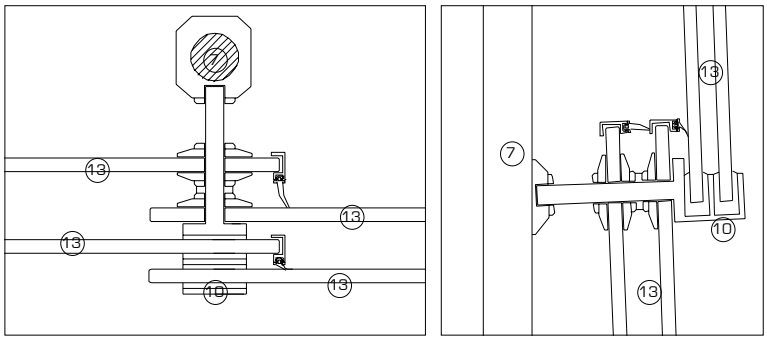
q | 3D detail view showing glass fin fixing detail



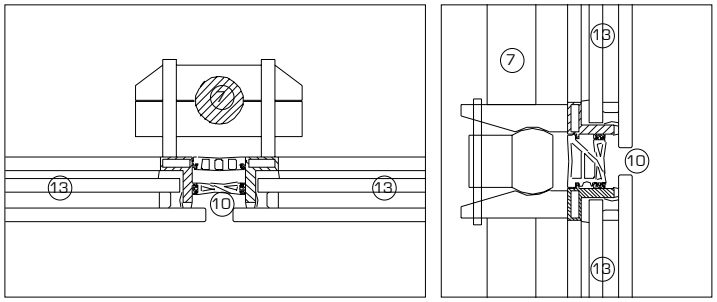
r | 3D view showing Glass fins in structural glass box assembly



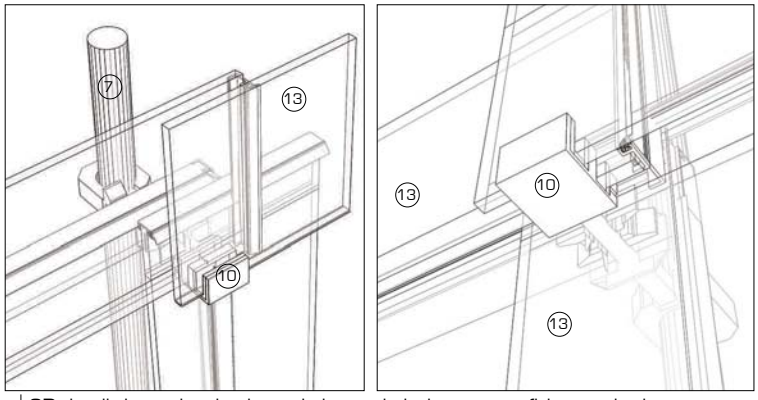
s | 3D view showing glass fins in structural glass wall assembly



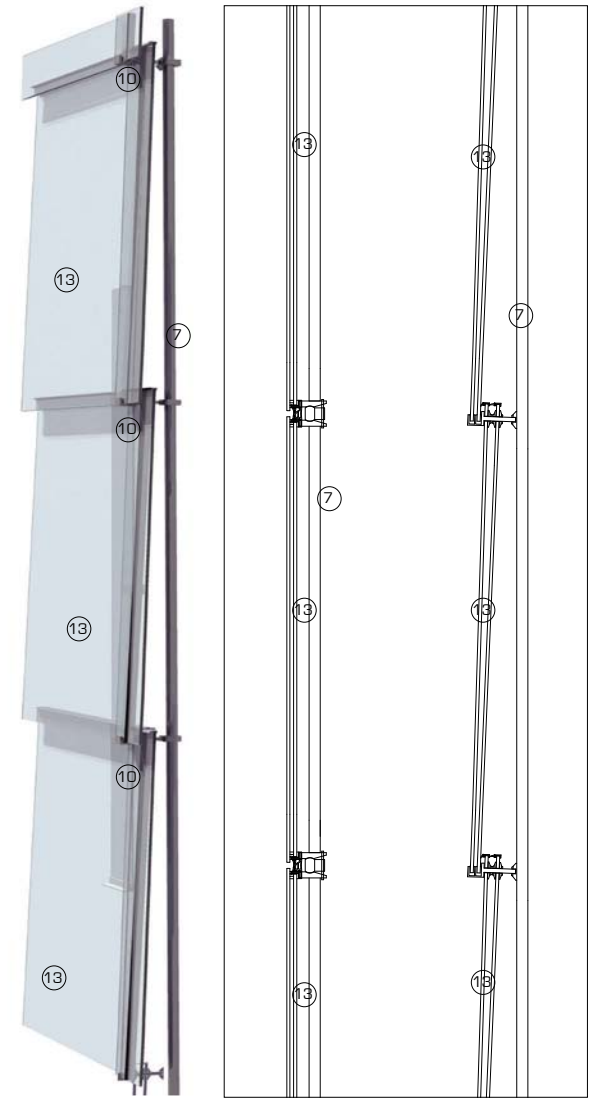
t | Horizontal and vertical sections 1:2.
Clamping configuration in lapped clamped cable hung system



u | Horizontal and vertical sections 1:2.
Clamping configuration in adjacent clamped cable hung systems



v | 3D detail views showing lapped clamped glazing system fixing method



w | 3D view and vertical sections 1:10. Clamping configurations in cable hung systems (lapped and adjacent)

panels and fins are joined with cleats and plates at the corner junctions, and are usually fixed through holes in the glass rather than through the joints in order to transfer loads effectively through the plates. Clamping plates usually have a polished finish for ease of cleaning, but brushed finishes are also used.

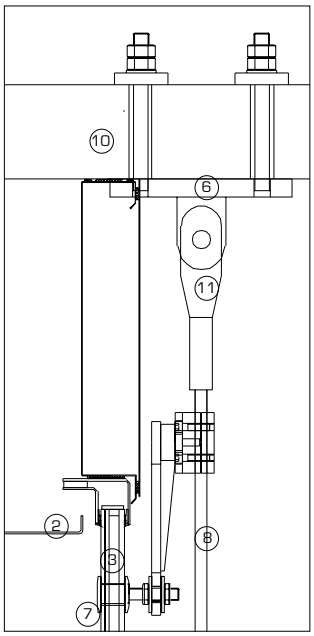
This method of glazing has evolved into an economic method of fixing glass to a continuous supporting frame behind the glass joints, as an alternative to the capped glazing techniques of stick and unitised systems, with silicone seals set between the glazed units (q). This makes it suitable for facades with complex frame design, particularly when combined with a glazed roof that uses the same system. Triangular framed glazed walls, where the glass is required to have a smooth, continuous surface free of cover caps, allow clamps to be fixed through the joints between the glass directly back to the supporting structure set behind. Clamp fixings can be set at the corners of glass panels, where units intersect (d), or be set along the length of joints. The choice of fixing position depends on both the geometry and size of the glazing.

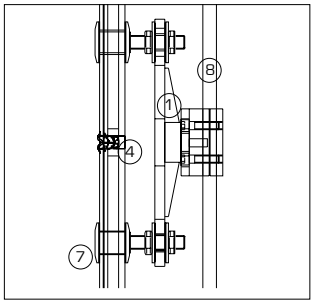
System details

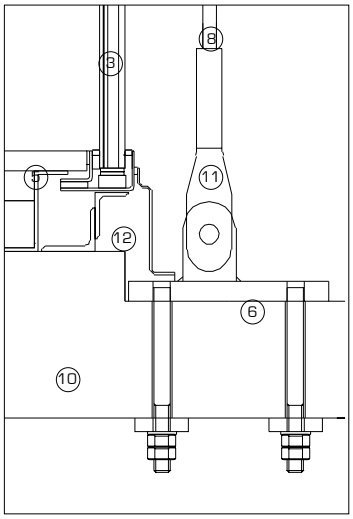
Clamped glazing with glass fins is usually set into a glazing channel at floor level in order to fix the glass in place and support its dead weight. A glazing channel also forms a reliable weather seal with the outside ground level. Supporting glass fins which are supported at floor level rather than ceiling level are usually set below floor level in order to conceal the patch plate brackets, which are usually set either within the floor finishes zone or within a pocket in the floor slab where this zone is insufficiently deep. The same solution is used where the fin is hung from the ceiling. Clamp plates are also used for doors to give a continuous appearance to the facade. Doors are typically set on floor springs, into the floor, and are supported at the top of the door leaf with a pivot which is clamped to the glass unit above.

Clamped glazing is usually able to accommodate higher amounts of structural movement than an equivalent framed glazing system, which has encouraged the use of tensioned cables, usually set vertically, to which the glass is fixed. Cables are usually set immediately behind vertical joints to reduce their number and visibility (w), since plates offset from the vertical joint require either an additional vertically-set cable, or a metal bracket to connect the two patch plates back to a single cable (v). In supporting cable structures, which allow higher amounts of structural movement, doors are required to be set independently of the glazed wall, usually with a metal frame around the opening which is fixed at floor level only, and is structurally independent of the glazed wall.

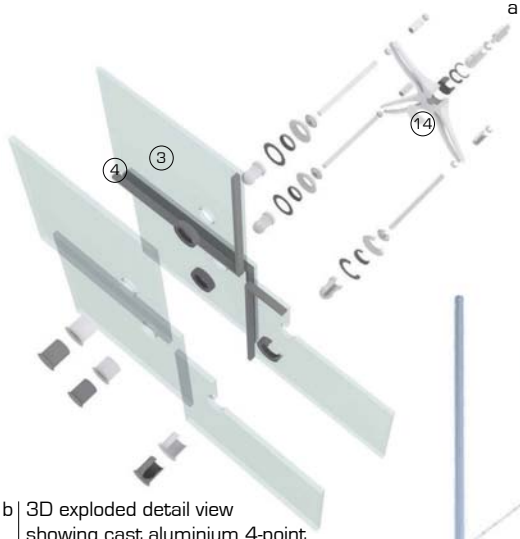
Glass systems 4: bolt fixed glazing



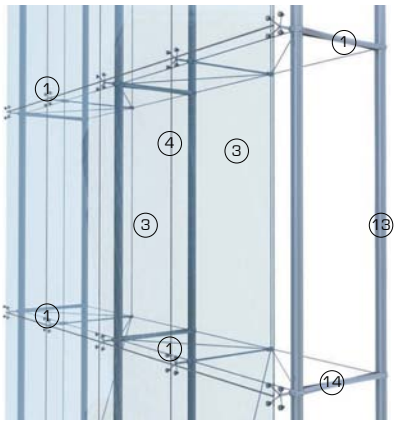




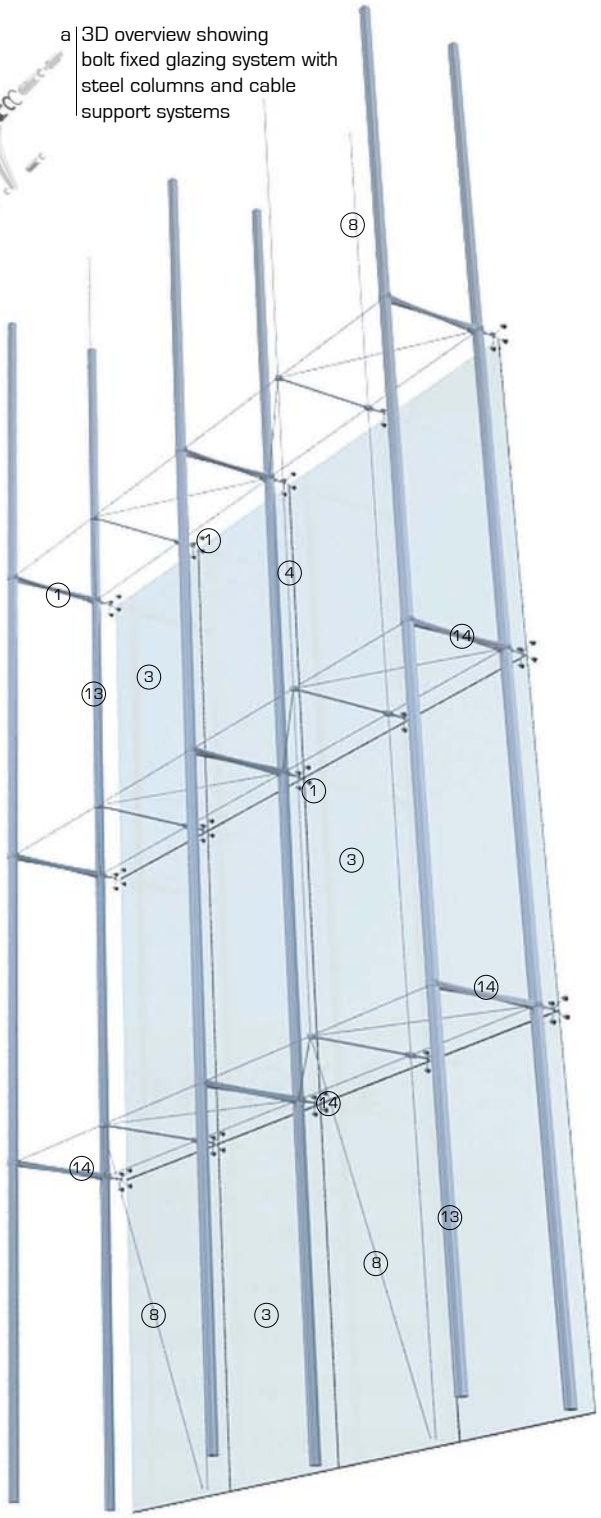
c | Vertical section of bolt fixed glazing system with cable support system



b | 3D exploded detail view showing cast aluminium 4-point spider clamp for bolt fixed glazing and connection to glazing panels

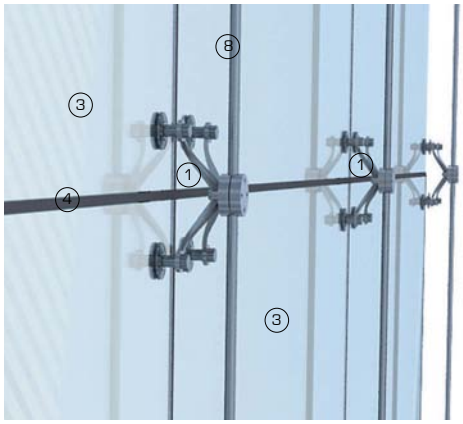


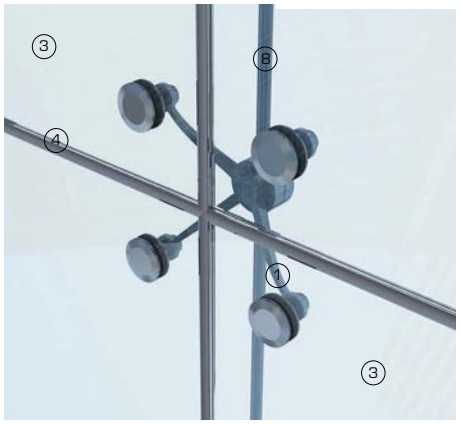
a | 3D overview showing bolt fixed glazing system with steel columns and cable support systems

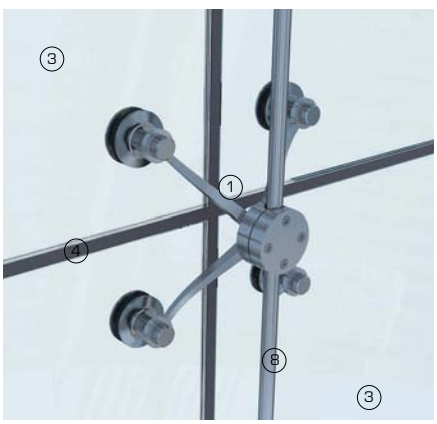


Details

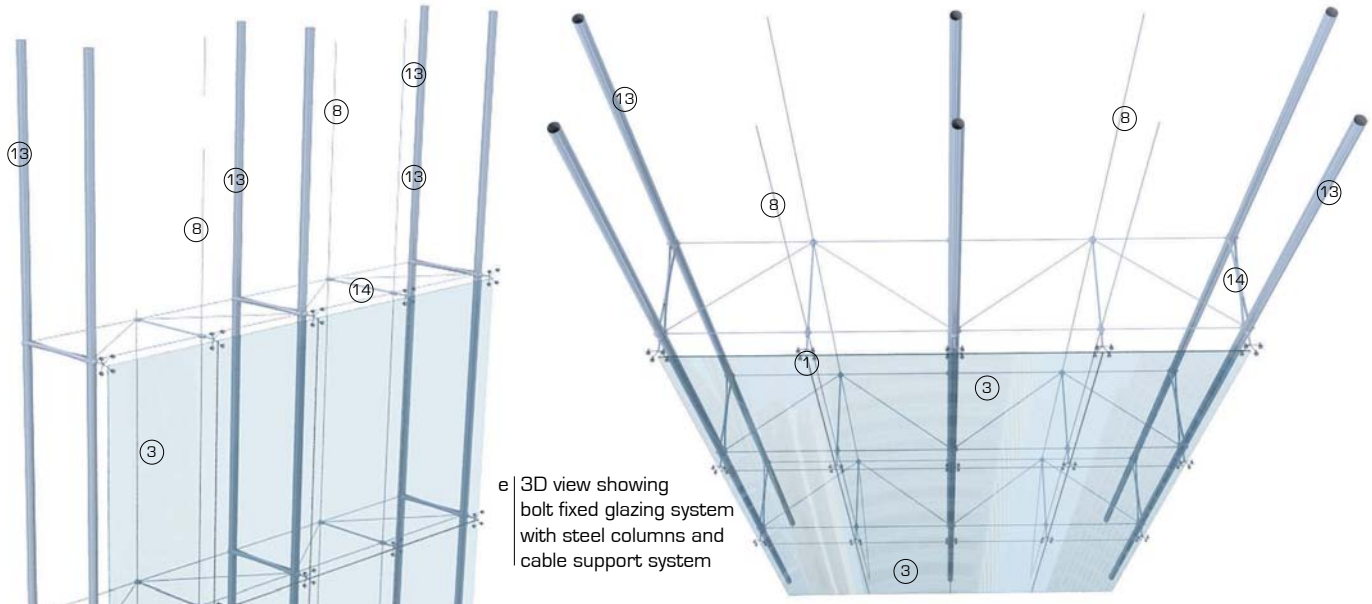
1	Cast steel connector
2	Mild steel or stainless steel angle bracket
3	Single-glazed or double-glazed unit to suit application
4	Silicone seal
5	Floor finish
6	Support bracket
7	Bolt fixing
8	Stainless steel cable
9	Insulated panel
10	Floor slab/structural wall
11	Bolt based cable end
12	Glazing channel at floor level
13	Structural column
14	Steel arm for lateral support





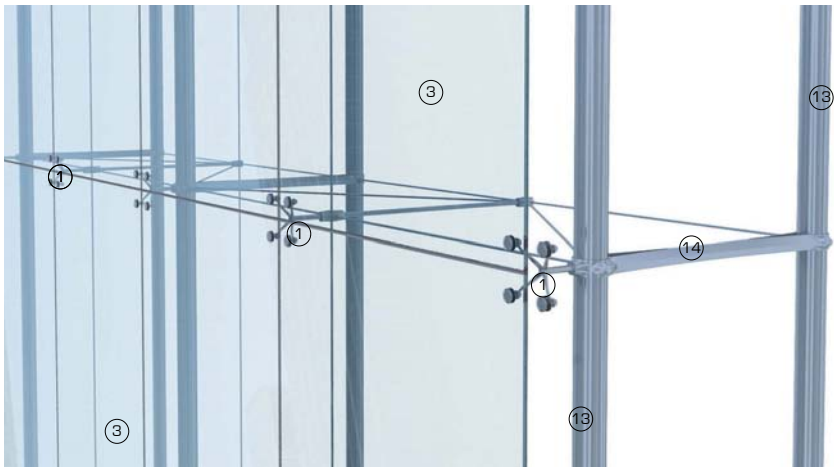


d | 3D views showing bolt fixed glass panels supported on cables



e | 3D view showing bolt fixed glazing system with steel columns and cable support system

f | 3D overview showing bolt fixed glazing system with steel columns and cable support systems



g | 3D detail view showing bolt fixed glazing system with steel structural support system

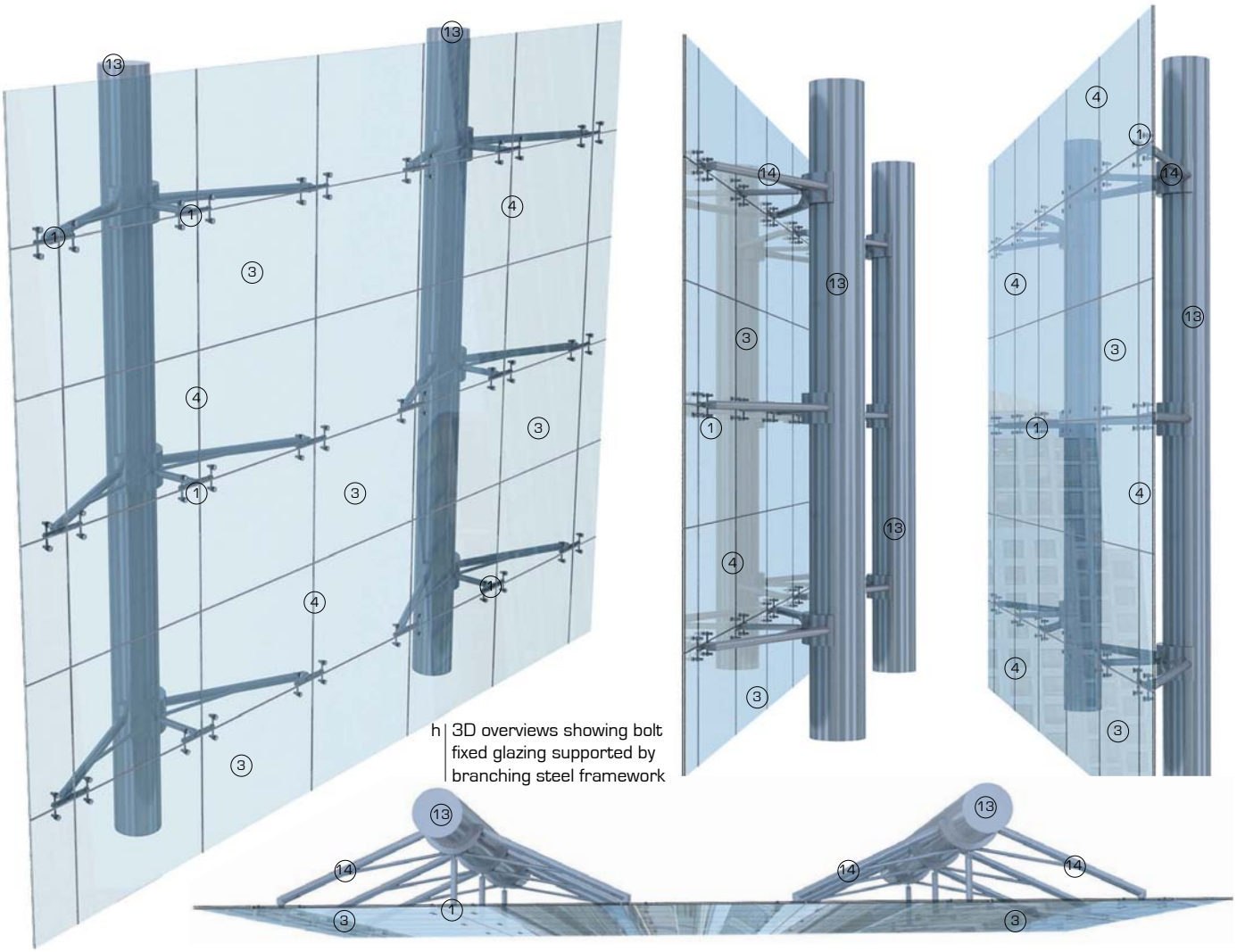
System design

Like clamped glazing, bolt fixed glazing is used for its ability to provide transparency, but usually with fixings set within the glass rather than at their edges (a). In common with that system, it was originally developed for single glazing but is more commonly used with double-glazed units, with their 50mm joint width which includes the edge of the unit. Despite the overall 50mm black joint width, the absence of framing and continuity of the reflective surface of glass makes this frameless system more visually lightweight than framed glazing. Setting bolt fixings within the glass (b) can have an advantage in reducing the span of the glass between fixings, ensuring that the glass thickness is optimised to a greater extent versus supporting the glass at its edges only.

Where clamped glazing is supported directly onto a supporting structure, bolt fixed glazing can be fixed on brackets which are cantilevered away from the supporting structure. The supporting structure can either be hung from the top of the glazed wall, or be supported at its base. These cantilevered brackets can also be fixed back to tensioned cables or rods (c), allowing a visually lightweight supporting structure to be used, but requiring lateral stability to overcome the higher deflections associated with cable structures. Lateral stability is usually provided by forming a vertically-set cable truss from the primary cable supporting the glass units (e), or by adding horizontal outriggers from structural columns to restrain the horizontal movement of the cables. In common with clamped glazing, glass fins or mild steel posts can be used to support the glazing, typically supported from their base (g). Glass fins are fixed perpendicular to the vertical joints between glazed units, with an L-shaped bracket with a bolt fixing at each end, with glass panels stacked one above the other, using the glass fins to provide lateral support. Glass fins can also be fixed at the top of the wall or at ceiling level, where they serve as stiffeners in a downstand condition, with the glass still being supported at its base. Glass fins have clamps fixed to them as per the patch plate system described in the previous section.

System details

With both top-hung and bottom-supported methods of support, bolt fixed glazing uses a similar fixing bolt which is determined by the size of the glass panel, the way it connects to the supporting structure and whether the fixing is countersunk or surface-fixed. The bolt fixing is the mechanical connection which is fixed through a hole formed in the glass sheet or double-glazed unit. Bolts can have a disc fixed to each external face of the glass (d), can be countersunk to be flush with the outer face of the glass, or can penetrate only the inner glass of a double-glazed unit. Structural movement and deflections between the supporting structure and the glass are accommodated with a rotating swivel connection at the junction of the bolt fixing that passes through the glass and the end of the threaded rod that projects forward of the glass which is connected to



h | 3D overviews showing bolt fixed glazing supported by branching steel framework

the supporting structure. The rotating joint is allowed to move 12º in all directions away from its regular position. The bolt fixings themselves can vary from those with a fully visible thread and nuts, to a fully integrated type where all these components are concealed in sleeves.

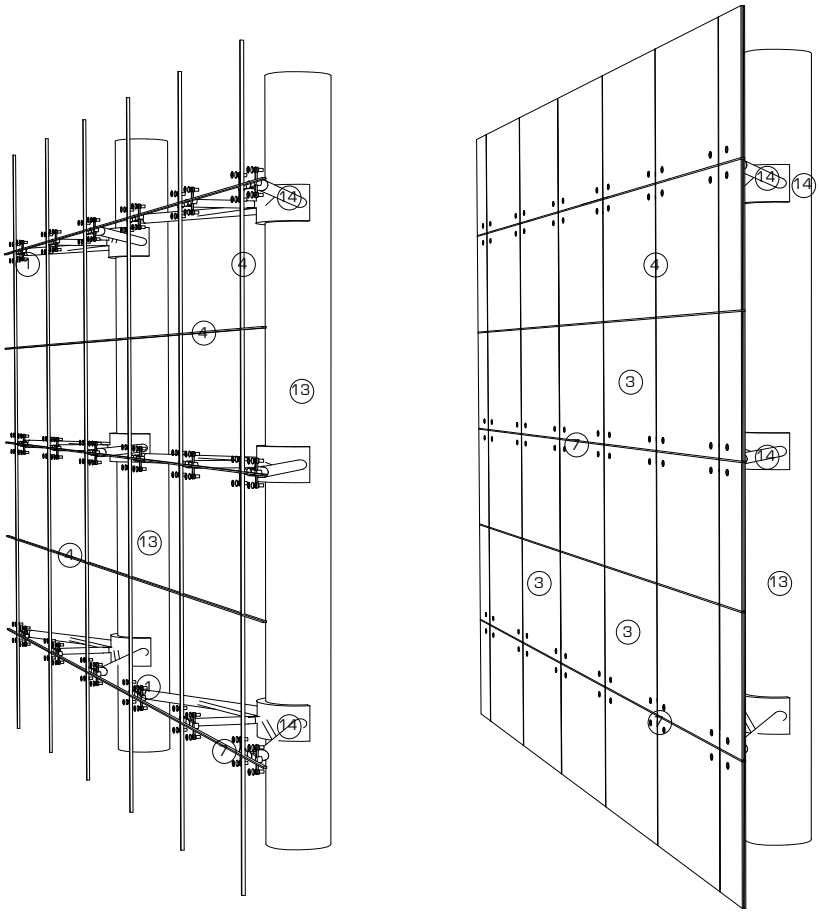
The bolt fixing is secured to fixing brackets whose shape suits the geometry of the intersection of four bolt fixings with the supporting structure. In small-scale applications, fixing brackets can be formed from a simple steel angle, with one side supporting the bolt fixing and the other side fixed to the supporting column or truss, for example. Larger-scale applications typically use X-shaped or H-shaped connectors to suit the position of bolts set around the intersection of four glass panels (k)(n). Connectors are made as either castings or machined/welded components depending on the quantity of connectors and their complexity. Where several parts are required to be welded and machined, it is usually more economic and visually preferable to use a casting.

Corner fixings are made either by cantilevering the meeting panels out in each glazed wall forming the corner and linking the glass panels together with bolt fixings in a pin connection, or by introducing structure at the corner, with bolt fixings being attached to a primary member. Where a corner bracket is used in conjunction with a cantilevered junction, manufacturers increasingly provide a limited range of standard components, though it is not uncommon for special connections to be provided, particularly for junctions where the meeting angle is not a right angle. Like clamped glazing, bolt fixed glazing is sealed between glazed panels with silicone seals, providing a single barrier to water penetration, but one which is reliable if properly undertaken.

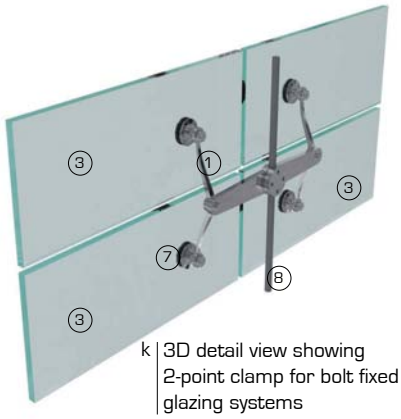
The ability of bolt fixings to provide limited rotation at their fixing point has led to their supporting structures being structurally ambitious, with a mixture of steel trusses and cables used to minimise the amount of material needed to support glazed units (h). Some have horizontally set wind trusses that stiffen an all-cable structure, while others use full-height vertical steel trusses with additional vertically set cables to reduce the number of trusses required. They also provide a fixing which is separate from the seals between glazed units, though both bolt fixed and clamped glazing methods have proved to be highly reliable in their weatherproofing performance. Where clamped glazing is used with flat surfaces or glazed walls of single curvature, bolt fixed glazing has the possibility of being set on a surface which curves in two directions, as in those created by cable net structures. Special care is needed to ensure that the angles of incidence at joints provide a reliable weathertight joint. An additional advantage is being able to fix the glass that is visibly forward of the supporting structure, sometimes creating a visual contrast between large structural members and a thin glazed skin set forward of it (j). This is particularly useful if the supporting structure is set in one primary direction, giving the impression that the glass is only partially supported, appearing to float free of its supporting structure.

Details

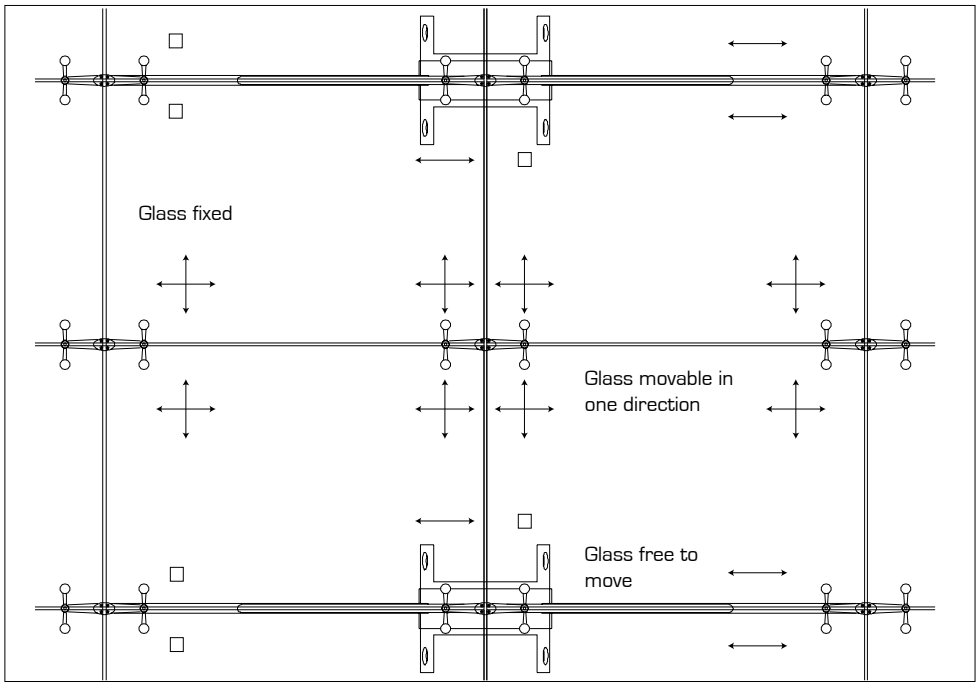
1 | Cast steel connector
2 | Mild steel or stainless steel angle bracket
3 | Single-glazed or double-glazed unit to suit application
4 | Silicone seal
5 | Floor finish
6 | Support bracket
7 | Bolt fixing
8 | Stainless steel cable
9 | Insulated panel
10 | Floor slab/structural wall
11 | Bolt based cable end
12 | Glazing channel at floor level
13 | Structural column
14 | Steel arm for lateral support

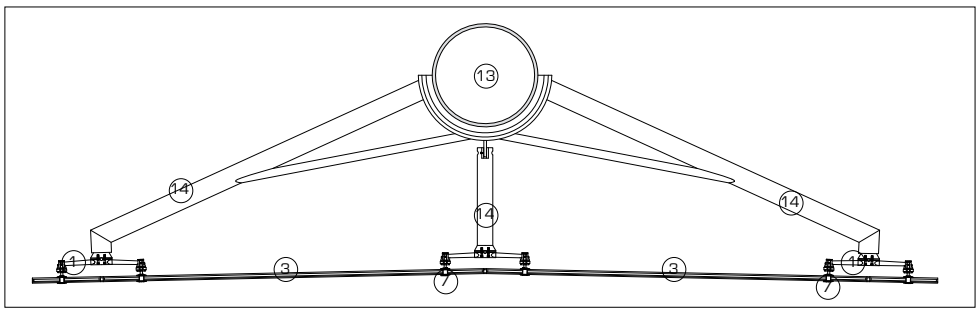


j | 3D views showing bolt fixed glazing supported by branched steel framework; depicted both with and without glazing panels

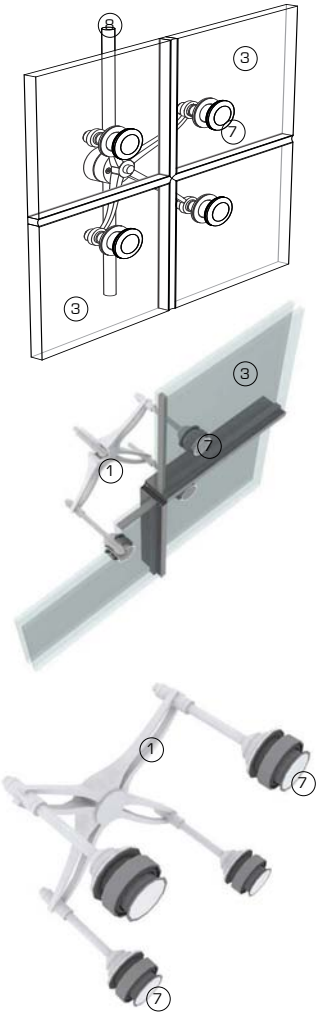


k | 3D detail view showing 2-point clamp for bolt fixed glazing systems

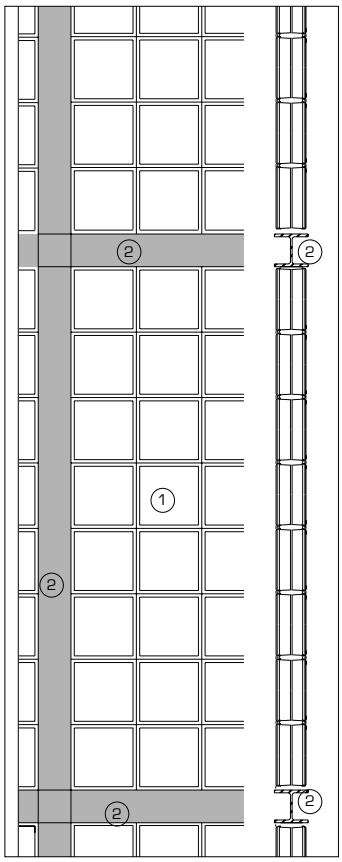




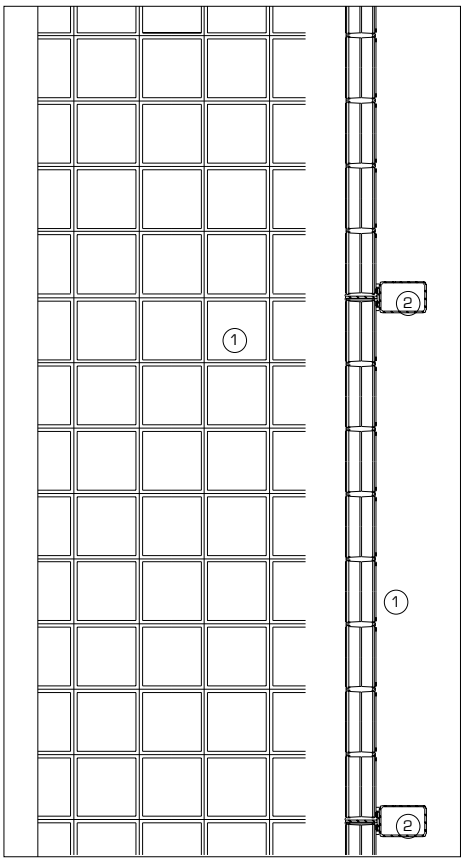
m | Elevation and horizontal section 1:50. Bolt fixed glazing supported by branching steel framework



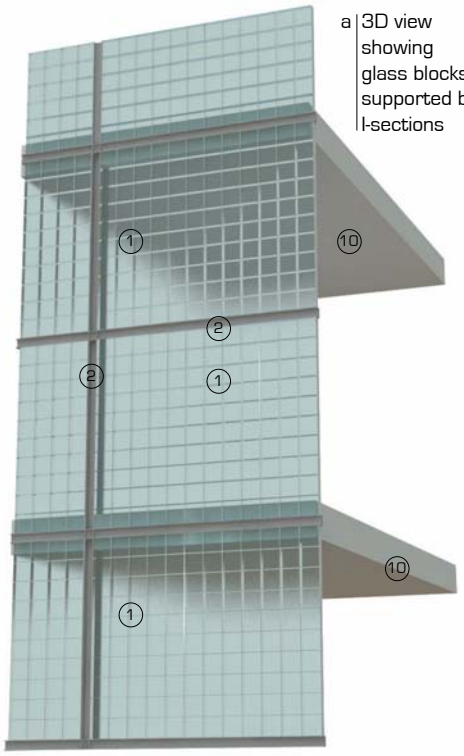
n | 3D view showing various 4-point clamps for bolt fixed glazing systems



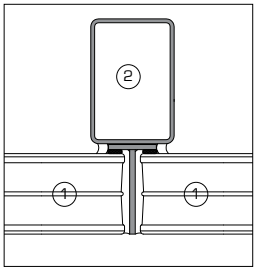
b | Elevation and vertical section 1:20. Glass blocks supported by steel I-sections



c | Elevation and vertical section 1:20. Glass blocks supported by box sections

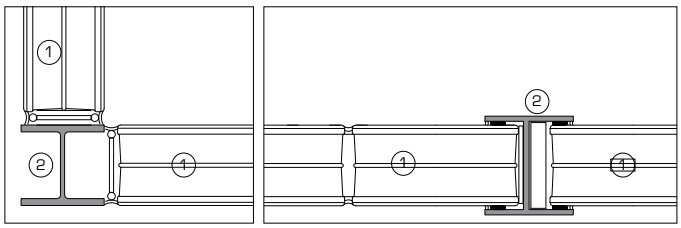


a | 3D view showing glass blocks supported by I-sections

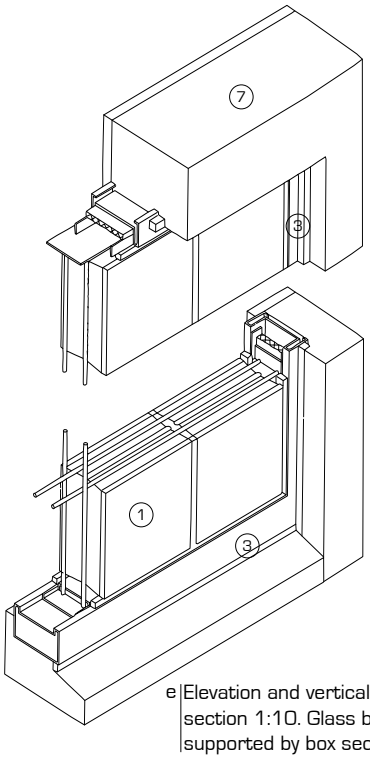


Details

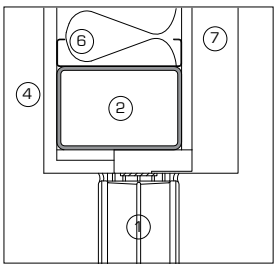
1 | Glass block
2 | I-section or box section
3 | Metal edge frame
4 | External cladding
5 | Steel flat or T-section
6 | Thermal insulation
7 | Enclosing wall or adjacent wall
8 | Window casement
9 | Cast glass channel
10 | Floor slab



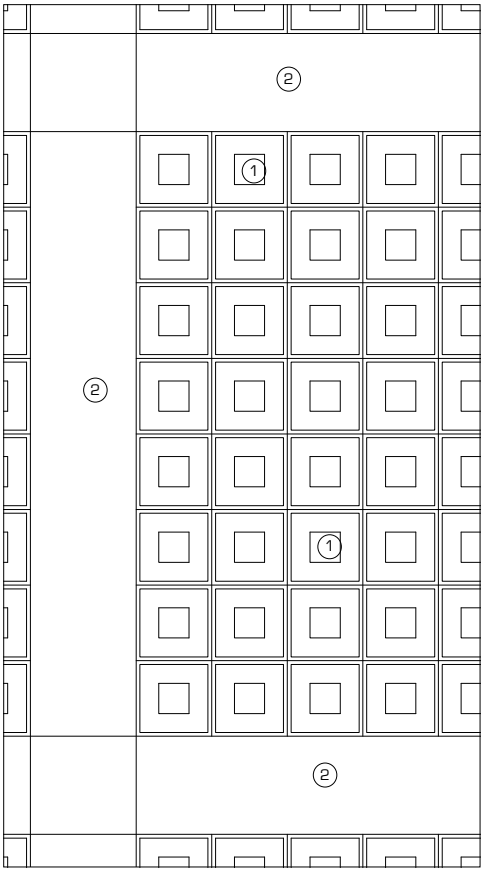
d | Horizontal section 1:10. Glass blocks supported by box sections







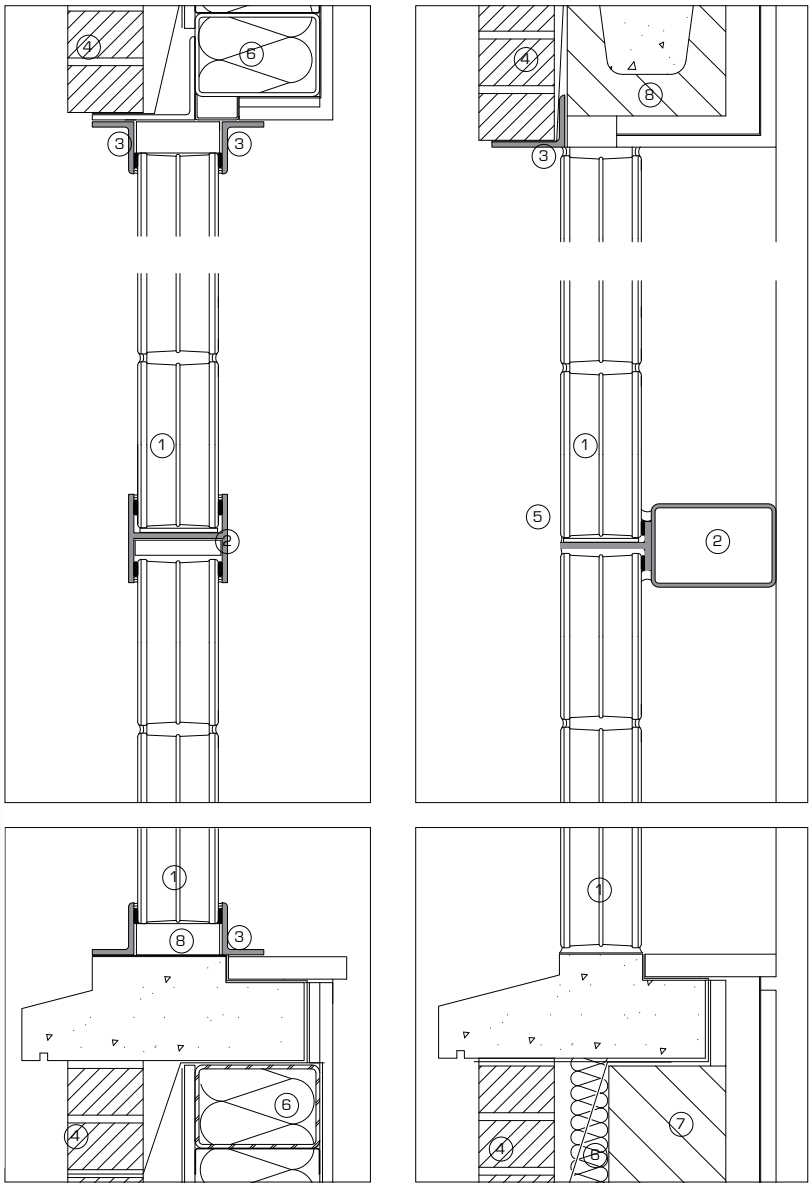
e | Elevation and vertical section 1:10. Glass blocks supported by box sections



f | Elevation and vertical section 1:20. Glass blocks supported by box sections



g | 3D view showing glass blocks within masonry wall



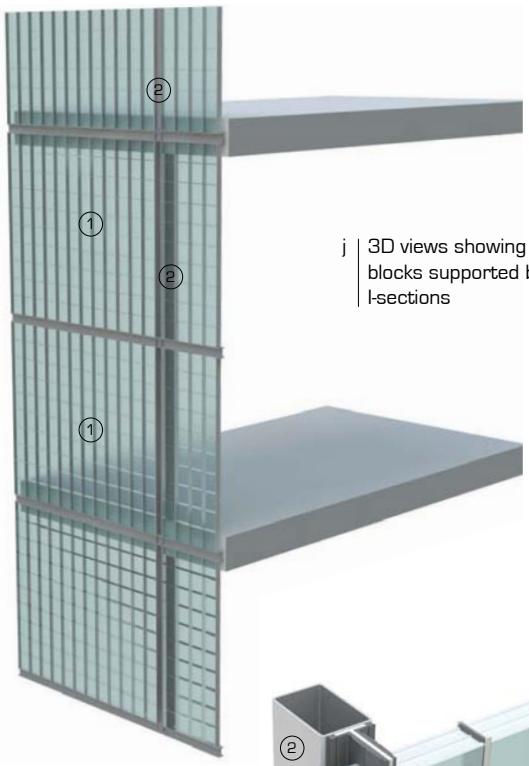
h | Vertical sections 1:10. Glass blocks fitted into window frames in masonry wall

System design

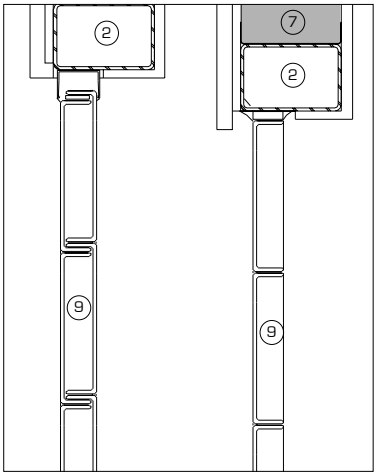
Glass blocks have been used in recent years for their qualities of robustness combined with fire resistance to form economic, translucent, glazed walls (a). Their translucency varies with the thickness of the wall of the individual glass block, which can range from solid to hollow type. The hollow type has the advantage of slightly greater thermal insulation and acoustic insulation, but the thermal insulation levels are well below those expected from regular double-glazed units, so they tend to be used in locations where this is not a design consideration, such as in naturally ventilated spaces. The most common block sizes are a nominal 200mm x 200mm and 300mm x 300mm, generally 100mm thick. Blocks are arranged in stack bonded rectilinear grids that form individual panels (b), formed either as openings in walls or as bays of a structural frame, typically in reinforced concrete or steel. The continuous vertical and horizontal joints of these non-loadbearing panels give their characteristic gridded appearance, with panel sizes limited from around 3600mm x 3600mm in area, to around 4500mm x 4500mm in area, depending on block thickness. The panel size can be adjusted in proportion to give a maximum height of around 6000mm and a maximum width of around 7500mm. Glass blocks are well-suited to providing an economic glazed fire resisting construction. One hour fire resisting panels can be made in panel sizes of around 3000mm x 3000mm in area, with a maximum height or width of 4000mm. Panels providing fire resistance greater than 60 minutes (usually up to 90 minutes) require metal channel restraints at the perimeter of the panel due to their greater reliability than cement mortar or silicone seals (c).

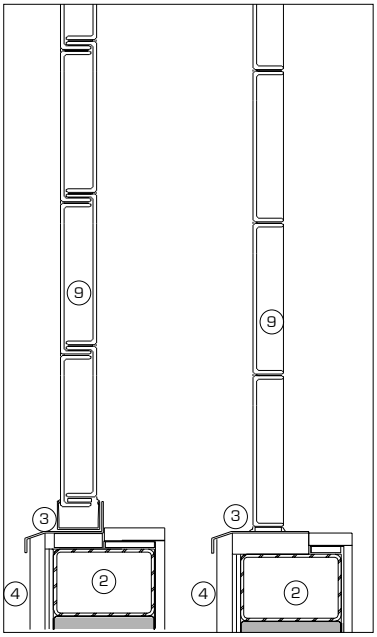
An alternative to glass blocks is cast glass channels, a long spanning material which can reach storey height without intermediary supports. Channels resemble half glass blocks in section, manufactured in lengths up to around 7000mm. Most are made around 250mm wide and 60mm deep. Channels are set either vertically or horizontally in a single layer, or can be interlocked by setting channels facing one another to form a double layer with a smooth internal and external appearance. The interlocked version also provides a U-value similar to that of hollow glass blocks. An advantage of glass channels is that they are made either with a patterned surface characteristic of casting, or are made clear, with no pattern or hue. They can be Low-E coated to assist thermal insulation, and when interlocked can be thermally insulated with proprietary gel to significantly improve their thermal performance, though this process can be disproportionate to the cost of the cast glass channels. Solar

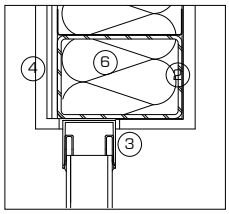


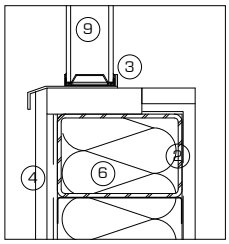


j | 3D views showing glass blocks supported by I-sections

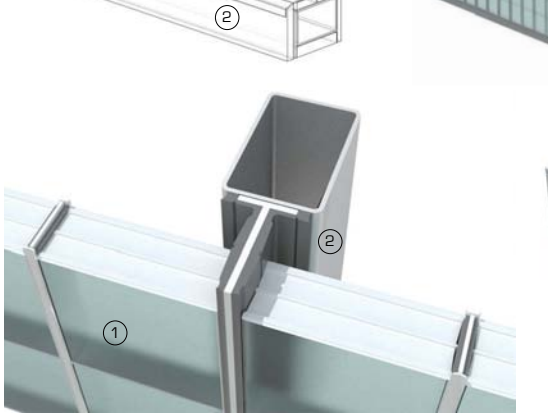








n | Horizontal and vertical sections 1:20. Vertically-set glass channels used as window







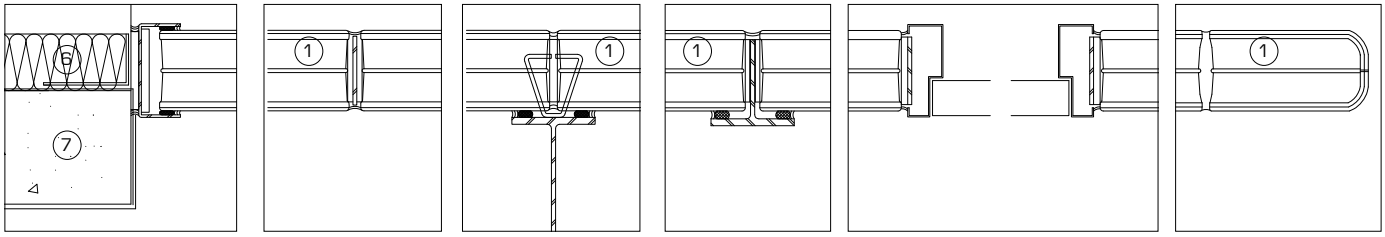
p | 3D view showing glass blocks within masonry wall

k | (Above) 3D view showing glass blocks supported by steel box-sections

m | Vertical sections 1:20. (Left) double skin of interlocking glass horizontal channels. (Right) Single skin

protection can also be added. Like glass blocks, cast glass channels are known for their properties of sound insulation combined with robustness (m). When stacked vertically, channels can be set out to form a curved wall, a characteristic well-known with glass block walls.

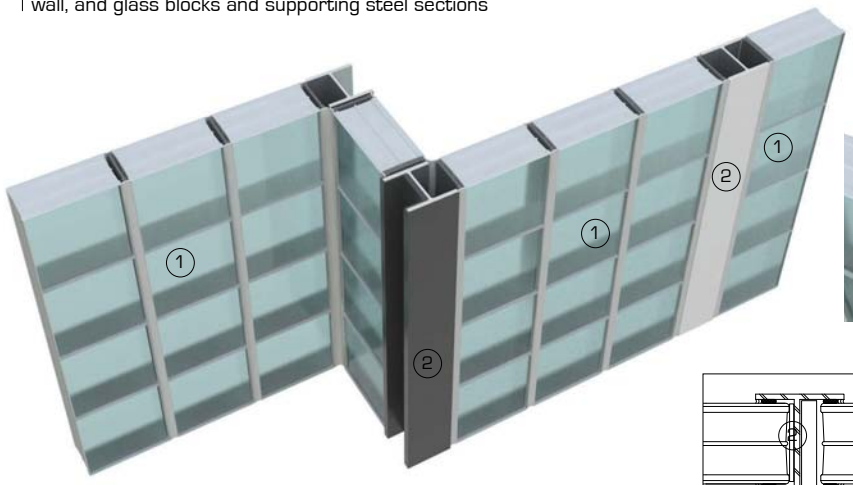
The relatively poor thermal insulation of glass blocks and cast channels, when compared to double-glazed units, can lead to condensation occurring on the interior face of the block, and adequate ventilation is required to avoid this. Consequently, their use remains ideally suited to semi-external conditions in temperate climates, such as circulation spaces. Glass block panels fixed into reinforced concrete frames or wall openings are bedded in either mortar or silicone (p), with flexible joints introduced on the sides and top edge to allow for structural movement. Glass blocks are set within the frame which forms the external wall, or on the edge of reinforced concrete floor slabs. Storey height panels on the edge of floor slabs require metal angle restraints at the top of the opening to accommodate the deflection in the slab. This can be overcome by setting the glass blocks forward of the floor slab on a steel frame in the manner of glazed curtain walling (q).

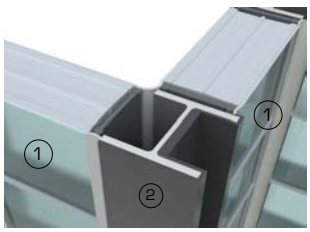


q | Horizontal section 1:10. Connection between glass blocks and cavity wall, and glass blocks and supporting steel sections

r | Horizontal section 1:10. Detail of door set into glass block wall

s | Horizontal section 1:10. Glass end block

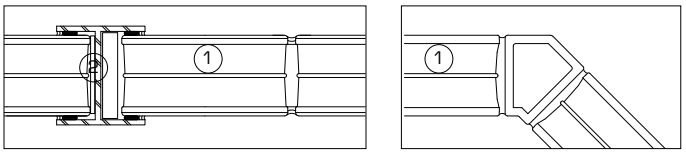




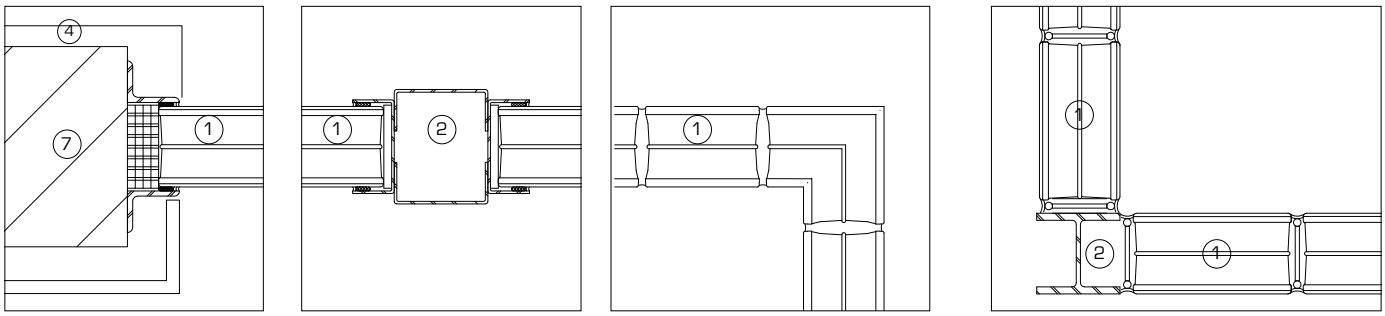
Details

1 | Glass block
2 | I-section or box section
3 | Metal edge frame
4 | External cladding
5 | Steel flat or T-section
6 | Thermal insulation
7 | Enclosing wall or adjacent wall
8 | Window casement
9 | Cast glass channel
10 | Floor slab

t | (Above) 3D views showing glass blocks supported by steel box-sections



u | vertical section 1:20. Double skin of interlocking glass horizontal channels



v | Vertical section 1:20. Double skin of interlocking glass horizontal channels

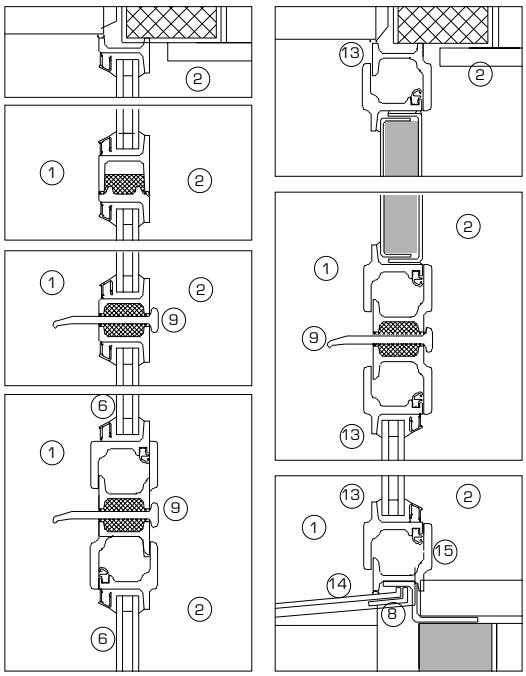
w | Vertical section 1:20. Double skin of interlocking glass horizontal channels

System details

Both glass blocks and cast channels can also be set into steel frames made from I-sections, box sections, T-sections or a combination of these (t). In smaller openings, a T-section is set into joints to stiffen the panels at mid-height between floor and ceiling/soffit. Larger panels can be formed by adding a rectangular box section to the back edge of the T-section to form a complete structural frame. Some manufacturers offer these materials as proprietary systems which include edge framing channels, though the appearance of these can be concealed by adjacent finishes.

Glass blocks usually have bed reinforcement between joints, typically a metal ladder-type reinforcing strip which is set within the joints and is not visible. Silicone is also used to bond blocks, with a sealing silicone used on the external face to provide a weathertight seal. Cement-based mortars are also used, with the choice of material being governed largely by visual considerations. Corners are formed usually with either the structure that supports the panel or special corner panels which form a part of most proprietary systems (u)(v), mainly 90º and 45º corners. Junctions of blocks with adjacent walls are formed with a flexible seal, either silicone-based or with metal angle restraints. The angles are usually concealed by wall finishes, both internally and externally. Flexible seals are used where a door or window opening is introduced into a glass block wall. The door is usually only fixed at its base in order to allow the block wall to be structurally independent, but sometimes the door is tied into the horizontal joints of the glass block wall, depending on the amount of expected structural movement.

Cast glass channels are fixed into aluminium extrusions at their ends, and are sealed with silicone-based seals between long joints (v). Vertically-set channels can be bottom supported, but in horizontally-set arrangements each channel is individually supported rather than being supported on the channel below. As with glass blocks, the edge frame can be concealed by wall finishes; but cast channels are increasingly being used as a primary material on facades where they are used, as they are not required to be set into framed panels, and can be used in storey height form in long lengths.



a | Vertical sections 1:5. Rolled steel frames glazed internally and externally

Details

1	Outside
2	Inside
3	Rolled steel glazing section
4	Transom
5	Mullion
6	Single-glazed or double-glazed unit to suit application
7	Fixing bead
8	Fixing lug
9	Projecting transom
10	Rubber-based seal
11	Fixed light
12	Inward opening light
13	Outward opening light
14	Window cill
15	Condensation tray
16	Internal finish
17	External wall
18	Thermal insulation



b | 3D view showing rolled steel window embedded within masonry wall construction



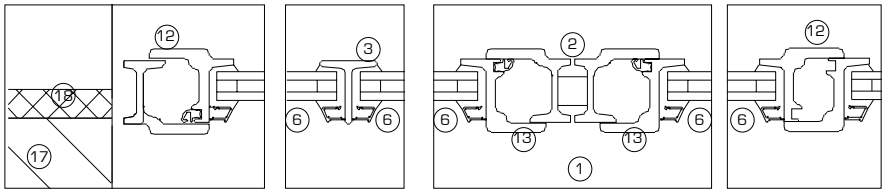
c | 3D detail views showing rolled steel window embedded within masonry wall construction at head and cill conditions

System design

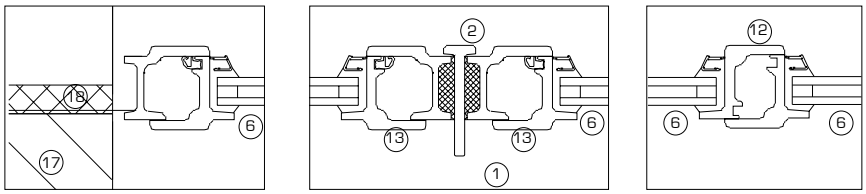
Steel framed windows made from rolled sections have been preferred for their thin sight lines when compared to those in aluminium for small-scale window openings (b). However, the thermal performance of the frames is considerably less than that of thermally broken aluminium sections, due to the difficulty of introducing a thermal break into small sections. Larger scale steel windows and glazed walls made from pressed steel sections, used mainly for their fire-resisting qualities, can incorporate a thermal break but their sightlines are similar to those of an equivalent aluminium window or glazed wall. Steel framed windows are either fitted into wall openings or are joined together to form a glazed wall with deeper sections as framing members (a), which is slightly different to full aluminium-based stick glazing.

Steel framed windows with thin frames excluding thermal breaks in thin double-glazed units are made with rolled steel sections to form windows of a maximum size of around 3000mm x 1800mm, down to a minimum size of 250mm x 400mm. Fixed lights and opening windows can be joined together with T-sections to provide a supporting frame (d)(e). Larger-scale steel curtain walling has a grid of pressed steel mullions (verticals) and transoms (horizontals) to which double-glazed units are fixed with steel pressure plates. Seals are provided with synthetic rubber gaskets similar to those used in aluminium curtain walling systems. Single-glazed units have small channels or angle-shaped glazing beads to hold the glass in place, while double-glazed units usually have extruded clips that hold the glass in place (f).

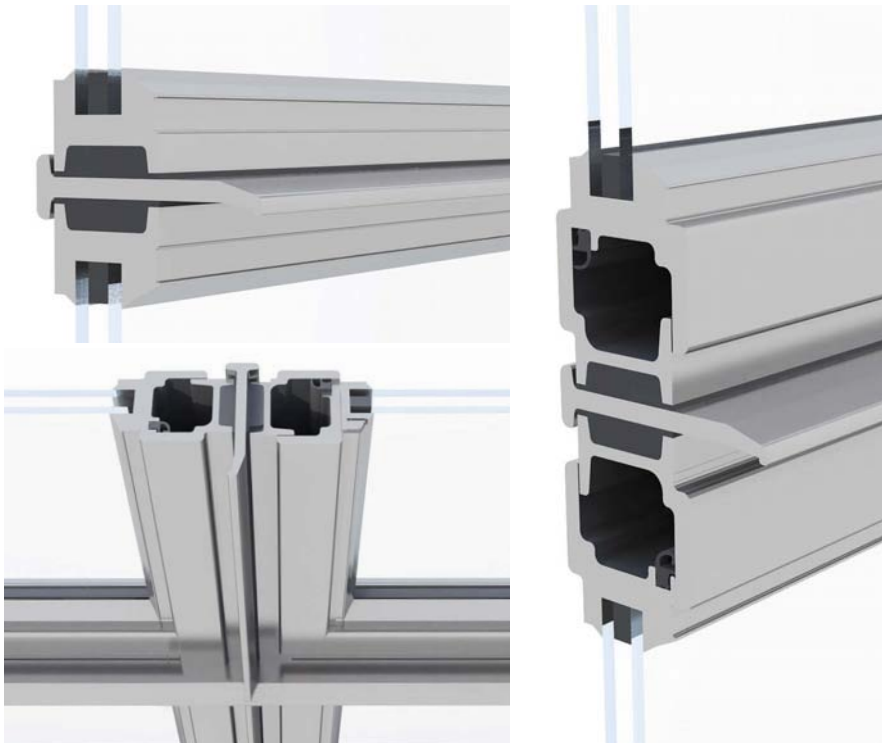
Larger scale, thermally broken windows and doors are used primarily for their ability to provide fire resistance. They are made as pressed steel sections in sizes similar to an equivalent in aluminium, but with slightly different profiles governed by the process of pressing, which cannot provide the complexity in section of extruded aluminium profiles. Unlike aluminium windows, where new extrusions can be made economic for each project, pressed and rolled sections for steel windows cannot produce new sections as easily. Fully glazed walls are made by fixing individual windows into a frame of pressed box sections with integral thermal breaks. There is a wide variety of standard sections available for the pressed steel profiles that support the glass, though it is more difficult to develop a profile for an individual project due to the constraints of pressing steel sheet, which is expensive to modify for individual projects.



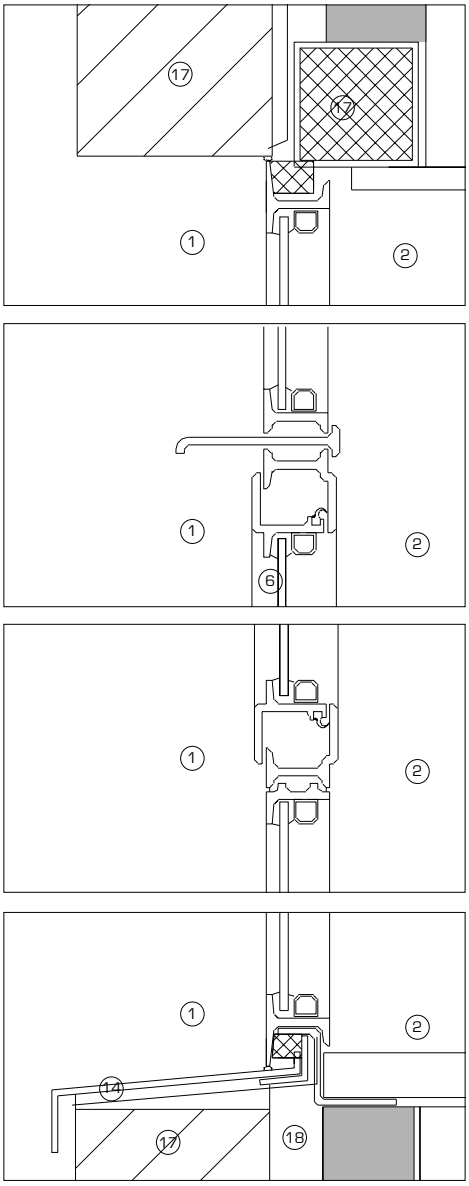
d | Horizontal section 1:5. Rolled steel frames glazed internally



d | Horizontal section 1:5. Rolled steel frames glazed externally



e | 3D detail views showing rolled steel frames with double glazing in glazing configurations



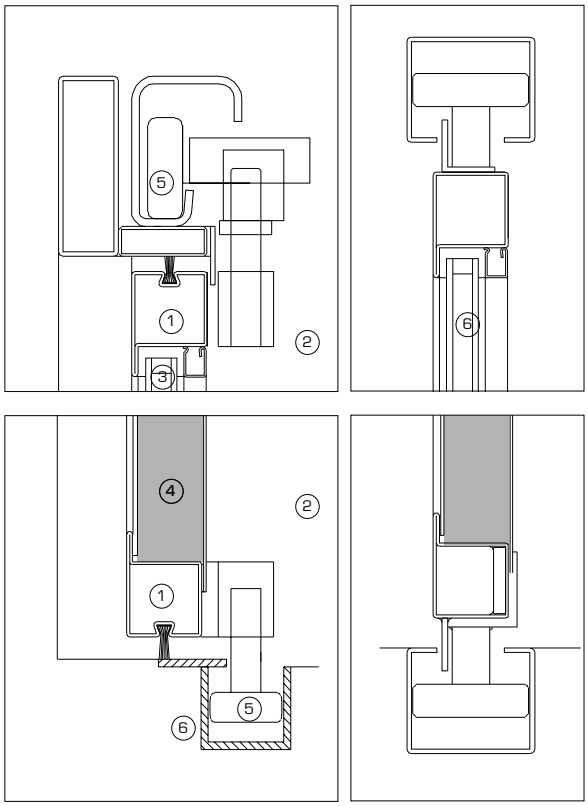
f | Vertical section 1:15. Rolled steel frame with single glazing

System details

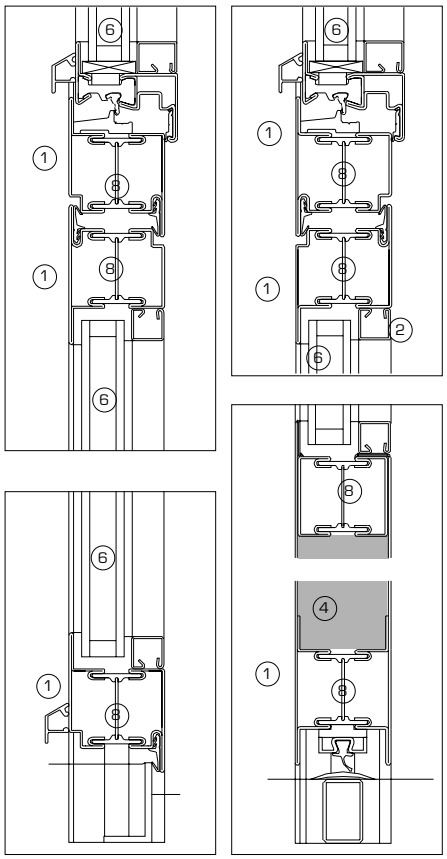
Outward opening lights for both windows in small-scale rolled sections and larger-scale pressed sections have profiles that lap over the front of the surrounding fixed frame, with a drip above the window to prevent rainwater finding its way in through the top of the frame (e). Any water that finds its way into the frame is drained down the sides and out at the bottom. Most windows have synthetic rubber seals to both assist drainage and reduce air infiltration through the opening light. With inward opening lights, the top of the window is protected by the top transom of the fixed frame. The window is more vulnerable at its bottom edge where it is protected by a projecting cill (f). With steel windows made from rolled sections, any water penetrating the outer seal runs around a groove in the frame of the opening light and down the sides into the bottom transom below, where it is drained through weep holes to the outside. This is similar to the principle of traditional timber windows, but windows made from thermally broken pressed sections can follow the principles of aluminium framed curtain walling, with a ventilated and pressure equalised chamber behind the outer seal which drains moisture away and back to the outside at the bottom. Opening windows and doors are set into steel framed glazing with an additional frame which is visible from the outside, a principle which is followed in aluminium windows and glazed walls. Door and window lights are formed from pressed steel sections which are folded together to form a family of profiles to suit different sizes and glass types. Steel framed windows and doors are also made as separate items for glazing into openings in masonry walls. In this instance they are fixed through the frame into the adjacent structural wall. An EPDM foil or silicone sealant is then used to seal the gap between the steel window/door and the adjacent concrete or masonry wall.

Larger-scale glazing has framing with a continuous indented groove that forms a channel into which toggle-type fixings are inserted to receive the fixings that secure the pressure plates. The synthetic rubber seals on either side of the glass provide a sealed chamber behind the pressure plate, which is used to drain away any water that penetrates the outer line of defence (d). This void is ventilated, with transoms draining water at the base of each glazed unit using a synthetic rubber strip that slopes down to drain water to the outside.

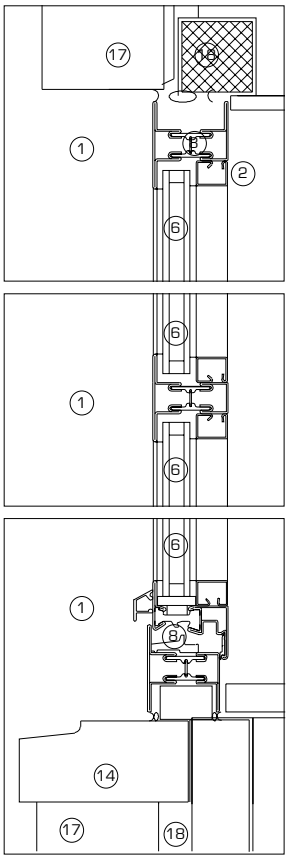
For both small-scale rolled sections and larger-scale pressed sections, doors are constructed in the same way as windows, but with horizontal



g | Vertical sections 1:5. Sliding/folding door with rubber seals



h | Vertical sections 1:5. Pressed steel doors with thermal breaks, both outward opening and inward opening



j | Vertical section 1:5. Pressed steel window, thermally broken

Details

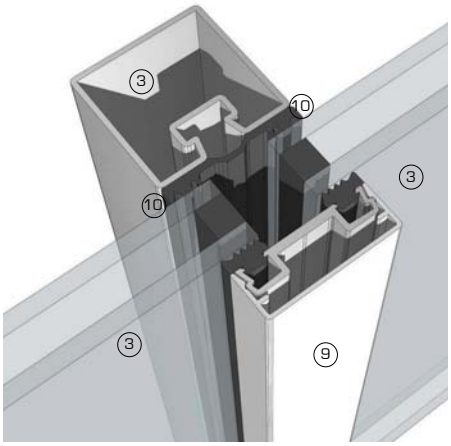
1 | Outside
2 | Inside
3 | Rolled steel glazing section
4 | Transom
5 | Mullion
6 | Single-glazed or double-glazed unit to suit application
7 | Fixing bead
8 | Fixing lug
9 | Projecting transom
10 | Rubber-based seal
11 | Fixed light
12 | Inward opening light
13 | Outward opening light
14 | Window cill
15 | Condensation tray
16 | Internal finish
17 | Concrete external wall
18 | Thermal insulation

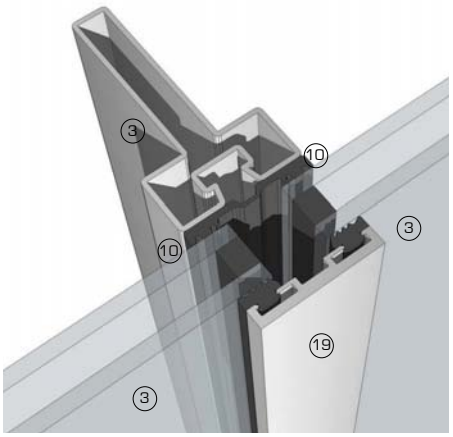


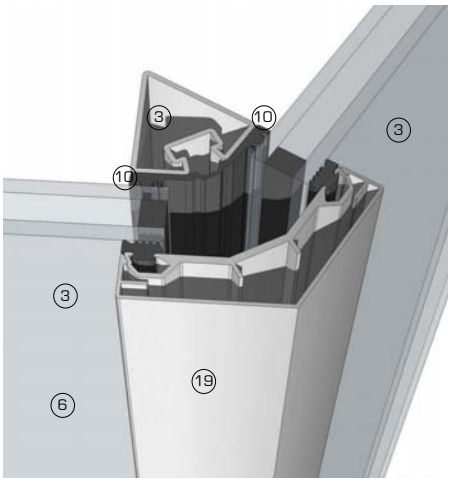
rails to provide greater stiffness where rolled sections are used, and with thicker horizontal sections in doors where pressed steel sections are used (g). Corners are framed with either glazed or glass-to-glass corners in the manner of aluminium curtain walling, but where the glazing is fire resistant, panel sizes are limited. Those in small-scale rolled sections are formed with either T-sections that meet to form a recessed corner, or with a square-shaped hollow section to form a solid corner (c). Corners using larger-scale pressed sections are formed in a similar way to stick glazing, with mullion profiles set together joined by a thermally insulated panel on the surface of the glass. Some manufacturers provide standard corner sections as part of a proprietary system. Parapets are formed by fixing a folded metal coping into the top transom and folding it over the parapet behind. Metal flashings with an EPDM foil behind it are also used to seal steel glazing against areas of adjacent walls, typically of masonry or concrete construction.

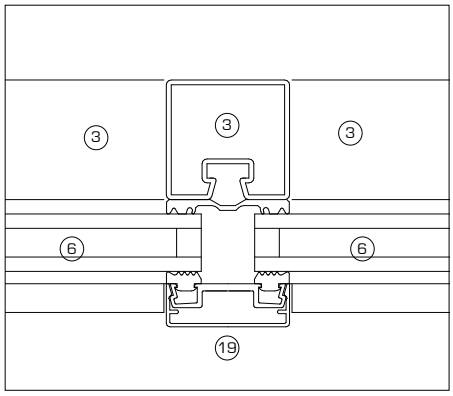


k | 3D views (internal and external) showing pressed steel window, thermally broken and set within masonry wall construction

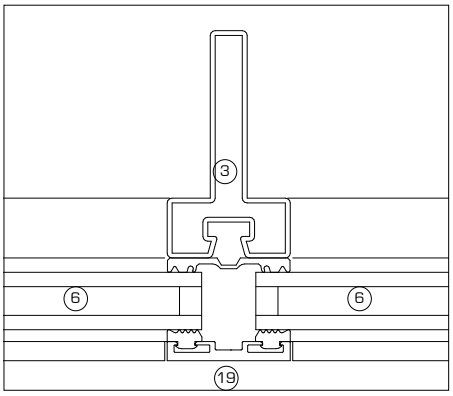




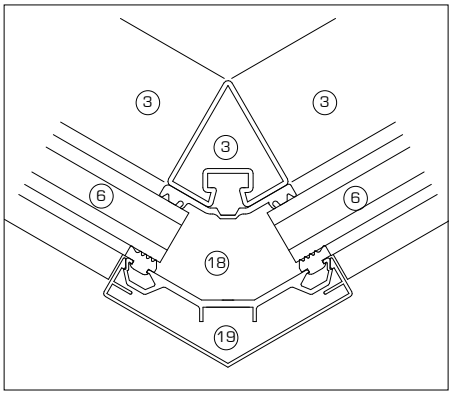




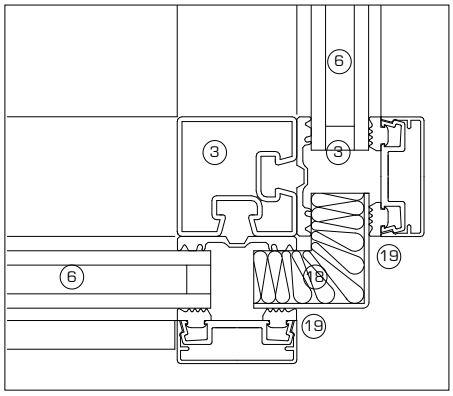
m | 3D view and horizontal section 1:2. Alternative capping profile for steel glazing system

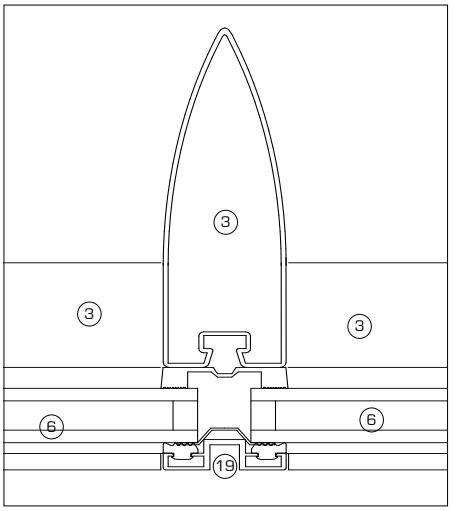


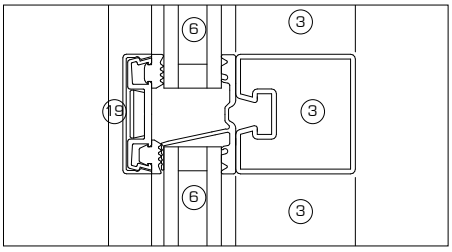
n | 3D view and horizontal section 1:2. Alternative capping profile for steel glazing system

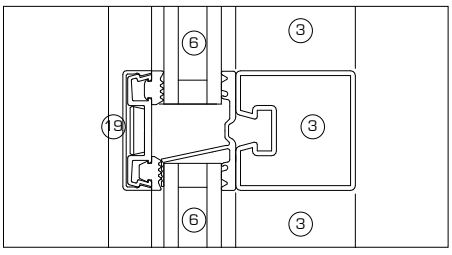


p | 3D view and horizontal section 1:2. Alternative capping profile for angled steel glazing system

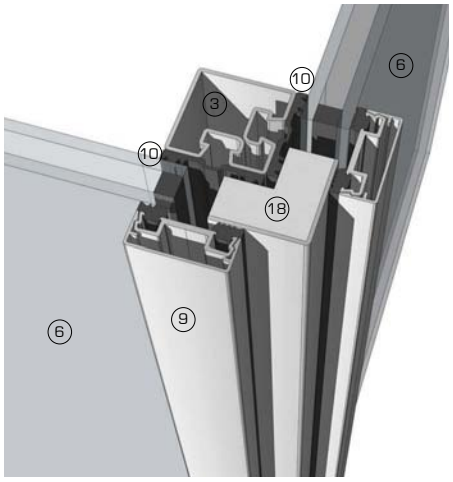




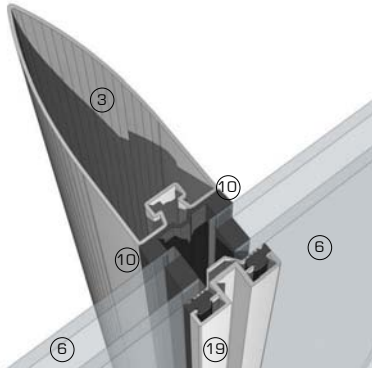




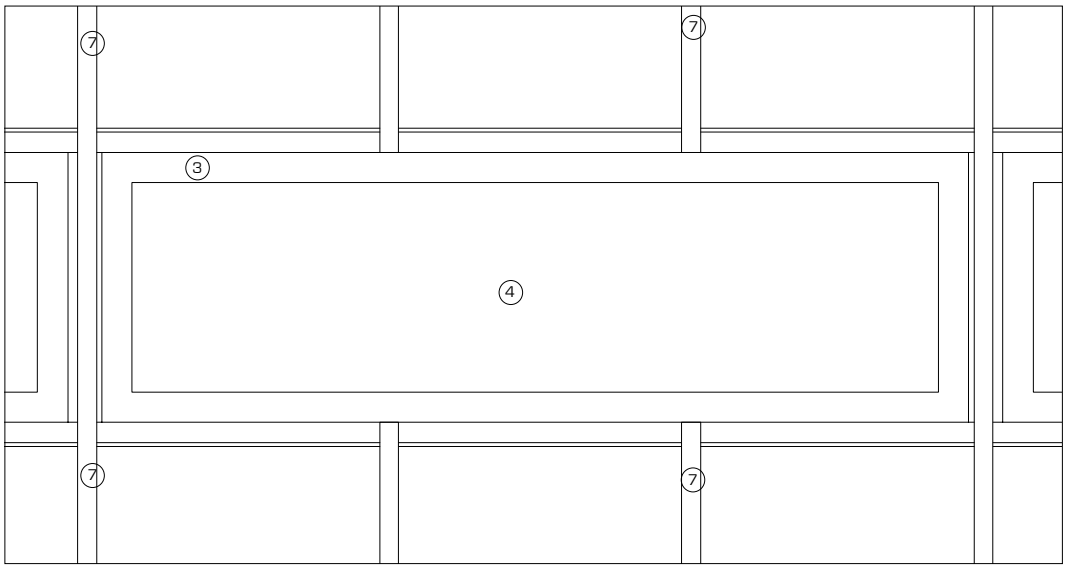
q | Horizontal section 1:2. Capping profiles for steel double-glazed system



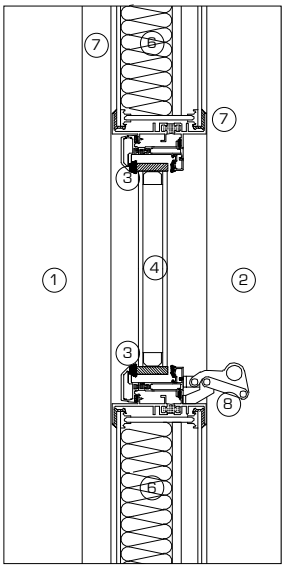
r | 3D view and horizontal section 1:2. Alternative capping profile for steel glazing system corner condition



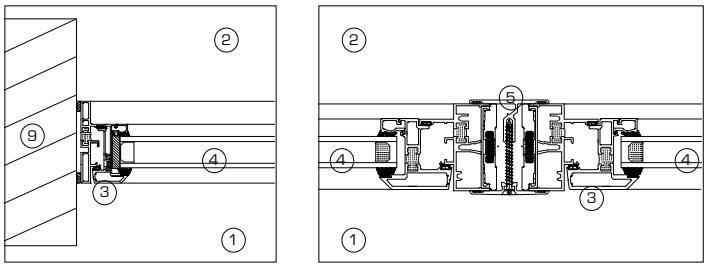
s | 3D view and horizontal section 1:2. Alternative capping profile for steel glazing system corner condition



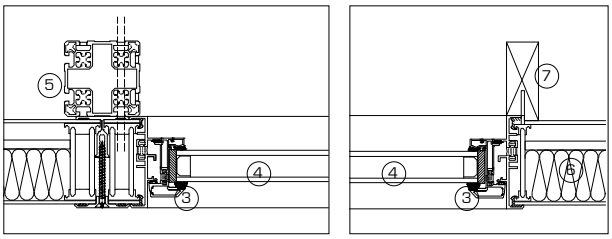
a | Elevation 1:10. Opening window set within large-scale aluminium window section



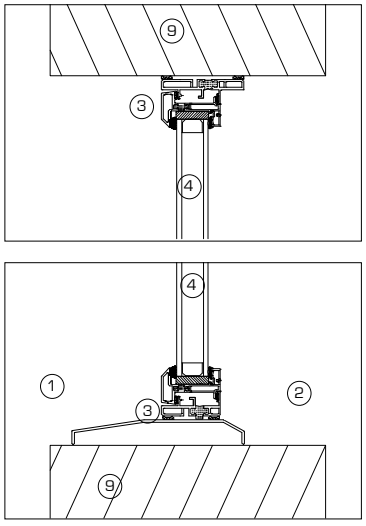
b | Vertical section 1:10. Outward opening aluminium window



c | Horizontal section 1:10. Outward opening window set typical wall construction



d | Horizontal section 1:10. Outward opening windows set within large-scale window assembly



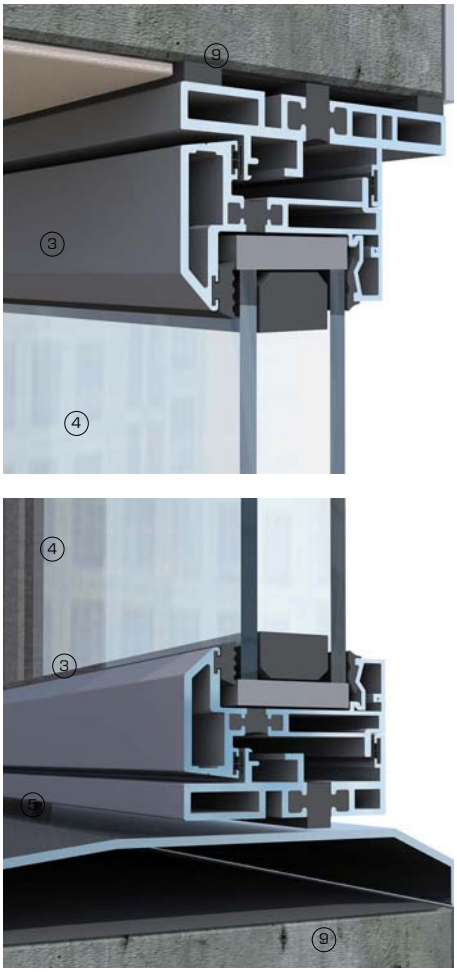
e | Vertical section 1:10. Outward opening aluminium window set within typical wall construction

Details

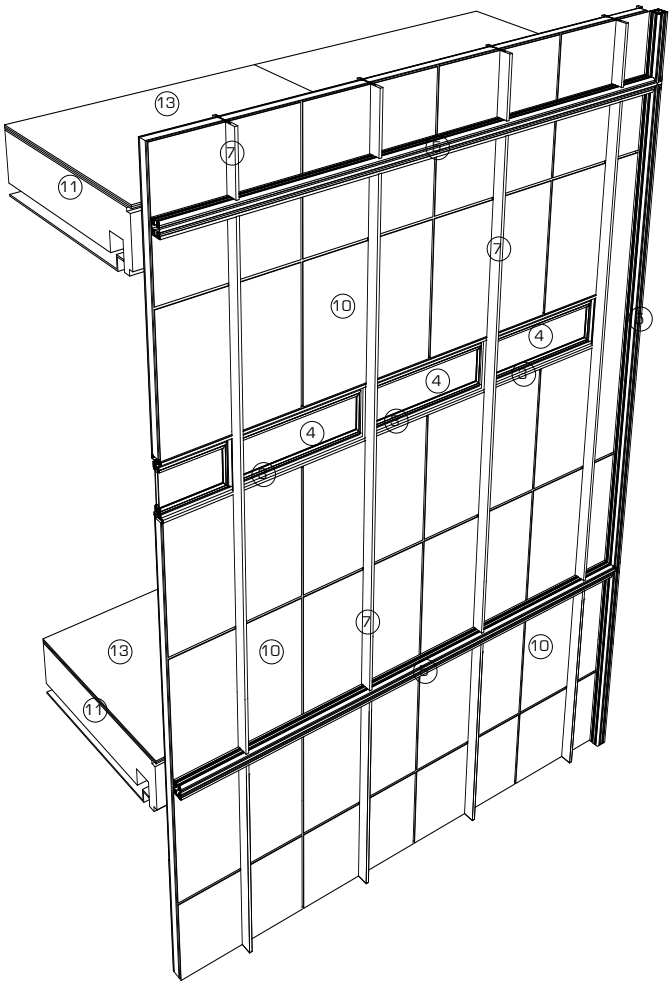
1 | Outside
2 | Inside
3 | Window frame
4 | Single-glazed or double-glazed unit to suit application
5 | Extruded aluminium section
6 | Thermal insulation
7 | Aluminium battens for decoration
8 | Opening mechanism
9 | Surrounding wall
10 | Insulated composite panel
11 | Floor construction
12 | Roof construction
13 | Internal finish



f | 3D view showing overview of aluminium glazing system set in masonry wall



g | 3D detail views showing aluminium glazing system set in masonry wall at head and cill



h | 3D view showing build-up of aluminium glazing system



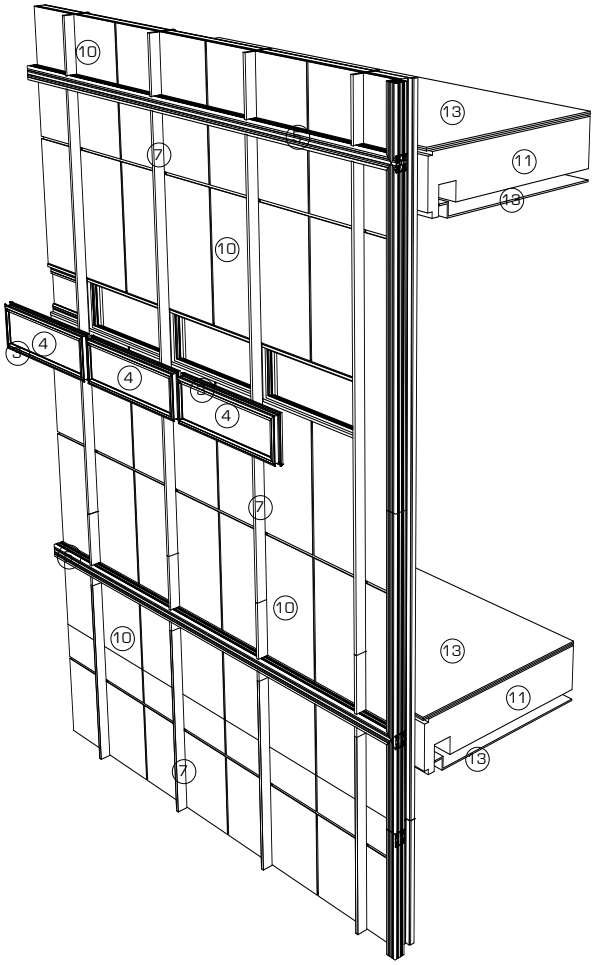
j | 3D cutaway view showing build-up of aluminium glazing system

System design

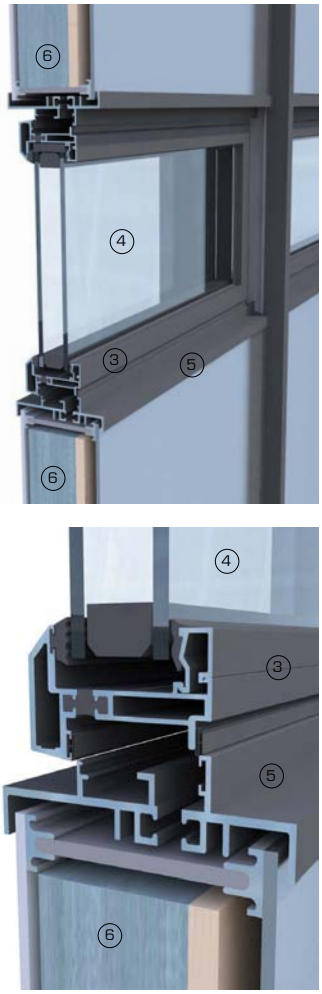
Windows made from aluminium are formed either as individual frames set into structural openings (a) or are set in groups to form a complete glazed wall where individual lights are linked to give the appearance of an overall modular glazed facade. A glazed wall, formed as a large-scale window assembly, is used typically where the glazed wall is not of sufficient size to require it to be supported or hung from floor to floor, which is the principle of stick glazing and unitised glazing in curtain walling. In contrast to curtain walling, which is a structurally independent external wall, 'window walls' have windows fixed onto a structural frame or backing wall, which is set into a larger structural opening in a facade. Window walls provide the appearance of a curtain wall combined with the acoustic and fire-resisting properties of its backing wall, making it suitable for apartments, for example. Window walls are typically supported at their base, but can also be top hung or side hung depending on their geometry.

An advantage of aluminium windows over those in other materials is their use of extruded profiles, which can take up complex shapes in section to which thermal breaks and seals can be fixed with ease (g), and within which water can be drained with a high level of precision. This allows aluminium window frames to be relatively well-insulated thermally, and have low rates of air infiltration when compared to other materials. The main disadvantage, from a visual point of view, is the wide sightlines required for structural reasons in accommodating seals for internal drainage and thermal breaks (f). Where sightlines are reduced, the overall depth of window is increased to compensate for the loss of stability of the frame. In common with aluminium curtain walling, extruded aluminium window frames are pressure equalised and internally drained in order to provide two lines of defence against rainwater penetration. An outer seal, typically a synthetic rubber gasket, excludes most of the rainwater; but any water that passes through is drained away at the bottom of the profile to the outside. The internal barrier serves as an air seal rather than as a full weathertight seal (c). An additional function of the gasket seal is to provide a continuity with the thermal break so that the air temperature of the inner chamber is much closer to the internal temperature than the external temperature.

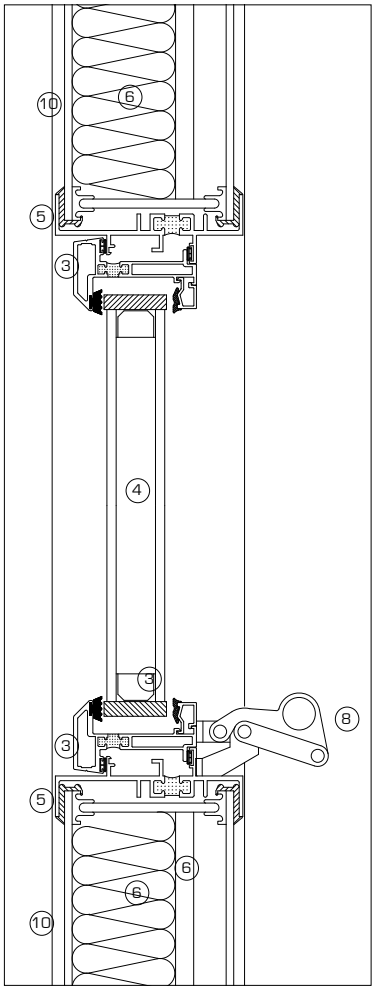
Where window frames tend to be narrow (j) and deep in section in order to accommodate the seals and thermal breaks, doors are usually wider in order to provide greater stiffness for the glazed units which they support. Doors were not usually thermally broken until recently, since the rigidity and durability of the frame is usually the most important consideration, but thermal breaks are becoming much more common in door sections. Doors with lower air infiltration rates and a thermal break are made from window sections rather than door sections. The increased performance usually results in smaller maximum size doors, at around 2400mm for a thermally broken, internally drained and ventilated door. Doors with thermal breaks can reach a maximum of around 3000mm to 3500mm without wide sightlines. Doors with thermal breaks can exceed 2400mm in height by silicone bonding



k | 3D exploded view showing opening window set into large-scale aluminium frame assembly



m | 3D detail views showing opening window set into large-scale aluminium wall system



n | Vertical section 1:5. Opening window detail

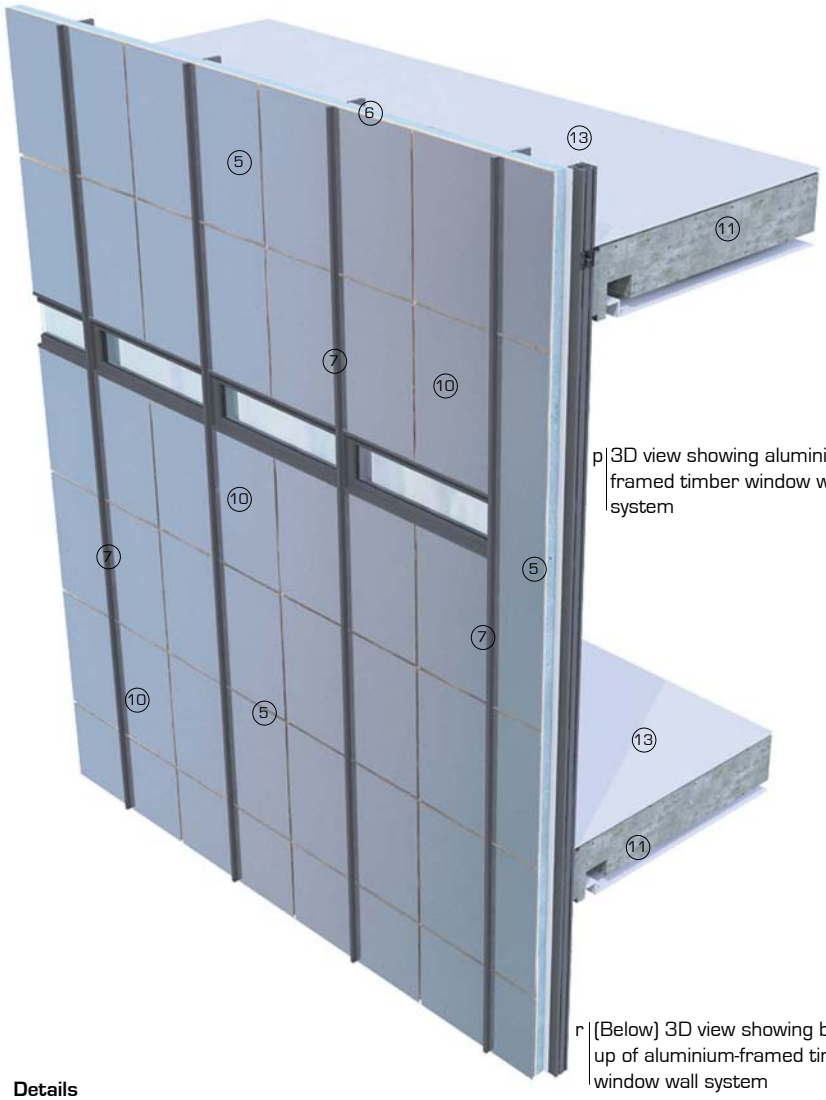
the glass to the frame so that it assists in stiffening the frame. The maximum width of doors is a function of their height in order to restrict the overall weight, but a 850mm wide door leaf forming a 1700mm wide pair of doors is not uncommon. Minimum width of opening lights is about 250mm where a double-glazed unit is used. Minimum heights of glazed ventilators, such as those set above doors for night-time ventilation, are around 250mm to suit the needs of the opening mechanism (k). Side hung, top hung, bottom hung and tilt/turn windows use similar aluminium profiles.

System details

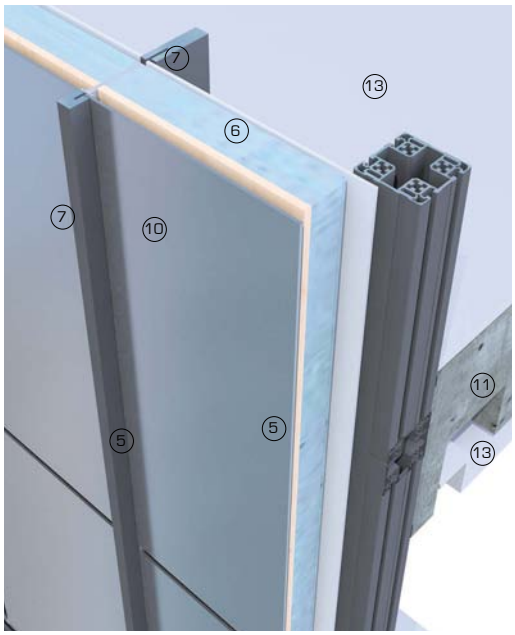
A recent development has been the introduction of parallel opening lights, where windows open in a direction parallel to that of the frame. This has an advantage of increasing the amount of air that is admitted without exposing a complete section of wall to the effects of both wind and solar radiation. If solar control glass is used in the opening light, then that shading function is largely maintained when the window is in the open position. These windows also help smoke evacuation when used as smoke vents; but an essential characteristic is visual, having opening lights in glazed walls which do not interrupt the visual continuity of the overall facade design. Parallel opening windows use a scissor-shaped hinge which slides within the frame to provide a stable support for the open window in any position. These opening lights (n) are used with windows that use stick glazing sections used in curtain walls, particularly where the double-glazed units are silicone bonded to reduce the visual impact of their supporting frames.

Windows and doors are sealed at their interface with the surrounding walls usually with a synthetic rubber strip which forms an integral part of the window frames, or alternatively with a seal between window frame and opening, typically with a silicone-based product. Some synthetic rubber seals have a metal facing for additional protection, called a 'foil', which is bonded to the adjacent wall and is usually concealed by the adjacent construction. The EPDM-foil seal is used where the window is fitted first, since the surrounding wall must be clear in order to fix it, and a perimeter seal is usually used where the window is fitted after the adjacent external wall has been completed.

Where aluminium window walls are used (p), opaque glazed infill panels are set between window panels as a facing to the insulated backing wall arranged immediately behind (q). Metal infill panels are also used, sometimes in rainscreen configuration, but more typically sealed in a supporting framework. Where opaque panels are used, opaque panels are fitted to a simple support as required by rainscreens and composite panels rather than a full window wall framing system (r). In this window wall configuration, windows are set in front of the opening where the complete facade is required to be in a single plane, rather than within the opening itself. The gap between window and opening is closed with metal flashings, which can be concealed with internal finishes (t).



p | 3D view showing aluminium-framed timber window wall system

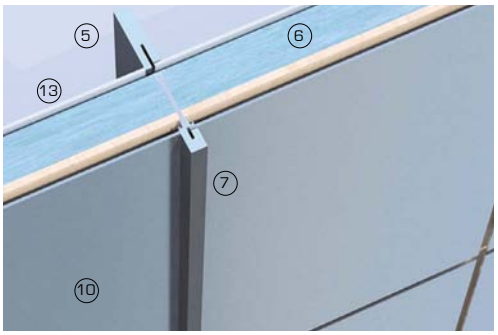


q | 3D detail view showing aluminium-framed timber window wall system

r | (Below) 3D view showing build-up of aluminium-framed timber window wall system

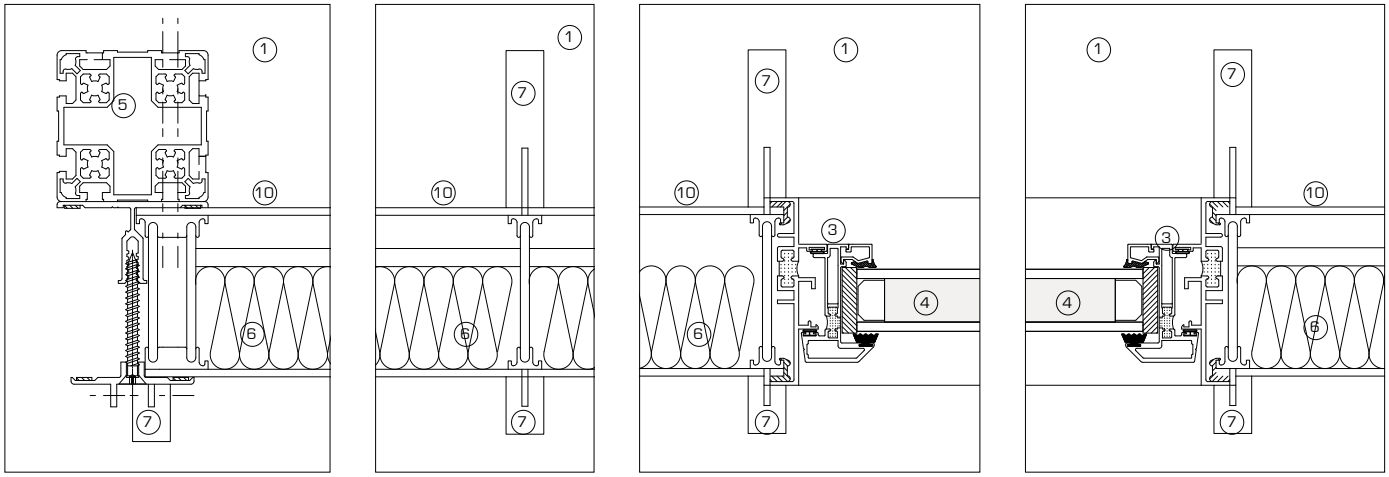
Details

1 | Outside
2 | Inside
3 | Window frame
4 | Single-glazed or double-glazed unit to suit application
5 | Extruded aluminium section
6 | Thermal insulation
7 | Aluminium battens for decoration
8 | Opening mechanism
9 | Surrounding wall
10 | Insulated composite panel
11 | Floor construction
12 | Roof construction
13 | Internal finish

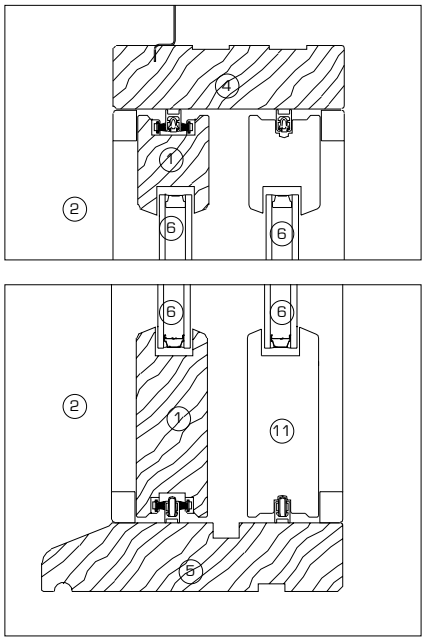




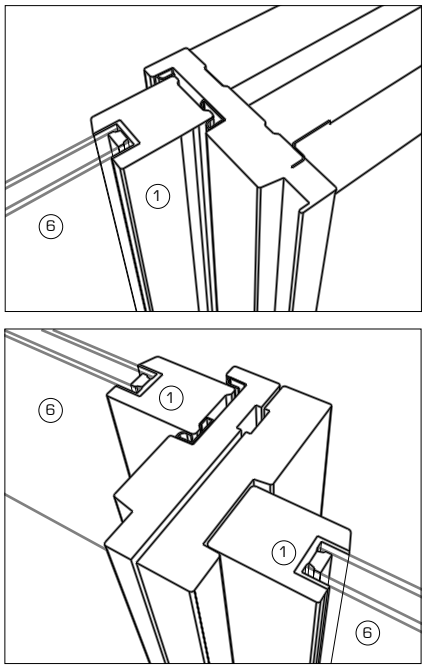
s | 3D rear view showing aluminium-framed timber window wall system



t | Horizontal sections 1:5. Aluminium window wall system showing typical panel and window details



a | Vertical section 1:5 Sliding doors



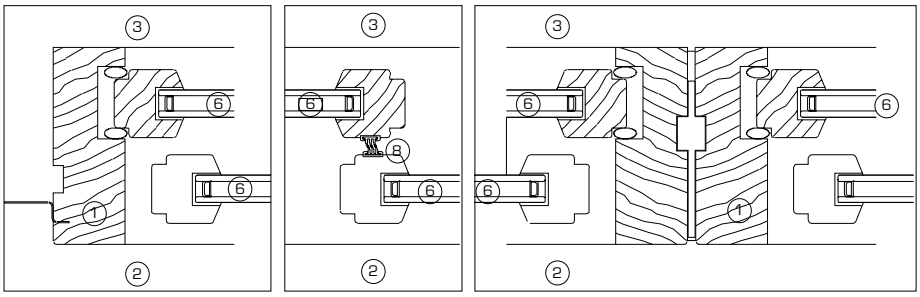
c | 3-D detail views of sliding doors



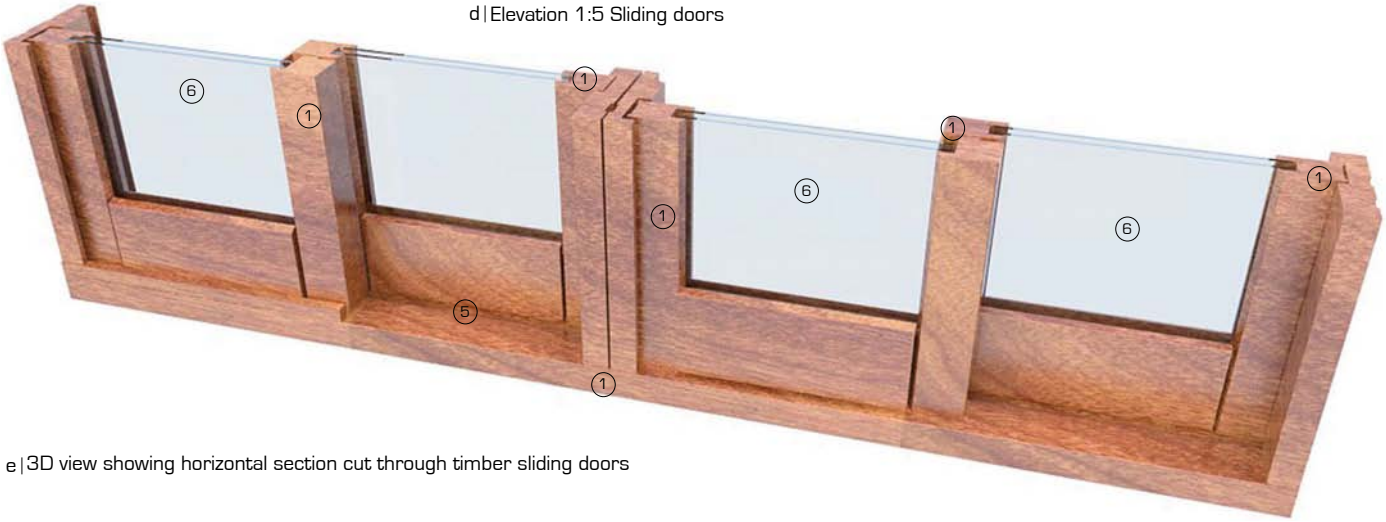
Details

1	Timber window frame
2	Outside
3	Inside
4	Head
5	Cill
6	Single-glazed or double-glazed unit to suit application
7	Fixing bead
8	Rubber-based seal
9	Structural concrete column
10	Timber spandrel panel
11	Thermal insulation
12	Concrete floor slab
13	Internal finish

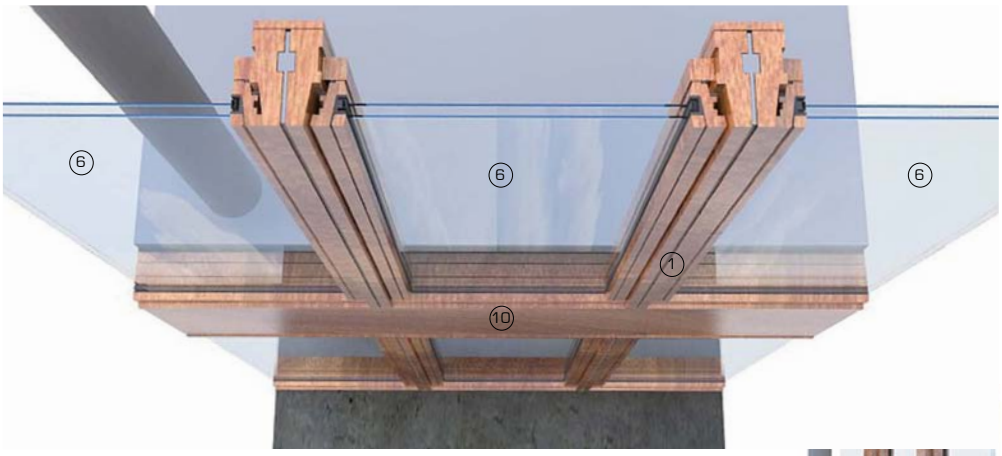
b | 3D view showing timber doors and windows in wall system



d | Elevation 1:5 Sliding doors



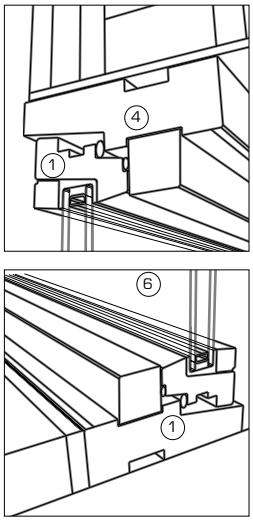
e | 3D view showing horizontal section cut through timber sliding doors



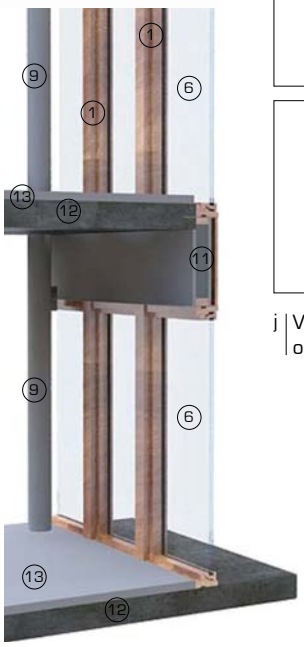
f | 3D view showing timber doors and windows in wall system

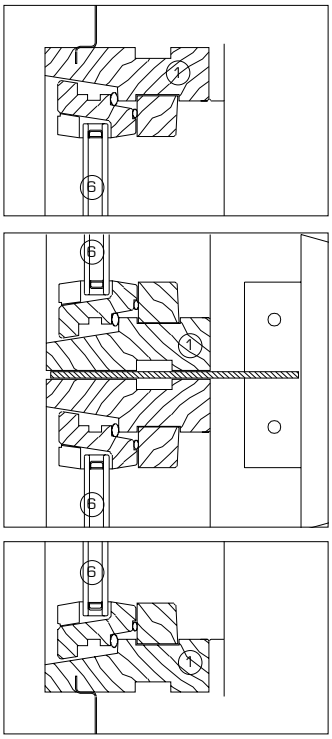


g | 3D detail view showing spandrel panel in timber door and window wall system



h | 3D views showing head and cill conditions in timber door





j | Vertical section 1:5 Outward opening casement windows

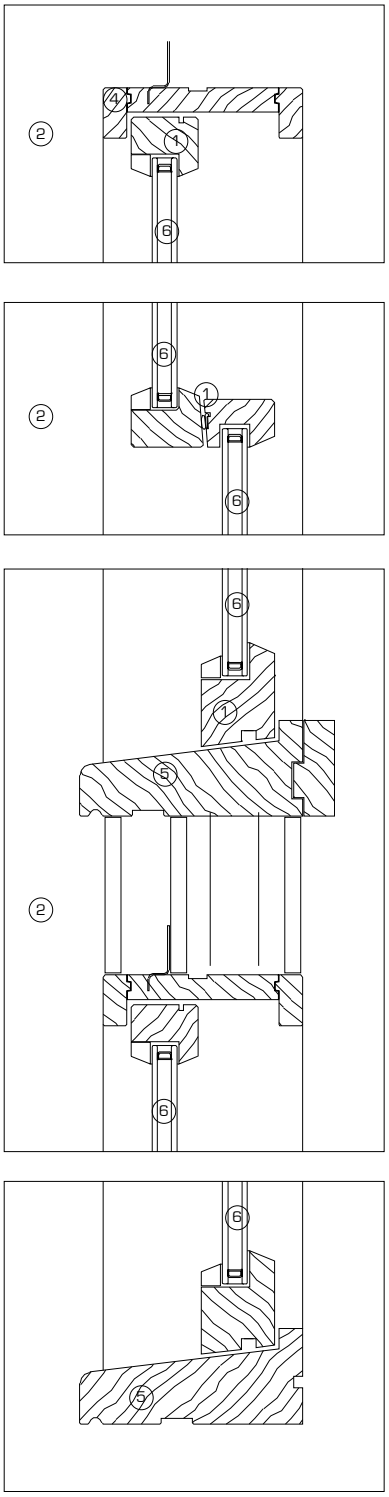
Details

1 | Timber window frame
2 | Outside
3 | Inside
4 | Head
5 | Cill
6 | Single-glazed or double-glazed unit to suit application
7 | Fixing bead
8 | Rubber-based seal

System design

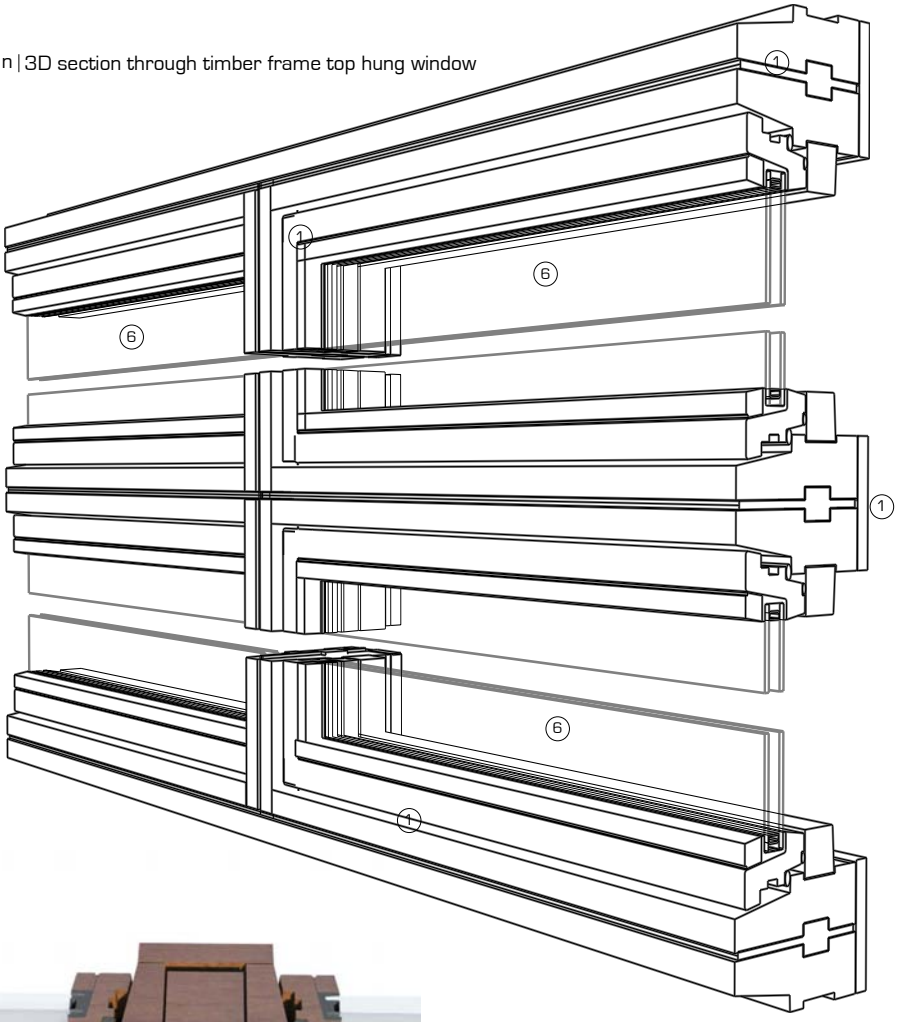
In common with aluminium windows, timber windows are used either individually within wall openings or are grouped to form a complete 'window wall' (b), formed by linking windows into a continuous arrangement. They are supported by an integral timber frame, typically reinforced internally by steel flats or sometimes supported by separate secondary steel supports in the form of columns or complete frames. Where individual windows are linked together with thin steel reinforcing plates, the panel size is limited to storey height, and the window wall arrangement is fixed back to the supporting structure of floor slabs or supporting wall. Where the visual presence of timber framing members is not the preferred expression of the facade from the outside, a secondary steel frame can be set internally, typically made from tubes, T-sections or box sections to reduce their visual impact. Alternatively, the steel components can be set within timber members forming the supporting frame to the window wall, depending on the required sizes of the steel members. These steel components are set within the timber construction to avoid being exposed to the effects of the weather. In addition, the high moisture movement associated with timber makes the penetration of the steel supporting structure through the external face of the timber glazed wall more difficult to waterproof. Where windows are linked and reinforced with a mild steel flat, a drainage groove set into the joint ensures that any water that penetrates the outer joint is drained away to the outside at the bottom of the window or window wall (f). Drainage channels are used on all four sides of the window in the manner of aluminium curtain walling. The steel stiffening rib or bracket does not extend forward of the drainage groove to allow water to be drained away unimpeded. Mullions and transoms (verticals and horizontals) may be of different depth to suit their individual structural requirements and may be in a different wood. Hardwoods and softwoods can be mixed in a single window wall construction, but the relative moisture movements associated with each type are taken into account to ensure that this movement does not adversely affect the appearance or stability of the window wall.

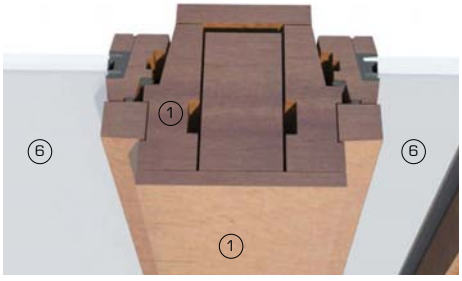
Timber framed window walls generally span up to two floors, typically restricted by the self weight of the panels, which are usually supported at their base. This is due to the need to tie the frame into large single units to avoid the effects of thermal movement of the sections. If timber sections are not tied together, they tend to wrap and twist when exposed to outside elements. Even if the surfaces are painted or sealed with varnish, any movement due to moisture will crack the outer finish and allow further movement to occur. Timber sections are jointed with either tongue-and-groove or rebated joints . Where tongue-and-groove joints are used, the linking material can be a durable hardwood or aluminium. Sections can also be bolted together if they are of sufficient size, such as around 75 x 50mm.

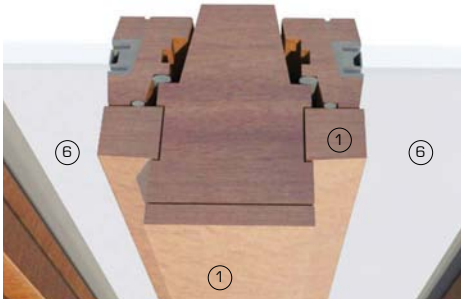


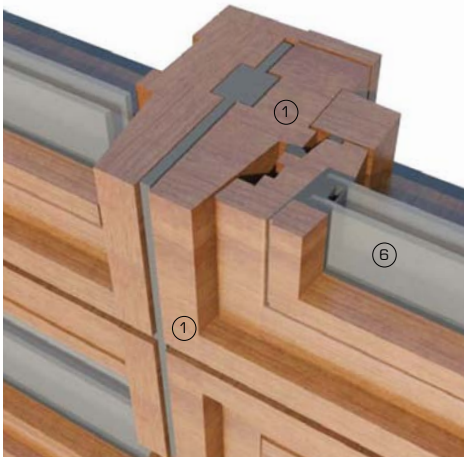
k | Vertical section 1:5. Vertical sliding sash window

n | 3D section through timber frame top hung window

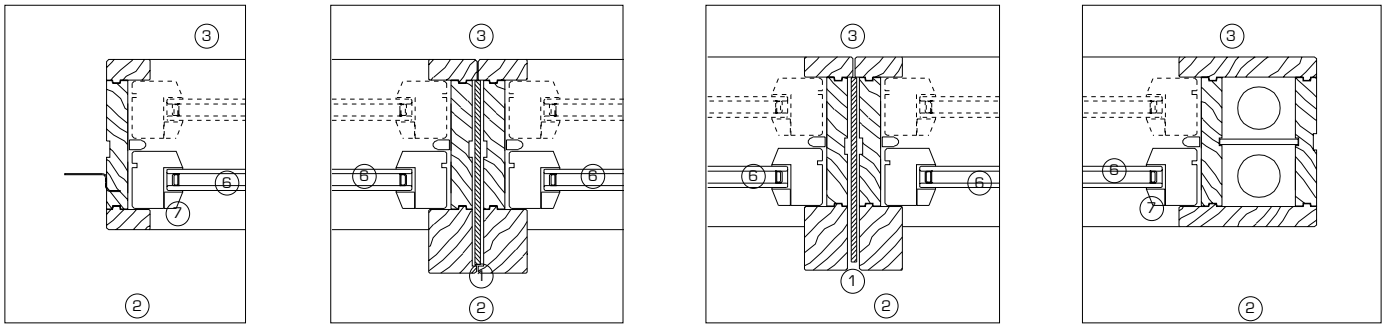




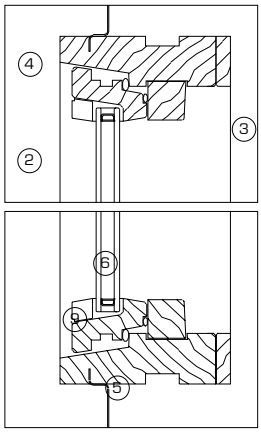




p | 3D horizontal section views showing various timber window frame configurations



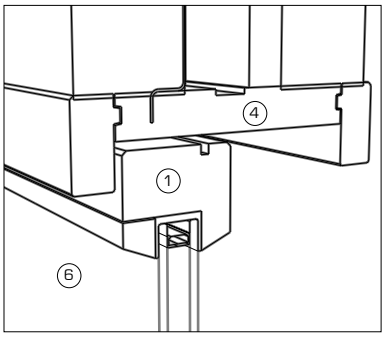
m | Horizontal sections 1:5. Sliding sash windows

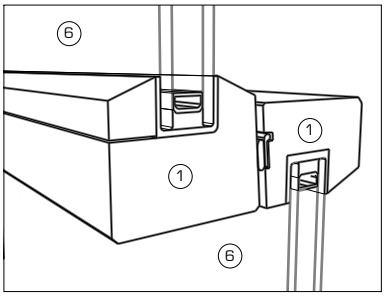


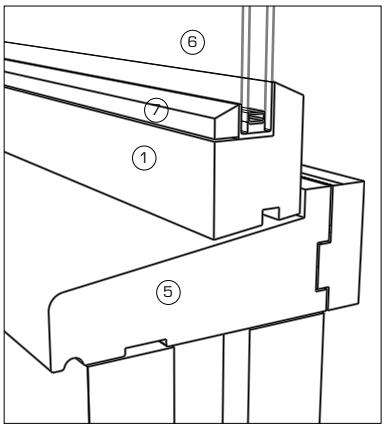
q | Vertical section 1:5. Top hung windows



r | (Right) 3D view showing timber window within masonry wall construction







s | (Far Right) 3D detail views showing timber window within masonry wall construction at head, window and cill junctions

Details

1 | Window frame
2 | Outside
3 | Inside
4 | Head
5 | Cill
6 | Single-glazed or double-glazed unit to suit application
7 | Fixing bead
8 | Rubber-based seal
9 | Surrounding wall
10 | Thermal insulation

System details

Inward opening windows are inherently vulnerable to water penetration at the bottom of the frame, while outward opening frames are weaker at the head of the frame. For this reason, drainage channels are provided within the frames, together with weather seals and weather bars (n). Like aluminium windows, timber windows use a single section for all four sides of an opening light, and a single section for three sides of the frame, with the cill being different in order to drain water away from the window. Timber windows can achieve relatively low levels of air infiltration and have vastly improved in their weather performance in recent years, primarily as a result of the use of synthetic rubber seals and aluminium weather bars. Weather tightness has been enhanced by the use of pressure equalised rebates in the window section (p), so that any water passing through its outer seal is drained away without being drawn through by capillary action as a result of an air pressure difference between inside and outside the framing. The inner synthetic rubber seal also serves as an acoustic barrier, providing improved sound insulation. Seals between the window and the opening have been enhanced in recent years with the increased use of folded aluminium and UPVC profiles, which are set into a groove around the window during manufacture and are sealed against the surrounding wall. There has been an increased control in moisture movement of the timber used with better controlled kiln-drying. Treatments to timbers are also changing to avoid toxic runoff while providing some protection against colour fading from UV radiation from sunlight. Some more economic timber window types have traditionally suffered from poor jointing at the corners of the frame. These have been improved across all window types in recent years with the use of double mortise and tenon joints and wood glues with better resistance to heat and moisture. Where timber windows are set into an opening rather than being part of a window wall, the most common materials used are masonry block (r), brick or timber boarding. With all these materials, timber windows are fixed either into the reveals of the opening or fixed into the face of the opening. The position of the window in the opening has more influence over the junction with the surrounding wall than the choice of material of that surrounding wall. In proprietary ranges of windows from manufacturers, a common frame design is used for different hinge arrangements in opening lights, which gives a harmonious appearance to window walls with lights that are required to open in different directions.

Timber glazed walls can be sealed against adjacent wall construction with metal flashings which can be formed either as an integral part of the window frame, or alternatively be fixed to it with synthetic rubber-based seals mechanically fixed to the frame. Corners can be formed with either a timber post forming the corner or as a fully glazed junction. Where transoms meet at a corner without the benefit of a mullion (vertical), the junction is usually joined with a toothed junction to ensure that no visible movement occurs. The full interlocking connection between components in these exposed conditions is vital to the success of timber glazed walls.

a | 3D view of concrete cast-in-place panels in structure



Details

1 | Concrete external wall
2 | Concrete internal wall
3 | Metal lining to gutter
4 | Window frame
5 | Slot formed as part of casting concrete
6 | Metal parapet flashing
7 | Single-glazed or double-glazed unit to suit application
8 | Metal cill, though precast concrete could be used
9 | Internal floor slab
10 | Single concrete wall
11 | Thermal insulation
12 | Internal finish

System design

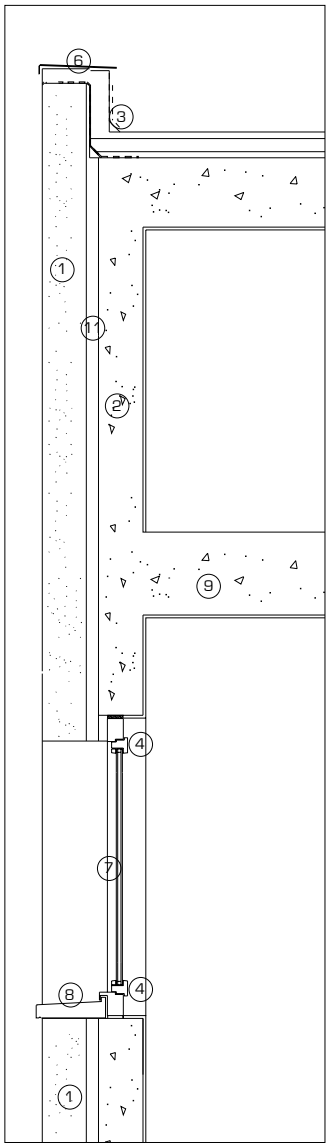
The method of forming concrete by pouring it into a shape created by formwork makes its construction quite different when working with other materials. While metal, glass, timber and masonry are made in relatively small panel and unit sizes, concrete is restricted only by the available formwork and the amount that can be poured at one time. The use of in-situ loadbearing concrete walls as a facade system exposes the cast concrete as a surface finish (a). This is in contrast to the use of in-situ loadbearing walls as backing walls to a different facade system, where the function of the wall is only as a primary structure, while the external skin is non-loadbearing cladding. The use of in-situ reinforced concrete as a self-finish to external walls was popular in avant-garde architecture throughout most of the 20th century, but walls were constructed without thermal insulation within the wall depth. Instead, insulation was eventually added on the inside face of the wall, which both prevents the thermal mass of the concrete wall from being used to regulate the air temperature within the building as well as preventing the concrete surface from being seen inside the building. An important development in recent years has been an increase in the provision of thermal insulation set typically within the depth of the construction, allowing the external face to have a visible concrete finish (b).

Setting thermal insulation within the wall allows the thermal mass of the concrete to contribute to night-time cooling as part of an environmental design strategy. Continuity of thermal insulation at the interface of concrete and glazed openings is increasingly important in order to avoid thermal bridging. In this method of construction, diaphragm walls are used with two structurally linked walls being set either side of a rigid thermal insulation core. This allows part of the concrete structure to remain closer to the internal temperature of the building to benefit from the thermal mass of the primary structure, as well as permitting the internal face of the building to have a visible concrete finish. In diaphragm wall construction, the two linked concrete walls are joined structurally by concrete ribs which form limited thermal bridges, or alternatively are linked by stainless steel ties. The use of metal ties reduces the thermal bridging with its associated risk of condensation and pattern staining forming on the inside of the wall in temperate climates.

An alternative method of constructing an in-situ cast concrete wall is to set the thermal insulation on the inside face of the wall; however this results in the loss of the wall's thermal mass. This method has the benefit of economy, especially where there is no requirement for night-time cooling.

System details

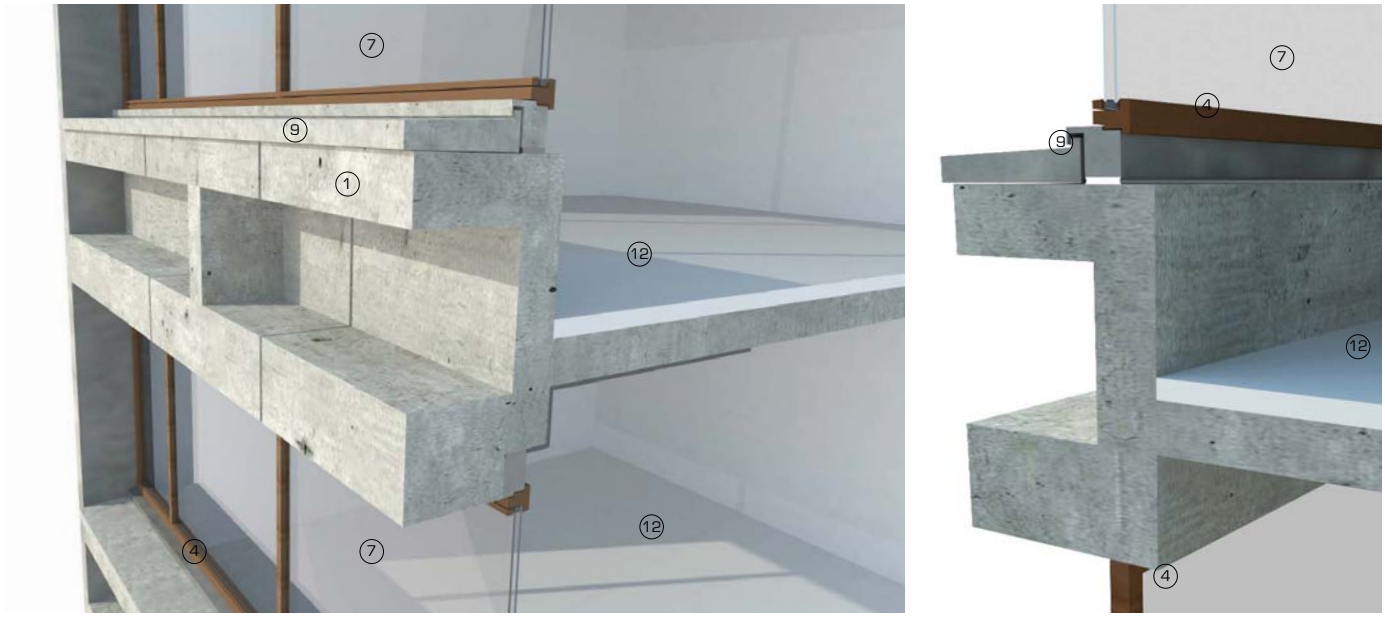
Dust particles that settle on horizontal or slightly sloping surfaces such as window cills are washed off during rain and can be deposited on the wall below. Consequently, openings, parapets and cills in exposed concrete walls have projecting cills and flashings (c)(d) to ensure that



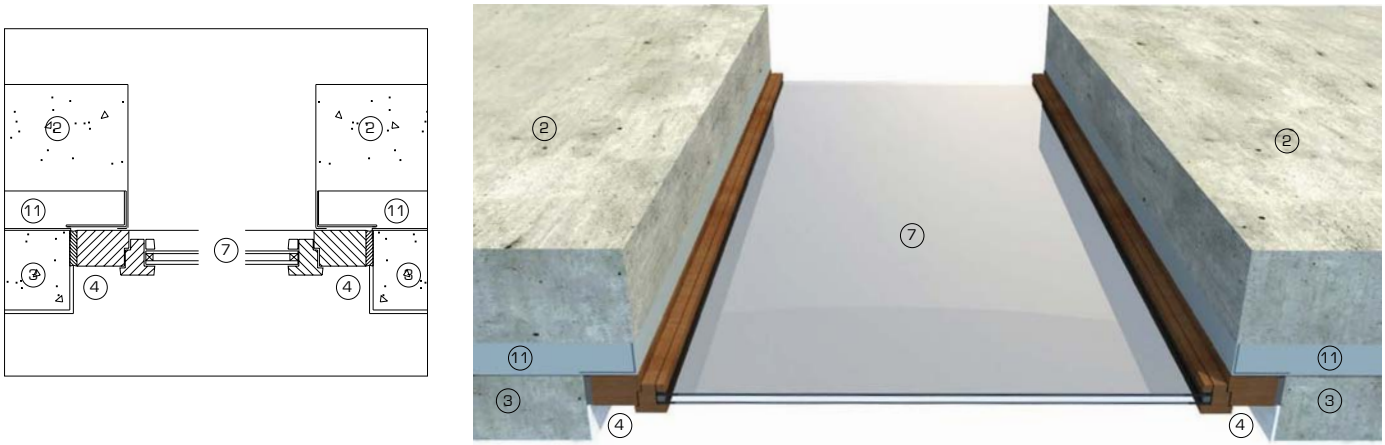
b | Section 1:25. In-situ cast concrete wall cast in two skins with rigid closed cell insulation between skins



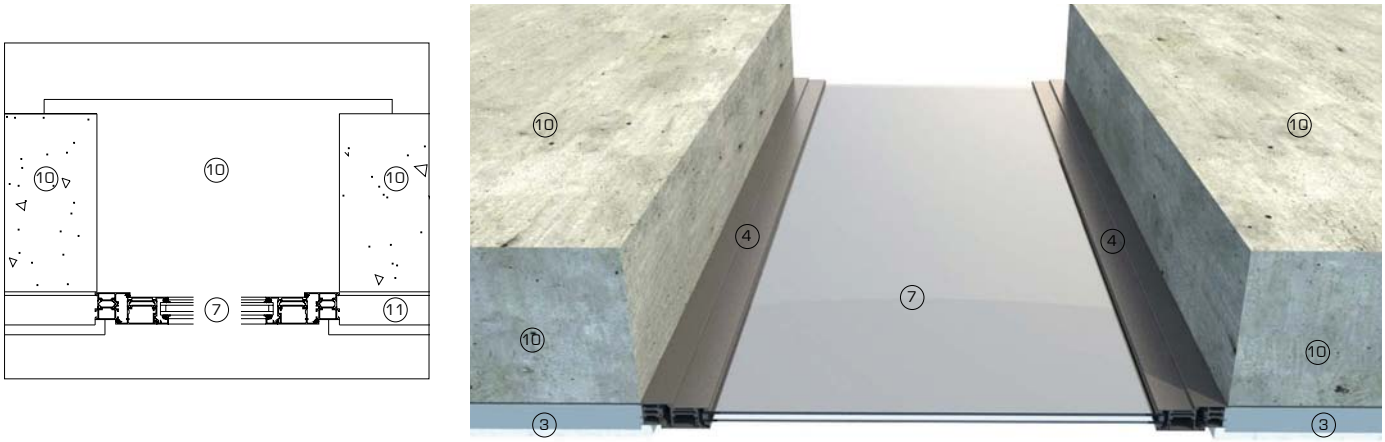
c | 3D view showing roof parapet and window details within cast in-situ concrete wall system



d | 3D sectional views showing window opening in in-situ cast concrete wall and floor slab interface



e | Horizontal section 1:10 and 3D view. In-situ cast concrete wall with internal insulation at window opening



f | Horizontal section 1:10 and 3D view. In-situ cast concrete wall with external insulation at window opening

rainwater is thrown as clear as possible from the external wall surface. In urban conditions, dust-catching surface textures are usually avoided and smooth finishes are often preferred. However, where protective treatments are applied to the external surface of the concrete to reduce porosity, this can give a reflectivity to the material that reduces its characteristic stone-like appearance.

Drips in the form of continuous grooves are cast into the tops of window reveals to reduce both staining to the soffit and the amount of water reaching the windows (e). Cills are usually formed with a metal sheet apron that helps throw water clear of the wall below, while metal copings are usually inclined in order to drain water onto the roof or gutter behind, rather than down the face of the concrete wall.

The colour of concrete for in-situ loadbearing concrete walls is influenced mainly by the choice of cement, with fair-faced visible concrete walls using either grey or white cement bases to produce the surface colours associated with each. The physical properties of these two cement types are very similar, with grey being associated with architectural concrete finishes which usually provide a consistent appearance when pouring methods and conditions remain consistent during construction of the facade. The tone of grey will vary with the cement/water ratio, the porosity of the shuttering, vibration conditions, formwork stripping time and weather conditions. White cement is much more tolerant of variations in methods and site conditions in providing a consistent white colour.

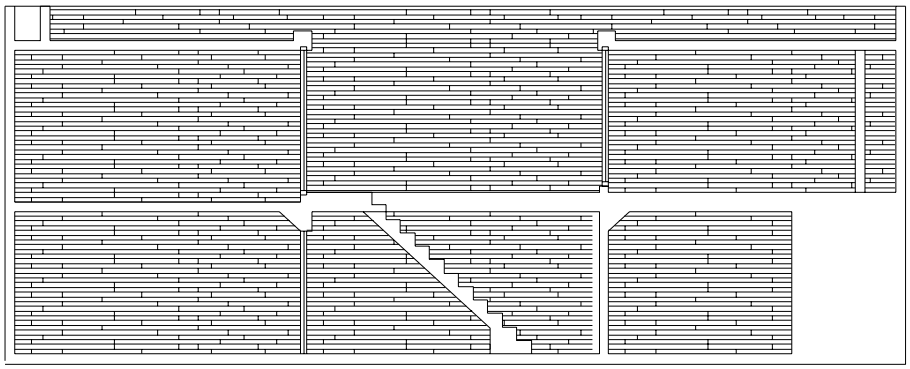
The most common finishes for concrete walls cast in-situ are either an as-cast finish or a washed finish. Other finishes are discussed in the section on precast panels: acid etching, sand blasting, tooling and polishing, though these additional finishes can be used on in-situ cast concrete. With as-cast finishes, the colour variations do not usually result from the cement colour, but rather from the marbling effect of fine particles of sand, becoming unevenly distributed during vibration when the concrete is poured in place. Smooth concrete is typically self-coloured in large areas of the facade to avoid colour variations associated with pigment additives. Smooth and visually consistent natural finishes are achieved largely by the accuracy of mixed proportions including water.

Textured finishes can be achieved with specially formed shuttering boards, or with an additional lining sheet containing the texture pattern (g). Polystyrene (one time use) or synthetic rubber sheet (multiple use) are commonly used. Recessed joints are usually introduced between the formwork boards (j) to avoid uneven and blurred lines at the junction between boards. Washed finishes are formed by applying a deactivator to the external face of the concrete, either to the face of the formwork before casting or to the concrete surface when the formwork has been removed. The deactivator is used to slow down or stop hydration of the cement, and is applied by brush or spray. The concrete is then sprayed with water or aqueous acid solution to remove the surface, revealing the material below.





g | Photos illustrating texture that can be achieved through in-situ casting

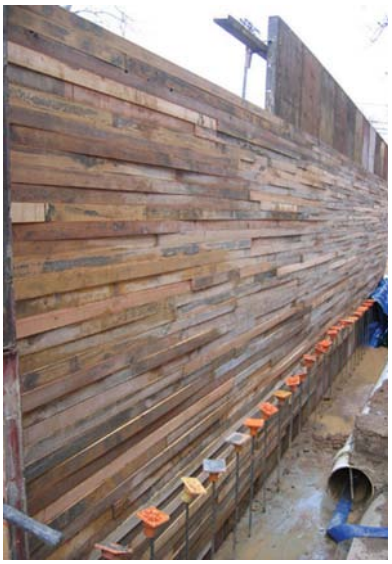


h | Internal wall elevation 1:50 In-situ cast concrete wall with textured effect as above right

Details

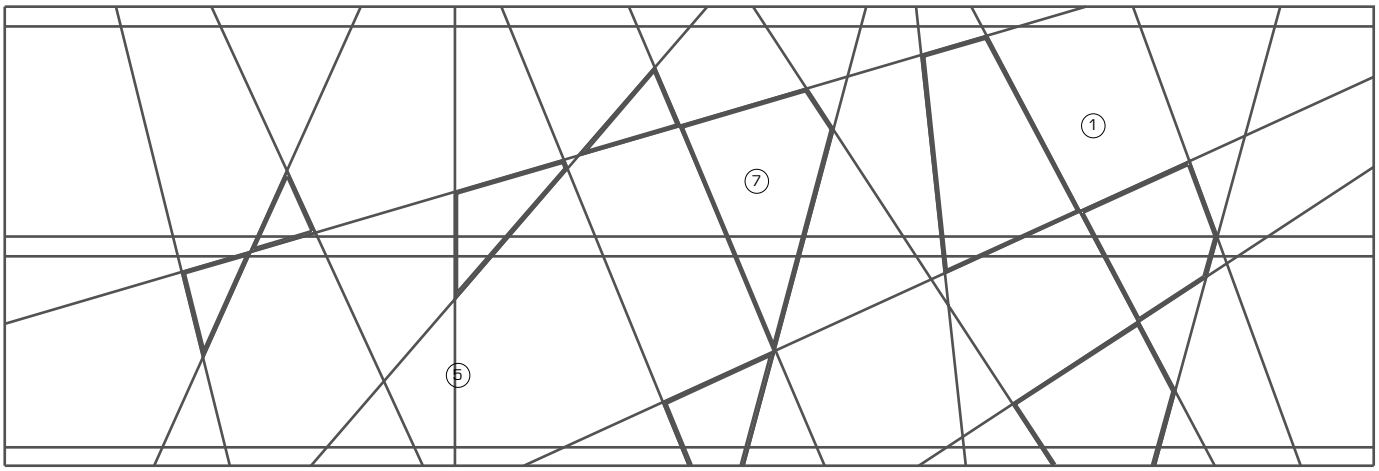
1 | Concrete external wall
2 | Concrete internal wall
3 | Metal lining to gutter
4 | Window frame
5 | Slot formed as part of casting concrete
6 | Metal parapet flashing
7 | Single-glazed or double-glazed unit to suit application
8 | Metal cill, though precast concrete can be used
9 | Internal floor slab
10 | Single concrete wall
11 | Thermal insulation





j | Timber/aluminium formwork on upper floors of building construction

k | Timber formwork used to achieve texture



m | Elevation 1:50 In-situ cast concrete wall showing how formwork can be arranged and cut to form different shaped panels and window openings



a | 3D views showing typical storey-height panel wall assembly with windows, in various panel configurations

System design

The method of casting in-situ walls described in the previous section is one of forming loadbearing construction. With precast panels, walls can be formed as either loadbearing walls or as cladding panels to a structural frame (a). Loadbearing types have storey height panels 'stitched' together to become integral with the floor slabs. Junctions are usually pin-jointed, with structural stability provided by other components such as service cores elsewhere in the building. Precast panels may have a decorative finish on one side, with thermal insulation set within the panel, or may be used as a backing wall to another facade system such as a rainscreen set forward of the panel, where thermal insulation is set on the outer face of the precast panel. In addition to setting panels full height from floor to floor, loadbearing panels can also be set horizontally to form structural beams between precast columns, typically around 1200mm high to provide spandrel panels. This allows full length glazing to be used, set between the top of the panel and the bottom of the panel above, rather than glazing individual openings associated with full-height precast panels. Non-loadbearing precast cladding panels typically span from floor to floor (b), with panels supported either directly on the floor slabs or set forward of them, fixed back to the floor structure with brackets made typically from stainless steel or reinforced concrete. The method of fixing panels is very dependent both on spatial requirements within the building and on whether concrete nibs can remain a visible part of the panel design or are required to be concealed within the internal finishes. Storey-height panels can have either thicker edges to form an integral 'frame' to the panels, or be completely flat (d), but the latter will usually be thicker, and consequently heavier. The 'framed' version has a visual language of framing which can be visible from either the outside or the inside.

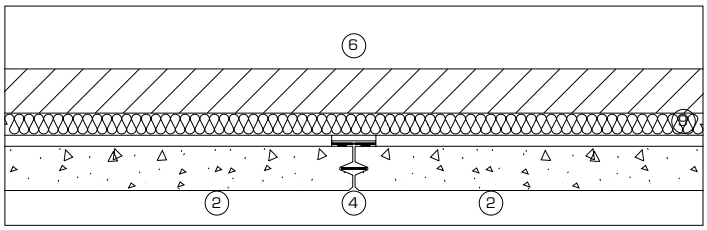
Due to their self weight, panels are usually supported at their base at the floor slab and are restrained at the top of the panel with mechanical fixings. Panels are usually a maximum of around 3600mm wide to suit road transportation, with a maximum weight of around 10 tonnes to suit regular site cranes. As with in-situ cast concrete walls, the thermal insulation can be set either on the inside face of the panels or within a diaphragm wall construction (c). Panels are manufactured in flat moulds, with the finished face at the bottom of the mould when the concrete finish is required to be visible, or with the finished face on the top of the mould where another material is applied such as ceramic tiles, or where metal fixings for a masonry finish are cast into the face of the panel. Where a concrete finish is formed in the bottom of the panel, textured finishes are formed within the mould, usually by a synthetic rubber

Details

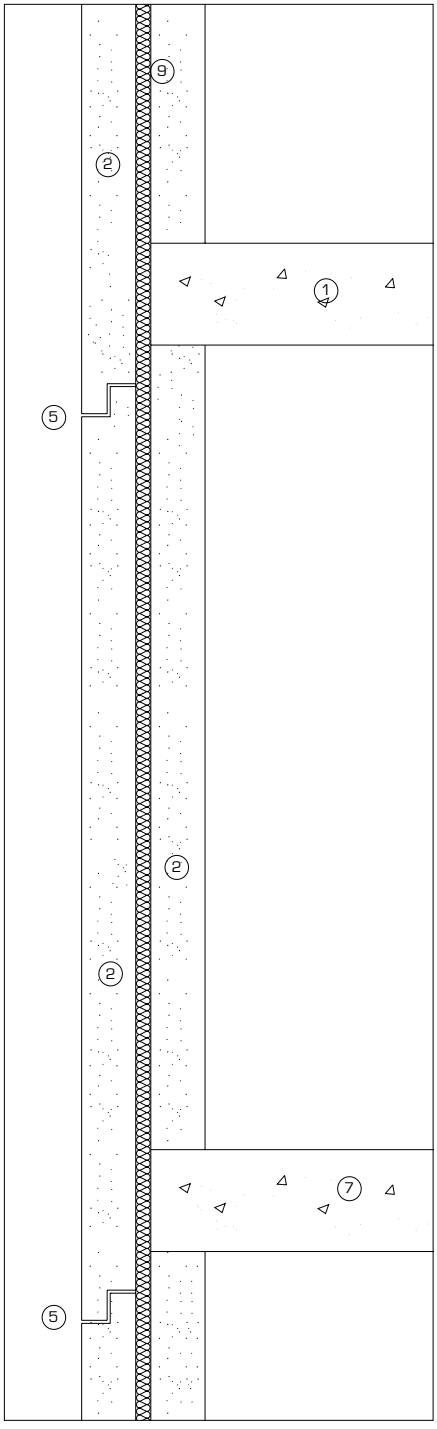
1 | Concrete floor deck
2 | Precast concrete panel
3 | Window
4 | Vertical joint (typically a baffle) between panels
5 | Horizontal joint (typically a lap) between panels
6 | Drywall/dry lining
7 | Steel dowel
8 | Concrete coping
9 | Thermal Insulation
10 | Roof construction



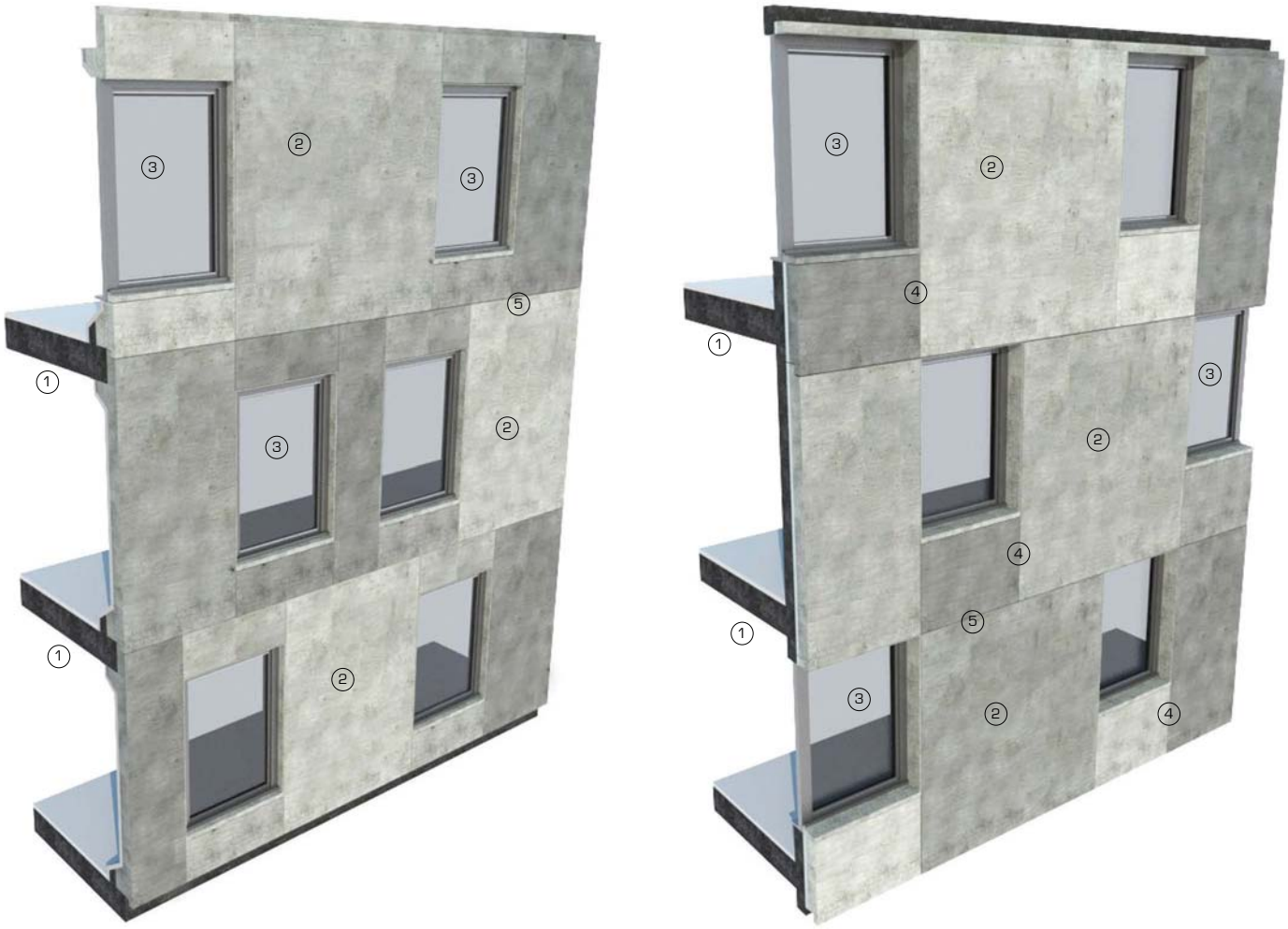
b | 3D detail view showing storey-height concrete panels at window and floor interface



c | Horizontal section 1:25. Typical wall construction



d | Vertical section 1:25. Typical wall construction



e | 3D views showing typical storey-height panel wall assembly with windows, in various panel configurations

mat or polystyrene. The shape of the panel is adjusted to suit the ease of removing the mould when the concrete has been poured in place, but most panels can achieve sharp lines that do not have an obviously 'moulded' appearance.

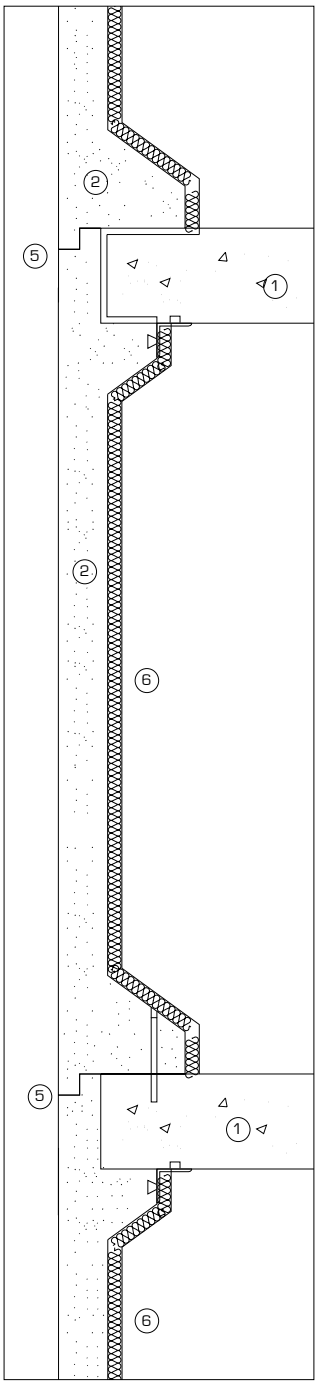
System details

Joints between panels are similar for both loadbearing and cladding panel types, with a common use of either 'open' or 'closed' joints. Open joints have an outer open joint that is narrow but admits small amounts of rainwater, which is drained down an inner chamber and released back to the outside at the base of the panel through a stepped horizontal joint (f). This internally drained and pressure-equalised system is similar in concept to that used in unitised curtain walling. In closed joints the outer face is sealed with a wet applied silicone or polysulphide sealant in a similar way to the sealing of joints between bolt fixed glazed panels. Joint widths both vertically and horizontally for both open and closed joints vary from 10-25mm increasing with panel width up to a maximum of around 6000mm. The inner chamber between panels in vertical open joints is closed with a synthetic rubber strip which provides a primary seal. The interior face of both vertical and horizontal joints is closed with an air seal formed with either an extruded synthetic rubber gasket or a wet-applied sealant. Loadbearing panels are sealed with a cement-based grout (g). Closed joints are mostly used in loadbearing panel construction where panels are joined together with mechanical fixings. Panel fixings are positioned near the corners, with slotted fixings used in order to allow for both thermal movement between the panel and supporting structure and for adjustment during construction (j). The cleats are typically fixed to a small channel fixing cast into the concrete. Panels are lifted into place on site by crane, using hooks that are screwed into threaded tubes set into the concrete, typically on top or on the back face of the panel. The hooks are unscrewed when the panel is in place, and the holes plugged.

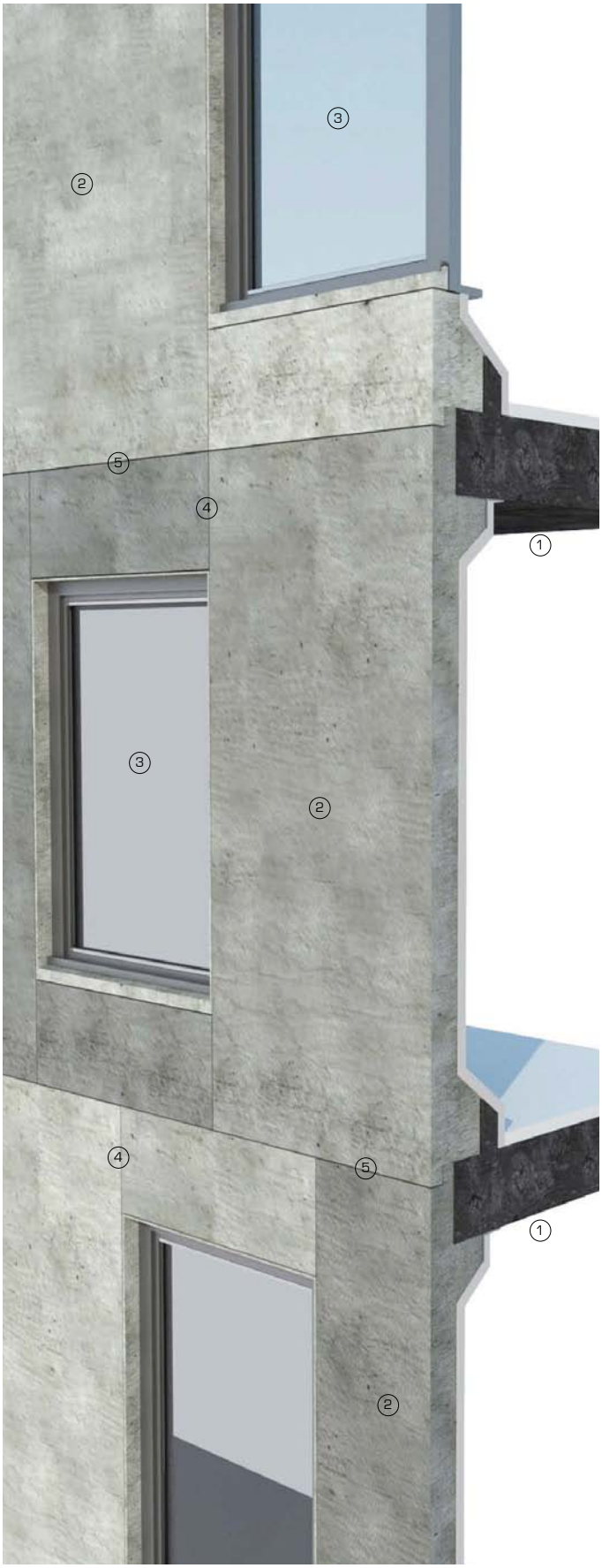
The most common finishes in precast panels are acid etching, polishing, sand blasting and tooling. The last two techniques are discussed in the next section on small precast panels, but can be equally applied here. Polished finishes are formed by an abrasive grinding wheel lubricated with water that removes up to 2mm of the material with a single pass of the grinder to a honed or fully polished finish. This exposes the colour of the aggregate but the surface does not shine naturally. Varnishes can be applied to achieve this stone-like appearance. Acid-etched finishes are well-suited to precast panels since the amount of acid applied can be more carefully controlled in the factory than can be achieved on site. The outer face of the panel is treated with hydrochloric acid to reveal the concrete texture beneath, which is then rinsed off, having the effect of revealing the concrete texture immediately beneath. Acid etching attacks limestone aggregates, and sometimes more quickly than it does the cement, while silica-based aggregate remains. The surface texture achieved varies with the fine aggregate used, being more granulated in the case of silica and less coloured in the case of limestone.

Details

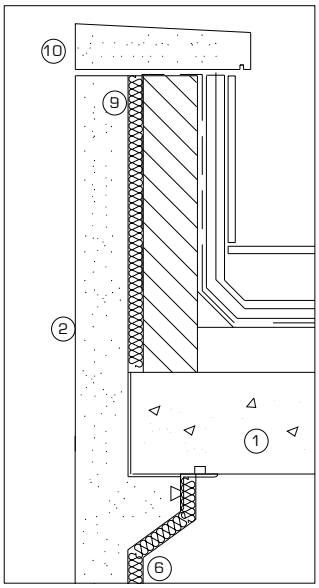
1 | Concrete floor deck
2 | Precast concrete panel
3 | Window
4 | Vertical joint (typically a baffle) between panels
5 | Horizontal joint (typically a lap) between panels
6 | Drywall/dry lining
7 | Steel dowel
8 | Concrete coping
9 | Thermal Insulation
10 | Roof construction



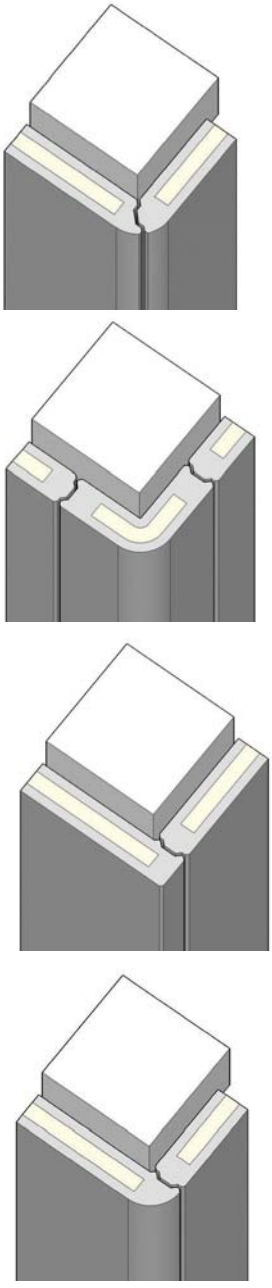
f | Vertical section 1:25. Typical details



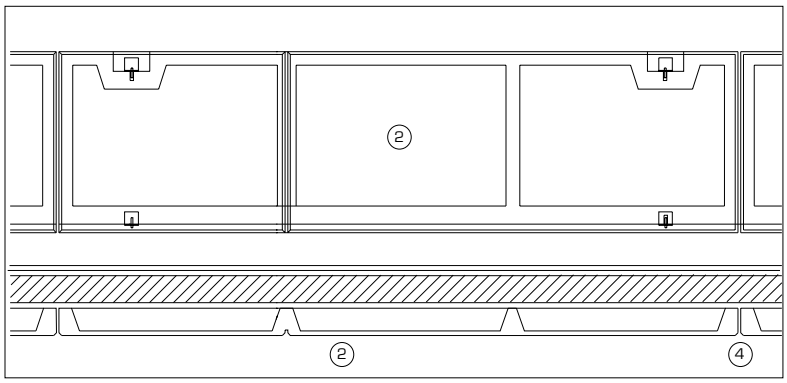
g | 3D detail view showing typical wall assembly



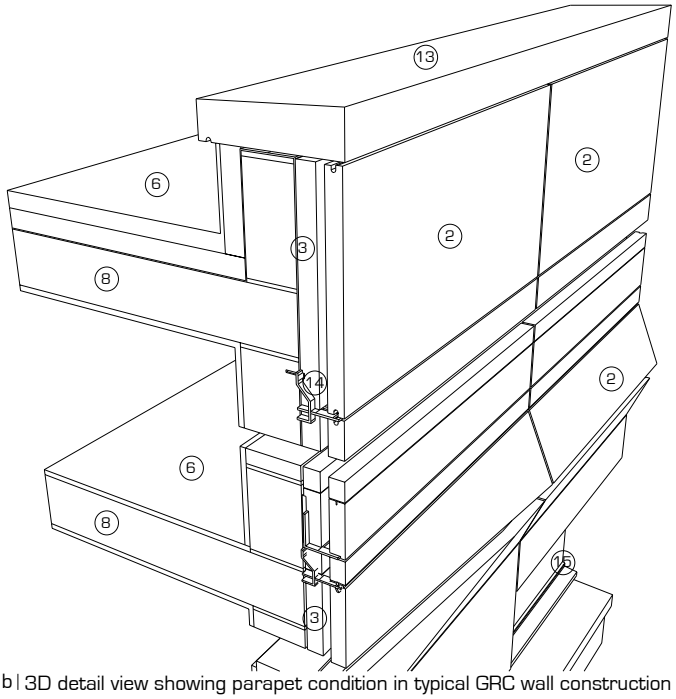
h | Vertical section 1:25. Parapet detail



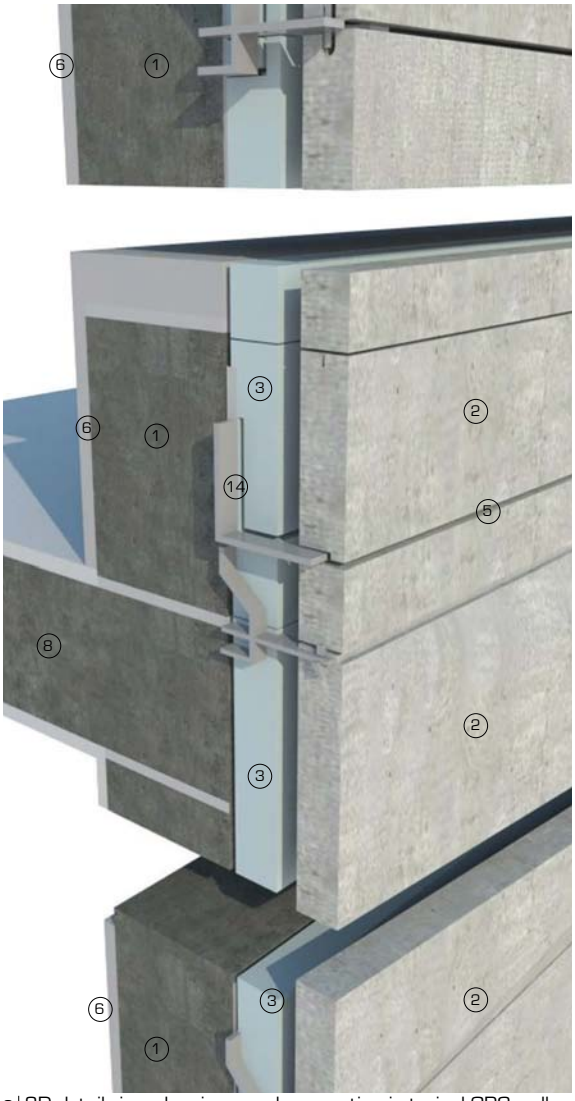
j | 3D detail views showing various corner details



a | Horizontal section 1:25. Glass reinforced concrete (GRC) panels with open joints



b | 3D detail view showing parapet condition in typical GRC wall construction



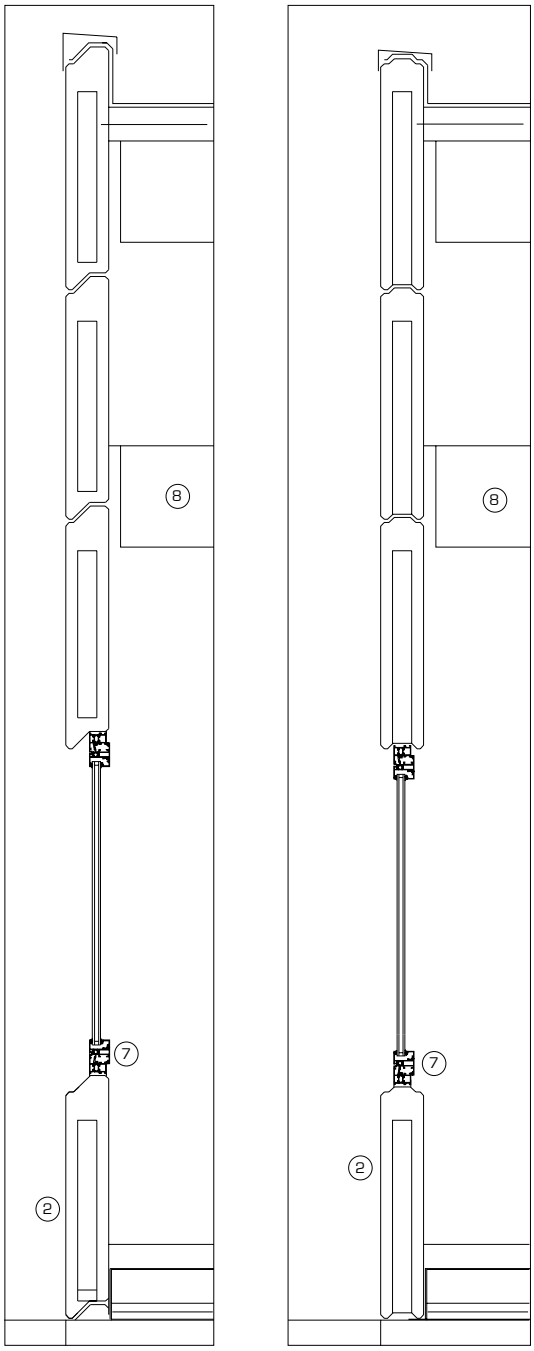
c | 3D detail view showing panel connection in typical GRC wall construction

System design

Small precast concrete panels have greater possibilities of visual variety with a reduced unit size than large panels. While storey height panels suit larger scale projects, smaller self-supporting and interlocking panels can be stacked together in the manner of composite metal panels (b). Panels have an inner core of thermal insulation (3) with a finished concrete face on each visible side of the panel. Alternatively, individually supported rainscreen panels use the visual language of stone or metal cassette facades to a backing wall in a different material. Small precast rainscreen panels are fixed to a backing wall either directly with individual fixing brackets or onto an aluminium or stainless steel carrier frame, with open joints that follow the rainscreen principle.

Panels can also be made as self-supporting walls supported at their base. These panels are shaped so as to ensure they interlock to provide a stable form of construction (d). Panels can be stacked to a single storey height of around 10 metres, with lateral restraint provided by the structural frame, and at every floor level in buildings with more than one storey. Panels at ground floor level are set on a beam edge to a concrete floor slab or structural beam. Panels are stacked with continuous vertical joints and are restrained by columns. The need to restrain panels on their vertical joints results in interlocking panels being long in order to optimise the distance between structural columns, avoiding intermediary posts that would be required to provide lateral restraint. In terms of weight, the long panels compensate by being low in height in order to ensure their weight can be lifted by a site crane, typically with a lifting capacity of 4 to 6 tonnes. Since the stacked, interlocking panels have concrete on all sides, both horizontal joints and vertical joints usually have a limited thermal bridge which can lead to pattern staining as a result of different rates of thermal transmittance in the material, in addition to the increased risk of condensation occurring on the internal face. The thermal bridge can be avoided by the use of internally located metal connections between two skins of concrete in place of a fully encased concrete panel (c), but this makes it more difficult to stack panels and to maintain the economy of the system. Self-supporting stacked panels fabricated in thicknesses of 75 - 100mm can also form the outer skin of a complete cavity wall construction of 200 - 300mm thickness. The inner wall can vary widely in its construction from concrete block to light gauge metal stud wall with an outer waterproof facing. The cavity between concrete panels and backing wall is 50 - 75mm, ventilated at the top and bottom of the wall.

Small precast rainscreen panels can be formed with narrower joints than those possible in full-height panels, together with the possibility of a non-rectilinear arrangement of joints. Fixing brackets are similar



d | Vertical sections 1:25. Typical precast concrete wall construction (Left) Panels with drained joint.
(Right) Panels with sealed joint

Details

1 | Backing wall
2 | Precast concrete panel
3 | Closed cell thermal insulation
4 | Vertical joint open or closed type
5 | Horizontal joint open or closed type
6 | Internal finish
7 | Window frame
8 | Concrete floor deck
9 | Precast concrete coping
10 | Steel angle
11 | Rubber-based baffle
12 | Waterproof membrane
13 | Parapet
14 | Metal bracket
15 | Double glazing
16 | Window cill



e | 3D view showing panel connection
in typical GRC wall construction

Details

1 | Backing wall
2 | Precast concrete panel
3 | Closed cell thermal insulation
4 | Vertical joint open or closed type
5 | Horizontal joint open or closed type
6 | Internal finish
7 | Window frame
8 | Concrete floor deck
9 | Precast concrete coping
10 | Waterproof membrane
11 | Rainscreen panel support rail
12 | Double glazing



f | 3D views showing wall assembly with profiled, precast concrete tiles

to those used for stone cladding, but are usually bigger to support the heavier panels. While stone panel sizes are typically around 1500mm x 750mm or 1500mm x 1000mm, depending on stone type, precast rainscreen panels can typically reach 1500mm x 3000mm. Panels are supported on stainless steel brackets which are fixed either to primary structure or to a carrier frame that is in turn fixed to primary structure (f). Slotted holes in the bracket provide adjustment vertically, horizontally and laterally. In common with stone cladding, individually supported concrete panels are supported on short lengths of stainless steel angles at each floor level in order to avoid the possibility of progressive collapse of cladding panels in the event of a single panel failing or slipping from its position. Fixings are designed so that they can support the full load of the panels immediately above them in the event of fixings to panels above failing either partially or completely.

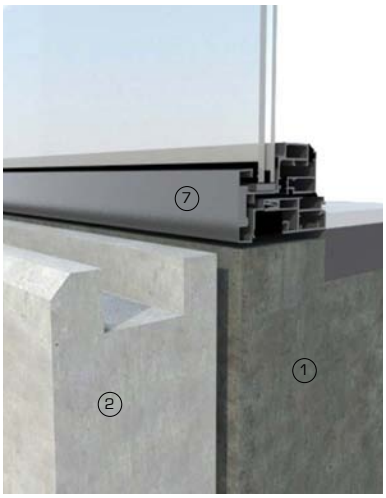
System details

Interfaces for individually supported panels are similar to those for stone cladding. An advantage of small precast panels is that interfaces of stacked panels with openings, parapets and cills are relatively straightforward. Windows are fitted into openings relatively easily, since the stepped profile at the base of the panel provides an integral cill profile to the opening (h). The concrete facing to all sides of the panel provides weathertight edges on the jambs and at the head of the opening. Windows are set in a position which suits the position of the thermal insulation in the precast panel; typically in the middle (g), but windows are positioned to provide continuity with the thermal insulation. The closing of parapets is provided by a metal flashing that covers the top of the panel and the vertical face of the parapet wall that may be set behind the panels to close off the roof (h). The coping is sloped towards the roof to ensure that rainwater is drained onto it and not directed down the facade. A precast coping can also be used instead of metal, but an additional membrane is set under both metal or concrete copings to ensure a fully watertight seal. The base of walls is detailed in a similar way to other forms of loadbearing masonry. A continuous damp proof membrane (DPM) extends up from the outside of the structure beneath and forms a damp proof course (DPC) which is positioned so that it extends at least 150mm above external ground level, depending on climate conditions. The DPC is positioned so that the lowest row of panels at ground level appears to sit on the ground with its bottom edge either level, or slightly above the adjacent ground level or pavement. This avoids the need for a 150 - 200mm waterproofed plinth at the base of the wall.

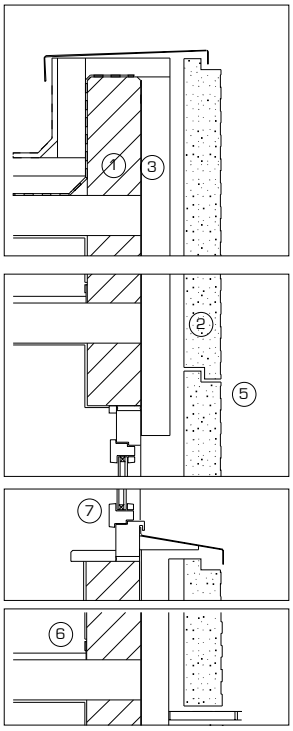
Sandblasting and tooling are common on small cladding panels. Panels are sandblasted with iron filings rather than sand particles, with the blasting slightly eroding the face of the concrete, either lightly or more deeply to the coarse aggregate beneath, resulting in a matt finish. Tooled concrete is a method of texturing concrete with chisels or picks to make grooves or continuous textures. The textures usually stop short of wall corners to give a crisp edge.



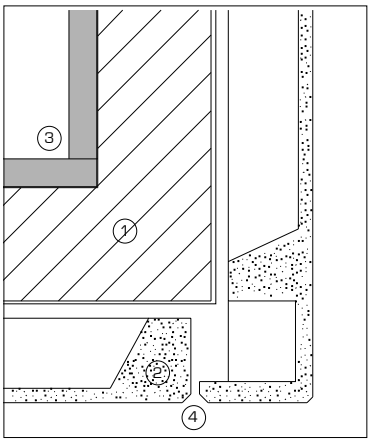
j | 3D detail view showing typical wall assembly for GRC panels with open joints and window



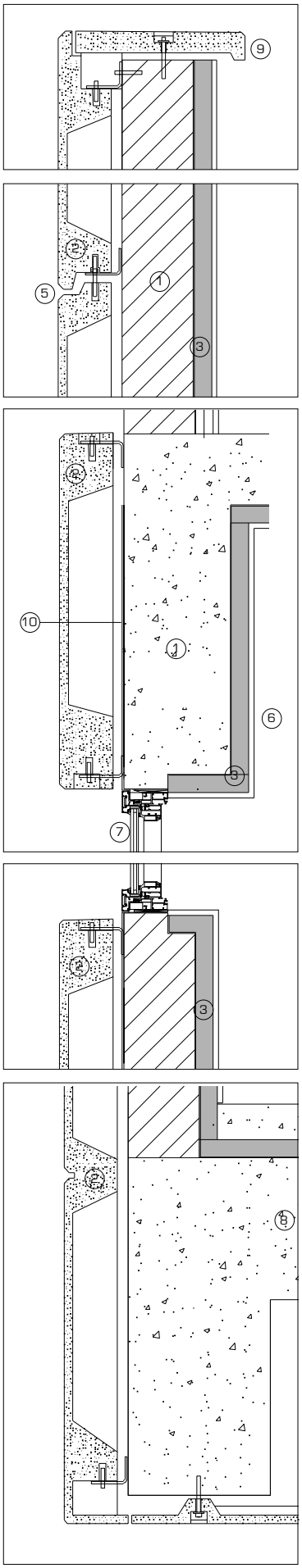
g | 3D detail view showing window opening in typical GRC panel wall system



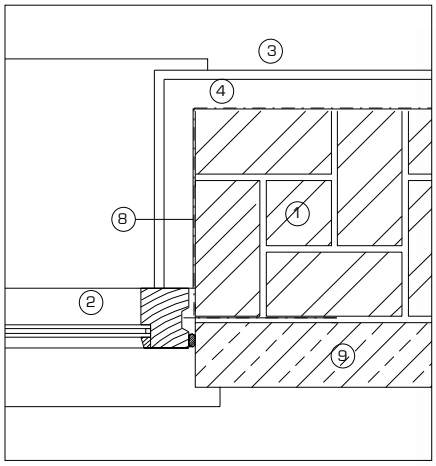
h | Vertical section 1:10. Junction at window jamb and at parapet



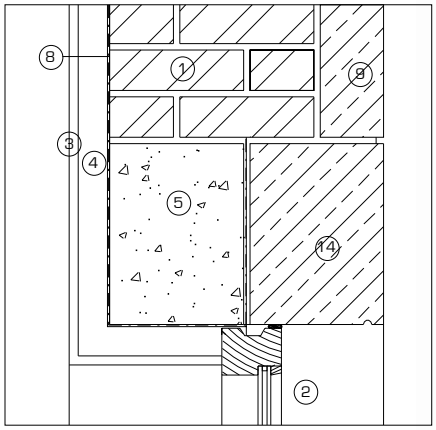
k | Horizontal section 1:10. Corner GRC panel with open joint



m | Vertical section 1:10. Panel soffit and window junctions of GRC panels with open joints



a | Horizontal section 1:10. Window jambs in brick loadbearing wall with stone facing blocks



c | Vertical section 1:10. Window jambs in brick loadbearing wall with stone facing blocks

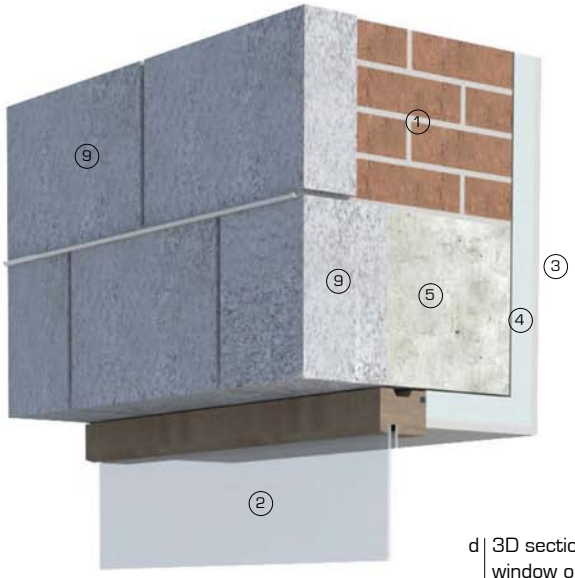


b | 3D sectional view through loadbearing wall with stone facing blocks

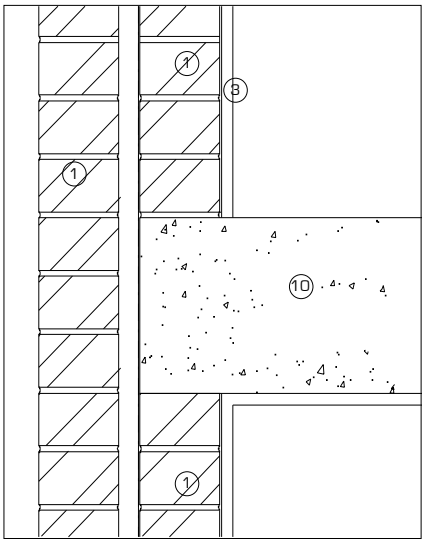
System design

Loadbearing masonry walls are used mainly in small-scale construction, but in recent years there has been a revival in their use for larger scale buildings as an alternative to the language of cavity wall construction. Walls are most commonly made from brick or concrete block. In continental Europe, terracotta blocks are more common, but are usually rendered on their external face, both to enhance their appearance and for their traditional role as a weathertight outer layer (b). Concrete blocks are similarly protected by render. Only brickwork is fully exposed, relying on the depth of wall to avoid the ingress of rainwater.

In brick construction, it is assumed that a 315mm thick wall (1½ bricks) is the minimum depth sufficient to resist rainwater penetration in temperate climates. This is dependent upon brick density and manufacturing dimensions. With brick, thermal insulation is set on the inside face to allow the material to be visible on the outside, but with concrete block, the insulation (4) can be set on the outside with an external layer of render to provide the weatherproof skin (a). An alternative solution is to set thermal insulation within the wall, creating a loadbearing diaphragm wall where the brick or block can be seen on both sides of the wall, and which also allows the internal face of the wall to be used for night-time cooling within the building. Two skins of brick, typically 215mm to 315mm thick, are set apart, joined by fin walls set perpendicular to the main walls. Concrete block walls are made from skins 200mm to 300mm thick (e). The position of the insulation within the walls, or on the internal face of the wall, allows a straightforward continuity with the thermal insulation provided by windows within openings. An essential benefit of using loadbearing masonry walls is their ability to avoid movement joints through the use of lime mortar. This traditional material has lower strength than mortars used in contemporary cavity wall construction but has greater flexibility, allowing it to move more freely without cracking. This reduces, or can even avoid the need for, movement joints which are introduced to avoid cracking in masonry walls. Movement joints in walls where cement-based mortars are used are set typically at 6.0–8.0 metres depending on the required strength and size of wall. In lime mortars the strength of mortars is varied by altering the proportion of cement and lime which are used to bind the mortar together. Increasing the proportion of cement will increase its strength, while increasing that of lime increases its flexibility, with mortar mixes having different proportions of strength and flexibility. In addition, the comparatively low water permeability of lime gives it greater resistance to rain penetration than mortar mixes with a high proportion of cement. Lime has the effect of making mortars



d | 3D section view showing window opening and connection to ground in typical brick loadbearing wall assembly

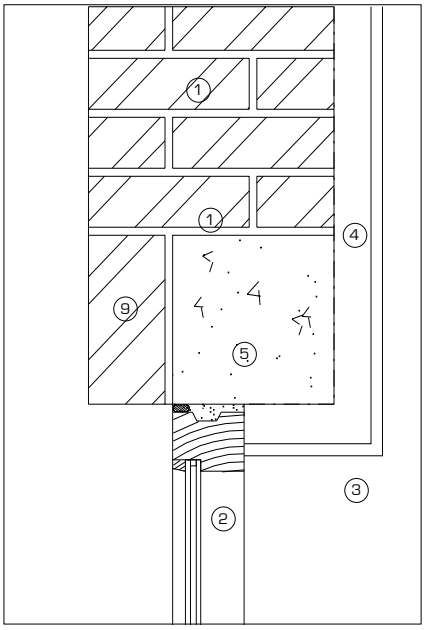


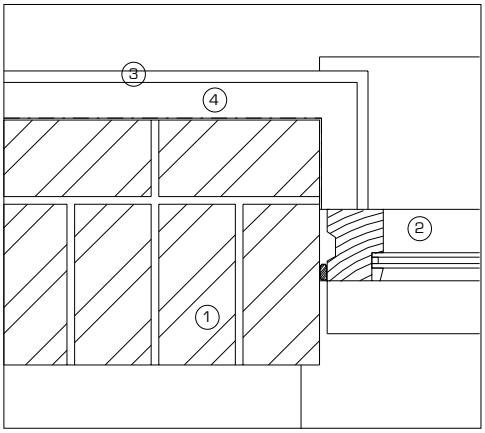
e | Vertical section 1:10. Floor connection in brick loadbearing wall



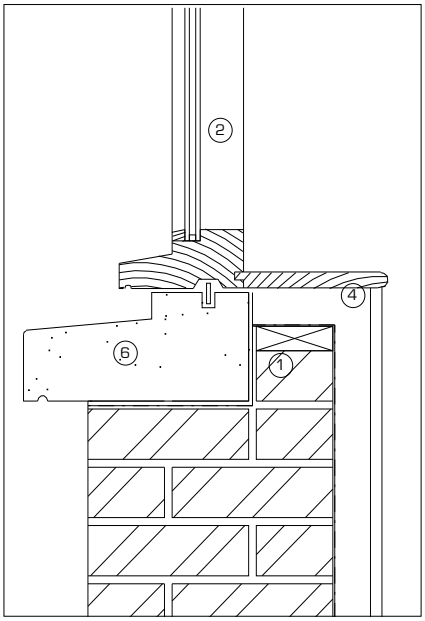
Details

1 | Loadbearing brick wall
2 | Timber framed window
3 | Internal plaster finish or dry lining/drywall
4 | Thermal insulation
5 | Precast concrete lintel
6 | Precast concrete cill
7 | Concrete loadbearing blocks
8 | Damp proof course (DPC)
9 | Stone facing blocks
10 | Floor slab
11 | Floor construction
12 | Hollow bricks
13 | Roof construction
14 | Stone lintel/arch
15 | Stone cill
16 | Parapet
17 | Loadbearing concrete block wall
18 | External finish
19 | Ground

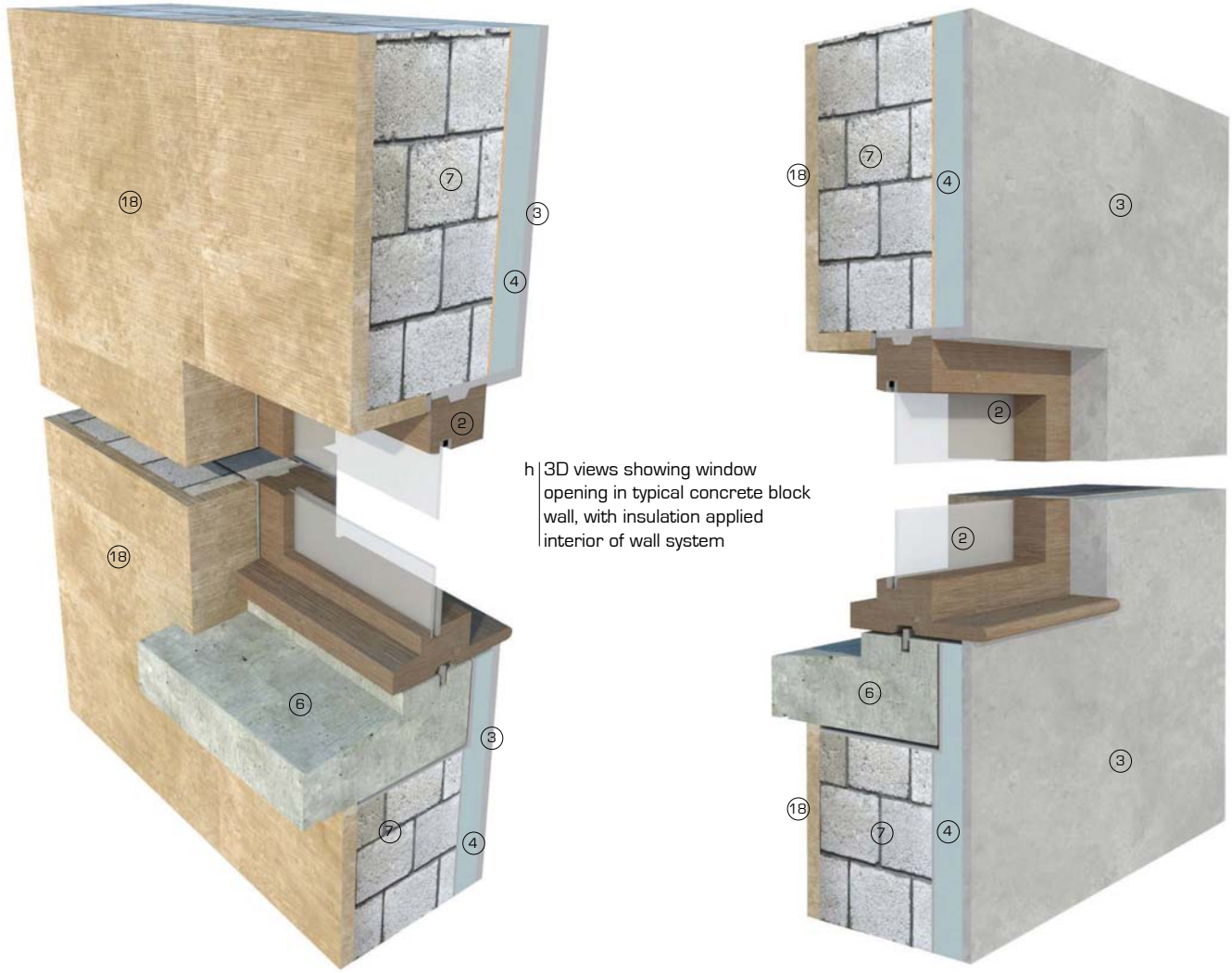




f | Horizontal section 1:10. Window jamb connection in loadbearing brick wall



g | Vertical section 1:10. Window opening in loadbearing brick wall



h 3D views showing window opening in typical concrete block wall, with insulation applied interior of wall system

increasingly light in colour with its increased proportion in the mix. However, mortar colour can be modified by adding pigments to the mix. Where stone is used on the outer face of the loadbearing wall, typically facing a brick wall behind it, the mortar has crushed stone added in place of sand in order to give mortar its texture and some of the texture of the stone itself.

System details

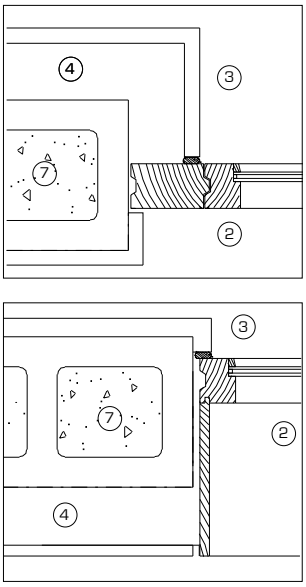
An essential aspect of loadbearing masonry walls is the need for the structural requirements of walls to take precedence in the ways openings are formed, particularly where the wall supports both itself and other elements such as floors and roof (e). For example, the use of flat arches for window openings that form the equivalent of lintels to support the wall above result in the structural requirements being the dominating criterion in bringing components together. There are visual benefits, such as openings in loadbearing masonry walls having the ability to reveal the thickness of the wall to give it a massive appearance. Cills to openings are formed from either the same material if stone is used for the wall or, more commonly, precast concrete (h). Sometimes the timber or metal cill that forms part of the window is used to form the cill where visual criteria permit its use. Cills are sloped with a projecting edge that throws the rainwater clear of the wall beneath. A throating is also used to avoid water running back to the external face of the wall from the underside of the projecting cill (j). Where stone is used to form cills, the material must be sufficiently impervious or alternatively have sufficient slope to ensure that water runs off quickly. Where softer stones are used, such as sandstones and limestones, the material must be sufficiently dense and durable to avoid staining occurring due to water absorption. Cills are usually made as single pieces to avoid joints being formed which are less impervious than the cill material. A DPC is set under the cill to ensure that rainwater penetrating the outer cill drains away any water that soaks through the cill, particularly at the joints. The heads of openings in loadbearing masonry walls are supported by lintels or arches which are structural, taking on an appearance informed by that primary requirement. In brick construction, a flat or curved arch is typically used to support the brickwork above. In concrete block construction, a reinforced concrete lintel is used, which spans the complete width of the wall (m), while in stone a thin arch is used on the outer face of the wall, often with a more rudimentary brick arch behind it, concealed by the window frame. In parapets, the coping piece has a damp proof course (DPC) set beneath it to avoid rainwater being absorbed into the wall beneath. The DPC is continuous with the waterproof layer used for the roof immediately behind the parapet. In common with copings in other facade systems, the top is sloped inwards to drain water towards the roof rather than down the facade where it would cause staining. The coping usually projects beyond the face of the wall on the roof side in order to throw water clear of the wall.



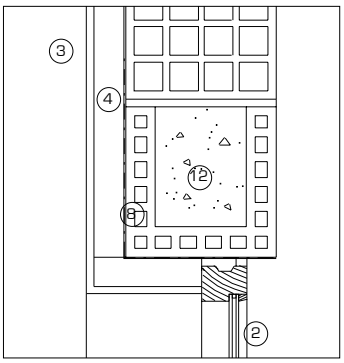
j | 3D detail view showing window opening in typical concrete block wall, with insulation applied to interior of wall system

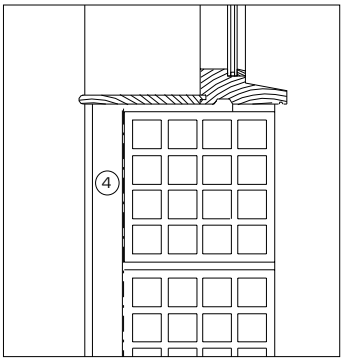
Details

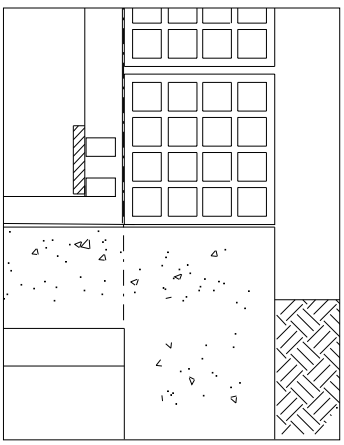
1 | Loadbearing brick wall
2 | Timber framed window
3 | Internal plaster finish or dry lining/drywall
4 | Thermal insulation
5 | Precast concrete lintel
6 | Precast concrete cill
7 | Concrete loadbearing blocks
8 | Damp proof course (DPC)
9 | Stone facing blocks
10 | Floor slab
11 | Floor construction
12 | Hollow bricks
13 | Roof construction
14 | Stone lintel/arch
15 | Stone cill
16 | Parapet
17 | Loadbearing concrete block wall
18 | External finish



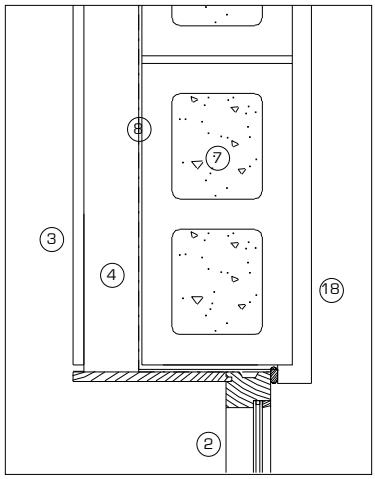
k | Horizontal sections 1:10. Window opening in concrete block wall illustrating application of insulation to interior or exterior of wall system

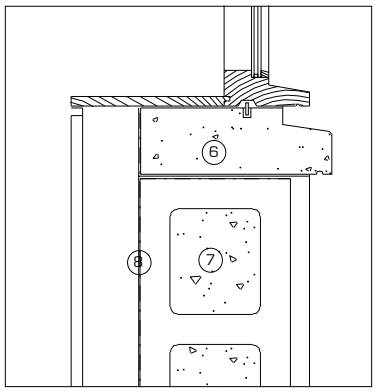




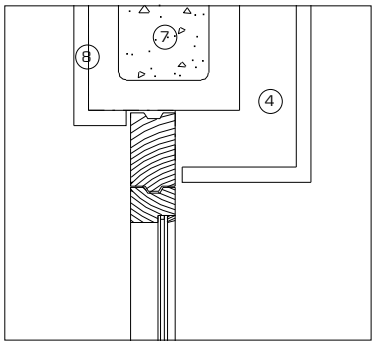


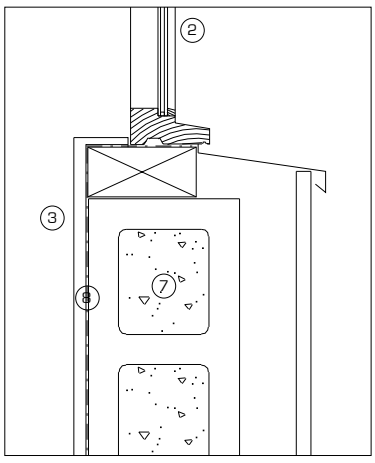
n | Vertical section 1:10. Window opening in hollow brick wall





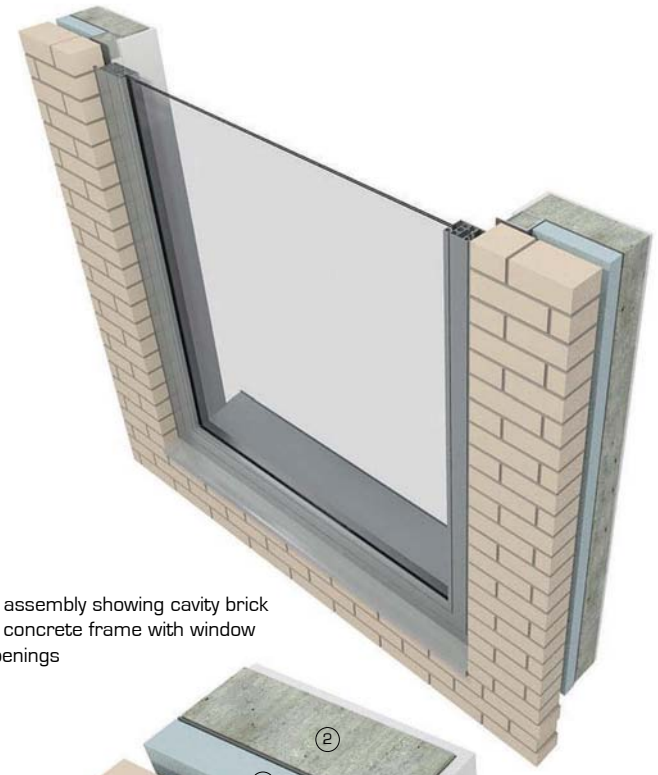
m | Vertical sections 1:10. Window opening in concrete block wall illustrating application of insulation to exterior of wall system



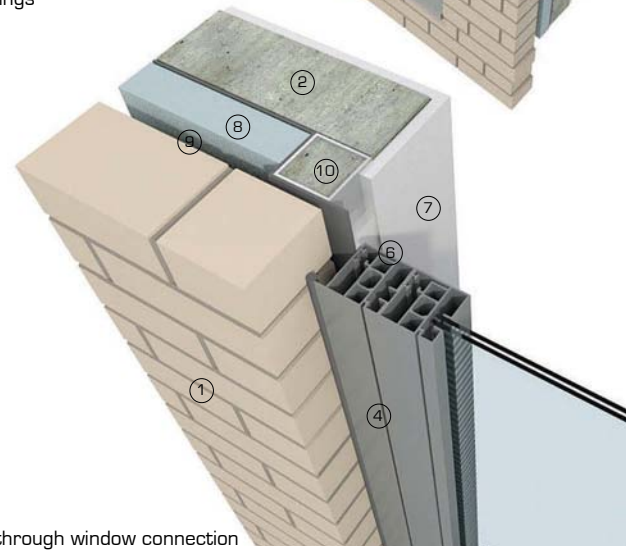


p | Vertical sections 1:10. Window opening in concrete block wall illustrating application of insulation to interior of wall system





a | 3D views of assembly showing cavity brick wall fixed to concrete frame with window and door openings



b | 3D detail view through window connection

Details

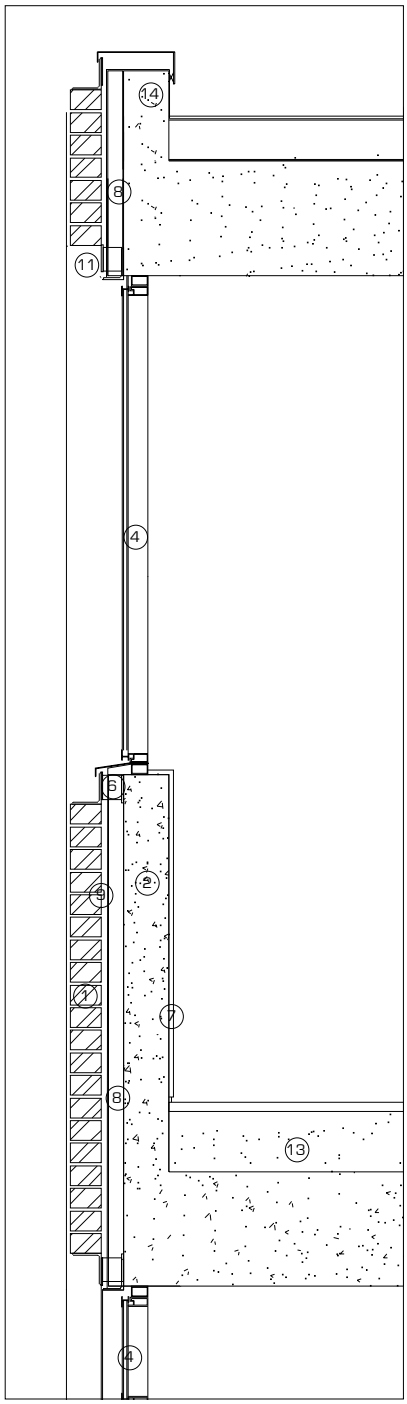
1 | Outer brick wall (or 'leaf')
2 | Inner blockwork wall (or 'leaf')
3 | Timber framed window
4 | Steel/aluminium window
5 | Timber cill
6 | Cavity closer
7 | Internal plaster finish or dry lining/ drywall
8 | Thermal insulation
9 | Air cavity (sometimes omitted where insulation fills cavity)
10 | Inner precast concrete lintel
11 | Pressed steel lintel
12 | Outer precast concrete lintel or brick flat arch
13 | Floor construction
14 | Roof parapet
15 | Stainless steel tie
16 | Damp proof course (DPC)
17 | Ground
18 | Primary structure

System design

Where loadbearing brick walls use the overall wall thickness to stop the passage of rainwater from outside to inside, cavity walls use two skins of masonry separated by a ventilated air gap (a), where only the outer skin is saturated with water. The inner skin is usually formed in concrete block (2) or timber studwork, with thermal insulation (8) usually set on the external face of the inner skin. Earlier examples of cavity walls were built by tying inner and outer skins together with floor slabs to form diaphragm walls, so that both inner and outer skins performed a structural function. Their use was reduced over concern about the thermal bridge created by linking the two skins of brick, with its attendant issues of heat transfer across the wall and condensation risk. Current practice uses the outer skin as cladding to a drained and ventilated void behind, with an inner skin that is waterproofed with a high level of thermal insulation. The cavity is vented top and bottom to ensure the free passage of air through the cavity. This allows the cavity to remain dry as well as assisting in drying out the outer skin of brick, which can become fully saturated in a rainstorm. The cavity is bridged only by openings for windows and doors (b), but typically this is done with proprietary cavity closers, which are insulated strips that create a thermal break between inner and outer skins. The outer brick skin is usually only one brick thick, typically of 100mm width, with both skins being supported at ground level (MCH_164, b), at intermediary floor levels and at the roof (c), depending on the height of the building. The inner skin is built off each floor slab and is restrained at the head by the floor slab or roof structure above. Taller buildings have the inner skin built directly onto floor slabs in the same way, but the outer skin is supported at each floor level on a series of continuous stainless steel angles, fixed back to the floor slab. A damp proof course (DPC) is set on top of the steel angle to drain the cavity. Weep holes (vertical slots) are formed in the vertical joints immediately above the steel angle in order to allow water in the cavity to drain to the outside. In addition to being restrained at floor slabs, the outer skin is also tied at intermediary points back to the inner skin with stainless steel ties (f). These are set typically at 450mm horizontal centres and 900mm vertical centres. Vertical movement joints are provided at around 7500mm centres, or are avoided altogether in the construction by keeping lengths of wall within this limit.

System details

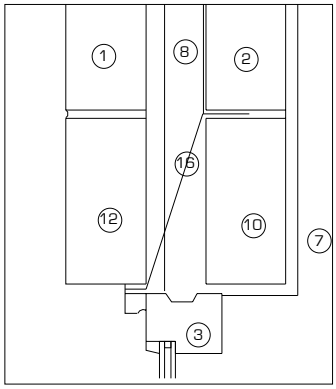
Unlike loadbearing masonry walls, the inner and outer skins of cavity walls can be supported separately, with the outer skin required to support only itself. However, when an opening is formed, the cavity is closed by



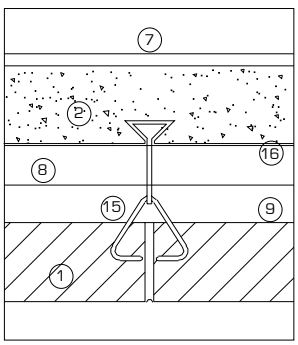
c | Vertical section 1:25. Wall assembly

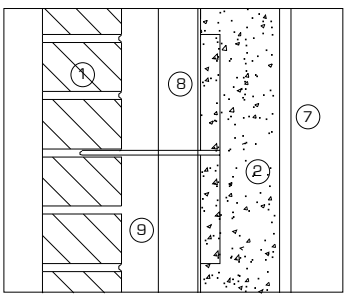
e | 3D view of assembly showing cavity brick wall fixed to concrete frame



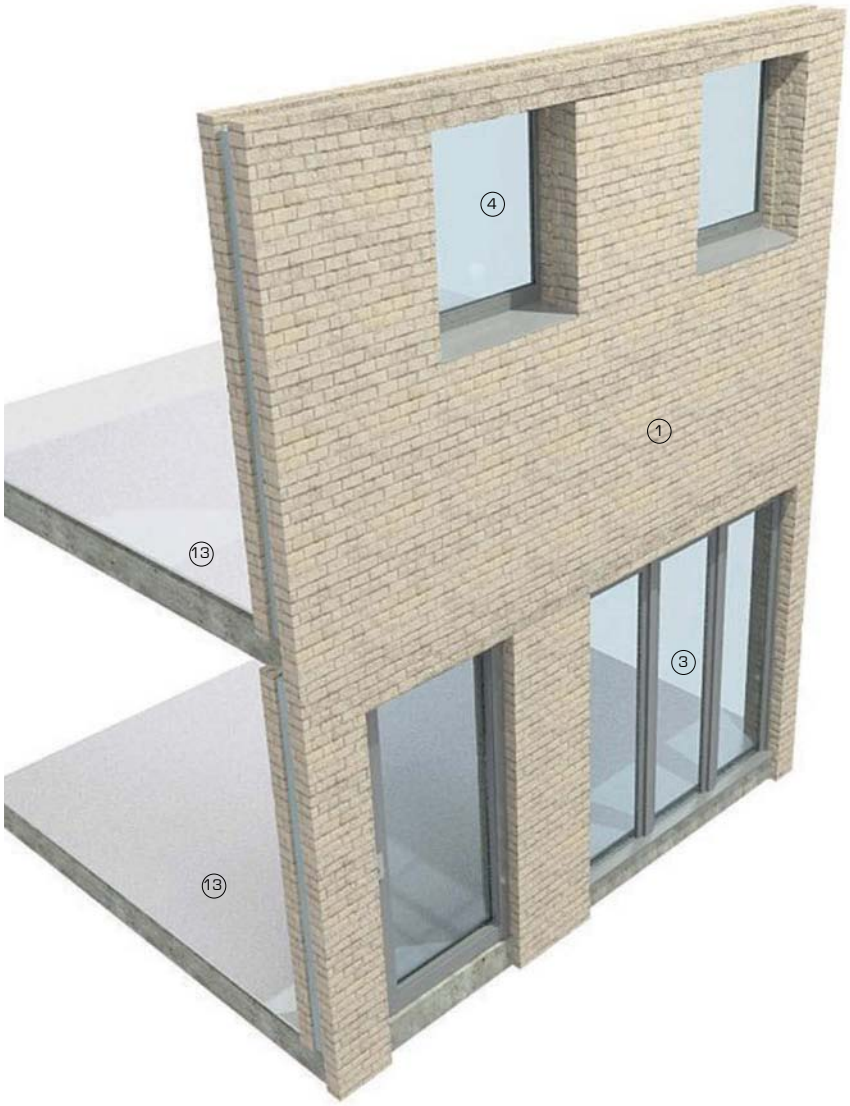


d | Vertical section 1:10.
Window assembly

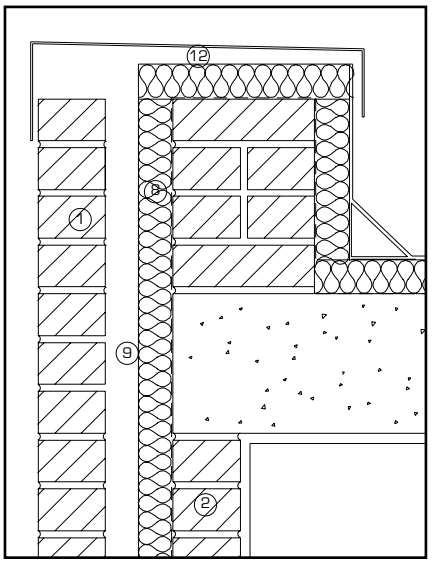




f | Horizontal and vertical section 1:10. Typical connection or restraint to primary structure



g | 3D view of double brick skinned cavity wall system



h | Vertical section 1:10. Junction at parapet

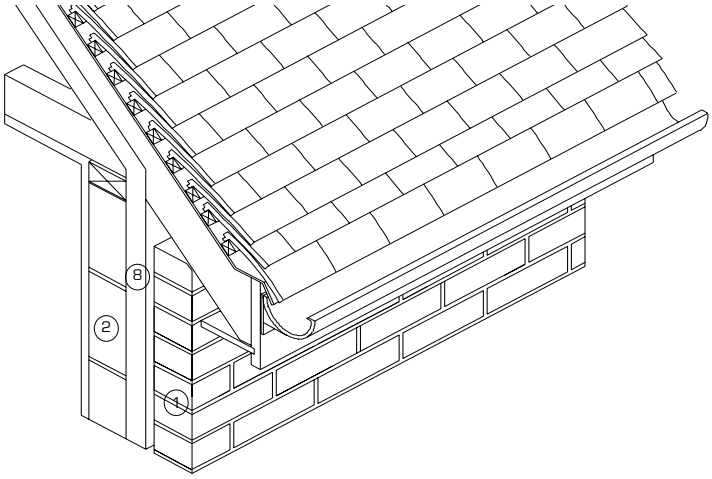
Details

1	Outer brick wall (or 'leaf')
2	Inner blockwork wall (or 'leaf')
3	Timber framed window
4	Steel/aluminium window
5	Timber cill
6	Cavity closer
7	Internal plaster finish or dry lining/drywall
8	Thermal insulation
9	Air cavity (sometimes omitted where insulation fills cavity)
10	Inner precast concrete lintel
11	Pressed steel lintel
12	Outer precast concrete lintel or brick flat arch
13	Floor construction

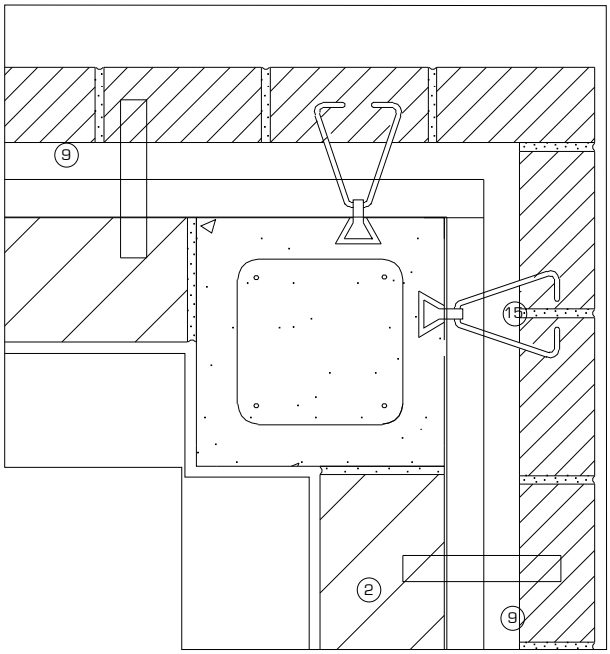
a lintel to support the inner and outer skins at the top of the opening, and is closed by a cill at the bottom of the opening (q). The jambs (sides) are closed either by returning one of the two skins so that they meet, or by setting an insulated cavity closer, usually made as an aluminium extrusion filled with thermal insulation. Because the downward passage of water inside the cavity is interrupted by the lintel (n) at the head of the opening, a cavity tray formed from bituminous felt is set above the lintel to drain water out of the cavity. Water is drained at the bottom of the tray through weep holes in the vertical joints immediately above the DPC. The ends of the DPC are tucked down into a vertical DPC set into the jambs of the opening, which is in turn linked to a DPC set under the cill to form a complete watertight seal to the opening, which in turn is then drained to the outside. A similar cavity tray principle is used to drain water at roof level and at ground level. In addition, a DPC is used at ground level to avoid water being drawn up into the wall construction on the inside face of the wall within the building. DPCs are also used beneath parapets and copings as well as at the junction of wall and pitched roof.

The position of the DPC at ground floor level is dependent upon the difference in height between ground floor level in the building and the adjacent external level. The DPC in the outer skin is set at around 150mm above external ground level (p). The DPC for the internal skin is set at the same level if the step up from outside to inside is around 150mm. If the difference between outside and inside levels is around 300mm then the DPC is stepped up from outer skin to inner skin in the same place, but a separate DPC is added to the inner skin at the same level as the bottom of the cavity tray.

At roof level there are many variations of eaves junctions, with the top of the wall maintaining a consistent principle of closing the cavity at the top with a brick or block that allows the load from the roof structure to be supported on the inner skin (j). Alternatively, the roof structure may be supported on a column set into the inner skin of the wall or on blockwork piers, also forming part of the inner skin. The closing of the cavity wall at the top allows for continuity of thermal insulation from cavity wall to roof structure, while allowing the roof construction to be ventilated if required and the top of the cavity in the wall to be ventilated. A DPC is set on the underside of the brick or block that closes the cavity to ensure continuity of waterproofing between wall and roof. Parapets are closed at the top by a coping, either in masonry or metal (h). A DPC is set beneath the coping to stop the passage of water downwards from the top of the cavity.



j | Isometric view of eaves junction detail

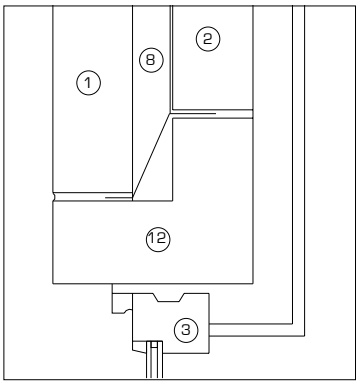


k | Horizontal section 1:10. Corner conditions

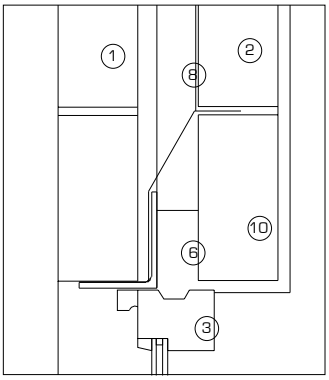
14 | Roof parapet
15 | Stainless steel tie
16 | Damp proof course (DPC)
17 | Ground
18 | Primary structure



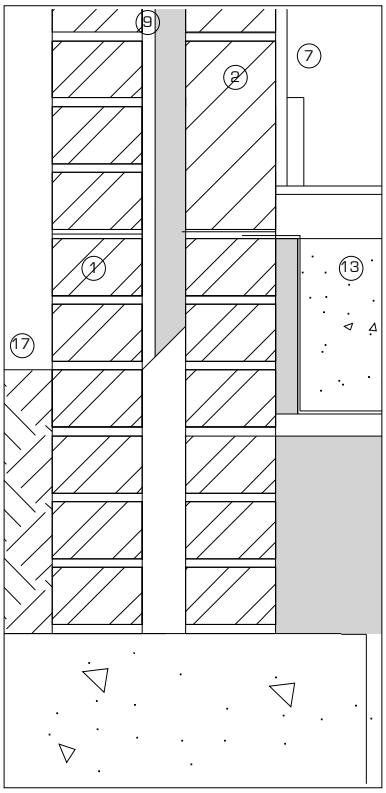
q | 3D view showing typical timber window connections in brick cavity wall



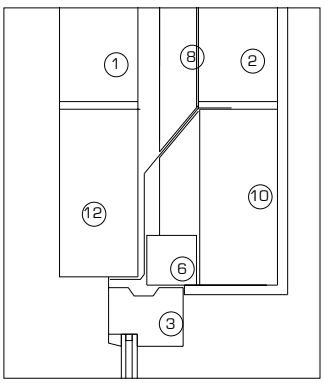
m | Vertical section 1:10. Window assembly



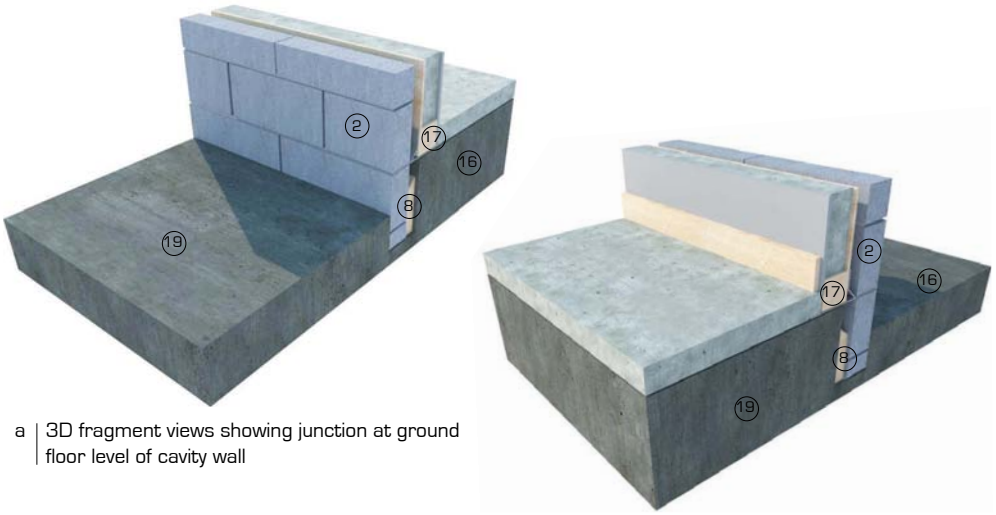
n | Vertical section 1:10. Window assembly



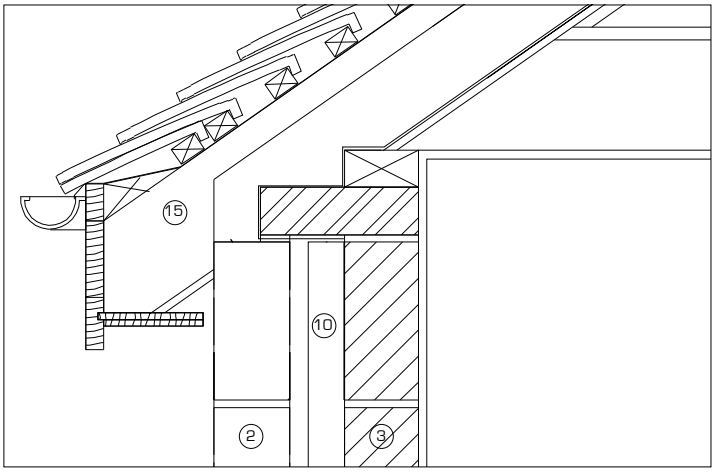
p | Vertical section 1:10. Junction at ground floor level



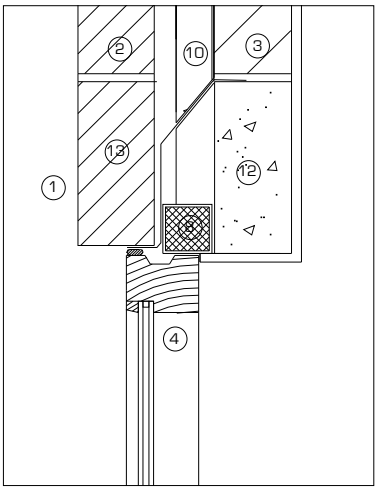
r | Vertical section 1:10. Window assembly

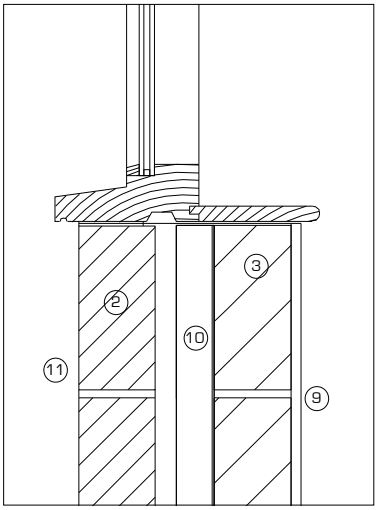


a | 3D fragment views showing junction at ground floor level of cavity wall



b | Vertical section 1:10. Roof connection to stone-faced cavity wall system





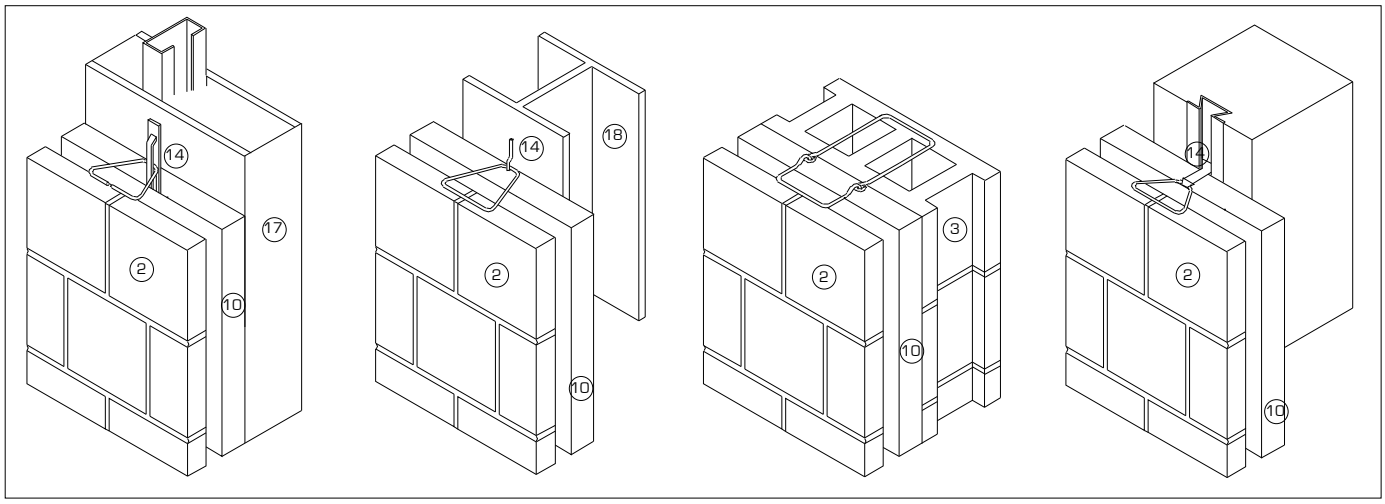
c | Vertical section 1:10. Typical window at cill and head in stone cavity wall

System design

The principles of cavity wall design are set out in the previous text on brick cavity walls. The same principles can be applied for use when stone and concrete blockwork are used to form an outer skin (a).

Stone can be used either as an outer skin approximately 100mm thick (b), or as panels around 40mm thick bonded to an outer brickwork skin. When used as a 100mm thick skin in order to be self-supporting, the stone becomes expensive, so sandstones and limestones are most commonly used. This method suits granites and denser limestones. An essential difference between the detailing of brick cavity walls and stone/block cavity walls is that there are fewer joints in the material due to their large size. Consequently there are fewer opportunities to design a damp proof course (DPC) with floor slabs, for example, particularly where shelf angles are used. The smaller unit size of brick makes it a very flexible material when detailing; stone/block requires careful co-ordination of stone/block size and floor-to-floor heights to allow for windows to be suitably placed. For this reason, alternating bands of thick and thin stone are used in coursing. This allows horizontal joint lines to be provided at shelf angles, cavity trays and DPCs at ground level, without disturbing the stone pattern with additional horizontal joints. Unlike open-jointed stone cladding, where the mortar is omitted, the mortar and joint profile have a big visual impact.

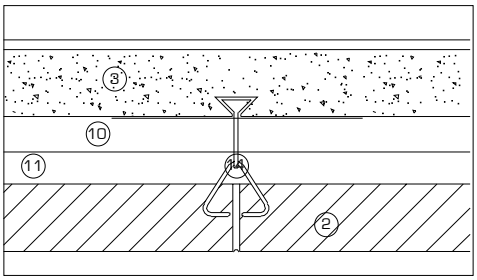
Loadbearing cavity walls used to support two storey structures on their inner skins are very common in housing construction in Europe and North America. Vertical movement joints are provided at around 7500mm centres, or else are avoided altogether in the construction by keeping lengths of wall within these dimensions. When cavity walls are used with large-scale building frames in either steel or concrete, the inner leaf is no longer loadbearing and instead the complete wall construction forms a cladding to the frame. When reinforced concrete frames are used, the junction between inner skin, typically concrete block or terracotta block, is straightforward with a gap between the two to allow for structural movement in the frame (d). Stainless steel sliding anchors are used either in the sides of the inner skin panel where it meets the column, or at the head where it meets the floor slab. The outer skin runs continuously in front of it. The situation is more complicated with a steel frame, where the column needs to be protected from water vapour corrosion in the cavity. Typically, the column is painted to form a protective coating and thermal insulation is set across the face of the steelwork to provide a continuity of thermal insulation. Sometimes the outer skin is restrained with cavity ties (e) fixed to the face of the reinforced concrete or steel column. This is particularly useful when forming a movement joint in lengths of brickwork, or movement joints that form part of the building structure, which typically occur at columns in the building frame. The vertical movement joint is filled with two parts polysulphide sealant that also matches the colour of the mortar as closely as possible and provides a seal that can accommodate the structural movement within the cavity wall.



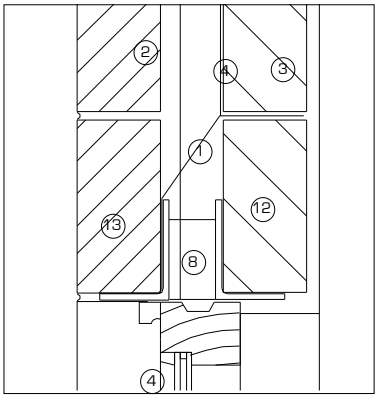
d | 3D fragment views showing various wall assemblies

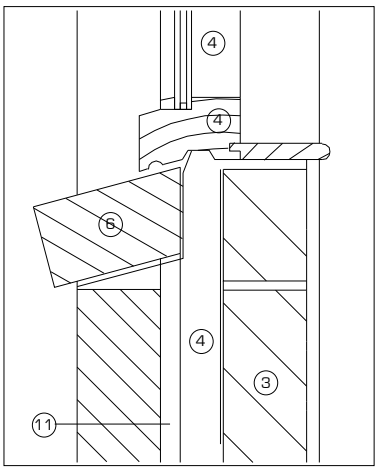


f | 3D view showing timber window frame in stone cavity wall



e | Horizontal section 1:10. Typical wall system showing wall tie





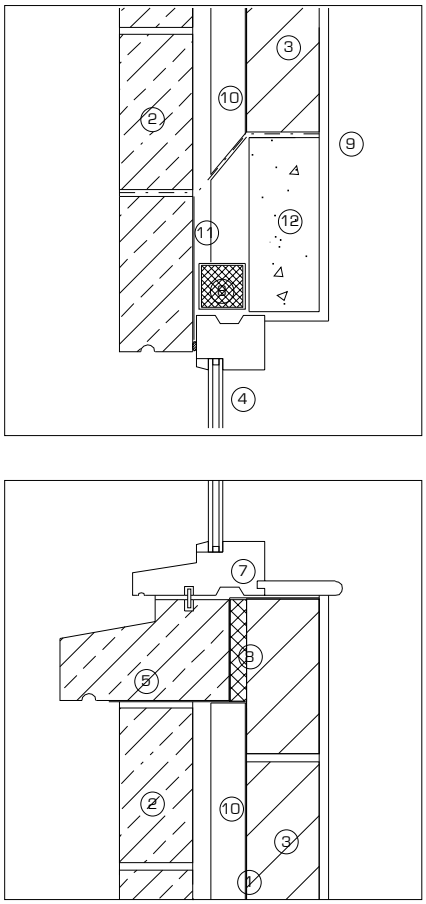
g | Vertical section 1:10. Typical window at cill and head

Details

1 | Damp proof course (DPC)
2 | Outer block wall (or 'leaf')
3 | Inner block wall (or 'leaf')
4 | Timber framed window
5 | Precast concrete cill
6 | Stone cill
7 | Timber inner cill
8 | Cavity closer
9 | Internal plaster finish or dry lining/drywall
10 | Thermal insulation in cavity
11 | Air cavity (sometimes omitted where insulation fills cavity)
12 | Inner precast concrete lintel
13 | Outer precast concrete/stone lintel
14 | Stainless steel tie
15 | Roof construction
16 | Floor construction
17 | Timber framed inner skin
18 | Steel framed inner skin
19 | Ground



h | 3D views showing typical window at cill and head in block cavity wall system



j | Vertical section 1:10. Typical window at cill and head in block cavity wall system

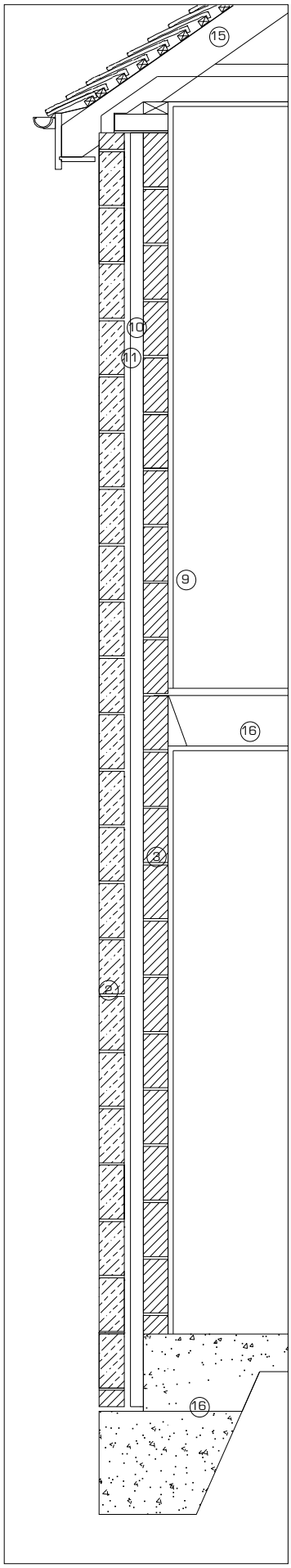
System details

This section discusses variations and details in addition to those set out in the previous section on brick cavity walls and focuses on different materials for the inner skin.

When a timber framed inner skin is used, the window is usually an integral part of that inner skin so that a complete enclosure is formed in timber with masonry used as an outer skin providing some lateral stability. The outer masonry skin can be returned to form a reveal up to around 125mm, depending on the thickness of insulation in the cavity. Alternatively, the timber window can be set forward close to the line of the outer face with a timber cill projecting forward of the wall (h). This gives the outer wall the impression of a brick texture, giving a planar appearance to the material.

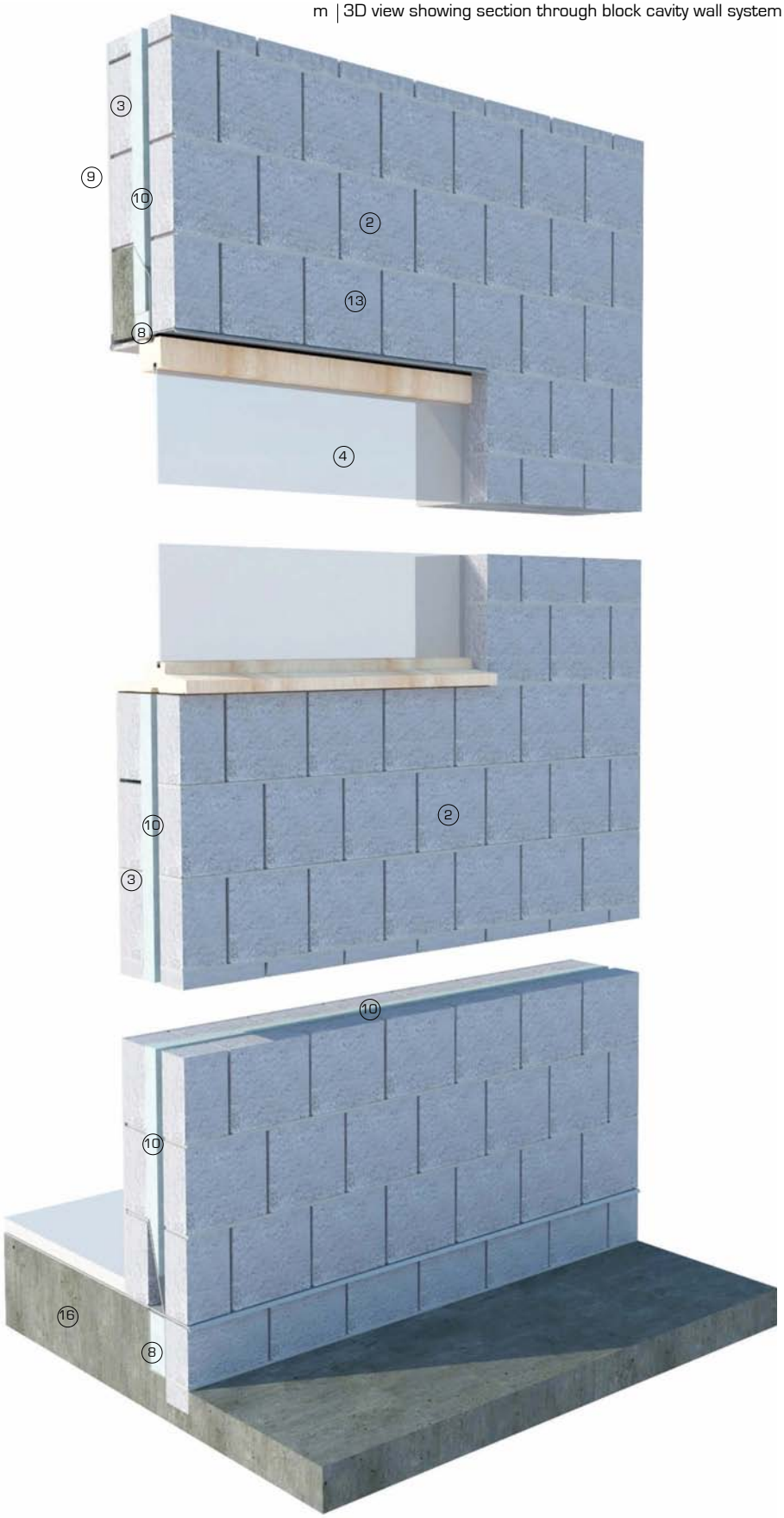
With reinforced concrete inner skins, stainless steel fixings and restraints are usually post-fixed to the concrete. In recent years, outer masonry skins have been made as prefabricated panels on some projects when fixed back to a reinforced concrete wall (d). Panels of stone, terracotta or even brick are bonded together with mortar and then held in a steel edge frame, which is fixed to the inner skin. The concrete inner skin is waterproofed with bituminous paint and thermal insulation is set on the outside face of the inner skin. The steel angle on the bottom edge forms a closer to the window below, while the steel on the top edge forms a cill to the window above. The vertical steel angles are usually concealed within the cavity to give a continuous masonry appearance. The masonry is sometimes restrained within the panel by vertical stainless steel rods which are tensioned against the frame to form lightly prestressed panels. Vertical joints between panels are sealed, typically with a polysulphide sealant.

For parapets, the inner skin is thickened up when used as a balustrade. A handrail on top of the coping is fixed by drilling through the top and bolting it to the inner skin beneath. The coping is cut to receive the balustrade or handrail, unless the uprights supporting the handrail pass between the joints. The adjacent area of flat roof or gutter usually has a waterproofing layer returning up the wall, regardless of the roof finish. The waterproofing layer is set into horizontal joints in outer masonry skin. A metal flashing is set into the same horizontal joint and is set over the top of the waterproofing to protect it from damage. Metal copings are used increasingly on parapets in order to match the appearance of windows and doors, particularly where metal cills are used. The same principles apply as for concrete copings, with a DPC set on top of the masonry wall. Drips are formed on either side of the vertical face to ensure that water is thrown clear of the wall. For all parapets, the waterproofing layer is continued up the wall to become continuous with the DPC in low parapets. For high parapet walls, a stepped DPC is used to drain water back to the inner skin to ensure that water inside this part of the cavity wall is drawn away.



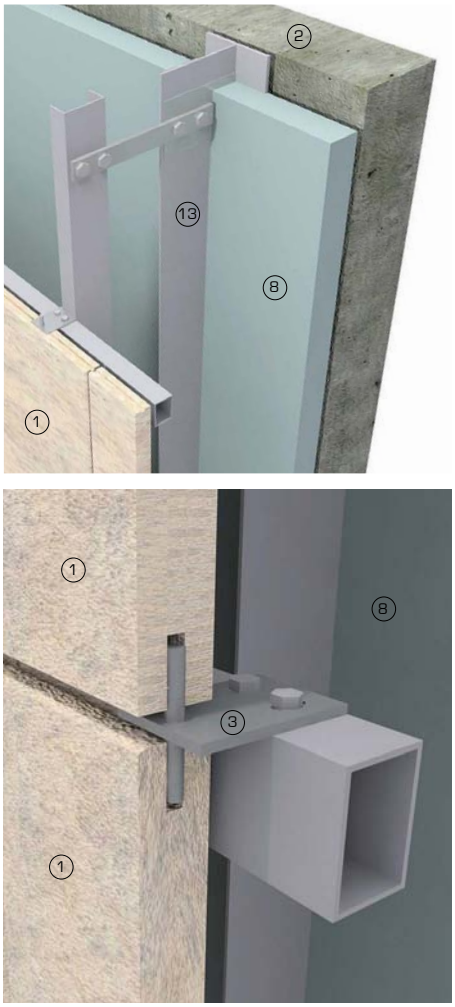
k | Vertical section 1:25 showing typical details

m | 3D view showing section through block cavity wall system



Details

1 | Damp proof course (DPC)
2 | Outer block wall (or 'leaf')
3 | Inner block wall (or 'leaf')
4 | Timber framed window
5 | Precast concrete cill
6 | Stone cill
7 | Timber inner cill
8 | Cavity closer
9 | Internal plaster finish or dry lining/drywall
10 | Thermal insulation in cavity
11 | Air cavity (sometimes omitted where insulation fills cavity)
12 | Inner precast concrete lintel
13 | Outer precast concrete/stone lintel
14 | Stainless steel tie
15 | Roof construction
16 | Floor construction
17 | Timber framed inner skin
18 | Steel framed inner skin
19 | Ground





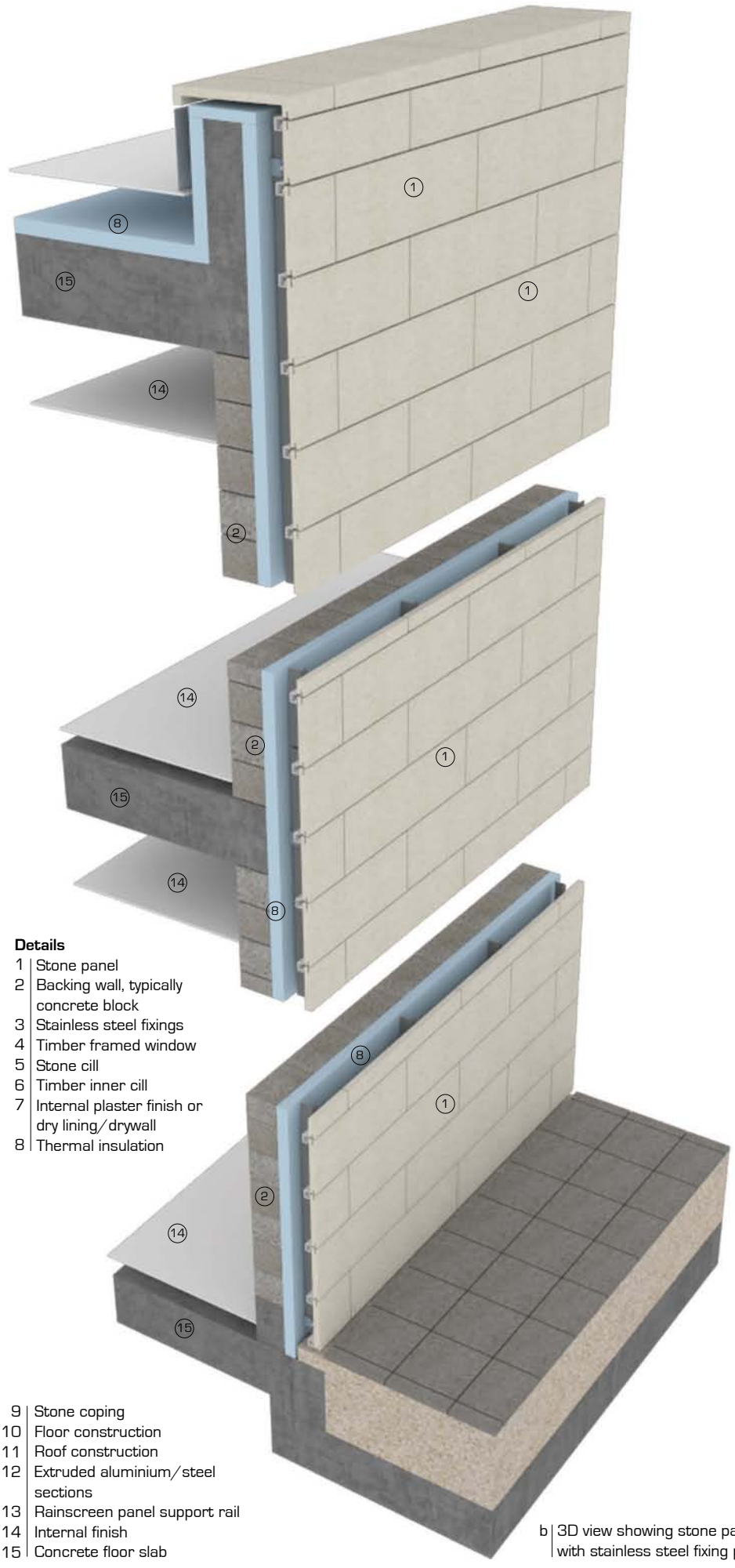
a | (Top left) 3D view of stainless steel fixing pins
(Bottom left) 3D view of stone panels on carrier system
(Right) 3D view of stone panels on individual fixings

System design

Stone cladding panels are typically fixed back either directly to a backing wall or to a metal carrier frame with a separate backing wall behind (a). The use of stone for cladding requires an emphasis in the design stage on choosing not only the specific material, but also setting the range of colours and textures of the material. This involves an investigation into applying the physical properties of the actual stone to be used (if this is not already known) to a structural-based design to establish or confirm maximum panel dimensions and suitable fixing methods for the proposed sizes of panel. The physical properties of the stone may be available from the quarry at an early stage, but sometimes testing is done during the early procurement stage to ensure that the material meets the requirements of the building code. The thickness of stone required for a facade is usually established by structural calculation. Flexural strength, also called the modulus of rupture, is usually the most significant structural consideration in establishing panel size. Codes of practice often set out minimum thickness for various panel sizes, but this is only a general guide and calculation is usually undertaken for specific facade applications. Since the material may not already be cut from the quarry at the time of its selection, stone facades can involve longer procurement times than other facade systems, particularly on larger projects. The stones used are typically granites, sandstones, limestones and slates, and are once again being considered as a material that could be locally sourced; a material available in abundance in the region in which the building is to be constructed.

Stainless steel is used for stone fixings (a) because of its resistance to corrosion combined with high strength and rigidity. Fixings have a three-way adjustment vertically, horizontally and laterally in order to align the stone panels accurately. The type of fixing used varies with the thickness and stone type used. Fixings are usually set at the top and bottom of the panel (b), with the bottom fixings being loadbearing and the fixings at the top of the panel being restraints. Side fixings are sometimes used depending on the weight and strength of the panel.

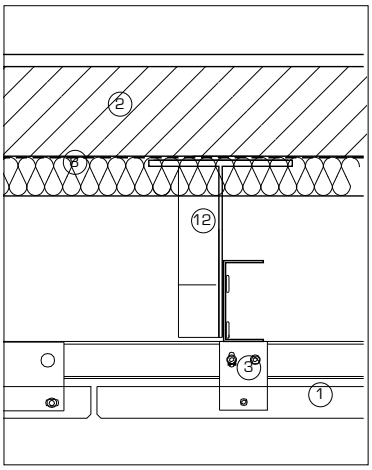
Stone cladding can be used as a 'wrap' to a structural frame as well as its more traditional use for cladding walls with punched openings. The mixture of large stone panels with long narrow panels associated with reinforced concrete structural frames gives a visual drama not usually associated with stone cladding until recently. The arrangement of stone panels can imitate traditional patterns of jointing such as stretcher bond, but can also benefit from the mechanical fixing of each stone panel (d) by forming an arrangement that is independent of the backing wall behind, mixing both stone sizes and different shapes in a single wall composition. The development of water jet cutting techniques in addition to advancements in established stone cutting tools has led to a greater variety in the size and shape that remains within the limits of economic construction. The introduction of triangular panels in rainscreen configuration has encouraged the use of stone cladding on folded facade surfaces to complement the geometries used in glazed



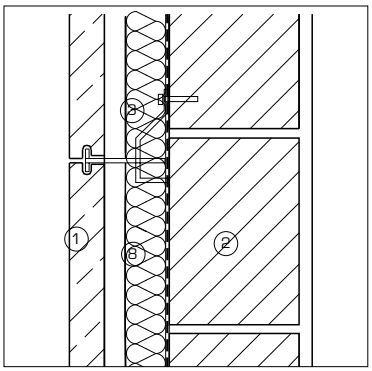
Details

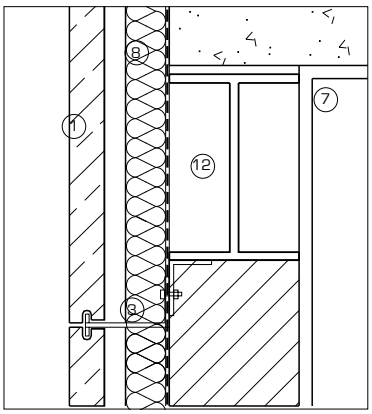
1 | Stone panel
2 | Backing wall, typically concrete block
3 | Stainless steel fixings
4 | Timber framed window
5 | Stone cill
6 | Timber inner cill
7 | Internal plaster finish or dry lining/drywall
8 | Thermal insulation
9 | Stone coping
10 | Floor construction
11 | Roof construction
12 | Extruded aluminium/steel sections
13 | Rainscreen panel support rail
14 | Internal finish
15 | Concrete floor slab

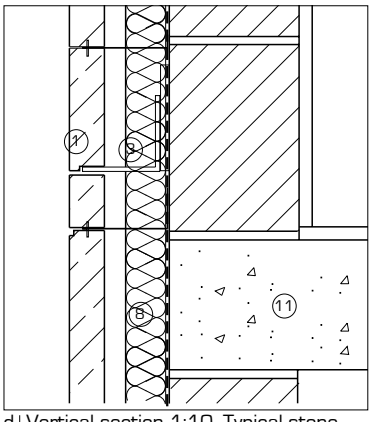
b | 3D view showing stone panels with stainless steel fixing pins



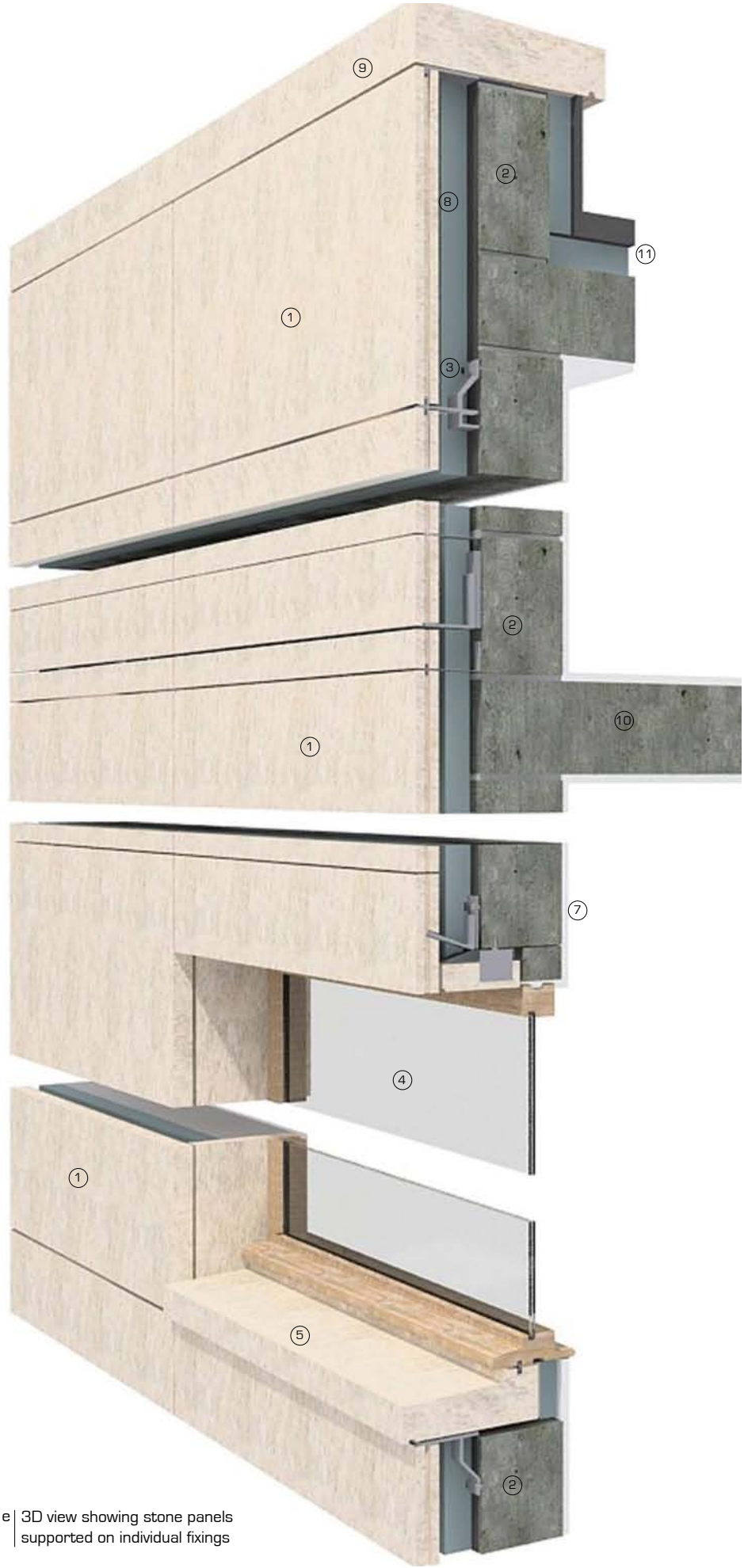
c | Horizontal section 1:10. Typical stone carrier system made from extruded aluminium section



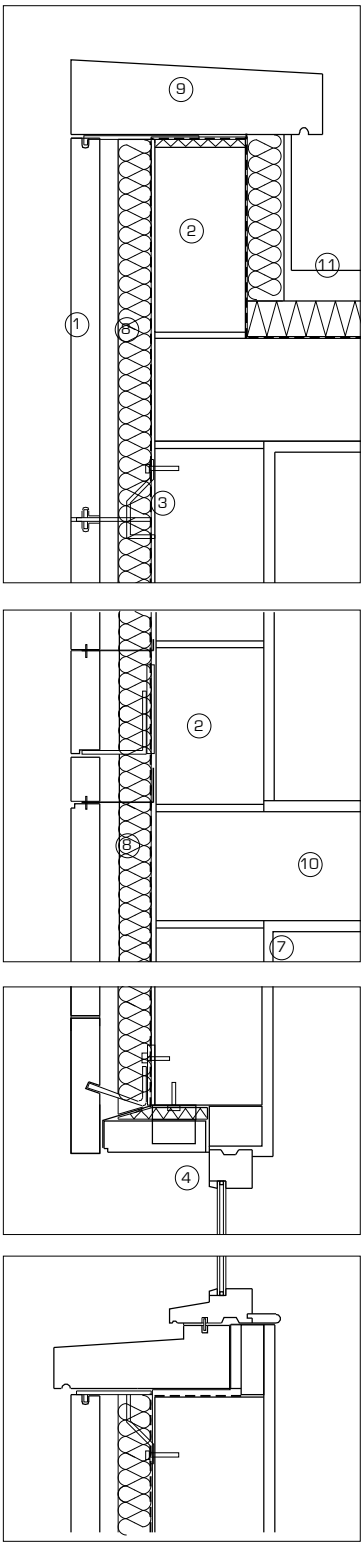




d | Vertical section 1:10. Typical stone carrier system made from individual fixings



e | 3D view showing stone panels supported on individual fixings



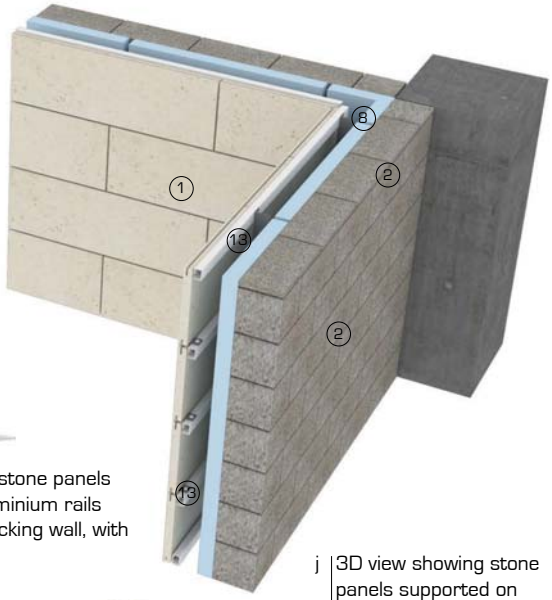
f | Vertical section 1:10. Stone supported on individual fixings

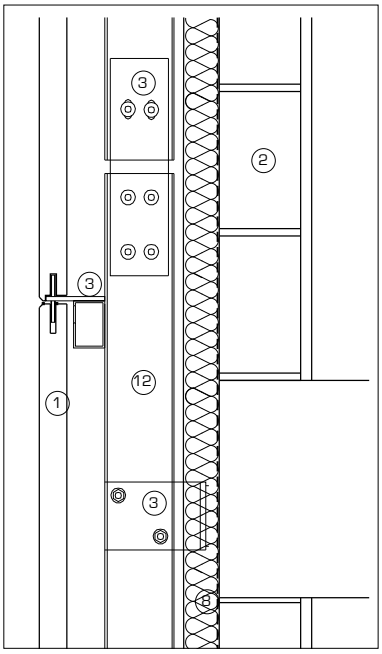
Details

1 | Stone panel
2 | Backing wall, typically concrete block
3 | Stainless steel fixings
4 | Timber framed window
5 | Stone cill
6 | Timber inner cill
7 | Internal plaster finish or dry lining/drywall
8 | Thermal insulation
9 | Stone coping
10 | Floor construction
11 | Roof construction
12 | Extruded aluminium/steel sections
13 | Rainscreen panel support rail



g | 3D view showing stone panels supported on aluminium rails and blockwork backing wall, at internal and external fold



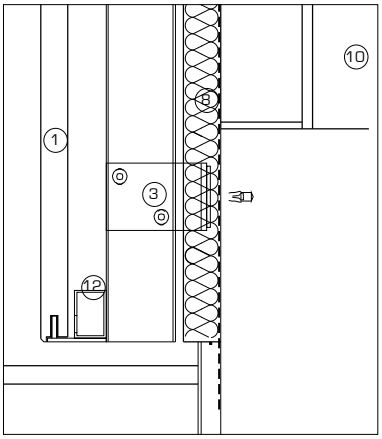




h | 3D view showing stone panels supported on aluminium rails and blockwork backing wall, with window opening

j | 3D view showing stone panels supported on aluminium rails and blockwork backing wall





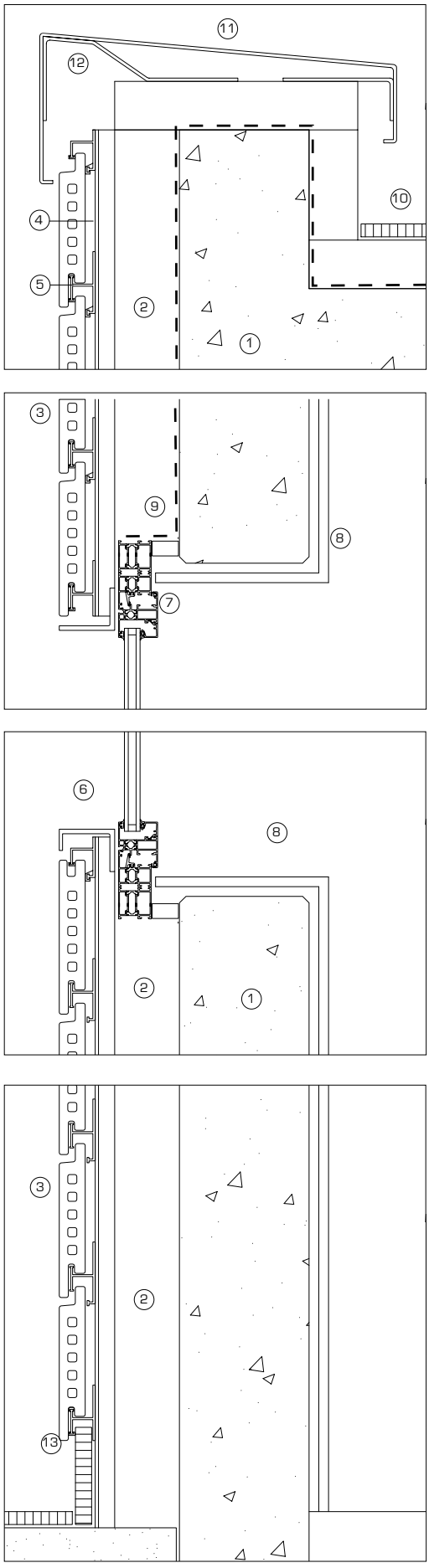
k | Vertical section 1:10. Typical stone panels on carrier system

walls. Finishes for stone have also developed in recent years, with rubbed, honed, polished and flamed finishes for different stone types.

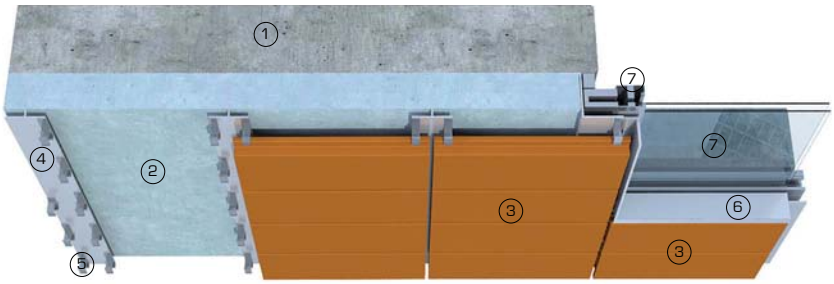
System details

Joints between stone cladding panels are either of open rainscreen type or are closed with mortar or sealant. Closed joints sealed with mortar or sealant are used where the cladding is supported at each floor level on stainless steel angles with jointed stones (e). With open jointed stones, each panel is individually supported in a rainscreen construction (f), where rainwater passing through the joints is drained away down either the back of the stones or down the face of the backing wall, which is typically insulated (8). The choice of joint type is partly a visual decision and partly one that ensures adequate ventilation to the cavity between the stone and the backing wall, allowing stones to dry properly. Closed joints allow the stone cladding to perform in a similar way to a cavity wall, with ventilation provided at the top and bottom to dry the void behind the stones. Joints in sandstones and limestones are usually filled with cement/sand mortar or cement/sand/lime mortar. Granites and slates are typically proprietary sealants such as two-part polysulphide. Mortar used for pointing is made frost-resistant when used in temperate climates, and is of similar strength to the joining mortar, with the structural mortar behind. The maximum width of mortar-filled joints is around 12mm, but sealant filled joints can exceed this subject to visual requirements. Joint widths are partly a function of the cutting tolerance of the stone, which can vary along its length by up to 2mm, depending on stone panel size and the cutting machine used. Joint widths of 4mm are common, but this can rise to around 12mm when required for visual reasons.

Movement joints are set both horizontally and vertically to accommodate movements in the building structure. Horizontal movement joints are used to deal mainly with structural deflections in floor slabs, and are usually provided at floor level, where the stone cladding is supported from either short lengths of stainless steel angle, or a continuous steel angle (h). The movement joint is set immediately below the stainless steel angle, where vertical deflection will occur. Horizontal movement joints can be set at intervals of two storeys if a carrier frame is used that will span the full height (j). The movement joint width is usually around 20mm, formed as an open joint. Vertical movement joints in the facade, located to correspond to movement joints in the building structure, are set immediately forward of these movement joints where they reach the facade. The distance between joints is typically around 6 metres in a continuous run of stone cladding with closed joints. The joint width corresponds to the expected movement in the cladding, but where sealed joints are used, the joint width is dependent on the amount of movement that the sealant is required to accommodate.



a | Vertical section 1:10. Terracotta rainscreen fixed to loadbearing concrete wall



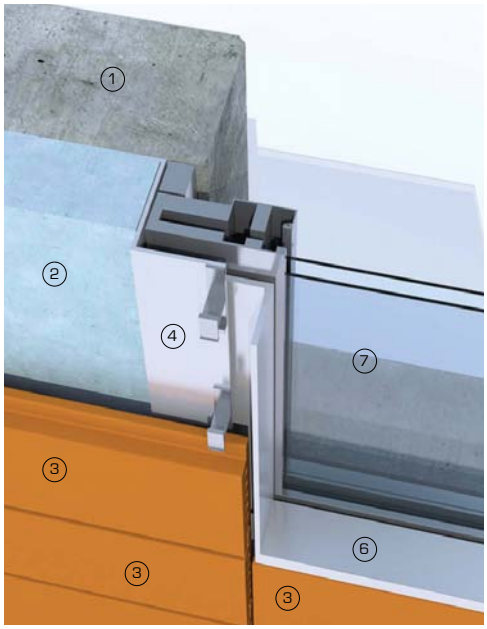
b | 3D views showing terracotta rainscreen system with window opening



c | 3D view showing terracotta rainscreen system with window opening

Details

1 | Backing wall, typically concrete
2 | Thermal insulation
3 | Terracotta rainscreen
4 | Extruded aluminium carrier frame
5 | Support clip, typically aluminium
6 | Aluminium window surround
7 | Metal framed window
8 | Internal plaster finish or dry lining/drywall
9 | Vapour membrane
10 | Roof construction
11 | Metal coping
12 | Coping support
13 | Stone paving



d | 3D detail view showing terracotta rainscreen system at window opening



e | 3D views showing build-up of terracotta rainscreen system

System design

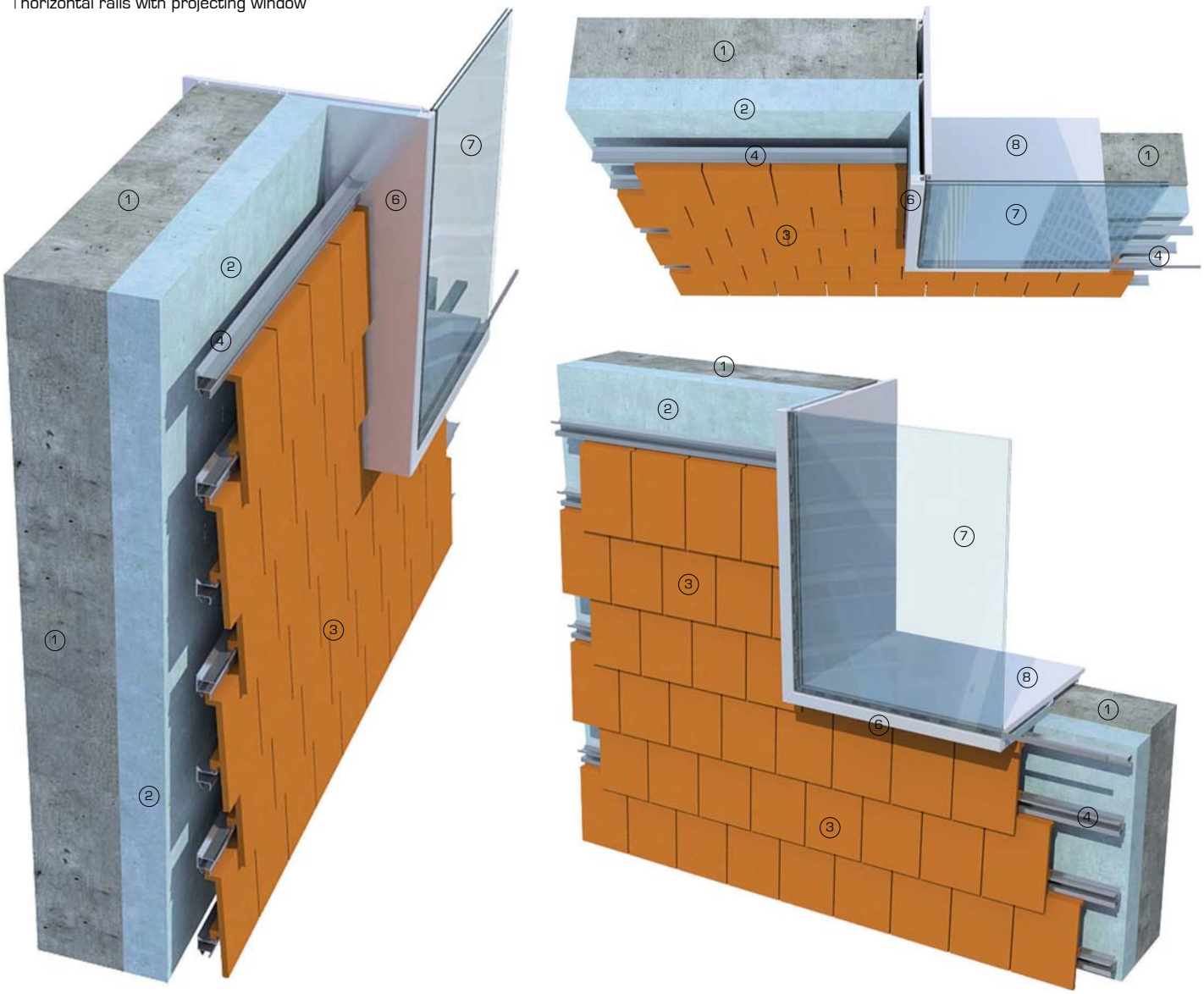
Terracotta rainscreens are a recent development over the past 15 years, and can be seen as a development of brick cavity walls to a fully ventilated version in full rainscreen configuration (a). Over that time, the sizes of terracotta panels have increased and fixing systems have developed, and have also been adapted for use as solar shading louvres to glazed walls, particularly where terracotta is also used as an adjacent wall cladding material. Terracotta louvres typically comprise hollow sections reinforced internally with aluminium sections to form louvered screens that can be matched with adjacent areas of terracotta cladding. Terracotta rainscreen panels are fixed either on rails (b), into aluminium or stainless steel panels, or onto individual brackets like masonry cladding with concealed fixings. Vertically-set or horizontally-set rails are used to suit a range of joint arrangements that imitate traditional masonry bonds, or can alternatively be fixed in a stack bonded arrangement. Recently developed systems have interlocking panels to provide visually crisp joints, and panels extruded as twin wall sections to provide long spanning panels (c). The range of glazed finishes has developed considerably in recent years to give a very wide range of textures and colour mixes derived from contemporary pottery. Terracotta is made from natural clay that is first extruded, then cut to the required length of panel, then fired in a kiln. The use of extrusion dies allows the manufacture of terracotta panels to be flexible from project to project. As with aluminium framed curtain walling, the die creates different heights and depths of block, while maintaining a hollow interior to keep the material relatively light and easy to handle, allowing long panel lengths to be formed.

System details

Terracotta panels have two extruded edges and two cut edges, resulting in panels being arranged on a facade so as to avoid a cut edge being visible at a corner. This arises because the surface finish and colour of the end face will not match that of the front face. The ends of panels are usually concealed with aluminium trims (d), sometimes at the corners but typically around window openings. Alternatively, special corner shapes can be formed by hand to match the standard extruded tiles, made by a pressing method, usually with a maximum length of 150mm on one leg and 300mm on the other. Large corner pieces are made by hand by joining two sections together, but these currently produce less reliable results that can lack a straight and crisp edge. In addition, manufacturers often provide extruded cill sections for parapets and window sections to suit wall constructions of 300mm to 500mm wide.

Fired terracotta is either left in its natural colour or is glazed. A glazed finish can give the material a reflective quality which provides better

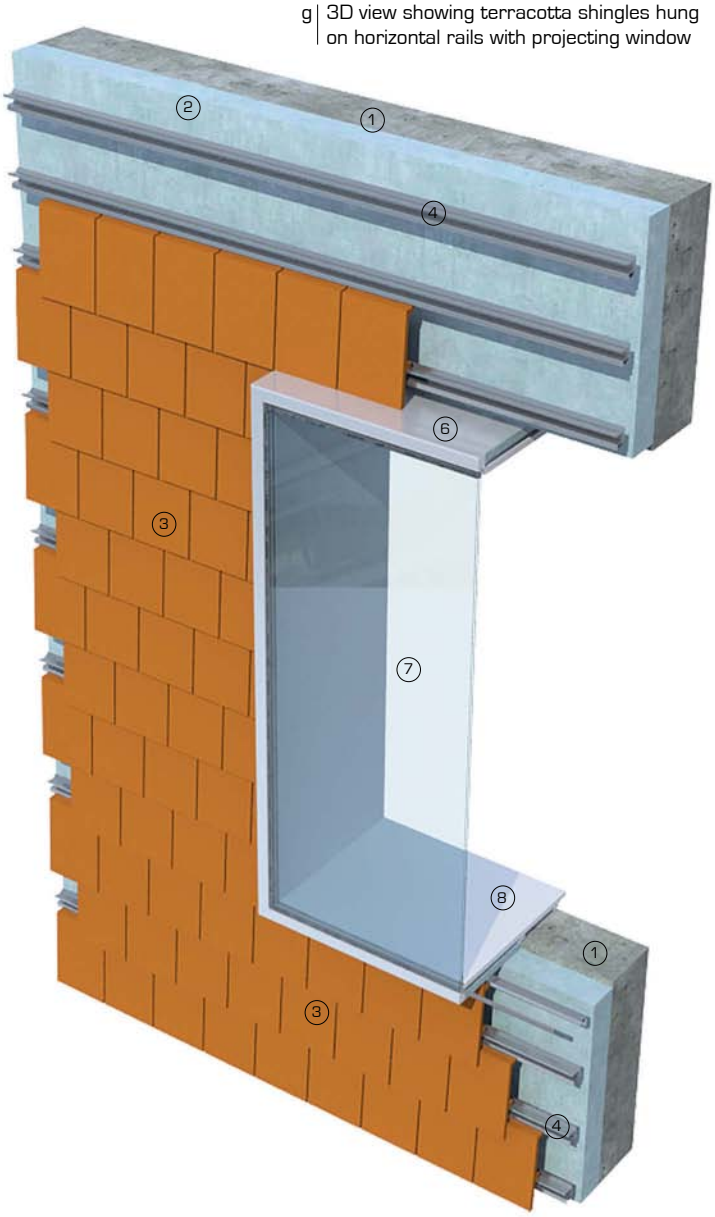
f | 3D views showing terracotta shingles hung on horizontal rails with projecting window

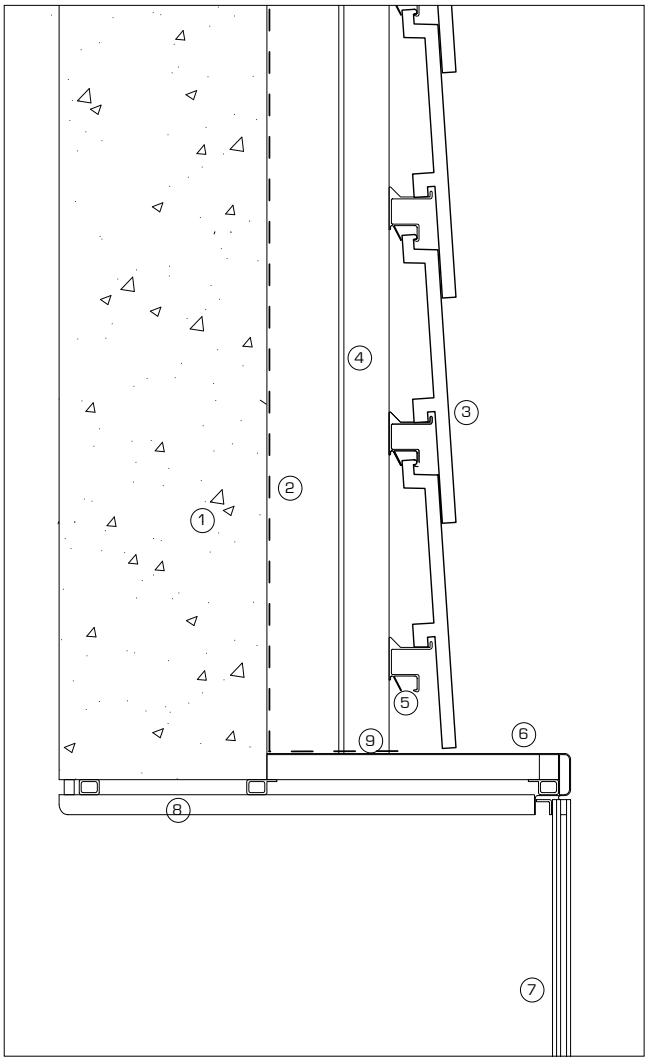


protection from surface staining. However, water absorption of regular terracotta panels is between 3% and 6%, with a density of around 2000kg/m³, making the use of glazes not essential for excluding rainwater, but important for more for visual reasons. Panels are fixed to support rails which are set either vertically or horizontally, made from aluminium for their ability to be formed precisely as extrusions for ease of fixing (a). Vertical rails are well suited to 'stack bonded' terracotta, where joints form a rectilinear grid of continuous vertical and horizontal joints. Horizontal rails are suited to staggered bonds of panels that imitate the stretcher bond used in traditional wall construction where vertical joints are not continuous. At least twice as many vertical rails are needed as those for a stack bond arrangement. Since horizontal joints are continuous, horizontal rails are used to fix courses of terracotta. Joint widths vary from 2mm to around 10mm, depending on the size of panel and type of fixing system chosen.

The largest panels are planks of up to around 1500mm long x 600mm wide x 40mm thick, requiring a more substantial aluminium support section behind the panels. The aluminium extrusions, set at the ends of each panel, sometimes project forward of the terracotta as structural fins to provide rigidity to the support framing without requiring greater depth in the cavity zone behind the terracotta. Where used, the projecting fins give the facade a characteristic appearance of vertical bays of panels where only vertical backing supports are used, divided by the visible edge of the aluminium support. Corner pieces can be made in sizes of 250mm x 300mm high, which often do not correspond with the maximum length that can be manufactured for the planks; but this constraint will no doubt be overcome with the development of this facade system. Thinner terracotta panels of 30mm thickness are used in sizes with a maximum length of around 800mm and a corresponding maximum height of 300mm. These thinner panels have maximum corner panels of 150mm on one leg and 300mm on the other leg. The minimum sizes that can be accommodated with the vertical rail system are terracotta panels around 200mm long x 200mm high, with a thickness of 30mm to 40mm. Windows and doors are set into terracotta rainscreen cladding by fixing them to, and sealing them against, the backing wall (g). Aluminium trims used at the corners and edges of the panels can also be used to close the gap between terracotta and window, with the trim on the bottom edge of window openings used to provide a cill. Windows and doors are positioned to

g | 3D view showing terracotta shingles hung on horizontal rails with projecting window

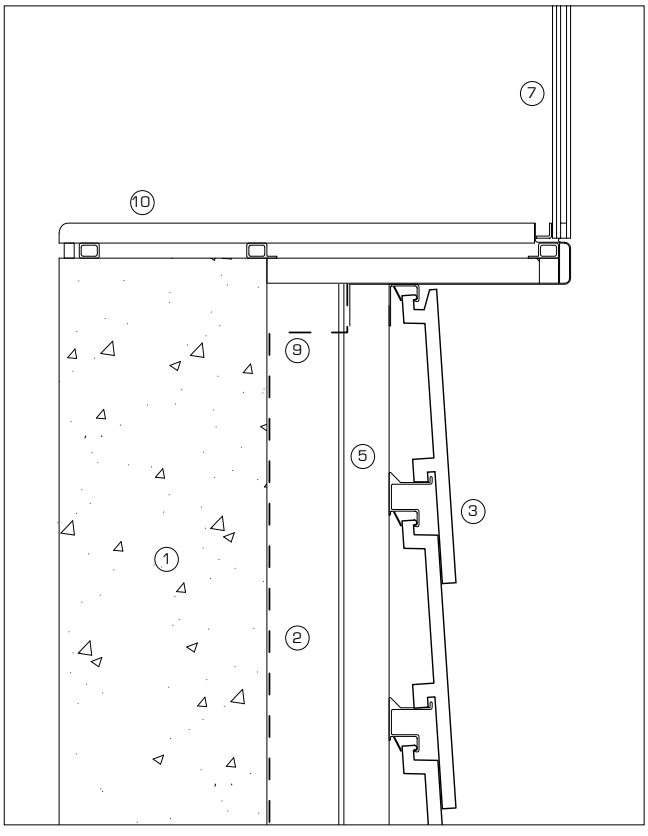




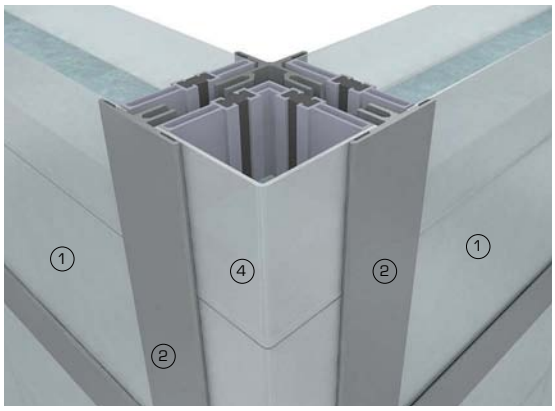
Details

1 | Backing wall, typically concrete
2 | Thermal insulation
3 | Terracotta rainscreen
4 | Extruded aluminium carrier frame
5 | Support clip, typically aluminium
6 | Aluminium window surround
7 | Metal framed window
8 | Internal plaster finish or dry lining/drywall
9 | Vapour membrane
10 | Roof construction
11 | Metal coping
12 | Coping support
13 | Stone paving

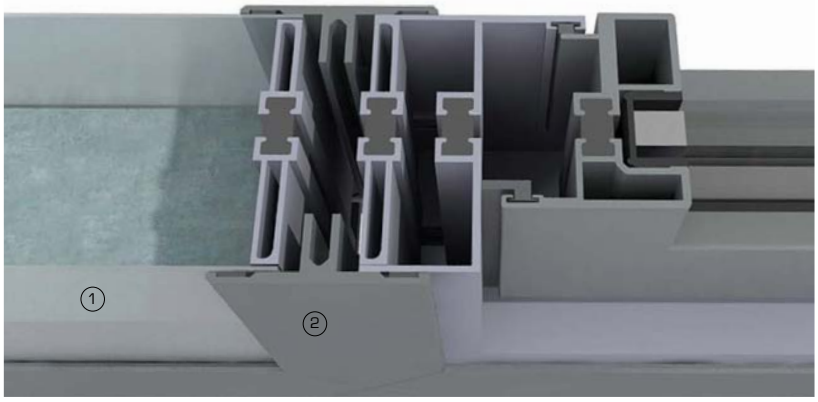
form a continuity of weather proofing, and are typically set back from the face of the terracotta panels (h), with the trim providing a crisp edge from a visual point of view. Typically, trims are made from either folded aluminium or rolled steel channels. The flat, planar nature of terracotta has led to the increased omission of reveals around window openings by pushing the window frame forward to align with the face of the terracotta panels, with insulated panels closing the gap between the window and the backing wall. Where terracotta is introduced as the material to form a reveal, corners are mitred with open joints if special corner panels are not used.



h | Vertical section 1:10 Terracotta shingles fixed to concrete loadbearing wall



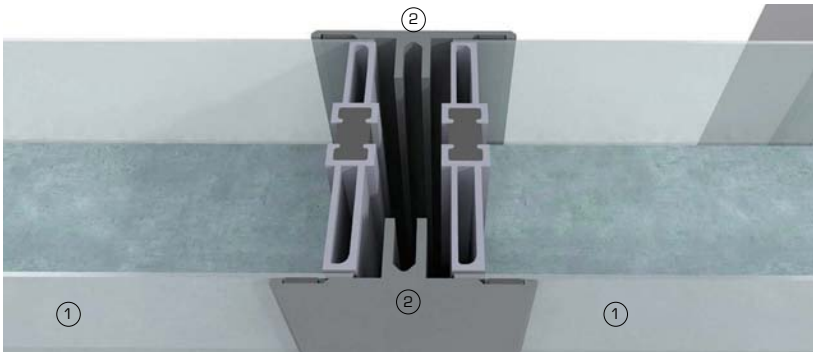
a | 3D detail view showing corner junction of polycarbonate composite panel wall assembly



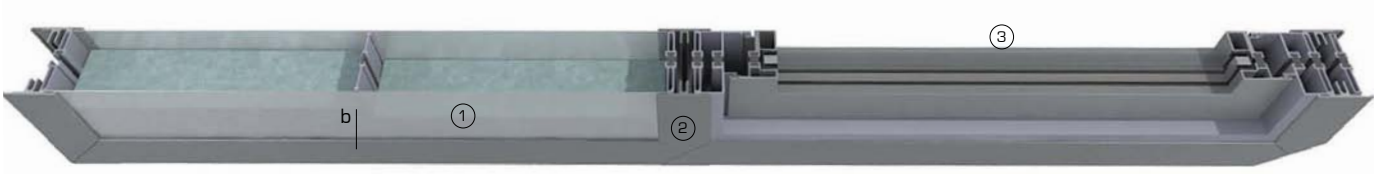
b | 3D detail view showing junction between GRP composite wall panel and window inserted into assembly framing

Details

1 | Translucent polycarbonate cladding panel, insulated
2 | Thermally broken extruded aluminium framing
3 | Window inserted into framing
4 | Insulated corner panel
5 | Adjacent wall



c | (Right) 3D detail view showing junction between panels in polycarbonate composite panel wall assembly



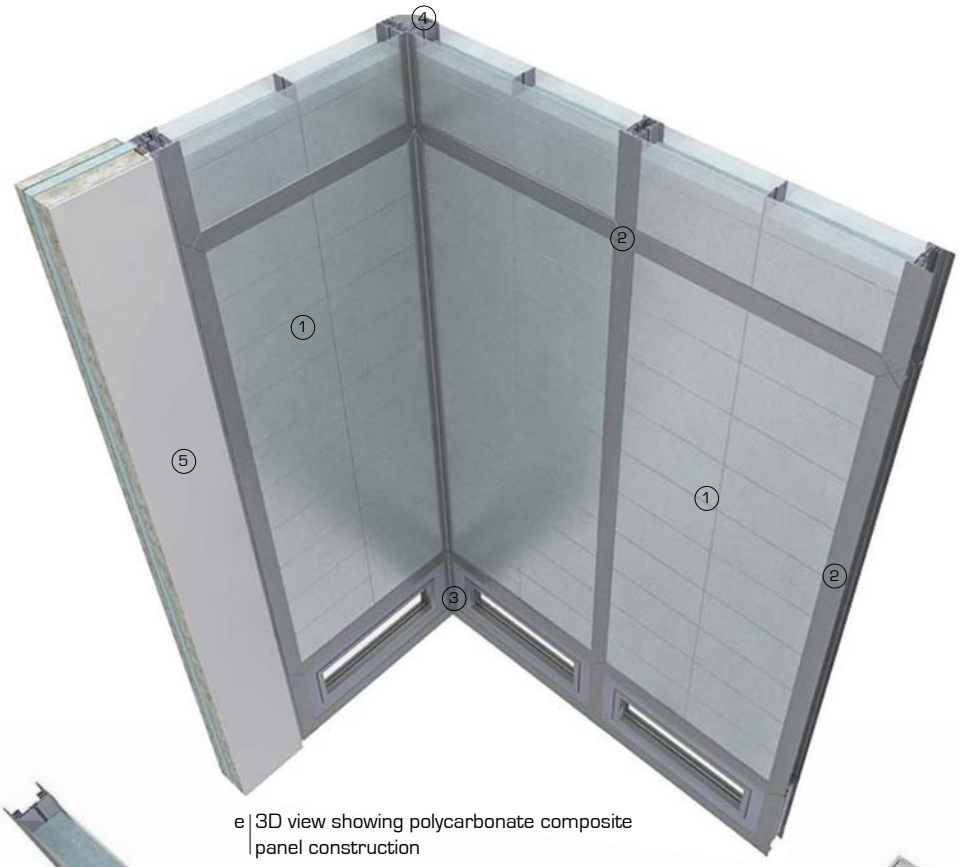
d | 3D sectional detail view showing window assembly within composite panel wall system

System design

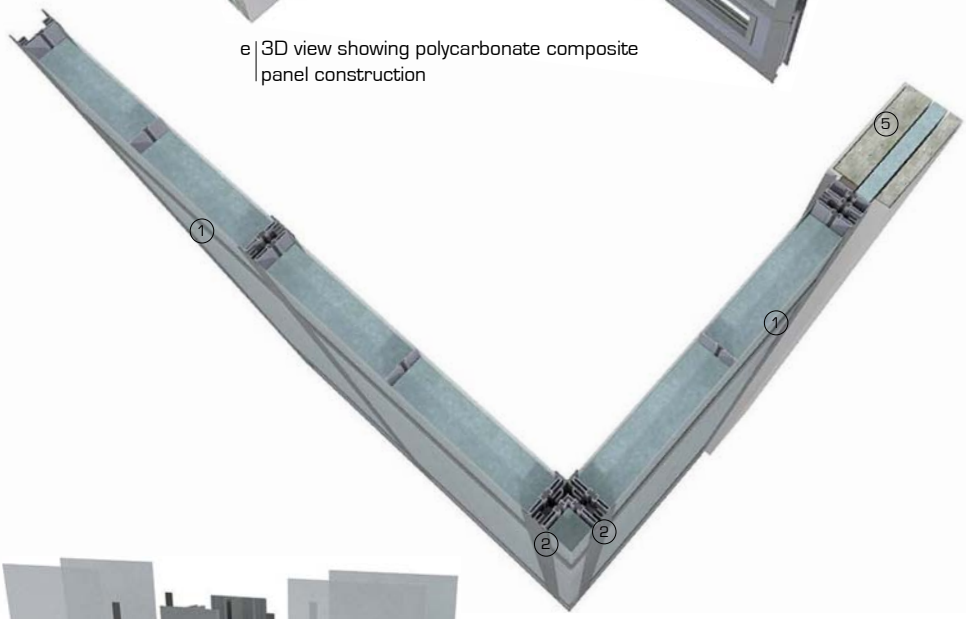
The use of plastics is based on both proprietary systems and those developed by manufacturers for specific projects. Plastics are resinous, polymer-based materials, used in facade systems as the primary material in both sealed cladding panels and rainscreen panels. As sealed cladding panels, their use has been enhanced by the successful use of proprietary systems which combine lightness in weight with high levels of thermal insulation and panels of visually elegant appearance (e). Concerns about the long term weathering aspects of plastics, with their tendency to deteriorate noticeably with time, have been largely addressed by manufacturers. The materials used are principally glass reinforced polyester (GRP), polycarbonate and UPVC. This section discusses the use of GRP in sealed cladding panels which is the most common material used. GRP is a composite material made from thermosetting polyester resins, which set hard and do not melt when re-heated, and that are mixed with glass fibre mat. This composite material has high tensile, shear and compressive strength combined with lightness and resistance to corrosion. However, like aluminium it deflects considerably under high loads and requires stiffening, but is more rigid than other plastics. GRP is not combustible and can reach one hour fire resistance in some cladding applications. GRP panels are formed by laying glass fibre cloth into a mould and coating it with resin and catalyst, or alternatively spraying a mixture of glass fibre and resin into a mould. The face of the mould is coated with a releasing agent to allow the GRP to be removed when it has set hard.

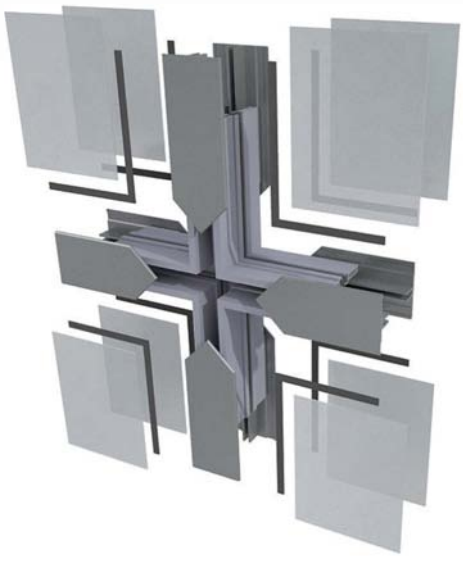
GRP panels are characterised by their lightness in weight combined with being manufactured by moulding, allowing them to be made in large panel sizes, of up to 6000mm x 1500mm. Panel thicknesses are usually 70-75mm to provide structural stability and high levels of thermal insulation. In common with metal composite panels, GRP panels have undergone much development in the use of adhesives to avoid delamination between the outer skins and the insulation core. GRP cladding panels can be made either as separate panels glazed into an aluminium pressure plate system (b) (in a similar way to glass) with a secondary supporting structure behind, or alternatively by setting thermally broken aluminium extrusions within the depth of the panels (c). That allows them to be fixed together in the manner of composite metal panels. Panels are also stiffened internally with aluminium I-sections or T-sections where large-scale panels are used. The arrangement of the framing can provide differing amounts of translucency across a panel, where some of the framing is either partly visible or completely concealed.

In addition to proprietary panels, GRP and polycarbonate (discussed in the next section) can be used to form larger scale panels which are made by fabricators for individual projects. These typically comprise two sheets of either profiled GRP or polycarbonate fixed either side of metal framing spanning floor-to-floor (e), or full height with some additional restraint, to suit individual projects. The main issue from a visual point



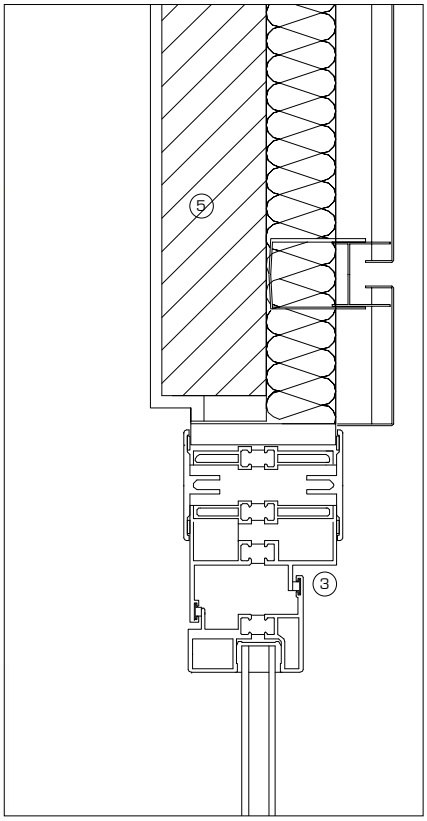
e | 3D view showing polycarbonate composite panel construction

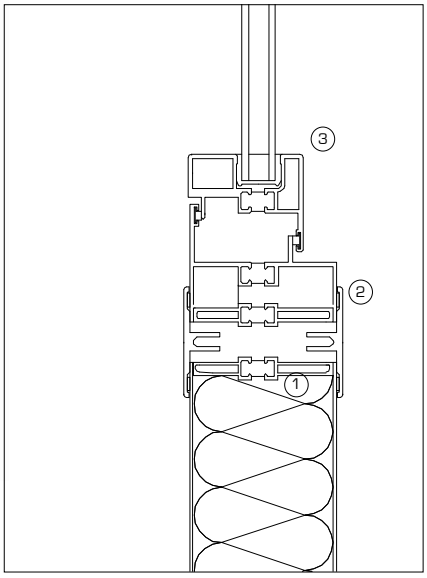


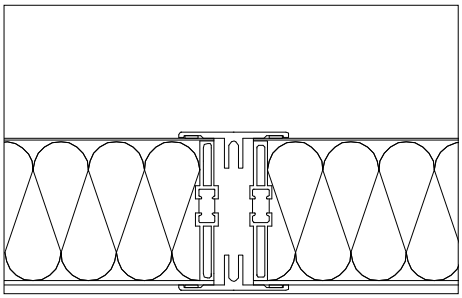


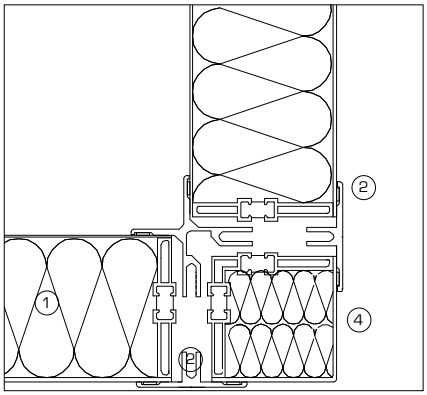
g | 3D exploded detail view showing polycarbonate composite panel construction

f | 3D view showing polycarbonate composite panel construction

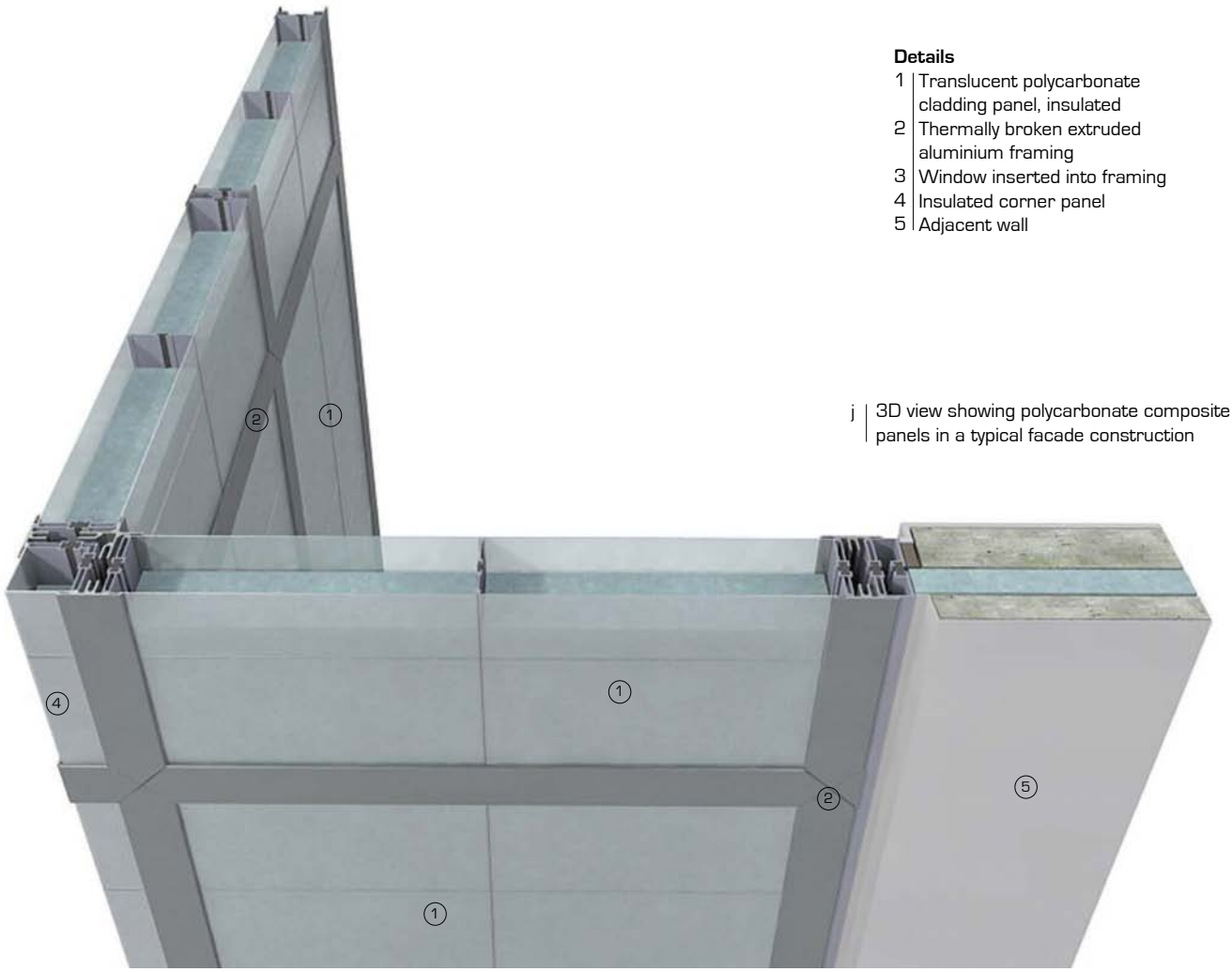








h | Horizontal section 1:10. GRP composite wall assembly showing typical details



Details

1 Translucent polycarbonate cladding panel, insulated
2 Thermally broken extruded aluminium framing
3 Window inserted into framing
4 Insulated corner panel
5 Adjacent wall

j 3D view showing polycarbonate composite panels in a typical facade construction

of view is the choice of thermal insulation, which can provide either translucency or opacity. Where translucent sheet is used, the insulation itself can form the primary visual expression of the facade panel rather than the plastics (j). Natural materials such as straw bales and wool have been used to this effect.

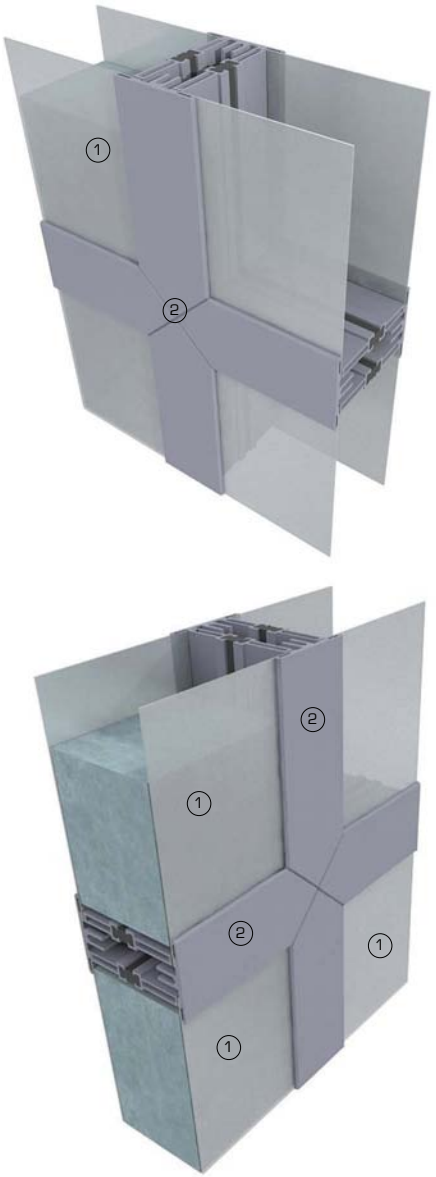
System details

When formed as translucent panels, aluminium framing is set within the panel forming a visible grid resembling that of traditional Japanese Shoji screens (k). These internal ribs are typically set out on a grid of between around 300mm x 300mm to 300mm x 600mm centres. The void between the two skins of the panel can be filled with translucent insulation quilt to increase thermal insulation, while still allowing a diffused light to pass through the panel. Light transmission without additional thermal insulation is typically around 15% with a U-value of 1.5W/m^2 ºK, similar to an argon-filled double-glazed unit, and a shading factor of 20%, which provides a high level of shading for a glass-based wall. Windows can be glazed into the panels, giving the possibility of a rich mix of windows, doors and translucent panels without the need for complex framing. Window frames can form part of the T-section extrusion around a window. Integrating the window frame into the extrusion that supports the GRP panels avoids the risk of leaks associated with single silicone-sealed butt joints when a separate window frame and panel frame are fixed together. The integrated window frame allows water to be drained from the frame. GRP panels can be glazed into large structural openings, from floor to ceiling for example, or can form a complete glazed wall restrained by a secondary steel frame. When glazed into an opening, the edge T-section aluminium profiles are sealed against the adjacent concrete floor slab with silicone, at both top and bottom. When fixed to a secondary support frame, panels are supported at each floor level on metal brackets in either aluminium, mild steel (if internal) or stainless steel (if exposed to the weather). Cills and copings are formed using the methods described in the section on metal composite panels.

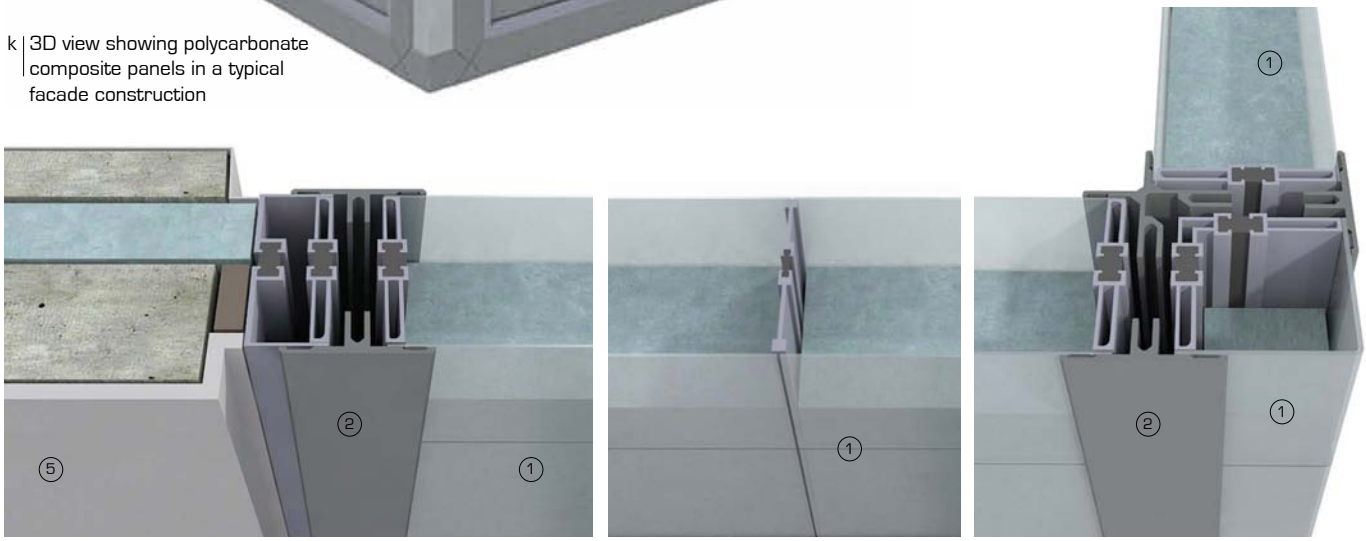
Where twin-wall polycarbonate is used in conjunction with other plastic-based panels (n), the material is fixed with either conventional aluminium framing for windows or, alternatively, framing for stick glazing curtain walling. Some manufacturers provide extruded I-sections, similar to those used in GRP cladding, to clip the twin wall sheets to provide a completely lightweight system (m). This is a very economic form of cladding which can be screen-printed to create visually dramatic translucent facades. As with profiled polycarbonate sheet, other standard components are not usually manufactured, and folded aluminium sections are used for drips and parapet copings instead of polycarbonate sections, which are expensive to produce as new profiles. Although plastic-based panels are usually made as panels fabricated in a factory and fixed together on site in an extruded aluminium glazing system, they can also be formed on site by fixing plastic-based sheet on either side of metal framing supports. The cladding may be formed into panels or as a continuous wall structure. The use of translucent insulation as an infill material that is not fully bonded to the supporting plastic skins provides considerable possibilities for innovation.



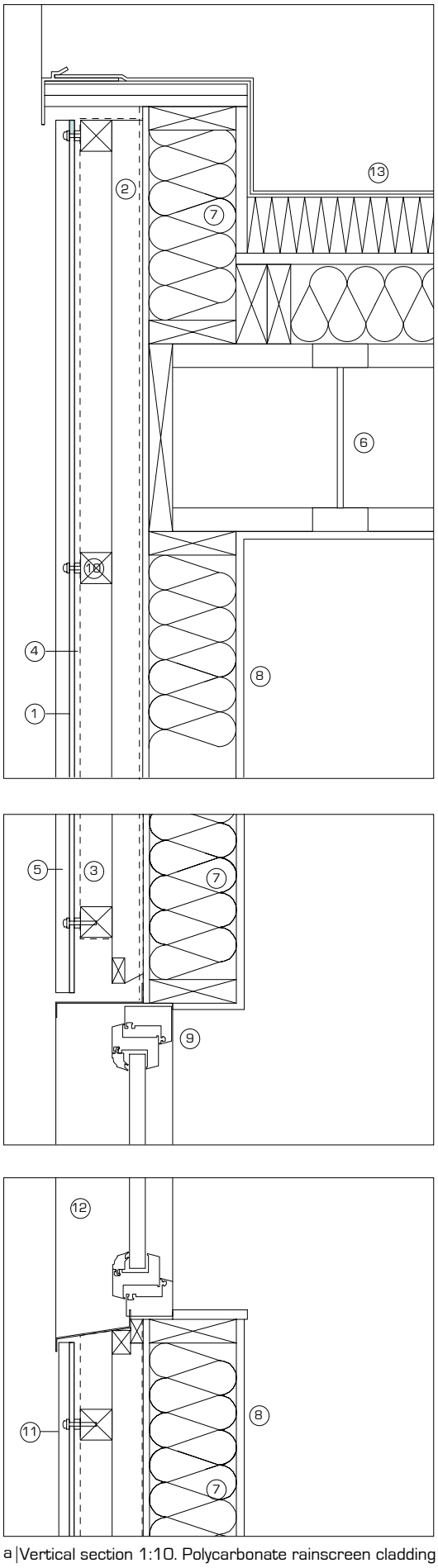
k | 3D view showing polycarbonate composite panels in a typical facade construction



m | 3D detail views showing polycarbonate composite panel construction



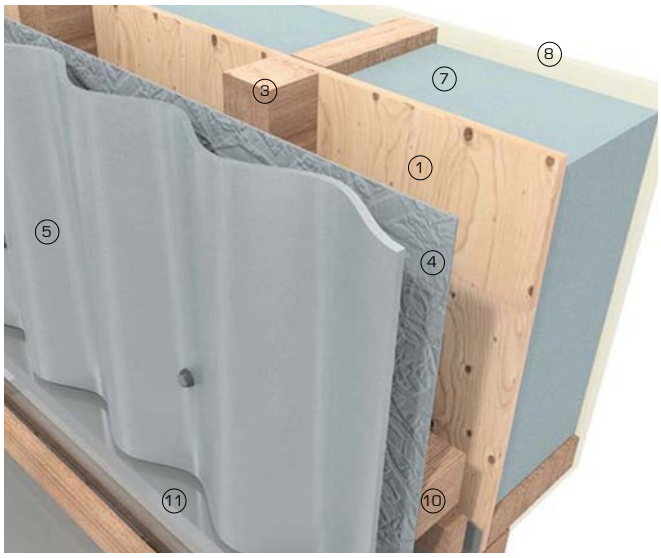
n | 3D detail view showing polycarbonate composite panel construction

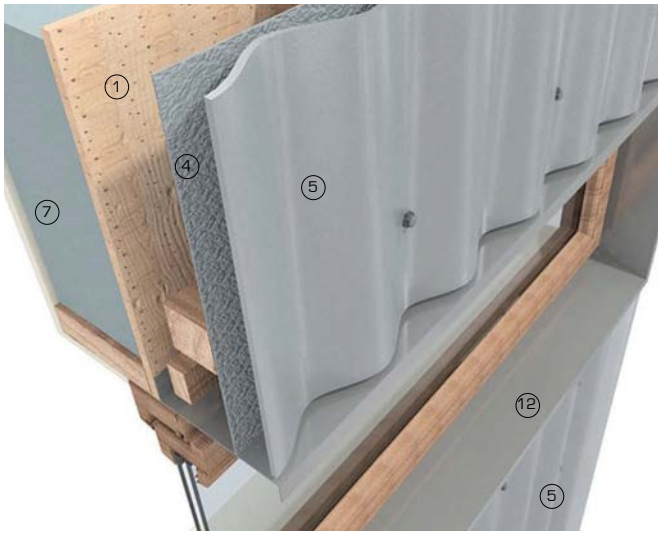


a | Vertical section 1:10. Polycarbonate rainscreen cladding



b | 3D views showing section through polycarbonate rainscreen







c | 3D detail views showing cutaway through polycarbonate rainscreen

Details

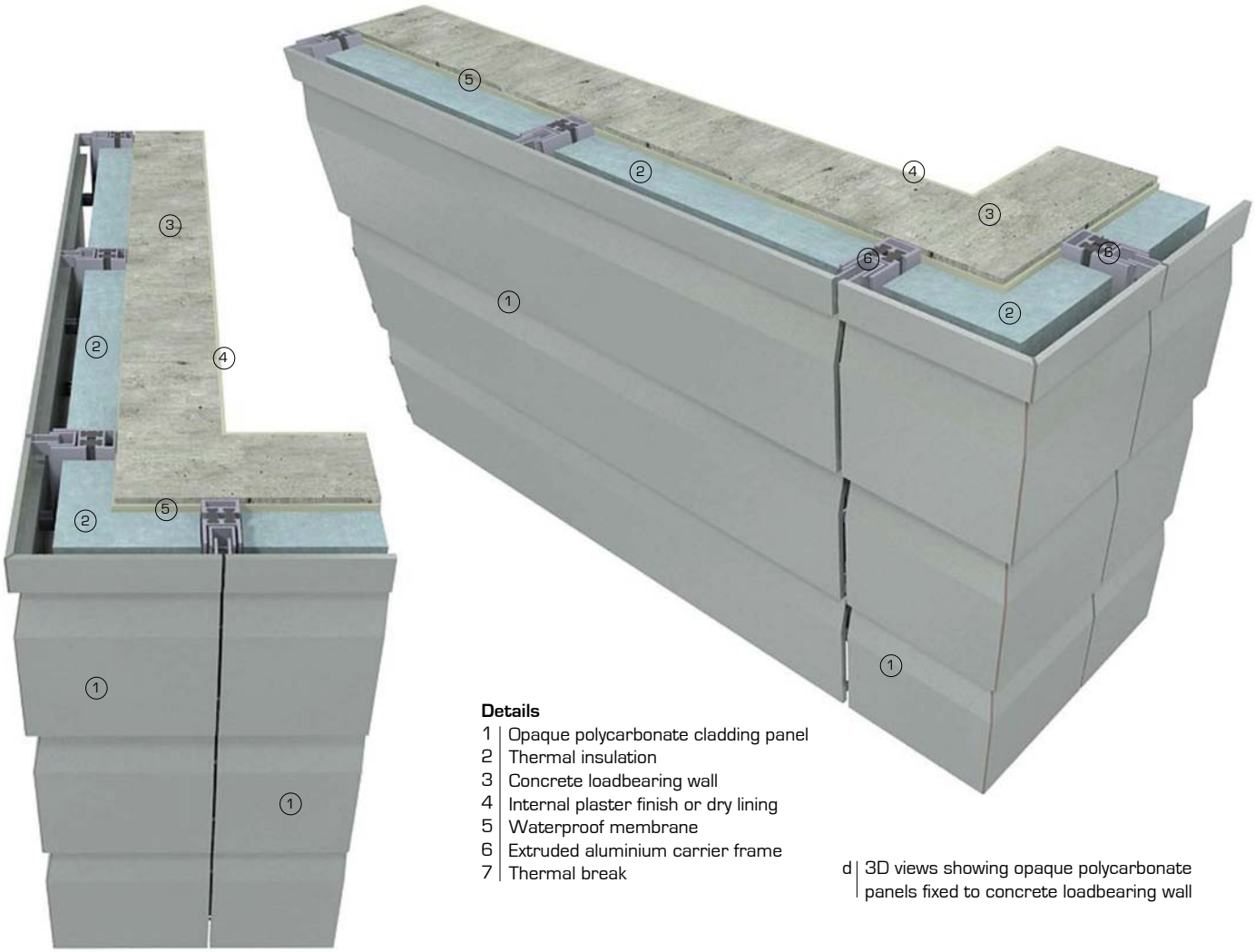
1 | 10mm plywood sheathing
2 | Breather membrane
3 | Vertical timber battens
4 | Reflective foil breather membrane
5 | Profiled polycarbonate cladding (orientated vertically)
6 | Composite timber joist
7 | Thermal insulation
8 | Internal dry lining
9 | Timber framed window
10 | Horizontal timber battens
11 | Screw fixing with plastic spacer
12 | Aluminium window surround
13 | Roof construction

System design

Plastic-based rainscreens are used in a variety of types reflecting the overall range made in other materials: flat panels, cassette panels, profiled sheet and shingled tiles. Plastic panels are used as either outer screens to glazed walls, typically as solar shading, or as rainscreen panels to an opaque wall (b). The materials used are either polycarbonate or glass reinforced polyester (GRP). The use of GRP is discussed in the previous section. Acrylic and UPVC, while softer than both these materials, are used for window frames and special moulded elements. In addition, composites are used for cladding panels, made from thermosetting polymer resins mixed with cellulose fibres to provide sheet materials with high durability which fade little in sunlight. In common with rainscreens in other materials, panels or sheets are fixed with either visible point fixings (a), vertical/horizontal rails with partially concealed framing members, or partially interlocking panels where there is no view through the joints. Polycarbonate is a thermoplastic; that is to say it melts at high temperatures and is used in cladding for its translucency and transparency, achieving up to around 90% light transmission. The material is extruded or moulded (from polymer-formed granules) to form sheet materials that are flat or profiled. Polycarbonate has a tendency to yellow with age, which can be overcome with an acrylic coating. It is also used for its high strength and impact resistance, ductility and lightness in weight. However, because the material is combustible, its use in facades is limited. It is also less durable than glass, scratching easily which makes the surface dull with time, and has high thermal expansion, up to 20% more than glass. Opaque flat sheet is fixed as rainscreen cladding panels, made in a wide range of colours, Sheets are fixed either at their corners with an aluminium clamp on both sides, or with visible point fixings. Generally, plastic panels can be used with the full range of rainscreen configurations of other materials, including the lapped construction of timber boards and shingles. Like sealed plastic panels, plastic rainscreen panels have the benefit of translucency, though the visual effects of dust settling on the rear face of the rainscreen, and any periodic cleaning they may require, varies between facade applications.

System details

Single layer polycarbonate sheet sizes are around 2000mm x 3000mm and 2000mm x 6000mm, in thicknesses from around 3mm to 8mm. Profiled sheets are produced in lengths of up to around 10 metres, around 1200mm wide, with thicknesses around 1mm. When opaque colours are used rather than the translucent or clear types, hook-on fixings can be secured to the rear face of the panel, secured to vertically- or horizontally-set rails without the fixings being visible. Profiled sheets are fixed with self-tapping screws sealed with a weathertight washer and lapped on all sides (c), in the manner of profiled metal sheet. This technique creates a shadow where they lap, which can be masked by the support structure behind, or may even contribute to the overall visual



Details

1 | Opaque polycarbonate cladding panel
2 | Thermal insulation
3 | Concrete loadbearing wall
4 | Internal plaster finish or dry lining
5 | Waterproof membrane
6 | Extruded aluminium carrier frame
7 | Thermal break

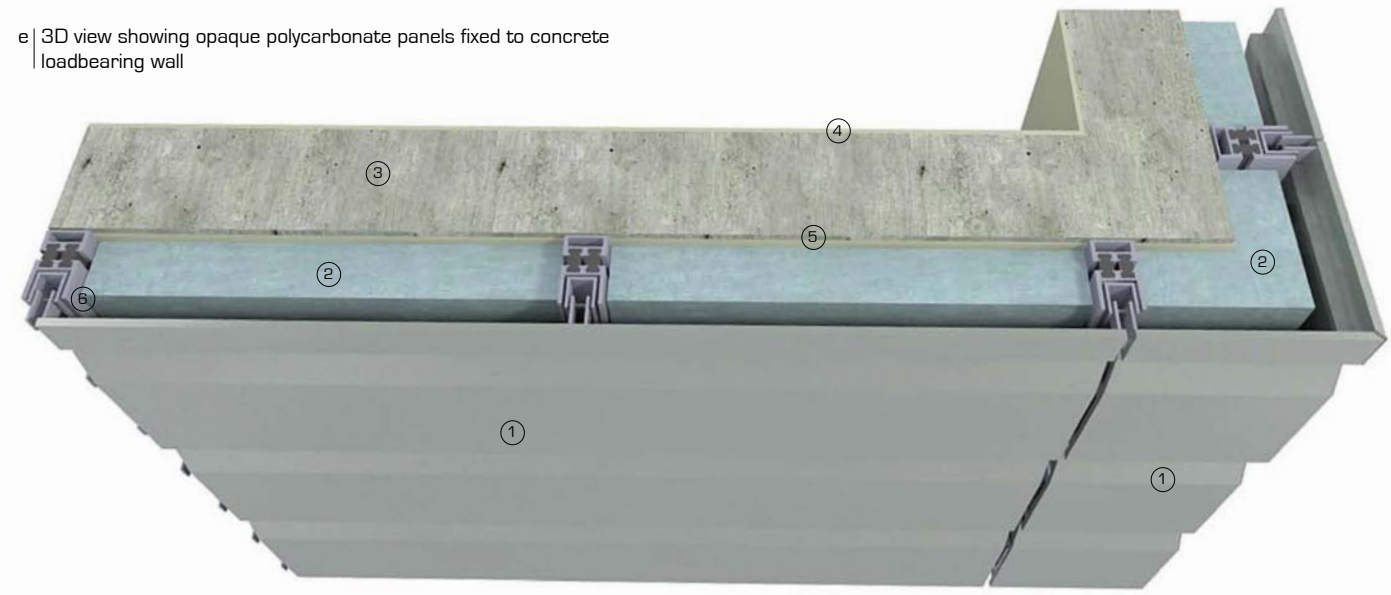
d | 3D views showing opaque polycarbonate panels fixed to concrete loadbearing wall

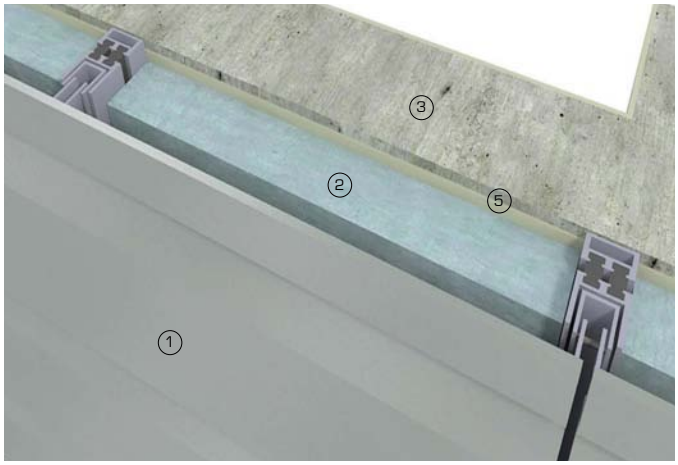
effect. Cill, drip and coping profiles are made from any of the typical materials used: extruded aluminium, extruded UPVC or GRP. Profiled sheet can be curved to a minimum radius of around 4000mm for a sheet of 50mm thickness, making it possible to create complex geometries with an economic translucent material. Profiled polycarbonate sheet is also made in a translucent white colour to provide a light transmission of around 45%, and in grey colours with a light transmission of around 35%. Multi-wall polycarbonate sheet can also be used for rainscreens, where its main advantage is the ability to provide large, flat panels as well as its inherently high level of thermal insulation. Thicknesses range from 4mm to 32mm, in sheet sizes from 1000mm x 6000mm to 2000mm x 7000mm. The material can be screen printed or coated to provide a wide variety of colours on a large format sheet. As with flat sheet, the material can be coated to give UV protection on one side or both sides to avoid yellowing. The sheet material is used in increasing numbers of walls, from twin wall to five or six walls thick. Panels are fixed using the same methods as flat sheet, with thicker sheets being supported at points up to 1800mm apart. Panels can be curved by setting them into a pre-formed aluminium edge frame, when the material can be curved to a minimum radius of 1500mm for twin wall sheets and around 4000mm for the thickest sheets.

Plastic-composite flat panels typically have a mixture of around 70% softwood fibre and 30% resin, manufactured at high temperature and pressure to provide coloured panels of smooth and almost impervious surface. Although the finish colour is formed by using pigmented resins as a top coat in the mould, the colour extends all the way through the material, allowing cut edges to be visible. Plastic-composite panels have high UV resistance, high colour stability, high fire resistance and can be cut and drilled easily, allowing them to be used as overlapping shingles (d). Their high impact resistance makes them well-suited to conditions susceptible to damage. The material is made in sheet sizes from 3600mm x 1800mm, 3000mm x 1500mm and 2500mm x 1800mm in thicknesses from around 5mm to 12mm. Corner panels and parapets are also manufactured in the same material (e). Plastic-composite flat panels can be fixed with visible fixings or concealed point fixings (f).

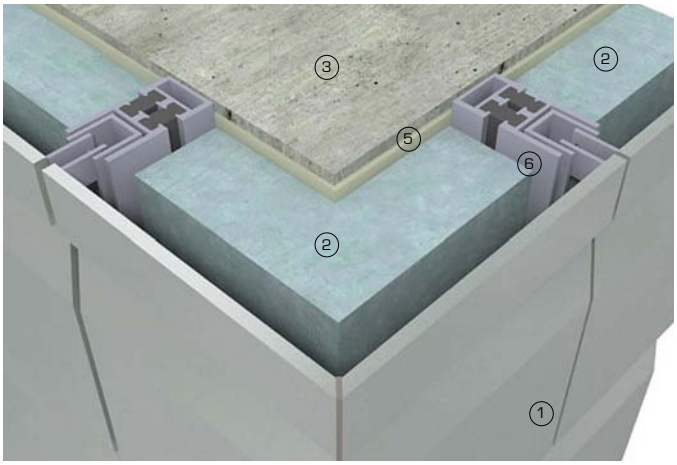
Polycarbonate is generally a more expensive material than GRP, making GRP more suitable for lower cost applications. However, GRP has one advantage over all the other plastic-based materials, which is its ability to be moulded easily and economically for small-scale applications. When used as rainscreen panels, the material needs a top gel coat to avoid its fibres being seen. The ability to see the fibres through the material makes it very unsuitable for transparent or translucent panels, but for moulded rainscreen panels it is possible to introduce some 3-D modelling into the facade panels. GRP can be bonded to honeycomb panels formed in the same material to produce large panels with high fire resistance.

e | 3D view showing opaque polycarbonate panels fixed to concrete loadbearing wall





f | 3D detail view showing vertical rail fixing opaque polycarbonate panels to concrete loadbearing wall

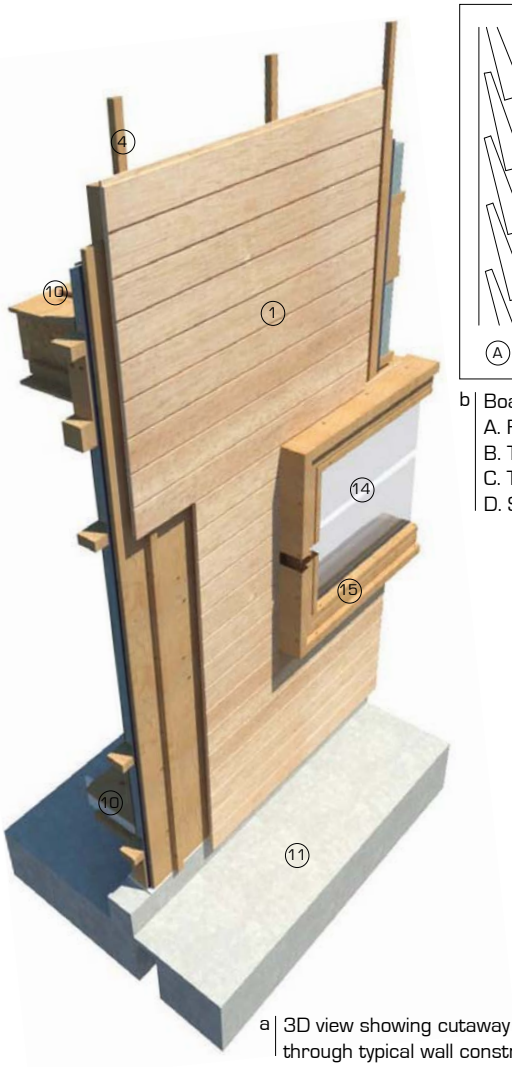


g | 3D detail view showing corner fixing of opaque polycarbonate panels to concrete loadbearing wall

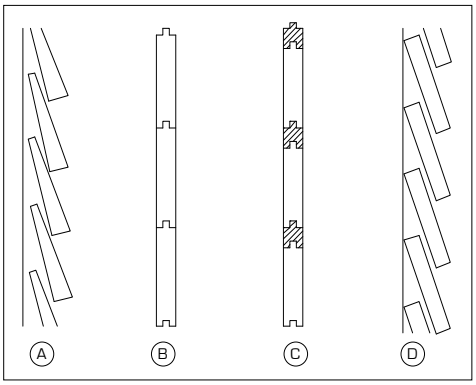
h | 3D views showing opaque polycarbonate panels fixed to concrete loadbearing wall







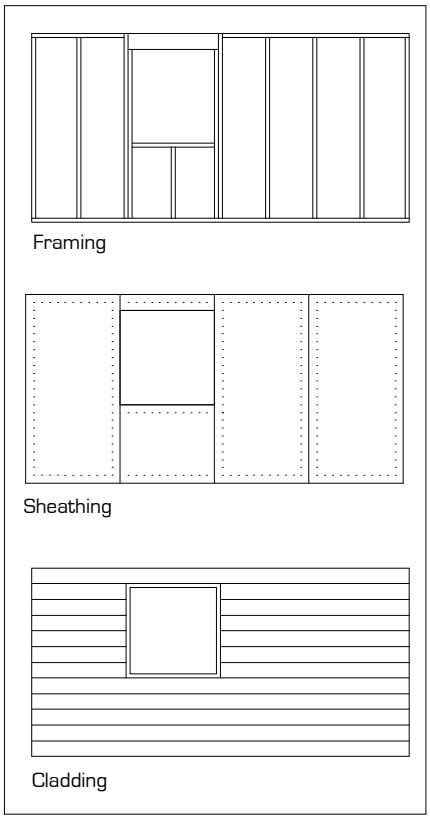
a | 3D view showing cutaway section through typical wall construction



b | Boarding arrangements
A. Feather edge boarding
B. Tongue-and-groove boarding
C. Tongue-and-groove boarding with inserts
D. Shiplap boarding

Details

1	Timber boards
2	Timber battens
3	Plywood sheathing
4	Timber studs
5	Timber rail
6	Breather membrane
7	Engineered floor joist
8	Damp proof course
9	Vapour barrier
10	Timber floor
11	Concrete ground slab
12	Internal plaster finish or dry lining/drywall
13	Thermal insulation quilt set within timber frame
14	Timber framed window
15	Timber cill
16	Air gap
17	Roof buildup



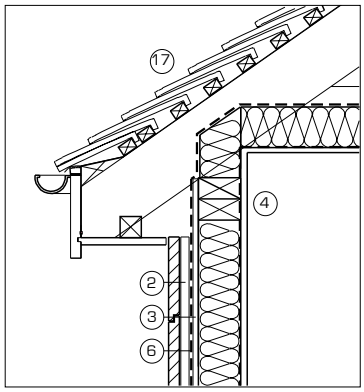
c | Assembly sequence

System design

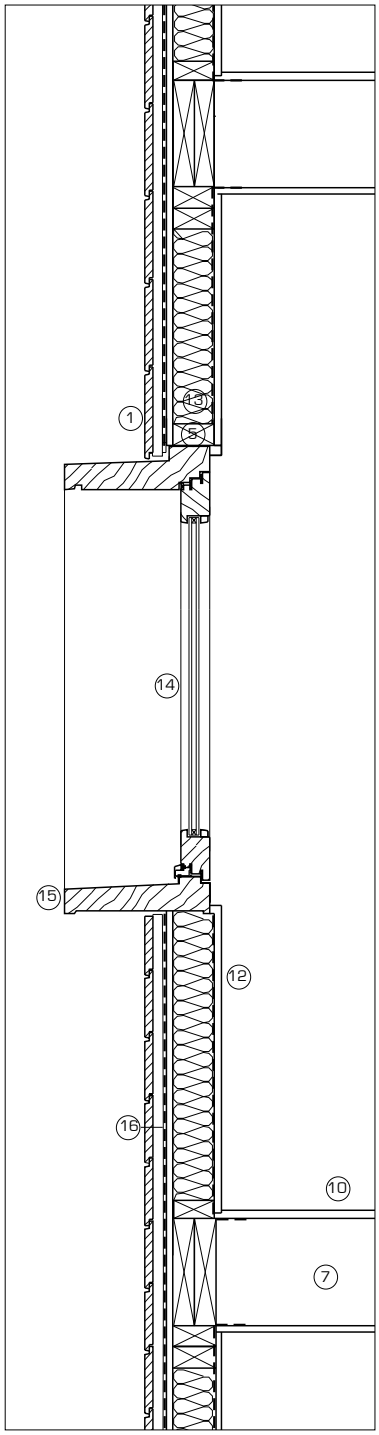
There are two enduring generic forms of loadbearing timber frame that use small section timbers to form framed loadbearing walls (a): the platform frame and the balloon frame. Both the platform frame and the balloon frame are based on softwood sawn timber sections. The platform frame comprises studs spanning from floor to floor, with the timber floor structure being supported at each storey-height set of timber frames. The balloon frame, which is now used to a much lesser extent, is enjoying a revival in light-gauge steel sections. This method has vertical framing members which are continuous, with the intermediary floors being supported by the wall running continuously past it. A recent development has been in 'solid' construction rather than the framed type. Laminated structural timber has been developed to make wall panels as complete proprietary systems where the material is glued together to make full timber panels. Thermal insulation is added to one side of these panels, with the possibility of exposing either the outside or inside, depending on exposure and location, but mostly these panels are clad with an additional material on the outside to provide weather resistance (b). Another system where plywood is bonded to each side of a rigid insulation panel, called structural insulated panels or 'SIP' panels, provides a solid panel where the insulation holds the structural plywood sheets in place, allowing timber wall construction to be thinner and lighter.

Timber frames comprise studs (vertical sections) fixed to rails (horizontal members) which are clad with plywood sheathing to provide lateral bracing (c), typically 12mm-18mm thick, depending on panel size and loads. Timber boards can also be used as sheathing, but this is an expensive solution. Framing members are typically formed from 100x50mm softwood sections at 400mm vertical centres which are nailed together. Voids between the framing members are filled with thermal insulation (e). A breather membrane is then fixed to the face of the sheathing layer. This provides a waterproof barrier which also allows the vapour to escape (6), allowing the timber wall to release and absorb moisture with changes in the weather. Outer timber cladding boards are then fixed on the outside of the breather membrane (1). Traditionally, timber cladding was used to stiffen the structural frame by fixing the boarding directly to the frame, with a breather membrane set between the frame and the timber boards as a weatherproof layer. More recently, the timber cladding is fixed to battens set forward of the breather membrane, or waterproofing layer, to ensure that the timber is ventilated on both sides. The inside face of the timber framed wall has a continuous vapour barrier set (in temperate climates) on the warm-in-winter side of the wall. The inner face of the wall is then finished with a dry lining (12).

Solid laminated structural timber is made in panels up to approximately 16000mm long, 3000mm wide and to a maximum thickness of around 500mm, varying between proprietary systems. The main benefit of the system is that it provides an alternative to steel and concrete



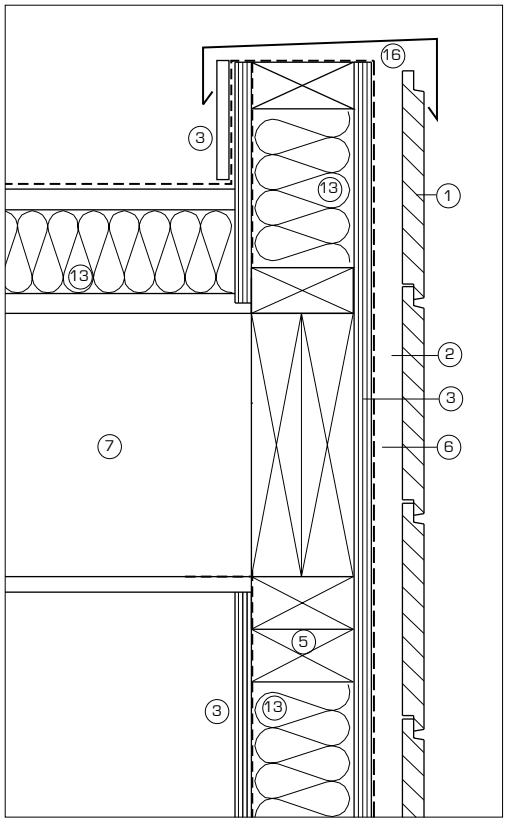
d | Vertical section 1:20. Roof junction



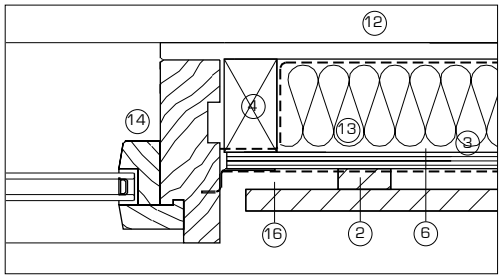
e | Vertical section 1:20 showing typical details



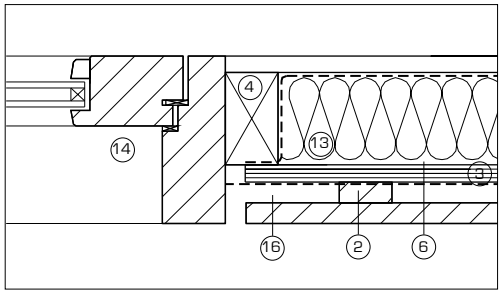
f | 3D view showing cutaway section through typical wall construction



g | Vertical section 1:20. Flat roof connection



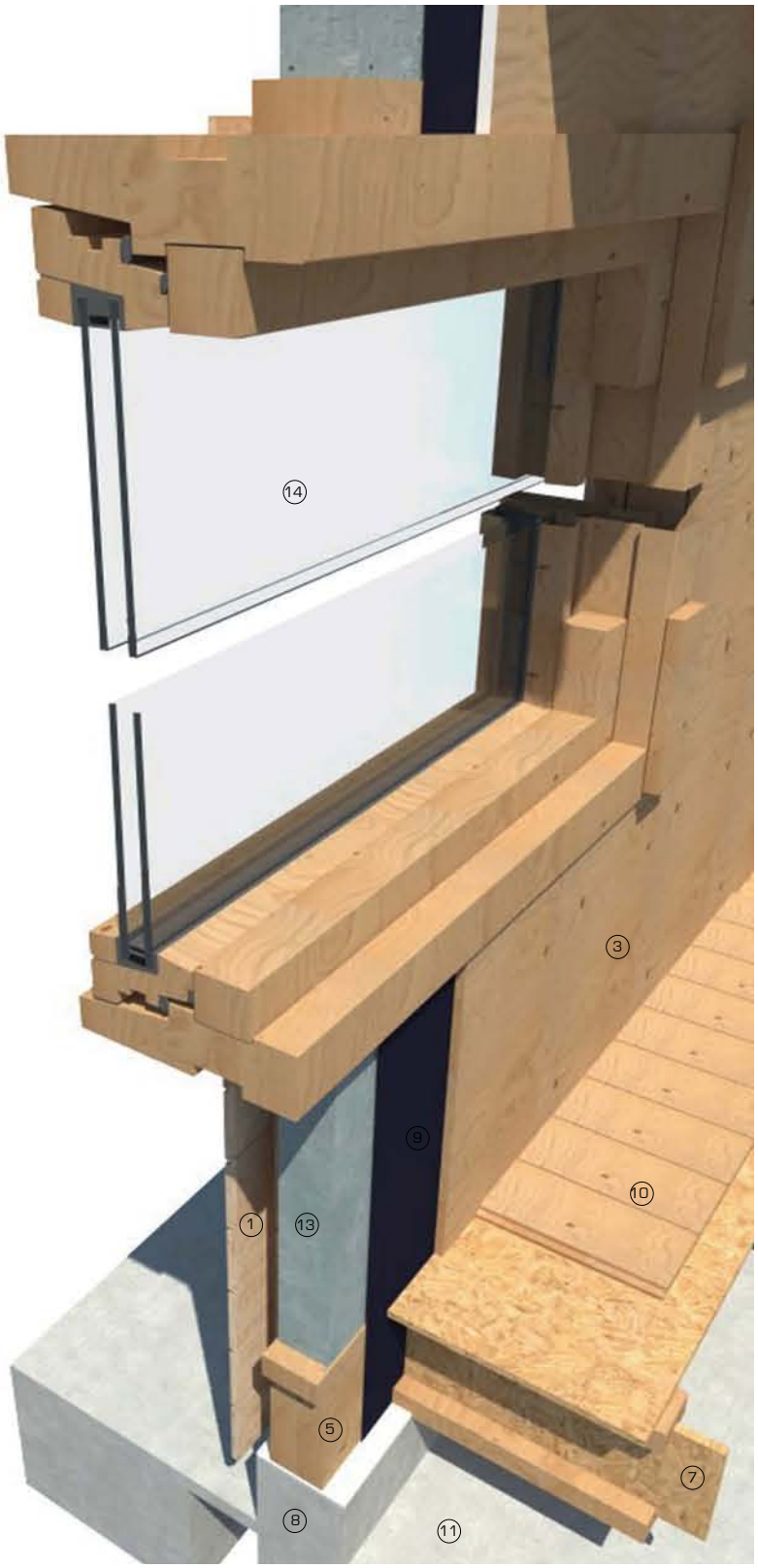
h | Horizontal section 1:5. Outward opening window



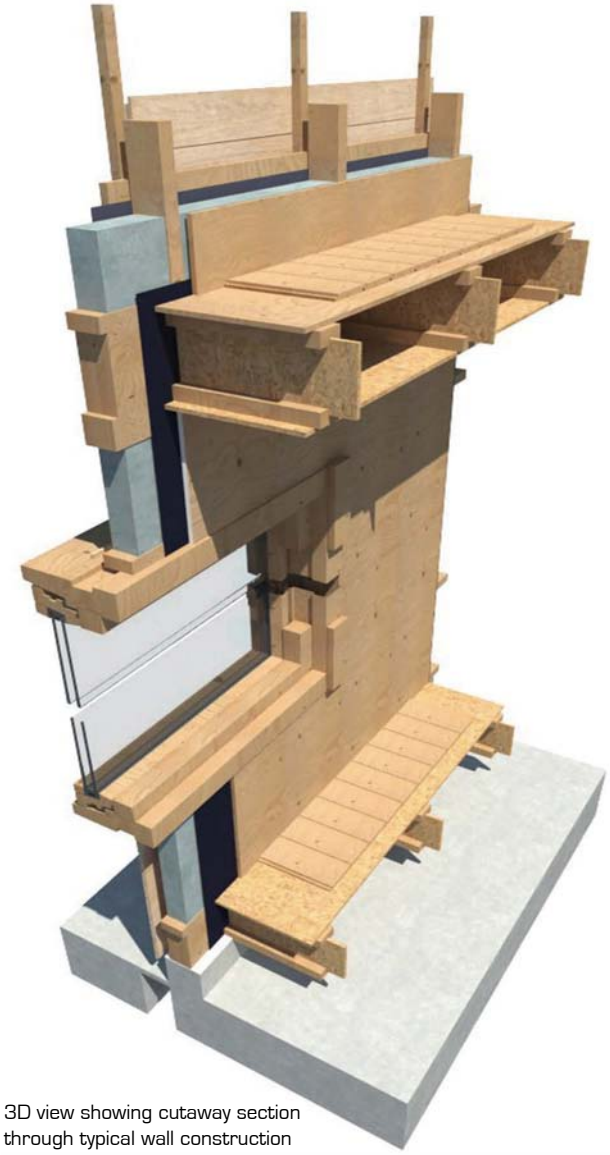
j | Horizontal section 1:5. Inward opening window

Details

1	Timber boards
2	Timber battens
3	Plywood sheathing
4	Timber studs
5	Timber rail
6	Breather membrane
7	Engineered floor joist
8	Damp proof course
9	Vapour barrier
10	Timber floor
11	Concrete ground slab
12	Internal plaster finish or dry lining/drywall
13	Thermal insulation quilt
14	Timber framed window
15	Timber cill
16	Air gap



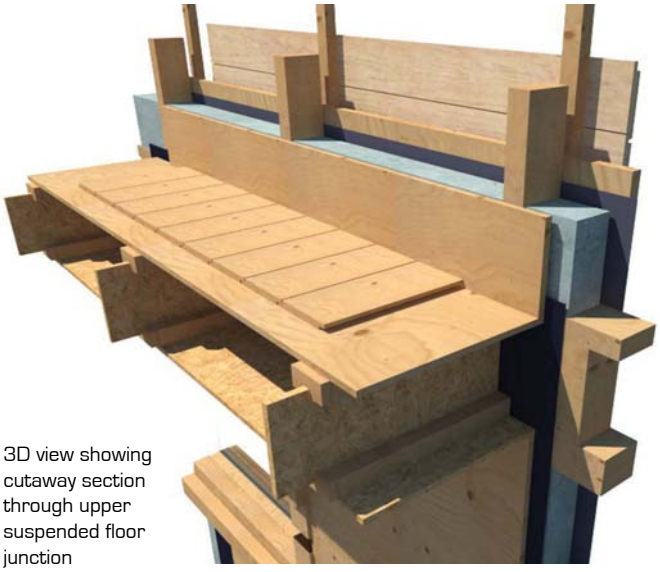
k | 3D view showing cutaway section through typical wall construction



m | 3D view showing cutaway section through typical wall construction



n | 3D view showing cutaway section through ground floor junction



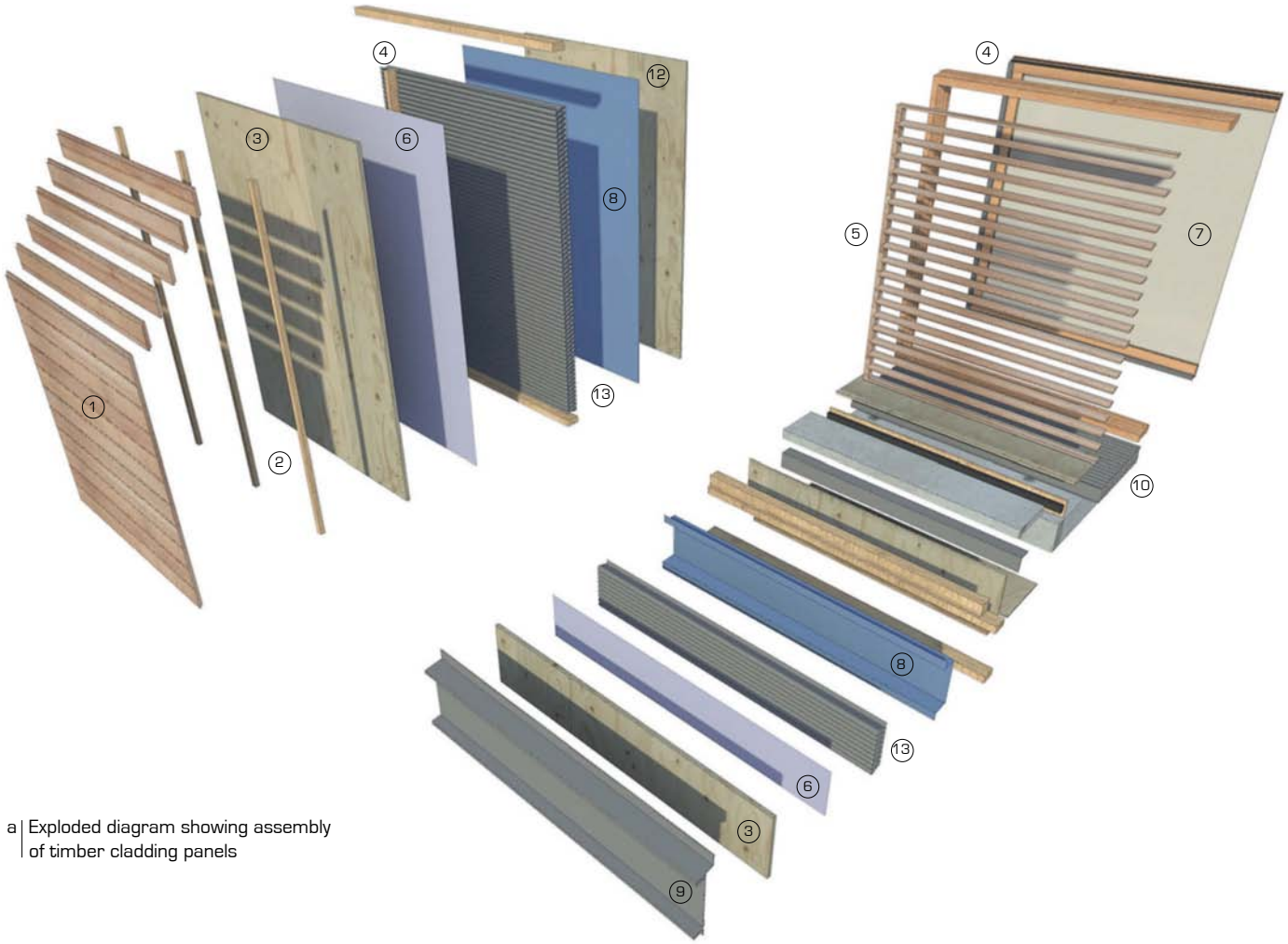
p | 3D view showing cutaway section through upper suspended floor junction

frames for larger scale projects. This panel system has recently been used for buildings of up to eight storeys high, providing loadbearing walls in a single material which is light in weight. Structural insulated panels, with integral insulation, are made in panels up to approximately 6500mm long, 1200mm wide and in thicknesses of up to around 150mm, depending on the manufacturer. Curved wall panels are made to a shallow radius. They are used typically as a direct alternative to traditional timber framed construction and like laminated timber panels, are set to become more widely used in timber construction.

System details

For all these timber wall types, the timber cladding is terminated at ground level at a minimum of 150mm above external ground level (k). The cladding is usually supported at ground level on a concrete slab or edge beam that forms part of the concrete wall. Alternatively, the wall can span between concrete pads at 3000mm–5000mm centres, with timber beams at the base of the wall to provide support between pads. Where an expression of a concrete floor slab is required, the edge of the slab is covered with thermal insulation, with an additional outer protection; typically a thin concrete facing panel. The timber wall frame is usually set on a continuous timber section at ground level, which is first fixed to the concrete slab to provide a level surface to set the timber in place (m). A damp proof course (DPC) is set beneath the continuous timber base plate usually extending down the vertical face of the concrete slab where it connects with the damp proof membrane (DPM) beneath the concrete slab or the vertical face of the basement wall. The DPC is also made continuous with the DPM set on top of the concrete slab. Where concrete foundation pads are used, the timber beam is set into stainless steel shoes fixed to the pads. Timber can also be supported on brick walls set at a minimum of 150mm above external ground level and be supported on a concrete strip foundation or ground beam. An insulated raised floor is then set into this brick wall. The void beneath the timber floor is ventilated with air bricks that encourage cross ventilation. This avoids stagnant air in the void from damaging and eventually rotting the timber floor.

Corners, both external and internal type, are formed typically with a timber bead set so that the timber boards on both sides butt into it. If a breather membrane is used behind the cladding, then an additional waterproof flashing is added to the corner. This is formed in a durable polymer-based sheet or metal sheet. Alternatively, the boards can be allowed to make a corner with a butt joint and an additional L-shaped timber trim, formed from two separate timber sections, is added on the face of the corner to protect the exposed end grain of one of the sides forming the corner. Boards can be joined with a mitred joint (45º) without any cover strip but the timber used must be of the highest quality to avoid the joint opening up with moisture movement. A waterproof layer or flashing is set behind the mitred joint.



a | Exploded diagram showing assembly of timber cladding panels

System design

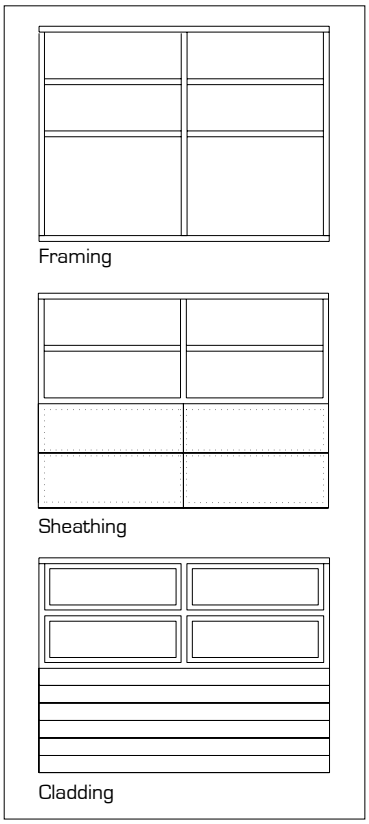
Timber cladding panels have been more widely used in recent years as a method of cladding steel and concrete frame buildings with prefabricated, factory made panels that have a natural finish (a). They are also used in twin wall facades, or 'double skin facades' where an inner timber wall with window openings has an additional glazed screen set approximately one metre in front of it to provide a thermal buffer to reduce the effects of heat and cold at different times of the year, as well as to allow the windows to be opened in taller buildings. Where timber cladding panels are fixed to a timber frame, or structural laminated frame, the cladding panels can be set between timber columns as well as in front of them to give a combined timber frame and panel building using a single primary material system. These cladding panels are typically faced in timber boards in rainscreen configuration. A recent addition to the language of timber rainscreens has been the use of thin slats to create a degree of translucency in timber screens, particularly when set forward of windows set into the panel behind (g). This can create a visually rich mix of timber panel assemblies that use a single timber species (b). However, the higher moisture movement associated with timber has the consequence of requiring junctions between cladding panels to provide an allowance for both structural movements and moisture movements both between cladding panels as well as within the panel itself.

Where timber cladding panels are set forward of floor slabs in the manner of glazed curtain walling (d), panels extend from floor-to-floor, either hung from a floor slab or, more typically, supported on it at floor level. Vertical joints between cladding panels have a stepped joint to allow for deflections in floor slabs between panels, following principles of glazed curtain walling. This stepped joint is covered on the outside with timber boards, set forward of the face of panels on battens in rainscreen configuration. The construction of panels follows the same principle of timber cladding described in the previous section. Horizontal joints have an inner chamber formed between two adjacent panels. Any rainwater that penetrates the outer seal, which is also kept open in some designs, is drained down an inner chamber where the water is discharged through the horizontal joint at the bottom of the panel. Where timber cladding is used in twin wall construction as an inner wall to an outer glazed wall, where the outer wall provides a thermal buffer, the outer screen provides protection by allowing the material to maintain its appearance without full exposure to outside conditions, other than the effects of the sun which cause the timber to change colour.

When cladding panels are set onto floor slabs and restrained at the slab above, timber posts that may form part of the structure can also be set between panels rather than inside the building, since there is no



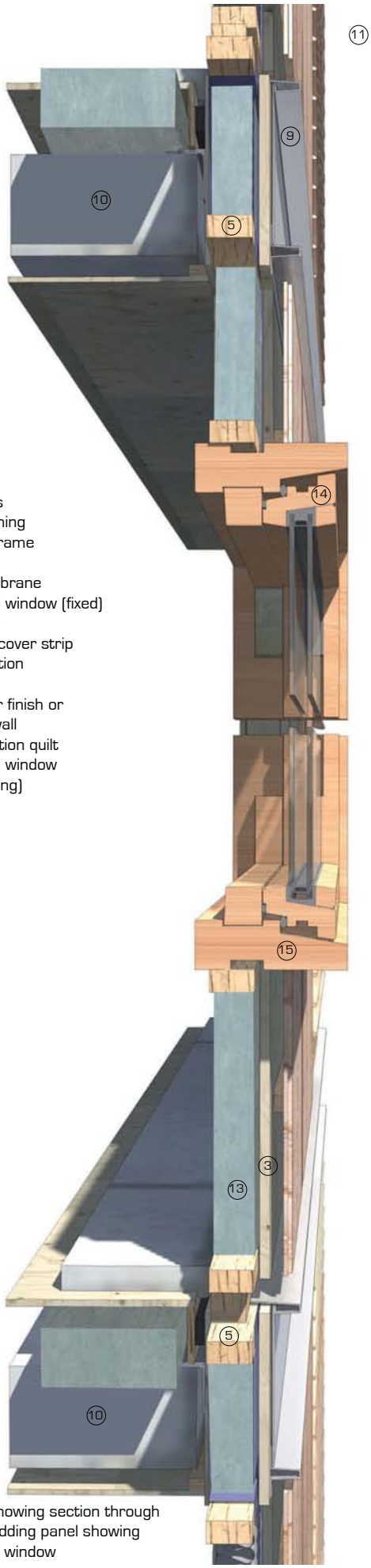
b | Elevation of timber cladding panels showing relationship with structural frame



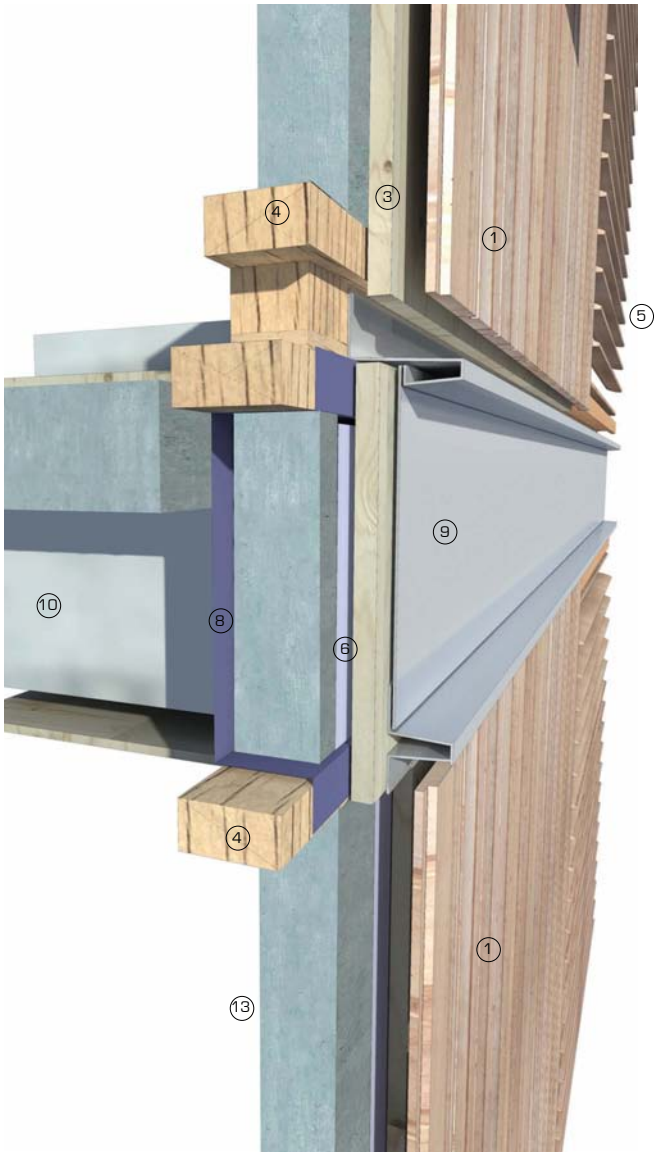
c | Assembly sequence

Details

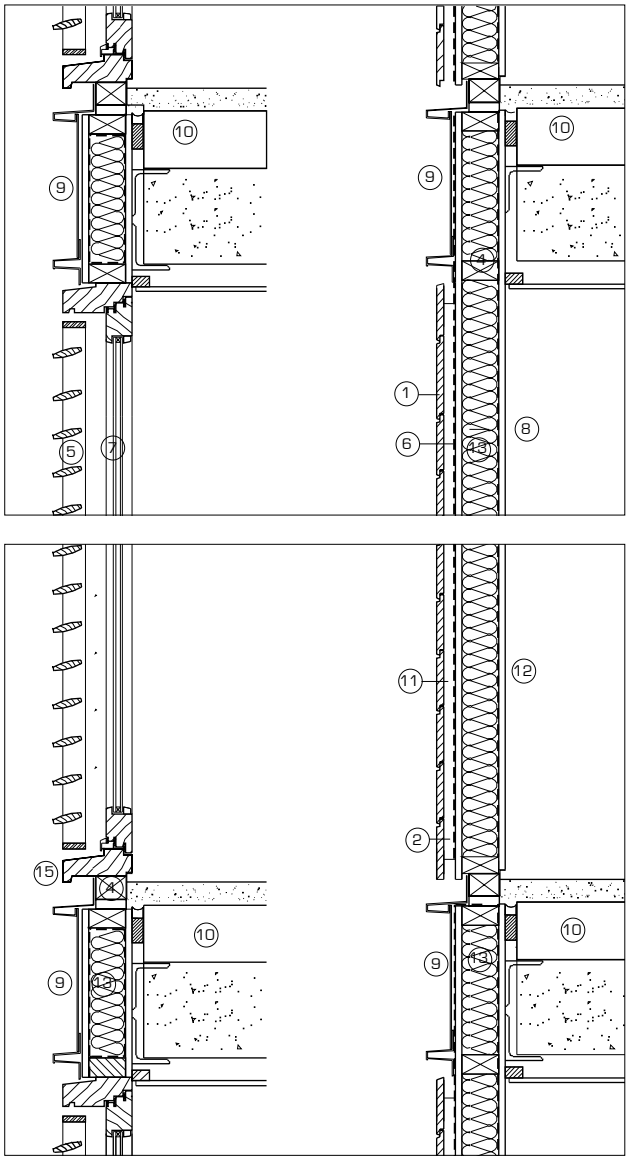
1 | Timber boards
2 | Timber battens
3 | Plywood sheathing
4 | Timber panel frame
5 | Timber louvre
6 | Breather membrane
7 | Timber framed window (fixed)
8 | Vapour barrier
9 | Profiled metal cover strip
10 | Floor construction
11 | Air gap
12 | Internal plaster finish or dry lining/drywall
13 | Thermal insulation quilt
14 | Timber framed window (outward opening)
15 | Timber cill



d | 3D view showing section through timber cladding panel showing integrated window



e | 3D view showing connection between timber cladding panel and supporting frame



f | Vertical sections 1:20 through timber cladding panels showing typical details

significant thermal bridge from outside to inside, allowing the structural frame to be exposed on the outside. Cladding panels are set into openings in laminated timber frames, with panels supported at their base on the beams set beneath. Floor decks in timber are then fixed to the side of the laminated timber beams. Timber panels are fixed at their base to the beam beneath, but have a lateral restraint at the top to allow the slab and panel above to deflect without damaging the panel below. A metal flashing at the base of the panel drains water and throws it clear of the beam beneath in order to avoid staining the timber beam (e). The outer timber rainscreen cladding is set flush with the outer face of the laminated timber frame to avoid any views into the waterproofing layer behind.

System details

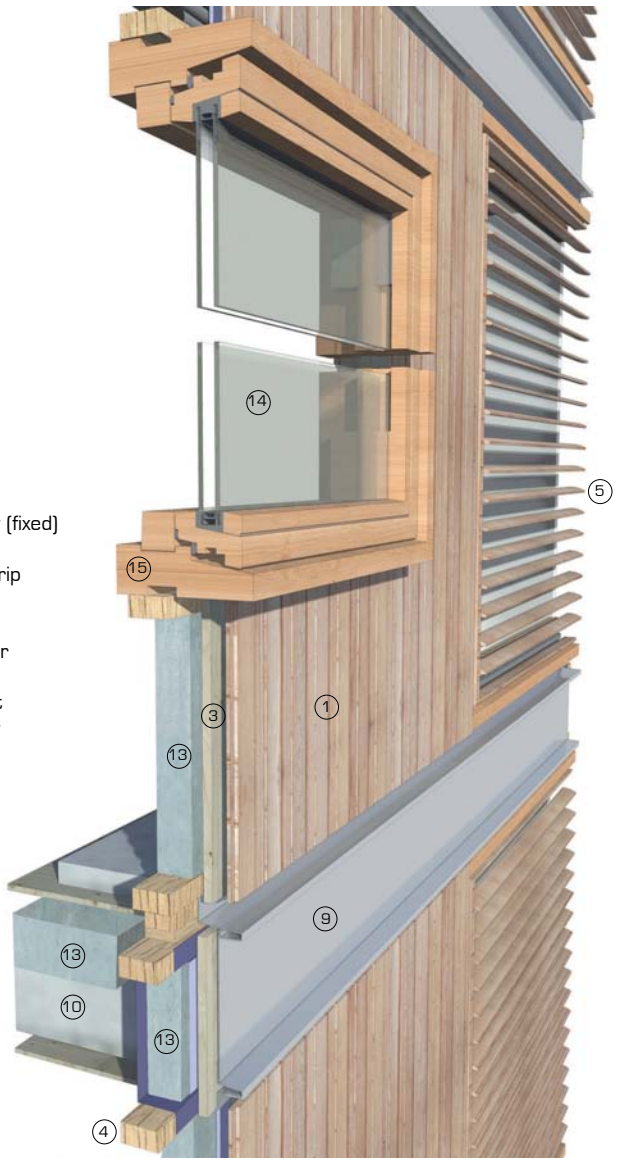
Both softwoods and hardwoods are used for cladding panels, with durable hardwoods being more commonly used for rainscreen applications. Where less expensive, less durable timbers are used, higher levels of both protection and maintenance are required. Softwood boards are usually made in 250mm widths, with trimmed boards with profiles routed into them usually trimmed down to 150 - 200mm widths. All timbers vary in moisture content with changes in temperature and air humidity, this being one of the essential aspects to be considered in timber detailing. Most timbers used in cladding will have a moisture content of around 5% to 20% when in use. Similar levels are found in timbers from timber suppliers, and are classified as 'dry', 'kiln dried' or 'seasoned'. The most common types of jointing of boards is 'ship lapping' where timber boards are set horizontally and lapped over one another with the upper board lapped over the top of the board below to protect it from rainwater ingress. Ship lapping can be assisted by the use of 'feathered' or wedge-shaped boards to give the lapping a more elegant appearance. Tongue and groove boards are used to give a continuous flat appearance, while having the advantage of locking boards together into a continuous plate-like structure. Boards are typically around 20mm thick, made as long as possible at around 3000mm – 3500mm, to avoid vertical joints which are a potential source of rainwater penetration except in rainscreen configuration. Timber cladding is finished with the timber being left either as supplied, with preservative applied or injected by the supplier, or alternatively is



g | 3D view showing timber cladding panel consisting of fixed glazing and louvre screen

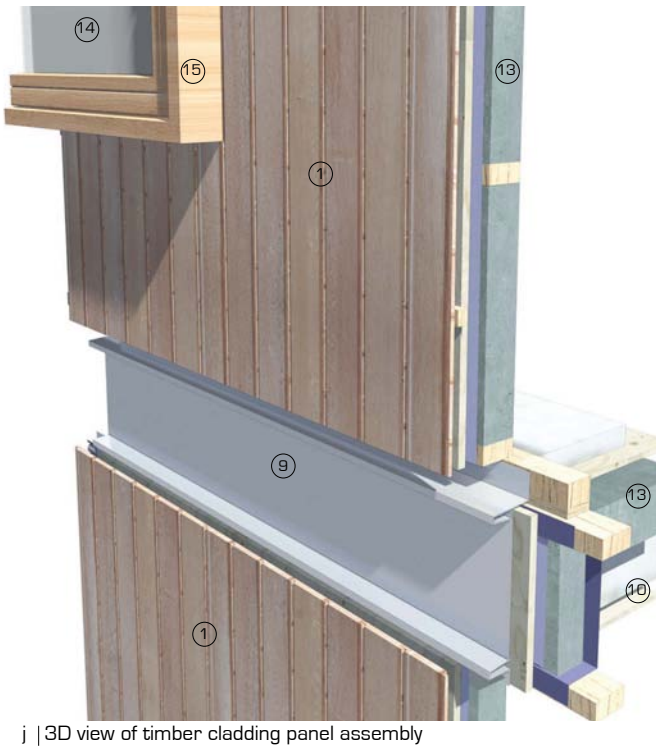
Details

1	Timber boards
2	Timber battens
3	Plywood sheathing
4	Timber panel frame
5	Timber louvre
6	Breather membrane
7	Timber framed window (fixed)
8	Vapour barrier
9	Profiled metal cover strip
10	Floor construction
11	Air gap
12	Internal plaster finish or dry lining/drywall
13	Thermal insulation quilt
14	Timber framed window (outward opening)
15	Timber cill



h | 3D view showing cladding panel assembly with built-in opening window

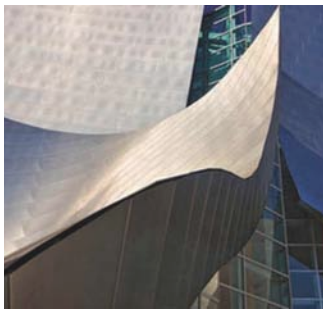
given coats of preservative in clear, stained or opaque finish on site with preservatives that repel rainwater, or wood stains and paint. Paints can be oil-based or acrylic, while preservatives are clear and can be used as a finish that does not appreciably change its appearance. It can also be used before staining or painting the timber. Preservatives help to prevent moisture absorption as well as reduce fungal growth, enhancing the life of the timber but not preventing the material changing colour and fading to its characteristic silver-grey appearance. An essential issue in the use of timber cladding panels and rainscreens is the coordination of timber types and finishes used for windows, doors, visible panel framing and rainscreen cladding, in order to give a controlled visual appearance that will weather consistently together.



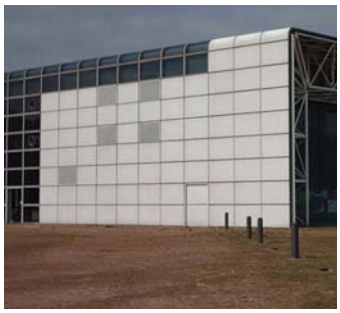
j | 3D view of timber cladding panel assembly

03
ROOFS

	Trends in roof design
	Metal roofs
1	Metal standing seam
2	Metal profiled sheet
3	Metal composite panels
4	Metal rainscreens
5	Metal louvres
	Glass roofs
1	Greenhouse glazing and capped glazing
2	Silicone-sealed glazing and rooflights
3	Bolt fixed glazing
4	Bonded glass rooflights
	Concrete roofs
1	Concealed membranes
2	Exposed membranes
3	Planted roof
	Timber roofs
1	Flat roof: mastic asphalt coverings
2	Flat roof: mastic bitumen-based sheet membranes
3	Pitched roof: tiles
	Fibre reinforced polymer roofs
1	FRP rooflights
2	FRP panels and shells
	Fabric systems
1	ETFE cushions
2	Single membrane
3	Single membrane: barrel-shaped roof



a | Metal standing seam: Walt Disney Concert Halll, Los Angeles, U.S.A. Architect: Frank Gehry



b | Metal composite panel: Sainsbury Centre for Visual Arts, Norwich, U.K. Architect: Foster Associates.



c | Profiled metal sheet: Atelier and House, Bwa-Cho, Japan. Architect: Shuhei Endo



d | Greenhouse glazing: The Glasshouse, RHS Wisley, U.K. Architect: Peter van der Toorn Vrijthof

An overview of roof systems

Where roofs were once considered to be either of traditional appearance, as with tiled and slated pitched roofs, or else completely concealed as flat roofs, they are now increasingly considered to be a part of a completely visible envelope design which is as visually important as the external walls, both in their appearance and their technical performance. In recent projects, walls and roofs have been taking on a single form, with the same construction methods, materials and detailing used on both walls and roof. The increased technical performance and long-term reliability of roofing materials of all types has led to a much more ambitious design approach. However, an essential difference between facades and roofs is that facades have rainwater running across their surface, but roofs can be submerged in water during rain. A roof has to be completely sealed in areas where water can collect, such as parapet gutters, with the assumption that rainwater will be expected to remain on the roof if the rainwater outlets become blocked.

Metals

The increased reliability of jointing, together with the increased use of aluminium sheet (with its increased flexibility) instead of steel sheet has led to more adventurous roof forms without affecting the waterproofing performance. By the early 1990s profiled metal roofs were using standing seam joints (a), which combined the long span capability of profiled sheet with the visually refined and very water-tight standing seams which are 'zipped' together by machine on site. Since the introduction of 'zip up' sheeting the difference between profiled metal and standing seam systems has reduced, with new hybrid systems having a lining panel system which can be fixed with metal sheets, some of which are hung down from the roof level without scaffolding. This makes large roof spans, particularly at high level such as in covered sports halls, much easier to construct since scaffolding is not required.

Composite roof panel systems have been in development since the 1980s, with panels that provide an internal ceiling finish and outer roof covering in single panels that are semi-interlocked, with either a lapped metal joint between panels or a metal capping that clips over a standing seam-type joint (b). Composite panels are now being used as an insulated structural deck to a separate waterproof membrane set on top. While lacking the visibility of metal faced panels, they are very adaptable and economic, with thermal insulation not only filling the voids between peaks and troughs of the metal sheet on its underside but also providing some structural stability.

Metal rainscreen panels are a recent addition to metal roofing systems. They do not use the outer seal as a first line of defence against rainwater penetration, but rather as a protection to the membrane beneath against the effects of the sun as well as foot traffic. Metal rainscreen panels are required to be sufficiently rigid and resistant to impact damage from occasional access. Composite sheets with a plastic core and thin metal outer facings are popular in this regard, since they achieve high levels of flatness and are flexible enough to withstand foot traffic, usually when aluminium sections are silicone-bonded on the underside of panels. Perforated and slotted metal sheets are also being used as metal rainscreen panels, partly shaping the expression of the building envelope in forming a continuity between different parts of a roofscape, ranging from covering air extract terminals, rooflights and gutters to producing a (seamless) smooth continuation of the facade below. These rainscreen panels can also accommodate complex geometries without having to make individual composite panels to achieve the same visual effect. Although such panels are an additional roof covering rather than being formed entirely from metal, they can provide varying amounts of translucency and transparency in a single metal layer that can reveal its depth both from inside the building and from outside.

A change over the past 10 years which has influenced all types of metal construction is the increased quality of the finishes. The quality of powder coating has improved enormously, with greater durability and colour-fastness, so that it competes strongly with the more expensive



e | Silicone sealed glazing: Dulwich picture gallery, London, U.K. Architect: Rick Mather



f | Capped glazing: House in London, U.K. Architect: Gianni Botsford Architects



g | Concealed membrane: Persistence Works, Sheffield, U.K. Architect: Fielden Clegg Bradley Studios



h | Exposed membrane: Tenerife Concert Hall, Spain. Architect: Santiago Calatrava

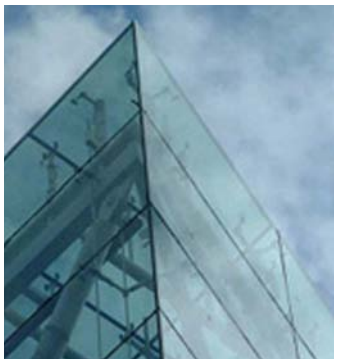
PVDF finishes. Consequently, the main constraint in the design of metal roofs in any of these systems is that metal sheet is produced in widths of around 1200mm or 1500mm, from which most metal panels in facades are made, but is usually available in long lengths where coil material is used; that is, where the metal is rolled into a long coil in the factory. Thicker plate, at a 4mm thickness and above, is made in flat sheet form, at around 1000mm x 2000mm in size, with larger sheets being more difficult to obtain easily in large quantities. Working with the width of the coil in forming joints and allowing for the folding or turning of the material at the joints is the main constraint, but metals can still be be curved and folded economically (c).

The use of metal shingles has been a recent development. This technique is a hybrid of lapped tile roofing and standing seam facades, and can be used to form both wall and roof in a single system that is both economic and able to deal with a variety of fixing angles. While shingles or tiles are hung from their top edge, metal shingles are folded over into a seam on their sides and lower edge, or edges if the shingles are not rectilinear, but are set at 45° to the vertical, for example. The top edge or edges are fixed with nails or screws with the shingle immediately above being lapped over the top of the nailed fixing in the manner of tiling. This fixing method secures the shingles on all sides while retaining a visual lap, allowing the shingle to be fixed in any position, even in a soffit condition. The fixing method usually follows rainscreen principles by assuming that rainwater will pass through the joints, which are drained in a ventilated cavity behind. Metal shingles are economic to fabricate, since they can be cut easily from sheet metal, aluminium, mild steel, copper or zinc. In addition, tiles can be formed into a curved shape in a press to give a very textured facade with a three-dimensional quality that has yet to be explored.

Glass

Although drained and ventilated systems have been in use for the past 25 years, the issue of the water tightness of the horizontal joint, running perpendicular to the fall of the roof, has been undergoing continual development. Glazing bars have been used to support glass down the slope of the roof where they do not impede the passage of rainwater. Horizontal joints have been supported with stepped joints where water runs off the top of the upper glass down onto a lower glass (d). The glass is traditionally secured with clips and is sealed with a proprietary sealant. This joint is difficult to seal reliably in order to achieve water tightness for higher wind pressures, and is difficult to adapt to a drained and ventilated system. This issue has been resolved over the past 20 years with the development of silicone sealed glazing that was originally used in glazed curtain walls. In this method, a metal channel is set into the edge of double-glazed units, with the units being set flush with one another along the horizontal joints. The units are then secured with metal 'toggles' held to the metal channels within the depth of the joint, and fixed to an aluminium frame below to provide a mechanical fixing. The flush horizontal joint between units is then sealed with silicone. The aluminium frame onto which the glass is fixed has ventilated drainage channels to take away any water that passes through the outer silicone seal. With the development of silicone bonding techniques, the double-glazed unit can also be bonded to aluminium profiles which are mechanically fixed with screws to a supporting frame. The joint between the glass units is then sealed with silicone in the same way as the previous example. An alternative approach has been to introduce horizontal glazing bars with pressure plates that are shaped to allow as much water to drain down the roof as possible, an approach which accepts that the same water will be trapped behind the upper edge of the pressure plate. Small amounts of water that find their way through the outer seal are drained away within the system back to the outside. Both the recessed fixing method with a silicone seal and the modified pressure plate 'toggle' system have been proved reliable in their performance.

Bonded glass rooflights are a recent development in glazed roofs (e), where double-glazed units are bonded directly onto a lightweight metal frame that has no visible fixings on its external face. While bolt fixed



j | Bolt fixed glazing: Tower Bridge House, London, U.K.
Architect: Rogers Stirk Harbour + Partners



k | Exposed membrane: Canary Wharf underground station, London, U.K.
Architect: Foster and Partners



m | Timber flat roof: Private residence, London, U.K.
Architect: Lynch Architects



n | Timber pitch roof: The Lighthouse, Watford, U.K.
Architect: Shepherd Robson Architects

glazing can conceal the fixing bolt within the double-glazed unit on one side, structural silicone glazing has no visible structure at all; with supporting glazing bars being concealed within the width of the joint behind the external seal. This has led to greater freedom in the forms used for rooflights with this technique, where the position of the glazing bars, and how they intersect, does not have to be considered in rooflight design. Bonded glazing has encouraged the use of structural glass beams, which suit a structurally glazed rooflight well. Most bonded glass rooflights with a gently sloping, but planar surface, are derived in part from examples of glass floor decks and staircases used in buildings that have been developed over the past 15 years. A new addition is to bond point fixings directly to the inside face of the glass, with brackets and support systems used for regular bolt fixed glazing (j).

Concrete

Developments in waterproofing membranes for concrete roofs over the past 25 years have focused on increasing the flexibility of the material used (h). Asphalt, a well established material for concrete decks, suffered traditionally from an inability to take up movement from either the building structure or from solar gain when exposed to the effects of the sun. A solution to this problem has been the 'inverted' roof configuration, where thermal insulation is fixed above, rather than below, the waterproof membrane in order to keep its temperature cool and relatively constant. Pebbles or paving slabs are set onto the insulation. In addition, the introduction of polymers into asphalt to provide greater flexibility has led to the material being easier to apply on site, particularly as torch-on membrane sheet rather than in liquid applied form. However, polymer materials, mainly thermoplastics and elastomers, are becoming more economic. Polymer materials have the advantage of increasingly exposable to sunlight, which is leading to roofs being covered in a few of these materials as a self-finish, with some buildings taking the membrane down the facades to form a complete building envelope. Where a smooth or level insulated substrate can be formed, these waterproofing layers can be fixed in a similar way to fabric membranes and welded together in the factory to form a membrane with straight and crisply formed joints that can form a visible self-finish to a roof, with an appearance similar to that of fabric 'tent' membranes. This change from roof membranes which are kept concealed, due to their poor visual aspect, to ones that are now capable of being a visual part of the design, is an increasing trend in roof design (k).

On pitched roofs, visually exposed polymer-based membrane, or polymer modified asphalt sheet are beginning to be used as materials in their own right rather than imitating the appearance of traditional roof tiles or shingles. The more refined fixing techniques that are being made available by manufacturers will assist in this change. Waterproof membranes are increasingly being used on substrates such as folded steel sheet decks and foam insulation-clad roof decks where there is a strong modelling of the form of the roof structure seen either from inside or from outside the building. Membranes are required to accommodate more structural movement and higher temperatures, combined with an external wearing surface that can be walked upon without reasonable risk of damage, for maintenance access.

Timber

Timber-based roofs (m) have developed over the past 20 years to improve their thermal insulation performance. So-called 'cold' roofs, with the insulation set at ceiling level and the roof void being ventilated, continue to be used; however 'warm' roofs have undergone much development in order to deal properly with the needs of ventilation in order to avoid condensation occurring within the roof construction. Some manufacturers prefer to have no ventilation within the roof construction where it cannot be easily provided, by using a high performance vapour barrier on the inside face of the wall construction immediately behind the internal finishes. Manufacturers also provide increasingly better performance vents to ensure that air can be drawn through the void between the roof tiles, slates or shingles and the breather membrane or roofing felt that is set above the thermal insulation. Most of the effort in ventilating pitched roofs of this type is in trying to retain the appearance of traditional roofs (n) in which ventilation ducts and boiler flues did not, until recently, play a part. Modern tiled, slated and shingled roofs use two lines of defence against rainwater penetration, where the outer



p | GRP roof: ARC, Hull, U.K. Architect: Niall McLaughlin Architects



q | Fabric ETFE cushions: Kingsdale school, London, U.K. Architect De Rijke Marsh Morgan



r | GRP panels: Bus Station, Hoofddorp, The Netherlands. Architect: NIO architecten



s | Single membrane fabric: National Tennis Centre, Roehampton, U.K. Architect: Hopkins Architects

layer is the outer line of defence to, and protection for, a waterproof membrane or breather membrane beneath.

Plastics

Translucent plastics are used mainly both to imitate the appearance of glass rooflights as flat sheet materials and to form composite panels. This is gradually changing, as plastics are no longer seen as economic substitutes for other materials but as construction materials in their own right. Earlier examples of plastic rooflights suffered from the effects of colour fading or of yellowing in transparent / translucent rooflights. The materials and finishes used in bonding are superior to those used previously, ensuring that colour fading is far less pronounced than it was. A greater acceptance of plastics as durable and capable of being moulded economically into complex shapes has prompted a revival in roof design (p). Some panels have been used as translucent rainscreen panels with lighting or graphic displays set beneath the outer plastic skin. The essential difficulties for plastics remain in the perception of them as being less durable than either glass or metal, for which polymer materials are seen as economic substitutes. This perception will change only when more complex geometries of external envelopes are demonstrated in buildings which could not otherwise have the budget available for such work in other materials (r). Work with plastics and composites is still undertaken in relatively small-scale workshops, where mock-ups can be produced easily and economically, allowing an interaction between designer and fabricator that is more difficult in larger scale factory-based methods where repeatability of large numbers of identical components still dominates production methods.

Fabrics

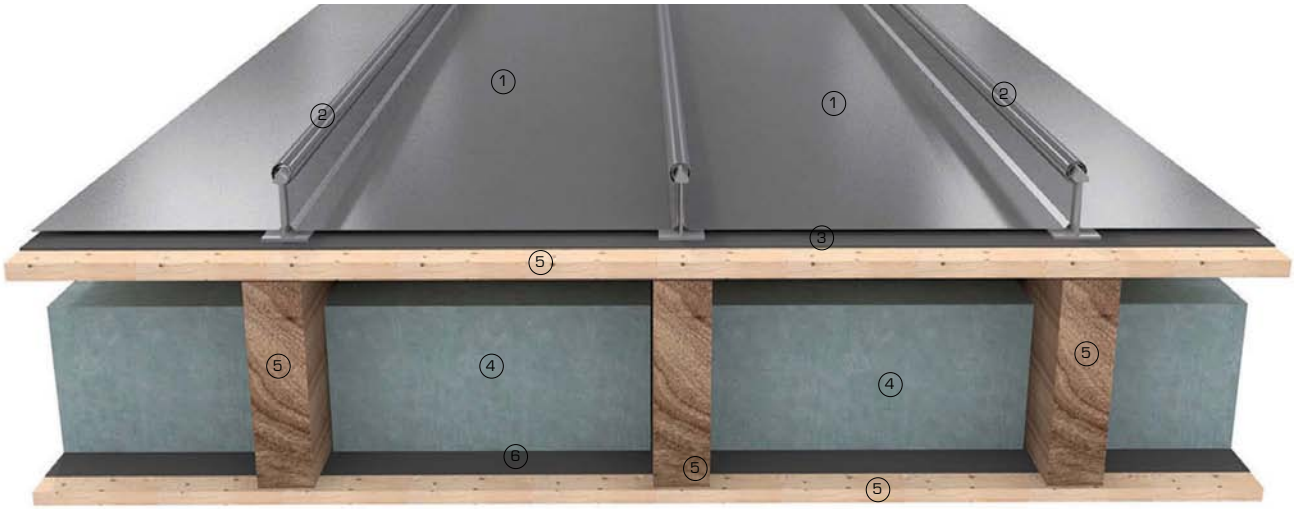
The use of woven textiles made from polymers has been focused on its application to form tent-like roof forms (s). Tent-based structures stretch a single membrane sheet, which is waterproofed on its external face, over a supporting structure that may use a mast to support the tent and cables to hold the membrane in position, in the imitation of a traditional tent. This has led to developments in the connection of membrane to cable and the restraint of cables to the adjoining structure. Alternatively, membranes are stretched over more sculptured supporting frames, which are derived more from the established language of building construction rather than from the masts and cables of tent-based roofs. The design life of these roofs is gradually increasing, a result of both observing earlier examples and developing them as well as an improvement in the performance of the protective coatings applied. The introduction of double layer membrane roofs will no doubt change their use from purely as a weather barrier to a thermally insulated roof, making them more attractive as roofs to internal spaces than as shelters for external spaces. More translucent insulation materials reduce the amount of light transmission lost through these roofs, with research being undertaken to form an economic and highly translucent thermal insulation material that would suit double layer membranes. An alternative method of insulating membranes is to fill the gap in a double layer membrane roof with air to form an inflatable roof. The concern with this approach is that it relies on a constant supply of air to hold the roof in place rather than on a supporting frame. This method has been adapted as small 'cushions' or 'pillows' filled with air to provide an insulated fabric membrane roof. The most visually striking examples use ETFE foil, which is both very durable when compared to other polymer fabrics, and also highly transparent (q). While this can be a disadvantage in rooflights, where some amount of solar shading is usually required, it is ideal for many facades and is finding use in complete building envelopes, where wall and roof are formed from a mixture of transparent and translucent panels. These panels are inflated and fixed to a permanent air supply that periodically refreshes the cushions with more air to maintain the pressure required to give them structural stability. The use of fabric is set to grow, with air cushions that can be used in conjunction with external solar shading or internal screen walls in a variety of twin roof or twin wall applications. Like sheet plastic materials, ETFE cushions are becoming liberated from the design language of glass rooflights, with more complex geometries to form curved roofs. Loadbearing air cushions, which do not require any supporting structure, are in their early stages of development and application, and we are likely to see much of this development in roof structures and self-supporting envelope structures in the coming years.

Details

1 | Metal sheet
2 | Standing seam joint
3 | Breather membrane
4 | Thermal insulation
5 | Substrate, typically timber/ metal rafters with plywood facing
6 | Vapour barrier
7 | Drywall/dry lining if required
8 | Outer standing seam sheet
9 | Inner lining sheet
10 | Clips at centres
11 | Folded metal gutter
12 | Curved eaves sheet
13 | External wall
14 | Structural frame
15 | Outersheet fixing bracket
16 | Rooflight
17 | Metal flashing
18 | Ridge piece



a | 3D detail view showing section through metal profile roof on timber structure



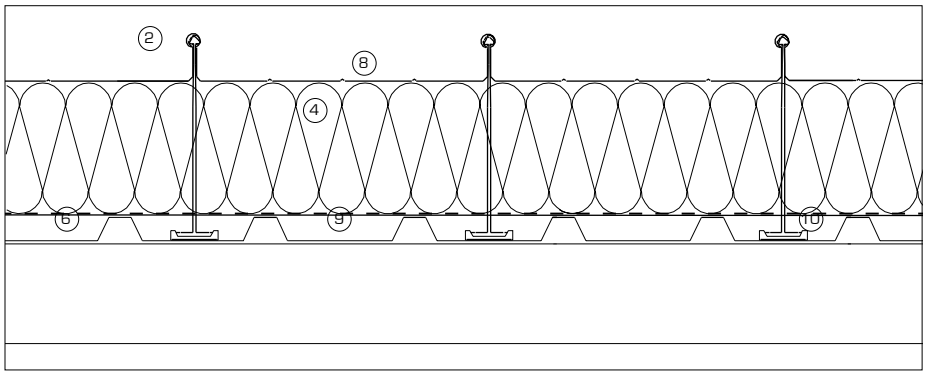
b | 3D sectional view showing section through metal profile roof on timber structure

System design

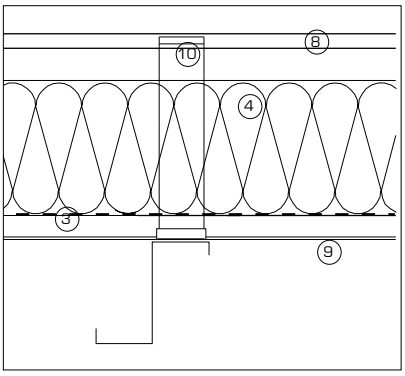
Standing seam roofs are increasingly being used for industrial and commercial buildings where concealed fixings and low roof pitches are required for visual reasons (a). The main advantage of standing seam roofs over profiled metal roofs is that almost no fixings pass through from outside to inside the construction. This gives the roof surface a visually crisp appearance with very few visible fixings. The standing seams allow the technique to be used on very low pitch roofs. The traditional method of forming a standing seam roof is to set the sheet onto a timber substrate, and to fold the long edges of the metal upwards to form a standing seam joint (b). However, this method is increasingly giving way to prefabricated systems where the sheet metal is folded to a specific profile either in a factory or on site with a rolling machine. The folded metal is then secured with a clip-based fixing system rather than onto a continuous substrate.

The site-based method of fixing sheet is well-suited to smaller-scale applications, or where complex geometries are used. These applications make the use of prefabrication both unnecessary and uneconomic, due to the time saved by forming junctions and edges on site. The use of a single sheet metal profile and angle support clips used in prefabricated methods is typically too inflexible for such conditions. This traditional method of forming standing seam roofs has timber boards or plywood sheet used to form a continuous substrate, or supporting surface. Standing seams are formed by timber strips of rectilinear or curved section which are set at 450-600mm centres down the slope of the roof, corresponding to the width of the sheet metal used (c). Sheet metal is laid along the length of the roof from top to bottom, with the sides of the sheet folded up and over the timber battens. Successive strips of metal sheet are lapped over the next to form a continuous sealed surface. The standing seam joint is produced by folding the metal together to create a seal. Because the roof is effectively formed as a series of linked gutters, the standing seam between each gutter is above the level of the water draining down it. Rainwater is avoided from being drawn through the joint by capillary action by one of two methods, in which the joint is either sealed or ventilated. In a sealed joint the seam is pressed tight, as in a traditional lead or copper roof, either by folding the metal over itself to form a thin seam, or by forming the metal over a timber roll or section. In a ventilated joint, a small gap is left between the folded sheets to allow air to pass through but not rainwater.

For prefabricated standing seam roofs, the most common configuration is to fix the brackets supporting the outer sheet to a set of metal purlins. A metal liner sheet is set below the purlins to support the thermal insulation quilt, set between the purlins (e). A vapour barrier is set between the insulation quilt and the liner tray on the warm (in winter) side of the thermal insulation (h). An alternative configuration is to have a full structural deck with insulation set on top and an outer (upper) sheet supported on brackets set onto the structural deck. In



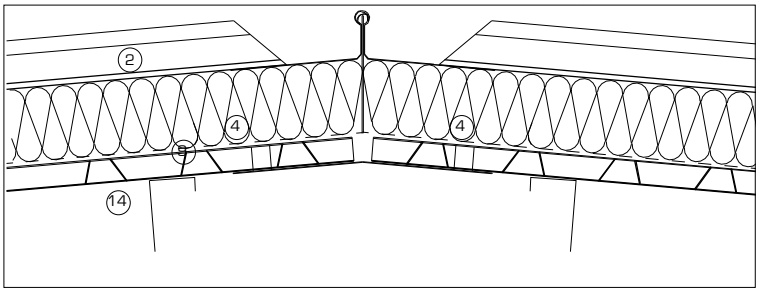
c | Vertical section 1:10. Typical roof assembly without acoustic layer



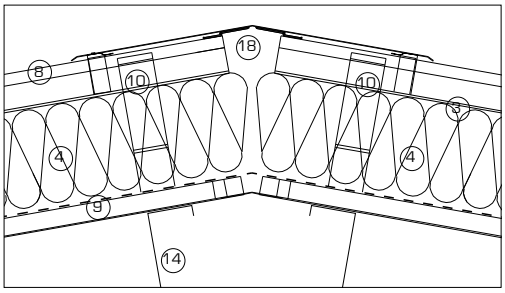
d | Vertical section 1:10 Typical roof assembly without acoustic layer



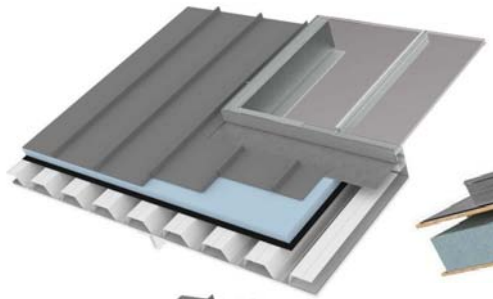
e | 3D cutaway view showing typical roof assembly

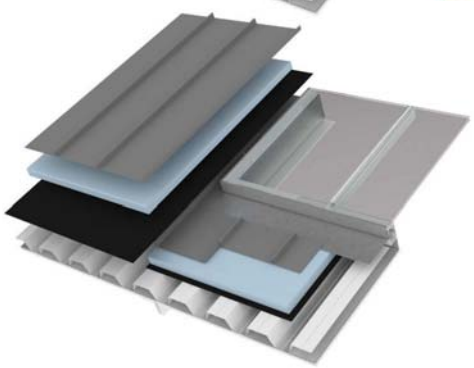


f | Vertical section 1:10. Ridge with recessed flashing



g | Vertical section 1:10. Ridge with flashing





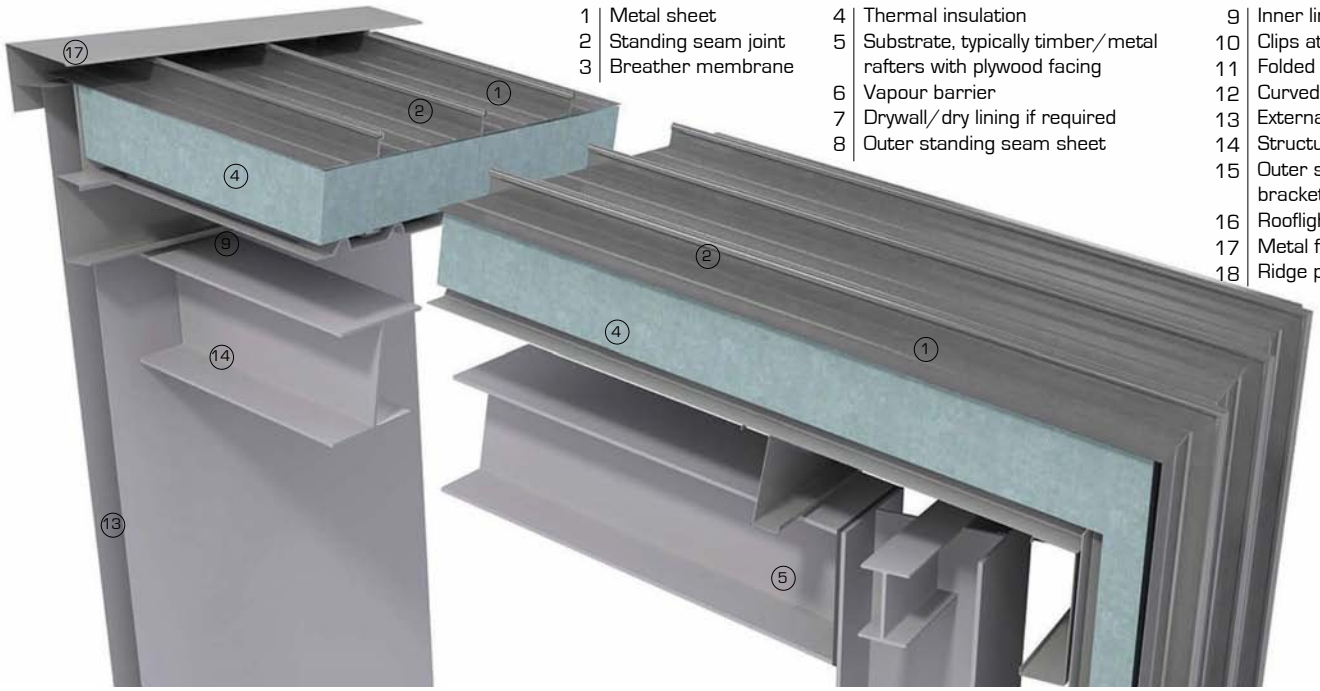
h | (Left) 3D views showing rooflight opening within sheet metal roof



j | 3D view showing sheet metal on pitched timber roof

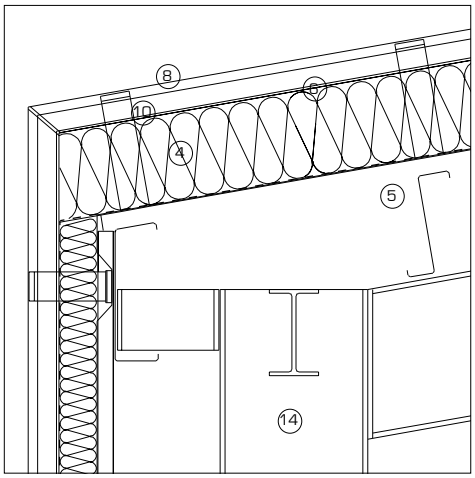
Details

1 | Metal sheet
2 | Standing seam joint
3 | Breather membrane
4 | Thermal insulation
5 | Substrate, typically timber/metal rafters with plywood facing
6 | Vapour barrier
7 | Drywall/dry lining if required
8 | Outer standing seam sheet
9 | Inner lining sheet
10 | Clips at centres
11 | Folded metal gutter
12 | Curved eaves sheet
13 | External wall
14 | Structural frame
15 | Outer sheet fixing bracket
16 | Rooflight
17 | Metal flashing
18 | Ridge piece

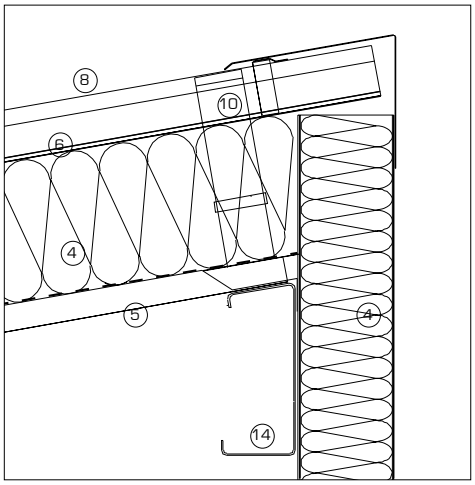


k | 3D view of folded eaves and ridge junction

m | (Below) 3D sectional view showing metal standing seam roof construction



n | Vertical section 1:10. Folded eaves



p | Vertical section 1:10. Monopitch ridge

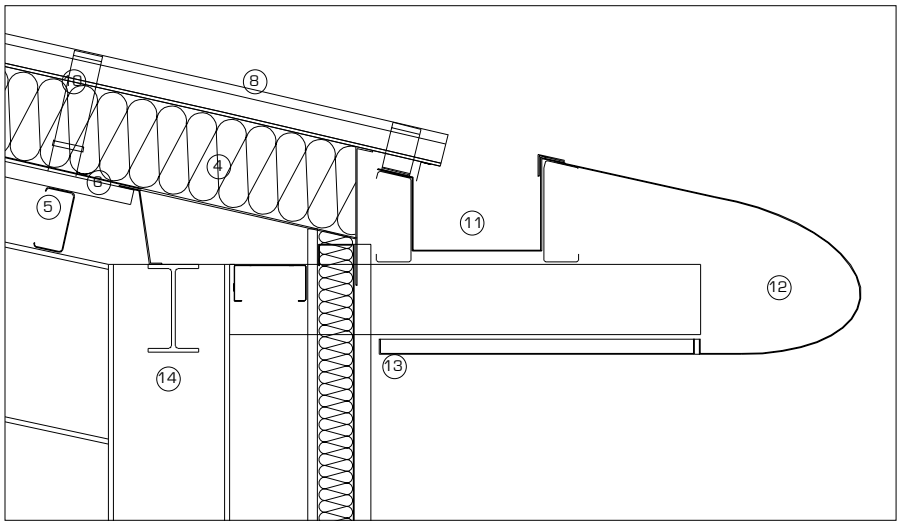


hot, humid countries an additional vapour barrier is set on top of the insulation where there is a risk of interstitial condensation from the outside as well as the inside (n).

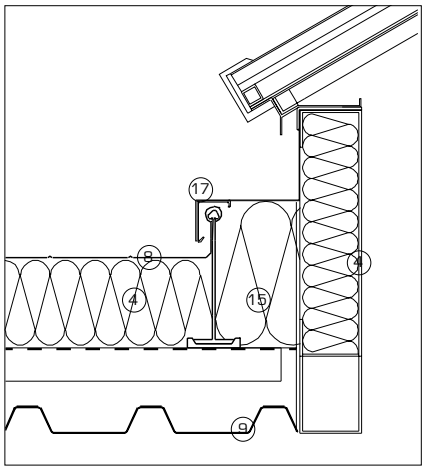
For both site-based and prefabricated construction methods, the roof pitch can go down to 1° (j), after taking into account any structural deflections that would further reduce this angle. Metal sheets can be made up to 40 metres in length, but road transport is difficult, being considerably longer than a trailer length. For larger projects, long sheets are formed on site with a rolling machine that can form the profile of the standing seam sheet to any length required; the profile being formed from metal coil.

System details

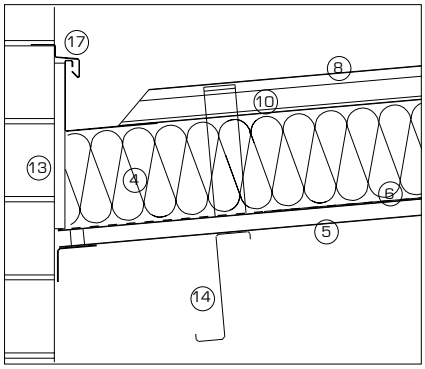
Support brackets are usually T-shaped and are fixed either to the structural deck or to purlins with self-tapping screws (q). The brackets are usually made from extruded aluminium in order to provide a profile that is both thick enough to form a rigid connection and sufficiently precise in section to retain a given standing seam profile in place. Metal sheet is formed in long lengths of folded trays which are then fixed onto the support brackets. Finally the standing seam joints are crimped to form a seal, usually with a 'zip up' tool that travels along the joint and



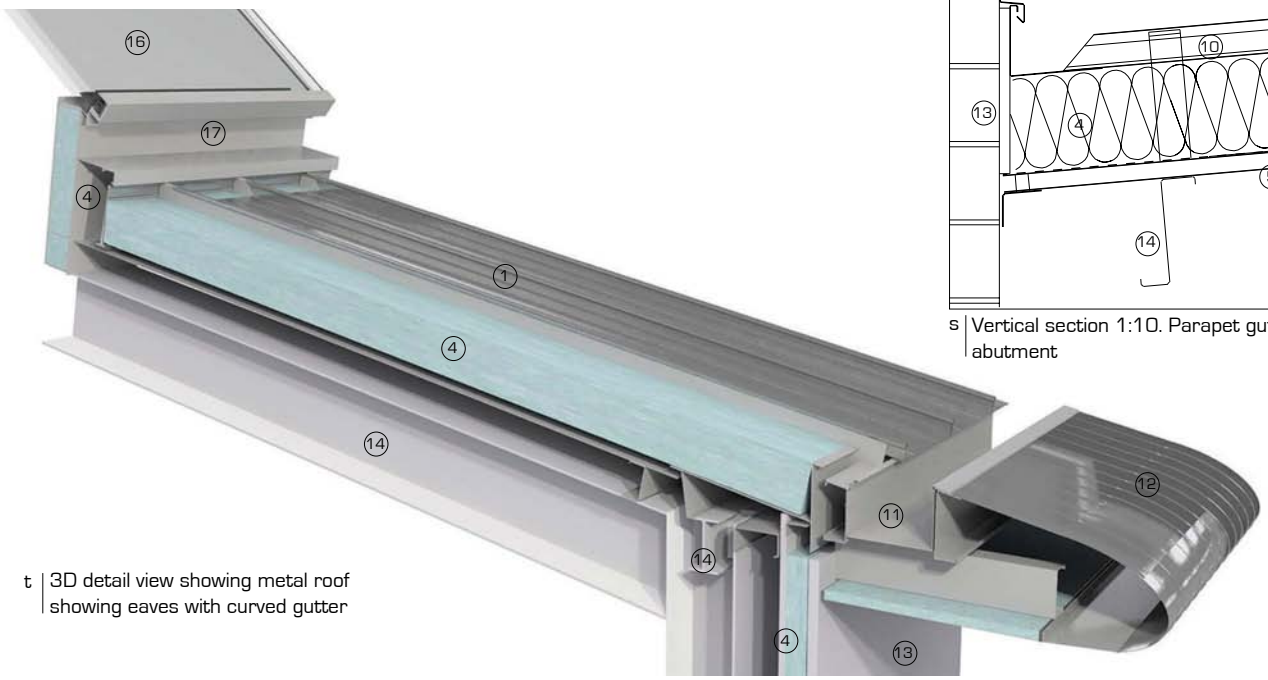
q | Vertical section 1:10. Eaves with curved gutter



r | Vertical section 1:10. Junction with rooflight



s | Vertical section 1:10. Parapet gutter at abutment



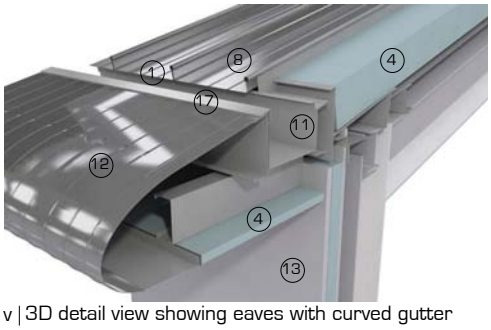
t | 3D detail view showing metal roof showing eaves with curved gutter

across the roof, sealing the joint as it moves along. Standing seam sheets can form shallow curves by gently bending the metal on site, or alternatively by curving the sheets in the factory, to give a smooth appearance. Small radius curves are formed by crimping the sheet in the factory, where the material is mechanically formed with small local folds. Sharp folded corners are made by welding two sheets together along the fold line.

Ridges are formed by a variety of methods, the visually sharpest being a ridge line formed as a standing seam joint, with the seams meeting the ridge being terminated to avoid the need for visually bulky filler pieces which could be seen from below. Valleys are formed by lapping the ends of the standing seam roof into a folded metal tray forming a continuous gutter. Eaves are formed in a similar way, with a gutter set at the edge of the roof (t). Increasingly, gutters are being integrated into roof forms in order to avoid a weak visual line formed by a gutter which is not continuous with the smooth lines of the roof. When additional closer pieces are used, such as bullnose profiles (v), the metal panels are usually designed to be drained and ventilated to the exterior and the line of waterproofing continues up the external wall to the underside of the standing seam roof.



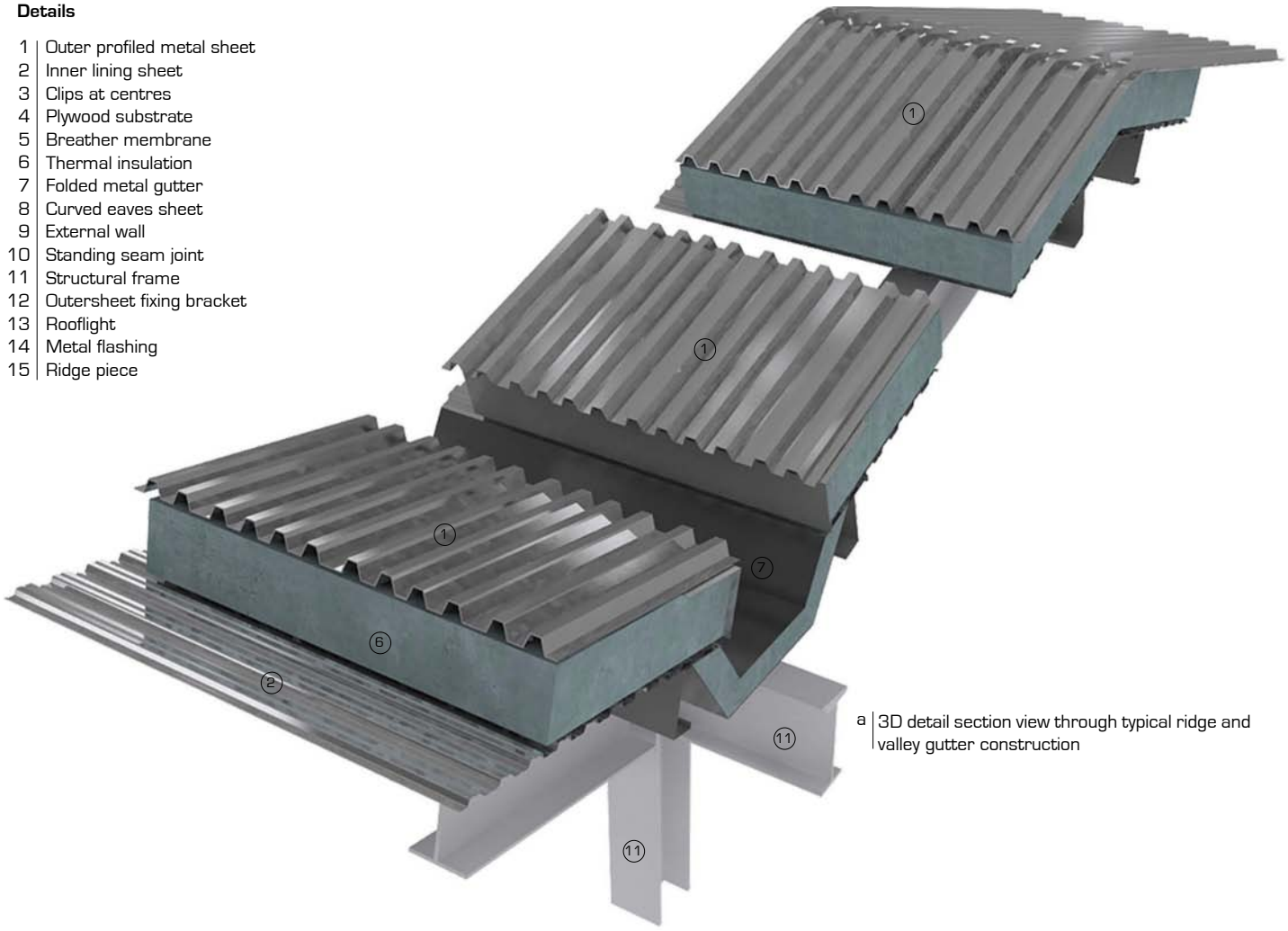
u | 3D detail view showing metal roof at abutment



v | 3D detail view showing eaves with curved gutter

Details

1 | Outer profiled metal sheet
2 | Inner lining sheet
3 | Clips at centres
4 | Plywood substrate
5 | Breather membrane
6 | Thermal insulation
7 | Folded metal gutter
8 | Curved eaves sheet
9 | External wall
10 | Standing seam joint
11 | Structural frame
12 | Outersheet fixing bracket
13 | Rooflight
14 | Metal flashing
15 | Ridge piece



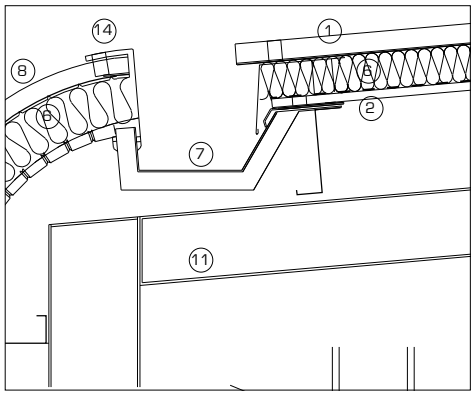
a | 3D detail section view through typical ridge and valley gutter construction

System design

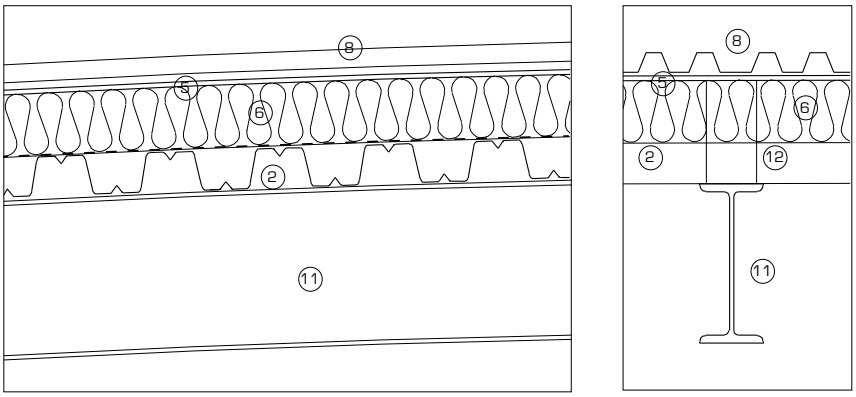
The main advantage of profiled metal sheet over other metal roof types is the ability of the material to span economically up to around 3.5 metres between primary structural supports. This self-supporting ability of the material, combined with its weather resistant, painted coating applied during manufacture, makes it able to be used as both a substrate material for a finish in a different material set onto it, or as a single layer structural and weatherproof material. While standing seam roofing, with its high projecting folds, is suited to long, straight, or gently curving spans, profiled metal sheet can both span between supports and form complex geometries. It is this flexibility of being both structural deck and waterproofing layer that has an advantage, where the interior finish is designed to be in a different material, such as dry lining or decorative boarding. In recent years roof pitches have greatly reduced to make the roof as flat as possible, usually for visual reasons. Most profiled sheet is laid to a minimum pitch of around 4°. Standing seam roofs can go down to a 1° pitch, depending on the geometry of the roof.

Profiled metal sheet provides a continuous weatherproof skin with the ability to be curved in one direction (a), where the supporting structure beneath requires only a few structural members to be curved, and most framing can be straight. The material is lapped on all four sides like metal standing seam roofs. The laps are made long enough to avoid capillary action through the joint. This simple jointing system provides large areas of reliable, weathertight roofing that can be installed quickly. In common with standing seam roofing, profiled metal roofs can be used as a roof covering in either sealed or ventilated construction. Ventilation is used mainly where a timber supporting structure is used, where the timber is ventilated to avoid rot in the material from moist air in the void that would otherwise be trapped within the construction.

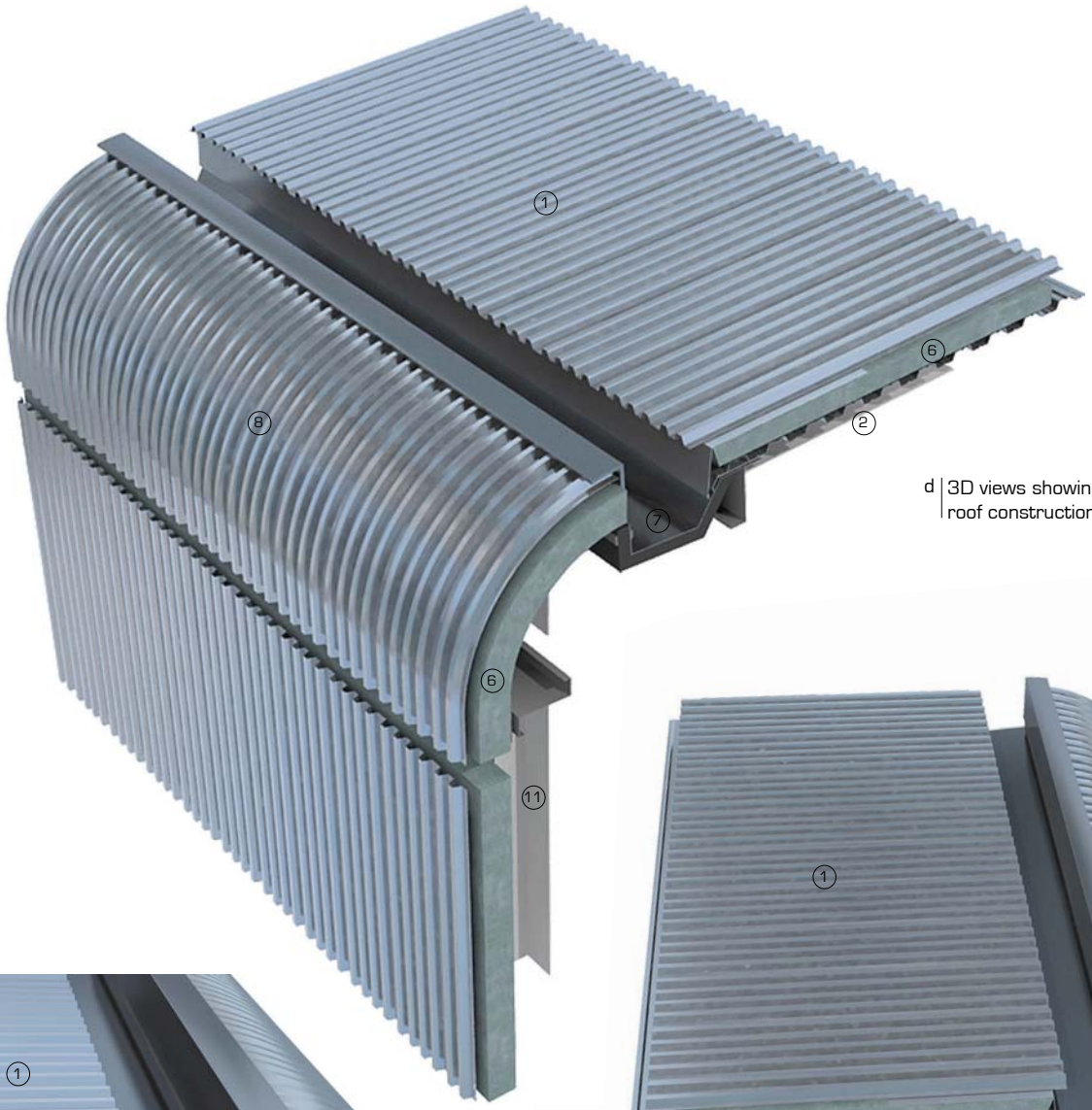
In sealed roofs, the thermal insulation usually fills the voids in between the inner and outer skins (c), but ventilators are often provided at the ridge and eaves to allow some breathing through the ribs of the profiled sheet. This helps to keep the insulation completely dry. Because the inner lining sheet presents a hard surface under the roof (e), perforated sheets are used to improve sound absorption. Sound is allowed to be absorbed partly by the insulation quilt. This helps to reduce reverberation, particularly in noisy internal environments. A vapour barrier is set between the thermal insulation and the thin layer of acoustic insulation beneath. Profiled metal sheet roofs have the ability to conceal the supporting structure within the depth of the roof construction. This gives a smooth-finished appearance to the inside face of the roof (d). An outer metal sheet is supported on metal roof purlins; and an inner lining tray, which supports the thermal insulation, is fixed to their underside. Sheets are fixed with self-tapping screws which, in addition to fixing the sheets to the supporting structure, are also required to be weathertight. A vapour barrier is provided on



b | Vertical section 1:10. Concealed gutter detail



c | Vertical section 1:10. Typical profiled metal sheet roof build-up and supporting structure



d | 3D views showing curved profiled metal roof construction



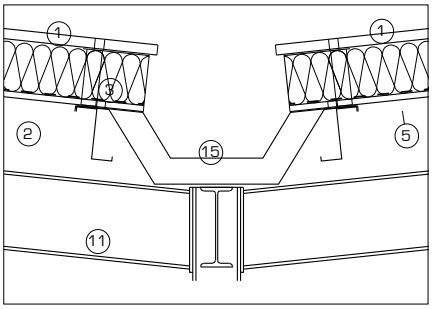
e | 3D views showing gutter condition in curved profiled metal roof construction

Details

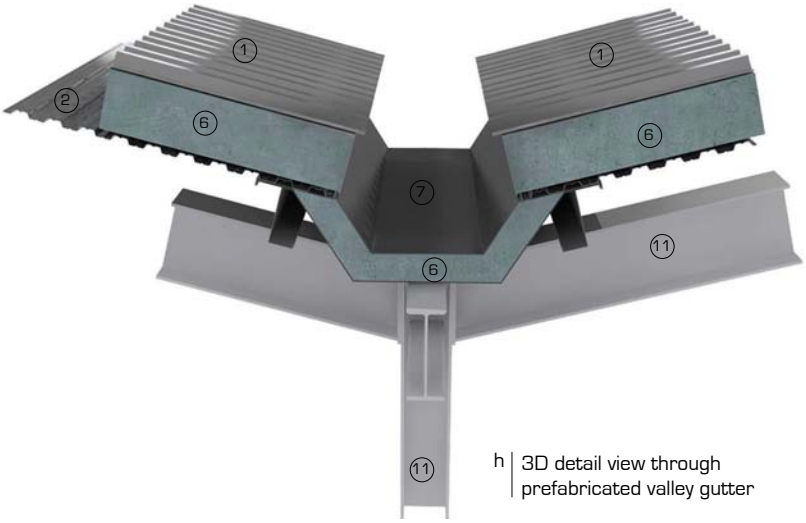
1 | Outer profiled metal sheet
2 | Inner lining sheet
3 | Clips at centres
4 | Plywood substrate
5 | Breather membrane
6 | Thermal insulation
7 | Folded metal gutter
8 | Curved eaves sheet
9 | External wall
10 | Standing seam joint
11 | Structural frame
12 | Outersheet fixing bracket
13 | Rooflight
14 | Metal flashing
15 | Ridge piece



f | 3D detail view through typical ridge construction



g | Vertical section 1:20. Prefabricated valley gutter



h | 3D detail view through prefabricated valley gutter

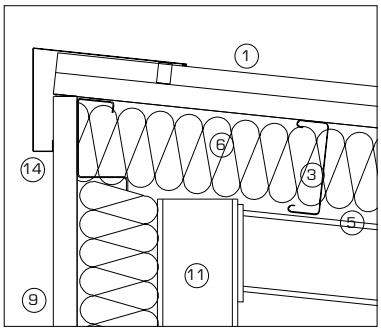
the warm (in winter) side of the insulation, between the liner tray and the thermal insulation. Laps between profiled sheets along their top and bottom edges are sealed with butyl sealant strip. Two strips are normally used, one at the end of the external lap and the other at the top end of the internal lap. The outer seal provides protection against the capillary action of rainwater being drawn up into the lap between sheets, while the other provides a vapour barrier that avoids moisture generated inside the building from condensing in the joint. Self-tapping screws that hold the sheets in place clamp the two sealed surfaces together. Sheets are normally lapped 150mm over one another, while laps between sheets on their side edges are made with a single lap of profile, with a single seal of butyl tape set at the centre of the lap.

System details

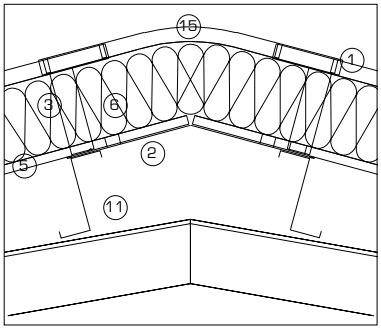
Ridges at the junction of a double pitched roof use a folded metal strip to form a continuous ridge sheet (k). These sheets can be folded on a straight line or formed to a curved line. The void beneath is filled with thermal insulation in addition to that used beneath the profiled sheet. Closer strips are used to seal the gaps in the profiled sheet where it meets the ridge cover strip set on top of the profiled sheet.

Parapets are formed by creating a gutter at the base of the profiled sheet, then continuing the line of the gutter up to a parapet coping with laps over the top. The gutter is formed from a single folded sheet to avoid the possibility of leaks, and is lapped under the vertical sheet that forms the seal between gutter and coping (h). Parapets in profiled metal sheet are often used where the external wall is formed in a different material, so that the parapet forms a visual break between them. However, many profiled metal roofs are used in conjunction with walls in the same material using a concealed gutter that allows wall and roof to be continuous.

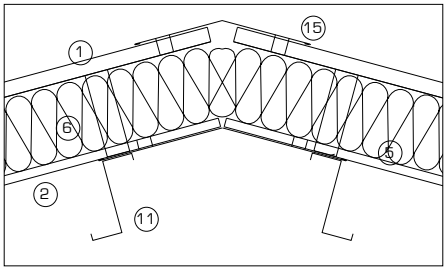
Ridges and valleys are formed using the same methods discussed in the previous section on standing seam roofs (p). But where standing seams can be cut down to form a flat ridge without a projecting ridge piece, this is not possible in profiled sheet, and instead a folded ridge piece is fixed to the upper surface of the profiled sheet (m). The gaps between the ridges and troughs of the profiled sheet are filled with a proprietary metal filler piece, usually forming part of the manufacturer's system. Ventilated roofs do not require this filler piece, with the resulting gap between the folded ridge sheet and the profiled sheet usually being sufficient to provide ventilation in the construction.



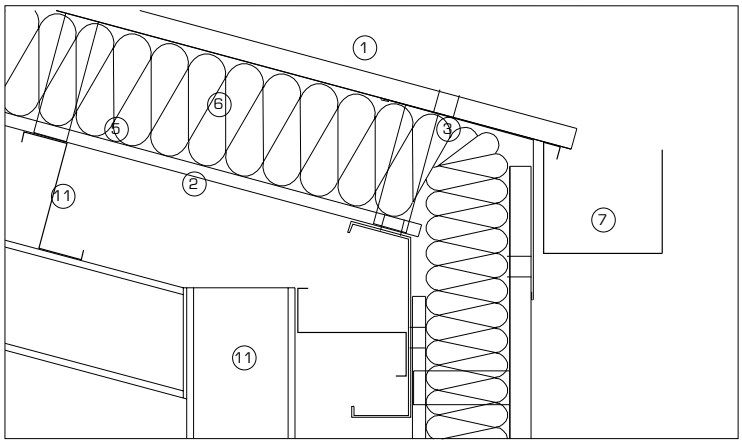
j | Vertical section 1:20. Monopitch ridge

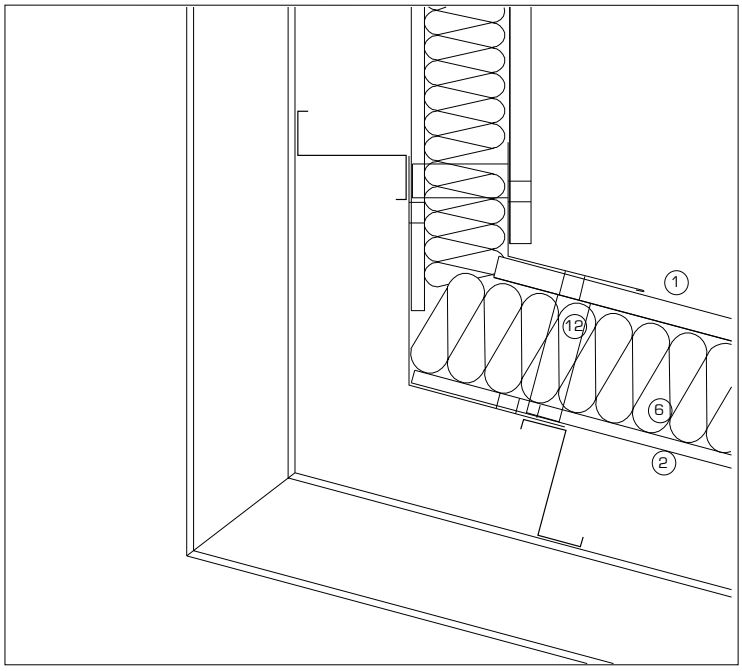


k | Vertical section 1:20 Ridge with flashing



m | Vertical section 1:20. Ridge with flashing





n | Vertical section 1:20. Eaves with exposed gutter and abutment with vertical roof panel



p | 3D detail view through prefabricated valley gutter

q | 3D detail view through typical ridge construction





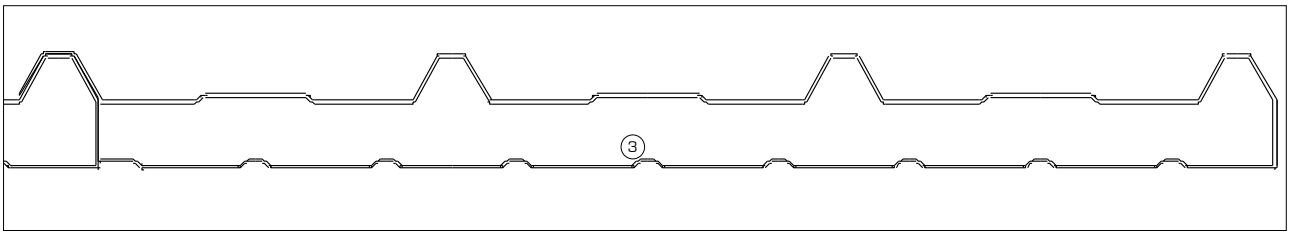
a 3D views showing vertical section through parapet edge and folded metal gutter between panels

System design

There are two types of composite panel used for roofs: double-sided panels and single sided panels. The first is a development of profiled metal sheet where outer sheet, thermal insulation and inner sheet are combined into a single panel . These are used in pitched roofs and have an appearance very similar to that of profiled metal roofs. Their main advantage over profiled metal roofs is the speed of erection on site, but they are usually a little more expensive than an equivalent profiled metal sheet roof. Single-sided panels consist of profiled metal sheet bonded to one side only of a layer of foam-type thermal insulation. The insulation is laid face-up to receive a separate waterproofing layer, typically a single layer membrane (a). The membrane is then typically finished in rainscreen panels (1) or smooth pebbles, depending on the geometry and required appearance of the roof. This second panel type can be used on nominally flat roofs.

Single-sided composite panels have a single sheet of profiled metal on the lower loadbearing face of the panel, which is bonded to a foam-based insulation that fills all the voids in the profiled sheet (3), providing a smooth, flat upper surface. The depth of the panel is determined by both structural requirements and the U-value required, varying the thickness of the thermal insulation. The upper face of the panel is waterproofed with an independent membrane, typically an elastomeric type that requires no upstands or special joints between sheets (c). Panels are usually set butted up to one another, with the gap between panels filled with foam-based thermal insulation. A separating layer is usually set between the waterproof membrane and the insulated panel to allow movement to occur freely in both the membrane and the composite panel substrate. The membrane is often protected with a lightweight covering of smooth pebbles that can be walked upon for maintenance access without puncturing the surface. Metal rainscreen panels are also used to protect the membrane from the effects of direct sunlight.

Double-sided composite panels which combine the separate components of profiled metal sheet have two joint types: a double seam with a cap on top in the manner of standing seam roofing, or a single projecting lap of metal profile that forms a lapped connection with the adjacent panel. With the first method, panels have raised edges on their long sides running down the slope. The raised edges are butted together and sealed with butyl tape. A metal capping is fixed over this joint to provide a weathertight seal which sheds water onto the panels either side of the joint, giving this method a distinct appearance of wider joints. The second method has an uninsulated rib of the outer sheet projecting from the panel on one long side which laps over the adjacent panel. This gives a continuous ribbed appearance to the roof that is visually no different on its outside face to profiled metal roof cladding (d) . Both methods have lapped joints on their short (horizontal) edges, where an uninsulated edge projects down to form a lapped joint very



b | Vertical section 1:10 through composite panel showing panel-to-panel junction

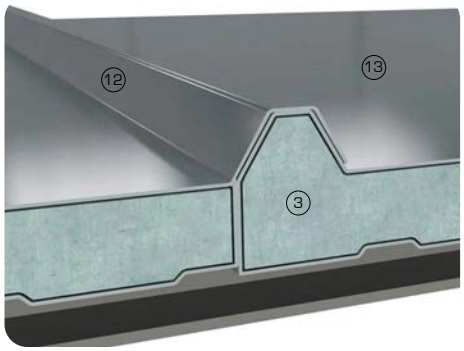




c | 3D detail views showing composite metal panel build-up



e | 3D view showing verge with parapet upstand

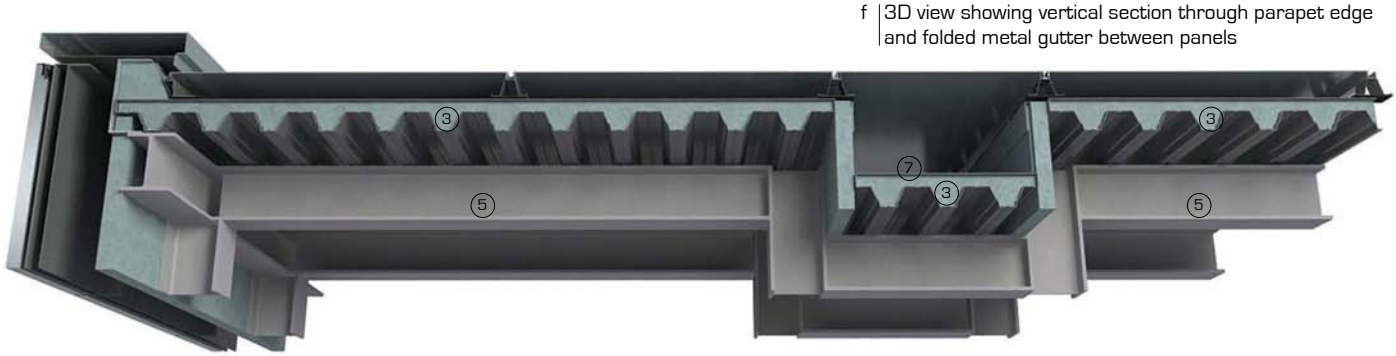


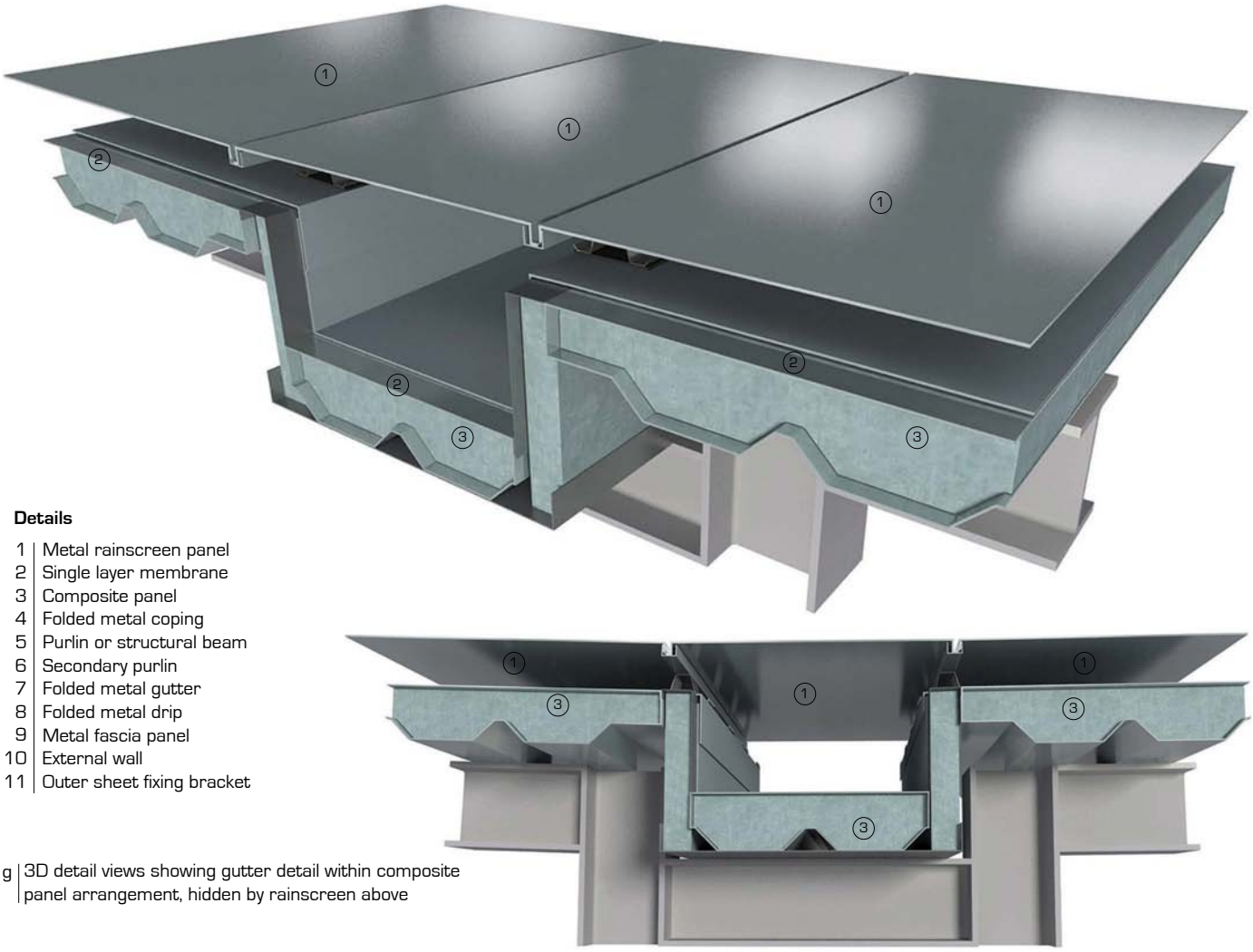
d | 3D detail view showing panel connection

Details

1	Metal rainscreen panel
2	Single layer membrane
3	Composite panel
4	Folded metal coping
5	Purlin or structural beam
6	Secondary purlin
7	Folded metal gutter
8	Folded metal drip
9	Metal fascia panel
10	External wall
11	Outer sheet fixing bracket
12	Panel 1
13	Panel 2

f | 3D view showing vertical section through parapet edge and folded metal gutter between panels





Details

1 | Metal rainscreen panel
2 | Single layer membrane
3 | Composite panel
4 | Folded metal coping
5 | Purlin or structural beam
6 | Secondary purlin
7 | Folded metal gutter
8 | Folded metal drip
9 | Metal fascia panel
10 | External wall
11 | Outer sheet fixing bracket

g | 3D detail views showing gutter detail within composite panel arrangement, hidden by rainscreen above

similar to that used in profiled metal roofs. These horizontal joints are also sealed with butyl tape to avoid capillary action from rainwater outside, and to prevent the passage of water vapour into the joint from inside the building.

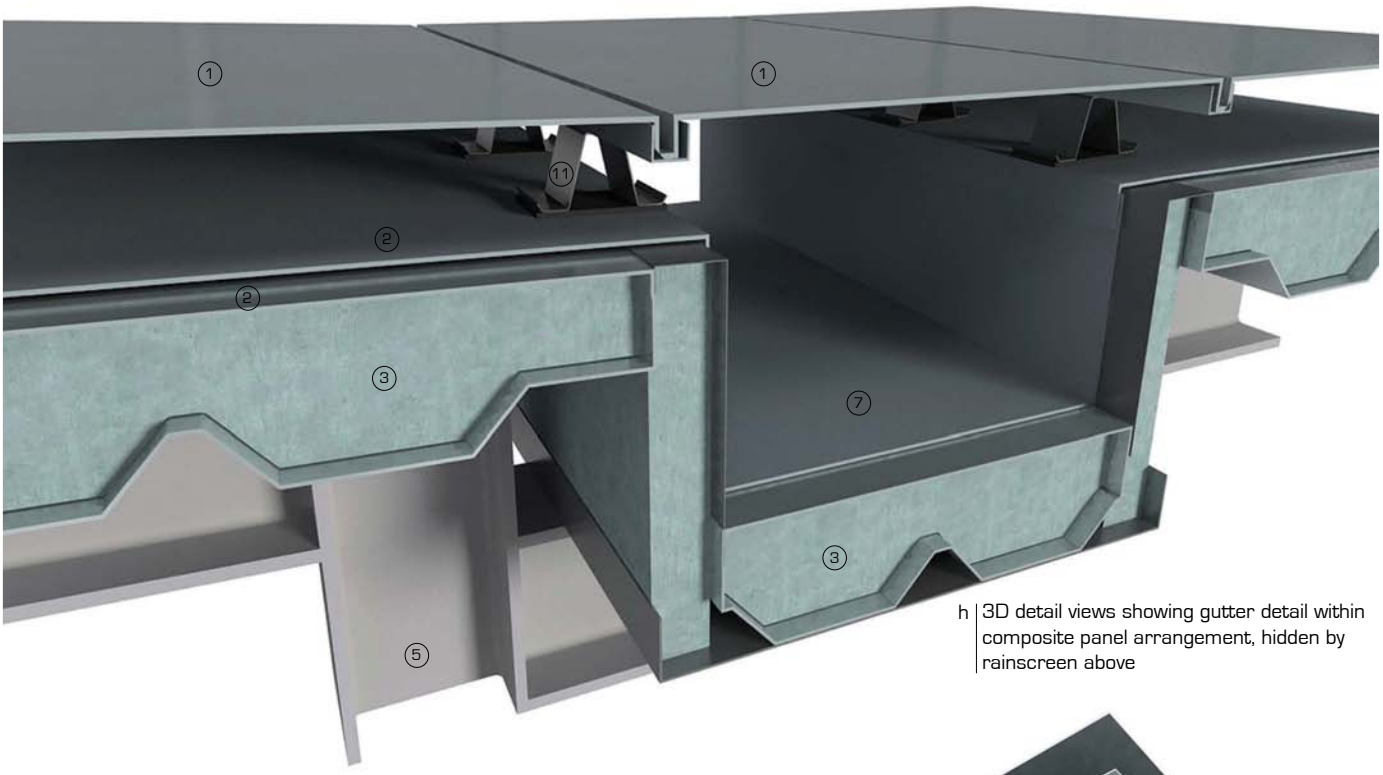
System details

Ridges and folds of single-sided panels are formed in the same way as the panel-to-panel joints, filled typically with a foam insulation applied by injection on site. The membrane sheets are usually joined at the fold in the roof and a strip of the same material is bonded along the joint to provide a weathertight seal. At parapet gutters of single-sided panels, an upstand is formed in the same insulation material as that used in the composite panels, the upstand being bonded to the composite panel beneath. The outer edge of the upstand is sealed and stiffened with a metal strip fixed to the underside of the composite roof panel or the supporting structure beneath (g).

Ridges for double-sided composite panels are formed by fixing a metal flashing over the junction between the panels. The flashing is profiled to match that of the panels onto which it sits. The gaps are then closed with a profiled filler piece as is used in profiled metal roof construction. The ridge flashing has visible fixings which are difficult to conceal, so that precise positioning is essential to the overall visual appearance of the ridge. The gap between the panels is filled with thermal insulation on site, with either mineral fibre quilt or, more frequently, with the same foam-based insulation used to manufacture the panels. Insulation is injected into the gap to provide a U-value to match that of the adjacent panels. The inner face of the panels forming the ridge is sealed with a folded metal sheet, typically fixed to adjacent roof purlins and sealed against the inner face of the composite panel to provide a continuous vapour barrier. This inner trim is made either flat or profiled to suit the composite panels used.

Eaves are formed in a similar way to profiled metal panels, by lapping the edge roof panel over a gutter. The gutter is closed against the underside of the composite panel either by folding it outwards and sealing it or by folding the top edge inwards, up the underside of the panel. Unlike eaves gutters, parapet gutters are thermally insulated, forming part of the external envelope (h). The gutter is usually prefabricated to form part of the overall composite panel system. The gutter shape, in cross section, is formed to provide continuity in the thermal insulation (j) from the roof panel through to the adjacent parapet wall.

The tops of parapets are closed with a pressed metal coping that is folded down over the face of the external wall and the inside face of the parapet to provide a complete weathertight seal. The top of the coping is usually inclined towards the inside face of the wall, into the gutter, to avoid dust settling on horizontal surfaces from being washed down the face of the external wall during rain.



h | 3D detail views showing gutter detail within composite panel arrangement, hidden by rainscreen above

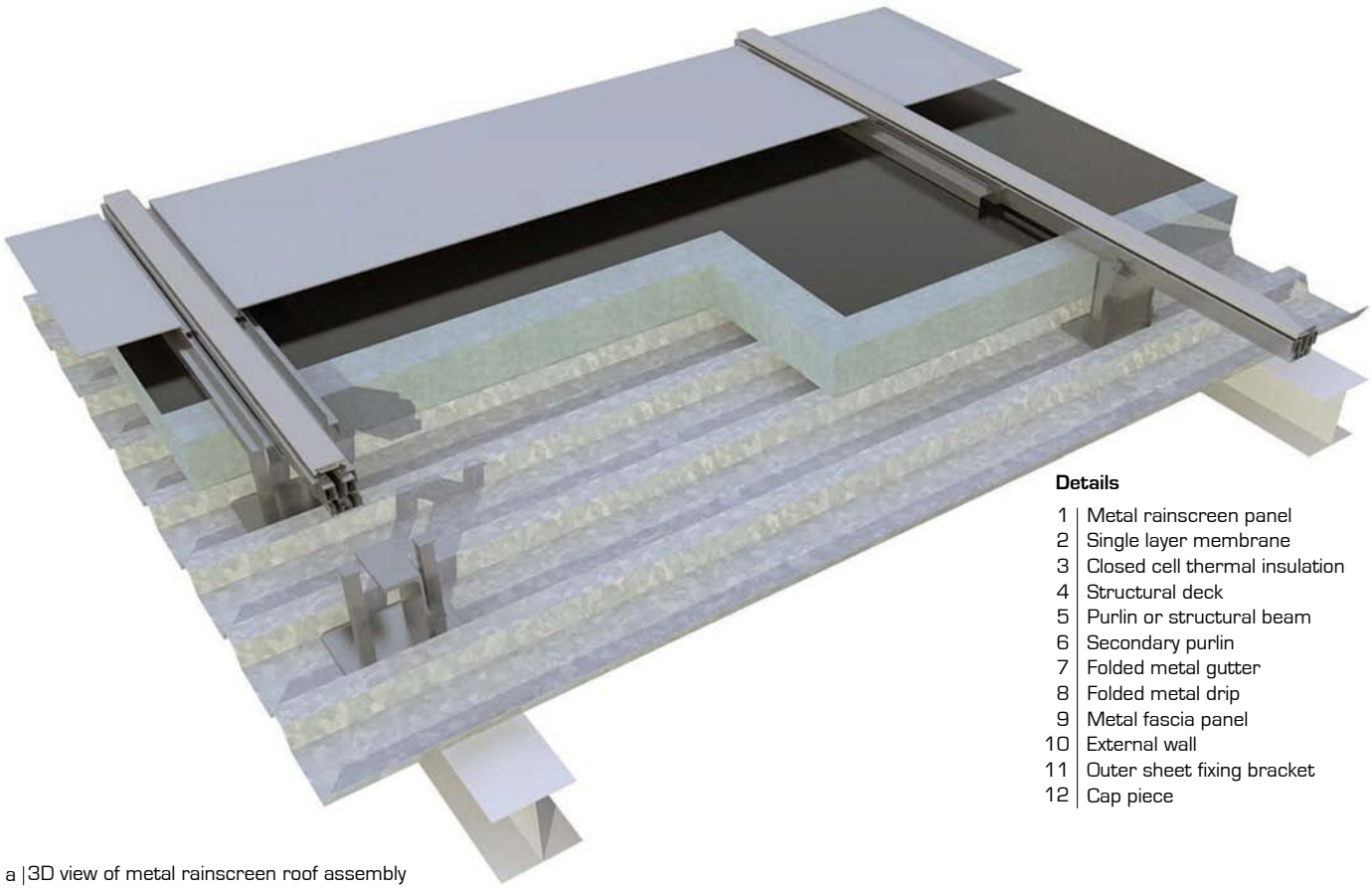




j | 3D detail view showing panel fixing method



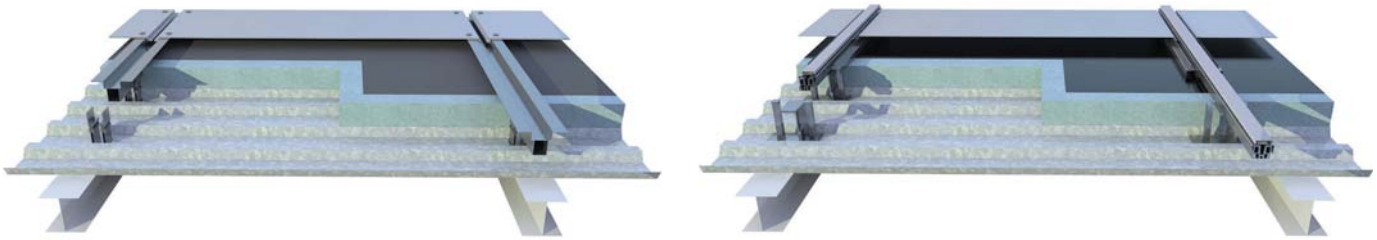
k | 3D detail view showing gutter detail within composite panel arrangement, hidden by rainscreen above



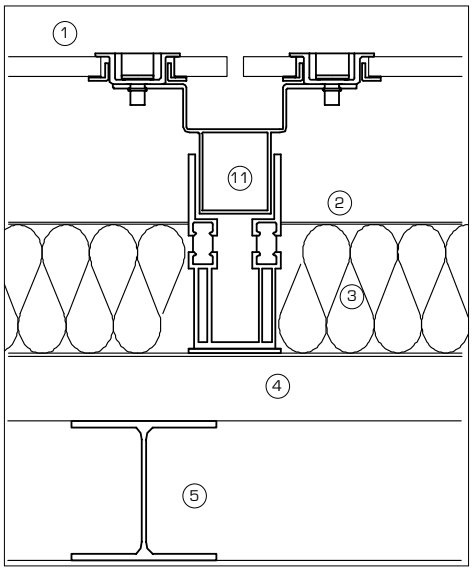
Details

1	Metal rainscreen panel
2	Single layer membrane
3	Closed cell thermal insulation
4	Structural deck
5	Purlin or structural beam
6	Secondary purlin
7	Folded metal gutter
8	Folded metal drip
9	Metal fascia panel
10	External wall
11	Outer sheet fixing bracket
12	Cap piece

a |3D view of metal rainscreen roof assembly



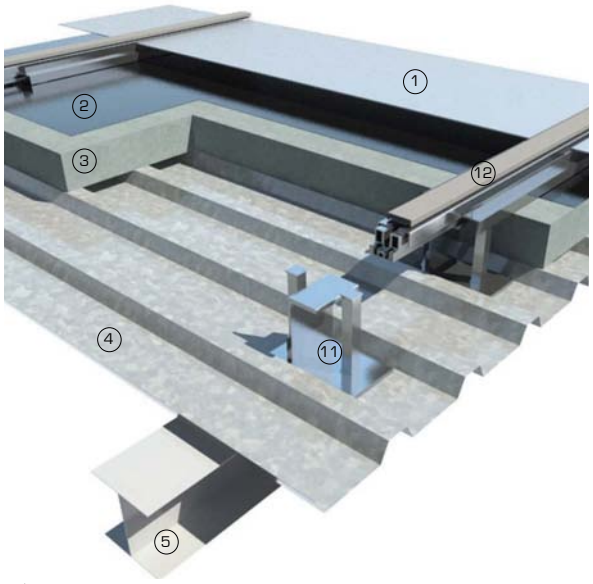
b | 3D views of metal rainscreen roof assembly with varying panels joint approaches



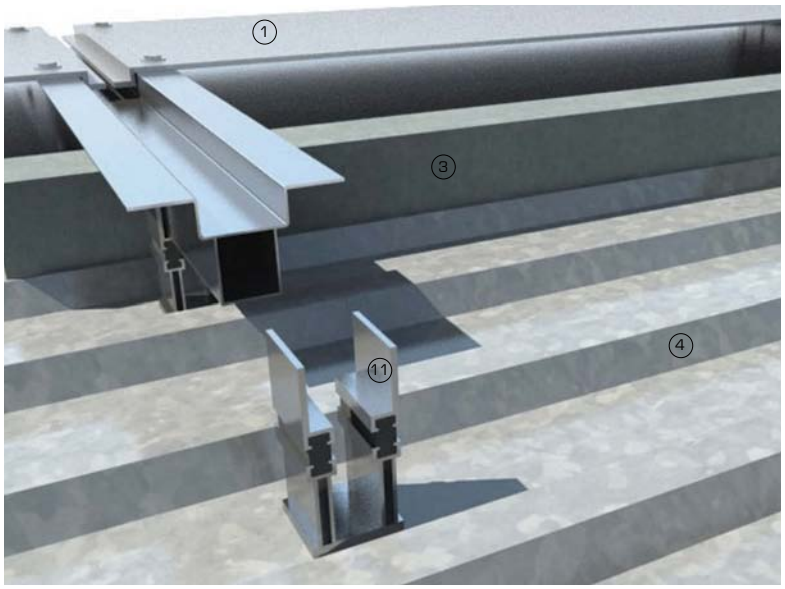
c |Vertical section 1:10 through roof assembly

System design

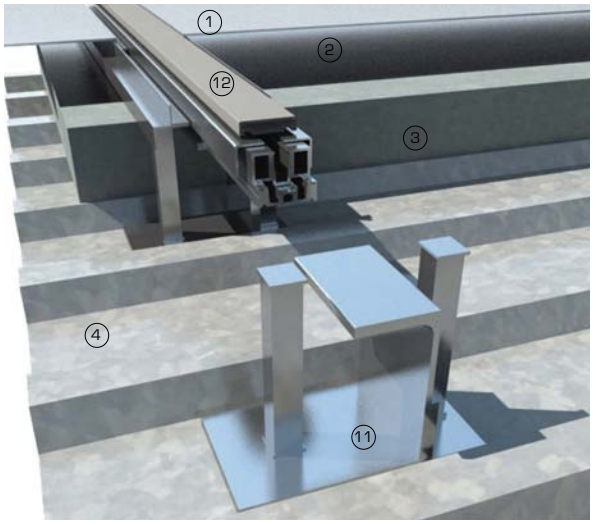
The use of metal rainscreen panels is relatively new in roof construction and has developed from using the panels in external walls, albeit in a different configuration. Firstly, most of the rain falling onto a metal rainscreen roof is not usually drained away on the outer layer of panels, unless the roof has a relatively steep pitch or curved section. Rainwater is still expected to drain onto the waterproofing layer beneath, as if the panels were not in place (a). The main function of the rainscreen panels on roofs is to protect the membrane from the effects of the sun (heat and UV radiation), from the worst effects of windblown rain and as protection for maintenance access (b). Rainscreen panels also provide a lightweight covering that forms part of the visual language of the external walls. Although smooth pebbles are also used to protect waterproofing membranes on non-visible flat roofs, they are obviously not suited to sloping or curved roofs. The use of metal rainscreen panels is well-suited to those more complex roof geometries which form a visible part of the design. These rainscreen panels allow traditional roof elements which are usually visually dominant such as gutters, parapets and ridges; these are to be accommodated within a smooth, continuous outer skin, allowing roofs to take on the visual characteristics of external walls, contributing to the overall architectural effect.



d | 3D view of metal rainscreen roof assembly with optional capping to seam



e | 3D view of metal rainscreen roof support system



f | 3D view of metal rainscreen roof assembly with optional capping to seam



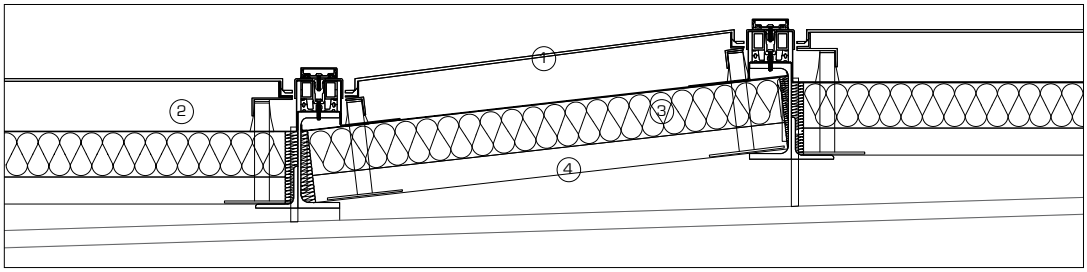
g | 3D view of metal rainscreen roof fixing channel

Although metal sheet is used for rainscreens, metal and plastic composites are becoming increasingly popular. In such materials a thin layer of plastic is faced with two thin sheets of aluminium which are bonded to the plastic sheet core to provide longer size panels than those of sheet metal, with the benefit of providing greater flatness. They are less likely to experience localised impacts from foot traffic during maintenance work, with the 'oil canning' effect of depressed or dented panels resulting from regular maintenance access usually avoided by using these composite sheet materials. However, the size of metal rainscreen panels is restricted more by the panel width that can be walked upon for maintenance access than by the sheet size available. The maximum size of metal sheet usually comes in a width of 1200mm or 1500mm metal coil. Composite sheets are typically 1000mm to 1200mm wide, in lengths from 2400mm to 3000mm, depending upon the manufacturer. In practice, panels may only be around 600mm wide if they do not have additional supporting framing beneath to stiffen them. Framed panels can reach the maximum sizes already mentioned, but care must be taken to avoid the pattern staining or denting that can reveal the frame behind during the life cycle of the roof.

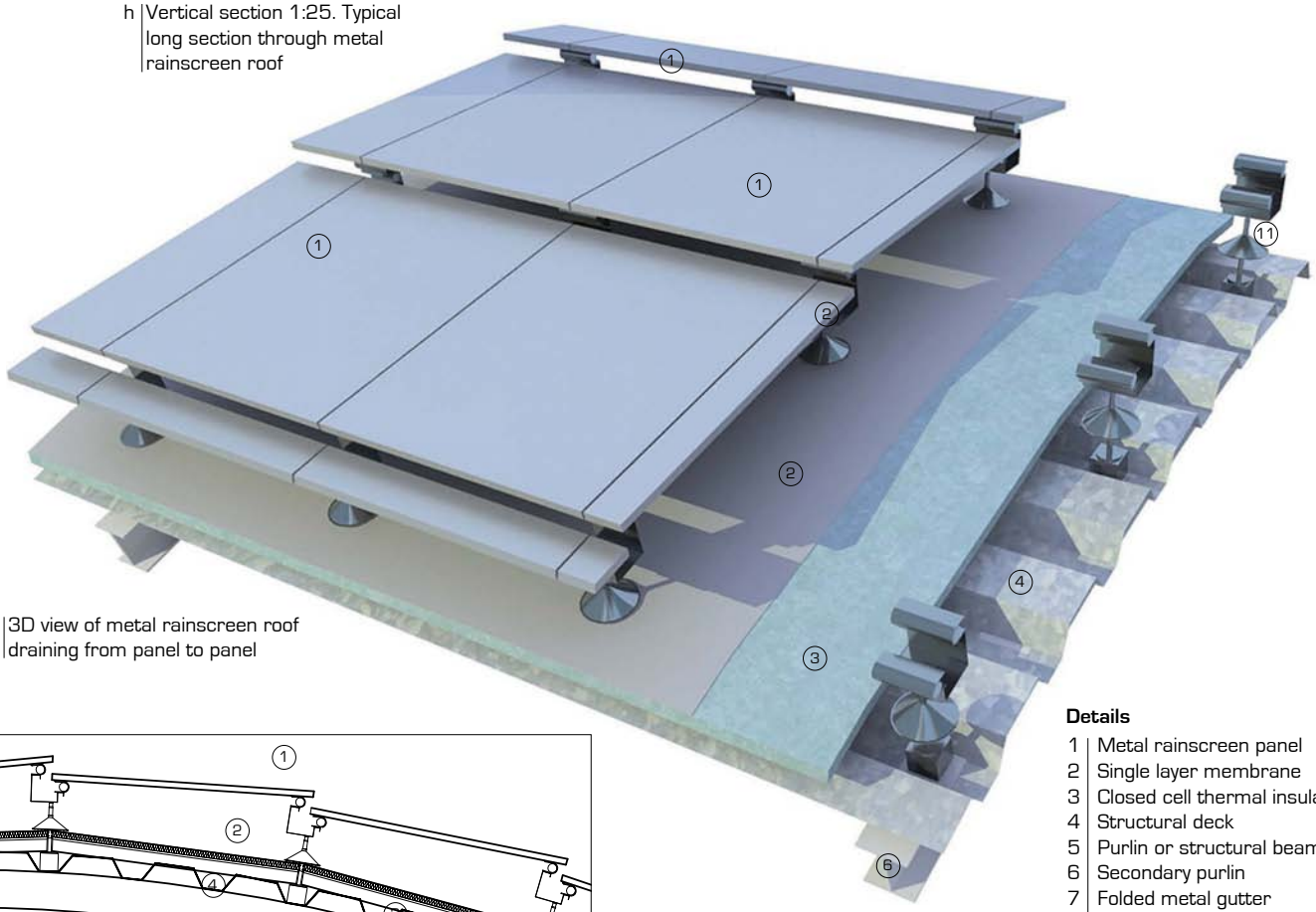
Rainscreen roof panels are typically arranged either as panels laid in a flat grid (d) or as lapped panels, where the bottom edge is lapped over the top of the panel beneath. Side joints remain open-jointed and are set in the same plane in this configuration. Panels in a flat grid are set onto metal Z-sections (e), which are either bonded to the top surface of the waterproof membrane to avoid any risk of water penetration through mechanical fixings, or are set above the membrane on support pads. These pads are usually covered with a waterproofing membrane to reduce the number of fixing penetrations through this layer. The rainscreen panels are then screw-fixed to the Z-section with brackets that avoid the screw fixings being seen at a distance where this is a visual requirement. Concealed fixings are more difficult to accommodate, though such systems are likely to appear over the next ten years as demand for this roof system increases.

System details

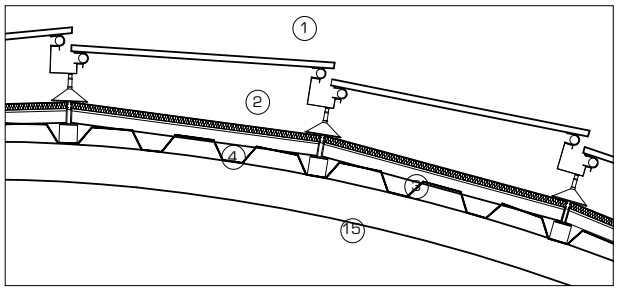
An advantage of rainscreen panels for parapets is that the gutter and upstand can be made without either element being visible (g), allowing parapets to function as concealed gutters while providing a visual continuity between wall and roof. Consequently, eaves,



h | Vertical section 1:25. Typical long section through metal rainscreen roof



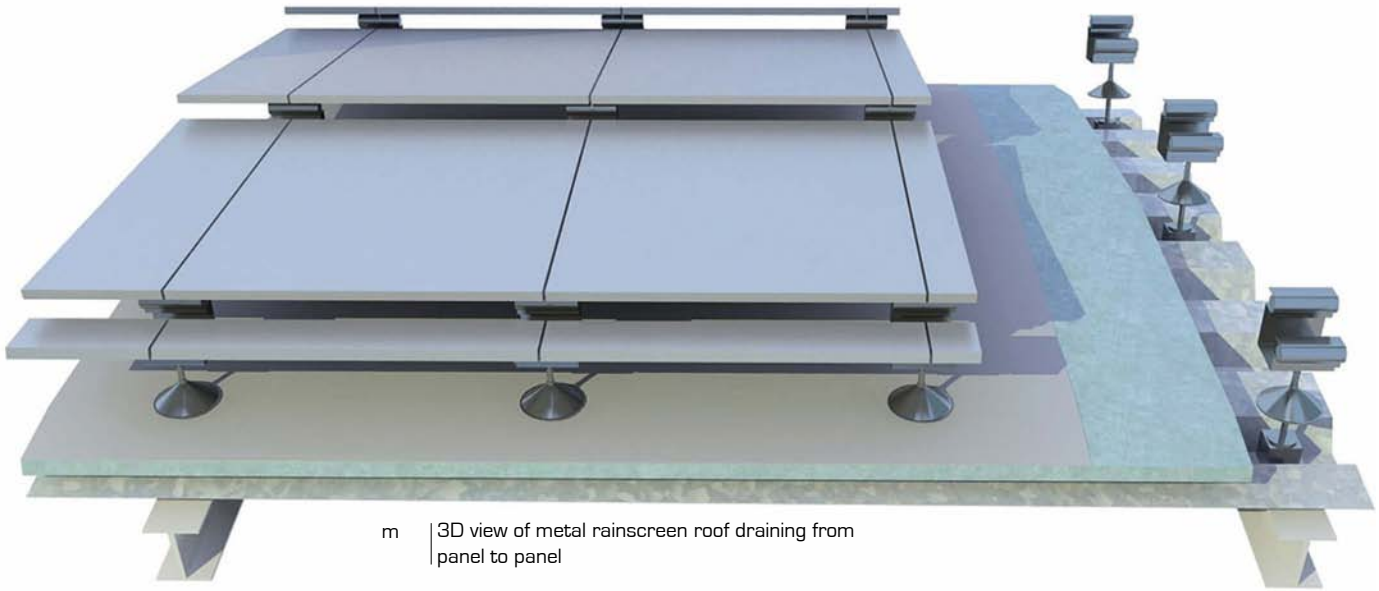
j | 3D view of metal rainscreen roof draining from panel to panel



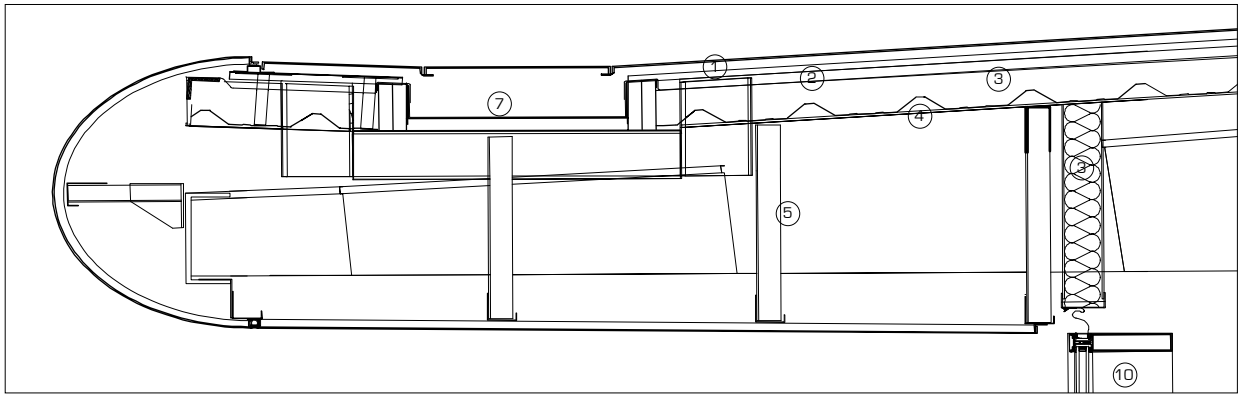
k | Vertical section 1:25. Typical section through curved metal rainscreen roof

Details

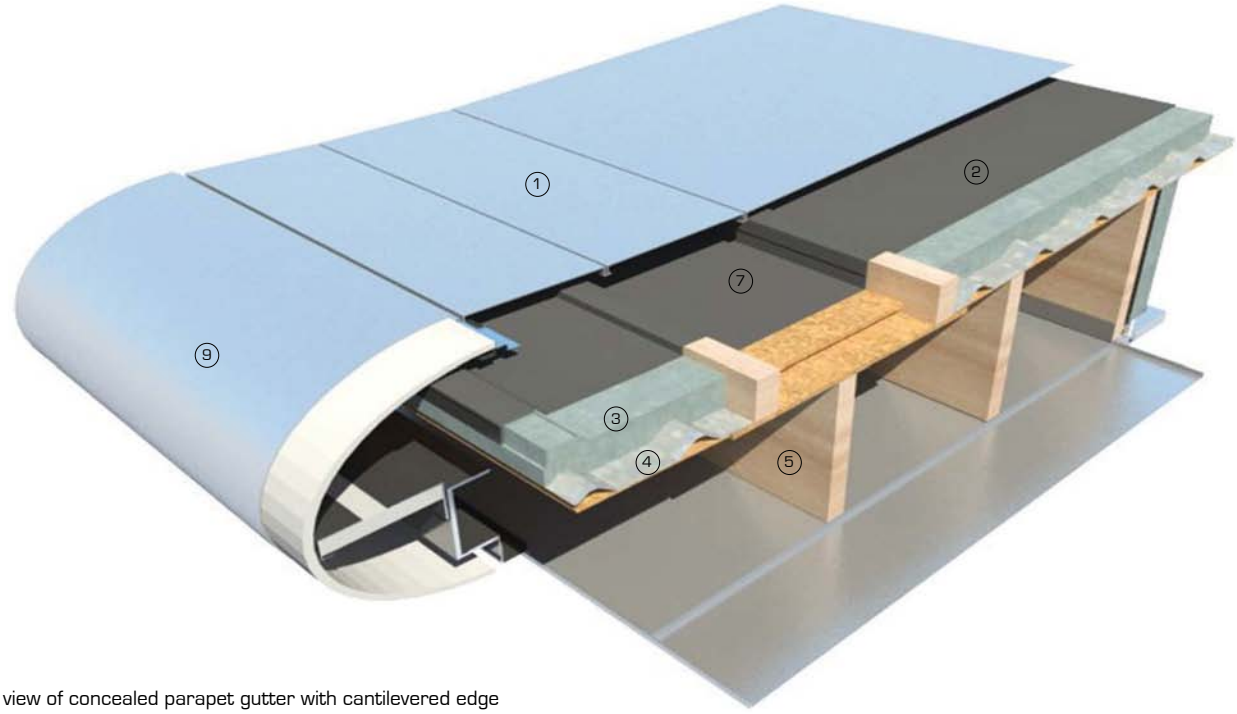
1	Metal rainscreen panel
2	Single layer membrane
3	Closed cell thermal insulation
4	Structural deck
5	Purlin or structural beam
6	Secondary purlin
7	Folded metal gutter
8	Folded metal drip
9	Metal fascia panel
10	External wall
11	Outer sheet fixing bracket



m | 3D view of metal rainscreen roof draining from panel to panel



n |Vertical section 1:10. Concealed parapet gutter with cantilevered edge



p |3D view of concealed parapet gutter with cantilevered edge

monopitch ridges and verges can have an outward appearance similar to an uninterrupted panel layout extending from the roof down to the external wall. Parapets are formed only by a gutter that also provides the necessary upstand height for the parapet itself. A coping is then formed by using the same rainscreen panels as elsewhere on the roof in order to provide a continuity of appearance. The waterproof membrane beneath is then sealed against the wall construction or against the side of the sealed roof deck, which is closed off with a folded metal strip in the case of profiled metal sheet or composite metal panels being used.

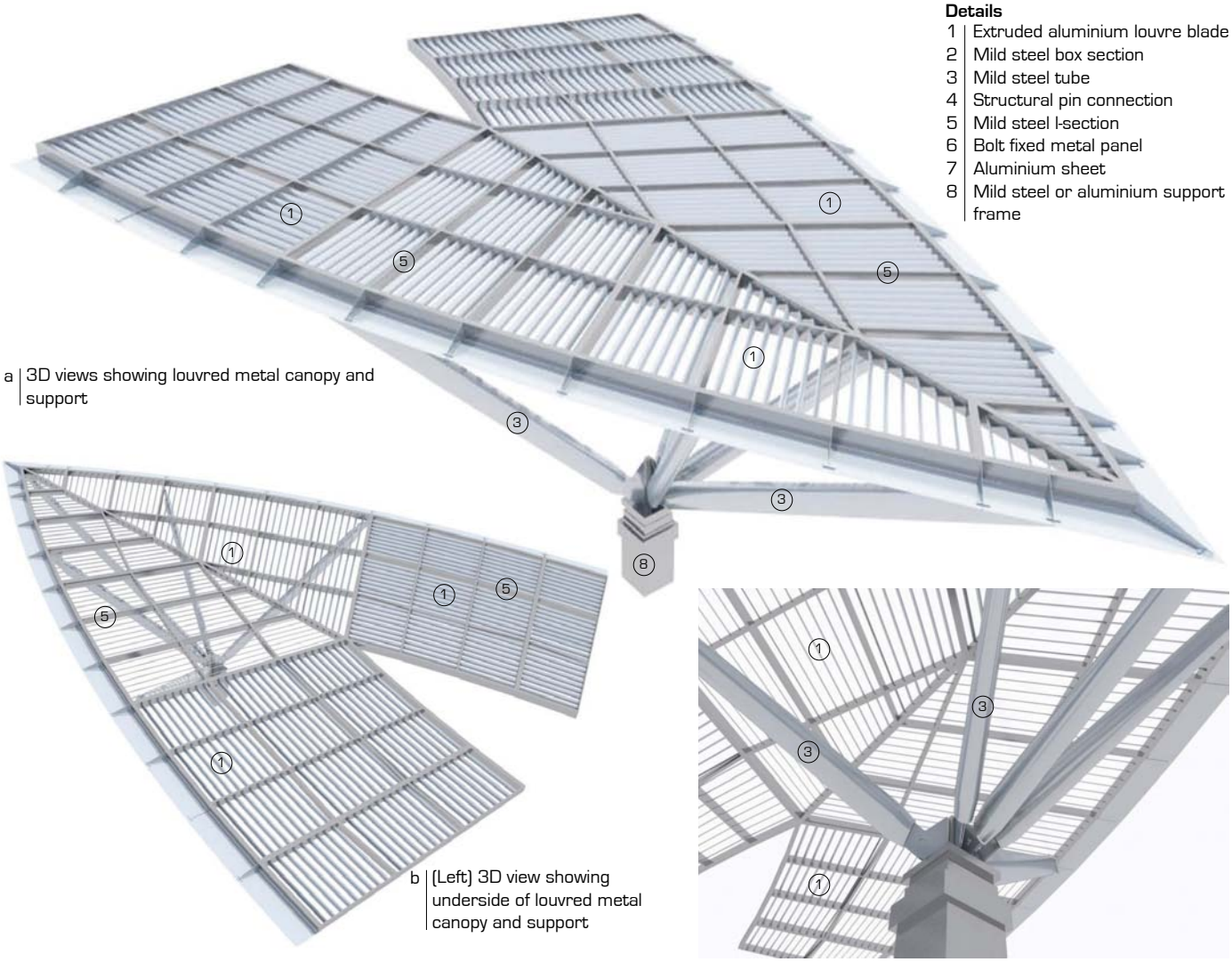
The depth of the roof construction is then finished with another rainscreen panel, set vertically, which is fixed in front of the parapet. Unlike parapets in profiled metal or composite panels, the vertical fascia panel can extend up to the top of the wall in order to conceal the coping flashing. In other types of metal roofing, the coping extends over the top of the wall, resulting in a thin visual edge to the top of the wall. This coping line can be concealed from view in rainscreen roof panel construction. The external wall beneath is typically sealed up to the underside of the roof deck.

The parapet gutter can be covered with a perforated or slotted metal cover in the same material and finish as the adjacent rainscreen panels (p). Since rainwater runs off each panel at its edges onto the membrane below, there is no need to leave the gutter uncovered, as is the case with other metal roof systems. Water running down the membrane is drained directly into the gutter, and water underneath the gutter cover drains through slots or perforations.

An advantage of rainscreen panels is their ability to form complex geometries from flat panel components (j). Since the panels are not required to be waterproofed, they do not require any joints between panels that would become difficult and expensive for roofs with complex geometries. Flat panels can be fixed down at their corners on a curved roof to create a set of gently curved panels that are turned in either one or two directions (k). Panels are increasingly being twisted in two directions in order to create genuinely curved roof finishes. Alternatively, panels can be set flat but with each panel at different angles to create a facetted roof section (m).

Details

1 Extruded aluminium louvre blade
2 Mild steel box section
3 Mild steel tube
4 Structural pin connection
5 Mild steel I-section
6 Bolt fixed metal panel
7 Aluminium sheet
8 Mild steel or aluminium support frame



a | 3D views showing louvred metal canopy and support

b | (Left) 3D view showing underside of louvred metal canopy and support

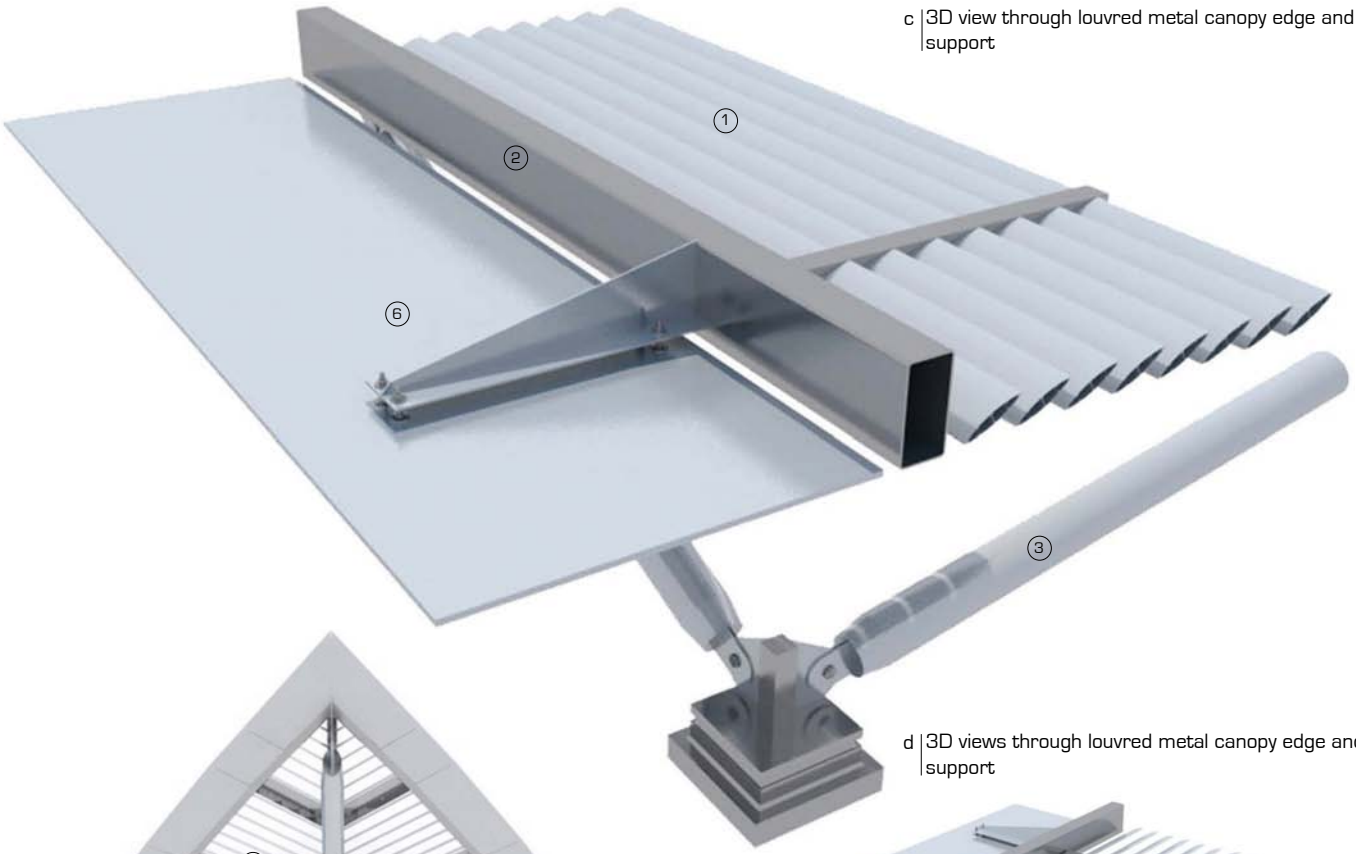
System design

Arrangements of metal louvres are used as canopies to provide solar shading while still allowing daylight to pass through the canopy (a). Louvre blades are set typically at 45° to the vertical in order to block the passage of direct sunlight, but allow the light to be reflected off its surfaces down to the space beneath the canopy. Louvre sections are created from folded strips of aluminium or mild steel sheet, but these have limited stiffness and stability, requiring restraint along their length to hold their straightness in length. Greater stiffness is provided by extruded aluminium sections, where the elliptical section is most commonly used (d), mainly for its ability to reflect daylight in a way that reveals its three-dimensional form, enhancing its appearance. Sections are either a half ellipse or a full ellipse. Flat louvre arrangements provide much less visual vibrancy when viewed from below. Extruded aluminium sections require end caps, usually for visual reasons, and these are either fixed with countersunk screws into the wall of the section, or are welded and ground smooth. Where end caps are screwed to the ends, the aluminium profile has screw ports that form part of the extrusion into which the screws are fixed. Aluminium extrusions can be made in lengths of up to around 6000mm, and are supported at centres to suit their structural depth. An elliptical section will span typically 1500mm for a 75mm to 100mm deep section, while a 250mm deep section will span 2500mm depending upon design wind speed and relative loads. When fixed at their ends, a fixed louvre assembly can be made without visible fixings (b).

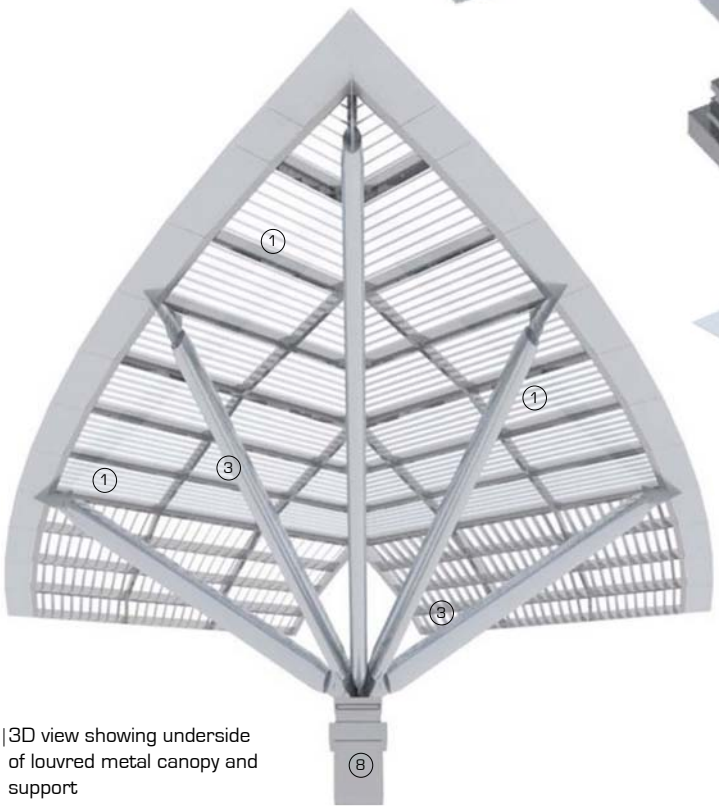
System details

The supporting structure to the example shown comprises a mild steel frame fabricated from box sections, supported by tube sections that spring from points below the roof (e). The box sections are shown bolted together to form a flat frame structure, into which are set louvre panels, prefabricated and finished in a factory, then fixed to the supporting mild steel frame on site. The steel tubes are fixed to the flat frame with pin connections. Two flat plates are welded to the ends of the tubes, and a single plate forming a cleat is fixed to the underside of the flat frame and the base support below the roof. The fork ends of the tubular supports and the support cleats to which it connects are fixed together with face-mounted or countersunk bolts to form a visually crisp connection. The tubes have tapered ends shown, which is typical of this type of steel construction (f). The aluminium louvre panels are fixed to the supporting flat frame with brackets that are welded to the sides of the bottom flange of the steel I-section. The aluminium louvre panel is supported on these brackets, with a nylon spacer between them to allow for thermal movement. The louvre panel is fixed to the cleat bracket with a countersunk bolt.

The supporting structure to the moving louvre assembly shown is made from either mild steel or aluminium sections. Aluminium sections are usually preferred for their durability but mild steel is often used for its greater rigidity (g). Mild steel is galvanised, painted, or both, while aluminium, with its greater durability, can be natural, anodised or



c | 3D view through louvred metal canopy edge and support



e | 3D view showing underside of louvred metal canopy and support





d | 3D views through louvred metal canopy edge and support



f | 3D view showing underside of louvred metal canopy and support



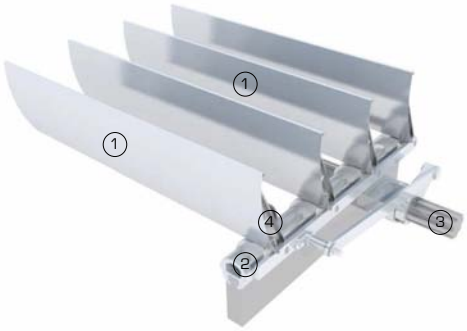
g | 3D views showing electrically operated louvre panel in open position



h | 3D views showing electrically operated louvre panel in open position



j | 3D view showing electrically operated louvre panel in open position





k | 3D view showing electrically operated louvre panel in closed position





m | 3D views showing electrically operated louvre panel in closed position



n | 3D view showing electrically operated louvre panel in open position

Details

1 | Extruded aluminium louvre blade
2 | Standard rackarm
3 | Drive shaft
4 | Slat clip

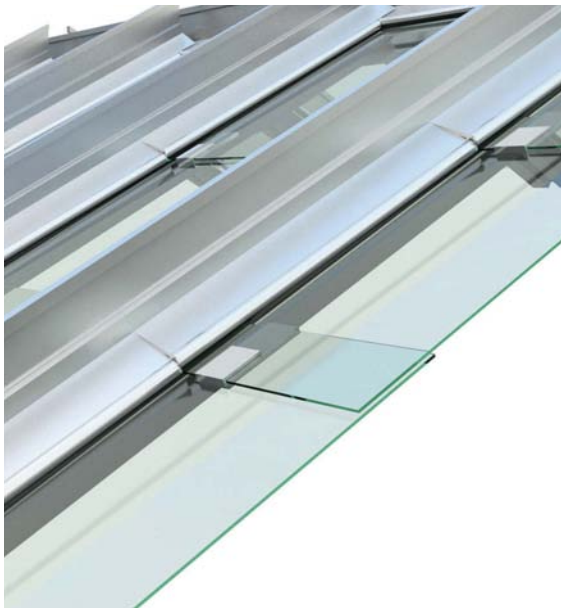


p | 3D view showing electrically operated louvre panel in open position

cromated (similar to anodising) depending on the individual application. Metal panels of large size, made from a 1200mm x 2400mm sheet, can result in a gentle oil-canning effect around their edges. This gives panels their characteristic soft edge, but they look smooth and consistent, and this is usually accepted visually as part of their appearance. If much thicker sheet is used, there is a disadvantage of increased cost as well as a greater difficulty in working the sheet to form smooth shaped pressed panels. Aluminium panels are typically either PVDF coated or polyester powder coated, while steel sheet is usually polyester powder coated only. The use of anodised aluminium as a finish on sheet has increased in recent years as the result of greater reliability of the finish, which until recently has suffered from uneven colour consistency. The silicone used to seal the joints can be applied in a variety of monotone tints, ranging from white, to greys, to black. Some silver-grey colours match well with silver coloured panels to give an overall appearance of a single colour for the complete canopy, particularly when recessed joints are used between panels. Flush joints in silicone tend to give the canopy surface an homogenous appearance, giving it more the appearance of concrete than metal. This can detract from the crisply fitted assembly of panels which is characteristic of metal and also one of the main advantages of its use.

Louvres are typically a maximum of around 6000mm long for those 75mm to 100mm deep, requiring support at 1000mm to 1500mm. Sliding arms typically support up to a 6000mm length of louvre blades (m), giving an overall square shape (in plan) to each set of controlled louvres of 6000mm x 6000mm size which are fixed into the supporting I-section frame. A 100mm deep I-section will span typically 1000mm-1500mm between supports, depending on the design of the glazed roof below. The distance between the moveable louvre panels and the glazed roof below is made sufficient to allow for access for cleaning the glass below and the louvre assembly itself.

Electrically operated louvre canopies are also used for horizontal and inclined glazed roofs, excluding up to 90% of solar heat gain when set at a 45° angle. Louvre blades are 75mm-100mm in typical proprietary systems but blades up to 300mm wide can be made as a single extrusion (n). Nylon sleeves and washers are used at the connection of moving parts, rather than metal, to avoid the need for regular lubrication. Louvres can be solid or perforated to different percentages of solid to void, from around 10% void to a maximum of 50%, though the latter is difficult to fabricate. Louvres are fixed by steel pins into a sliding aluminium section at each end of the profile. The louvres are also fixed at their centre in section. As the sliding aluminium rod moves, the aluminium louvres move together, opening and closing together (p). The sliding rods are connected at each end of the louvres and are fixed to a supporting frame of aluminium I-sections. The single tube is powered by an electric motor, and as it turns, the sliding arms move through the arrangement of gears.



a | 3D detail view showing glazing support

Details

1 | Extruded aluminium glazing bar
2 | Single-glazed sheet
3 | Rubber seal
4 | Aluminium glazing clip
5 | Extruded aluminium section
6 | Aluminium clip on capping
7 | Aluminium footing
8 | Concrete base
9 | Polycarbonate sheet
10 | Double-glazed unit



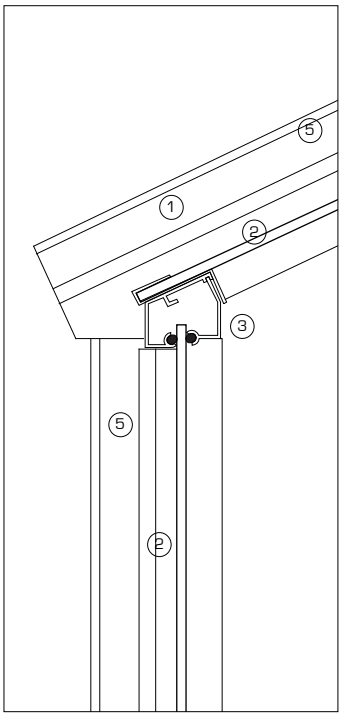
b | 3D view of typical eaves connection

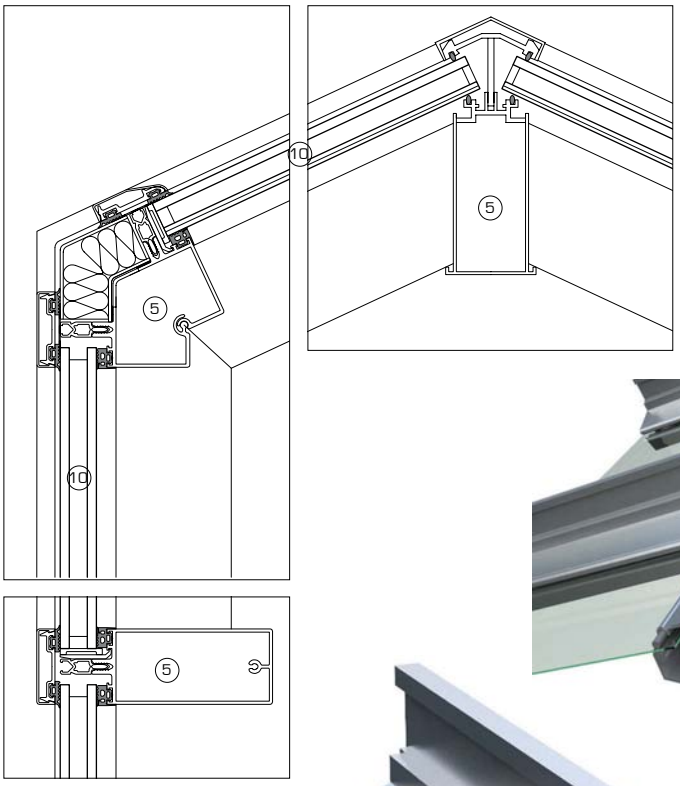
Systems design

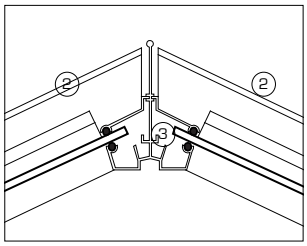
Curtain walling principles used in external walls have been adopted, over the last 20 years, as a reliable method of constructing glazed roofs to replace earlier systems developed from greenhouse glazing. This glazing system is still used in greenhouses for agricultural activities but has poor thermal insulation, since its purpose is to absorb the heat from the sun rather than excluding it. The use of single glazing, with no thermal breaks and high air infiltration rates (by curtain walling standards) (a), makes it ideal for agricultural use, but very poor for use in general building construction. However, the concept of greenhouse glazing has been developed into the highly insulated, air sealed and watertight glass roof systems used in contemporary buildings.

An essential component of greenhouse glazing that has been retained in modern glazed roofs is the glazing bar, which corresponds to a mullion in glazed walls. The greenhouse glazing bar has a condensation channel beneath the glass to drain away water that passes through the outer seal during rain. The condensation channel also serves as a drain for moisture inside the building that has condensed within the framing. Condensation channels are either open at the edges or are enclosed. Modern greenhouse glazing is made from extruded aluminium sections with no thermal break, since high thermal insulation is not required, but includes the condensation channels to avoid water from dripping below (b). The horizontal joint between lapped glass sheets is sealed with either a sealant, typically silicone, or with continuous aluminium clips. Some greenhouse systems still have lapped glass with no seal between the glass sheets, making them very economic but not very airtight, which suits certain agricultural applications.

Ventilation in greenhouse glazing is provided at the eaves and at the ridge (d), while opening lights are used for more closely controlled ventilation. Single-glazed sheets are held in place on their sides by being supporting on the glazing bars and secured in place with continuous aluminium clips that snap onto the glazing bar (f). The aluminium sections are separated from the glass by extruded rubber-based seals which are held in place on the aluminium glazing bars and which press against the glass to provide both a cushion for the glass as well as a water and air seal (h). The strength and stiffness of the glazing bar is provided by the central flat bar that extends beyond the glazing line either inside or outside the glazing. Unlike curtain walling based systems, where the structural mullion extends on the inside face of the glass with a pressure plate on the outside, greenhouse glazing only has clips on either side of the control bar, allowing it greater freedom to extend both inside and outside the face of the glass. The rubber seals are deep enough and soft enough to allow the bottom of the glass sheet to lap over the top of the sheet below on the horizontal joints.



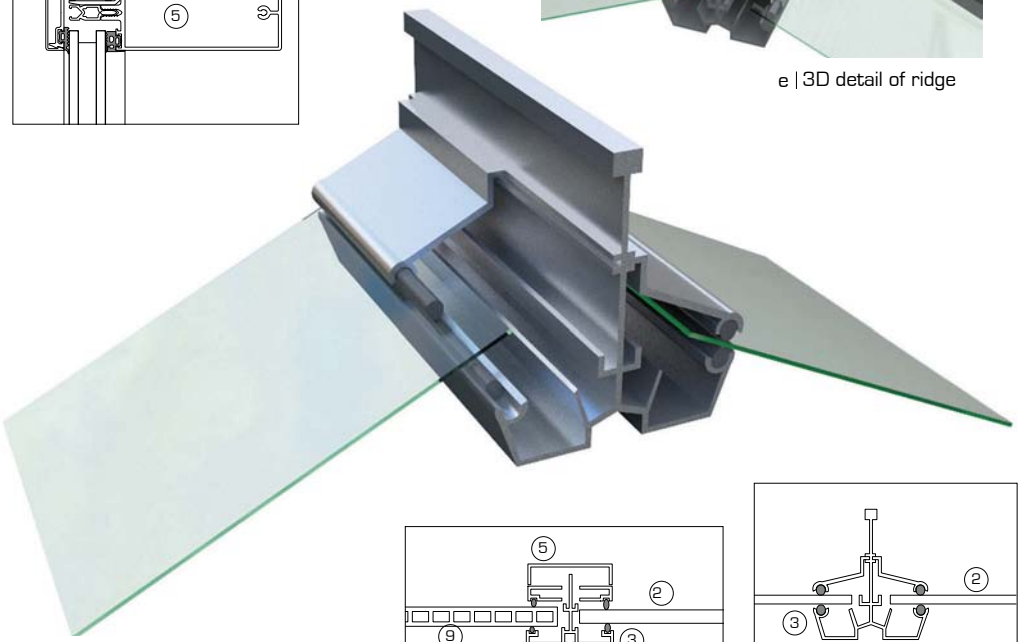




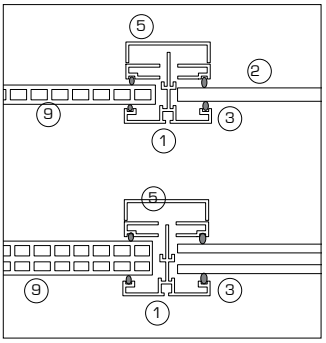
d | Vertical section 1:5. Ridge in greenhouse glazing



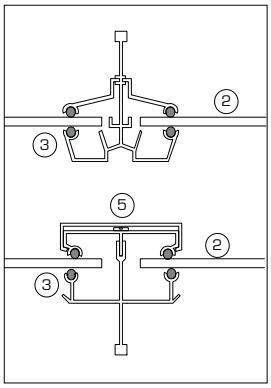
e | 3D detail of ridge



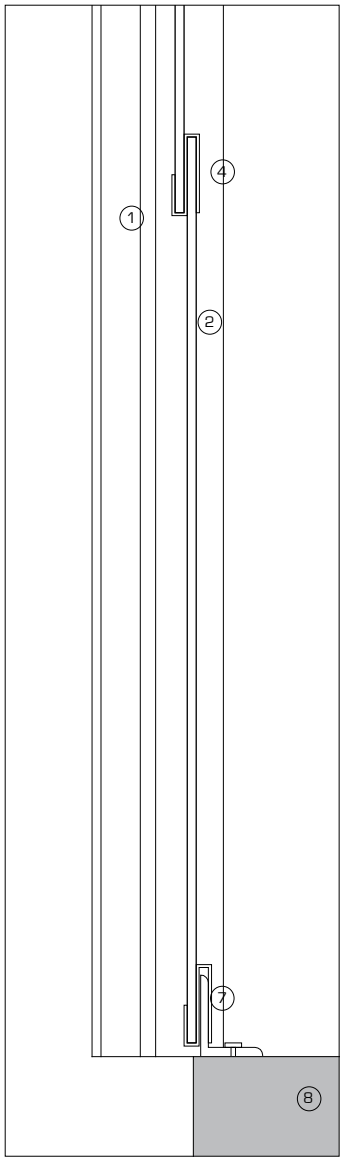
f | 3D view of ridge in greenhouse roof



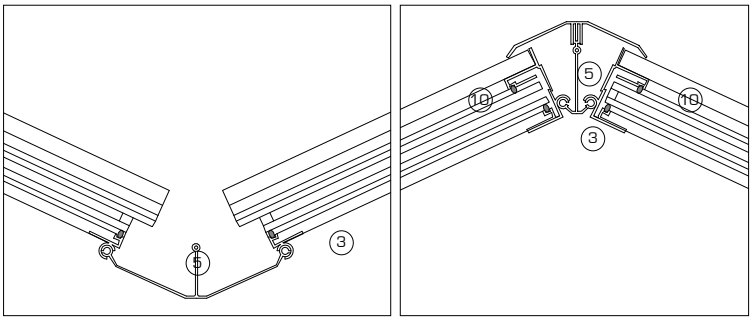
g | Vertical section 1:5. Clamping details for glass to glass connection



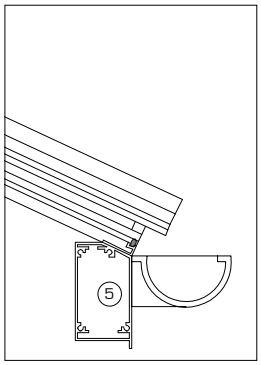
h | Vertical section 1:5. Clamping details for glass to polycarbonate connection

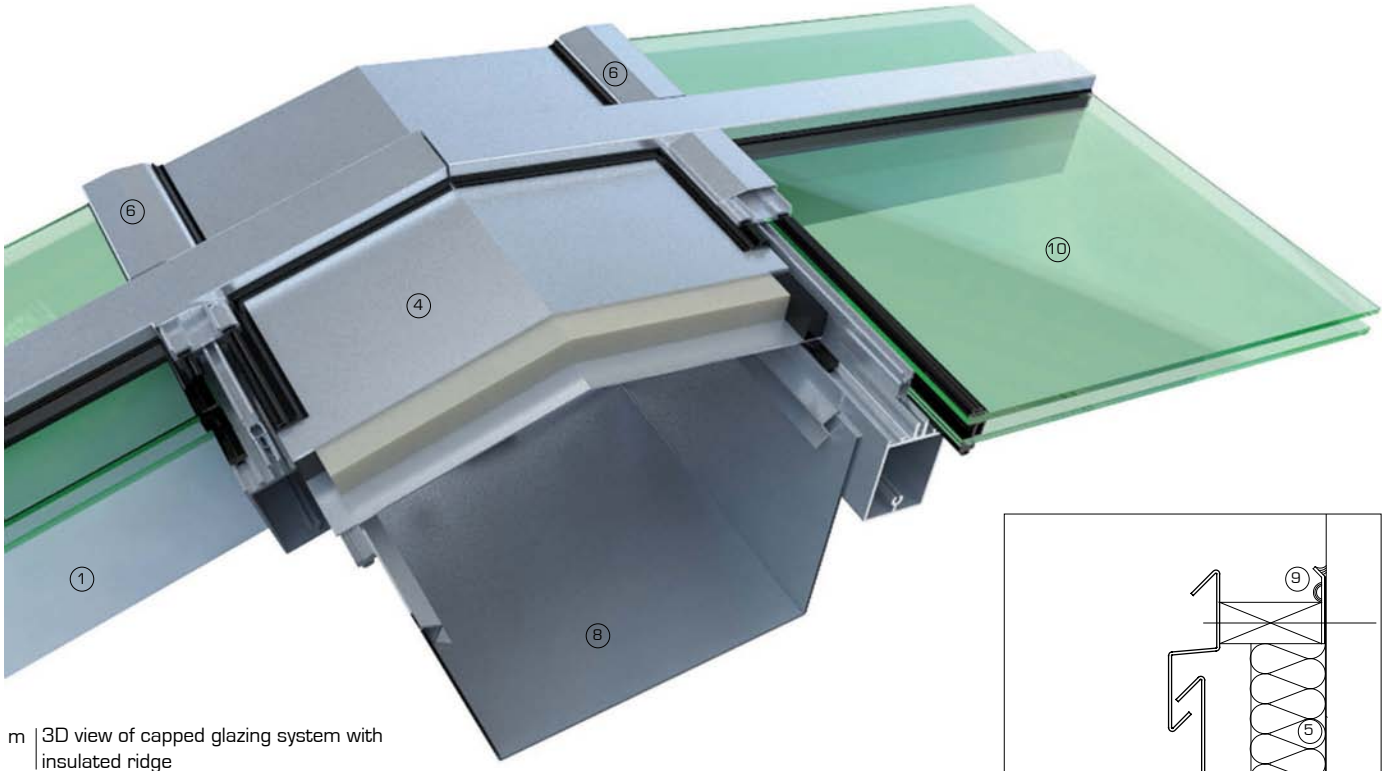


j | Vertical sections 1:5. Greenhouse glazing system showing typical details

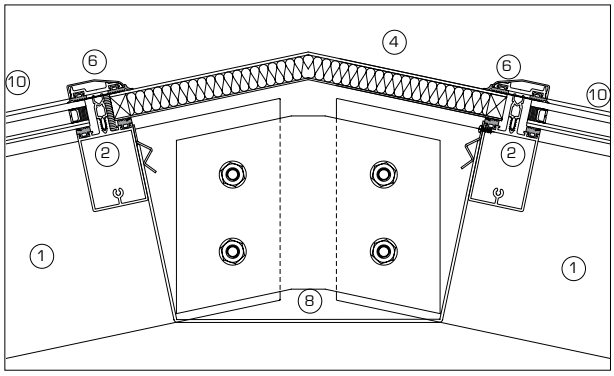


k | Vertical section 1:5. Typical ridge and valley details

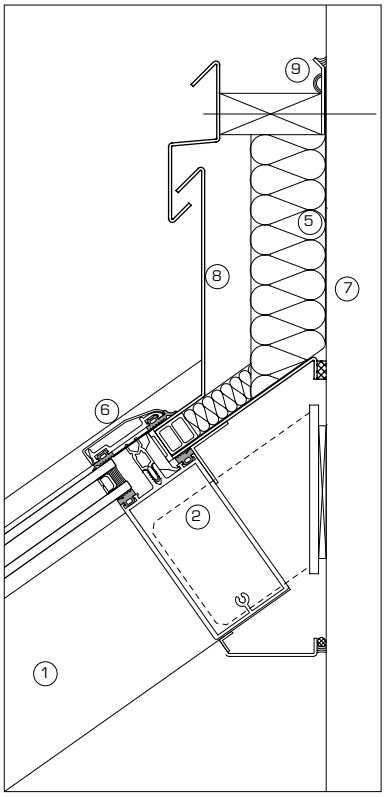


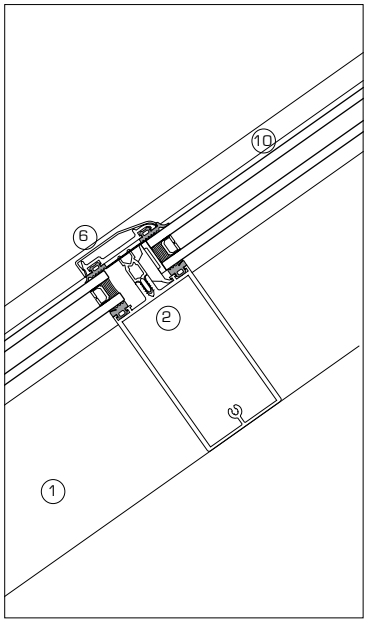


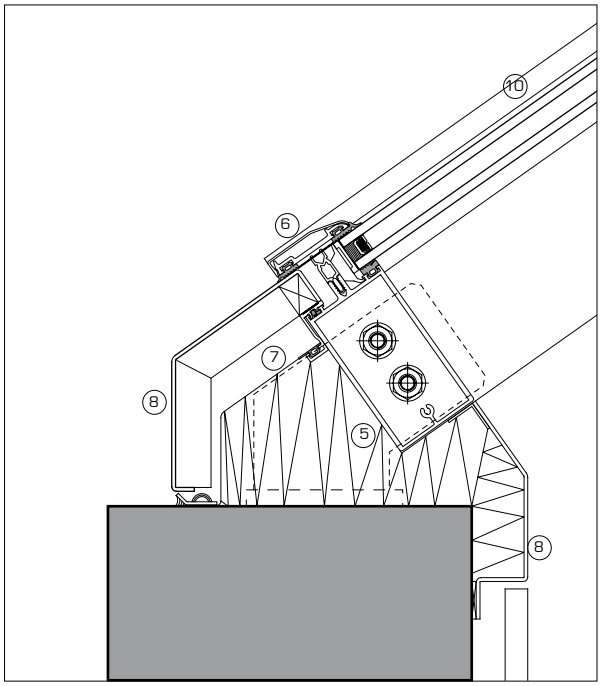
m | 3D view of capped glazing system with insulated ridge



n | Vertical section 1:10. Ridge detail



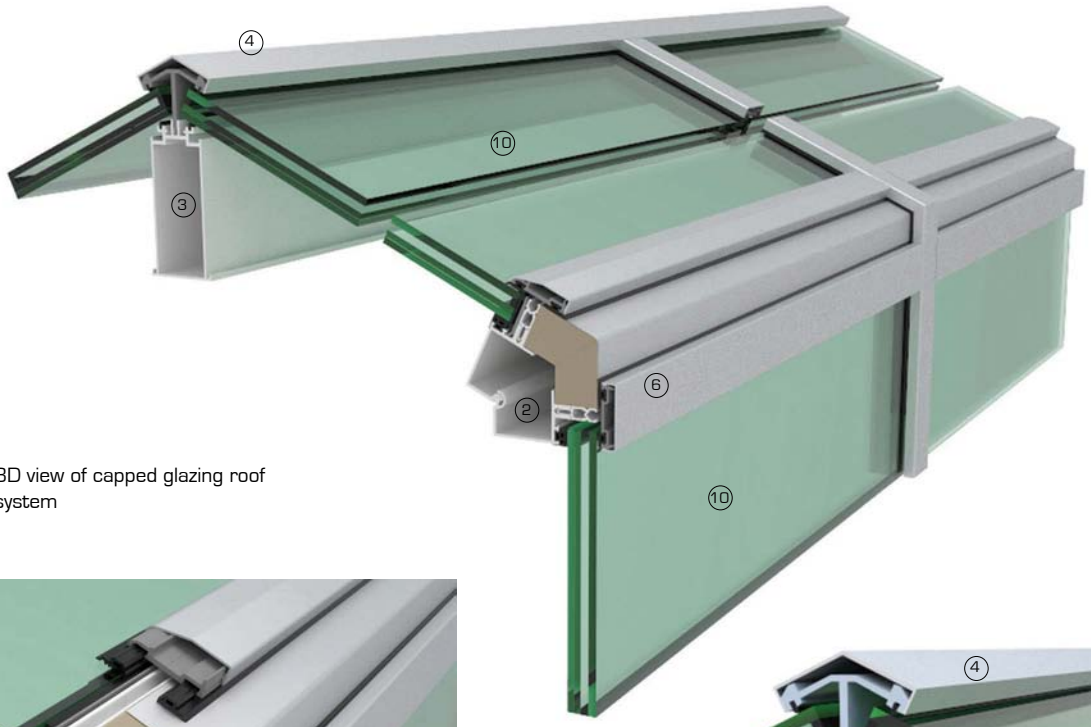




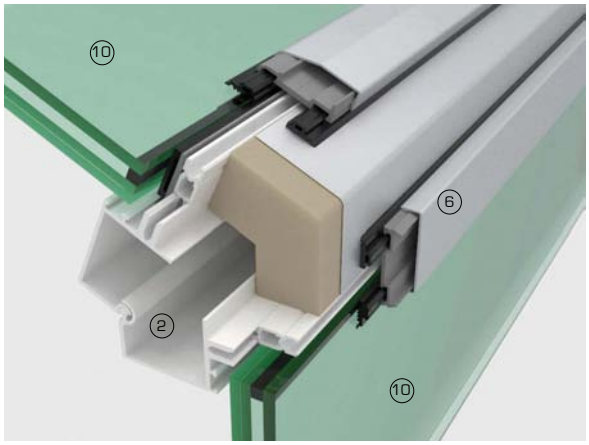
p | Vertical section 1:10. Capped glass roof with abutments

Details

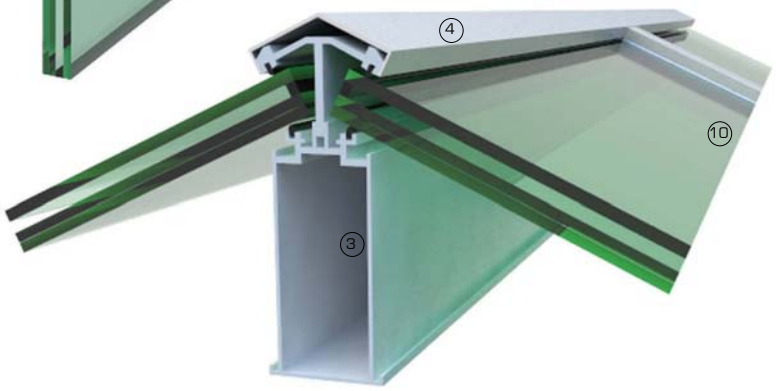
1	Extruded aluminium glazing bar
2	Extruded aluminium transom
3	Ridge bar
4	Ridge capping
5	Thermal insulation
6	Pressure plate and capping
7	Rubber seal
8	Aluminium flashing
9	Aluminium clip on capping
10	Double-glazed unit



q | 3D view of capped glazing roof system



r | 3D cutaway of glass to glass corner detail in capped glazing



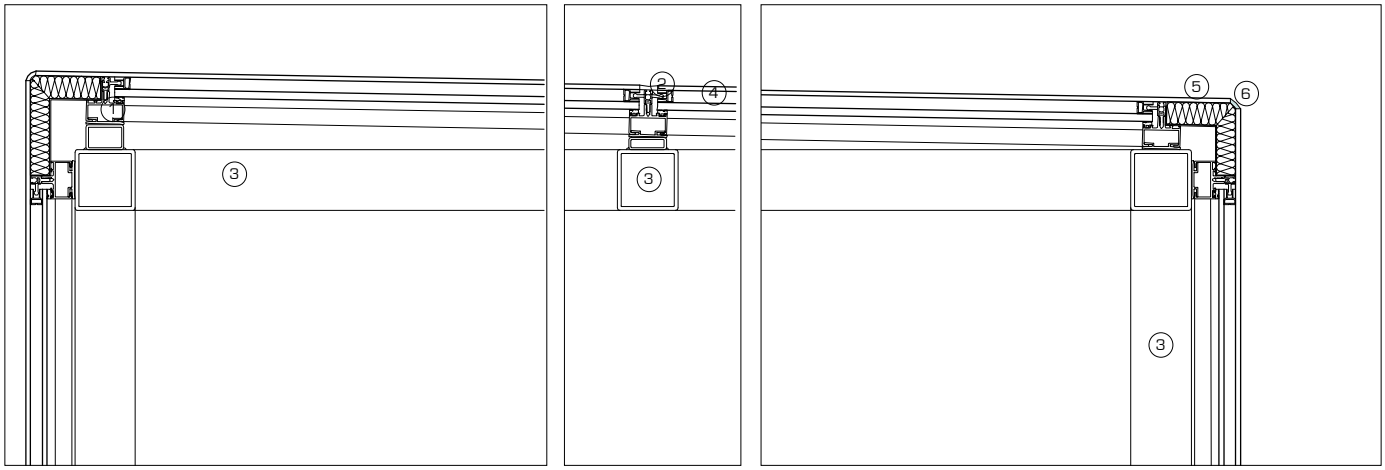
s | 3D detail of capped ridge

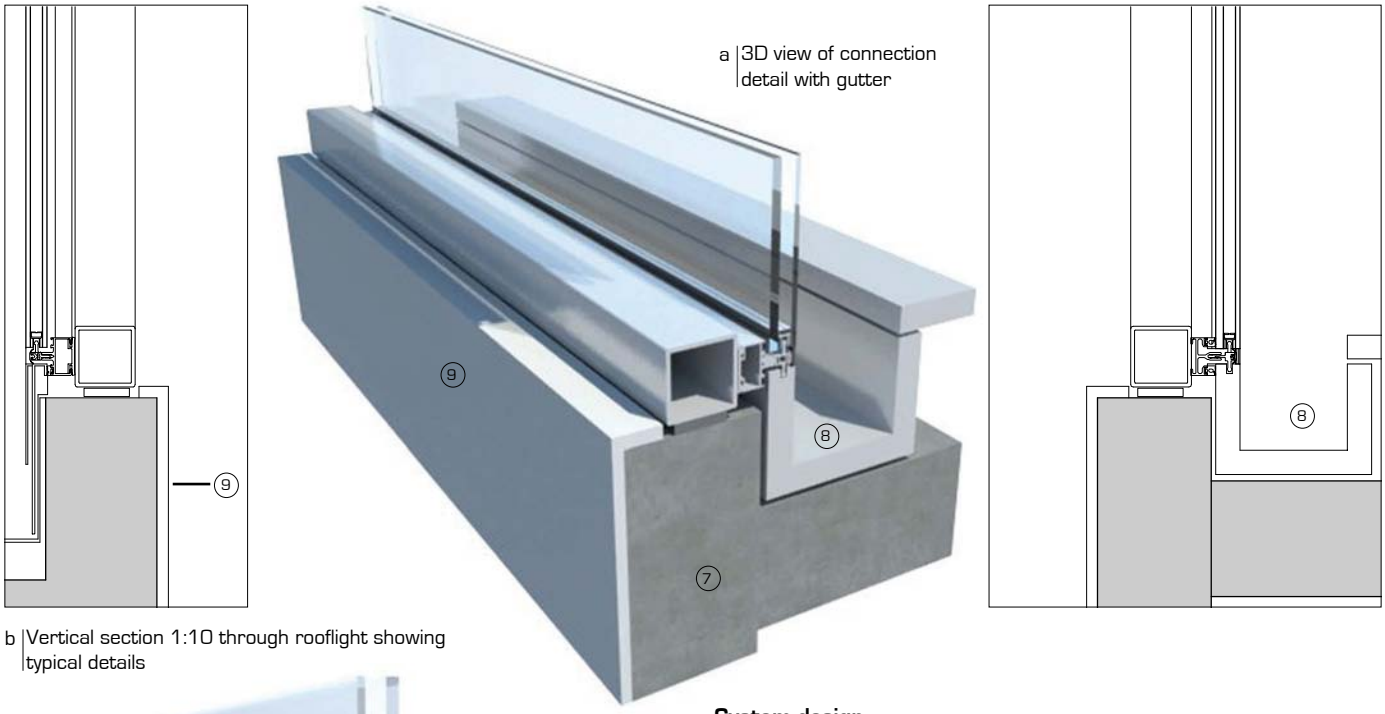
System details

Systems for contemporary glass roofs use the principles of traditional greenhouse glazing, but incorporate the techniques of glazed curtain walling. Drained and ventilated systems are used with thermal breaks and double-glazed units (m). Pressure plates rather than clips are used to hold large glass units in place in capped systems, and toggle-type plates are used to provide flush joints in silicone based systems (n). This latter type is discussed in the next section on silicone sealed rooflights, while this section focuses on pressure plate systems, so-called 'capped' glazing. A typical system comprises glazing bars which are assembled on site in a grid of members that resemble the mullions and transoms of stick glazed curtain walling (p). The base of the curtain wall, at the bottom of the extruded profile, may have an additional condensation channel as shown. This provision can also be made by setting the condensation channels immediately beneath the glass. The glass is set onto rubber-based air seals fixed to the glazing bar and is secured with a continuous pressure plate of extruded aluminium. A strip of extruded EPDM is set between the pressure plate and the glass to provide a weathertight seal. As with glazed curtain walling, the glazing bars are drained and ventilated, or pressure equalised, internally (r). Water that is able to find its way through the outer seal drips into an internal channel where it is drained away safely to the bottom of the roof, typically at the eaves. In smaller roofs without eaves, where the roof angle changes from pitched to vertical wall, rainwater is allowed to run on down the wall to the base of the roof. At the 'fold' point of the roof the internal drain in the glazing bar is continuous with the vertical wall and the system is drained at the base of the wall, which could be a reinforced concrete slab at roof level.

While glazing bars running down the roof project above the surface of the glass, those running along the roof which hold the top and bottom edges of the glass in place require a method of allowing the water to run over the junction. Some systems use a step at this point, without a pressure plate on top that would otherwise impede the passage of water down the roof. Other systems use a pressure plate and cover capping with chamfered edges that allow rainwater to pass over it easily. A small amount of water is left trapped on the top edge of this horizontally-set glazing bar, but this is soon blown away by the wind or else evaporates. Any water that penetrates the outer seal is drained away through the internal drain in the glazing bar.

Ridges, like glazing bars, follow the main principles of greenhouse glazing. The box section, or chosen profile of the typical glazing bar, is usually made deeper to take the higher structural loads of the ridge (s). Gutters, at both valleys and eaves, are very different to greenhouse glazing. Instead of lapping the glass into the gutter, the gutter profile (or downstand flashing) is clamped into one side of the horizontally-set glazing bar at the base of the pitched roof.





a | 3D view of connection detail with gutter

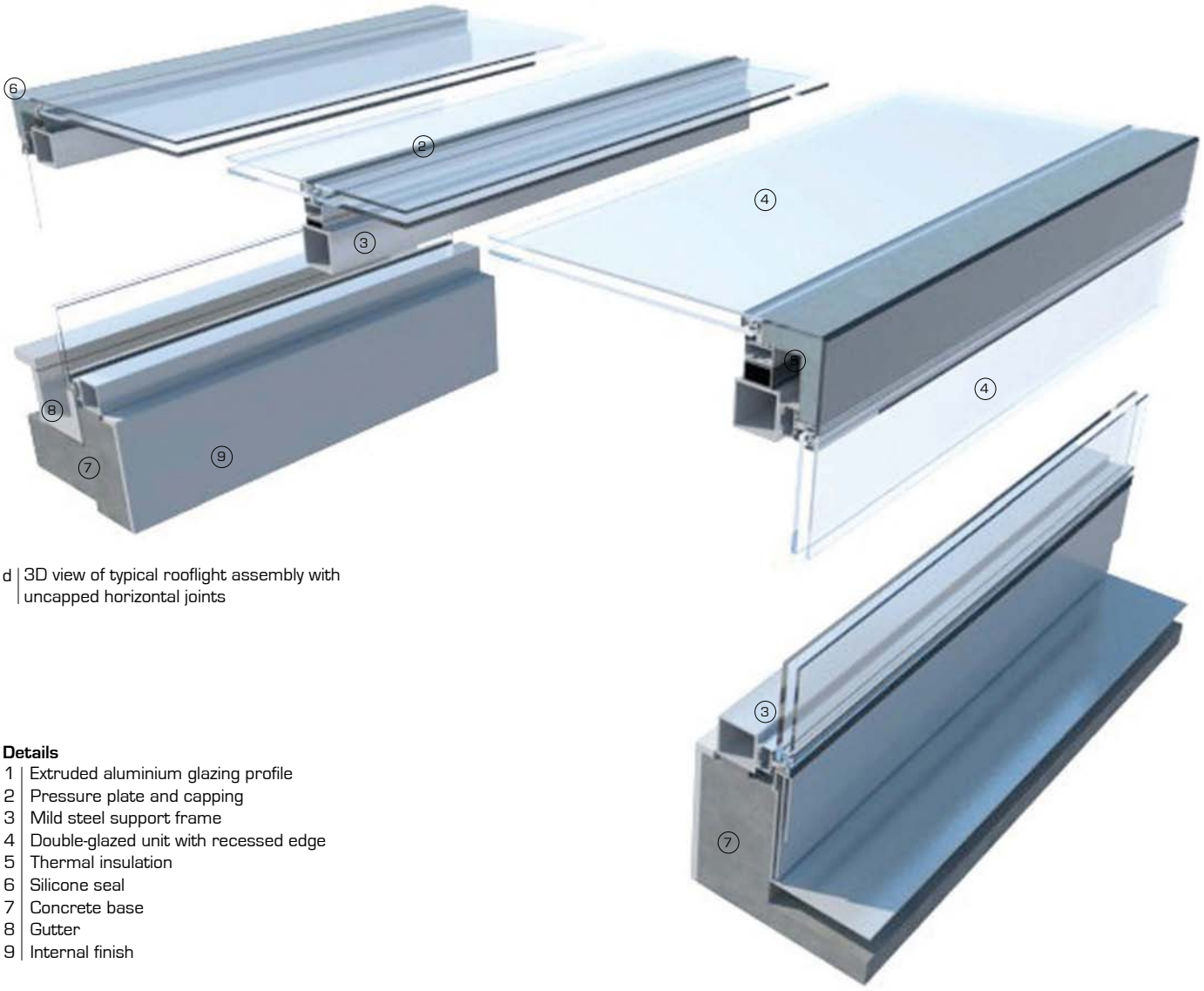
b | Vertical section 1:10 through rooflight showing typical details



c | 3D view of connection to concrete base

System design

While capped systems, described in the previous section, suit pitched roofs, they cannot reliably be used on nominally flat roofs where the roof pitch is usually 3° to 5°. This is mainly because the rainwater running down the roof cannot pass the horizontal glazing bars which project above the surface of the glass. The smooth, continuous finish required for flat glazed roofs is achieved with a silicone seal between glass panels that is set flush with the surface of the glass (b). The glass is clamped in place with short lengths of pressure plate that are recessed below the outer seal. The recessed plates are secured to an aluminium channel which forms an integral part of the double-glazed unit and which is continuous around its perimeter. The extruded aluminium channel is recessed into the gap at the edge of the unit usually used to bond the unit together and to seal the edges behind the spacer (d). The adjacent spacer in the double-glazed unit both keeps the glass at a fixed distance apart as well as having desiccant within it to absorb any residual moisture within the sealed cavity between the glass sheets. The recessed aluminium channel is bonded to each glass sheet and also provides the edge seal to the completed unit, as in a regular double-glazed unit. The short lengths of pressure plate are then set into the gap formed by the recessed channels of abutting glazed units, and are clamped to the glazing bar with self tapping screws, typically



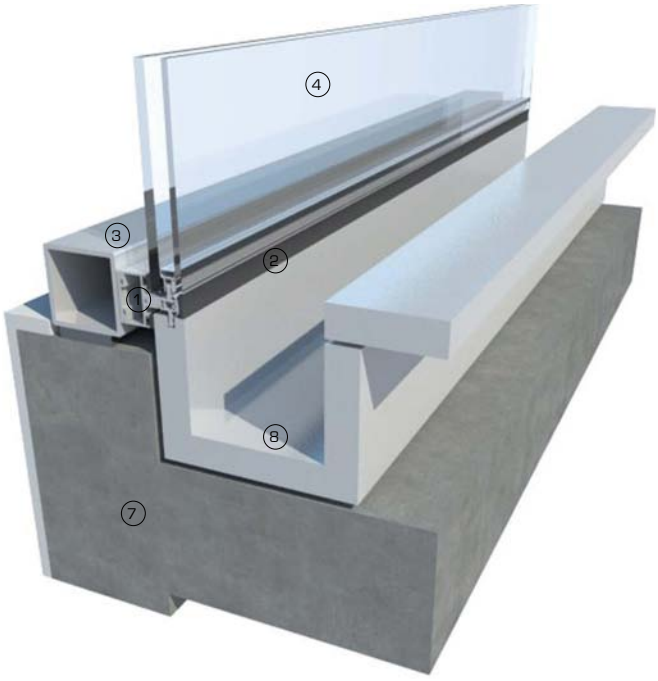
d | 3D view of typical rooflight assembly with uncapped horizontal joints

Details

1 | Extruded aluminium glazing profile
2 | Pressure plate and capping
3 | Mild steel support frame
4 | Double-glazed unit with recessed edge
5 | Thermal insulation
6 | Silicone seal
7 | Concrete base
8 | Gutter
9 | Internal finish

at 300mm centres. The gap between the glazed unit is sealed with silicone, typically 15mm to 20mm wide, and with a backing strip or 'backing rod' behind it to form a back edge to the silicone seal.

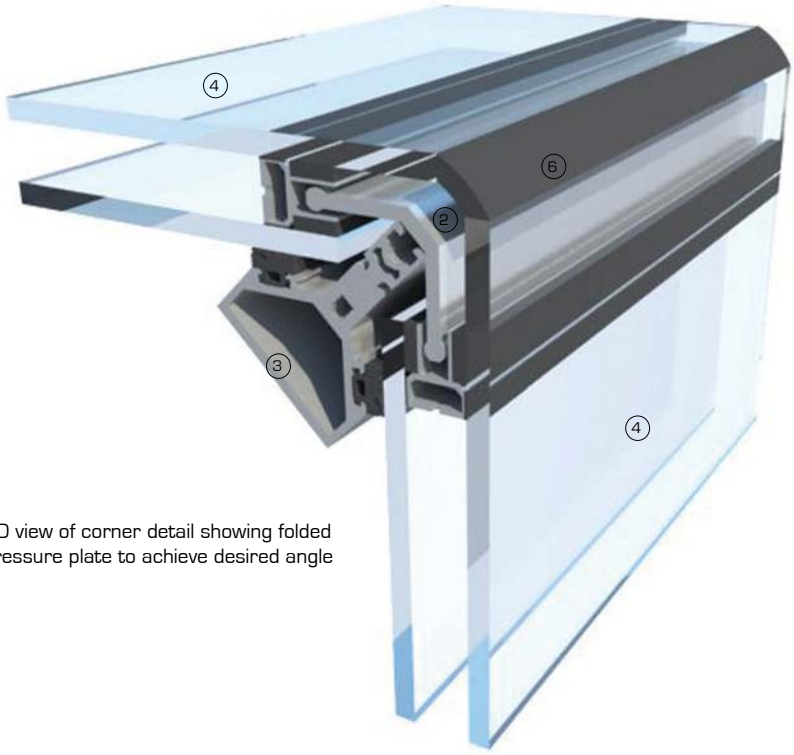
The glazing bar has its structural box or fin removed in order to fix it directly to a steel support frame. Alternatively, an all-aluminium glazing bar can be used. As with capped systems, small amounts of rainwater that pass through the outer silicone seal are drained away in the condensation channels set below the glass, within the glazing bar. In practice, silicone seals are very reliable but are dependent upon correct workmanship on site, so the condensation channel is often not used in practice but serves as a secondary chamber to support the inner air seals. Silicone-sealed glazing bars can be used in all directions across a roof, unlike capped systems, since the glazing bars present no barrier to the passage of water.



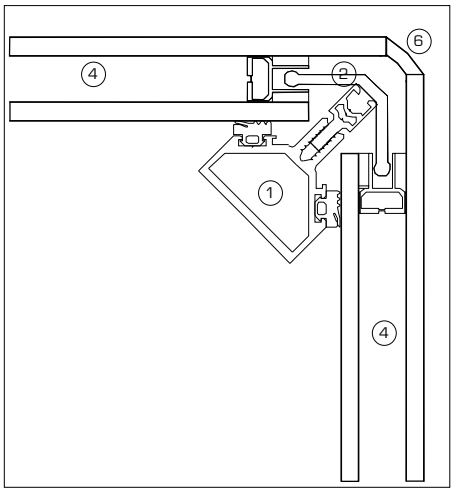
e | 3D view of gutter detail

System details

Since the advantage of silicone-sealed systems is of continuous glazed surfaces uninterrupted by visible glazing bars, ridges and valleys are treated only as folds in the surface of the glazing, for rainwater runs across the complete sealed surface of the glass rather than being



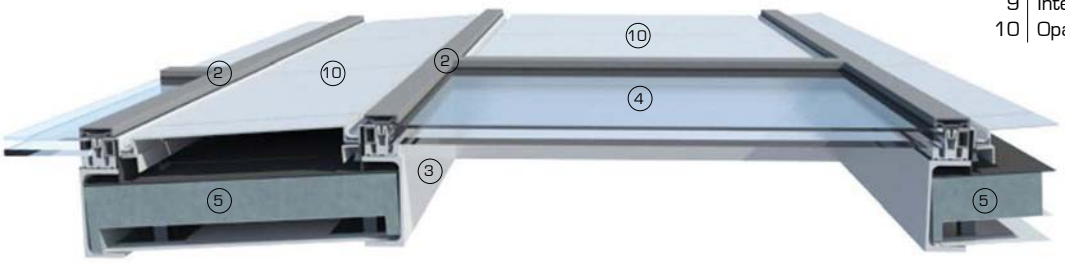
f | 3D view of corner detail showing folded pressure plate to achieve desired angle



g | Vertical section 1:5. Corner detail

Details

1	Extruded aluminium glazing profile
2	Pressure plate and capping
3	Mild steel support frame
4	Double-glazed unit with recessed edge
5	Thermal insulation
6	Silicone seal
7	Concrete base
8	Gutter
9	Internal finish
10	Opaque roof cladding panel



h | 3D view showing silicone-sealed rooflight set within opaque-panelled roof configuration

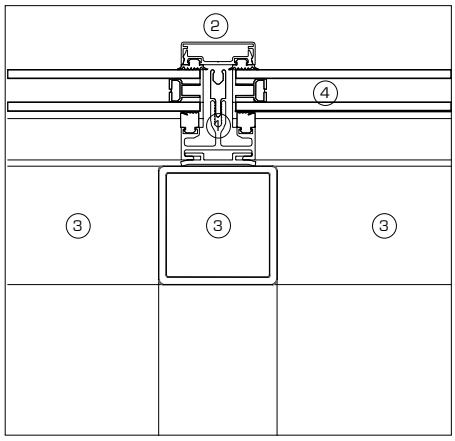
directed into gutters set across its surface. The short lengths of pressure plate can be folded in the factory to the required angle, while the glazing bar forming the ridge is the same as that used elsewhere on the roof, with some modifications to the angle of the clips that hold the inner EPDM seal in place. The edges of roofs are also treated as folds, with rainwater usually allowed to run off the edge into a gutter; either just below the roof, or down to the base of the glazed wall below the glazed roof (e). An advantage of this system is the ability of the roof to be continuous with a glazed wall in the same system with a simple 'fold', without reducing its weather tightness. Typically the wall is not very high, forming part of a larger glazed roof. Dust that is carried down off the roof during rain is washed down the vertical glazing, rather than being carried away in a gutter, but in practice glazed rooflights require regular cleaning to maintain their crisp appearance.

Folded corners are formed with either a single specially formed glazing bar (f), or with two glazing bars meeting (n). The recessed lengths of pressure plate are folded to form the required angle, and the silicone is chamfered to form a flat surface between the two meeting glass panels. Silicone is rarely used to make a sharp angle between the two double-glazed units, as it is very difficult to achieve a straight line without the assistance of an additional metal angle bedded into the silicone. The alternative method of forming a roof edge requires the edge of the double-glazed unit to be coated or 'opacified' to avoid the frame behind being visible through the glass. This is often achieved by stepping the glazed unit, with the outer glass extending to meet the corner, while the inner glass stops at the glazing bar to allow the recessed aluminium angle to be bonded in its usual position adjacent to the glazing bar. The glass unit is secured in the same way, with a recessed length of pressure plate, while the outer glass is cantilevered to meet the adjacent glazed unit at the corner (n).

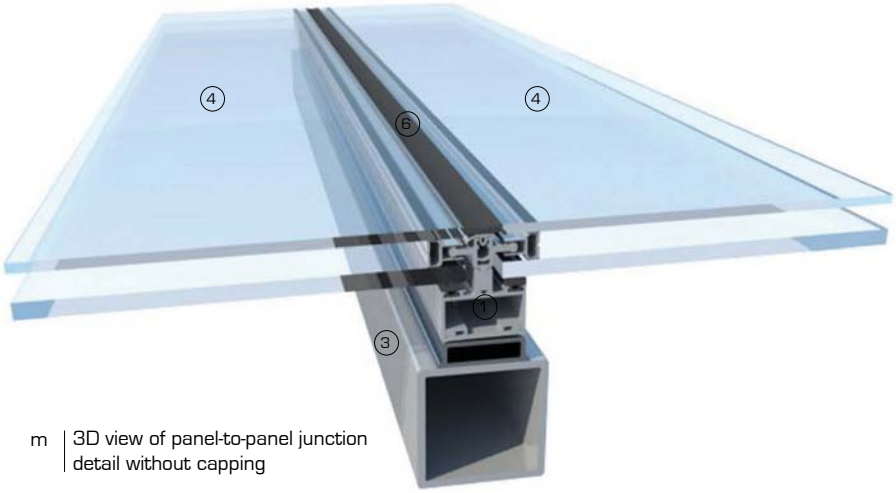
An advantage of silicone sealed glazing is its ability to be mixed with capped glazing (j). Since both systems are drained and ventilated (pressure equalised), the same glazing bar can be used in a mixed roof system of flush silicone joints and capped profiles (p). Although this mix is often done for visual reasons, it does allow for easily formed junctions with adjacent areas of roof in different materials, and for a mix of actual panels and glazed panels in a single roof using a reliable drained and ventilated system. The most common application of this method is where capped profiles are used for the vertically-set glazing bars running down the slope of a roof, while silicone-sealed glazing is used on horizontal joints to allow rainwater to pass down it unimpeded by any projecting glazing bars. Junctions in silicone sealed glazing, such as edges of roofs and ridges, are formed in the same way, while the capped system follows the folds with continuous pressure plates that are mitred and sealed at the folds. Butyl tape is used as an extra seal at folds, set between the pressure plate and the outer EPDM gaskets. Cover caps are also mitred to give a crisp appearance.



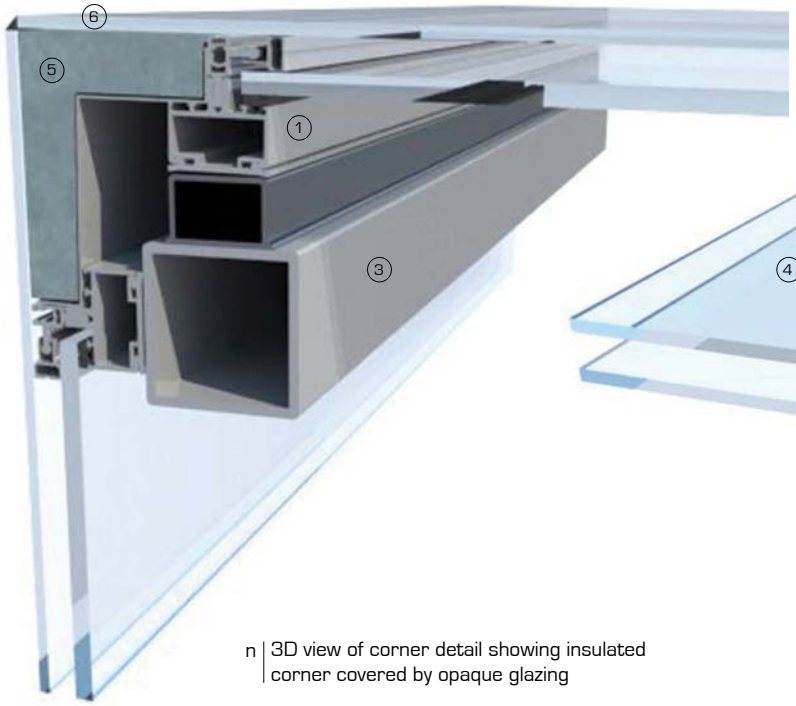
j | 3D view showing capped rooflight set within opaque-panelled roof configuration



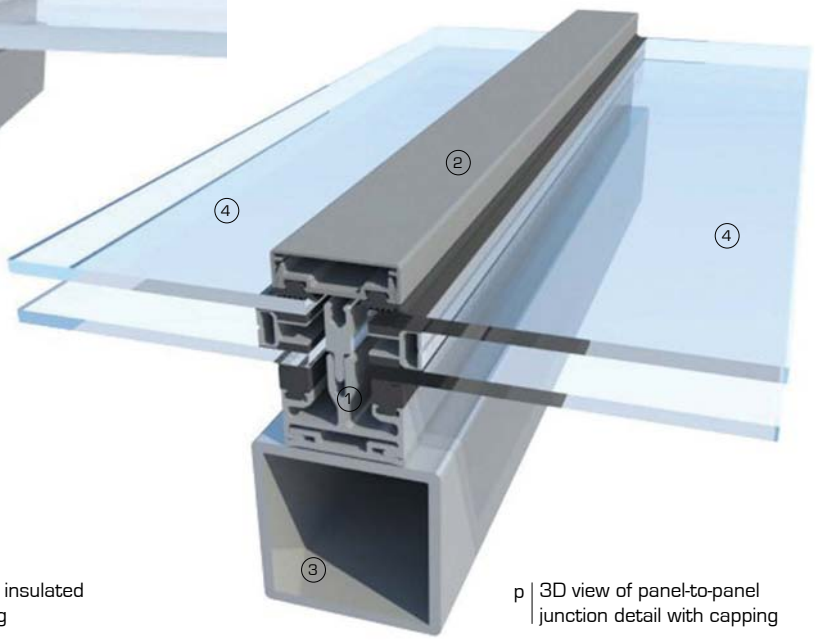
k | Vertical section 1:5. Panel-to-panel junction with capping



m | 3D view of panel-to-panel junction detail without capping



n | 3D view of corner detail showing insulated corner covered by opaque glazing



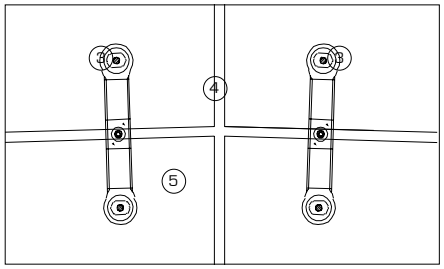
p | 3D view of panel-to-panel junction detail with capping

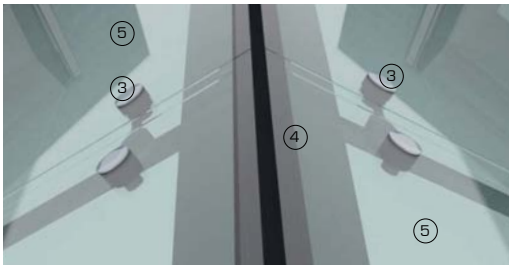


a | 3D view showing bolt fixed glazing with internal fold



b | 3D view showing bolt fixed glazing with external fold





c | (Far Left) Horizontal section 1:25. Typical clamp assembly

d | (Left) 3-D view showing typical clamp assembly

System design

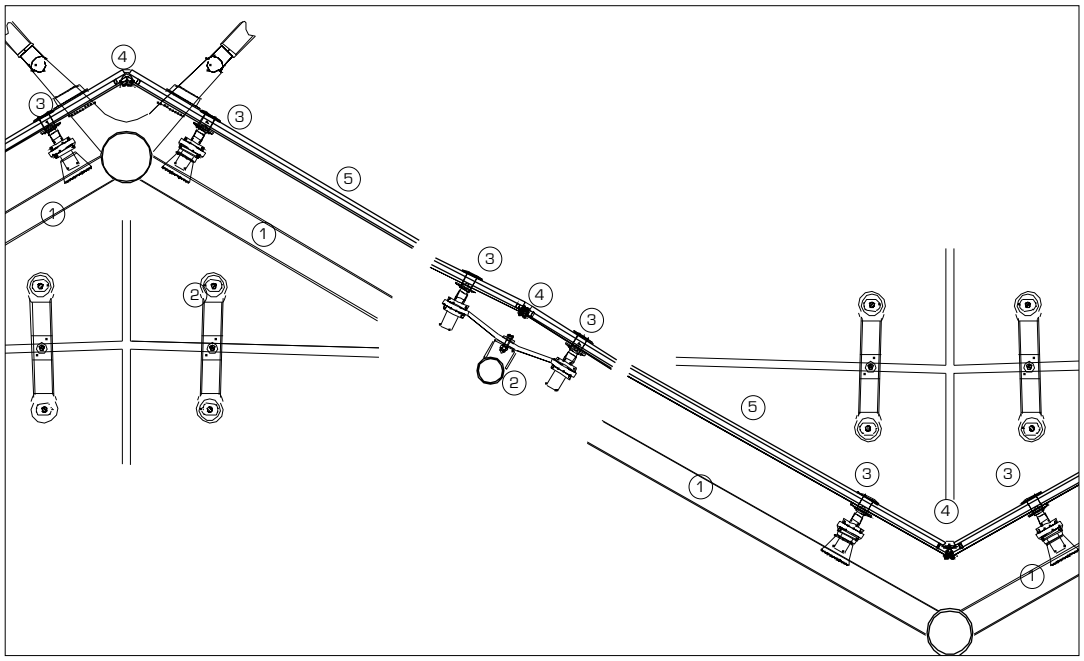
This method of glazing for roofs has been adapted from the technique used for glazed walls, where glass is fixed at points with specially designed bolts rather than with a frame supporting the perimeter of the glass (h). Bolt fixed glazing for facade construction developed from earlier patch plate glazing, where single-glazed sheets of glass are bolted together with mild steel brackets. Glass fins are used to stiffen the glazed walls to replace the aluminium mullions. The L-shaped patch fittings bolt the fins and glass together, as well as bolting the glass to the supporting structure at the top and bottom of the wall.

Where glazed walls are usually structurally supported by either top-hung or bottom-supported methods, the support of glazed roofs is by trusses, steel sections or purlins that span across the roof opening. For nominally flat roofs, the most common arrangement is a supporting beam set under each glass joint, so that bolts are supported on each side of the beam by a short bracket (a). Only half the number of beams are required to support the same three panels of glass. This is achieved by setting the beam in the middle of alternate glass panels. Brackets are cantilevered from the beam to support the edge of the panel above as well as one side of the panel next to it. This method provides greater visual transparency but requires larger brackets, which in practice detract little from the increased effect of transparency.

The single tube section shown in the diagrams (b) would suit only a short span, as in a rooflight, but large span roofs require deeper beams, usually formed as open trusses in order to maintain the sense of transparency at oblique viewing angles. Triangulated trusses provide both structure and support for the glass, but tend to be visually heavy. Cable trusses are often preferred, but they require a ring beam around the edge of the glazed roof to form a tensile supporting structure like a tennis racquet. The cable trusses, always in tension, require an equivalent surrounding structure in compression to transfer the loads to the main building structure.

System details

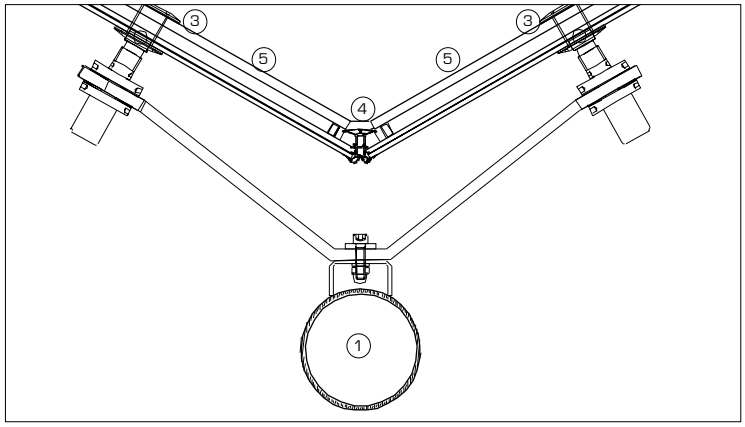
The essential component in this glazing method, the bolt fixing, is made typically in stainless steel and consists of several components that form the complete assembly. The part that passes through the glass has either a disc on each side of the glass to clamp the glass (d) or double -glazed unit together, or alternatively is angled to form a countersunk device within the depth of the double-glazed unit. The countersunk fitting is set flush with the outer face of the glass, and the face-fixed disc type is set forward of the face of the glass. A polished stainless steel finish is mostly used on the outside in order to make it easy to clean and maintain. In the face-fixed type, which is currently the most commonly used fixing, the inner disc screws over the threaded shank that forms part of the outer disc until it is tight up to the inner face of the glass (k).



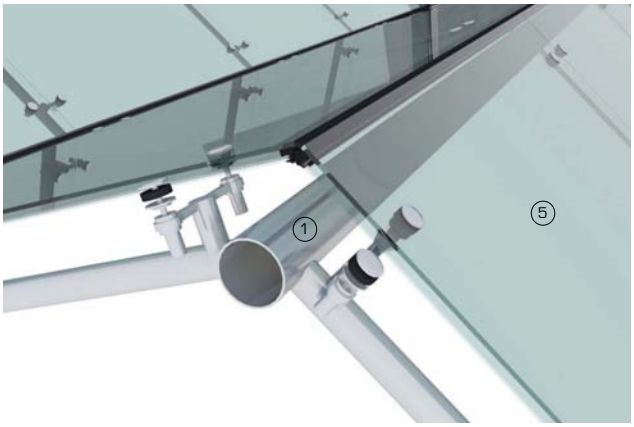
Details

1 | Structural steel support
2 | Connector plate
3 | Bolt fixing
4 | Silicone seal between glass panels
5 | Single-glazed or double-glazed unit
6 | Support bracket
7 | Silicone seal
8 | Adjacent external wall
9 | Insulation
10 | Extruded metal cylindrical section
11 | Roof construction
12 | Concrete base

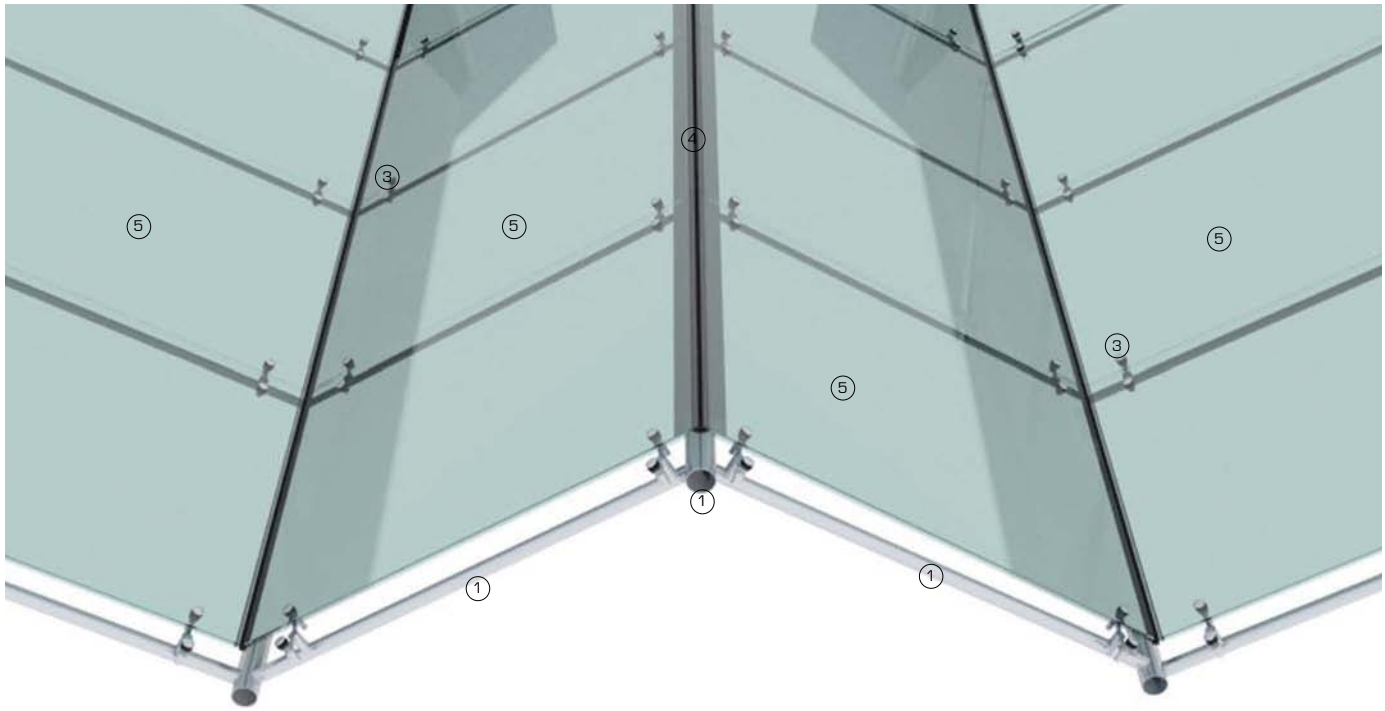
e | Vertical section & elevations 1:25. Bolt fixed roof with folded profile



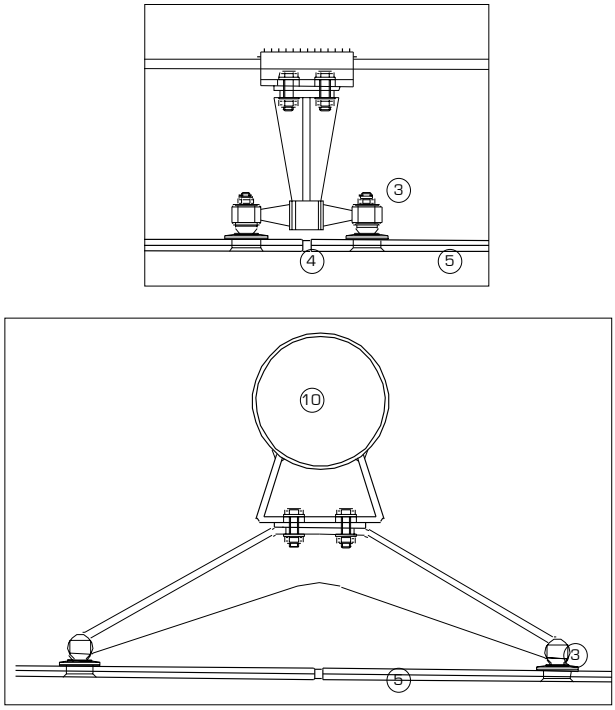
f | Vertical section 1:10. Internal fold



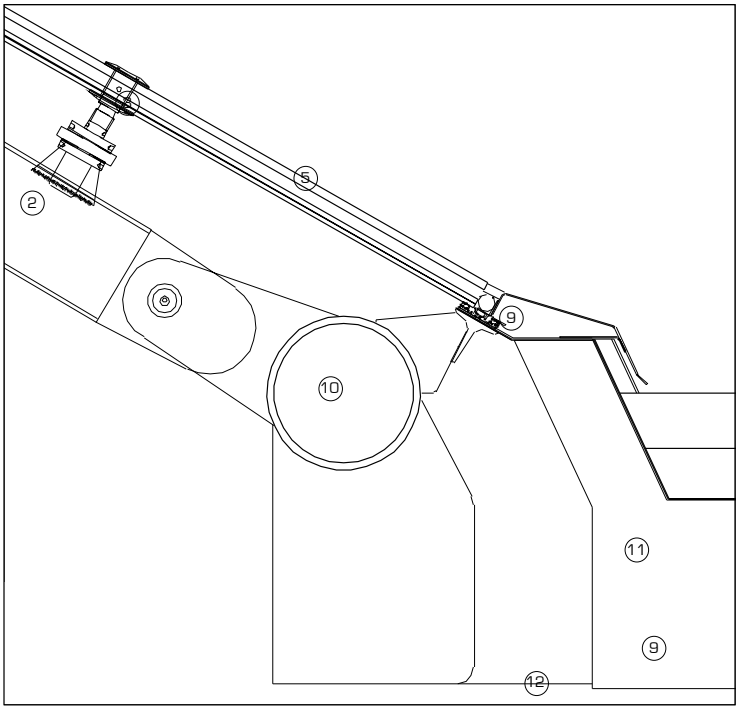
g | 3D view showing external fold



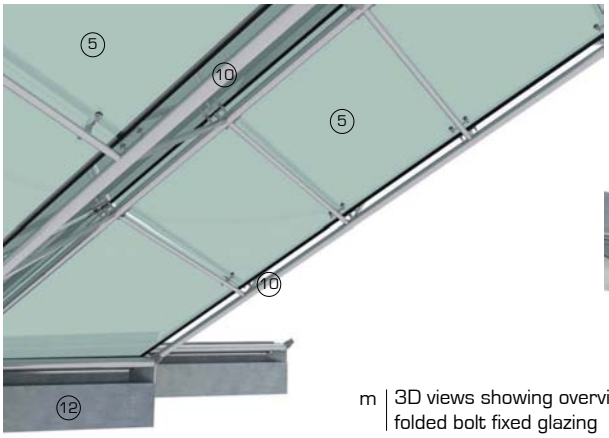
h | 3D view showing bolt fixed roof with folded profile



j | Vertical sections 1:10. Bracket support



k | Vertical section 1:10. Connection to roof deck





m | 3D views showing overview of folded bolt fixed glazing

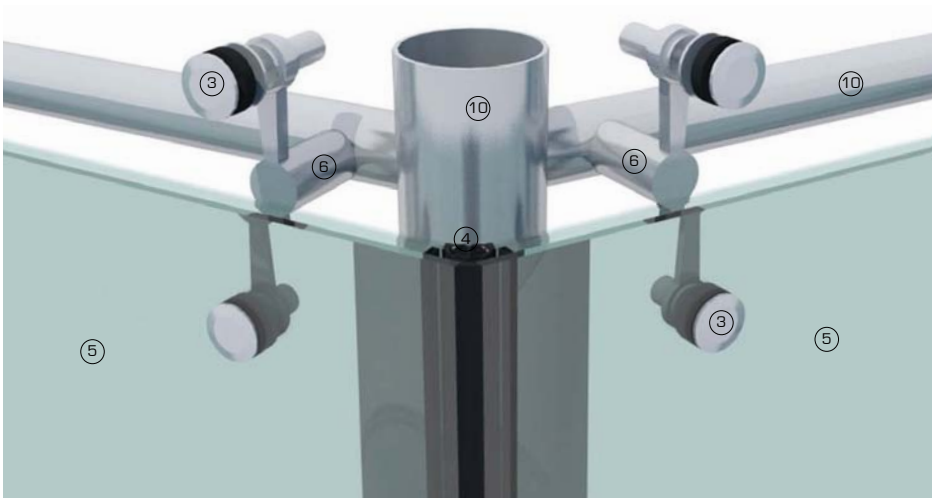
The threaded shank projecting into the building is able to rotate about a ball bearing where it meets the inner face of the double-glazed unit. This allows the double-glazed unit to rotate up to around 12° under wind load and associated structural deflections. This swivel joint is essential in avoiding the over stressing of the glass under full wind load that would otherwise result in breakage of the glass unit. The threaded shank is then used to clamp the complete bolt fixing to a support bracket with either threaded discs or nuts. The visible thread in the shank can be either left exposed, or be covered with threaded sleeves and stop ends. This bolt type is used regardless of the orientation of the roof, whether flat or pitched.

In common with other glass roof types, the inner glass of a double-glazed unit is usually made from laminated glass. In the event of a double-glazed unit being broken, the inner laminated sheet remains intact while the broken pieces of the heat-strengthened or fully toughened outer sheet come to rest on top of the damaged, but intact, inner sheet. The double-glazed units are first fixed and adjusted to form even joint widths between all the units. Joints of 20-28mm are used, though around 20mm is the most common joint width (in elevation) that allows for both structural movement and the slight variations in the size of the glass panels. Unlike capped roof glazing systems, the entire double-glazed unit is visible from both outside and inside; the edges are not set behind pressure plates that conceal any variations in glass panel size (c). Joint widths of up to around 28mm, which is deemed close to the maximum practical joint width for the adhesion of silicone sealant in a regular double-glazed unit, is used where brackets penetrate the outer seal from inside the roof to outside. If required, these brackets are used to support external sun shading and maintenance equipment. These brackets are usually in the form of flat plates that are welded to the internal supporting structure, and project through the joint. Although an additional lip around the projecting plate may provide additional protection to water penetration between the silicone and the bracket, in practice it has been found that this detail performs well if the seal is applied to a good level of workmanship.

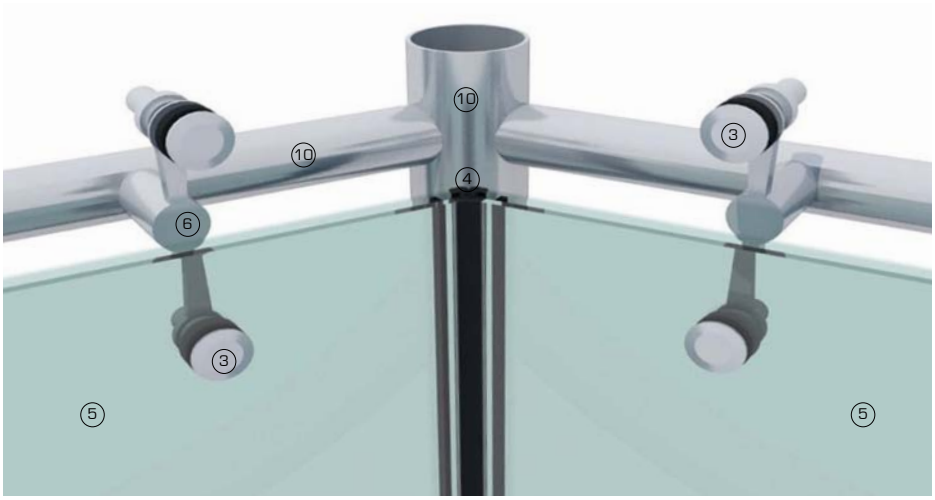
Seals between double-glazed units are made as an outer silicone seal with an inner backing rod of extruded EPDM. The gasket has projecting flaps on each side to form a 'fir tree' section, which prevents any water that penetrates the external seal from reaching the inner face of the seal (p)(4). This EPDM gasket also serves as an inner air seal, and provides a crisp appearance of sharp lines in the interior face of the glazed roof.



n | 3D view showing bolt fixed glazing with external fold



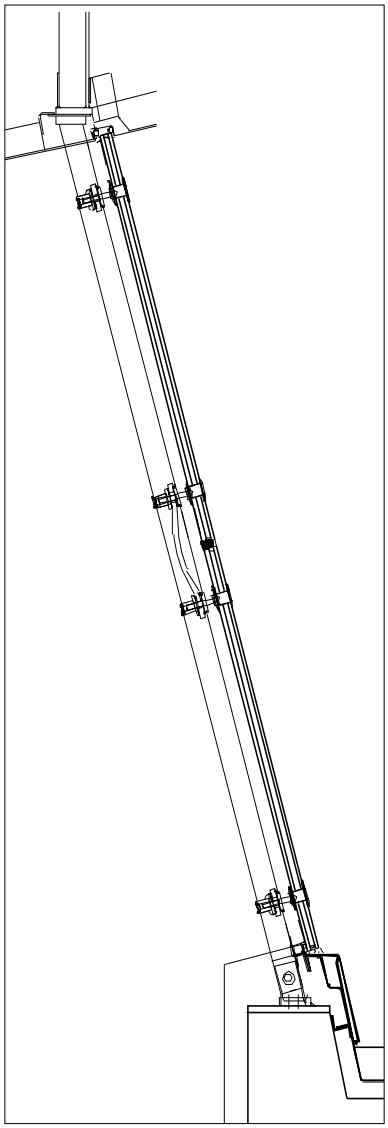
p | 3D view showing bolt fixed glazing with external fold



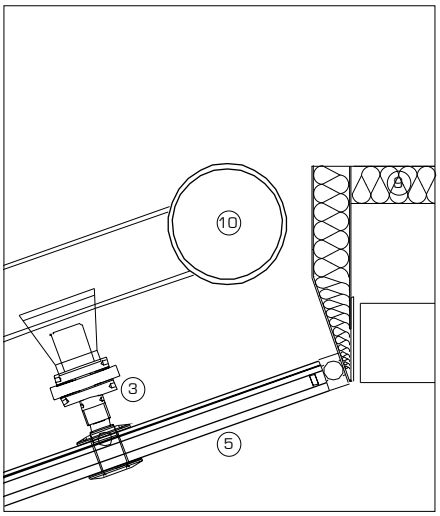
q | 3D view showing bolt fixed glazing with internal fold

Details

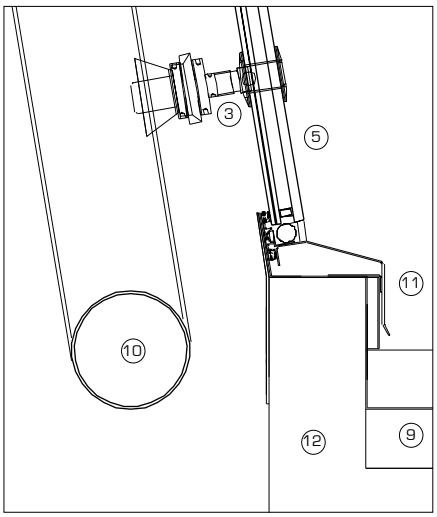
1	Structural steel support
2	Connector plate
3	Bolt fixing
4	Silicone seal between glass panels
5	Single-glazed or double-glazed unit
6	Support bracket
7	Silicone seal
8	Adjacent external wall
9	Insulation
10	Extruded metal cylindrical section
11	Roof construction
12	Concrete base



r | Vertical section 1:10. Junction with adjacent wall



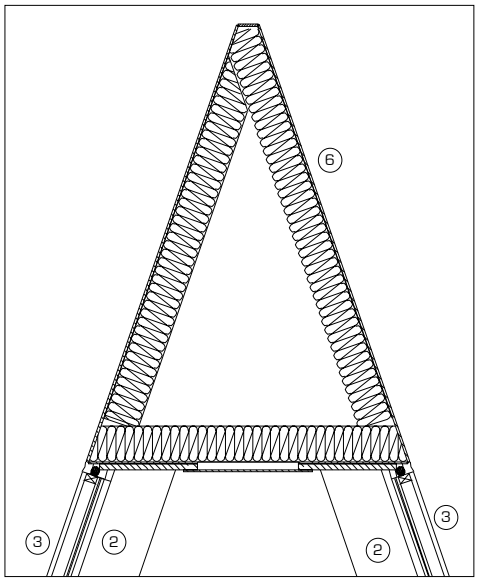
s | Vertical section 1:10. Upstand at base

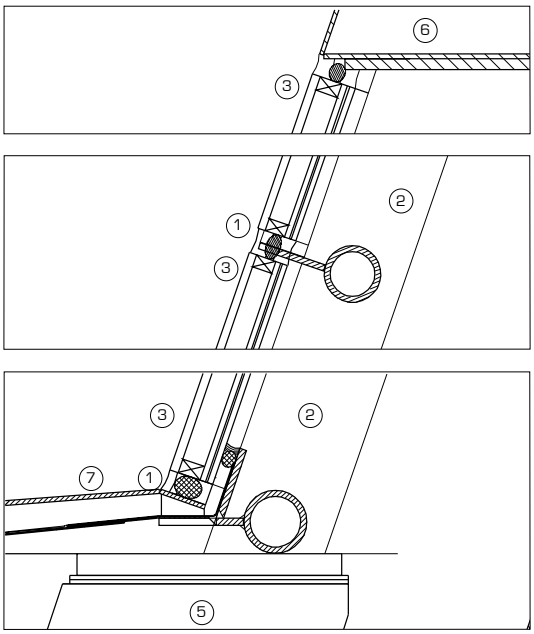


t | Vertical section 1:10. Base upstand junction

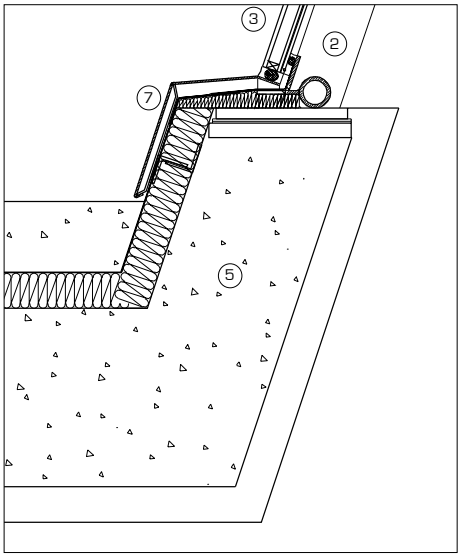
Details

1 | Silicone bond
2 | Mild steel support frame
3 | Laminated glass panel
4 | Silicone seal
5 | Concrete base
6 | Insulated metal panel
7 | Folded metal flashing
8 | Reinforced concrete support frame
9 | Folded aluminium protective cover
10 | Steel aluminium support shoe
11 | Structural glass beam

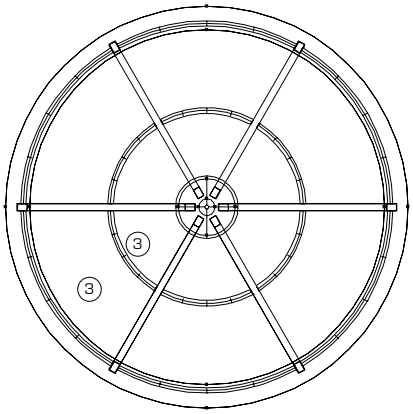




a | Vertical section 1:5 through rooflight showing typical details



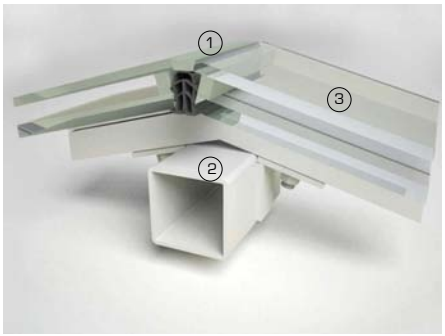
b | Vertical section 1:10. Base upstand, Junction with adjacent material

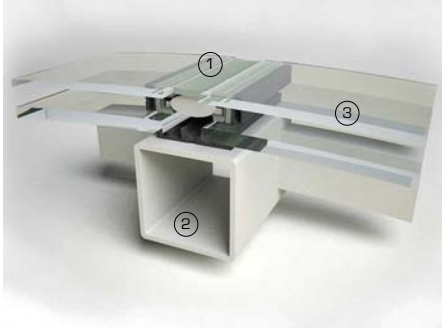


c | Horizontal section 1:20 of typical rooflight layout



d | 3D view of typical rooflight assembly





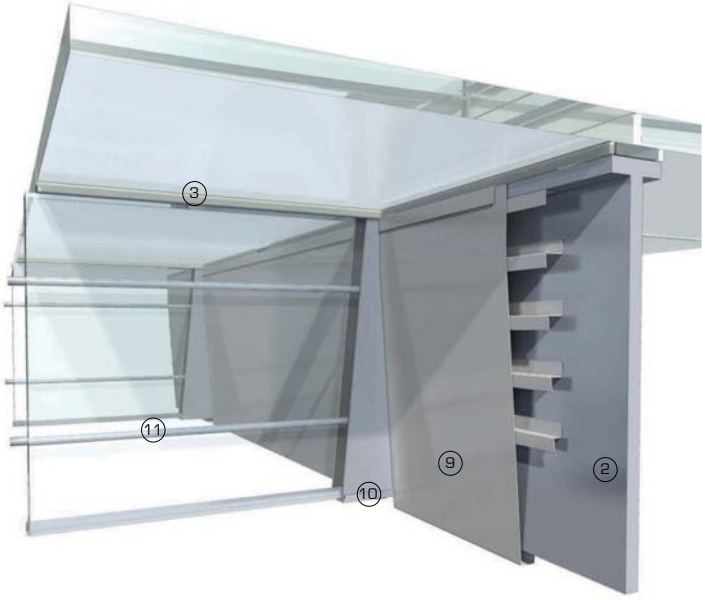
e | 3D Details showing glass-to-glass junctions

System design

The method of silicone bonding glass to aluminium framing is well developed for use in glazed curtain walling to provide visually smooth glass facades with no visible cappings. The use of silicone sealed rooflights can be taken a step further to become a full bond without the need for the mechanical restraint of pressure plates. In silicone bonded rooflights, the glass is glued to a supporting frame (a). The glue is also the external seal. This technique is useful for small rooflights, where cappings would be very difficult to fabricate, and in rooflights which are walked upon, where the rooflight is an external glass floor.

The generic conical rooflight shown has curved double-glazed units bonded to an aluminium frame (d). Silicone bonding avoids cover caps that would have to be curved both vertically and horizontally, which would be extremely difficult to fabricate. The rectangular rooflight shown is bonded together without a supporting structure; the glass provides its own support. The flat monopitch rooflight is bonded to a frame to provide a small rooflight from one double-glazed rooflight, with laminated glass sheets used to form a surface which can be walked upon. Similar to a glass floor used inside a building, it must also take heavier traffic loadings and be weathertight (f).

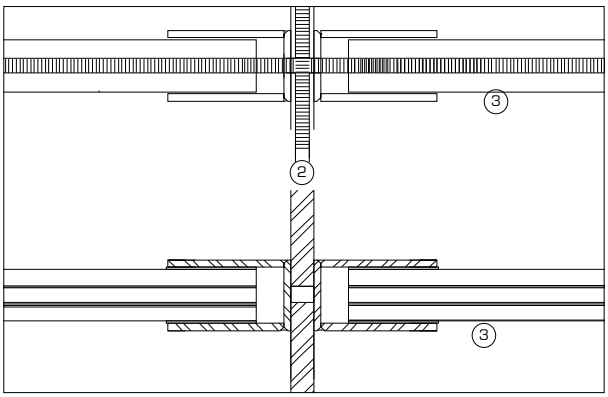




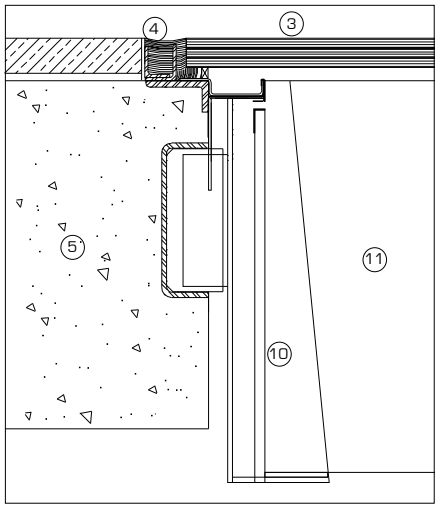
f | 3D views of underside of glass beam and steel support beam



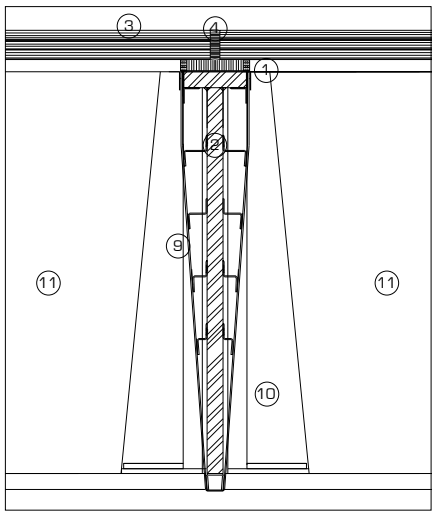
g | 3D view of glass beam with central steel support beam



h | Vertical section 1:10. Support systems for rooflight



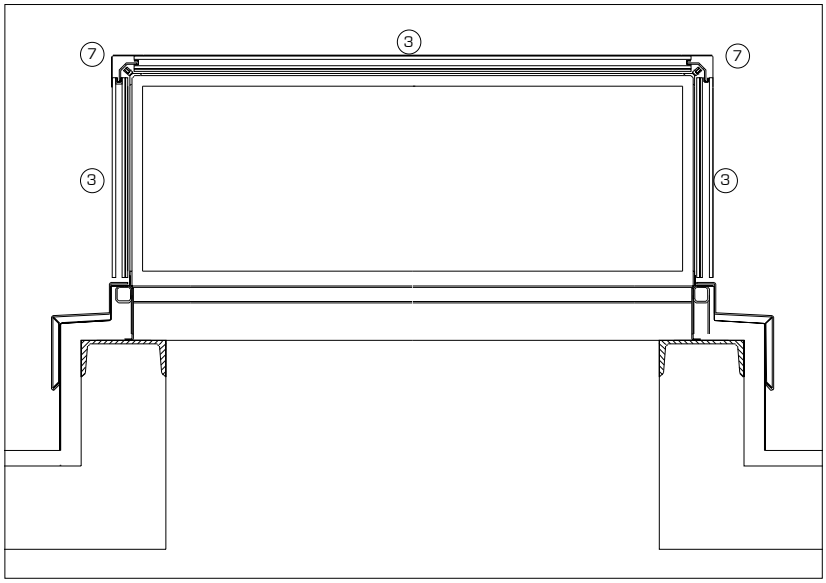
j | Vertical section 1:10. Junction with adjacent wall



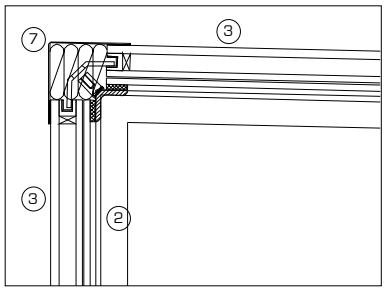
k | Vertical section 1:10. Bracket support

The generic conical rooflight shown has a lightweight steel frame used to support double-glazed units that form a rooflight (b). The structural frame comprises box sections set vertically, held in place by thin tube sections running horizontally to form a circle (c). The glass panels are supported on steel flat sections which are welded to the horizontally set tube section. The glass is levelled on blocks set onto the horizontal flat section, and the silicone is applied to the joint. At the base, the horizontal metal section projects out to form a flashing over the upstand in which the rooflight is set. An additional inner metal upstand can be provided with another silicone seal if there is risk of future flooding from blocked rainwater outlets, for example. The waterproof membrane for the roof slab is continued up the upstand and is bonded to the base of the horizontal section that supports the glass. This provides a complete seal from the glass to the roof membrane, with the metal flashing providing both a protection to this seal and a means of concealing the closed cell thermal insulation set on top of the waterproof membrane.

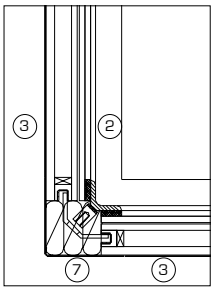
The generic rectangular rooflight shown is constructed without a supporting frame. Mechanical restraint is provided at the corners in the form of pressure plate clips (h). The double-glazed units at the



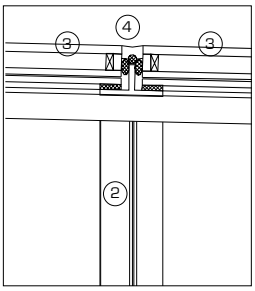
m | Vertical section 1:50 through bonded glass rooflight showing typical details



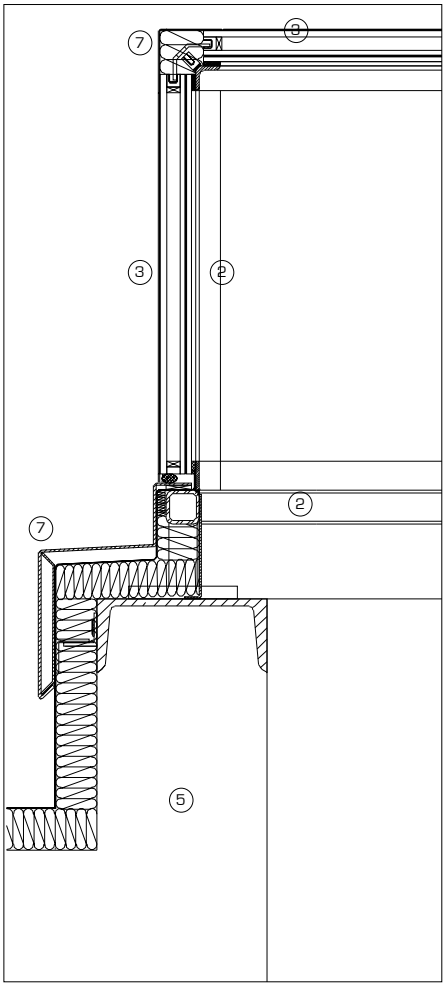
n | Vertical section 1:10. Typical corner detail



p | Horizontal section 1:10. Typical corner detail



q | Vertical section 1:10. Bonded glass-to-glass connection



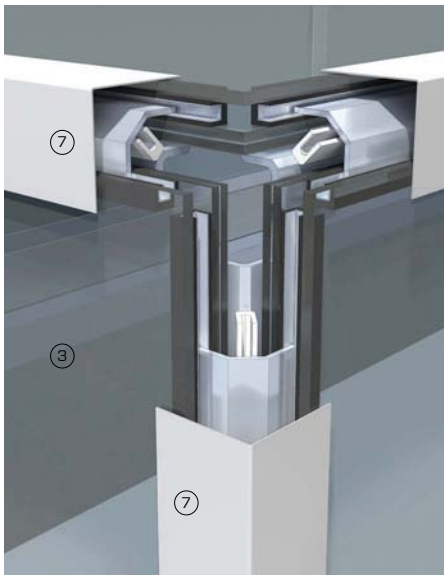
r | Vertical section 1:25. Typical connection to roof

corners are fabricated with a recessed groove on the two sides of the panel forming the corner in order to receive the clip (n). An alternative method is to fix the metal clip to the outside of the glass at the corner. This avoids the need for specially-made corner pieces but it does form a visible fixing. The modest size of this rooflight allows the horizontally-set glass to span from side to side with no additional support (m). The corners of the rooflight are stiffened by short lengths of pressure plate which hold the glass in place (r). The glass has a specially shaped groove in the depth of the double-glazed unit, to which the pressure plates are fixed. Corner joints have an outer corner piece of folded aluminium which is silicone bonded either to the face of the adjacent glass units, or is folded at 90° to bond it to the side of the unit. Glass-to-glass joints between horizontally-set units have a silicone seal with an aluminium angle set on the inside face to provide a second seal (q).

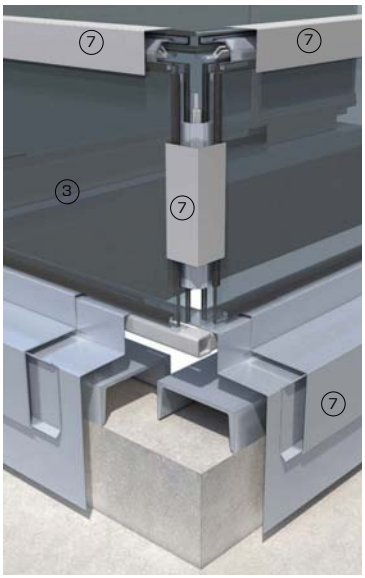
System details

Rooflights formed as nominally flat, accessible roof decks have been in use over the past 10 years. Previously used only inside buildings for walkways and stairs, they are now being used as fully waterproofed external decks, manufactured as proprietary systems. Single glazing is used since double-glazed units are difficult to use as a result of solar gain around the edge of the unit, where the glass is exposed to the outside but is supported on its underside allowing heat to enter but not to escape. Where black coloured edge 'fritting' is used, the situation is made difficult. However, double-glazed roof decking is in development and will no doubt become much more common over the next 10 years. The glass used is laminated, in common with other rooflights, both to avoid the possibility of any falling objects from penetrating the glass on impact, as well as to prevent damaged glass from falling immediately into the space below. The glass is set into a series of extruded aluminium angles to which it is bonded on its underside (s). A gap between the frame and the top of the glass is sealed with silicone of a different type. An additional condensation channel is set below the glass to catch any water that penetrates the silicone seal, or any water that passes through a damaged joint.

The details here show alternatives for both steel beam and glass beam supports to the glass panels (w)(x). A typical rooflight is shown with glass panels 2400mm x 1200mm in size (y). The supporting structure has a glass beam set in the centre, spanning the full length of 6000mm. Its depth is approximately 600mm, but the beam depth will vary depending upon the individual design. Here, steel plate is used to provide a beam instead of laminated glass; a steel flat is welded to the top of the beam to form a T-section that gives enough bearing for the glass deck. The ends of the glass beams are supported by a metal shoe support, made from either mild steel or aluminium. Stainless steel is used where corrosion is an essential consideration of the design. The metal shoe is bolted back to the supporting structure or reinforced concrete floor slab (v). The gap between the edge of the glass deck and the adjacent roof finish material is made with a silicone seal.



s | 3D cutaway of typical corner detail



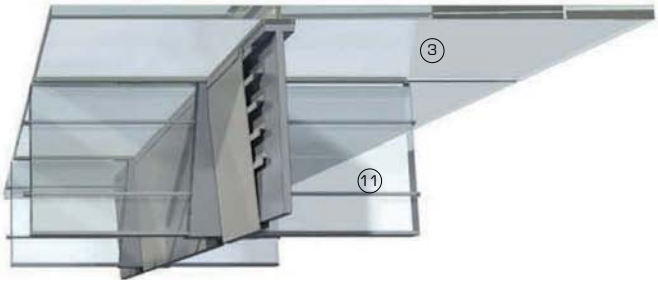
t | 3D cutaway of typical rooflight assembly



u | 3D cutaway of typical junction with roof



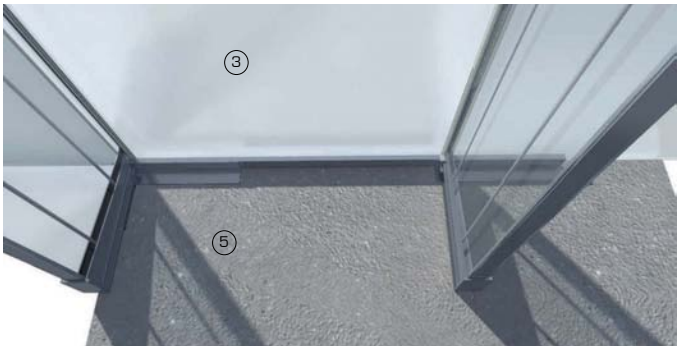
v | 3D detail of connection between glass beam and concrete wall



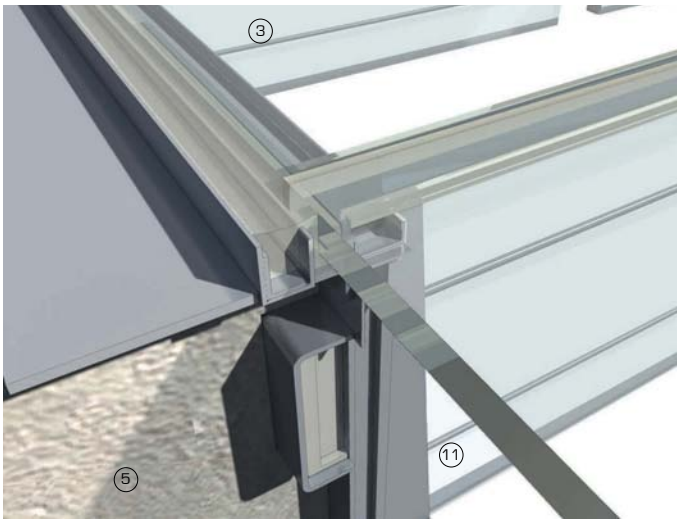
w | 3D detail of junction between glass and steel support beams



x | 3D detail of connection between glass beam and concrete wall



y | 3D view looking up at interior finish at edge of glass beam and concrete base



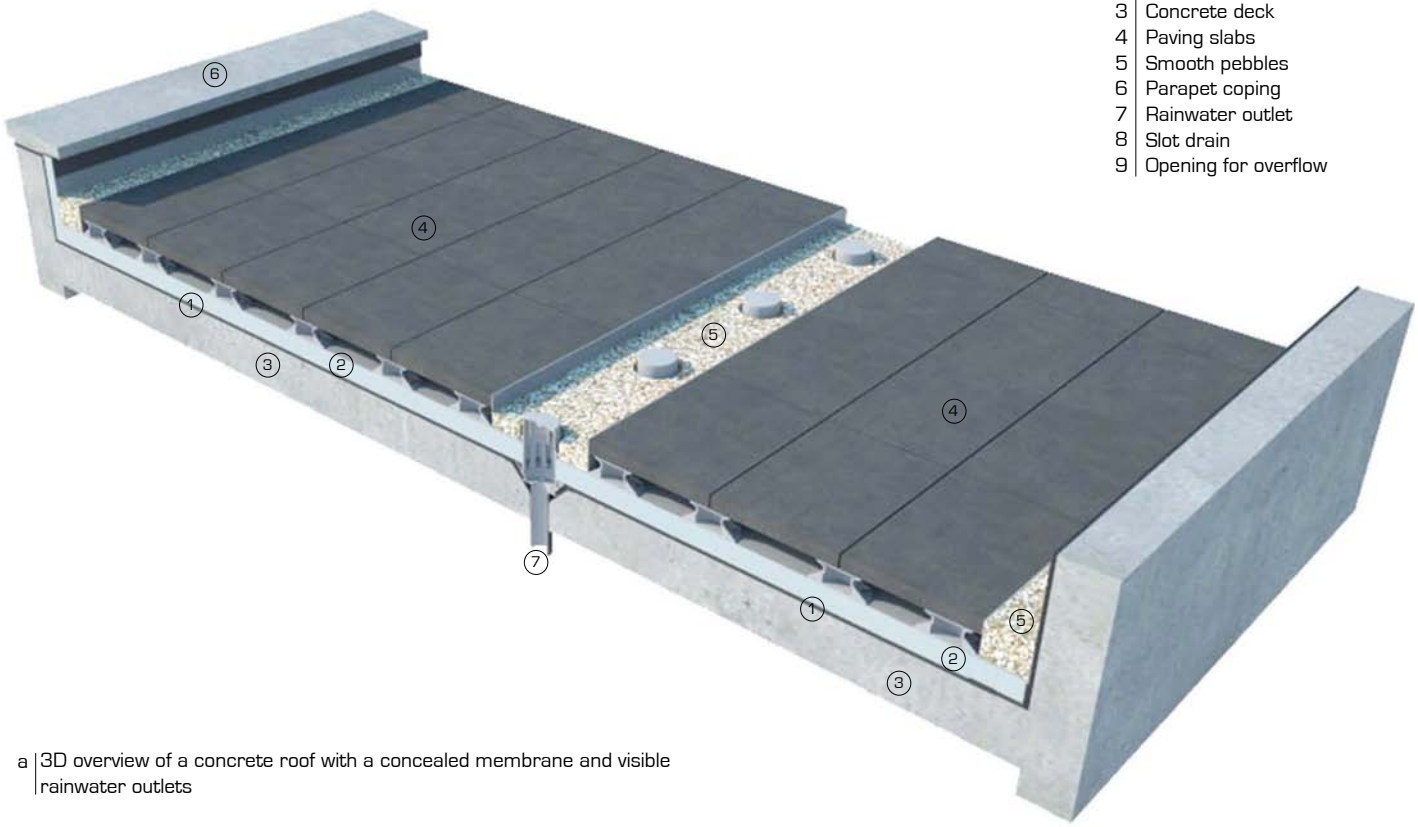
z | 3D view of junction at edge of glass beam and steel support

Details

1	Silicone bond	8	Reinforced concrete support frame
2	Mild steel support frame	9	Folded aluminium protective cover
3	Laminated glass panel	10	Steel aluminium support shoe
4	Silicone seal	11	Structural glass beam
5	Concrete base		
6	Insulated metal panel		
7	Folded metal flashing		

Details

1 | Waterproof membrane
2 | Thermal insulation
3 | Concrete deck
4 | Paving slabs
5 | Smooth pebbles
6 | Parapet coping
7 | Rainwater outlet
8 | Slot drain
9 | Opening for overflow



a | 3D overview of a concrete roof with a concealed membrane and visible rainwater outlets

System design

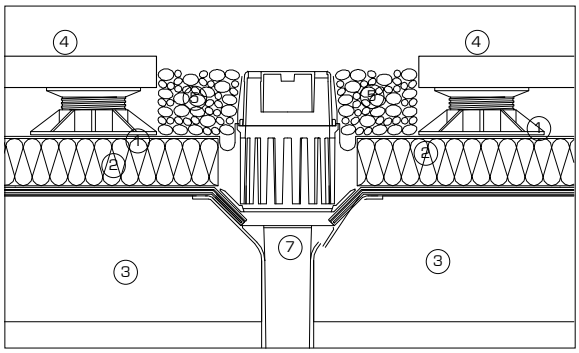
Bitumen has traditionally been used as a waterproof layer, applied while hot in liquid form onto a concrete roof slab. As it cools it hardens, forming an impervious membrane, but will soften again if heated by the effects of solar radiation. For this reason, in order to keep the material cool, bitumen membranes are concealed by smooth pebbles or paving slabs, usually with thermal insulation set between the bitumen and the pebbles or paving (a). Traditional bitumen roofs are usually laid in two layers, with an overall thickness of around 25mm. One of the limiting factors with bitumen is folding the material at a corner or edge. When the material turns through a right angle from the horizontal roof to a vertical parapet wall, it can pass through a maximum of 45° in a single fold. For this reason, 45°angle fillets are used to make a 90° turn from roof to wall.

Modern bitumen-based membranes that are concealed beneath roof finishes are typically a combination of bitumen-based sheet mixed with synthetic rubber to give flexibility combined with a reinforcement to give dimensional stability and tensile strength. This reinforcement often allows the material to be folded through 90° (d), making its use considerably easier where angle fillets are not required.

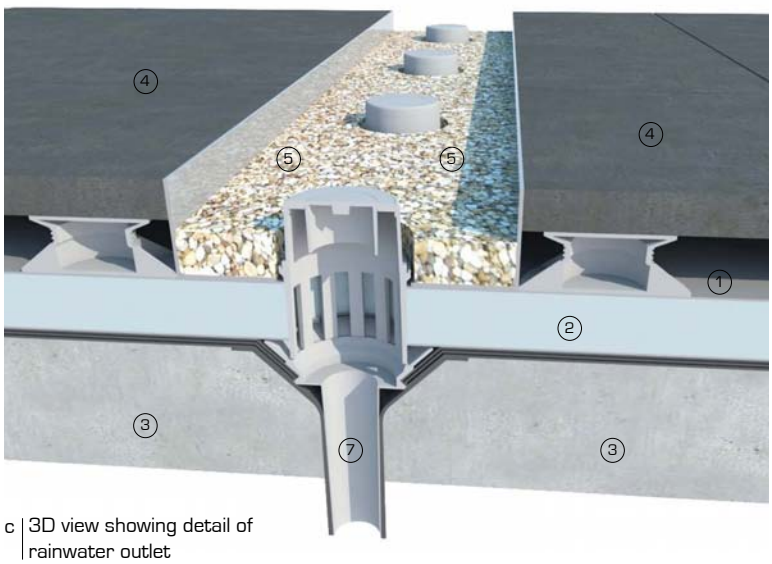
With the development of much thinner membranes in thermoplastics and elastomers, together with their competitive costs, there have been considerable efforts made by manufacturers over the past 20 years to make the bitumen layers thinner, in order to reduce the material required while enhancing its properties of strength and flexibility. This has been achieved by replacing the thick two-layer method with a mixture of thin layers, still applied in hot liquid form on site but reinforced with an elastomeric sheet, usually bedded between the layers. This is typically two layers, each 3mm thick with reinforcing layers bedded into the material. This allows the bitumen to accommodate both small amounts of movement at these junctions as well as the sharp fold in the material, creating a weakness in the membrane which might otherwise be damaged during the life of the building. An outer protective layer is added for vulnerable locations, such as at gutters and at upstands (e).

System details

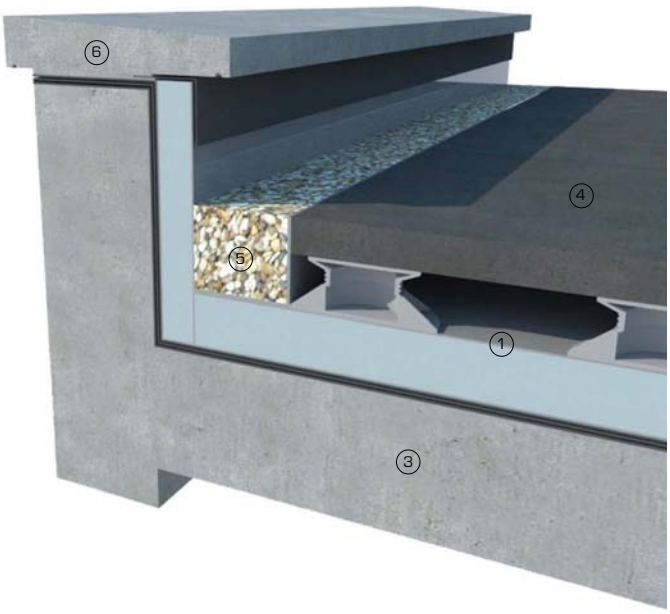
Concealed membrane roofs are typically in an 'inverted' roof configuration, with either open joints or sealed joints in the top layer that covers the thermal insulation, usually paving. In the open joint version the membrane, bonded to the concrete slab, is covered by a protective layer, with closed cell and rigid thermal insulation set on top. A polyester filter sheet is set on top, with paving or smooth pebble ballast on top to hold the insulation in place as well as to walk on. Pebbles are 20mm - 40mm diameter, while paving slabs are around 600 x 600mm in size and 30 mm - 40mm deep (b). In the sealed joint configuration, the bitumen membrane with its protection layer has a drainage layer on top, onto which is laid a minimum 65mm sand/cement screed, usually

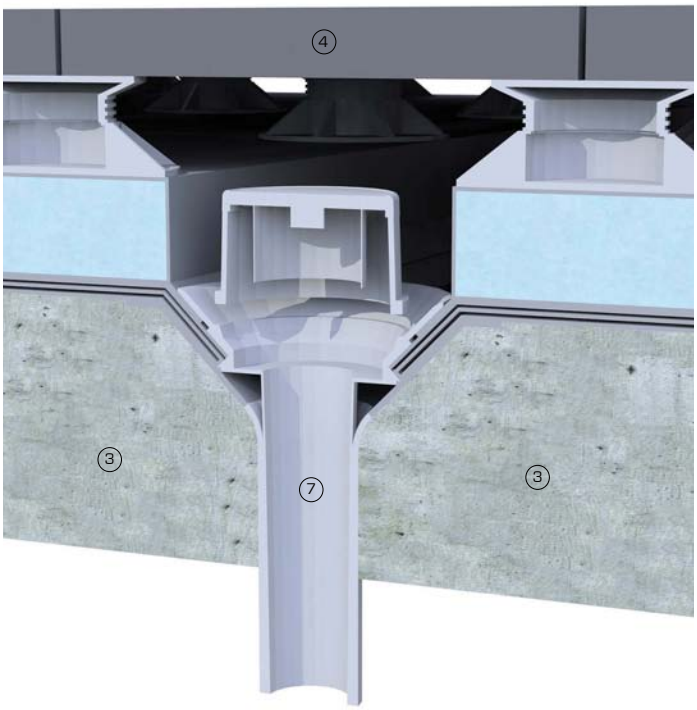


b | Vertical section 1:10. Rainwater outlet detail

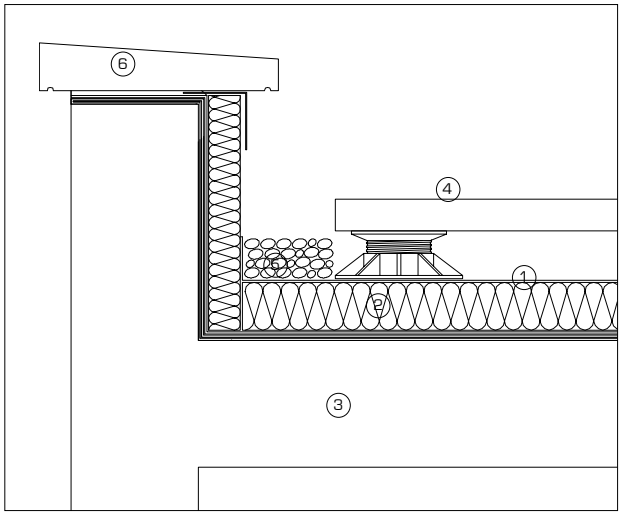


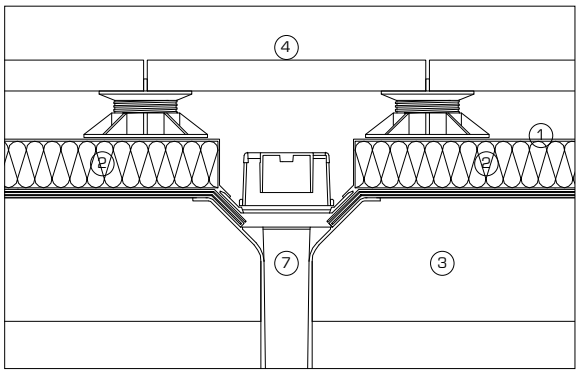
c | 3D view showing detail of rainwater outlet



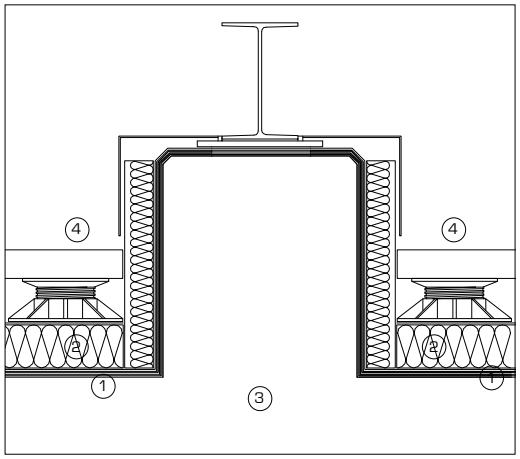


d | 3D view showing details of parapet and rainwater outlet

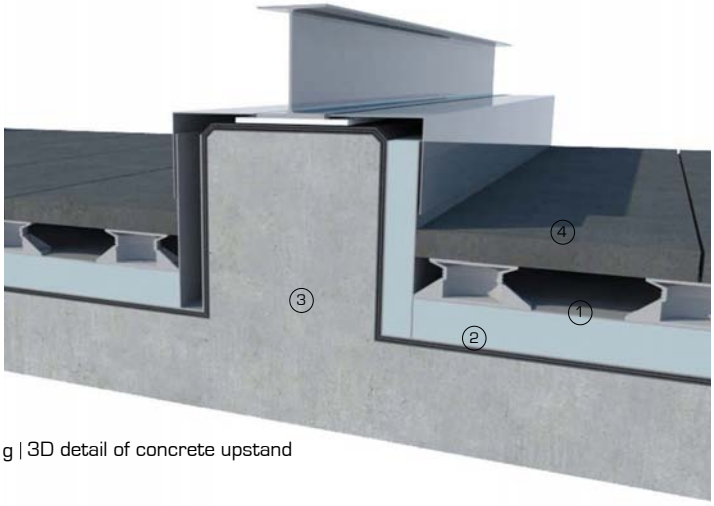




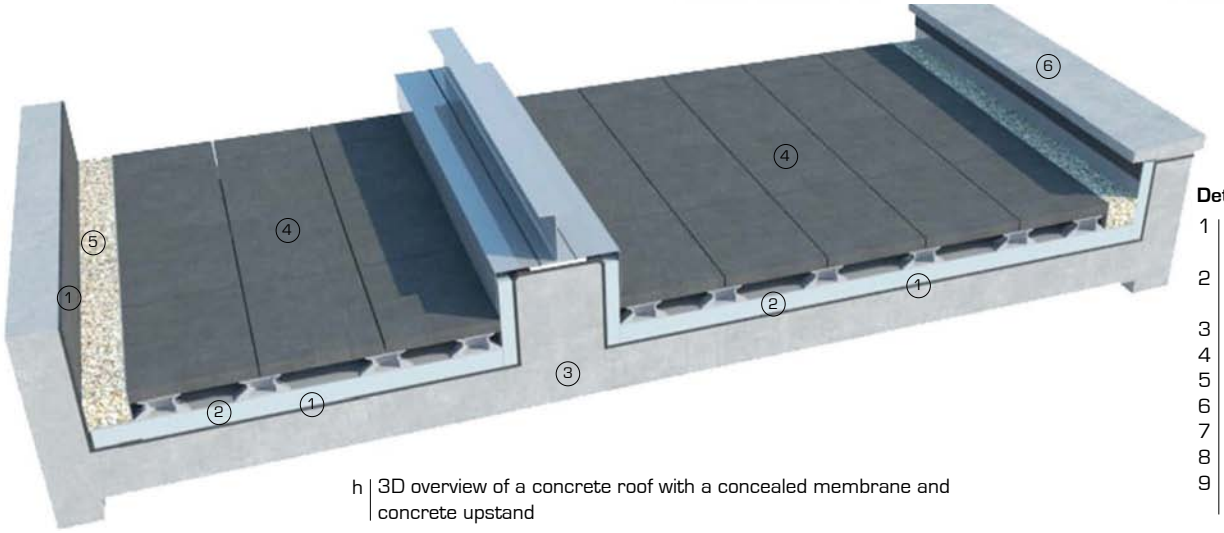
e | Vertical section 1:10. Parapet and rainwater outlet details



f | Vertical section 1:10. Concrete upstand



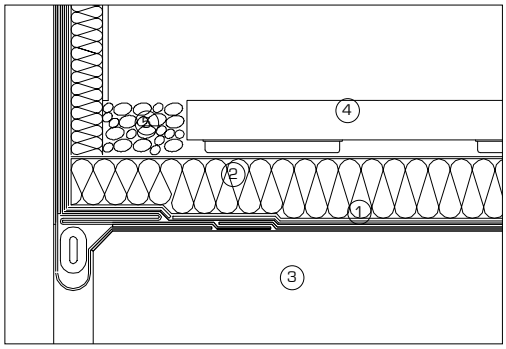
g | 3D detail of concrete upstand



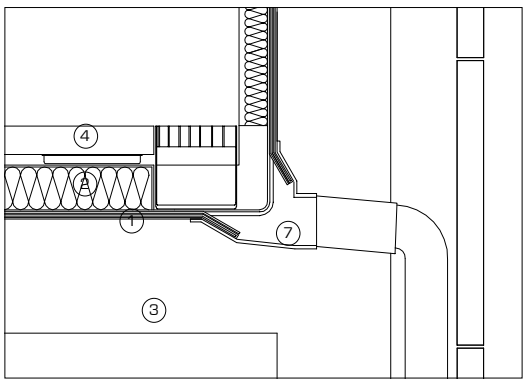
h | 3D overview of a concrete roof with a concealed membrane and concrete upstand

Details

1 | Waterproof membrane
2 | Thermal insulation
3 | Concrete deck
4 | Paving slabs
5 | Smooth pebbles
6 | Parapet coping
7 | Rainwater outlet
8 | Slot drain
9 | Opening for overflow



j | Vertical section 1:10. Junction of external wall and roof slab

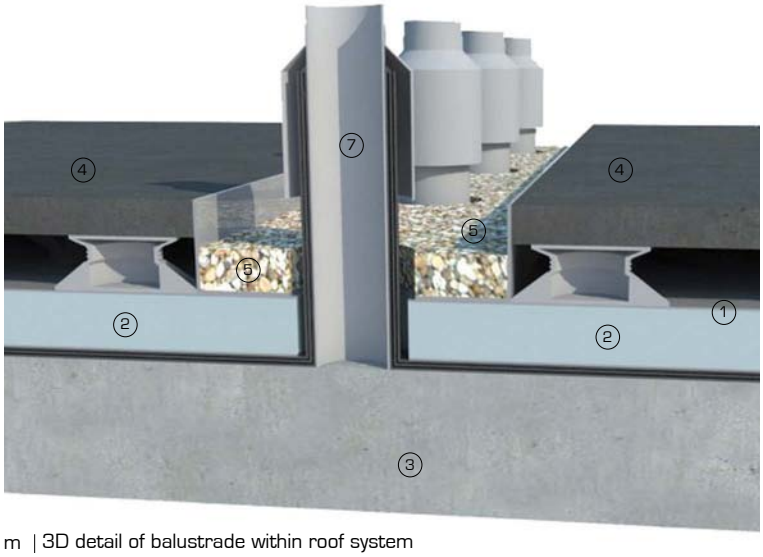


k | Vertical section 1:10. Two-way drain outlet

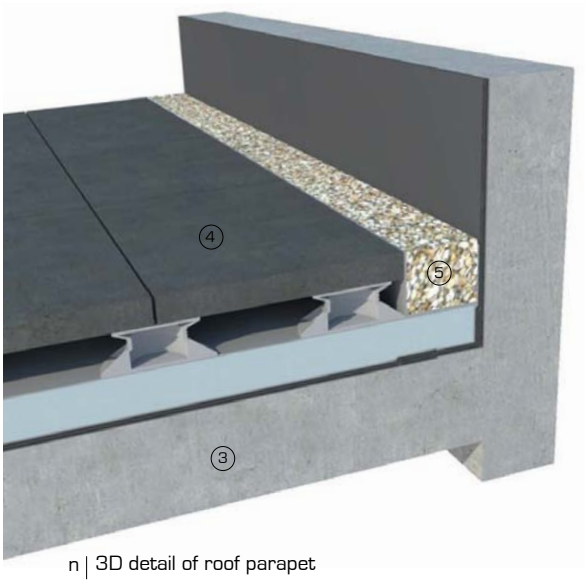
reinforced or made sufficiently thick to avoid cracking both in the screed and the sealed paving above. Paving slabs or blocks are bonded to the screed with mortar and grouted.

Expansion joints between concrete slabs with widths of between around 10mm to 50mm are formed by stopping the material each side of the joint and setting a rubber-based strip that dips into the gap between the slabs, linking the membranes into a continuous seal (p). The joint is protected and reinforced with an additional layer, either flat and bonded on one side only, or formed as a folded, S-shaped cover that folds back over itself, held in place by an additional protection sheet on top. The gap between the membrane, dipped into the joint, and the reinforcement cover is filled with a foam backing rod or tube, as used in the glass joints of bolt fixed glazing (q). The material used for the reinforcement is either the same bitumen based material, or increasingly, a rubber-based strip.

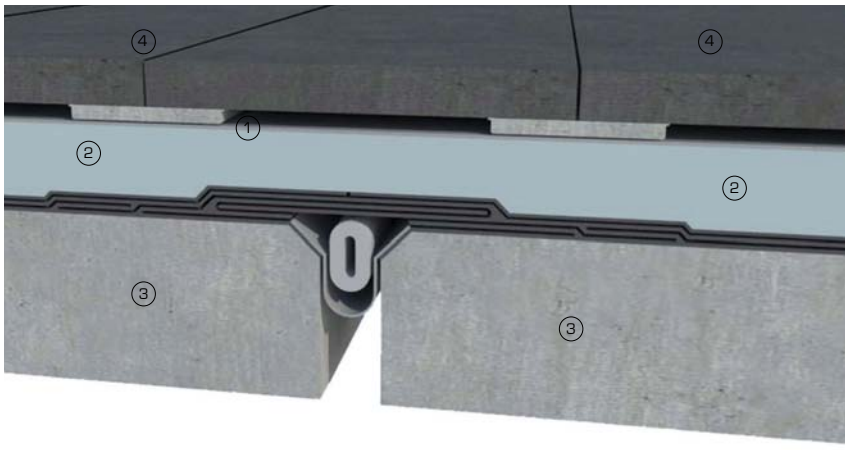
The top of the joint is finished as level as possible with the adjacent areas of roof to allow water to drain freely from the roof. The reinforcing membrane is sometimes folded down into the gap, separated from the membrane below with a foam backing rod. It can be difficult to drain water from this groove at the edge of the slab unless water at this lower level can discharge into a rainwater outlet.



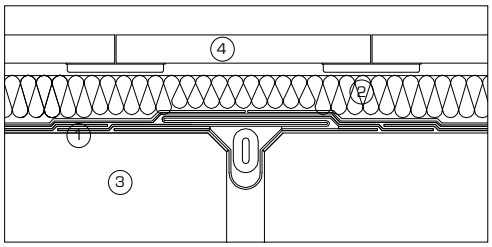
m | 3D detail of balustrade within roof system



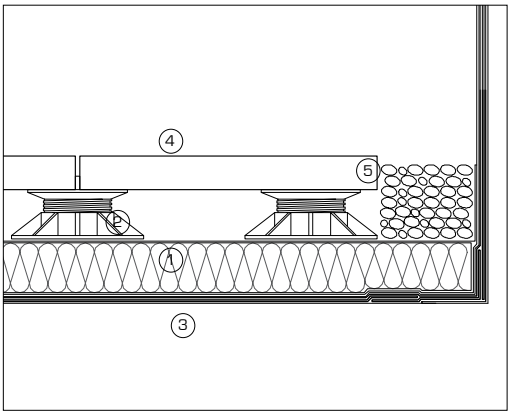
n | 3D detail of roof parapet



p | 3D detail of expansion joint in concrete slab



q | Vertical section 1:10. Expansion joint in concrete slab

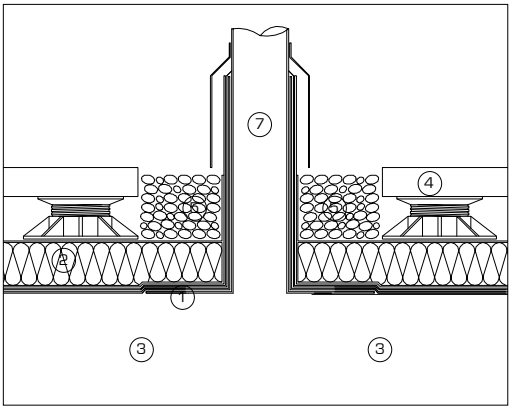


r | Vertical section 1:10. Parapet detail

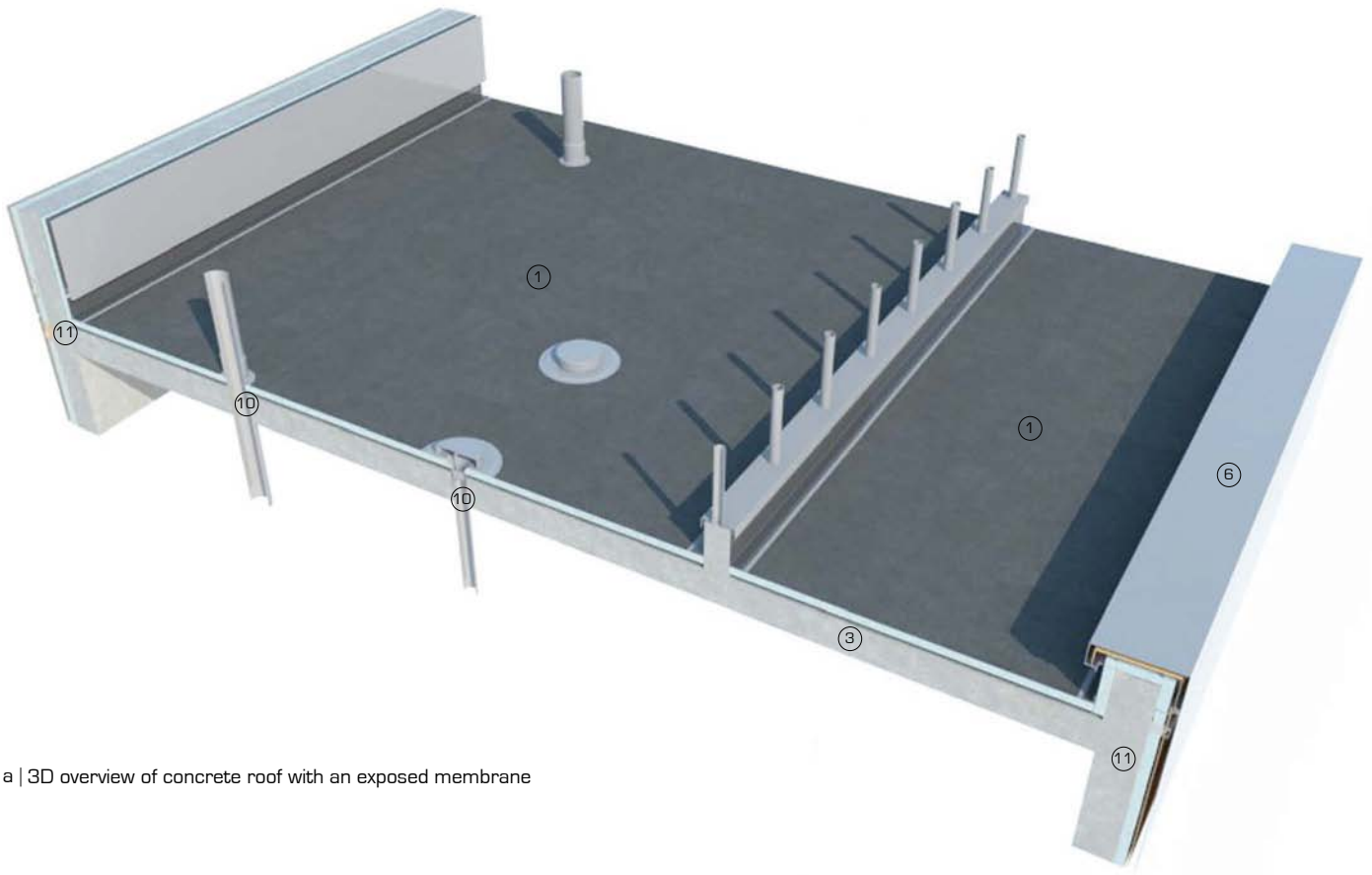
In forming parapet upstands, an essential requirement is to keep the waterproof membrane as well-protected from the effects of the sun as elsewhere on the roof. For this reason, thermal insulation is applied to the inside face of the parapet, even if this has no direct benefit to the passage of heat through the building. The membrane is turned through a full 90° as shown in the drawings (f), but an angle fillet is required by some manufacturers to limit the angle of any fold to 45°. A reinforcing strip is usually added where a 90° fold is made.

Plinths which are formed as short columns for the support of roof-mounted mechanical equipment or balustrades are waterproofed in a similar way to a parapet upstand. The membrane is folded up through 90° from the roof level and is formed to cover the complete plinth. The thermal insulation extends across the complete plinth to prevent a thermal bridge through the roof construction (h).

Rainwater outlets are set at the level of the waterproof membrane, drained at both the level of the sealed paving and the level of the waterproofing layer (b). The base of the rainwater outlet is fixed to the concrete slab. The waterproof membrane is dressed down into the top of the rainwater outlet and the upper part of the rainwater outlet is bolted down onto the part already fixed and sealed (k). The geotextile sheet is wrapped around the outlet to avoid dirt and debris being washed into the rainwater drainage system.



s | Vertical section 1:10. Base of balustrade



a | 3D overview of concrete roof with an exposed membrane

System design

Exposed membranes have been used for flat roofs which are not visible from below, but this has changed in recent years as membranes are produced in increasingly smooth and regular finishes (a). Because of their lightweight nature, they are often used in conjunction with lightweight roofs such as profiled metal deck and timber. This section considers their use in concrete construction, though the same principles of waterproofing can be applied to these other materials.

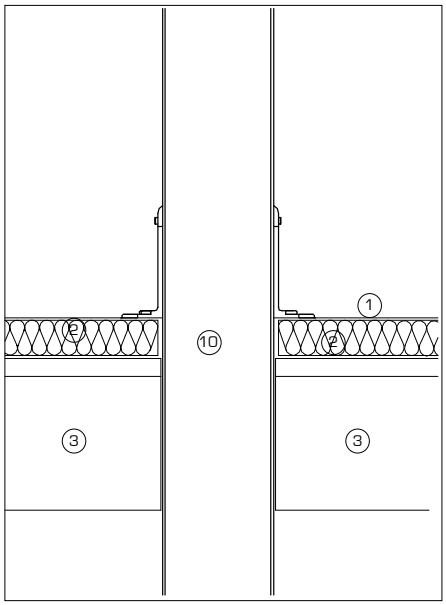
The introduction of polymer-based membranes provided economic waterproofing materials that are more flexible than their bitumen-based predecessors. The increased flexibility of the new sheet materials allowed for greater degrees of movement between adjoining components and assemblies, allowing the detailing of junctions to be relatively straightforward in forming a reliable weathertight roof membrane (b). As a result of these developments, polymer modifications were also made in the earlier generation bitumen-based materials to make them more flexible, in order to compete with the polymer-based sheet materials. As a result there is now a wide range of exposed membrane materials available to suit different budgets and individual roof designs.

Polymer-based membranes have the main advantage of an ability to be cut and formed into complex shapes, allowing them to take up a given shape with precision, sometimes pre-formed in the factory before being delivered to site. Single layer membranes are very practical on roofs with a large number of penetrations, typically in commercial buildings where mechanical ventilation equipment is regularly being modified or replaced during the lifetime of a building. Single layer membranes are made from either elastomeric materials, typically EPDM, or from thermoplastic materials, typically plasticised PVC (PVC-P). Elastomeric materials are very popular in the US, while thermoplastics are preferred in Europe. EPDM (ethylene propylene diene monomer) is a flexible and elastic material that has the appearance of a synthetic rubber. EPDM is manufactured in the limited colours of black, grey and white.

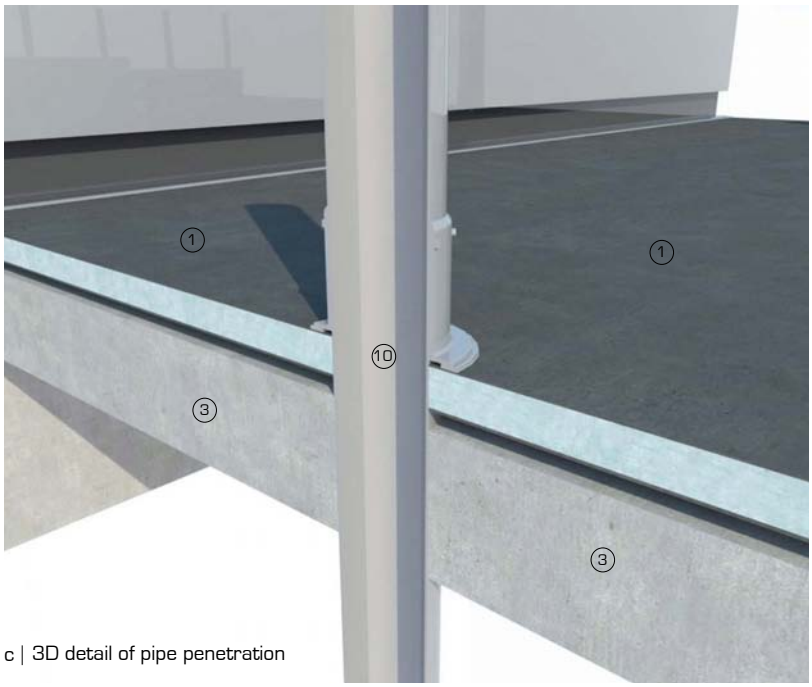
Both elastomers and thermoplastics can be mechanically fixed, bonded or secured with ballast to the concrete deck beneath. Developments in these materials have led to them being used on timber decks and profiled metal decks in addition to the concrete decks discussed here. Both thermoplastic and EPDM membranes can be welded together to form a continuous waterproof sheet. While both material types are glued, there is an increasing use of hot air welding methods, which avoids the need for flame techniques or adhesive bonding methods that can be both slow and can damage adjacent work during their application. In hot air welding, a jet of heated air is used to soften the materials and weld them together, applied from a range of tools that are either hand-held or fully automated, depending on the application.

Membranes are reinforced with glass fibre sheet or polyester fabric. These layers are bonded into the material. The glass fibre provides dimensional stability, making it more stable for bonding to the substrate. The woven polyester fabric, used in tent membrane structures, has high tensile strength to resist wind loads.

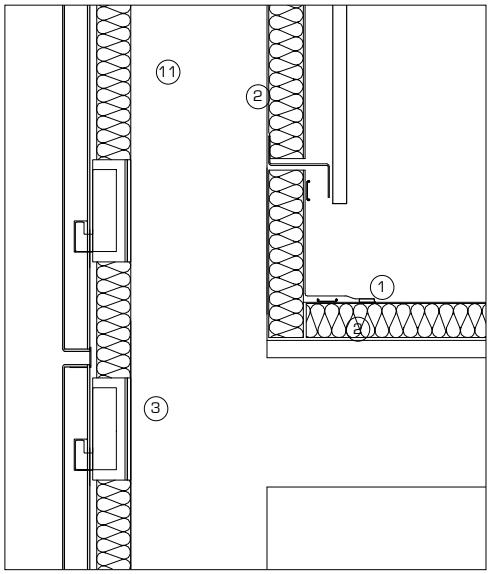
A typical build-up for a single layer membrane is a concrete deck with a vapour barrier set on top, with thermal insulation above that, sealed on



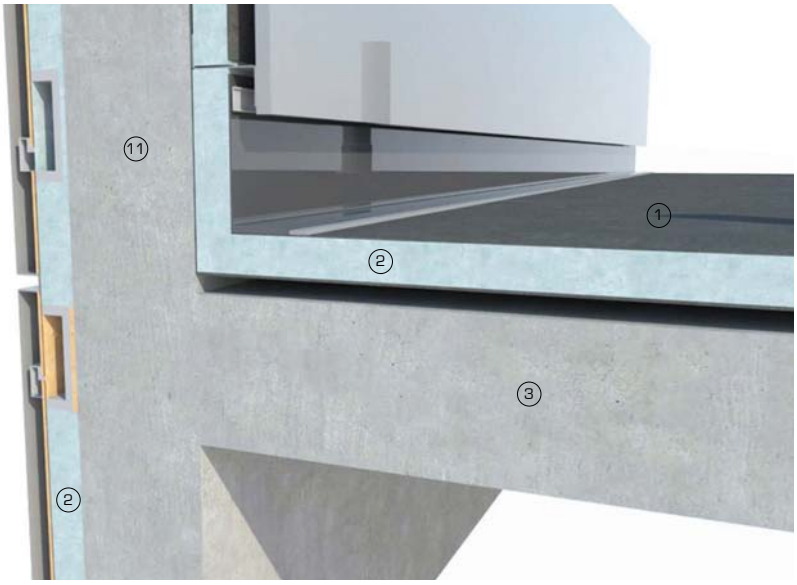
b | Vertical section 1:10. Pipe penetration



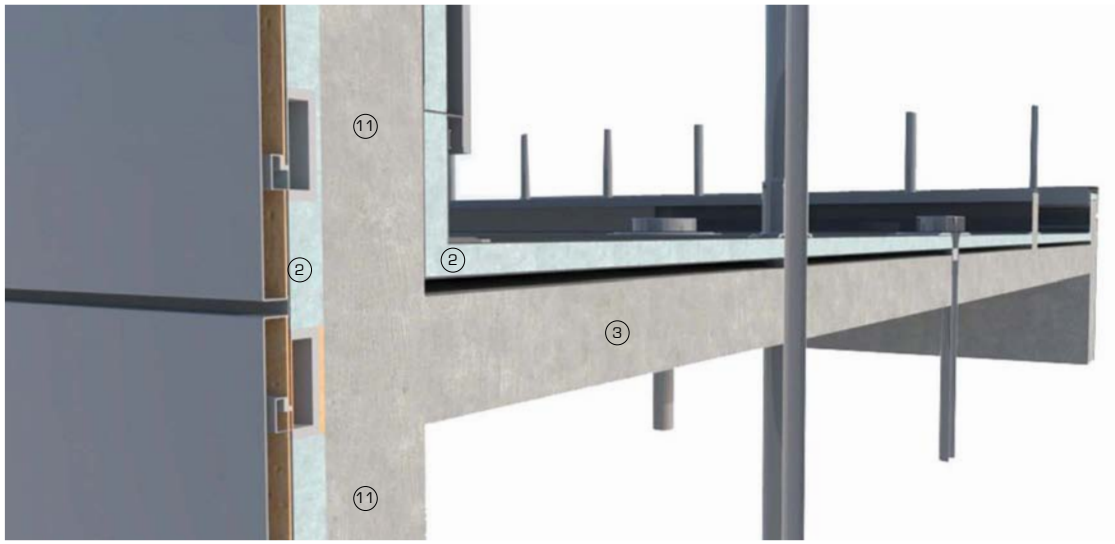
c | 3D detail of pipe penetration



d | Vertical section 1:10 Junction of external wall and roof slab



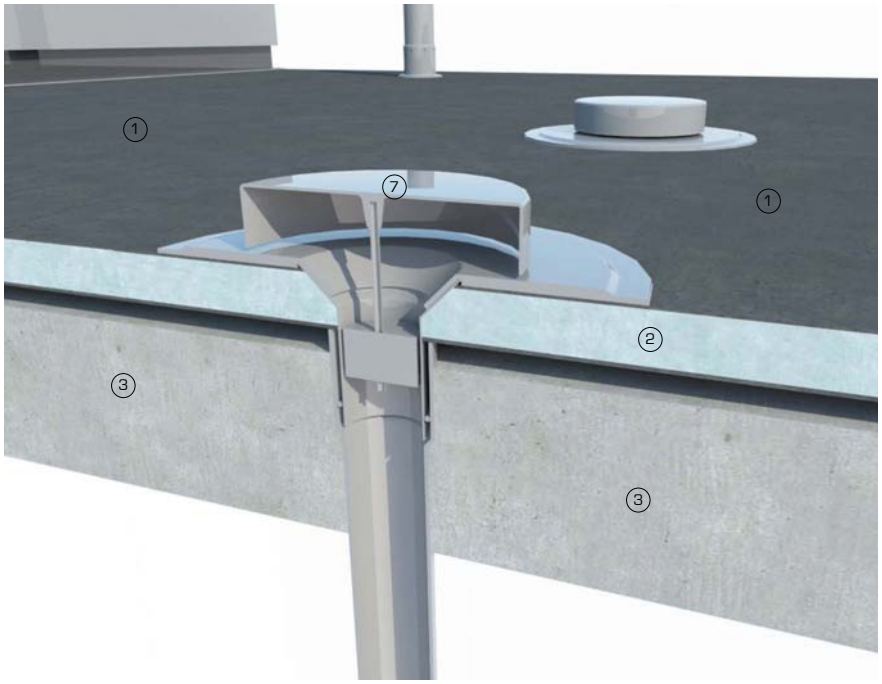
e | 3D detail of junction between roof slab and external wall



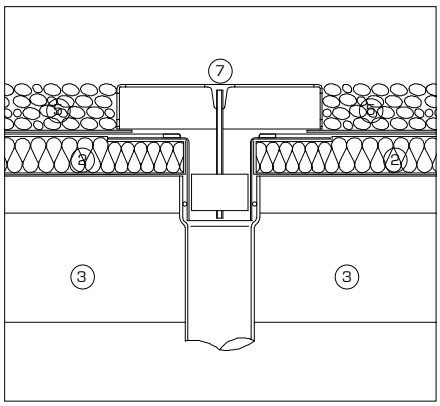
f | 3D detail of junction between roof slab and external wall

Details

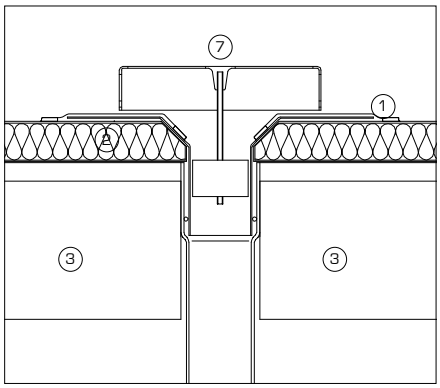
1	Waterproof membrane
2	Thermal insulation
3	Concrete deck
4	Paving slabs
5	Smooth pebbles
6	Parapet coping
7	Rainwater outlet
8	Opening for overflow
9	Balustrade
10	Pipe or duct
11	External wall
12	Rooflight



g | 3D detail of rainwater outlet within exposed membrane roof



h | Vertical section 1:10. Rainwater outlet (balusted method)



j | Vertical section 1:10. Rainwater outlet (bonded method)

top with a single layer membrane (e). PVC-P membranes are typically 1.5mm - 3.0mm thick, while EPDM membranes are typically 1.0mm - 1.5mm thick.

The mechanically fixed method is suited to applications with high wind uplift forces, as bonded systems tend to be limited by the bonding strength of the vapour barrier to which the membrane is itself bonded through the thermal insulation layer, which is typically made from expanded polystyrene board. The vapour barrier is loose-laid on the concrete deck and thermal insulation is then mechanically fixed through this barrier to the deck beneath. The spacing of the fasteners varies with the design wind loads. A separating layer of glass fibre sheet is usually laid onto the insulation with an outer single layer membrane. The membrane is mechanically fixed with pressure plate bars, similar to those used in glazed curtain walling systems to hold the glass in place. Bars form strips of pressure plate to hold the roof build-up in place. The pressure plates are fixed by bolts at centres along their length to the substrate below.

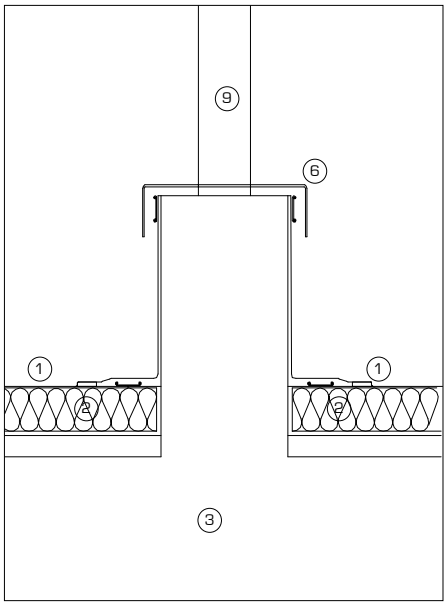
System details

Membranes can also be secured by point fixings rather than by pressure plates. 50 - 75mm diameter rigid plastic discs are used to hold the build-up in place. These are set at centres to suit the design wind loads. The closed cell rigid insulation is typically made in panel sizes of 1200mm x 2400mm, in thicknesses from 25mm to 100mm.

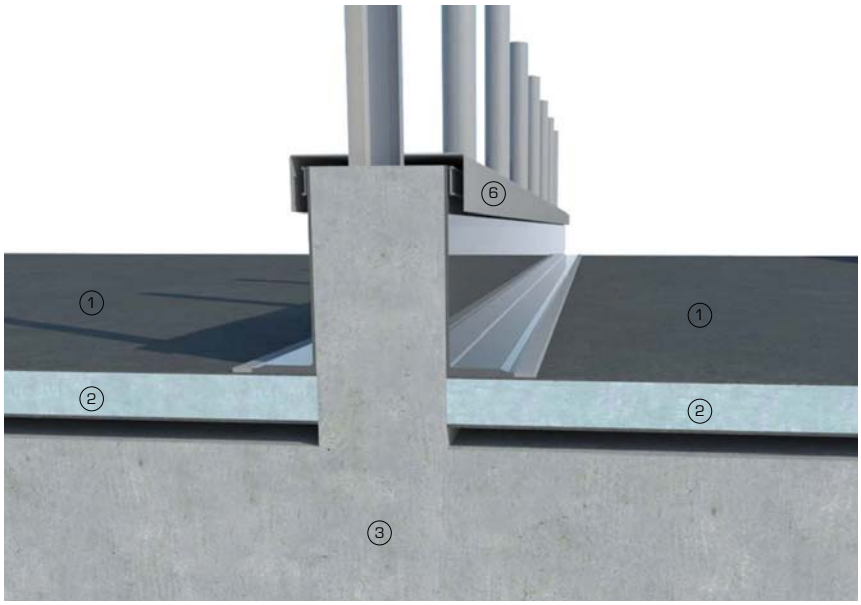
In the bonded fixing method, the exposed membrane of the vapour barrier is usually bitumen-based and is bonded to the deck. Joints between the vapour barrier sheets are lapped to avoid any risk of vapour passing through the roof structure from inside the building. The thermal insulation is then bonded to the vapour barrier. Insulation can also be mechanically fixed with pressure plates to the concrete deck beneath. The membrane is then bonded to the insulation with a continuous layer of bonding adhesive on its underside. Some systems still bond the membrane at points only rather than across the entire surface of the membrane, but this is dependent upon the wind load and the proprietary system used.

Bonded membranes have a visually smooth appearance, making them suitable where the roof surface is seen from points around the building. This fixing method still requires mechanical fixing at the edges, and around openings such as rooflights.

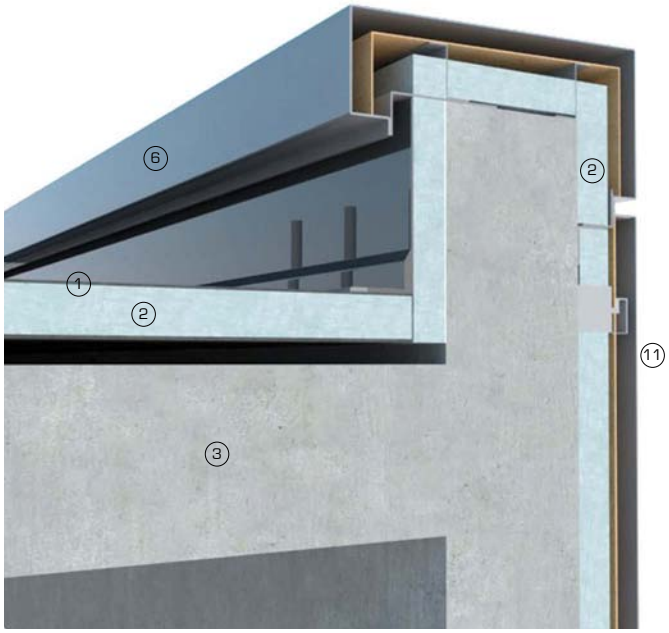
Membranes can be bonded or mechanically fixed to parapet upstands (m). The fixing method that is used on the main area of roof is usually continued on these vertical areas. With mechanical fixing, the pressure plate can be fixed either to the upstand or to the flat roof area. The pressure plate forms a junction between the membrane sheet forming the upstand and the membrane sheet of the roof (p). Intermediate pressure plates are applied horizontally on the upstand when its height exceeds around 500mm, depending on the specific material used.



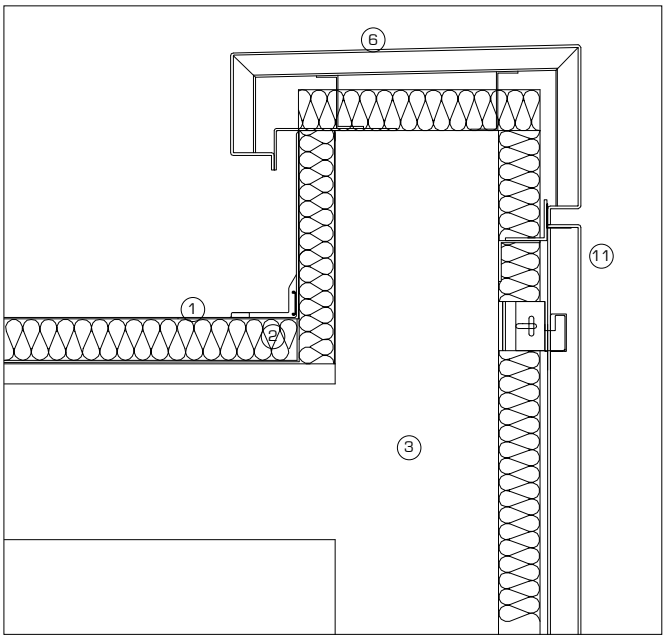
k | Vertical section 1:10. Upstand for balustrade



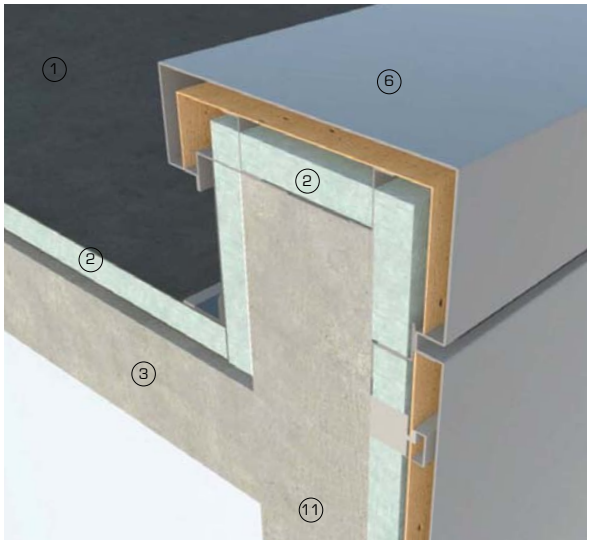
m | 3D detail of upstand

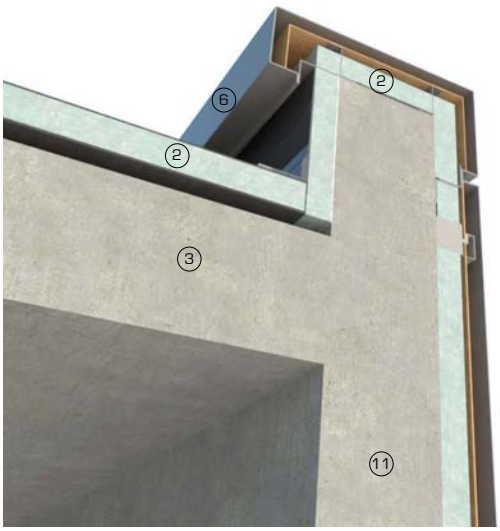


n | 3D detail of low parapet



p | Vertical section 1:10. Low parapet





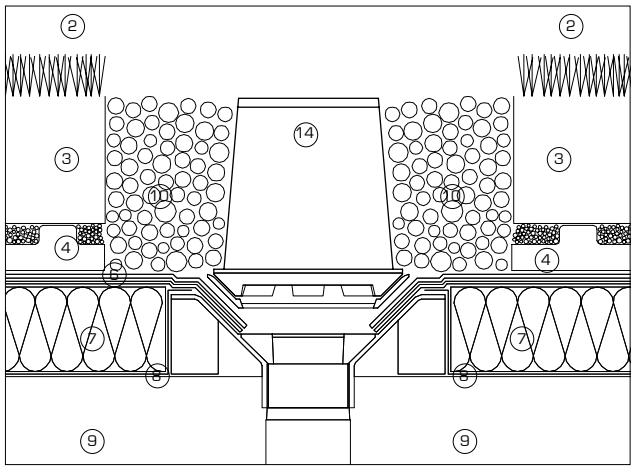
q | 3D details of low parapet

Details

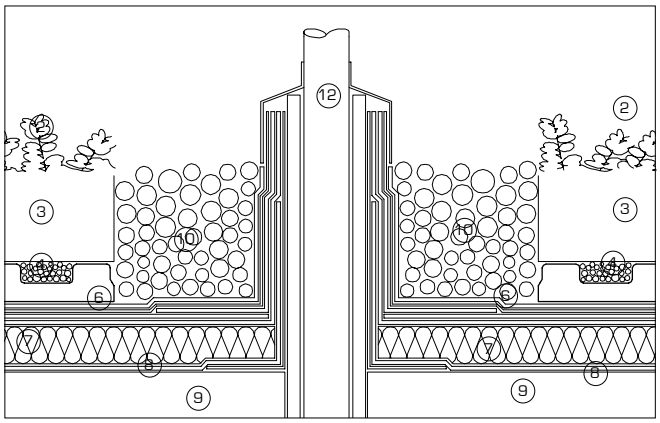
1	Waterproof membrane
2	Thermal insulation
3	Concrete deck
4	Paving slabs
5	Smooth pebbles
6	Parapet coping
7	Rainwater outlet
8	Opening for overflow
9	Balustrade
10	Pipe or duct
11	External wall
12	Rooflight



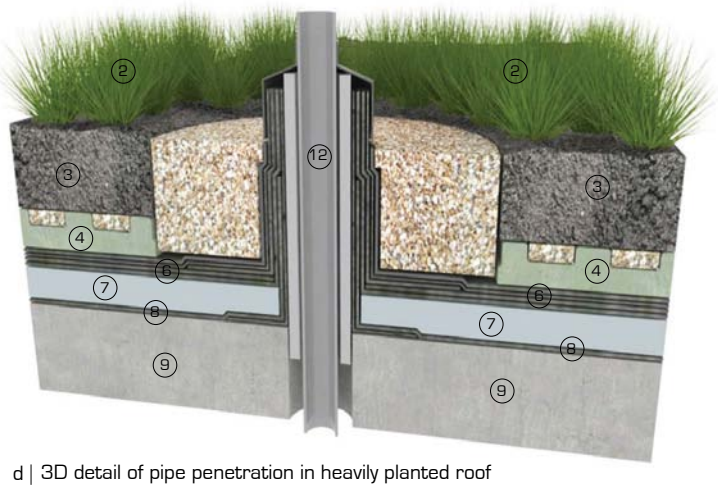
a | 3D detail of rainwater outlet in heavily planted roof



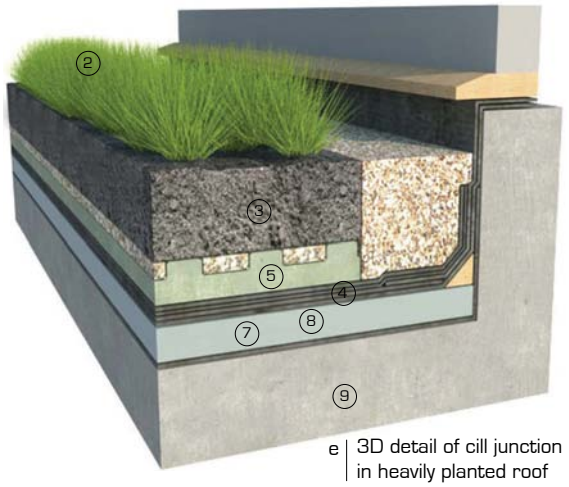
b | Vertical section 1:10. Heavily planted roof rainwater outlet detail



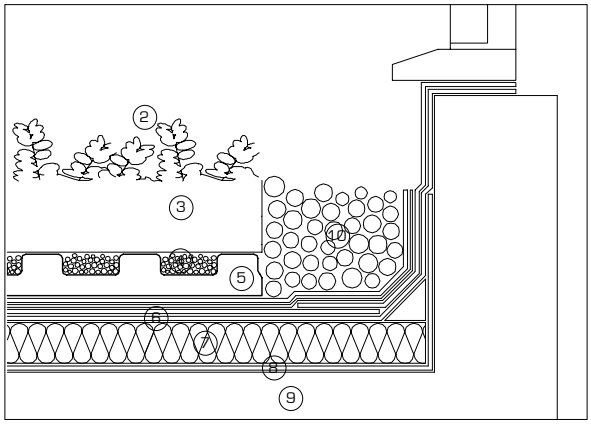
c | Vertical section 1:10. Heavy planting. Pipe penetration.



d | 3D detail of pipe penetration in heavily planted roof



e | 3D detail of cill junction in heavily planted roof



f | Vertical section 1:10. Heavy planting. Cill junction.

System design

Concrete decks used for planted areas can be waterproofed with either a concealed membrane or an exposed membrane, as discussed in the previous sections. Planted roofs are of two types: light-planted and heavy-planted. Unlike other concrete roof types, planted roofs are not always insulated as they often form the roof of underground structures such as car parks, providing a planted roof at ground level.

Light-planted roofs have resilient plants that require little or no irrigation and will grow in a thin layer of soil or organic growing medium (n). They are not usually used on a roof accessible to building users, but are seen from vantage points around the building. Light-planted roofs have plants and flowers that require little maintenance and do not usually have an irrigation system to supply water at controlled times, relying on rainwater and modest amounts of watering during maintenance at specific times of the year. These lightweight planted roofs suit a lightweight deck, such as a thin concrete shell, although profiled metal decks are commonly used as substrates. Maintenance access is provided by the pebble strips at the roof edges or by individual paving slabs that avoid the need to walk across the planting.

Heavy-planted roofs permit a wide variety of plants, shrubs and trees to grow on a concrete roof deck (a). Due to the size and intensity of the planting they require an automated irrigation system, usually from pipes set into the soil that provide a trickle of water fed to the soil at

g | 3D overview of concrete roof with heavy planting



Details

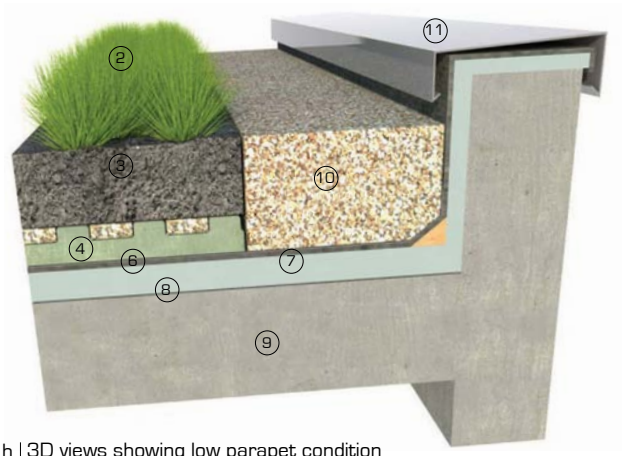
1	Light vegetation	8	Vapour barrier
2	Heavy vegetation	9	Concrete deck
3	Soil/growing medium	10	Smooth gravel
4	Filter sheet	11	Coping
5	Drainage layer	12	Pipe/ duct
6	Waterproofing layer	13	Supply pipe
7	Thermal insulation	14	Rainwater outlet
		15	Wall cladding

specific times which may vary during the course of the year. Heavy-planted roofs require regular maintenance provided by paved paths or by areas of grass (e).

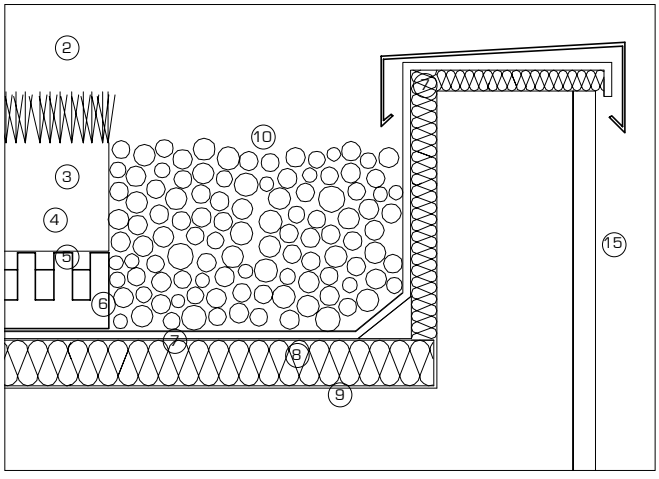
Both light-planted and heavy-planted roofs have drainage layers beneath the growing medium (4) that hold water and release it back to the plants when required. This allows the soil depth (3) to be much less than that which would be required for older landscaping methods, where the soil was expected to hold all the water. The reduced depth of soil allows planting to be considered for concrete roof structures that would require no significant strengthening in order to receive the added weight of soil. In terms of drainage it is estimated by manufacturers of proprietary systems that 50% to 90% of rainfall is retained in planted roofs, but this varies considerably with local climate conditions and rainwater drainage provision.

System details

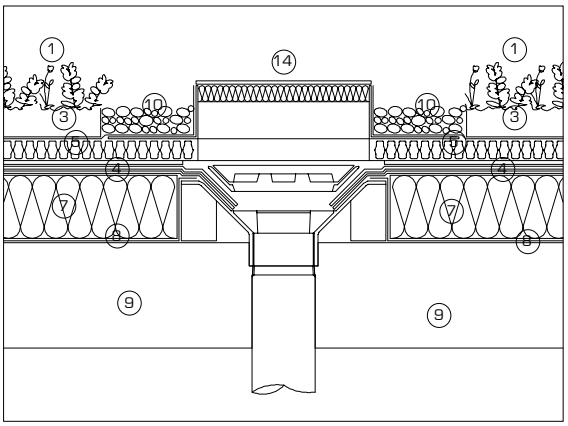
Both light-planted and heavy-planted roofs have a similar build-up, typically comprising a top layer of planting with a growing medium or soil beneath. A filter layer is set underneath, and below this, a drainage layer and moisture mat. Beneath this lowest layer is set thermal insulation if required (j). Although planted roofs provide a limited amount of thermal insulation from the soil, in practice this is reduced due to the varying amounts of water held within the soil. A root barrier is set beneath



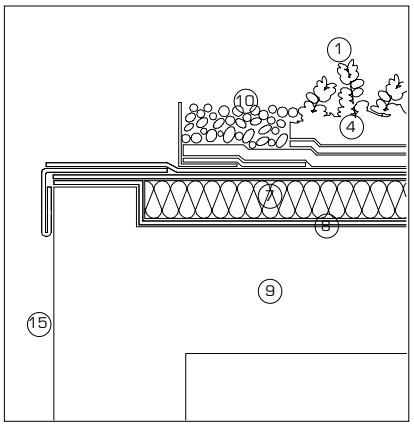
h | 3D views showing low parapet condition on heavily planted concrete roof



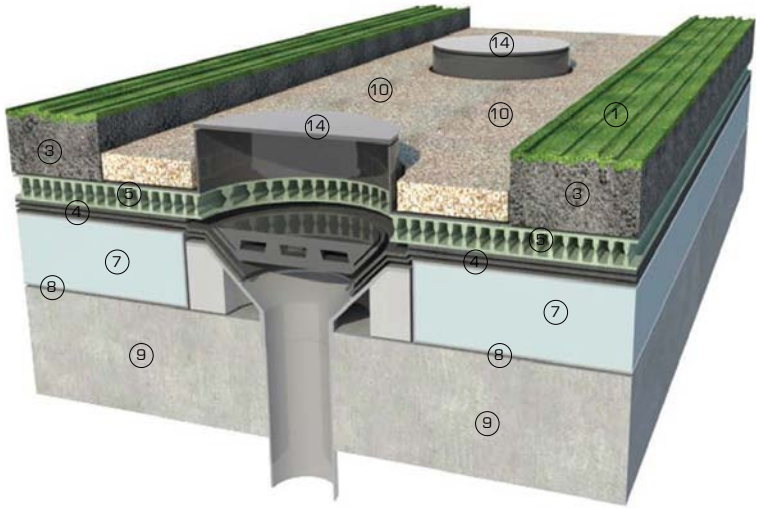
j | Vertical section 1:10. Heavy planting. Low parapet.



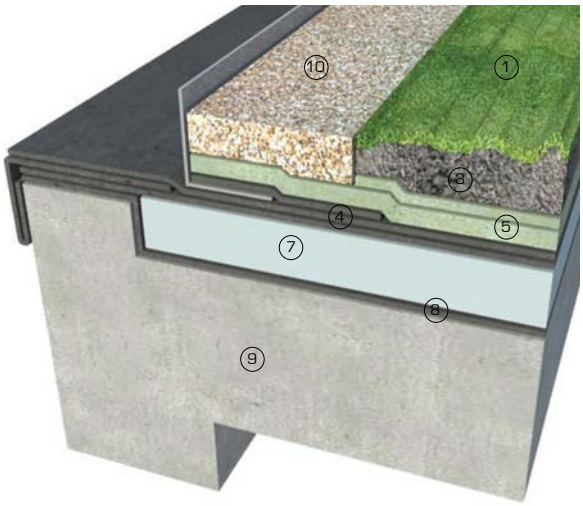
k | Vertical section 1:10. Light planting. Rainwater outlet



m | Vertical section 1:10. Light planting. Low parapet junction



n | 3D detail of rainwater outlet in lightly planted roof



p | 3D detail of low parapet in lightly planted roof

the insulation to protect the waterproof membrane, that is the bottom layer, bonded to the concrete roof deck. The root barrier is sometimes bonded to the waterproofing layer, usually when the complete build-up is a single proprietary system. To prevent the passage of organic matter and fine particles into the water drainage system, a filter sheet is set underneath the planting. This sheet is lapped up the sides of upstands where where it meets the edge of a natural planting layout (p).

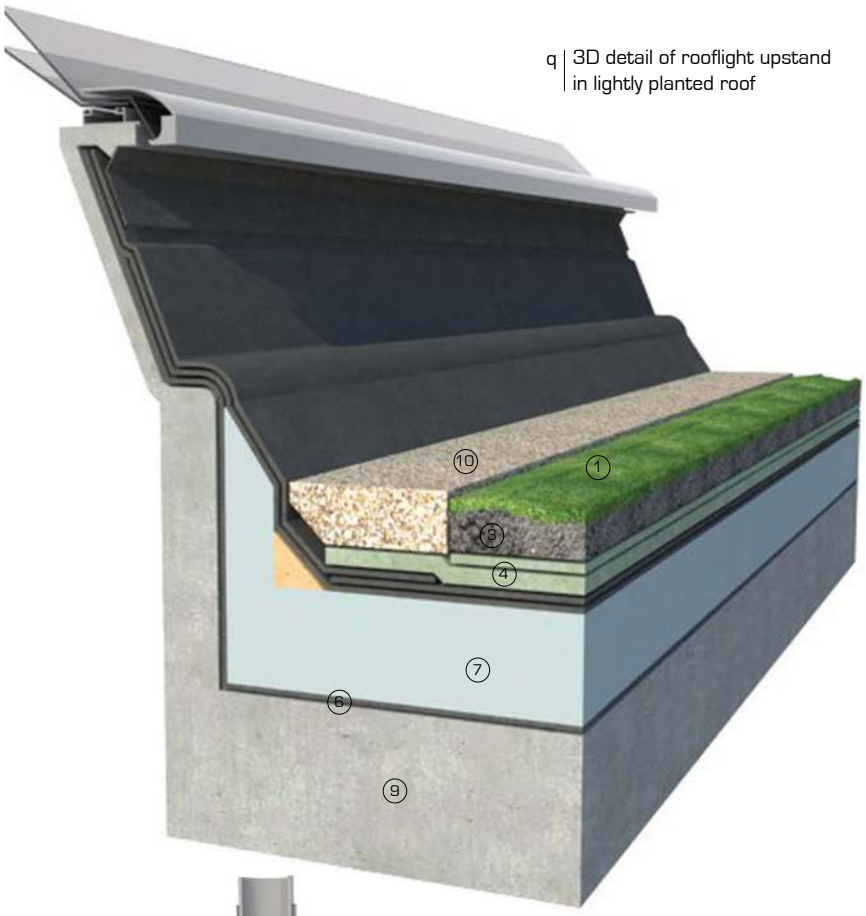
The drainage layer beneath the filter sheet retains water that drains through the planting. Water is retained in profiled troughs in a typically polystyrene egg-crate shaped tray that releases water back into the planting (5). This method also performs satisfactorily on sloping concrete roofs. Excess water is drained away through gaps between the drainage trays. The egg-crate form allows aeration, permitting the soil to absorb the water stored here. In drier months, water diffuses up through the soil to the plant roots. A moisture mat is often set under this layer to catch water that runs off the drainage layer. The mat is made from a durable fibre that retains moisture and nutrients as well as serving as protection to the root barrier beneath. It is not used in inverted roof configurations. In inverted roofs, a root barrier is set immediately below the insulation to protect the waterproof membrane forming the lowest layer. This layer prevents planting roots from damaging the waterproofing. In warm roof construction, the waterproof membrane is set on top of the thermal insulation, positioning the insulation within the building envelope. A vapour barrier is set between the thermal insulation and the concrete deck. In this configuration a moisture mat is set between the waterproof membrane and the drainage layer above.

The soil depth in light-planted roofs ranges from 50mm to around 150mm. Water is stored in the growing medium and drainage layer, making it efficient in mild, temperate climates (n). Light-planted roofs can be grown on both nominally flat roofs and on sloping roofs with a pitch of up to 25° to 30°. Heavy-planted roofs have a deeper drainage layer to provide greater water storage. The soil depth, in excess of 150mm, requires an automatic irrigation system to provide a reliable water supply coverage of the complete roof.

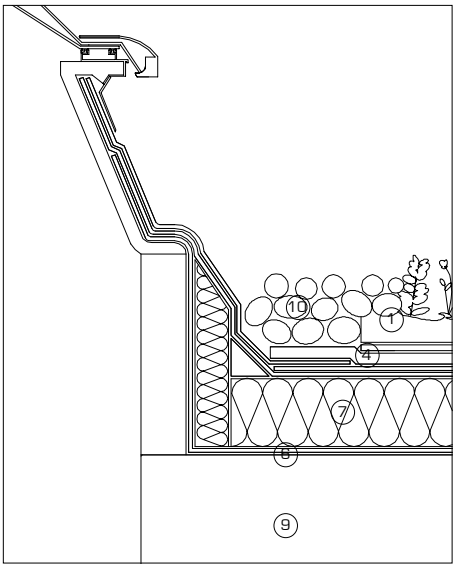
At upstands and eaves the same principles apply to planted roofs, as discussed in the previous sections. The waterproofing extends a minimum of 150mm above the level of the planting, providing a continuity from the roof membrane to the flashing at the top of the upstand or to the adjacent wall construction (q). Upstands for parapets and door sills, high walls and rooflights are formed by extending the waterproof filter sheet and root barrier up to a minimum of 150mm above the level of the soil or growing medium. The visible membranes and sheets are concealed with thermal insulation and typically either paving turned on edge, as per the paving used for adjacent access paving, or a metal sheet to match that of the parapet coping where a metal coping is used.

Details

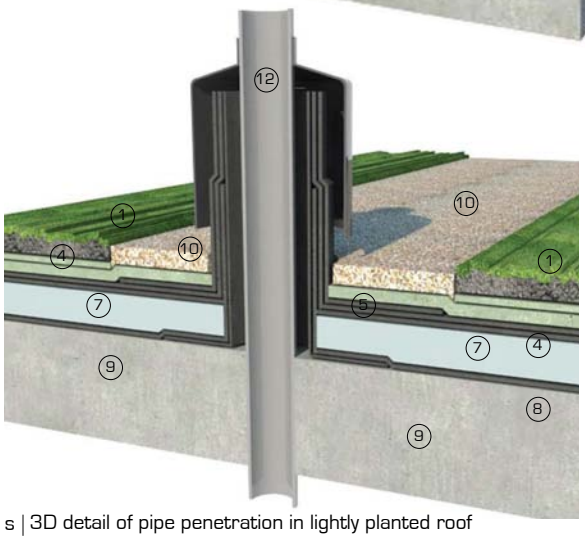
1	Light vegetation	8	Vapour barrier
2	Heavy vegetation	9	Concrete deck
3	Soil/growing medium	10	Smooth gravel
		11	Coping
4	Filter sheet	12	Pipe/ duct
5	Drainage layer	13	Supply pipe
6	Waterproofing layer	14	Rainwater outlet
7	Thermal insulation	15	Wall cladding



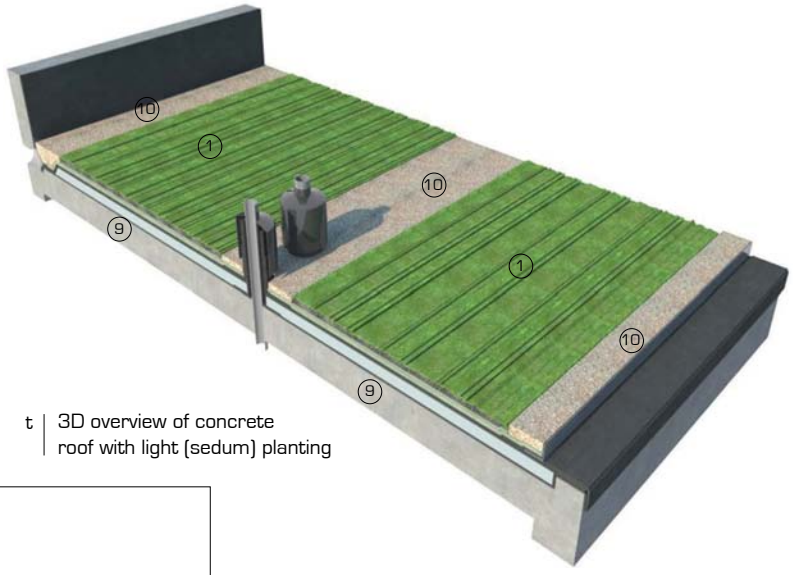
q | 3D detail of rooflight upstand in lightly planted roof



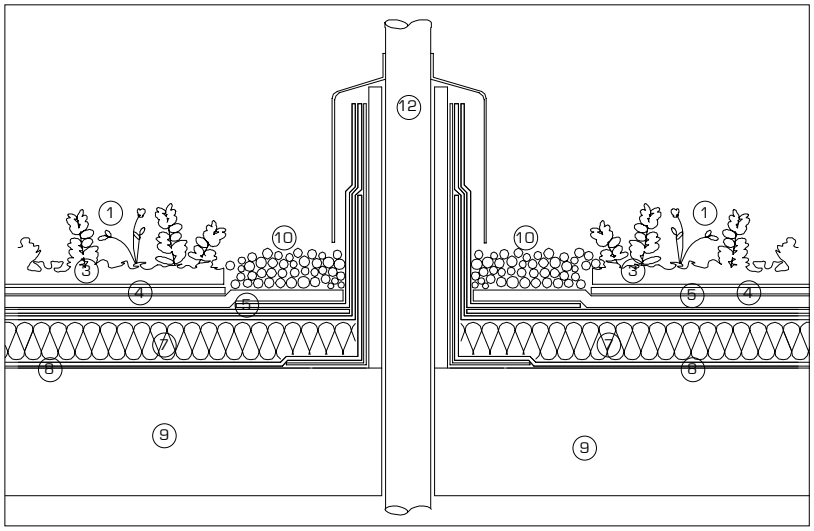
r | Vertical section 1:10. Light planting. Rooflight upstand



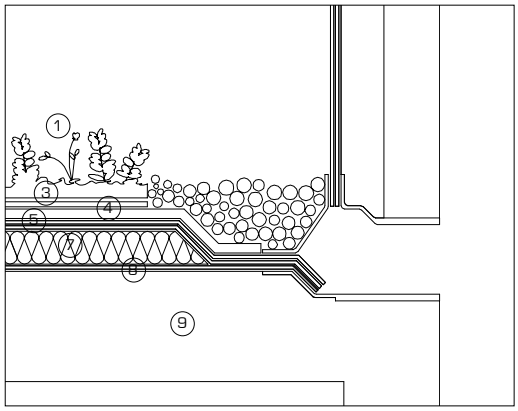
s | 3D detail of pipe penetration in lightly planted roof



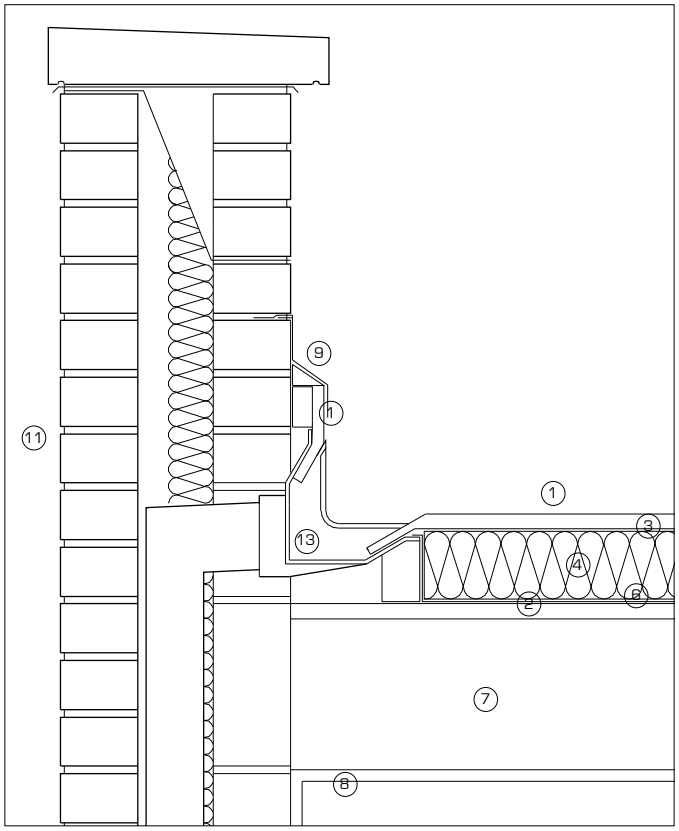
t | 3D overview of concrete roof with light (sedum) planting



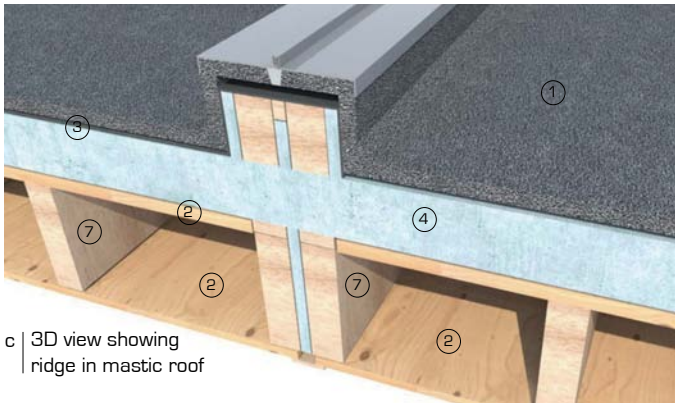
u | Vertical section 1:10. Light planting. Pipe penetration



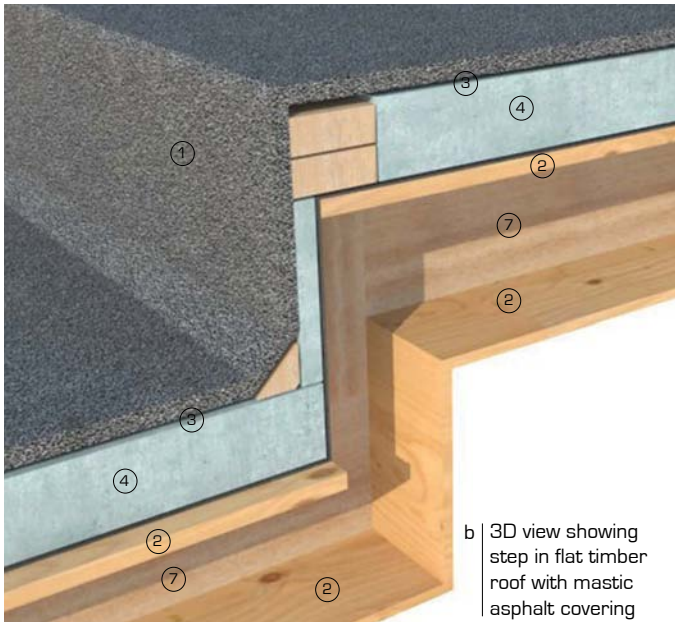
v | Vertical section 1:10. Light planting. Two-way outlet



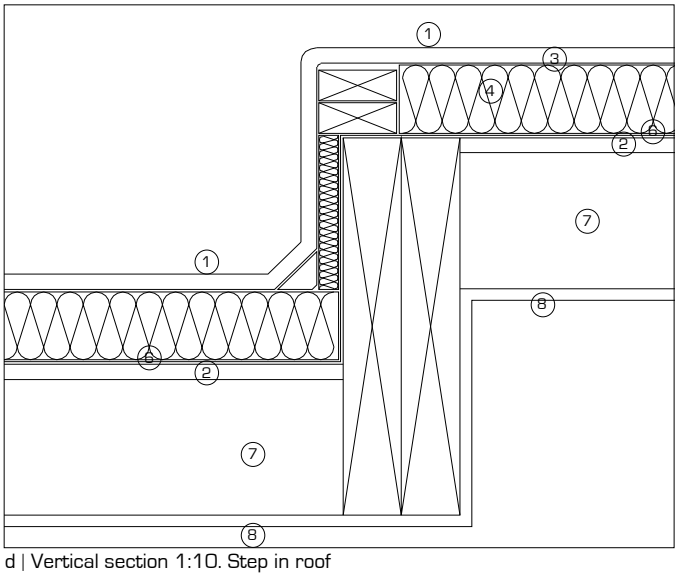
a | Vertical section 1:10. 2-way drain outlet



c | 3D view showing ridge in mastic roof



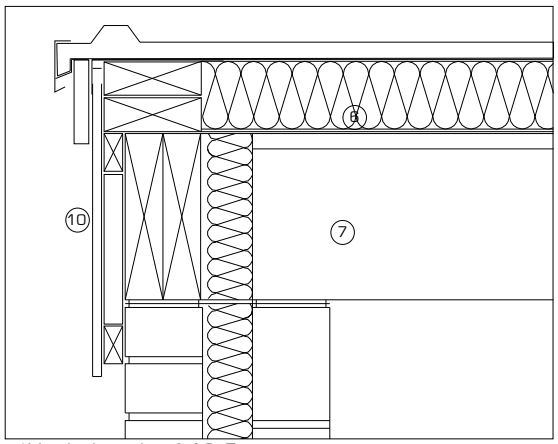
b | 3D view showing step in flat timber roof with mastic asphalt covering



d | Vertical section 1:10. Step in roof

Details

1	Mastic asphalt	8	Drylining/drywall internal finish
2	Plywood sheet or timber boards	9	Metal flashing
3	Separating layer	10	Fascia
4	Rigid thermal insulation	11	External wall
5	Freestanding timber upstand	12	Expanded metal lathing
6	Vapour barrier	13	Rain water outlet/other penetrations
7	Softwood joists		

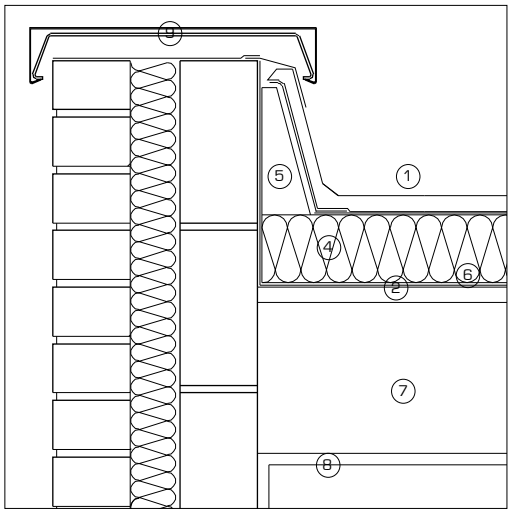


e | Vertical section 1:10. Eaves

System design

This section discusses flat timber roofs that use the common combination of bitumen sheet-based membrane as a waterproofing layer in a warm roof. Although other membrane materials are used on flat timber roofs as both warm and cold roofs, typically formed in elastomeric and thermoplastic membranes, their application is discussed in the earlier section on exposed membranes in concrete roofs (MCH_240). The principles of detailing covered in that section can be similarly applied to timber roofs. Bitumen-based sheet can also be used in 'inverted roof', or concealed membrane configuration, as described in that earlier section where the detailing is similar, but bitumen-based sheet is generally less robust than the membranes described in that section. Membranes applied to concrete decks are usually laid in hot liquid form and are reinforced to suit the specific conditions of folds and joints occurring within the structural deck. In this section the material is considered as an exposed and visible material on a relatively lightweight deck.

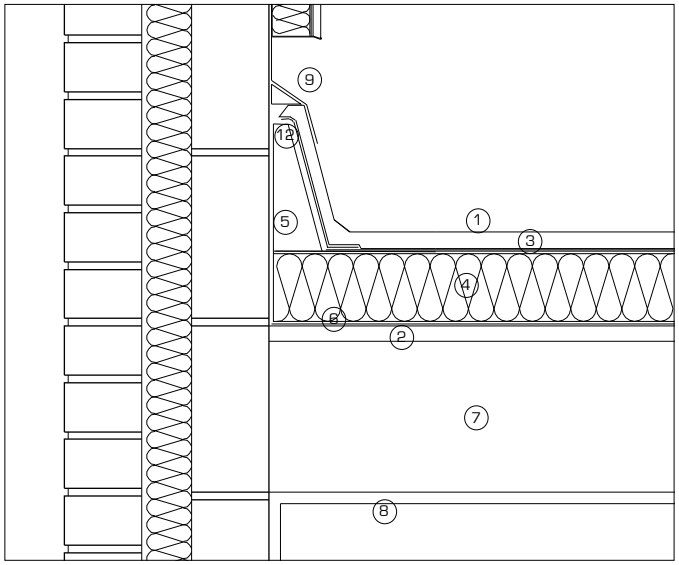
Bitumen sheet membranes are economic and are often used with timber roof decks which together provide an economic roof design for relatively small-scale applications, or designs with a complex geometry



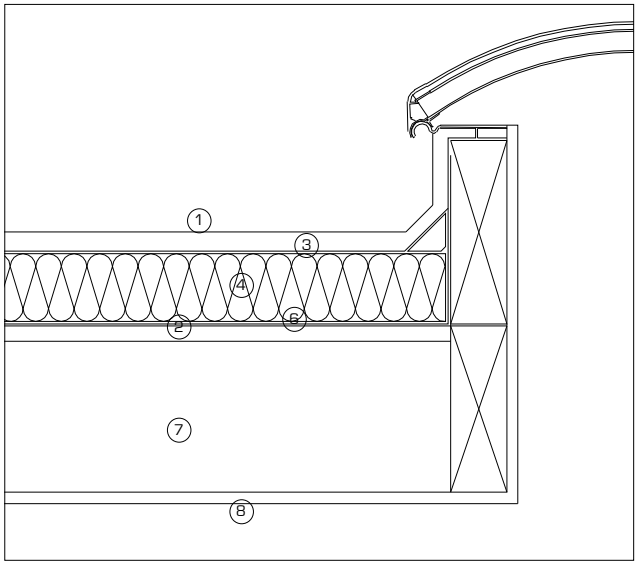
f | Vertical section 1:10. Low parapet wall



g | 3D view of low parapet wall



h | Vertical section 1:10. High parapet wall



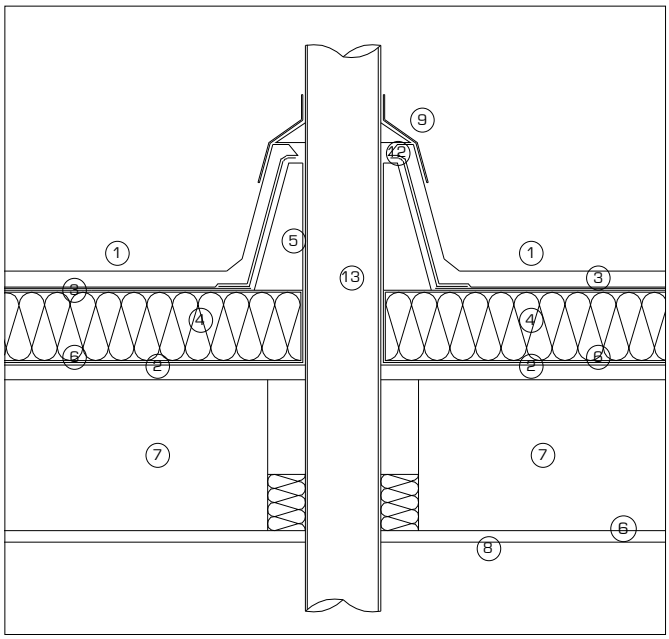
j | Vertical section 1:10. Rooflight junction

of low pitched roofs as are often used in housing and in school buildings (b). Bitumen-based membranes have developed over the past 25 years to compete with the newer elastomeric and thermoplastic materials by increasing their flexibility and making them thinner, requiring less material, which helps to reduce their overall cost. Bitumen-based membranes can also be used with concrete and metal decks, and the principles here can be applied in a similar way to those roof deck types.

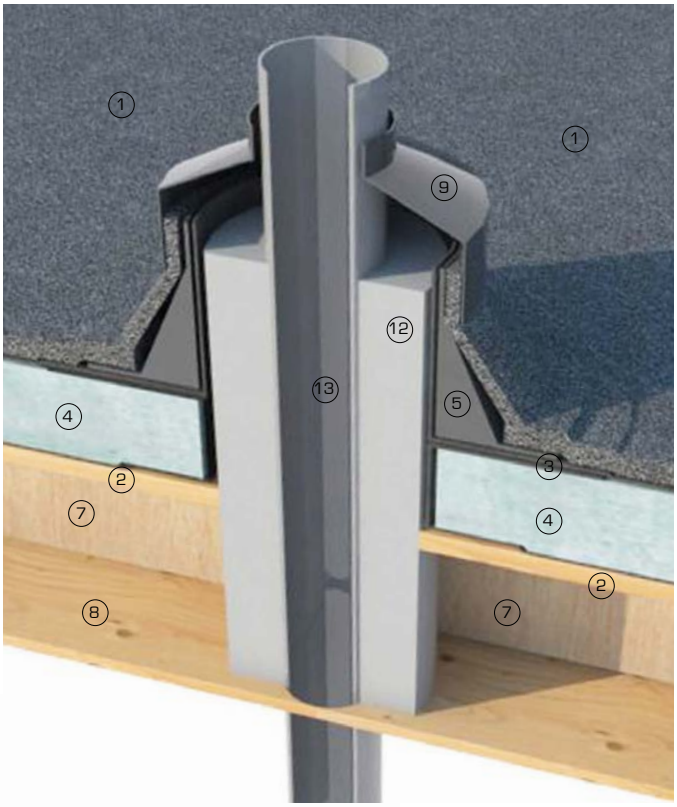
Bitumen-based sheet is manufactured in roll form in widths of around 1000mm, is black in colour, and is typically mixed with SBS (styrene-butadiene-styrene) polymers or with TPO (thermoplastic polyolefin) polymers. The addition of these polymers raises the melting point which ensures stability in hot weather, as well as increasing the flexibility of the material at low temperatures (usually in winter in temperate climates) and enhancing the fire resistance of the material. Bitumen-based sheet often has a glass fibre reinforced upper face to provide greater dimensional stability and resistance to accidental damage, as well as a polyester reinforced core to increase tensile strength. These sheet materials are typically around 4mm thick, depending on the proprietary system used. Even with these additives, bitumen-based sheet is slowly oxidised by heat, making the material gradually more brittle which eventually results in cracks. The polymer additives reduce this effect, particularly the TPO additives that help to increase the life of the material, which can now be up to around 25 years. TPO-modified sheet can be exposed to the effects of the sun, requiring no additional solar protection, since the material provides better UV resistance than older-type bitumen-based membranes. SBS-modified sheet is usually covered with stone chippings or solar reflective paint to protect them from the effects of the sun.

System details

Where plywood is used to form the structural deck of a timber roof, the joints between plywood boards are usually taped to provide a continuously smooth surface. On timber boarded decks, where this is not as practical a method, a thin layer of bitumen is laid onto the deck, applied typically in thick liquid form to seal the joints between the boards; the bitumen setting to form a smooth substrate. A vapour barrier is set onto the prepared timber deck, the barrier often being bitumen-based as part of a proprietary system. Rigid closed cell insulation such as polyurethane is bedded in hot bitumen onto the vapour barrier to hold



k | Vertical section 1:10. Pipe Penentration



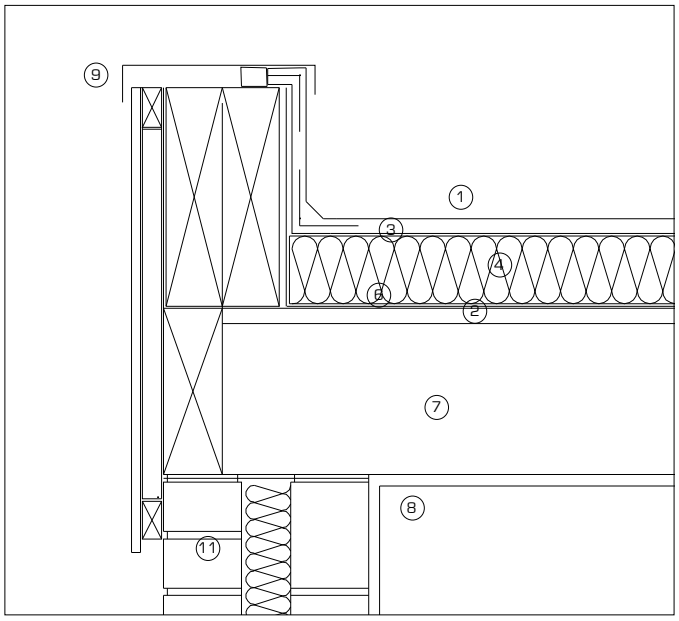


m | 3D views showing pipe penetration in mastic roof membrane

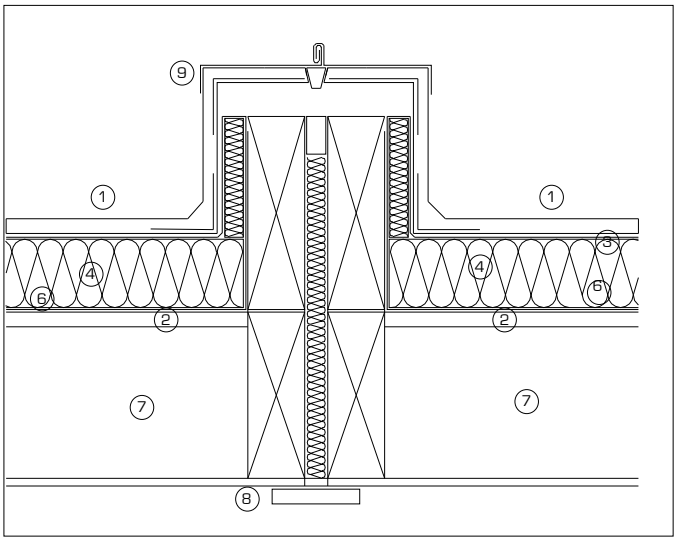
the insulation securely in place. A loose-laid perforated isolating layer is set onto the thermal insulation, which is used to allow the membrane and thermal insulation to release gases (which are formed as a result of bonding the bitumen to the insulation) into the isolating layer. The bitumen-based membrane is then bonded to the thermal insulation through the holes in the isolating layer (m).

Resistance to UV radiation is provided by either a coating of fine stone chippings or by aluminium solar reflective paint applied to the visible surface of the bitumen-based sheet. As a result of providing this additional UV protection, these coatings have the extra benefit of reflecting heat, which has the effect of reducing the surface temperature of the roof in order to reduce thermal expansion of the roof covering. Solar reflective paint gives the roof a metal appearance, which provides a visual alternative to the characteristic black colour of bitumen-based sheet. Membranes can also be provided with a solar protection layer during manufacture as part of a proprietary bitumen-based membrane system. Bitumen-based membranes are typically fixed by either torching, bonding or mechanical fixing methods. With torching, a flame is used to melt an adhesive layer on the underside of the sheet so that the membrane adheres to the substrate. Sheets are lapped by around 100mm to ensure a watertight seal. Torches are usually gas-fuelled, supplied from a small canister as part of a hand-held tool, or are supplied from a large gas cylinder set onto the roof to a variety of tools, either hand-held or wheeled, for larger-scale applications.

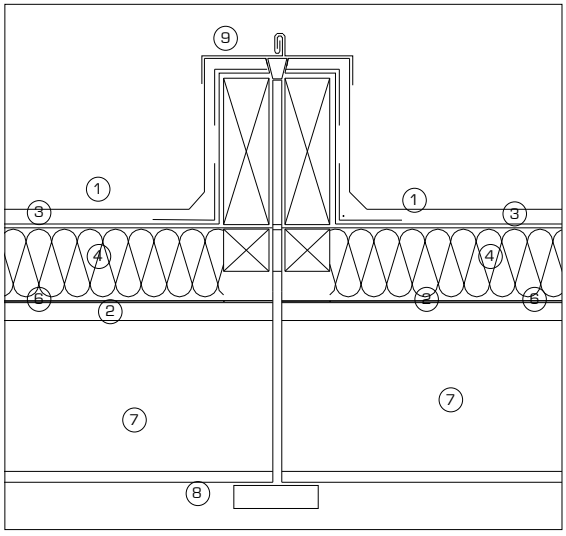
Upstands in bitumen-based sheets are formed by either fixing the sheet to the plywood face of a timber framed upstand or to the face of the thermal insulation, depending on the configuration of the external wall (n). Where a timber roof deck meets a masonry wall, with the concrete block wall being clad in timber rainscreen panels, the bitumen-based sheet is shown fixed to the face of the upstand (f). With a low upstand, the membrane continues up the full height and extends across the top of the wall underneath the coping (r). The roof membrane is made continuous with the waterproof seal of the external wall, with the membrane terminating against the bitumen paint finish of the external face of the blockwork wall. The coping can be made from any impervious and durable material. A pressed metal coping, overhanging on both sides, provides additional protection to the membrane as it folds over the top of the wall.



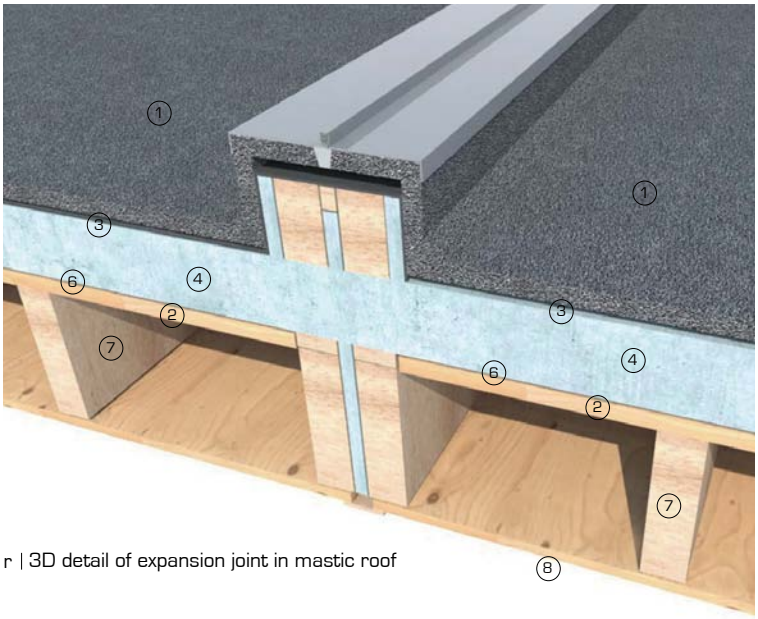
n | Vertical section 1:10. Eaves



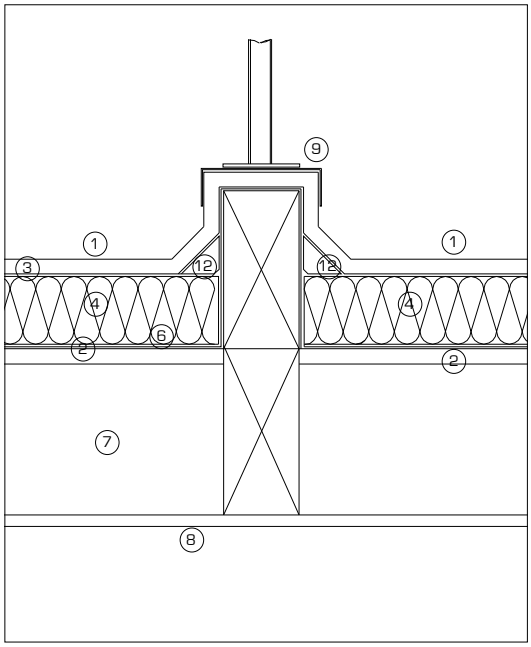
p | Vertical section 1:10. Expansion joint



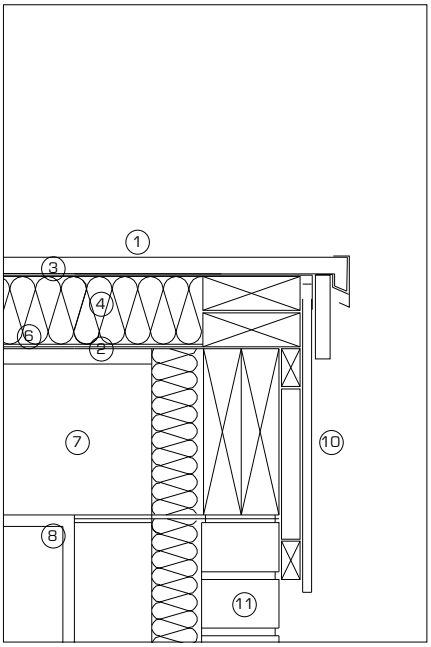
q | Vertical section 1:10. Expansion joint



r | 3D detail of expansion joint in mastic roof



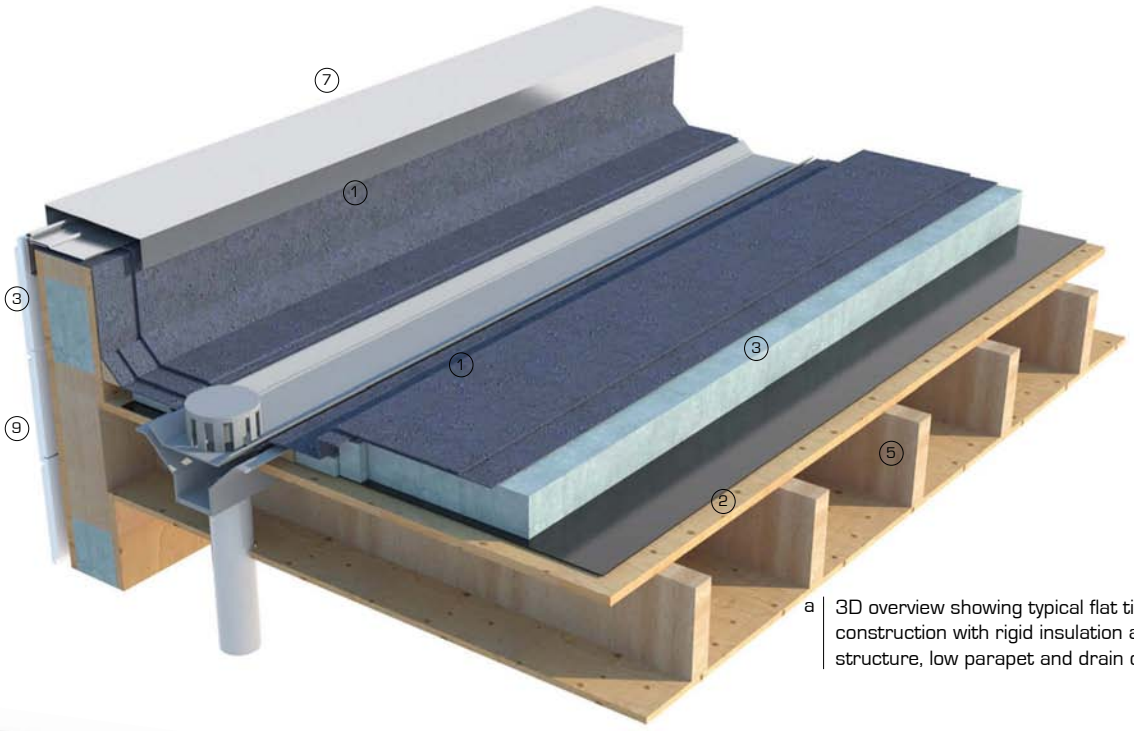
s | Vertical section 1:10. Balustrade



t | Vertical section 1:10. Eaves

Details

1	Mastic asphalt
2	Plywood sheet or timber boards
3	Separating layer
4	Rigid thermal insulation
5	Freestanding timber upstand
6	Vapour barrier
7	Softwood joists
8	Drylining/drywall internal finish
9	Metal flashing
10	Fascia
11	External wall
12	Expanded metal lathing
13	Rain water outlet/other penetrations



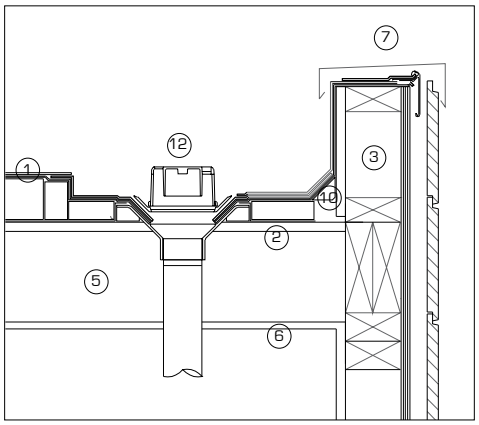
a | 3D overview showing typical flat timber roof construction with rigid insulation above roof structure, low parapet and drain outlet



c | 3D view showing drain outlet detail on flat timber roof arrangement



b | 3D view showing alternative drain outlet detail on flat timber roof arrangement

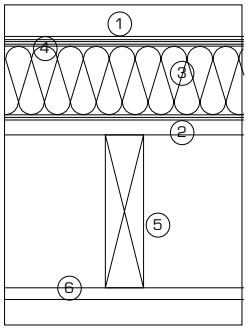


d | Vertical section 1:10. Low parapet wall with drain outlet

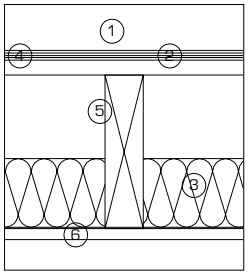
System design

Flat timber roofs are described as being in either a 'warm' roof or 'cold' roof configuration. In the warm roof configuration, thermal insulation is set on top of the timber deck, which is protected by a waterproof layer set onto its upper face. A vapour barrier is set between the thermal insulation and the timber deck (a). The roof build-up is not required to be ventilated as the timber structure is maintained at near internal temperature conditions. In the cold roof configuration, the waterproof layer is set directly onto the timber deck. Thermal insulation is set beneath the timber deck in the voids between the timber joists and air is allowed to circulate in the void to provide ventilation that prevents the possibility of rot forming in the timber. A vapour barrier is set beneath the insulation, on the warm (in winter) side of the insulation, with a dry wall or internal lining board set below this. In both warm and cold roofs, the vapour barrier prevents the passage of damp air up into the thermal insulation, where interstitial condensation can form that might damage the internal construction of the roof.

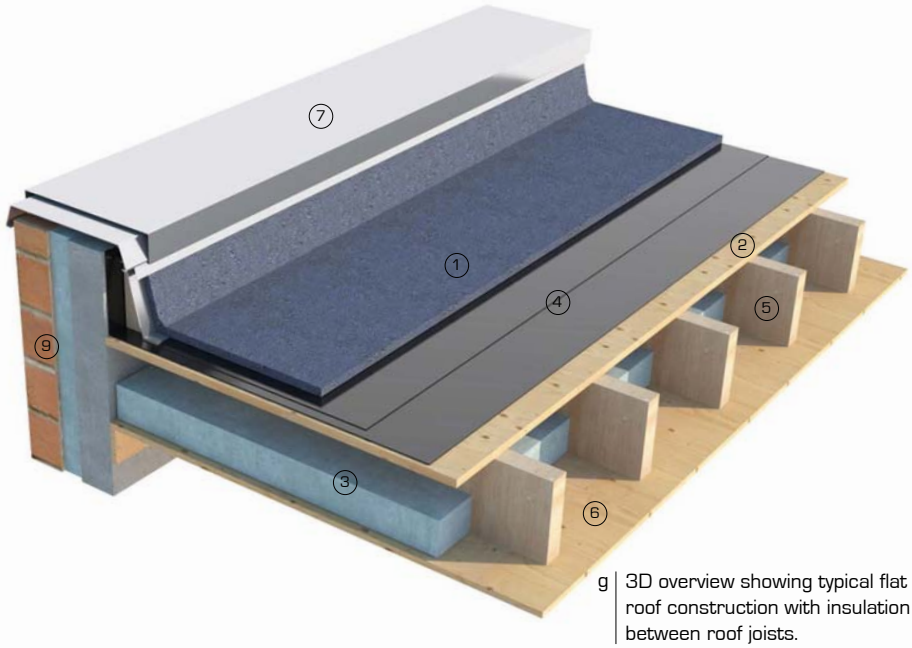
In a mastic asphalt waterproofed warm roof, thermal insulation is set on top of the timber deck, with an asphalt layer on top of this (h). A separation layer is set between the asphalt and the thermal insulation. A vapour barrier is set between the thermal insulation and the timber deck.



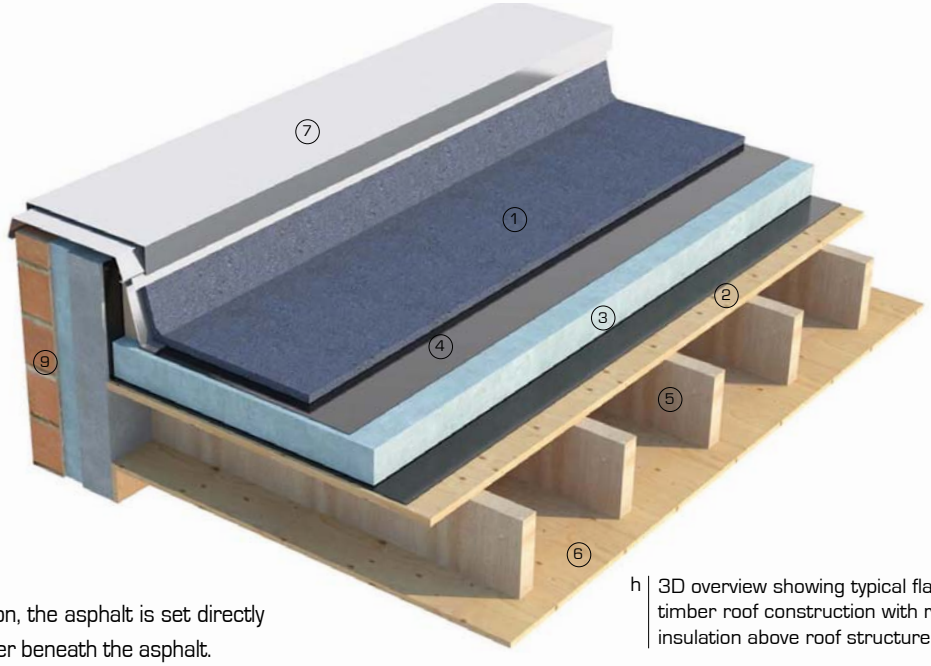
e | Vertical section 1:10. Flat roof with rigid insulation above roof structure



f | Vertical section 1:10. Flat roof with insulation between joists



g | 3D overview showing typical flat timber roof construction with insulation between roof joists.



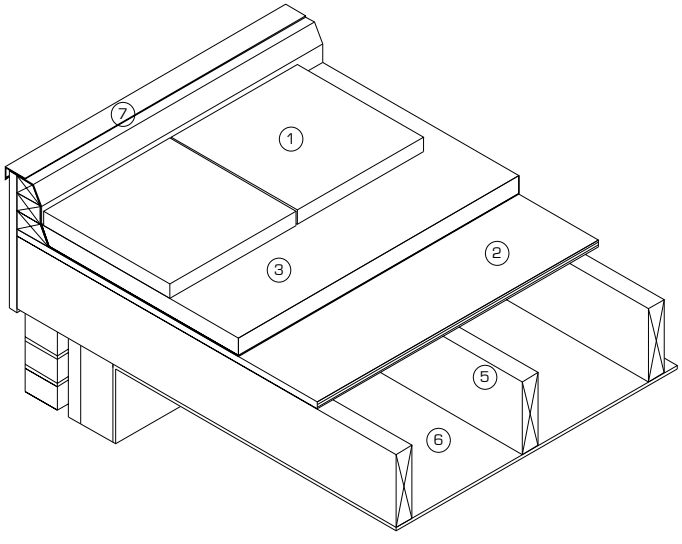
h | 3D overview showing typical flat timber roof construction with rigid insulation above roof structure

Details

1	Bitumen based sheet
2	Plywood sheet
3	Rigid thermal insulation
4	Vapour barrier
5	Softwood joists
6	Dry lining/drywall internal finish
7	Metal flashing
8	Timber upstand
9	External wall
10	Angle fillet
11	Proprietary skirt flashing
12	Rainwater outlet
13	Paving bonded to bitumen based sheet

In the mastic asphalt cold roof configuration, the asphalt is set directly onto the timber deck, with a separating layer beneath the asphalt.

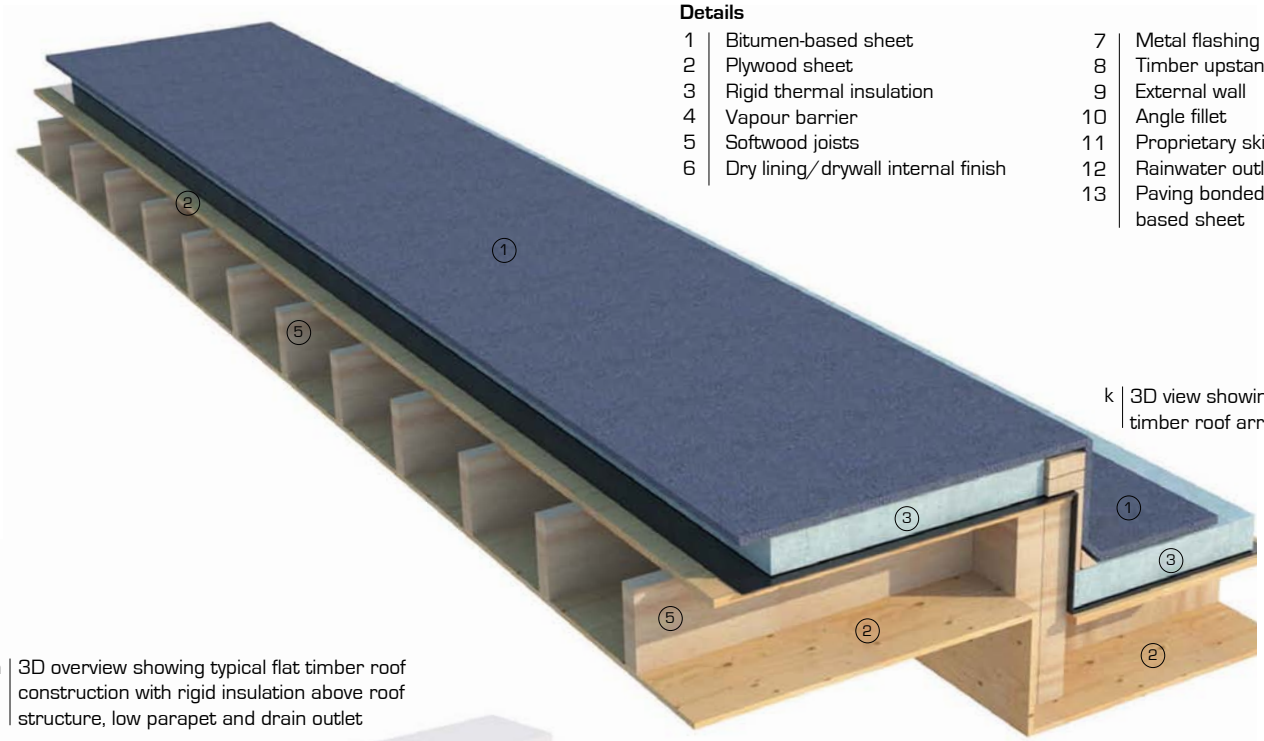
Mastic asphalt, used to form a continuous waterproof covering on flat or sloping roofs, sometimes contains polymer additives to provide stability at the relatively high temperatures experienced when exposed to the effects of the sun; as well as to provide flexibility to the material at low temperatures, which allows it to take up movements in the substrate. Asphalt is applied in a hot liquid form on site, allowing it to form a homogeneous material at complex junctions such as at upstands, roof penetrations and changes in level (d). It was used more commonly 25 years ago, and its popularity is being challenged by single layer sheet membranes, which have greater strength, flexibility, a higher melting point and UV resistance. However, the use of this material is set to continue, mainly as a concealed membrane, but its use as an exposed membrane is discussed here since this application is much more common in timber construction. Mastic asphalt is laid on rigid substrates, typically reinforced concrete decks, but its use as an exposed membrane on a timber deck is set to continue, particularly as a result of additives which make the material more flexible than was previously the case. In warm roof construction, a protective surface is usually applied to all exposed



j | 3D isometric showing typical flat timber roof construction with rigid insulation above roof structure

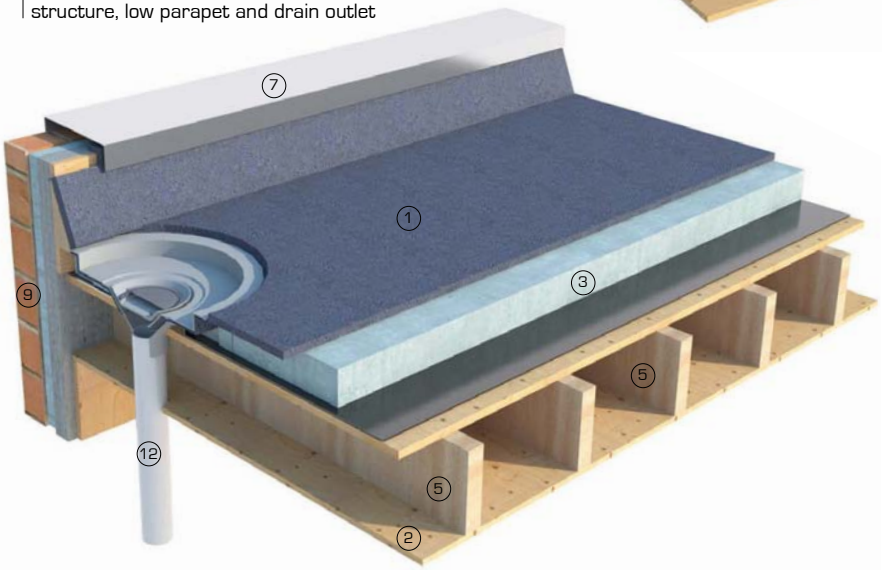
Details

1	Bitumen-based sheet
2	Plywood sheet
3	Rigid thermal insulation
4	Vapour barrier
5	Softwood joists
6	Dry lining/drywall internal finish
7	Metal flashing
8	Timber upstand
9	External wall
10	Angle fillet
11	Proprietary skirt flashing
12	Rainwater outlet
13	Paving bonded to bitumen based sheet



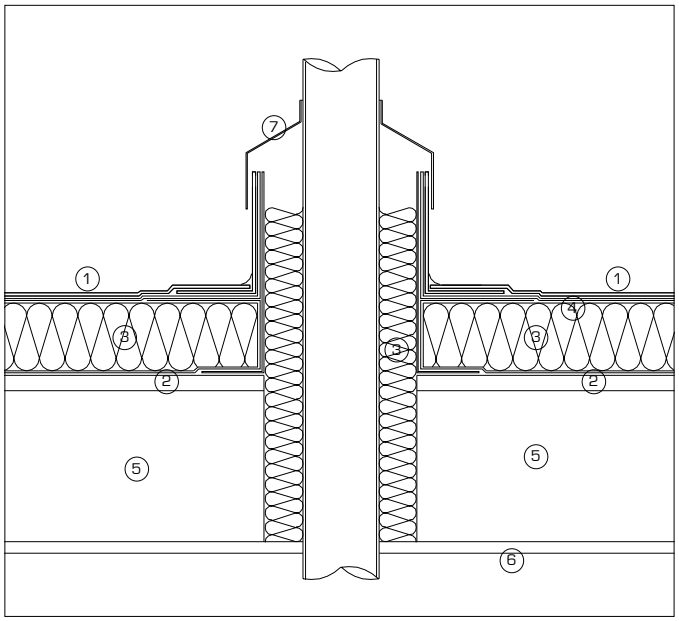
k | 3D view showing step in flat timber roof arrangement

m | 3D overview showing typical flat timber roof construction with rigid insulation above roof structure, low parapet and drain outlet

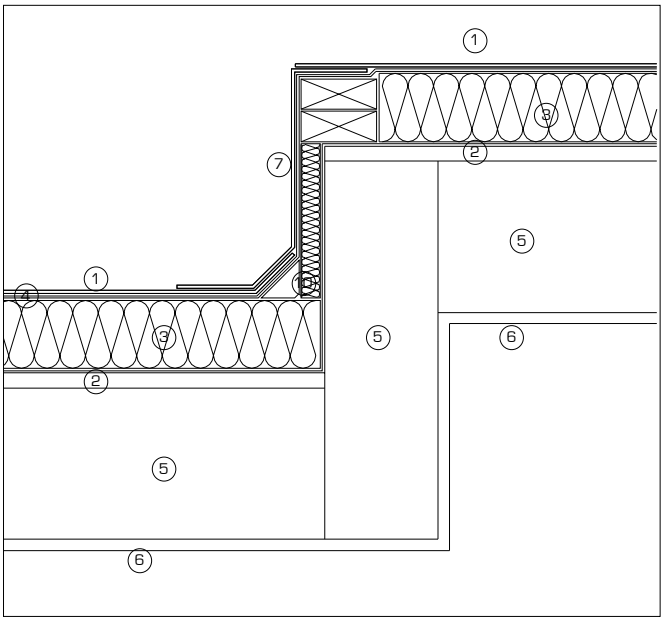




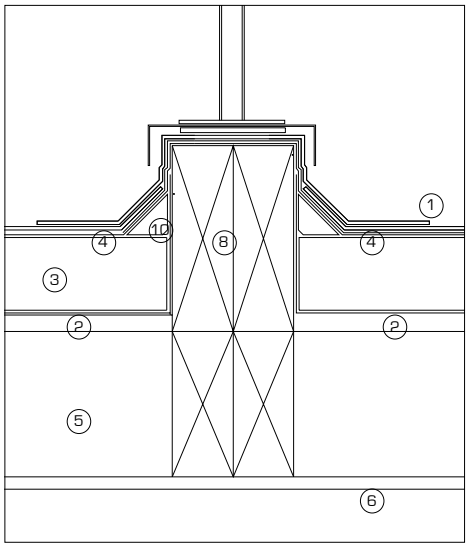
n | 3D detail showing step in timber roof construction



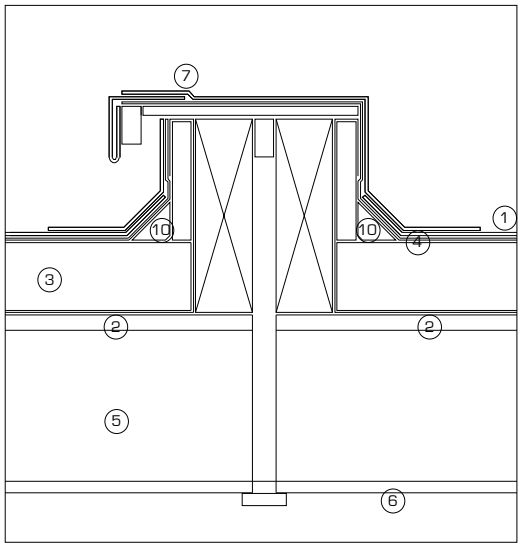
p | Vertical section 1:10. Pipe penetration



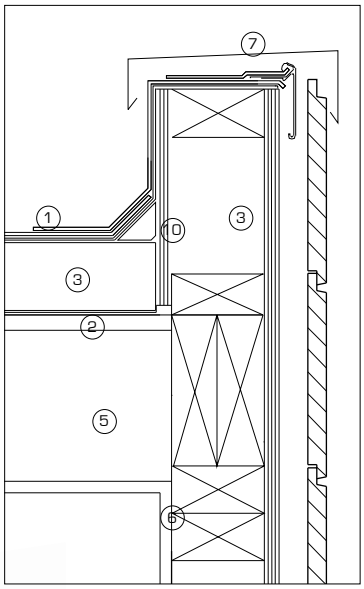
q | Vertical section 1:10. Step in roof



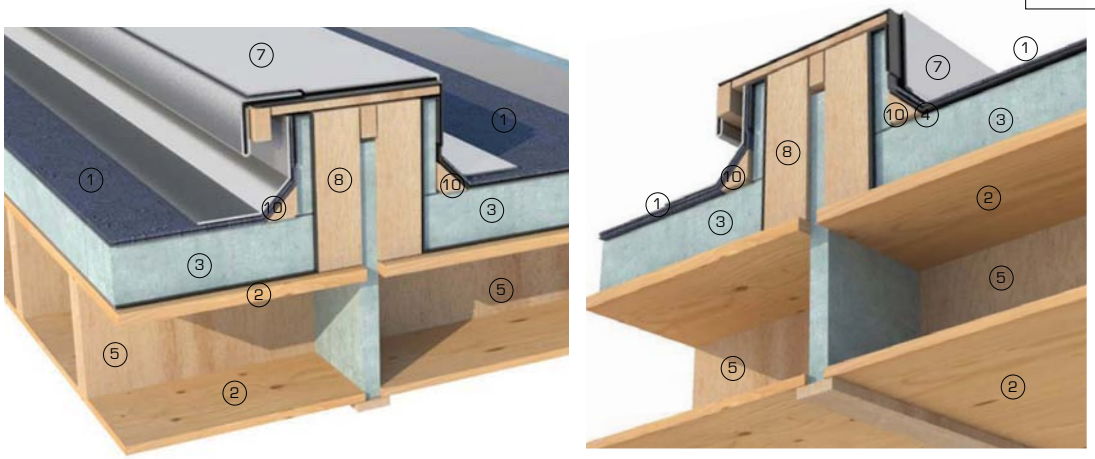
r | Vertical section 1:10. Balustrade detail



s | Vertical section 1:10. Expansion joint



t | Vertical section 1:10. Low parapet wall



u | 3D views showing expansion join in typical timber flat roof construction

areas with a solar reflective paint, stone chippings or thin paving slabs which are bedded into the asphalt surface with a proprietary adhesive. A single layer of 10mm – 14mm stone chippings is used as a permanent surface protection for asphalt. The chippings are usually bonded to the asphalt after the asphalt has cooled, with a bitumen solution to provide only a limited bond. This allows the chippings to be removed easily at a later date for repair and maintenance work.

System details

At upstands, where the asphalt is usually set vertically, or at a steep slope, the material is laid in three coats (n). The first coat is very thin in order to key in the substrate, then two further separate coats are applied to give an overall thickness of around 20mm. In forming an upstand, sheathing felt is fixed to the substrate; often a separate upstand fixed to the roof, as mentioned earlier. Expanded metal lathing, typically at 150mm centres, primed in bitumen, is fixed to the face of the sheathing layer, which provides a 'key' to which the asphalt will bond. Where the upstand is formed in lightweight concrete block, the surface is faced with either a sand cement render, or metal laths and sheathing felt is used as described.

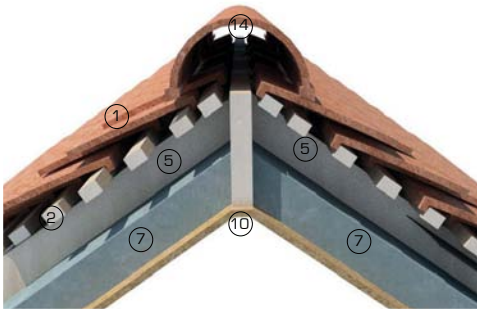
Trims to verges and eaves are formed with a GRP or aluminium trim in order to support the bottom edge of the asphalt (h). Some installations use no trim at all, but the edge becomes vulnerable to damage and can result in a visually uneven appearance. When the asphalt edge is terminated by a gutter, a metal flashing can be set under the bottom of the asphalt (b). Verges can be formed by creating an asphalt upstand, built to a height of around 50mm to suit the expected flow from the roof. An alternative detail is to stop the asphalt at the edge of the roof and terminate in a metal strip so that the asphalt cannot be seen from below, but in practice it can be difficult to achieve a reliable seal between the asphalt and the metal trim.

Penetrations through an asphalt-covered roof are formed by extending the asphalt up by 150mm to create a collar round the material. The top of the asphalt collar has an apron flashing around it to protect the top of the asphalt. An alternative method of sealing a roof penetration is to form a complete upstand around the penetration which can be insulated to the top of the opening (d). An insulated metal panel can then be mechanically fixed and sealed, or bonded, to the duct or pipe creating the penetration. An additional secondary seal, formed typically with either EPDM or metal sheet, forms a secondary seal to this penetration.

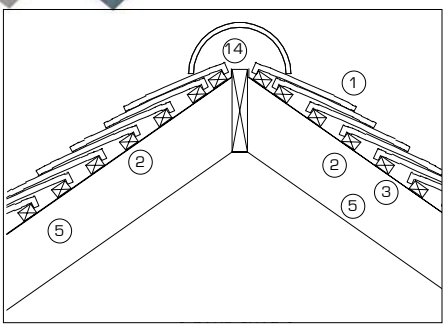
Gutters can be formed to any shape created within the timber deck since asphalt can be laid to suit a complex geometry without the need for joints in the material. Where the gutter is formed as a parapet gutter at the base of the tiled roof, the asphalt is carried up over the tilting fillet of the tiled roof. Rainwater outlets are formed by setting the outlet at the level of the structural deck. The asphalt is stepped down with 45° folds down into the rainwater outlet, and the metal grating and cover is fixed down onto this (b). The sheathing felt extends up to the edge of the rainwater outlet.



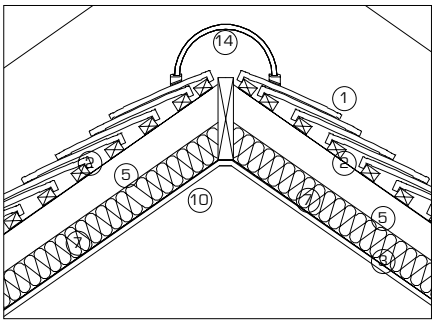
a | 3D view of ventilated roof with terracotta tiles



b | 3D view of ventilated roof with terracotta tiles



c | Vertical section 1:20. Unventilated roof



d | Vertical section 1:20. Ventilated roof

System design

Clay tiles for roofs are most commonly made from clay or concrete. In the clay type, natural clay is mixed with additives such as quartz, mica, iron oxide and crystalline aluminium oxide. Clay tiles are fired in a kiln at around 1100°c to make the material both rigid and resistant to moisture penetration. Plain tiles are used on pitched roofs ranging from vertical tile hanging (f) to pitches as low as around 35° above the horizontal (a). Interlocking tiles with grooves and complex laps can be used down to a minimum pitch of 22.5° above the horizontal. Concrete tiles are made from aggregate and Portland cement, which are mixed together and then cured in temperature-controlled chambers in the factory. Their appearance tends to imitate those of traditional clay tiles in both shape and variety of colour, but large interlocking tiles are available in sizes that are difficult to achieve in clay. In common with clay tiles, concrete plain tiles are used in roof pitches down to 35° above the horizontal. An advantage of concrete tiles over clay tiles is that some concrete interlocking tiles can be used for pitches as low as 12.5° above the horizontal.

Both tile types are fixed to timber battens set horizontally, that is, at right angles to the direction of the slope. The battens are fixed onto roofing felt, which forms a second line of defence and a full weathertight barrier to the roof. The roofing felt is set on timber rafters (sloping timbers) or full timber trusses. The tiles provide the first line of defence against rainwater penetration as well as protecting the roofing felt from direct windblown rain, the effects of the sun, and also protecting the felt from accidental damage (b). Many tile shapes and profiles are available which have been developed from historical examples. The design life for tiled roofs in both clay and concrete types is around 30 years, but they are actually expected to last for around 100 years.

Like flat roofs, pitched roofs are formed as either warm roofs or cold roofs. In the cold roof, horizontal joints are insulated and the void is ventilated to ensure that any condensation forming in the roof void can escape, which avoids damage to both the timber and the thermal insulation (d). In recent years it has become more common to use a vapour permeable membrane or 'breather' membrane as the underlayer to the tiling instead of waterproof roofing felt. This is done to avoid ventilating the roof void, which can become very damp in temperate climates during winter.

In the warm roof, the sloping rafters are filled with thermal insulation in order to allow the internal space of the roof void to be used. As with the cold roof, a vapour barrier is set between the thermal insulation and the internal dry wall lining. A vapour permeable membrane is set on the outside face of the sloping rafters as an underlay to the tiling. If the insulation completely fills the void between the rafters, then this breather membrane serves to allow moisture trapped within the construction to escape. If the thermal insulation does not fill the void and is set against the internal dry lining, then the void between the insulation and the breather membrane is ventilated at the ridge

e | Vertical section 1:20. Ridge detail for ventilated roof

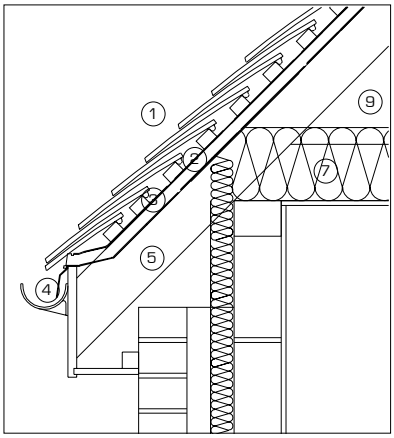


f | 3D view of timber shingles on timber roof construction

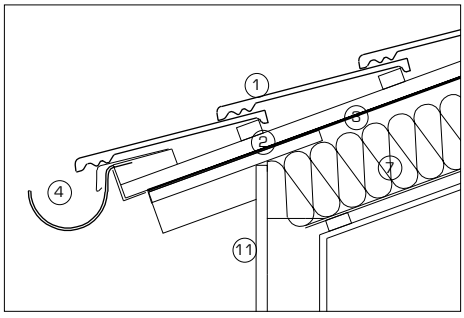
g | 3D view of timber shingles on timber roof construction

Details

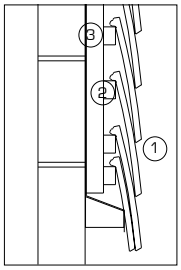
1 | Roof tiles, slates or shingles (tiles shown)
2 | Softwood battens
3 | Roofing felt
4 | Gutter
5 | Softwood rafter
6 | Ventilation void
7 | Thermal insulation
8 | Vapour barrier
9 | Softwood joist
10 | Dry lining/drywall internal finish
11 | Soffit board to conceal rafters but allow ventilation to air gap behind
12 | Fascia board
13 | Supporting wall (brick cavity wall shown)
14 | Ridge capping (ridge tile shown)
15 | Metal flashing
16 | Standing seam sheet



h | Vertical section 1:20. Eaves detail



j | Vertical section 1:20. Eaves detail for profiled tile

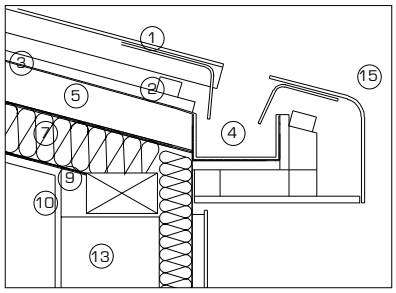


k | Vertical section 1:20. Tiles applied to vertical wall

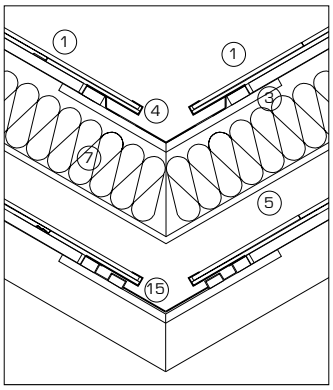
m | 3D view showing slate tiles on unventilated timber roof at ridge



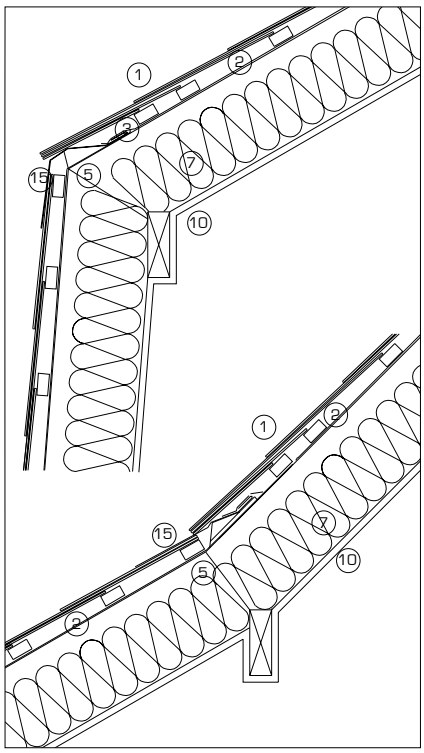
n | 3D section through slate tiles on unventilated timber roof showing valley and fold details



p | Vertical section 1:20. Eaves detail. Standing seam roof covering



q | Vertical section 1:20. Valley details for ventilated and unventilated roof



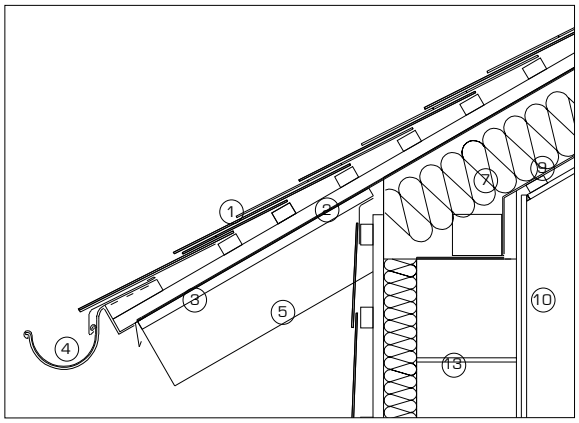
r | Vertical section 1:20. Internal fold

and at the eaves (c). Where a breather membrane is used, the cavity between the outside face of the membrane and the tiles is increased from 25mm to 50mm with counter battens to allow the air within the void to move more freely, ensuring that vapour being released to the outside can be dispersed easily (g).

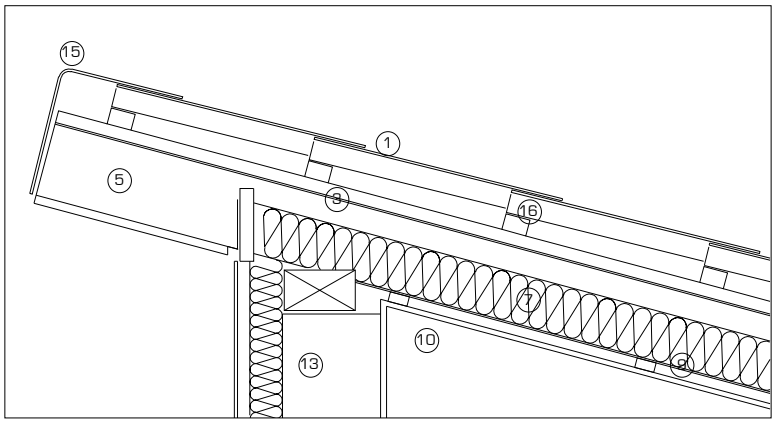
System details

Both plain tiles and interlocking tiles are terminated at their base with a gutter (p). In order to maintain a constant pitch of tiles down to the gutter, the bottom row of battens is raised up on a wedge-shaped timber profile called a tilting fillet. This allows the underlay to meet the underside of the bottom tile, and drain both rainwater running down the tiles as well as any moisture running down the underlay into the gutter. A ventilator, typically in PVC-U, is set between the bottom tile to ventilate either the roof void in a cold roof, or the cavity between the underlayer and the tiles in a warm roof configuration.

In the cold roof version the proprietary ventilator is set beneath the underlayer. Fresh air is allowed to flow into the ventilator set beneath the bottom tile and is released into the roof void without affecting the thermal insulation of the roof at ceiling level, which is continuous between wall



s | Vertical section 1:20. Eaves detail of slate tile



t | Vertical section 1:20. Ridge detail. Metal tiles on timber roof



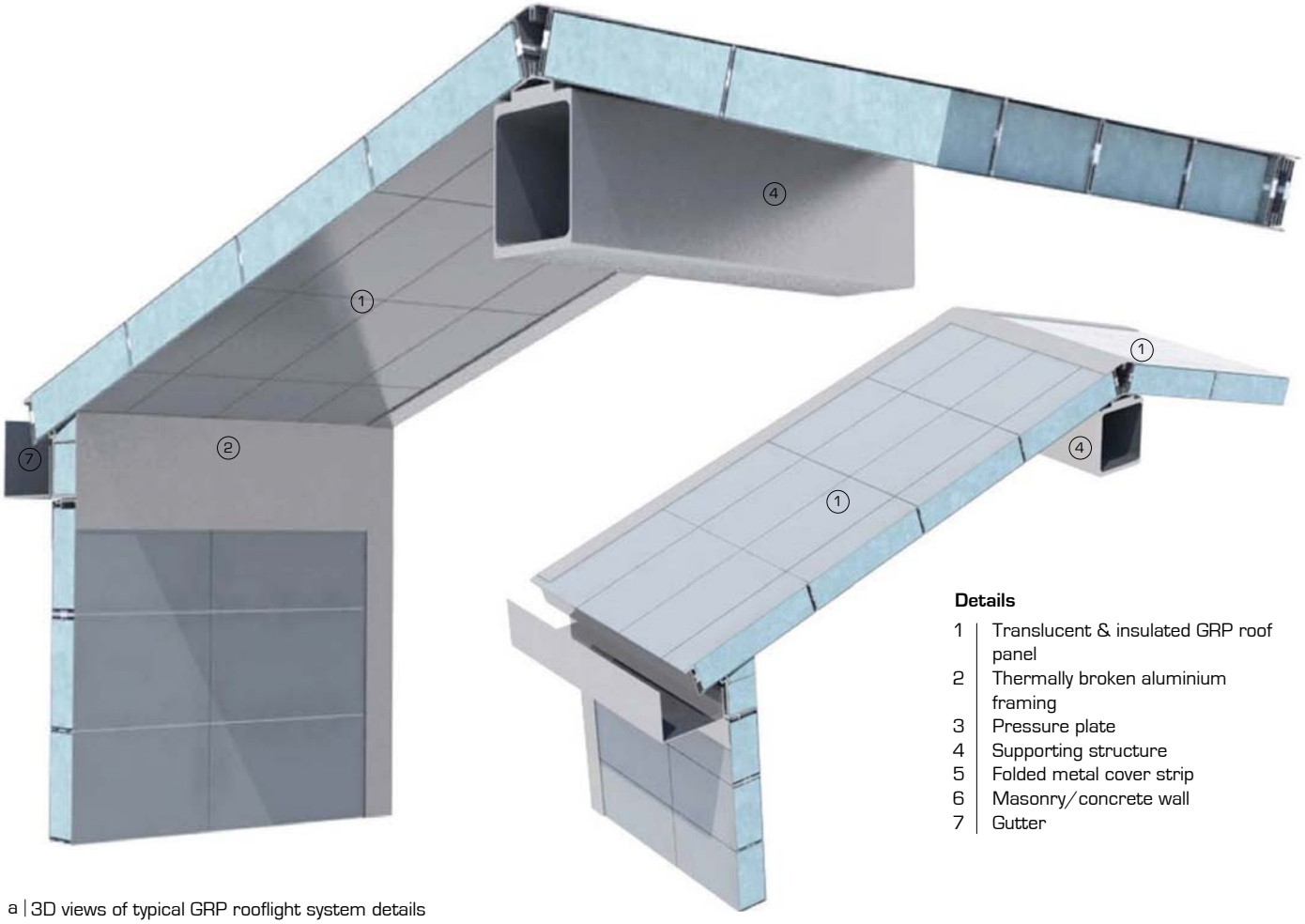
u | 3D section through standing seam roof on timber structure

and roof. In the warm roof version, a ventilator set between the bottom tile and the felt underlay introduces air into the void between the tile and the breather membrane. The thermal insulation either continues to the fascia board and then returns horizontally back from a continuity with the wall insulation, or alternatively the wall insulation continues vertically until it reaches the sloping insulation set between the rafters (u). In the second version, the void forming the fascia and soffit immediately beneath it is in 'cold' roof configuration and is required to be ventilated in order to avoid damp, stagnant air from damaging the timbers.

Where a sealed ridge is required, ridge tiles are either bedded in a sand cement mortar, or are dry-fixed with metal screws, typically stainless steel, where a rapid installation is required (m). For ventilated ridges, proprietary fixings usually made in PVC-U with ventilation slots are used to ventilate either the batten cavity between the underlay and the tiles in a warm roof, or the roof void in a cold roof configuration (a). Where the batten cavity is ventilated, the cavity is sealed across the ridge. Air is allowed to pass through a gap between the bottom of the ridge tile and the roof tile immediately beneath; the gap being formed by the PVC-U ventilator. Where the complete roof void is vented to the outside in a cold roof, a gap of around 10mm in the underlay is formed at the ridge.

Details

1	Roof tiles, slates or shingles (tiles shown)
2	Softwood battens
3	Roofing felt
4	Gutter
5	Softwood rafter
6	Ventilation void
7	Thermal insulation
8	Vapour barrier
9	Softwood joist
10	Dry lining/drywall internal finish
11	Soffit board to conceal rafters but allow ventilation to air gap behind
12	Fascia board
13	Supporting wall (brick cavity wall shown)
14	Ridge capping (ridge tile shown)
15	Metal flashing
16	Standing seam sheet



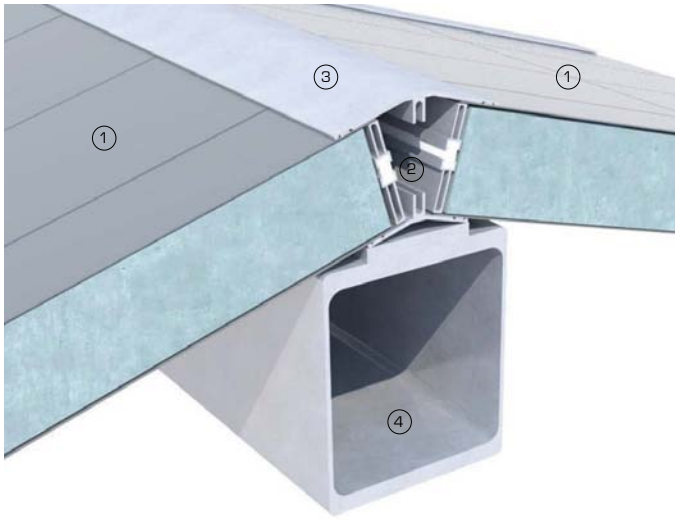
Details

1	Translucent & insulated GRP roof panel
2	Thermally broken aluminium framing
3	Pressure plate
4	Supporting structure
5	Folded metal cover strip
6	Masonry/concrete wall
7	Gutter

a | 3D views of typical GRP rooflight system details



c | 3D view of typical gutter/eaves detail

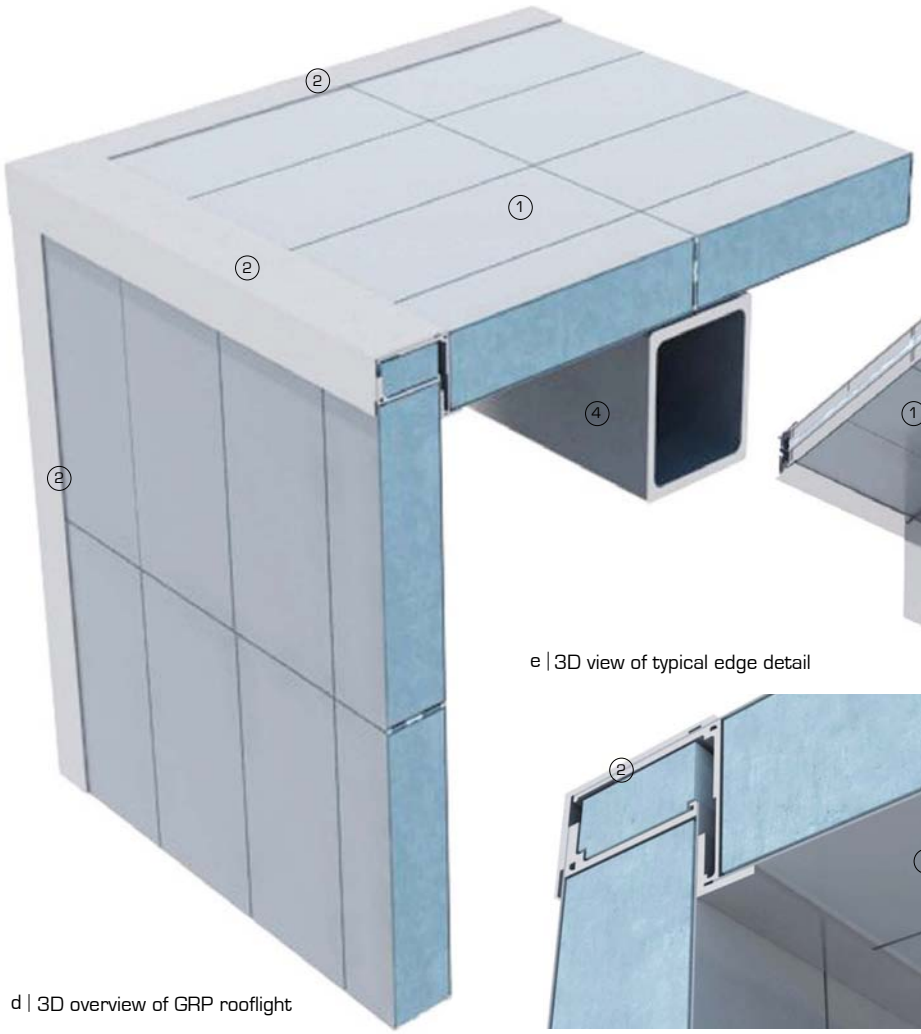


b | 3D views of typical ridge detail

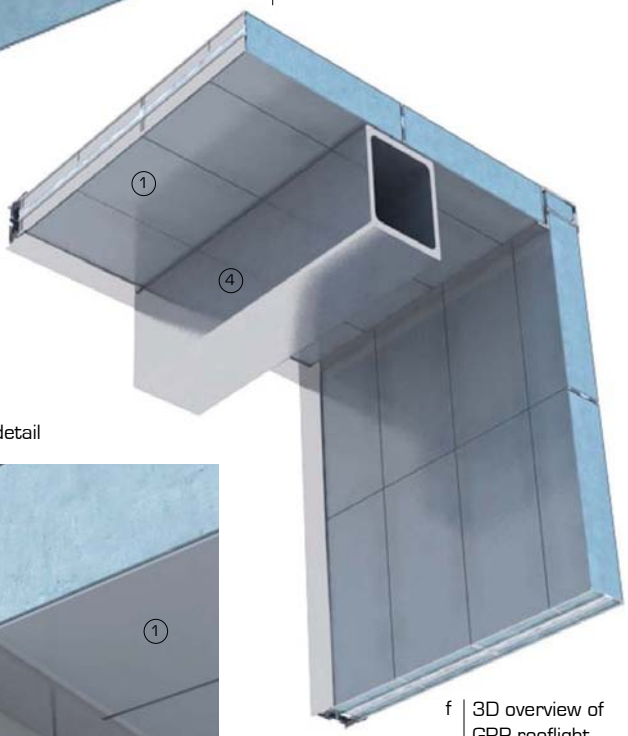


Details

1 | Translucent & insulated GRP roof panel
2 | Thermally broken aluminium framing
3 | Pressure plate
4 | Supporting structure
5 | Folded metal cover strip
6 | Masonry/concrete wall
7 | Gutter



d | 3D overview of GRP rooflight



f | 3D overview of GRP rooflight

e | 3D view of typical edge detail



System design

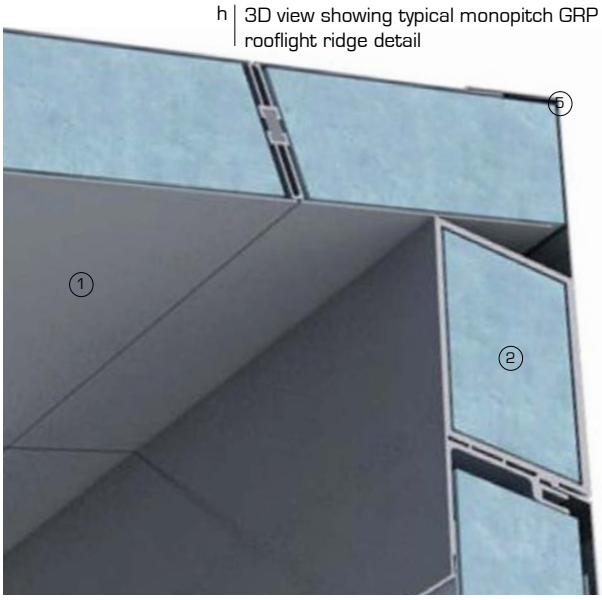
Glass reinforced polyester (GRP) is used in the form of thermally insulated panels to form translucent rooflights which are robust and economic when compared to an equivalent glazed rooflight with double-glazed units. The advantages of GRP over glass are its strength, lightness and flexibility as well as the material's high resistance to impact damage. GRP is a composite material formed by reinforcing flexible fibreglass mat (or fibres) with thermosetting polyester resins that provide high tensile and compressive strengths. The material is not combustible, making it a suitable material for rooflights as well as an opaque roof cladding material. While GRP rooflight systems do not usually achieve the high levels of resistance to wind-blown rain of internally drained and ventilated curtain walling systems, they are robust and economic, making them ideal where translucency is required rather than the transparency provided by glass panels.

Rooflights are made from GRP sheet which is bonded to an aluminium carrier frame around its edges (a). Thermal insulation set into the void is usually bonded to the outer GRP facing sheets to provide true composite action between the GRP skin and the insulated core. Like metal composite panels, GRP panels increasingly have a thermal break introduced into the framing (2) to reduce the possibility of condensation forming on the underside of the panel in temperate climates, as well as to improve the overall thermal insulation value of the rooflight. Thermal breaks are usually made from an extruded polymer that has a much lower thermal conductivity than aluminium, and are bonded to the extrusion in the manner of glazed curtain walling or are clipped to it and secured in place by self-tapping screws that hold the pressure plate in position (b). In small rooflights, up to around a 3000mm span, GRP composite panels require no additional support; while those of greater span use an additional aluminium or steel frame beneath to support the composite panels over the greater span. Panel sizes vary with the proprietary system and with the individual rooflight design. Typical panel sizes range from around 400mm x 800mm to 800mm x 3000mm. GRP rooflight panels use a lightweight framing system rather than a lapped junction or raised edges, providing a standing seam-type joint used in metal composite panels. These make their appearance more refined, since the framing is very visible in translucent GRP panels, unlike their metal equivalent. An extruded aluminium T-section forms the support to the panels on all four edges, with an extruded aluminium pressure plate being used to hold the panels in place on the outer face of the GRP panels (d). Most support frames are now internally drained and ventilated to provide a second line of defence against rainwater penetration. The outer seal is provided by an extruded EPDM gasket clipped into the aluminium extrusion. Proprietary tapes are also used but are more dependent upon good workmanship on site than gaskets, which are fixed to the pressure plate in factory conditions.

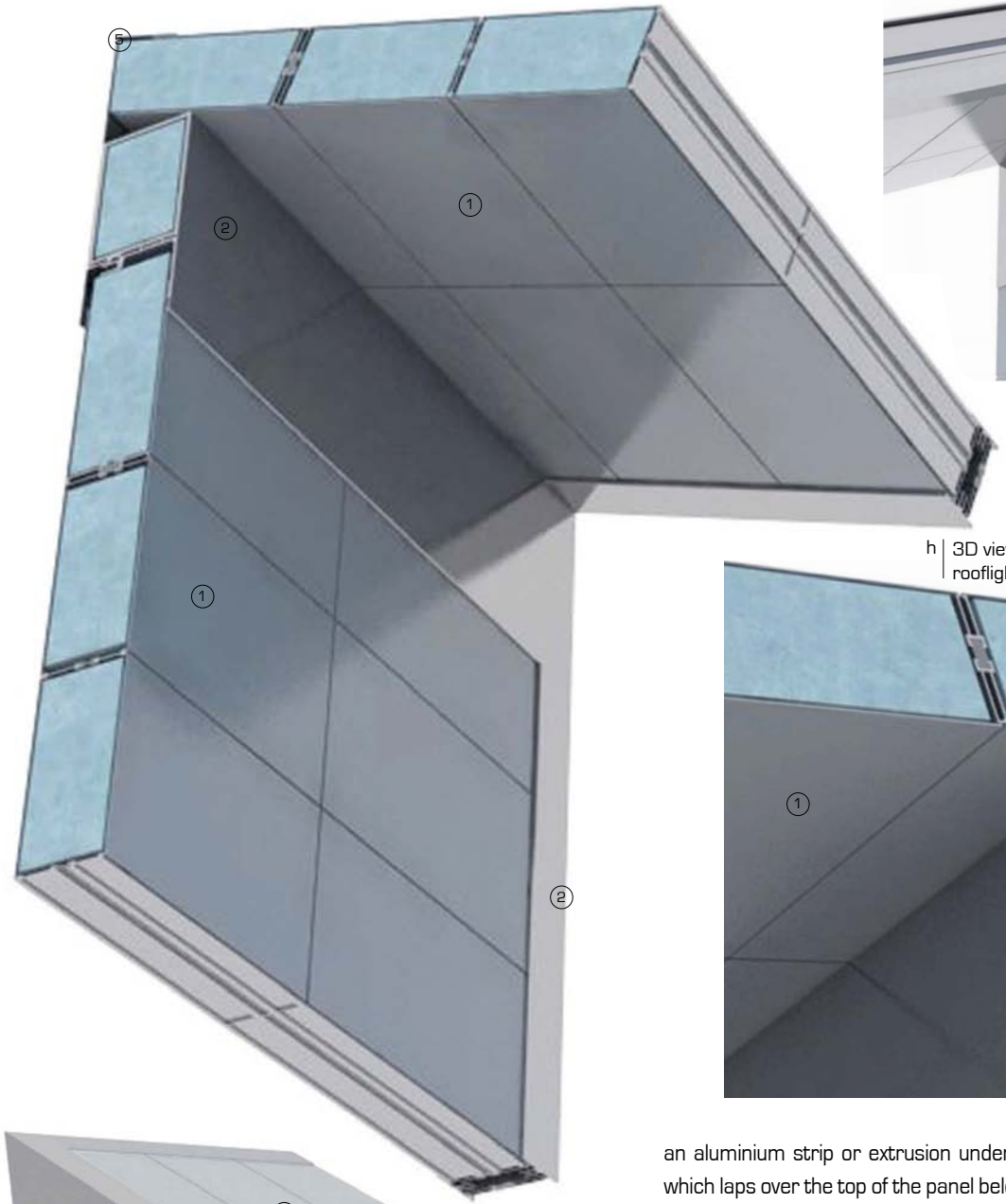
Pressure plates for panel joints running down the slope are set over the joint between the panels in the manner of glazed curtain walling. Joints running across the slope sometimes have pressure plates with lapped joints in order to avoid water building up on the upper side of the joint and being unable to run over the joint. The lap is formed by setting



g | 3D view showing typical monopitch GRP rooflight



h | 3D view showing typical monopitch GRP rooflight ridge detail





j | 3D view showing typical monopitch GRP rooflight ridge detail

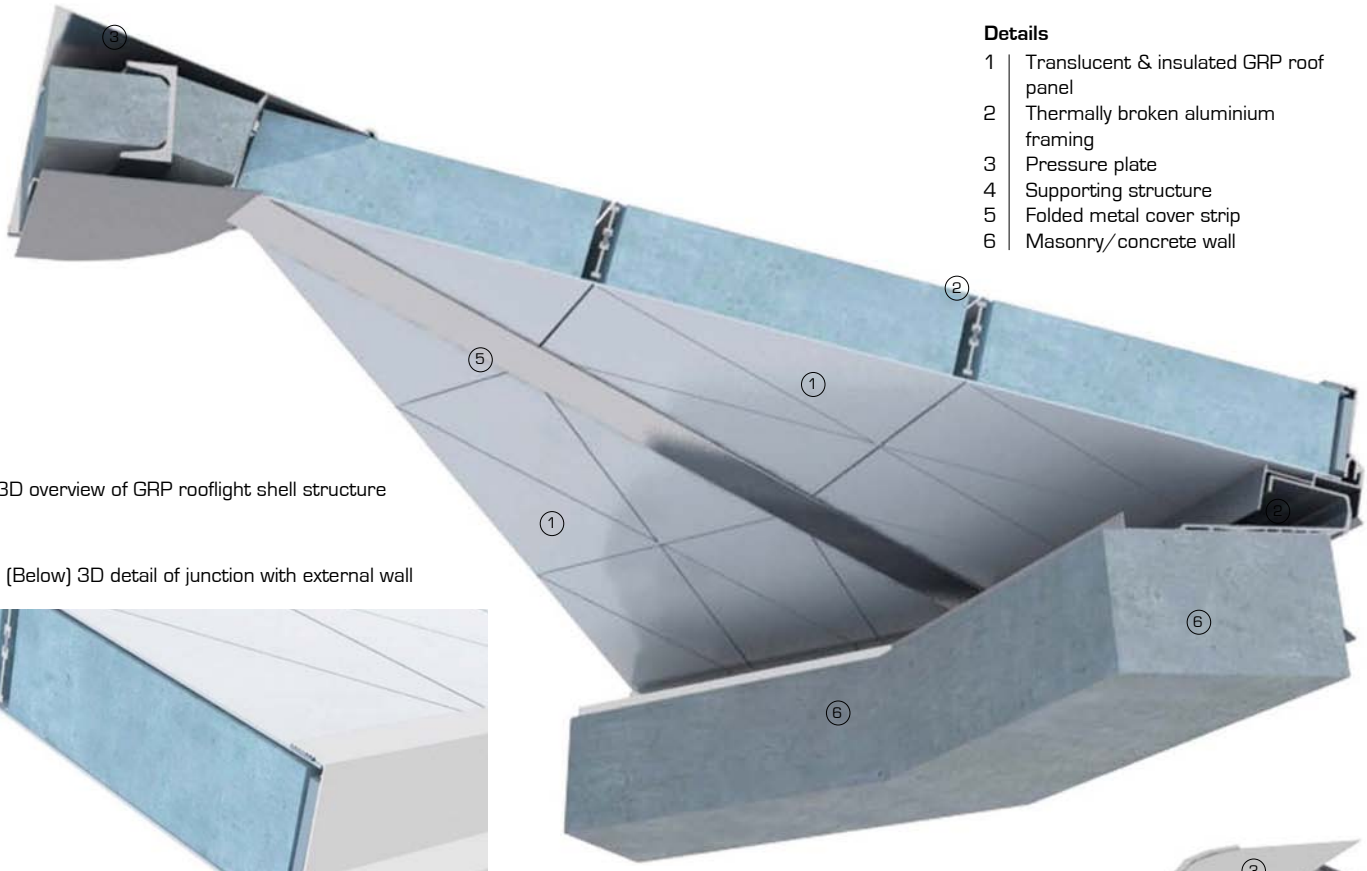
an aluminium strip or extrusion under the bottom edge of the panel, which laps over the top of the panel below. In addition to these standard junctions, which form part of proprietary systems, panels are jointed with folded metal sheets where unusual junctions are to be formed (g). An inner metal sheet is bonded to the junction of the panels to provide an inner seal and vapour barrier.

System details

When a rooflight terminates in an eaves (m), an intermediary aluminium extrusion or folded sheet is used to form the junction. An outer EPDM or extruded silicone seal is used as an outer line of defence against rainwater penetration at the junction with the GRP roof panel. Drainage slots formed in the bottom of the aluminium closer piece drain away any water that passes through the outer seal (p). These drainage slots also take any water to the outside, away from the drainage channels within the joints between panels that run down the slope of the roof. The GRP panel beneath the closer piece that forms a vertical part of the rooflight is formed by setting the panel behind a vertical aluminium strip that forms a lapped joint over the top of the panel, avoiding the possibility of rainwater passing through the joint. The gap between the aluminium closer and the GRP panel is sealed with either an EPDM

Details

1 | Translucent & insulated GRP roof panel
2 | Thermally broken aluminium framing
3 | Pressure plate
4 | Supporting structure
5 | Folded metal cover strip
6 | Masonry/concrete wall



k | 3D overview of GRP rooflight shell structure

m | (Below) 3D detail of junction with external wall





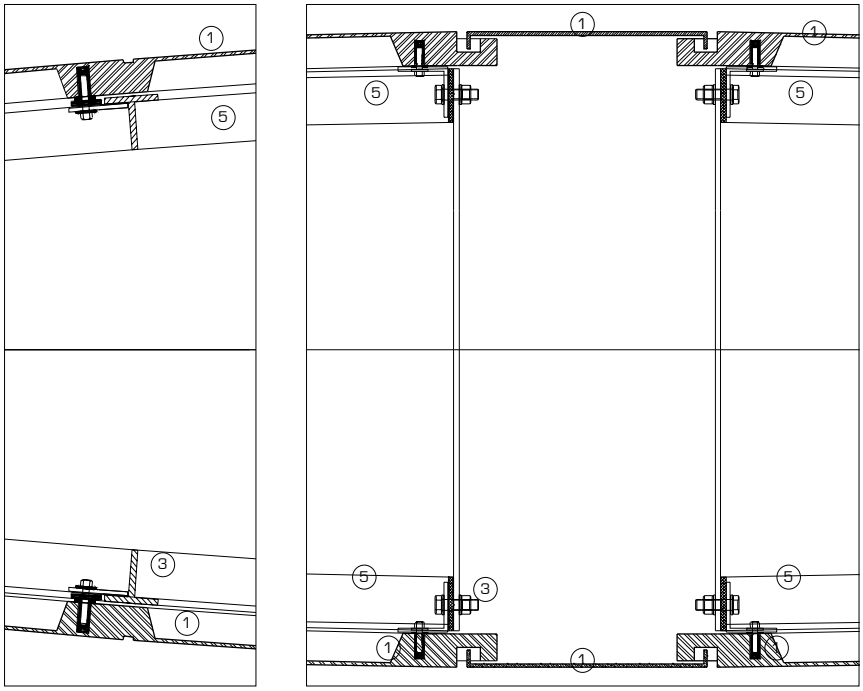
n | 3D overview of GRP rooflight shell structure

gasket, a proprietary tape or a silicone sealant. A metal gutter is fixed to the metal closer if required, but this is usually exposed unless it forms part of a fascia, such as the curved eaves used in profiled metal roofing, for example. In smaller rooflights the rainwater typically runs off onto the surrounding area of the flat roof.

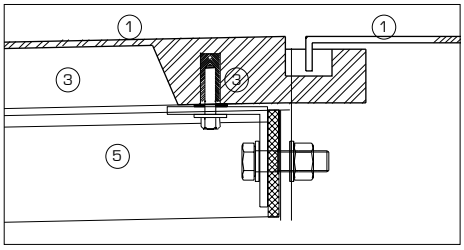
The gable ends of sloping GRP rooflights are formed with an aluminium flashing that is bonded, or mechanically fixed and sealed, to the metal edge frame at the side of the GRP panel forming the sloping panel, and to the top of the triangular-shaped vertical end panel. The sloping panel extends slightly forward of the vertical panels to give a thin edge to the roof (g), but alternatively the roof can terminate in a sharp edge, with a folded aluminium sheet or angle closing the gap between the panels. As with other panel-to-panel junctions, a waterproof membrane is set on the underside of the outer metal flashing as a second line of defence against rainwater penetration. The void between the panels is filled with mineral fibre quilt-type thermal insulation, which has the flexibility required to fill the irregular-shaped voids between GRP panels. An additional aluminium angle is used at the junction of the inner face of the panels to provide an additional seal and vapour barrier.



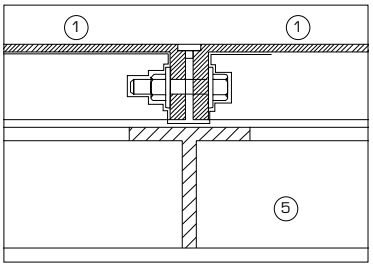
p | 3D detail of junction with external wall



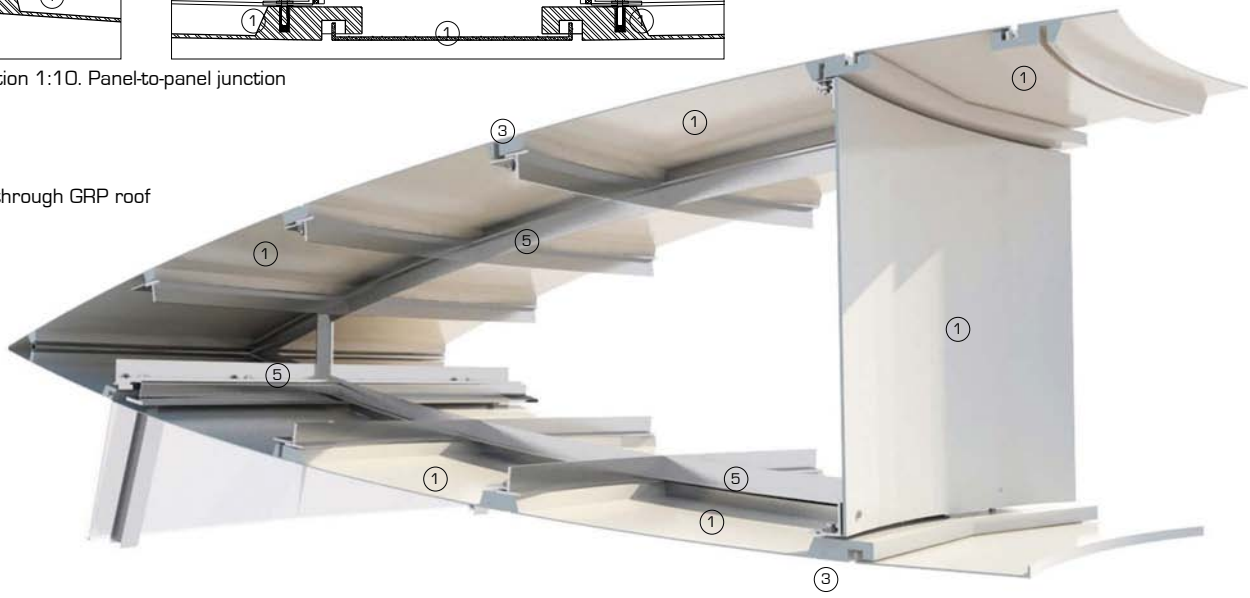
a | Vertical section 1:10. Panel-to-panel junction



b | Vertical section 1:5. Panel-to-panel junction



c | Vertical section 1:5. Panel-to-panel junction



d | 3D section through GRP roof panels

System design

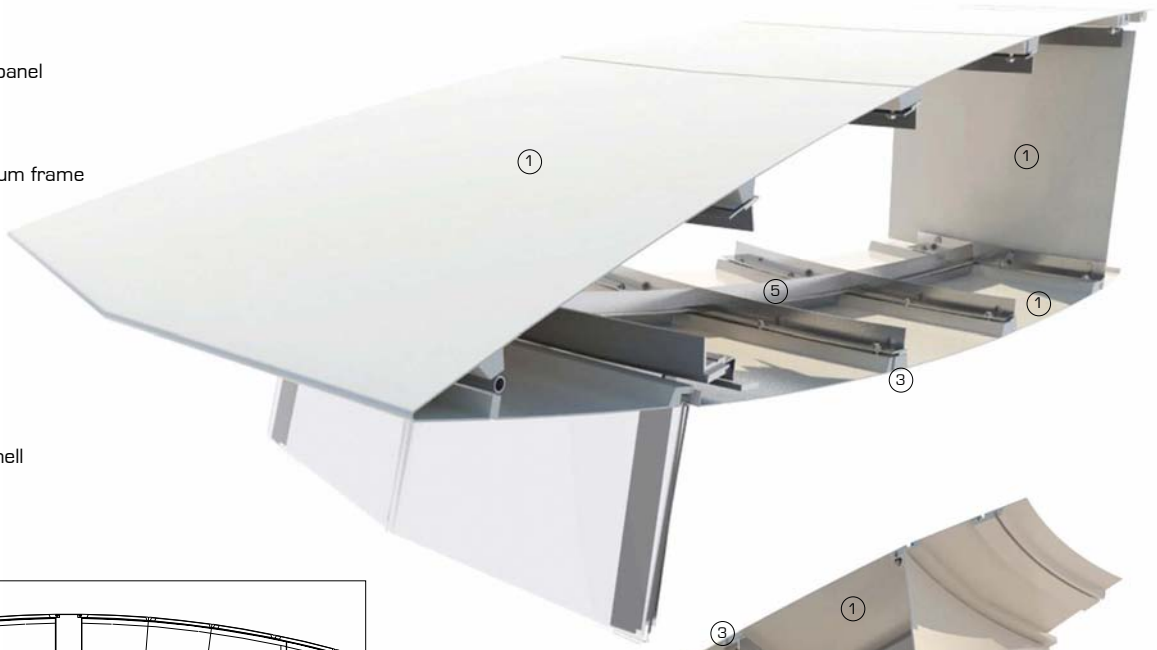
While glass reinforced polyester (GRP) rooflights – discussed in the previous section on rooflights (MCH_280) – are made as panels which are joined to form translucent rooflights, opaque GRP panels can be made as monolithic, self-supporting shells (d); usually from panel segments which are brought to site and bolted together (c). The segment sizes of GRP shells are made in sizes which are suitable for transportation by road, usually set upright on a trailer. The shells can then be lifted by crane into place as a completed assembly, which makes them quite different from roof structures in other materials.

The example shown is of a small shell for a rooflight. The shell consists of a set of segmented panels which are bolted together to form a roof shell of approximately 7.0 metres diameter, supported by an additional frame (g). Panels are made in a mould, usually from a single segmented panel type to form a complete rooflight. Moulds are usually made from plywood to create the shape and are then finished in GRP to create the negative shape of the panel being formed. GRP panels are fabricated by first applying a release agent to the mould to allow the finished panel to be removed easily, then thermosetting polyester resins are applied to the face of the mould with flexible fibreglass mat being laid into the resin, usually with rollers. The process of fabricating GRP panels is very labour intensive but requires no expensive equipment, making panel production a craft-based technique rather than an industrial process. When the panels are released from the mould they are trimmed along their edges and ground smooth where necessary. An alternative method is to apply a mixture of resin and glass fibre particles as a spray directly into the mould. The mixture is applied at a thickness of 3mm to 5mm depending on the panel size required.

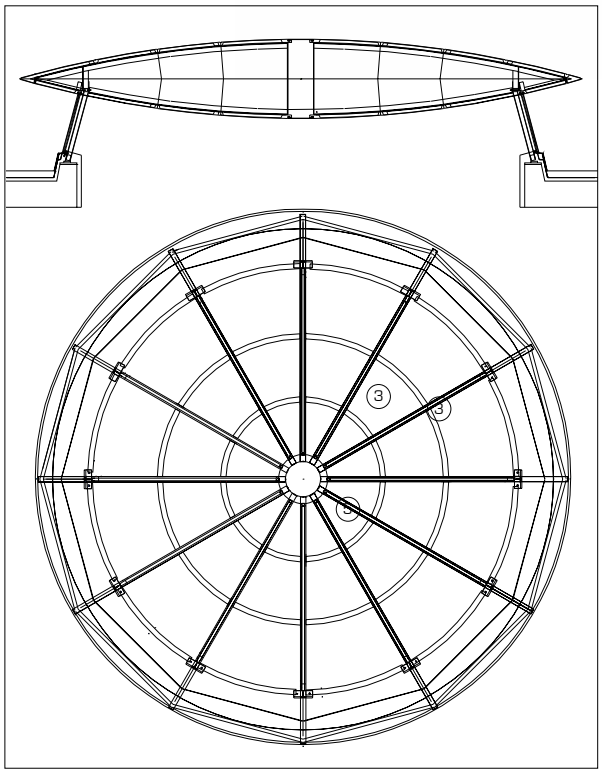
In the example shown, GRP panels are supported by a light metal frame beneath. The frame comprises steel or aluminium T-sections which are welded together to form a structure that supports the complete outer skin (e). The frame has curved members that radiate from the centre at the top to the edge, and from the centre at the lowest point of the structure back to the perimeter. The radiating 'spokes' of the wheel are held in place by T-sections that, in plan, form concentric circles. This 'bicycle wheel' form is supported near its perimeter by a metal ring beam that is set immediately above the glazing beneath the GRP roof (h). The ring beam is supported by posts that are fixed to the roof deck beneath.

Details

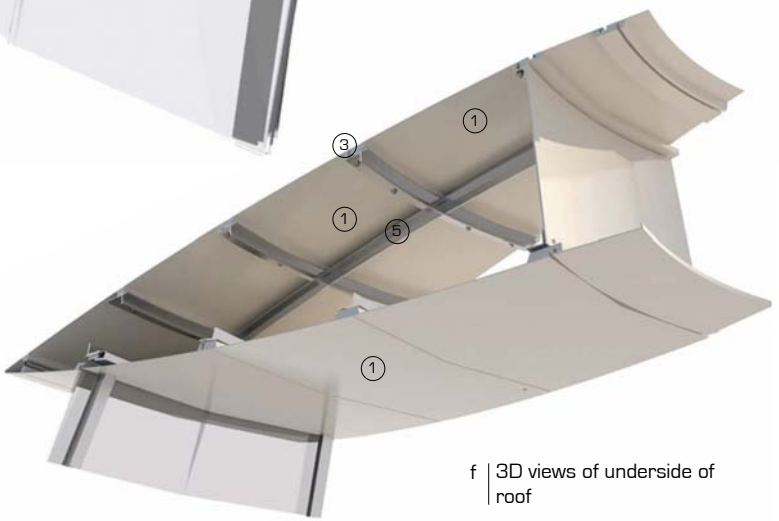
1 | GRP shell panel
2 | GRP outer cladding panel
3 | GRP structural rib
4 | GRP thin panel with honeycomb core
5 | Mild steel or aluminium frame



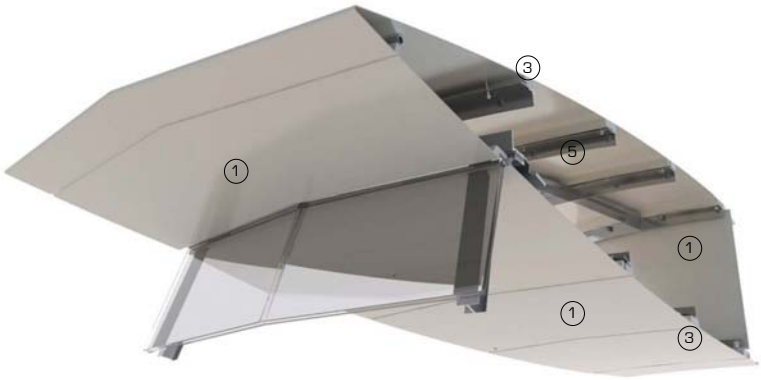
e | 3-D overview of GRP shell



g | Horizontal and vertical sections 1:50. Generic example of roof geometry



f | 3D views of underside of roof





h | 3D section through roof assembly

j | 3D overview of GRP shell

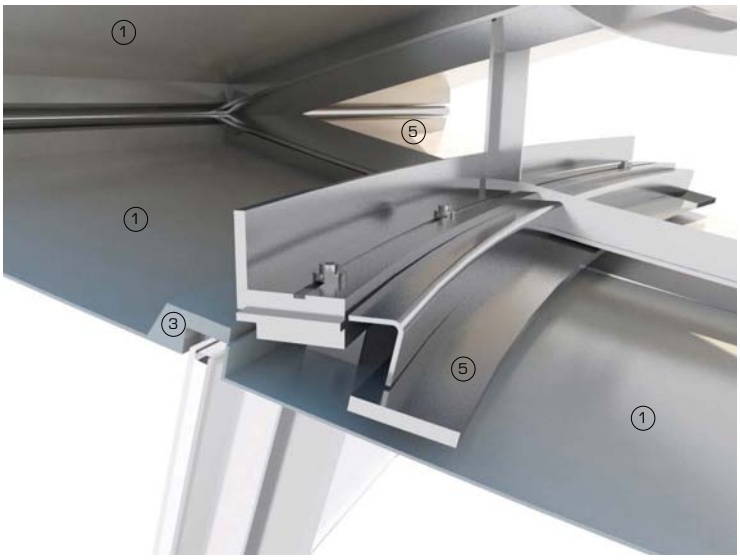


Details

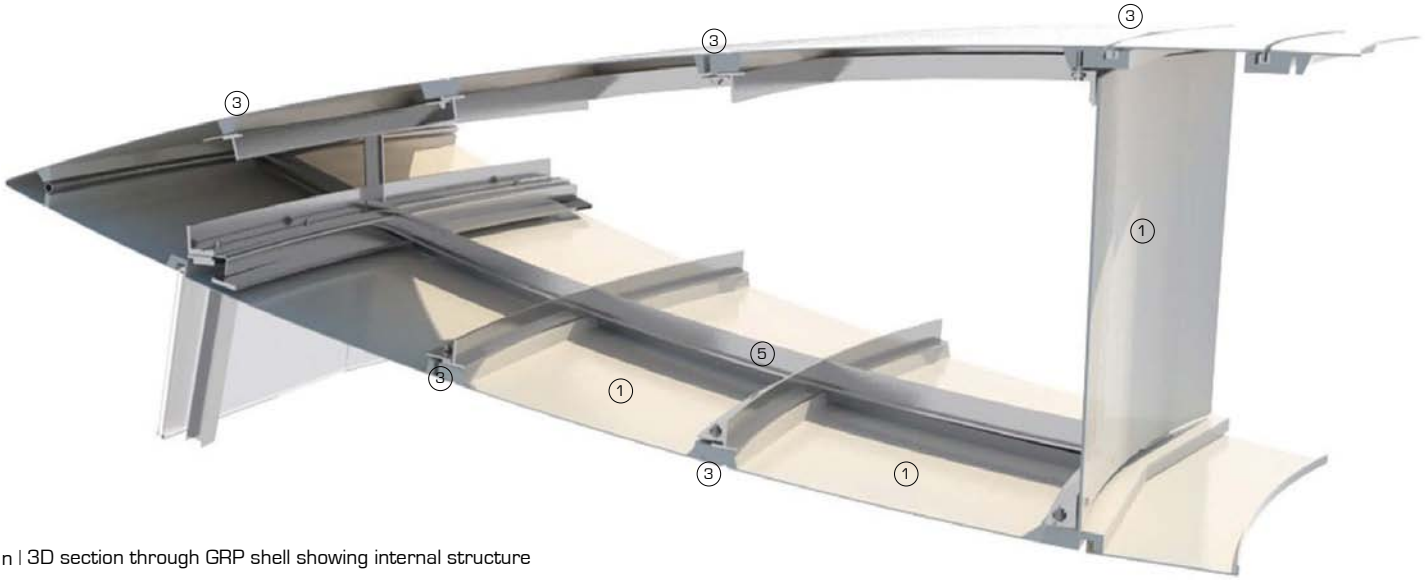
1	GRP shell panel
2	GRP outer cladding panel
3	GRP structural rib
4	GRP thin panel with honey comb core
5	Mild steel or aluminium frame
6	Mild steel or aluminium truss
7	GRP flashing
8	Waterproofing membrane
9	Metal fixing bracket
10	Thermal insulation



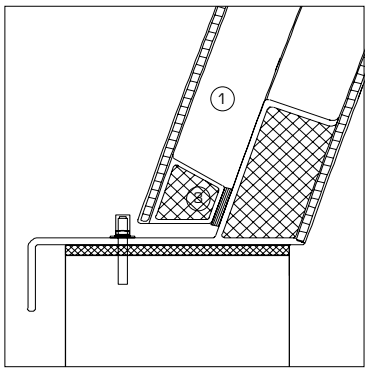
k |3D detail of GRP panel connection



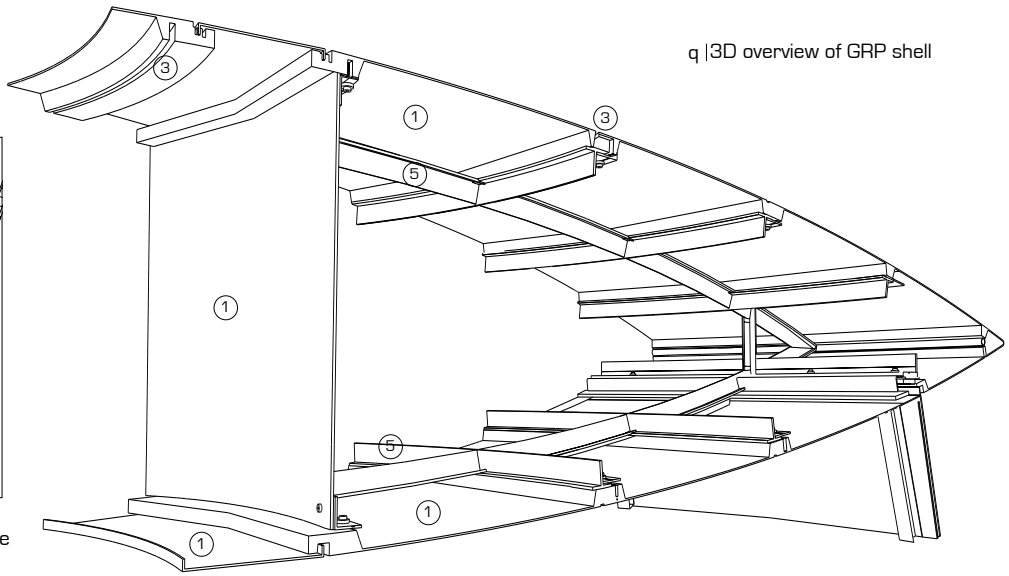
m | 3D detail of GRP panel connection to supporting aluminium frame



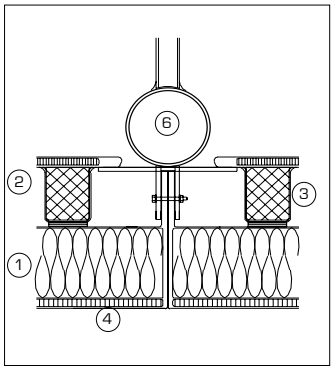
n | 3D section through GRP shell showing internal structure



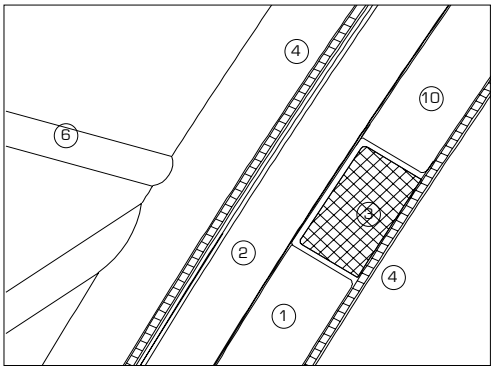
p | Vertical section 1:10. Junction at base



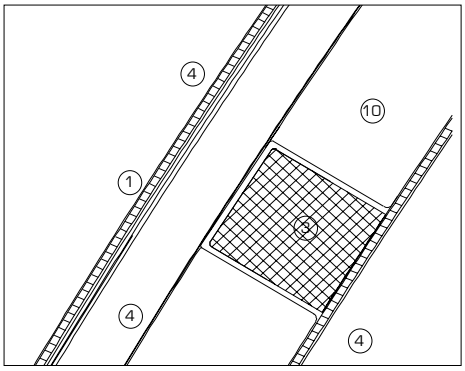
q | 3D overview of GRP shell



r | Horizontal section 1:10. Panel-to-panel junction



s | Vertical section 1:10. Panel-to-panel junction



t | Vertical section 1:10. Panel-to-panel junction

System details

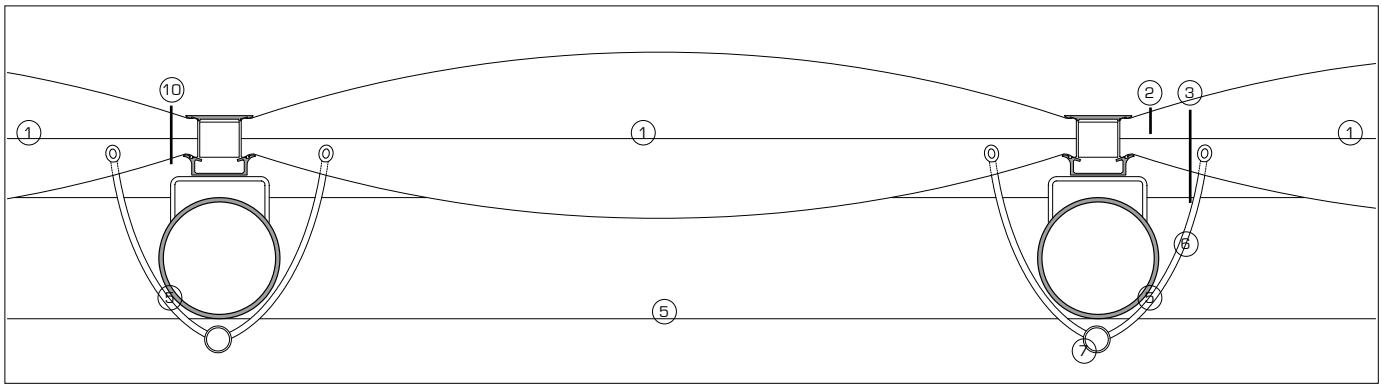
The metal frame is clad in prefabricated GRP panels which are bolted to the support frame on their internal face in order to avoid visible fixings (k). Panels are made with an outer skin of GRP around 5mm thick, with an overall panel depth of around 45mm for the panel sizes shown of 3500mm long and 1800mm wide. The GRP panels are stiffened by concentric ribs around 120mm wide, but ribs on the edges are thin in order to facilitate their bolting together (n). Panels are secured with bolts which are fixed through the metal support frame into reinforcing ribs at the edges of the GRP panels. Joints between GRP panels are formed by butting panels up to one another and sealing the gap between the panels (r). The seal is formed in a continuous step profile on the long edges of each panel that creates a continuous groove at the joint between panels. The groove is filled with a lamination of glass fibre and resin to fill the groove to the level of the top of the panels. The external face of the GRP is then ground smooth, usually by a hand-held grinder, to achieve a uniform, smooth surface that conceals the joint lines. Finally, a paint finish is applied, usually as a spray, to give a smooth and reflective finish. Where pigments are applied to the top coat, or 'gel' coat, in the factory, a more limited range of colours is available. Thermal insulation is set on the underside of the shell, being bonded to the inner face of the GRP panels in order to achieve continuity of insulation.

Alternatively, the glass fibre ribs that form part of the shell to provide it with integral structural stability could be made around 200mm deep to avoid the need for an additional steel frame. Panels would be bolted together to form a self-supporting GRP shell. Ribs would be made in solid GRP in order to allow them to be bolted together easily. Panels would be joined and sealed on their external face in the same way as the example shown. Where panel segments converge at the top of the shell, a separate centre panel would be used to create a smooth external finish. A central external panel avoids the difficulty of bringing up to 16 panels together at a single point, which would make it difficult to achieve a smooth transition from one side of the shell to the other. In the example shown, a shadow groove is set around the joint between the central panel and the segments in order to avoid any misalignment between segmented panels from being visible (q). The perimeter joint of the panel can be filled and sealed using the method described earlier, with additional grinding required on site to ensure a smooth finish.

The internal part of the shell, on its underside, has the same panels with the same finish but without any thermal insulation, which is typically set around the outer edge of the shell in order to keep temperatures within the void close to those within the building. Close to the edge of the shell, on the underside, the joint between the top panel - which curves around the edges - and the adjacent panel underneath, has a groove formed along the joint to serve as a drip (m). Windblown rain will still be pushed along the underside of the soffit panel, but the drip reduces the amount of water that runs down to the glazing below.



a | 3D views showing joint between ETFE cushions showing air supply pipes



b | Vertical section 1:20. Connection between ETFE cushions

System design

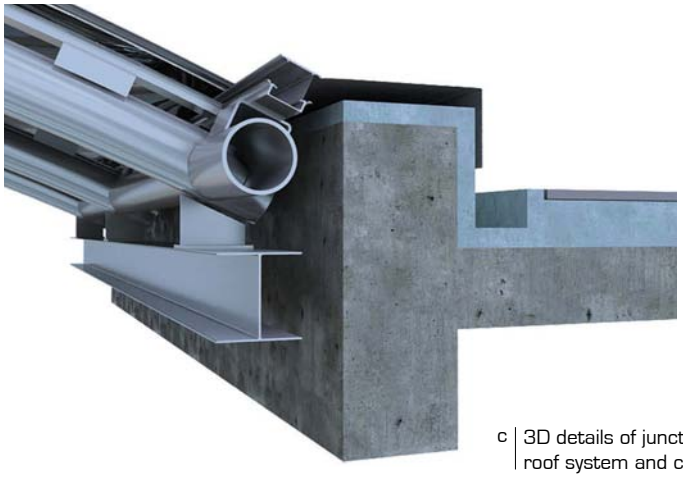
Fabrics used as roof membranes have the advantage of being light in weight, strong in tension and durable; and have the ability to be cut to different shapes and joined together economically, which is difficult to achieve so easily with metal and is very expensive to achieve with curved glass. Roof membrane fabrics are used in tension structures, either by stretching the material, 'prestressing' the membrane between structural supports or, alternatively, by supporting the material pneumatically in inflated structures. The use of fabric membranes in prestressed roofs is discussed in the next two sections on single layer fabric membranes. This section considers ETFE cushions (b); also called 'pillows' or 'foils', which are the most common application of inflatable fabric roofs.

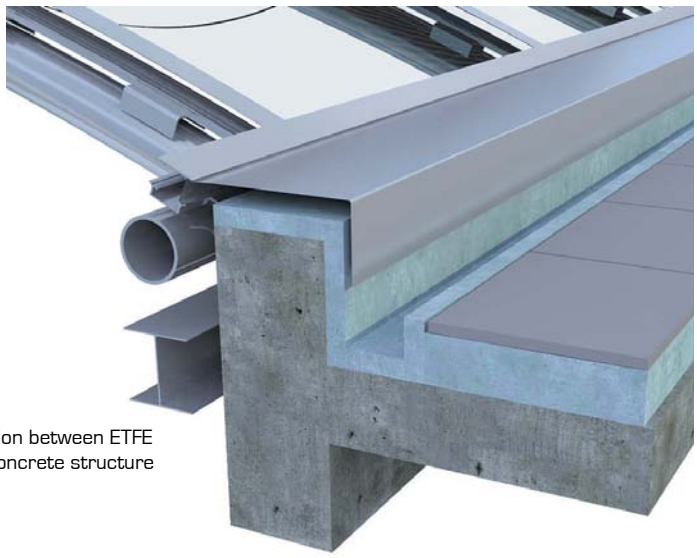
Although large-scale self-supporting inflatable roof structures are in use, particularly for covering sports stadiums, they remain structurally stable only while air is being supplied to the structure. If the air supply is interrupted, the complete roof structure deflates. In smaller-scale applications, air-filled cushions remain in place when the air supply fails or is switched off when used as non-loadbearing panels. This type, where ETFE sheet is used to make panels formed as air-filled 'cushions', provides highly transparent, lightweight and resilient roofs that have thermal insulation values similar to those of double-glazed units. The complete ETFE cushion assembly is supported by a structural frame beneath (a), with mild steel, aluminium and laminated timber all being used to suit the design.

ETFE cushions usually consist of a minimum of two layers of ETFE sheet, which are set back-to-back to form a flat panel and are sealed at the edges. The void within the cushion-shaped panel is inflated with air to a pressure that varies with cushion size and the manufacturer's proprietary system to provide structural stability to the panel. The increased air pressure stretches, or 'prestresses', the outer membranes, giving ETFE cushions their characteristic curved shape. The cushions are held in place by clamps that form a frame around the cushions in the manner of glazed rooflights. The clamping frames are then supported by a mild steel structure formed typically as box sections or tubes (d). Cushions typically have three layers that form two chambers. The two chambers are linked by a hole formed in the middle (flat) membrane in order to allow air to pass to both chambers from a single air supply, and to ensure that the air pressure in both chambers remains equal. This three-layer cushion provides a U-value of around 2.0 W/m2K, which is similar to a double-glazed unit used in glass roofs.

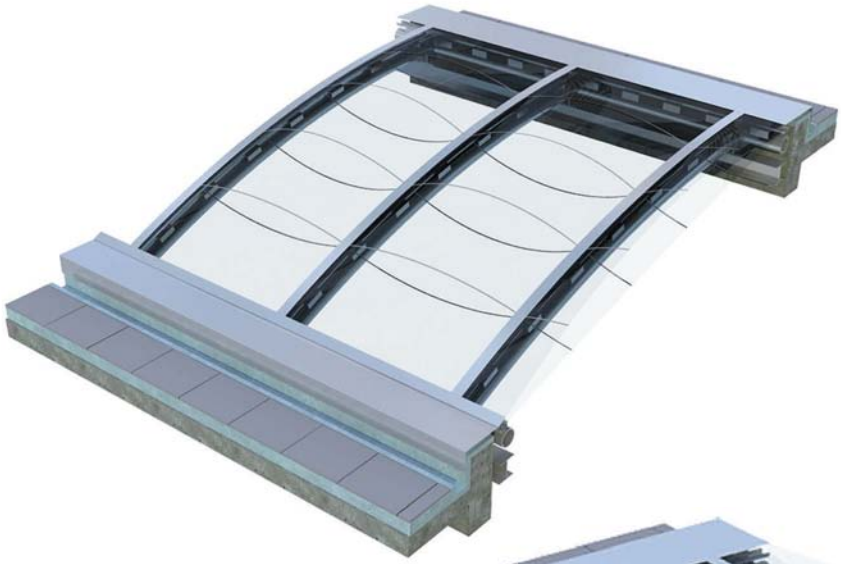
System details

Air is supplied to cushions from rubber pipes or flexible plastic pipes that are connected to the underside of the cushion near the clamping assembly (b). Pipes are usually of around 25mm diameter, and are connected to a larger pipe that supplies the air to all the cushions either side of a single structural support. This main pipe is also usually made from plastic and can be concealed within the supporting structure, being only up to a diameter of around 60mm. The air supply, which

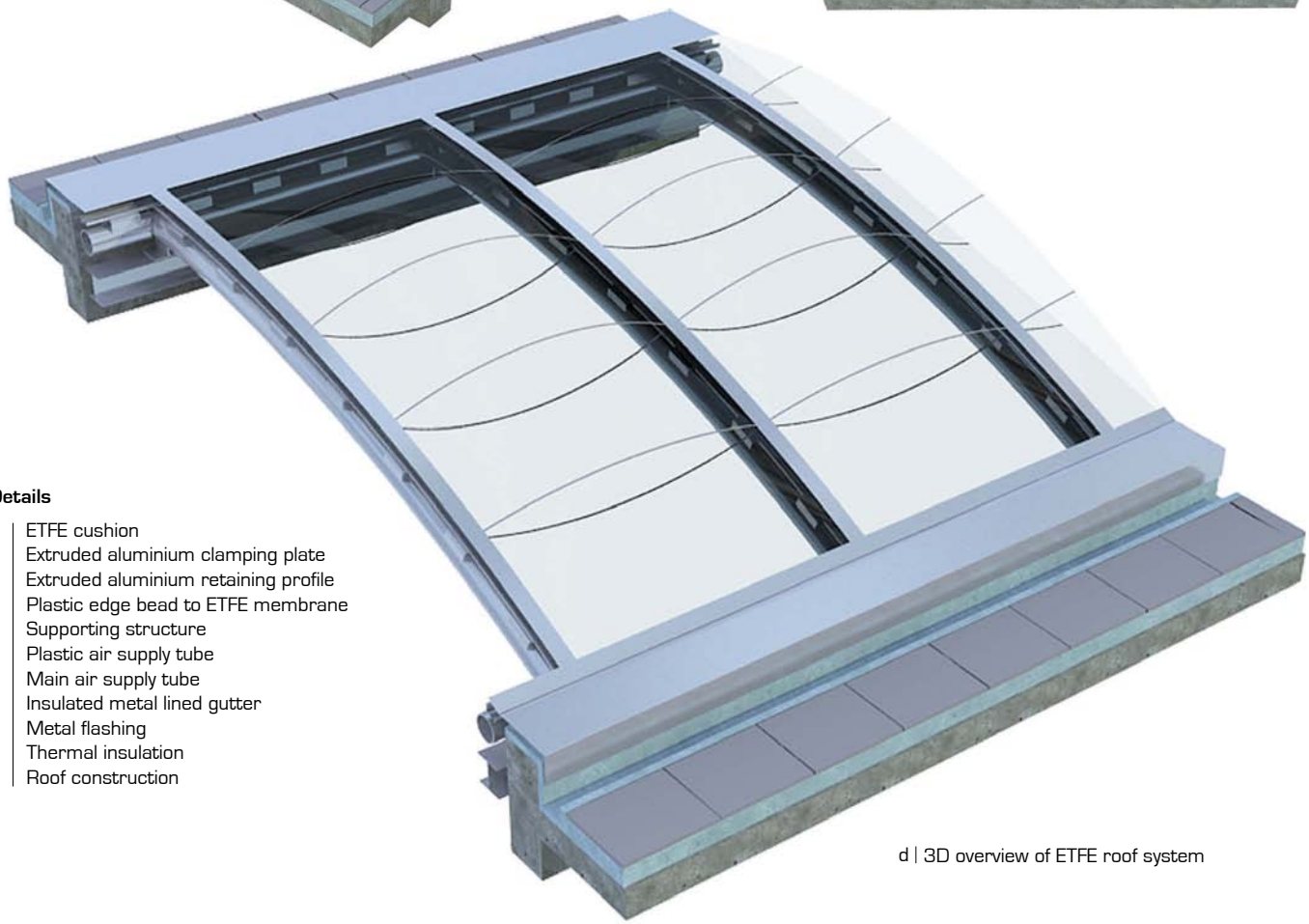




c | 3D details of junction between ETFE roof system and concrete structure







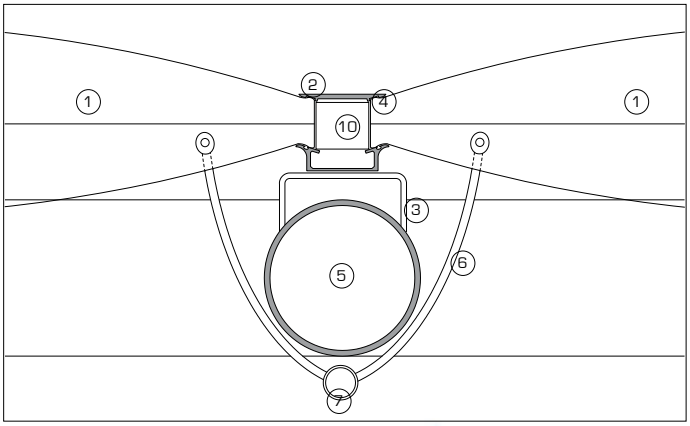
Details

1 | ETFE cushion
2 | Extruded aluminium clamping plate
3 | Extruded aluminium retaining profile
4 | Plastic edge bead to ETFE membrane
5 | Supporting structure
6 | Plastic air supply tube
7 | Main air supply tube
8 | Insulated metal lined gutter
9 | Metal flashing
10 | Thermal insulation
11 | Roof construction

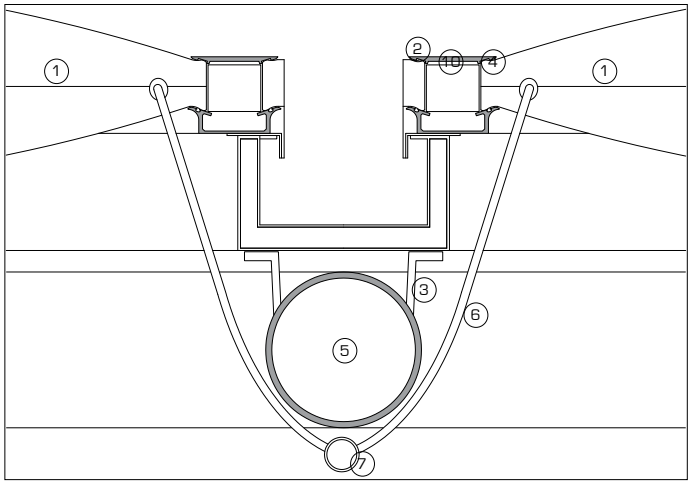
d | 3D overview of ETFE roof system



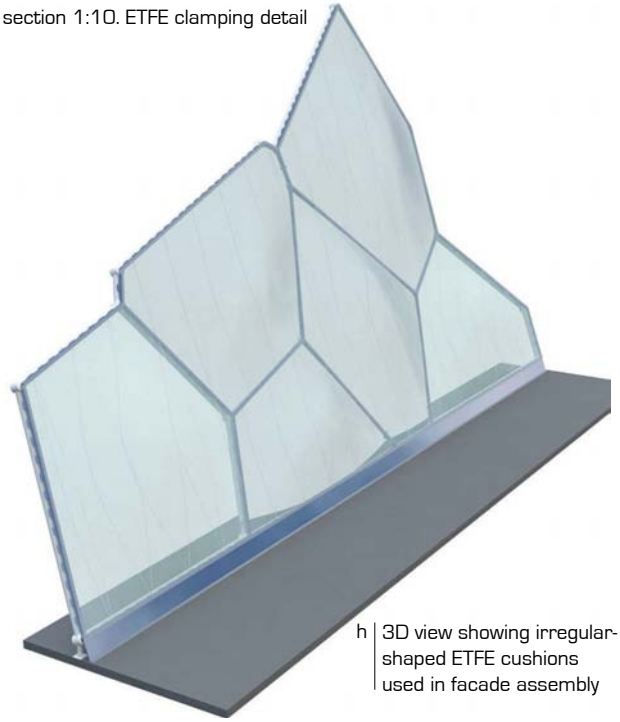
e | 3D detail of cushion-to-cushion air supply



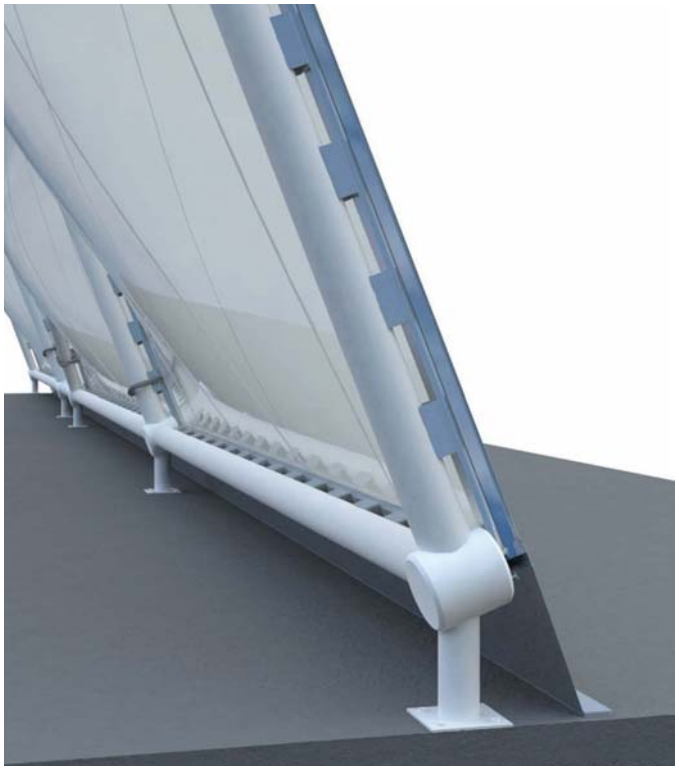
f | Vertical section 1:10. ETFE clamping detail



g | Vertical section 1:10. ETFE clamping detail with insulated gutter



h | 3D view showing irregular-shaped ETFE cushions used in facade assembly

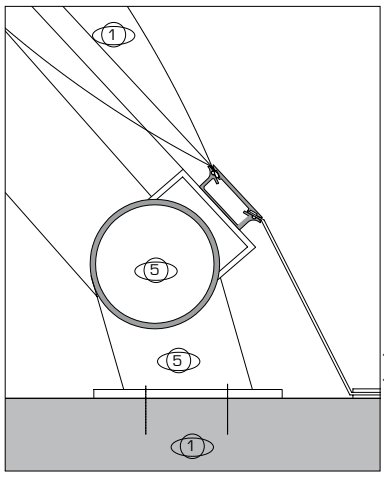


j | 3D detail of junction between ETFE facade and ground

maintains the air pressure within the cushions at a constant level, is supplied by electrically powered fans with air filters (to avoid the passage of dust), as used in mechanical ventilation systems within buildings. The humidity level of the air is usually controlled to avoid the possibility of condensation forming within the cushions. Once the ETFE cushions have been inflated, air is supplied to the cushions for only around 5–10 minutes per hour to compensate for loss of air pressure caused by leaks from cushions or from air supply pipes.

If air pressure within the cushion is lost as a result of damage to one of the outer membranes or from loss of air pressure in the supply pipe, the cushion deflates to its flattened shape. As wind pressures are applied to the external face of the cushion, the outer skin will deflect either inwards or outwards as a result of the positive or negative pressures. This does not usually cause damage to the cushions before the air supply is restored. Some manufacturers' systems have one-way valves to prevent loss of air pressure from the cushions back to the supply pipes.

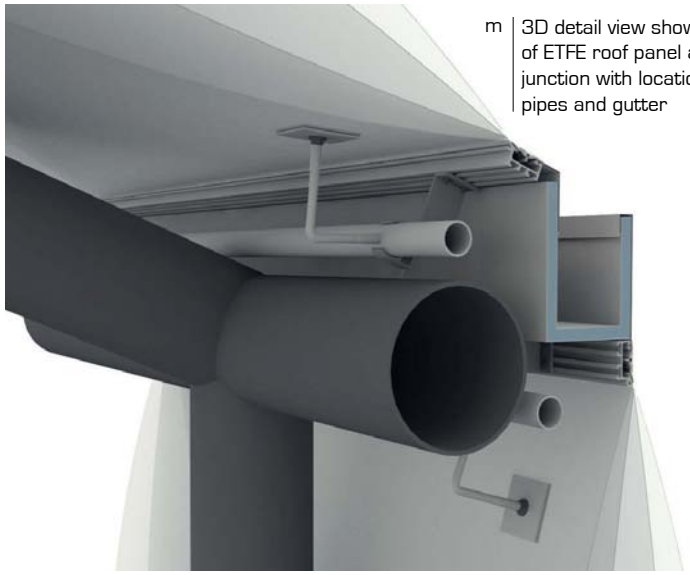
ETFE cushions are usually fabricated in the workshop but can be assembled on site to suit project conditions. The material is manufactured in rolls of considerable length but of a width of around 1.5 metres. For this reason, ETFE cushions are often made with spans in widths of around 3.0 metres to 4.0 metres between clamped



Details

1 ETFE cushion
2 Extruded aluminium clamping plate
3 Extruded aluminium retaining profile
4 Plastic edge bead to ETFE membrane
5 Supporting structure
6 Plastic air supply tube
7 Main air supply tube
8 Insulated metal lined gutter
9 Metal flashing
10 Thermal insulation
11 Concrete slab

k | Vertical section 1:10. Junction at base



m | 3D detail view showing underside of ETFE roof panel at roof-wall junction with location of air-supply pipes and gutter

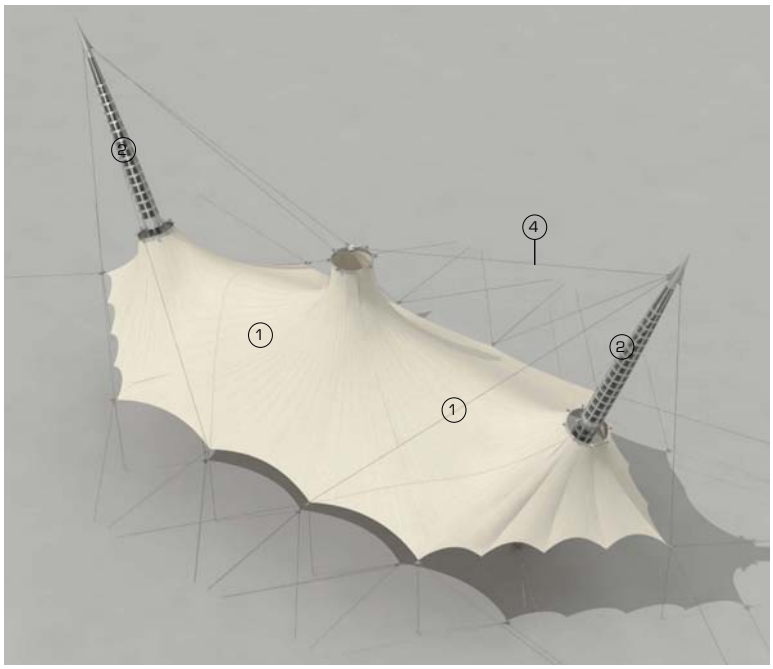




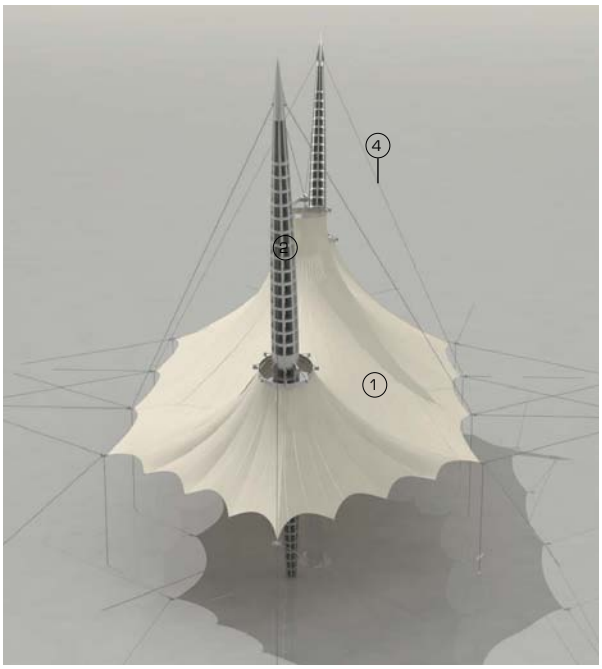
n | 3D sectional views showing ETFE roof and wall panel construction with steel tube support structure

frames, in lengths of up to between 15 - 30 metres, but lengths of up to 60 metres have been used. Larger cushions are made by welding sheet together in the workshop to form wider sheets for cushions that vary from the rectangular form created from a standard width of ETFE sheet. Cushions of up to around 7.0 x 7.0 metres have been made in a variety of shapes from circles to hexagons using a hot welded process undertaken in the workshop. Larger cushions sometimes use a net of connected cables to provide additional restraint.

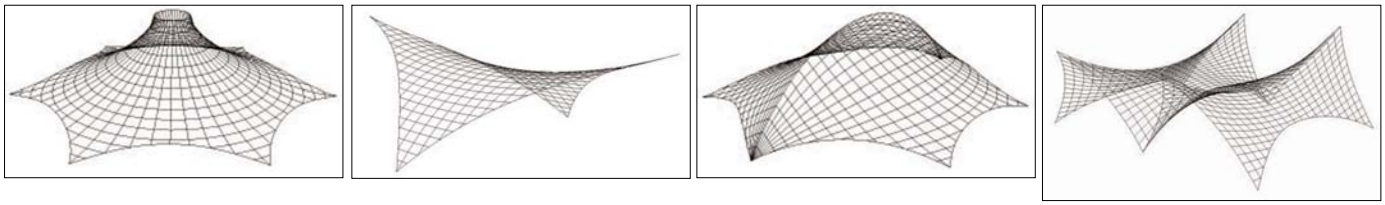
The cushions have an edge bead, typically in plastic, which is used to retain the panel in its supporting frame. The cushion is set into a clamping frame, usually made from extruded aluminium, that holds the panel in place by clipping it into an aluminium profile, then holding it in place with an aluminium pressure plate that clamps the edges (f). The complete assembly usually performs in a similar way to the framing used for glazed roofs, with a drained and ventilated inner chamber that serves as a second line of defence against rainwater penetration. Any rainwater that passes through the outer clamping plate is drained away in grooves formed adjacent to the edges of the ETFE cushions, the water being drained back to the outside of the roof (m). The clamping assembly is typically around 100mm wide, which is wider than that used for glazed roofs, but less framing is required than that used on glazed roofs .



a | 3D overview of cone-shaped roof with tension cable support.



b | 3D overview of cone-shaped roof with tension cable support.



1. Cone 2. Saddle 3. Arch 4. Wave

c | Tensile roof shape types

System design

Roof membranes are made from individual panels of fabric which are cut from sheet material; the curved forms of membranes being formed from flat sheet material. The conical-shaped example shown here is made from panels with edges that curve inward (a), while the barrel-shaped roof shown in the next section is made from panels with edges that curve outward. PVC coated polyester fabric is made in widths from 2000 - 3000mm, in thicknesses up to 1.2mm, while PTFE coated glass fibre fabric is made in widths up to around 5000mm in thicknesses up to 1.0mm. Large panels are usually cut by CNC cutting machines, with small pieces cut by hand, but even small pieces are now being made increasingly by a cutting machine. Fabric panels are usually made slightly undersized to allow for the stretching of the material when it is under tension as a roof membrane. Fabric panels are joined together with lapped seams which are either sewn, welded, bonded or joined in a combination of stitching and welding, with all processes being carried out in the workshop. The width of the lap, which is visible from below the roof as well as from outside the building, is determined by the structural forces on the membrane with higher loads requiring wider seams.

Edges of membranes are usually either gently curved or straight. Curved edges are formed with a cable held in a continuous pocket at the edges of the membrane. An alternative detail used in PTFE/glass fibre canopies is to have an exposed cable connected to the clamped edges of the membrane with a series of stainless steel link plates (d).

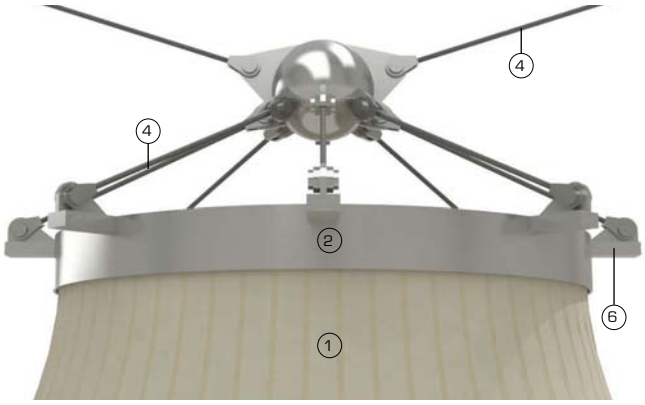
Straight edges are usually formed with an edge bead made from a flexible PVC or EPDM rod in a small pocket. This reinforced edge is then held captive within an aluminium clamping plate assembly similar to that used for ETFE cushions, or alternatively in a luff groove extrusion (k).

System details

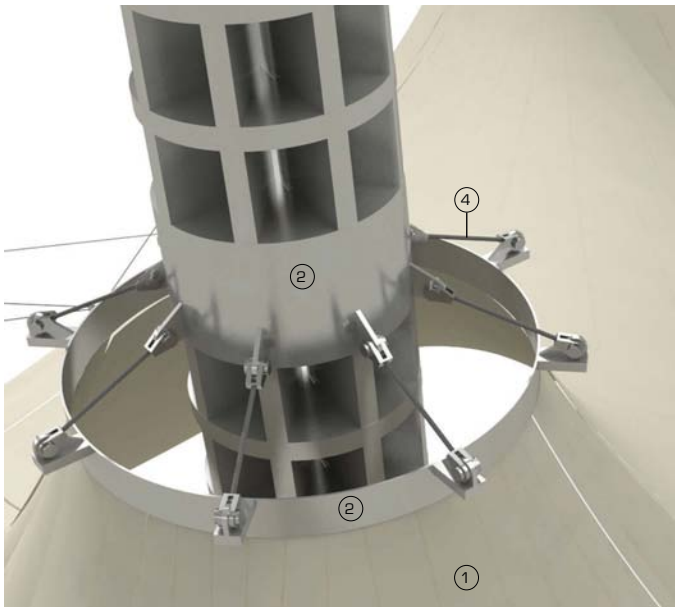
Cable restrained curved edges to fabric roofs usually follow a circular or catenary shape. A sleeve is formed by folding the membrane back over itself and stitching or welding it to form a continuous pocket in which a stainless steel cable is inserted (h). A 25mm diameter stainless steel cable is typical, depending on the structural forces. A strip of membrane material or plastic is set between the cable and the membrane to allow the two to move independently without abrasion occurring. A reinforced plastic strip is sometimes added into the pocket but this is not visible from either above or below the roof. Straight-clamped edges use clamping plates around 100mm wide, set back to back and bolted together, which comprise two flat, grooved plates rather than the clamping plate and supporting extrusion used at joints between panels (n). Where two cables meet at membrane corners or points, they are usually fixed to a single mild steel plate. The cable is fixed into a stainless steel cable fixing which is secured with a pin connection back to a supporting steel plate. The corner of the membrane is cut to form a curved end. Additional straps are sometimes added to ensure that the membrane does not slide away from the corner.

Details

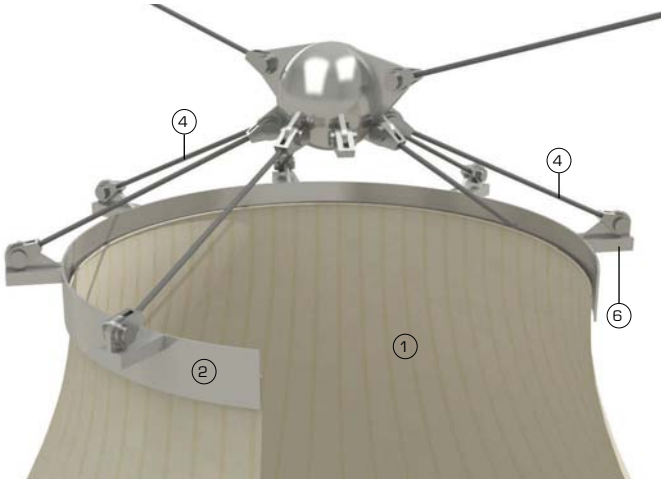
1 | Fabric membrane panel
2 | Supporting mild steel structure
3 | Extruded aluminium clamp
4 | Stainless steel cable
5 | Membrane hood
6 | Plastic edge bead to membrane panel



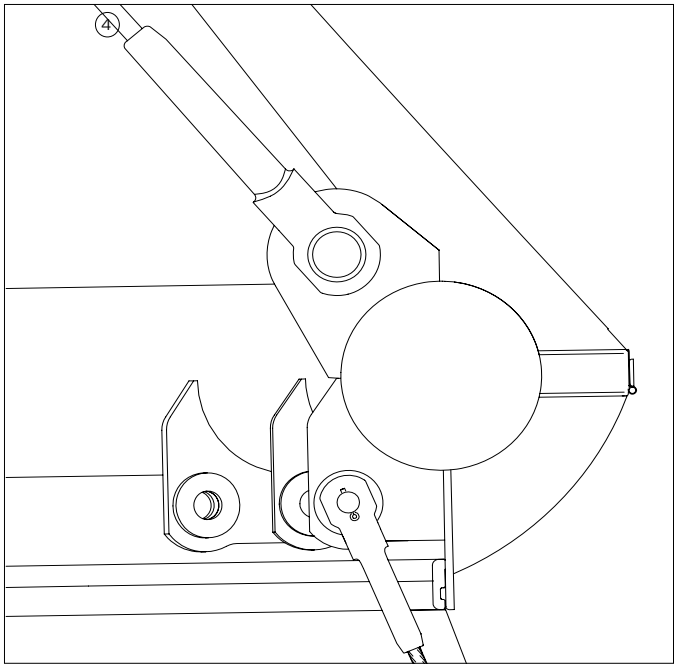
d | 3D detail of edge ring supported by tension cables



e | 3D detail of alternative pinnacle condition with membrane hood



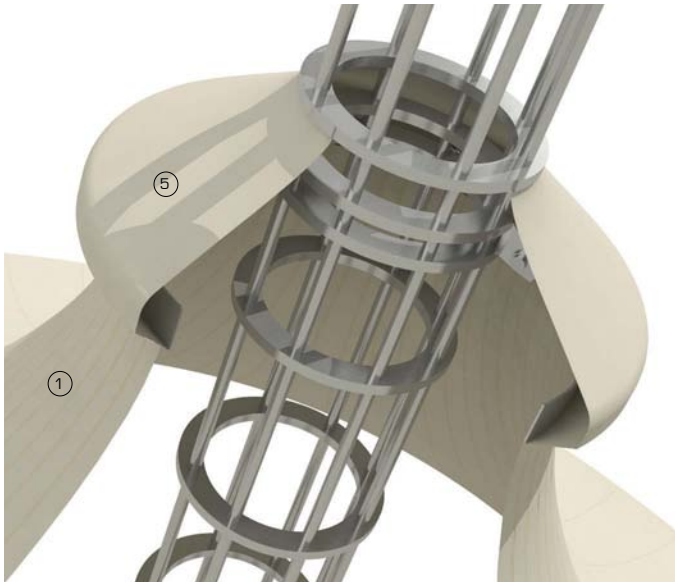
f | 3D detail of edge ring supported by tension cables



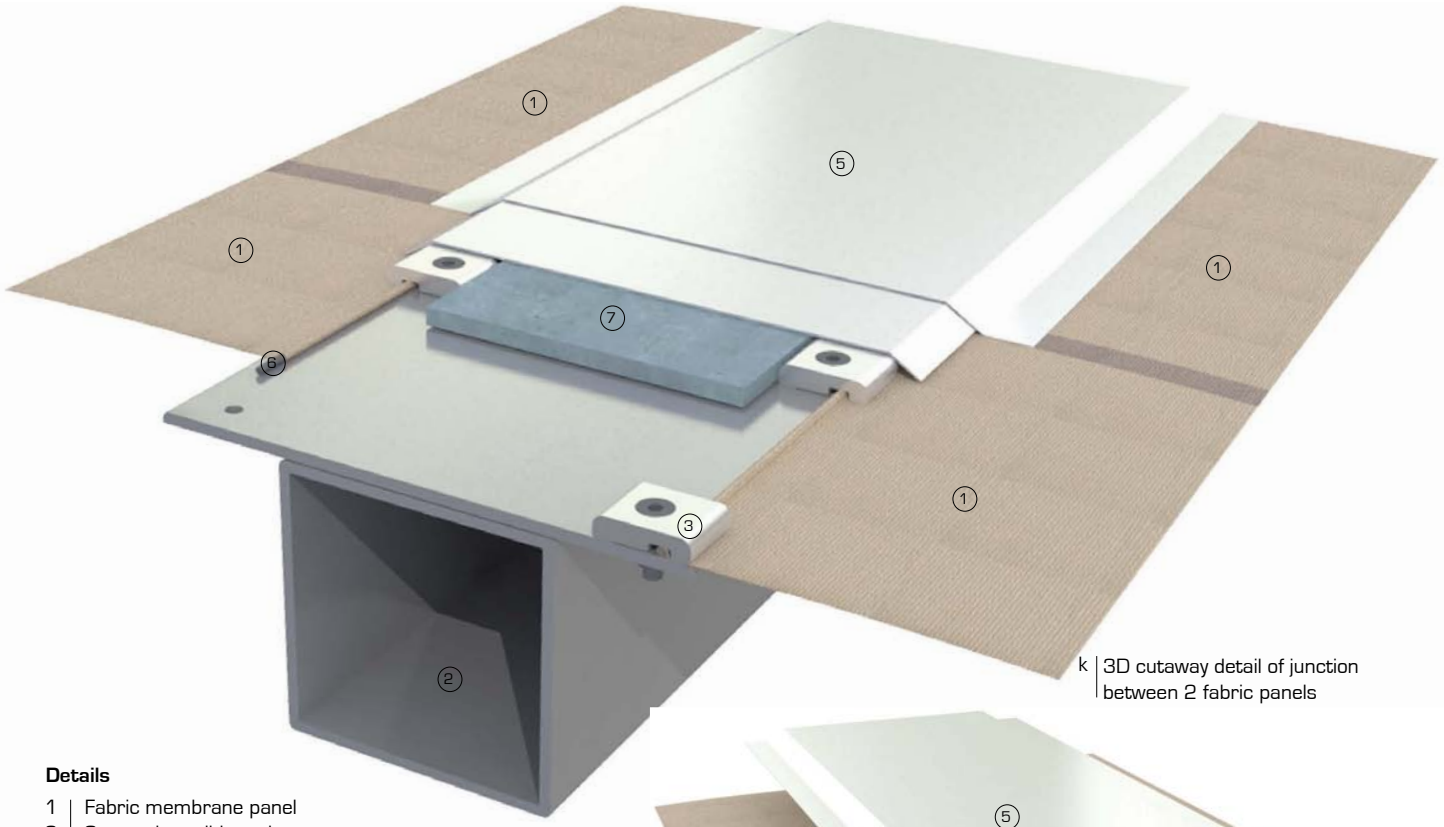
g | Vertical section 1:5 Clamping ring with membrane skirt



h | 3D detail of cone top with protruding structural support



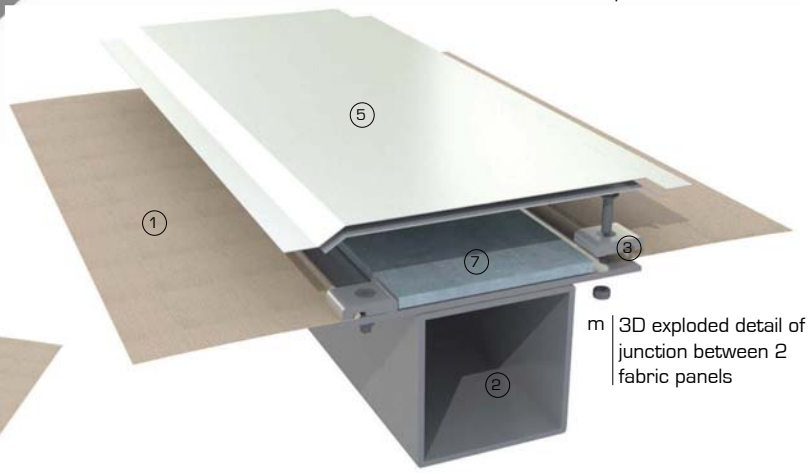
j | 3D detail of cone top with protruding structural support



k | 3D cutaway detail of junction between 2 fabric panels

Details

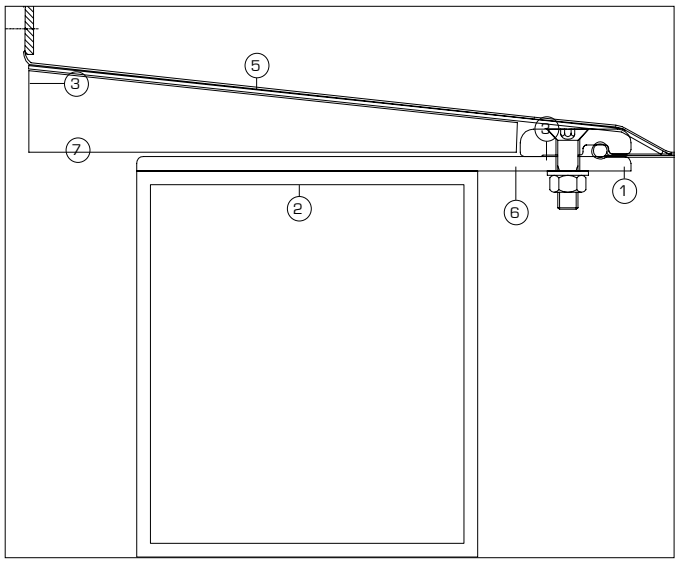
1 | Fabric membrane panel
2 | Supporting mild steel structure
3 | Extruded aluminium clamp
4 | Stainless steel cable
5 | Membrane hood
6 | Plastic edge bead to membrane panel
7 | Thermal Insulation



m | 3D exploded detail of junction between 2 fabric panels



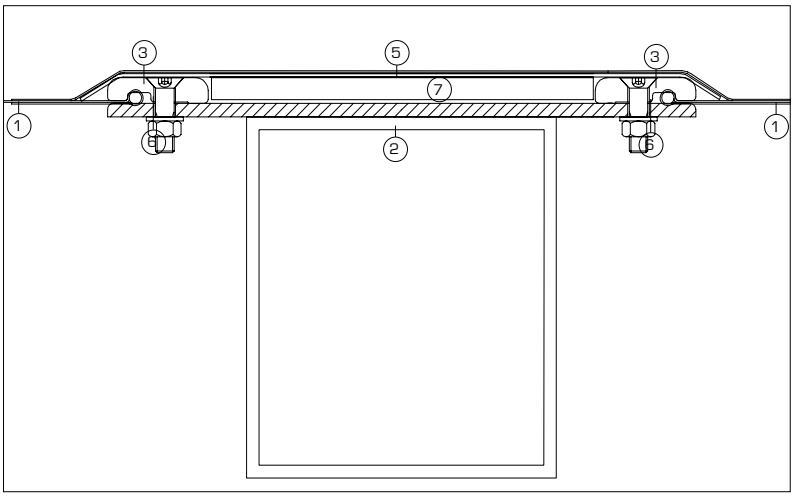
n | 3D detail of junction between 2 fabric panels

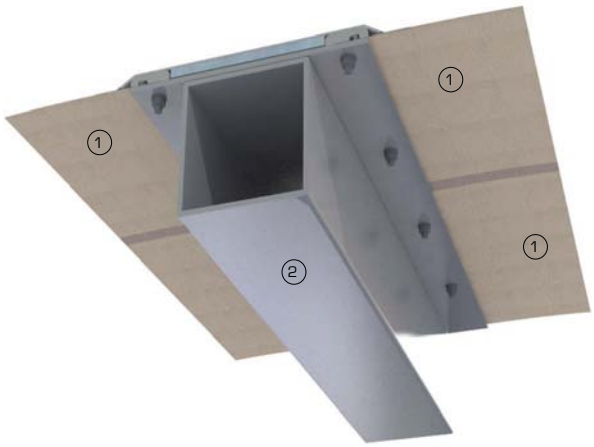


p | Vertical section 1:5 Edge of roof at abutment

Suspension points at the top of a cone-shaped fabric roof are usually formed either by a metal ring (e), which is fixed back to a central mast by cables or cantilevered brackets, or alternatively by a 'palm tree' arrangement of projecting curved metal brackets which serve to tension the continuous membrane against its supporting mast set within the building.

The first option with a metal ring requires an additional membrane cover piece (j), while the second 'palm tree' option forms a continuous membrane with a smooth curved top, without any breaks in the continuity of the membrane. In the 'ring' solution, the membrane is clamped between an inner ring and an outer ring fixed together with bolts. A second clamp is used to fix the cone-shaped membrane that covers the top of the ring (g). The top of the conical-shaped cover is either pulled over the top of the central mast or clamped around it. The ring is either freely suspended from cables or is firmly fixed to the mast with cantilevered brackets to which the ring is secured. In the 'palm tree' supported solution, cantilevered brackets with a curved shape are set out radially in order to create a smooth curved form on which the membrane is set. The brackets are usually aligned with joints between membrane panels.





q | Vertical section 1:5 Junction between panels



r | 3D detail of junction between 2 fabric panels

In an external fold in a roof membrane, the material is draped over the supporting structure, fixed with fabric strips that are sewn or welded to the underside of the membrane and clamped to the supporting structure. An additional membrane cover strip is fixed to the top of the joint to conceal the stitching if required (s). An alternative method is to form a joint between two membranes at the external fold, clamping them with a pressure plate to an aluminium extrusion which is supported by the primary structure, such as a mild steel tube, curved to form the shape taken up by the membrane. Internal folds are formed in the same way as ridges, with the membrane folded outwards rather than across the ridge and downwards. In some cases the membrane may pass under the cable. These junctions are formed by clamping the ends of adjacent membranes that form the valley. The edge of each membrane is clamped with an edge bead, while the clamp itself is fixed to a central cable. The gap between the membranes is closed by two membrane strips which are sewn or welded to the base of the strip and are clamped down to a thin pressure plate between the membranes. The clamp that closes the two membrane strips is supported off the metal straps beneath (r). By raising the closing strips above the height of the joint, two adjacent gutters are formed, with the clamping strip securing the closing flaps above the level of the water being drained.



s | 3D exploded detail of clamp and membrane skirt

Details

1 | Fabric membrane panel
2 | Supporting mild steel structure
3 | Extruded aluminium clamp
4 | Stainless steel cable
5 | Membrane hood
6 | Plastic edge bead to membrane panel
7 | Thermal insulation
8 | Perimeter wall build-up
9 | Fixing clip
10 | Aluminium clamp assembly



a | 3D detail of edge clamp



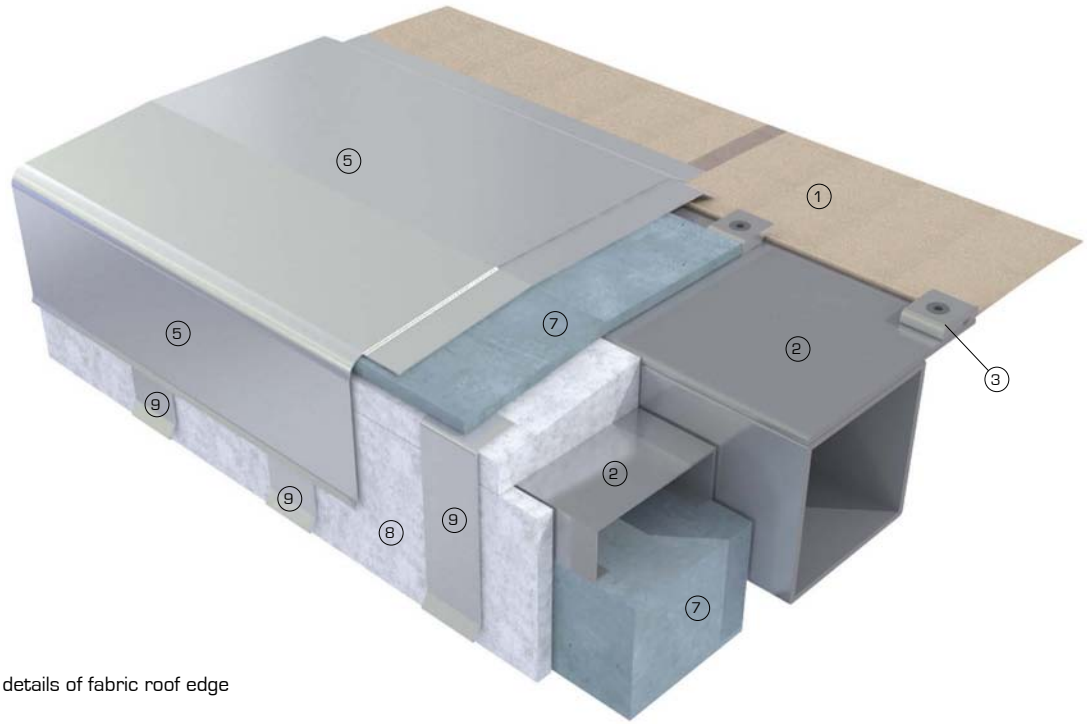
b | 3D cutaway detail of fabric roof edge

System design

The advantages of single membrane fabric roofs are their smooth curves, typically with different, directionally opposing, and thin, sharp edges that provide translucent roofs allowing diffused daylight to pass through them. They use their curvature as a method of tensioning the membrane against a supporting structure, which is typically a mixture of mild steel tubes and stainless steel cables.

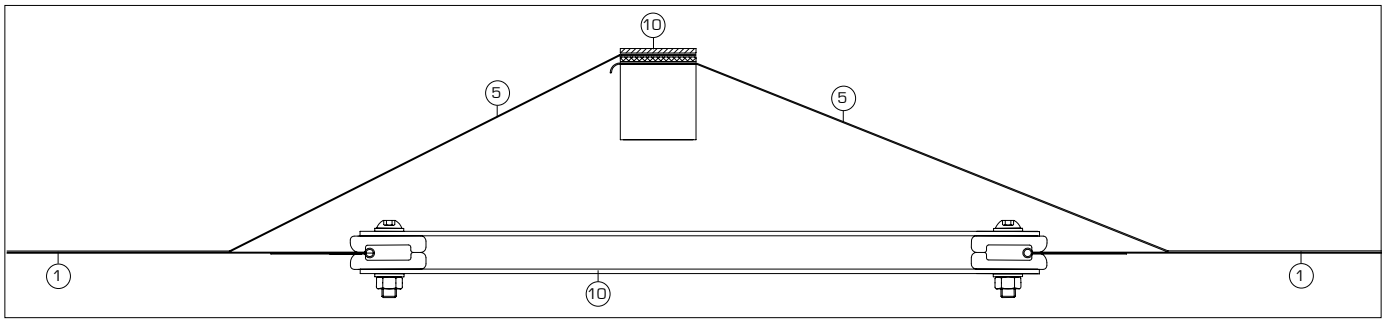
In a fabric roof the membrane is structurally modelled so that the resultant form developed between architect and structural engineer distributes the tensile forces within the membrane without over-tensioning some parts and under-tensioning other parts of the membrane; with the resulting design resisting all load combinations in their different directions. This work is usually developed in the form of a computer model, either by specialist structural consultants or by manufacturers as part of the design development process. The minimal surface form must also be suitable for draining away rainwater, which forms another aspect of design development together with the treatment of interfaces with adjacent areas of roof and external wall. The resulting form is designed to keep all parts of the fabric membrane in tension (f), not just from the supporting structure but from imposed loads; mainly wind loads. Wind pressures are resisted by re-distributing the forces within the fabric membrane. Any areas of the fabric roof that go into compression as a result of slackness in the membrane reveal themselves as creases in the material.

Both the cone-shaped example in this section and the barrel-shaped example in the following section make use of an internal steel structure that supports part of the membrane by holding it in tension at its edges. The membrane is fixed and tensioned, either at points (a) or with continuous clamped fixings (b) similar to those described in the previous section on ETFE cushions (MCH_268). Generally speaking, the high points of the supporting structure take up the downward loads from the membrane and imposed loads (mainly wind loads) and the lower points at the edges take up the effect of wind uplift. In shallow-sloped roof membranes, more of the structural loads are taken by the edges (j) or points at the base, often resulting in large columns or posts being required at these points. The distribution of loads within the fabric roof design is revealed in the supporting structure, which can be as visually lightweight and elegant as the fabric membrane itself, or can become visually heavy which can detract from the intended lightweight effect of the membrane (m). Where roofs transfer forces to an adjoining structure, rather than contain the loads within their own supporting frame, the visual effect on the adjoining structure is balanced with the requirements of the membrane roof and its own frame. As imposed loads such as snow or sand can cause permanent stretching of the fabric membrane, the form of the roof and its associated slopes are made sufficiently steep to avoid creating areas or pockets on the fabric roof where they can collect.

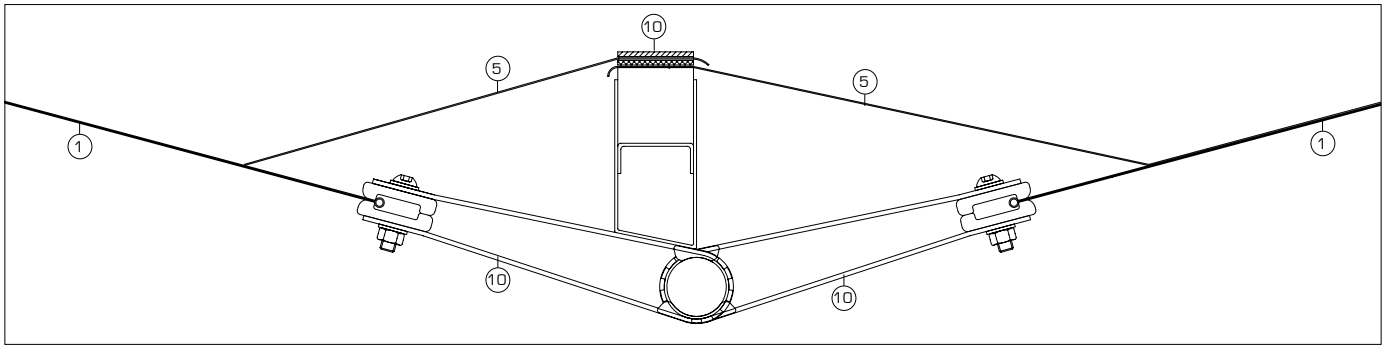


c | 3D cutaway details of fabric roof edge





d | Vertical section 1:10. Junction of adjacent fabric membrane meeting at same angle



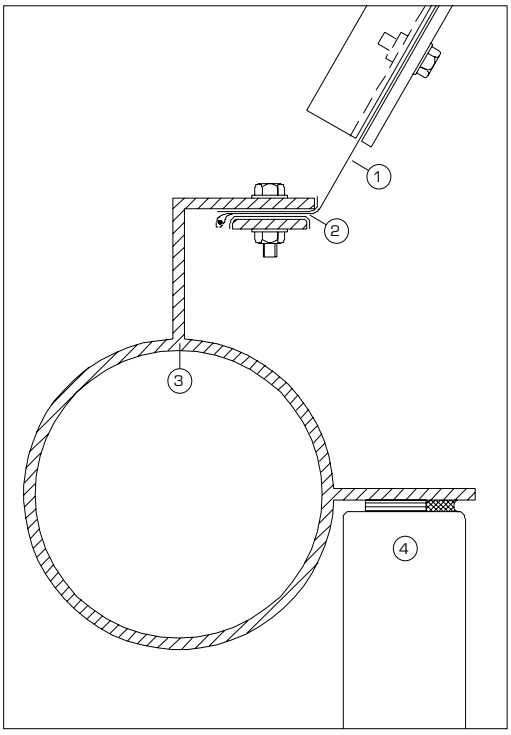
e | Vertical section 1:10. Junction of adjacent fabric membrane meeting at same angle



f | 3D fragment view showing barrel roof configuration



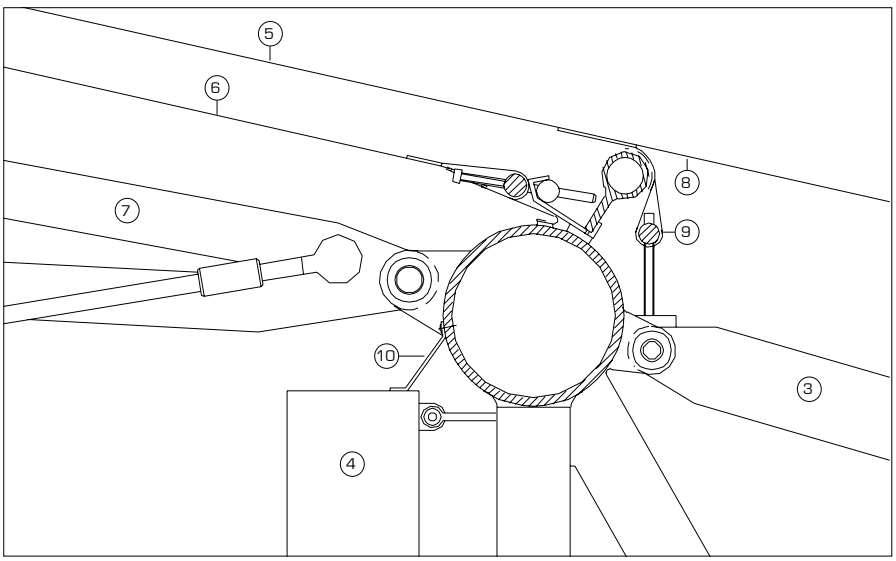
g | 3D fragment view showing barrel roof configuration



h | Vertical section 1:10. Single skin system with steel edge support



j | 3D detail view showing membrane barrel roof connection to steel support structure



k | Vertical section 1:10. Double skin system with steel edge support



Details

1 | Fabric membrane
2 | Edge seal clamped to continuous plate
3 | Structural support
4 | Wall panel
5 | Outer membrane
6 | Liner membrane
7 | Steel supporting structure
8 | PTFE film or similar slip layer
9 | Continuous stainless steel or aluminium bar
10 | Pressed metal flashing

m | 3D fragment view showing barrel roof configuration



n | 3D fragment underside view showing barrel roof configuration

System details

The two most common fabrics used are PVC-coated polyester fabric and PTFE-coated glass fibre fabric. Both are woven cloth materials which are protected by coatings, usually applied on both sides. Other open-weave materials are used as solar shading only, and are manufactured without protective coatings. These are made from polymer threads, sometimes with a protective coating applied to the manufactured thread itself to increase the life expectancy of the material. In all these woven materials the strength of the fabric can be different in the two directions in which the 'cloth' is woven. When selecting a material, the strength of the 'warp' threads running the length of the material is compared to the 'weft' threads running the width. In most commonly used roof membranes, the tensile strengths of the warp and weft directions are similar, but these need to be checked when the material type is chosen.

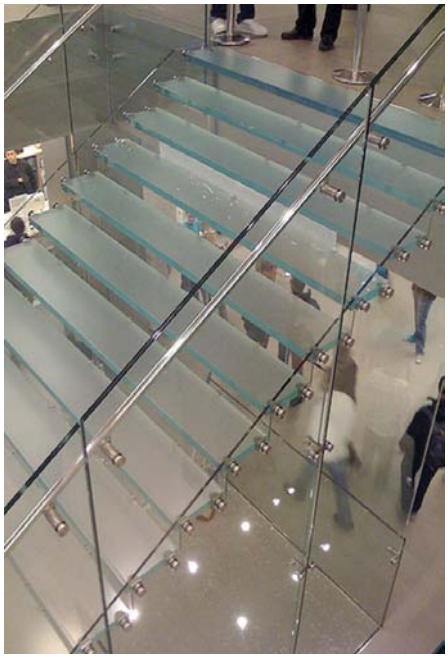
Most fabric roof materials imitate the appearance of natural canvas (M), but this material is used only where its appearance and individual texture is considered to be the most important feature. Natural canvas is less stable than synthetic fabrics when used in tension structures, and is difficult to clean. A modified acrylic canvas material, with a similar texture to natural canvas, is sometimes used for its greater dimensional stability. Neither material is suitable for long-span fabric roofs.

Fabric roofs are highly susceptible to damage from sharp objects. Small cuts in the membrane can be repaired with patches made from the same material which are glued into position. Larger tears are repaired with hot air welders, usually undertaken by the specialist contractor who installed the fabric roof. Large repairs are visible, and panels are replaced where visibility is the most important consideration. Since large tears can affect the overall structural performance of the membrane, the complete membrane is sometimes removed for another panel to be stitched or welded, and re-coated in the factory.

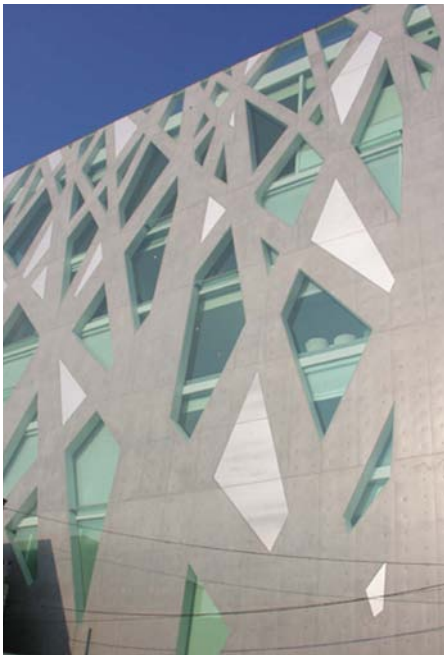
The outer surfaces of fabric roofs are cleaned with soft brushes that wash the membrane surface; the work being done typically from either a mobile platform or by rope access cleaners (abseilers) who are attached in harnesses and suspended from cables attached to a steel bracket anchor point on the top of the membrane roof. The anchor point forms part of the steel or timber supporting structure to the membrane roof. Cleaning is also an important consideration in areas of high humidity, where there is a higher risk of mould forming on the surface of the fabric which can cause permanent staining. Regular cleaning prevents mould growth. PVC/polyester is more susceptible to mould growth than PTFE/glass fibre fabrics, essentially because the latter has lower surface friction.

04 STRUCTURE

	Material systems for structures
	Elements of structures
	Braced frames
1	Reinforced concrete
2	Steel
3	Timber
	Portal frames
	Loadbearing boxes
1	Reinforced concrete
2	Brick
3	Glass
	Trusses
	Arches and shells
	Space grids
	Floor structures
1	Cast in situ/Cast in place concrete
2	Precast concrete
3	Steel and steel mesh
4	Timber
5	Glass
	Stairs
1	Concrete
2	Steel
3	Timber
4	Glass



a | Glass stair. Apple store, Regent Street, London, U.K. Architect: Bohlin Cywinski Jackson



b | Reinforced concrete structure. Tod's Building, Tokyo, Japan. Architect: Toyo Ito



c | ETFE Roof structure. Eden Project, Cornwall, U.K. Architect: Grimshaw Architects



d | Curved concrete frame. Science Park, Valencia, Spain. Architect: Calatrava



e | Curved concrete frame. Science Park, Valencia, Spain. Architect: Calatrava

Structural stability

This chapter sets out the most commonly used material systems for structures together with the relationship between structure and enclosure. Typical details are shown for each material system and its interface with walls and roofs. Structural 'types' in this chapter are described as systems based on the use of a primary material used to make a complete building structure. Each example can be used as a single structural system for a complete building or, more commonly, be combined in a mixed construction. Building structures are put into categories depending on whether they are either 'braced' or 'unbraced' in their construction. Braced types use devices such as internal walls or service shafts, or alternatively use cross bracing to stabilise the structure. This vertical bracing is usually provided in two vertical planes at right angles to one another in order to stabilise the structure both along its length and across its width (j). Horizontal bracing is provided by the floor structures which act as horizontal girders (q). The roof, if sufficiently rigid in the horizontal direction as in a reinforced concrete slab, can also be considered to be horizontal bracing. Unbraced structures, in contrast, are allowed to sway as a result of their being unbraced in one direction. Their stability is provided by rigid connections that provide stiffness within the structural elements, such as in portal frames. Like braced structures, bracing in the horizontal direction is provided by floors and, in the case of single storey structures, by bracing in the plane of the roof. The most common elements used to make building structures are braced frames, portal frames, loadbearing boxes, trusses, arches and shells, and space grids. Reinforced concrete (e) and masonry structures, despite their essentially monolithic nature, are considered to be braced structures as some walls provide specific bracing elements.

Structural movement

The term 'structural movement' covers a wide range of effects of deformation and movement in building structures. Dead and imposed loads, together with wind and snow loads and forces specific to use or location such as dynamic and seismic loads, can bring about movements seen as bending and shear deformations which are a normal part of the building in use. An essential aspect of structural movement in the overall design of buildings is that its effects need to be taken into account in the external envelope and its interfaces, primarily at roof level. Temperature changes and differences in temperature between different parts of a structure can cause expansion and contraction of structural members, possibly with some local bending of those members. The detailing of both the components and any associated weatherproofing or internal



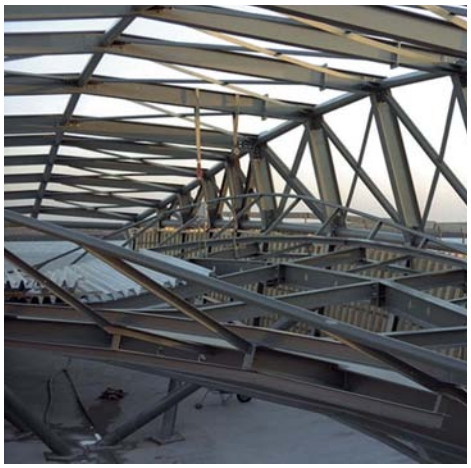
f | Loadbearing glass box. Broadfield Glass Museum, West Midlands, U.K. Architect: Design Antenna



g | Glass footbridge. Rotterdam, Holland. Architect: Dirk Jan Postel



h | Timber truss roof structure. Resource Centre, Cumbria, U.K. Architect: Sutherland Hussey



j | Braced steel frame. Saltwater Pavilion, Neeltje Jans, Holland. Architect: Oosterhuis Associates



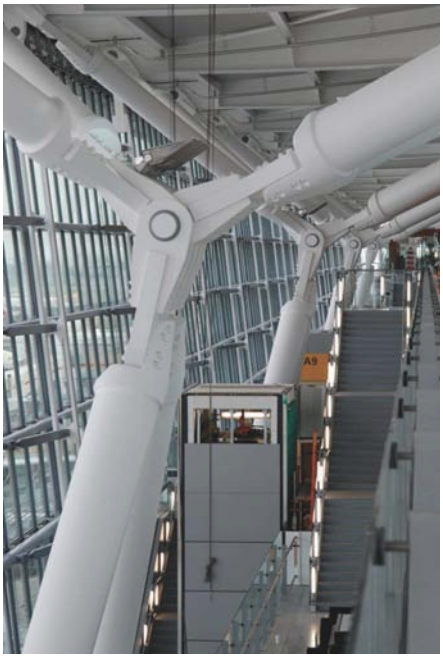
k | Concrete frame. Siobhan Davies Dance Studios, London, U.K. Architect: Sarah Wigglesworth



m | Steel frame structure. Fawood School, London. U.K. Architect: Alsop Architects



n | Reinforced concrete structure. CAC Museum, Cincinatti, U.S.A. Architect: Zaha Hadid Architects



p | Branced steel roof structure. Heathrow Terminal 5, London, U.K. Architect: Rogers Stirk Harbour



q | Braced steel frame. Lerner Hall Student Center, New York, U.S.A. Architect: Bernard Tschumi Architects



a | Loadbearing masonry. Brindleyplace, Birmingham, U.K. Architect: Porphyrios Associates.



b | Loadbearing glass box. House extension, London, U.K. Architect: Paul Archer Design



c | Steel staircase. Museum of Contemporary Art, Los Angeles, U.S.A. Architect: Arata Isozaki and Associates



d | Concrete staircase. Hyogo Museum of Art, Japan. Architect: Tadao Ando



e | Steel stair. City Hall, London, U.K. Architect: Foster and Partners

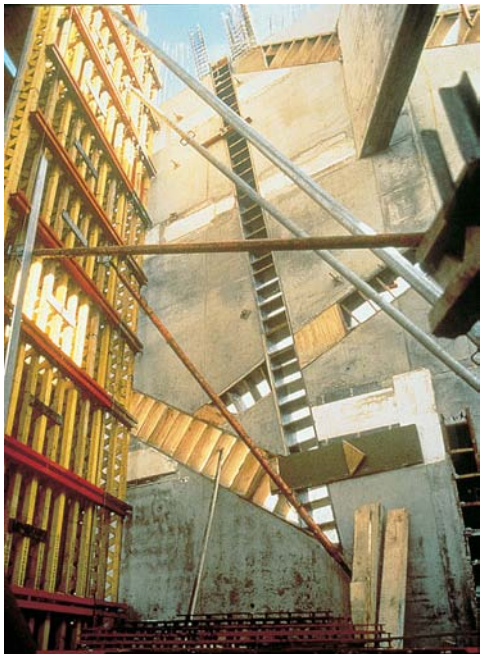
finishes must accommodate this movement without causing damage to these finishes. Moisture penetration can cause expansion and contraction in concrete, masonry and timber structures. Frost action, caused by the freeze/thaw cycle of moisture within structural materials can eventually cause damage if the detailing is not sufficiently robust.

Trends in the use of building structures

Much effort in the design of building structures is focused on economy combined with safety, in terms of both the quantity of material used and the amount of fabrication needed to assemble the structure. The appropriate use of structure can often be seen in the 'fine tuning' of the balance of material used and fabrication undertaken. This approach is being increasingly paralleled in architectural design in the external envelope and internal fittings, where there is a growing tendency to use the least number of components while tempering this approach with the needs of their fabrication. This has led to an important trend in structures of their increased visibility and as self-finished components within buildings (b). This brings the aims of structural design and architectural design much closer together where the relationship between structure, enclosure and internal finishes are co-ordinated at an early stage of the design, continuing through the following detailed design and construction phases.

In steel structures, frames have become a full part of the language of architectural design (h). Assemblies in steel, ranging from small lattice trusses to cable-stayed structures that resemble 'kits of parts', have led to their widespread use as highly visible structures, set either outside or inside the building enclosure (k). The necessity of joining steel sections with either welds or bolts has led to a visual richness in both the design of structural members and the joints between them. This has been helped enormously by the development of intumescent paints, which protect the structure during a fire by expanding to form a heat-insulating layer that protects the integrity of the structure for a limited period, usually one hour. These finishes, once only roughly textured or trowel-applied, can now achieve a smooth finish previously associated only with the regular paint finishes used in unprotected structures such as single-storey roof structures. Issues of thermal bridging in steel structures and the penetration of the waterproofing layer with steel components are now easier to overcome with thermal breaks, within joints and across weatherproofing membranes such as with the use of a set of bolted connections that are difficult to achieve in either concrete or timber.

Concrete structures are now being exposed as self-finishes within buildings (g), both on the external walls and in the soffit (underside) of structural slabs, with a quality of finish traditionally associated with



f | Clad steel frame. Jewish Museum, Berlin, Germany. Architect: Daniel Libeskind.



g | Loadbearing concrete. Lyon-Satolas Station, Lyon, France. Architect: Santiago Calatrava



h | Braced steel framed construction. Wood Street, London, U.K. Architect: Richard Rogers



j | Organic concrete forms. Phaeno Centre, Wolfsburg, Germany. Architect: Zaha Hadid



k | Braced steel frame. Pompidou Centre, Paris, France. Architect: Richard Rogers

only plastered walls and ceilings. Exposed finishes in concrete are now less common due to their poor weathering, from a visual point of view, but are enjoying a revival in predominantly dry climates where thermal insulation is set within the depth of the wall. The renewed interest in precast concrete structural systems, other than those used for parking garages, is set to continue with the ever-greater expression of jointing forming part of the visible language of detailing.

Timber structures are becoming ever more complex, both in terms of construction techniques and the geometries used in their design. The development of pinned jointing systems, as well as the interest generated in the material by its low levels of embodied energy, have resulted in the revival of exposed timber structures. The new generation of pinned joints helps to overcome the traditional problem of creating reliable and elegant joints that perform well in tension, particularly in large-scale glue-laminated structures.

The use of CAD/CAM techniques, or computer aided design/computer aided manufacturing for both timber and steel structures, as well as the use of these materials for concrete formwork, is set to transform the geometries of structures built from all these materials. The use of CAD/CAM permits much greater accuracy and closer tolerances in assembly with joints that are increasingly visually elegant. CAD/CAM is set to push further the drive towards prefabrication. Timber and concrete, traditionally considered to be materials that are worked on site, are now more frequently fabricated at the factory; for example in the pre-cutting of timber components and in the precasting of concrete components instead of their casting in-situ. The building site will inevitably become a place where assemblies are fixed together rather than being the temporary workshop to which we are accustomed.

Thermal bridging, and the related effects of condensation associated with the integration of building structure with walls and roofs, continues to be a significant issue in building design in almost all climates. This has led to the increased use of vapour barriers and the careful placing of thermal insulation, which need to be co-ordinated with the structural design in order to avoid interstitial condensation. The thermal mass of exposed concrete structures is being used for the night-time cooling of buildings in conjunction with ventilated facades. The increased prefabrication of both structures and facades has led to a greater awareness of issues of co-ordination at an early stage of the project to ensure that highly visible finished components, which in earlier buildings would have been covered over by successive building trades, can be successfully exposed as high-quality finished components.



a | 3D view showing reinforced concrete frame construction

The use of precast and in-situ cast (cast in place) concrete in frames provides a homogeneous structure where joints are made as rigid connections (a). These frames require additional stiffness from bracing that can be provided typically by either concrete shear walls (d) or steel cross bracing. Alternatively, lateral stability can be introduced into concrete frames by stiffening other elements such as cores, shafts or stair enclosures. The inherent fire resistance of concrete provides structures that require no further fire protection measures. With in-situ cast construction, the ability to re-use formwork is important in keeping its use economic. Each 'lift' of concrete, typically a floor with its supporting walls and columns, takes longer to construct than an equivalent steelwork structure since the concrete takes time to reach an adequate strength to allow another floor to be built on top. Although the construction of an in-situ cast reinforced concrete frame is considered slower than erecting a steel frame, the construction times can be matched if the concrete work is well-organised. Frames in concrete combine easily with ground structures such as retaining walls and foundations because they are of the same material and can be continuous.

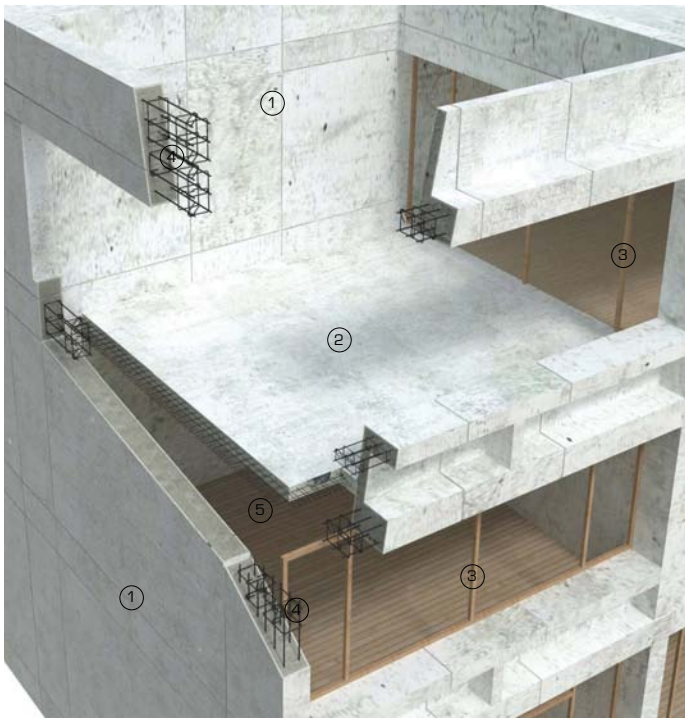
Joints and Connections

Stiffness at the junctions of the frame is important both to provide sufficient rigidity in the frame itself and to make its deflections compatible with the cladding and internal elements such as staircases. This can be achieved either within the joints forming the frame, by including extra reinforcement, or by using additional stiffening walls such as those used to enclose elevator (lift) shafts and service cores. Typically, deflections in concrete beams or slabs are designed to be compatible with the external cladding, partitions and fittings within the building.

Movement joints are introduced to allow for thermal movement. These junctions are effectively breaks in the structure, resulting in the overall structural frame comprising a set of smaller linked frames, each an independent stable structure. Movement joints are usually taken through the external walls and roof, requiring envelope details that allow for structural movement while remaining weatherproof.

Interface with external envelope

Concrete frames can be either exposed outside the weather line of the cladding, that is, the non-loadbearing walls, or be completely enclosed by the external envelope. When exposed externally, the penetration of the frame through the walls and roof requires careful detailing to overcome weatherproofing and thermal bridging around penetrations of structural members through the cladding. Grooves are often cast around penetrating beams in order to allow flashing pieces to be inserted to assist in forming a weather seal. Cladding is fixed either by a continuous stainless steel channel that is cast into the edge of the concrete slab, or by expansion bolts secured into the slab when the cladding is fixed. The bolts may also secure stainless steel angles, brackets or continuous rails depending on the nature of the lightweight cladding. Reinforced concrete panels can be secured with additional metal pins cast into the top surface of the concrete slab.



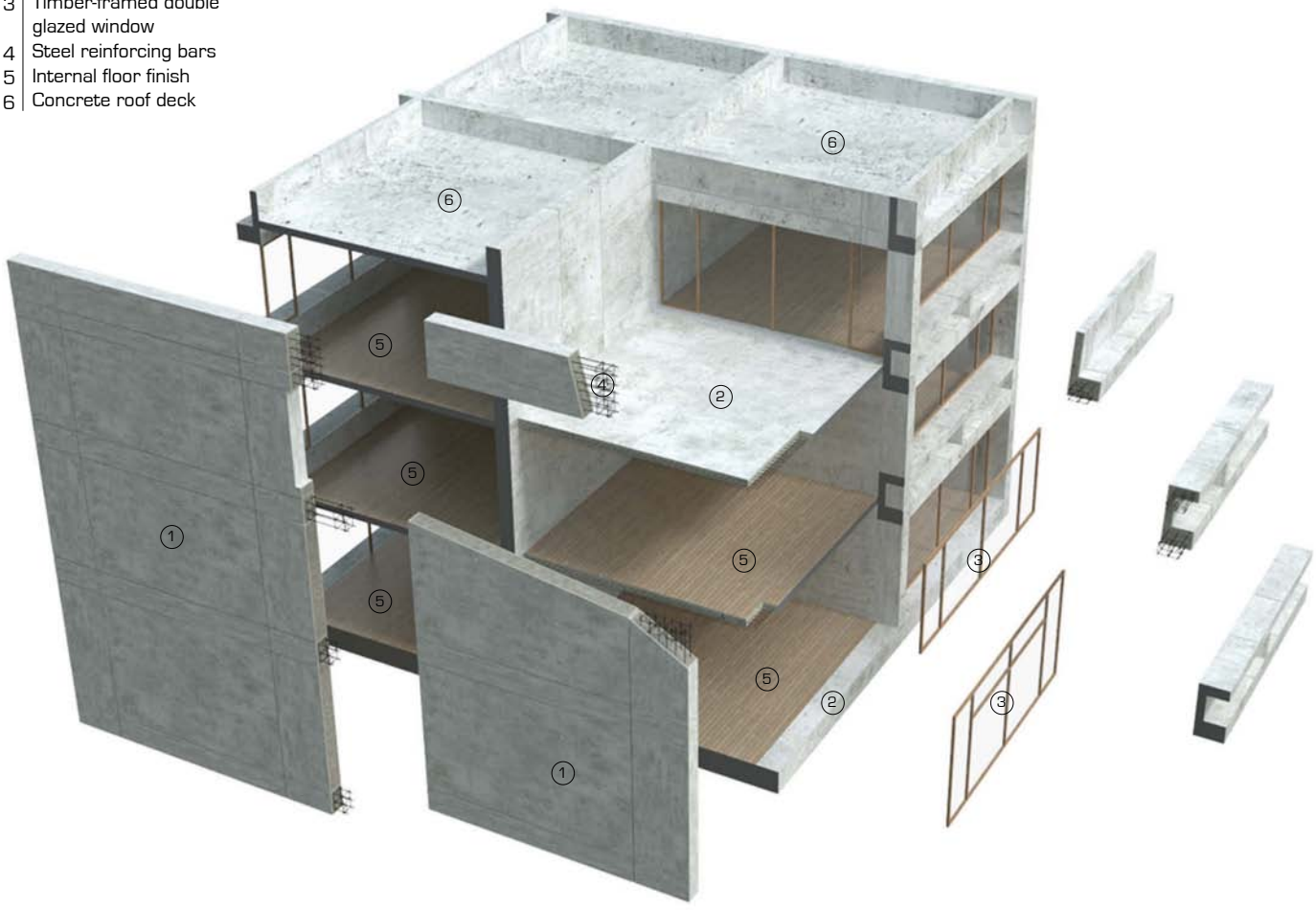
b | 3D cutaway view showing concrete frame and steel reinforcing bars



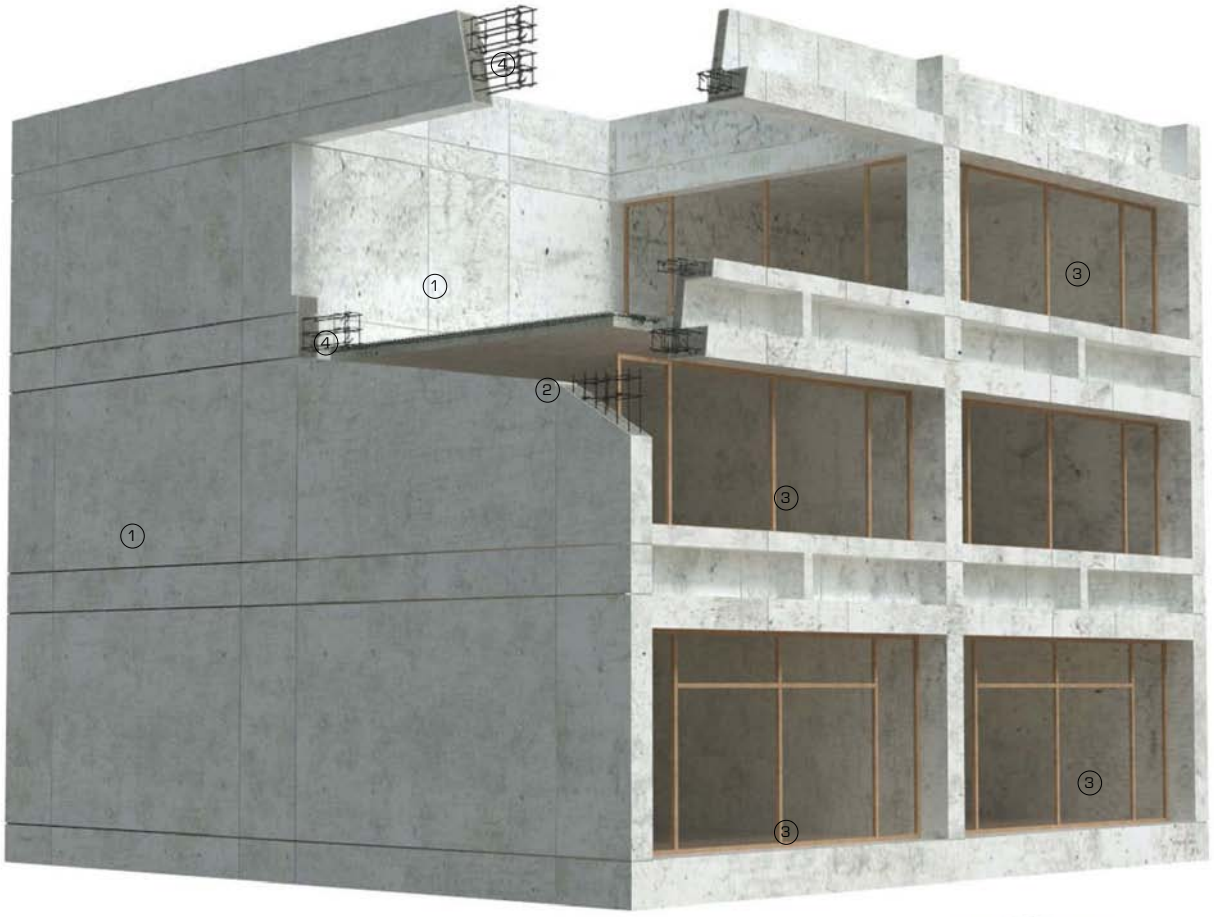
c | 3D cutaway view showing concrete frame and steel reinforcing bars

Details

1 | Reinforced concrete wall
2 | Concrete floor deck
3 | Timber-framed double glazed window
4 | Steel reinforcing bars
5 | Internal floor finish
6 | Concrete roof deck



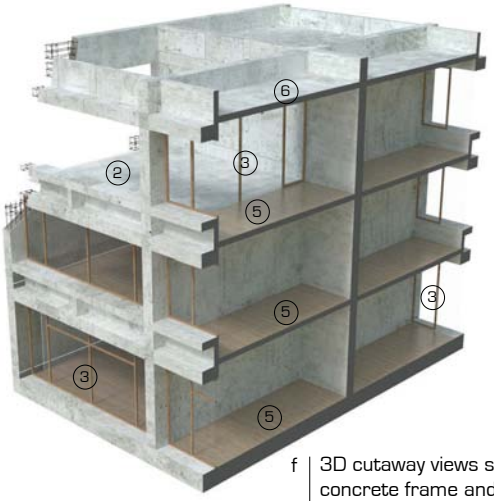
d | 3D exploded view of concrete frame and panel system



e | 3D cutaway view showing concrete frame and steel reinforcing bars

Details

1 | Reinforced concrete wall
2 | Concrete floor deck
3 | Timber-framed double glazed window
4 | Steel reinforcing bars
5 | Internal floor finish
6 | Concrete roof deck

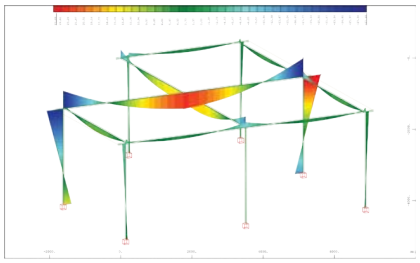


f | 3D cutaway views showing concrete frame and steel reinforcing bars

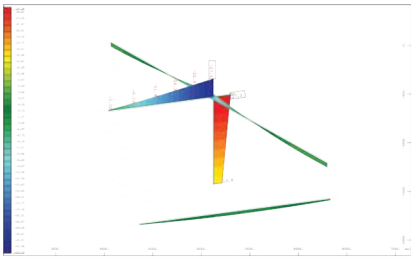


g | 3D cutaway view showing concrete frame and steel reinforcement bars

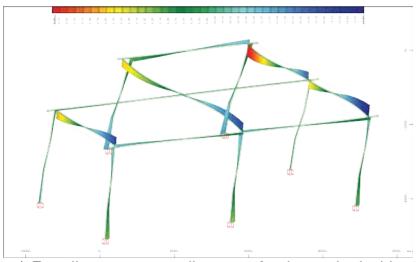




h | Bending moment diagram for dead loads.



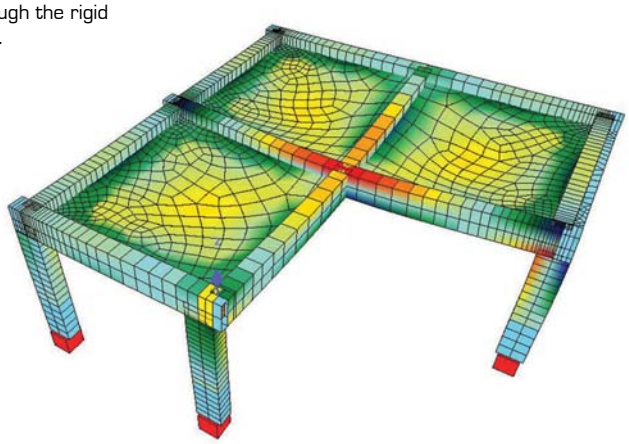
j | Bending moment is transmitted from the beam to the column through the rigid connections of the frame.



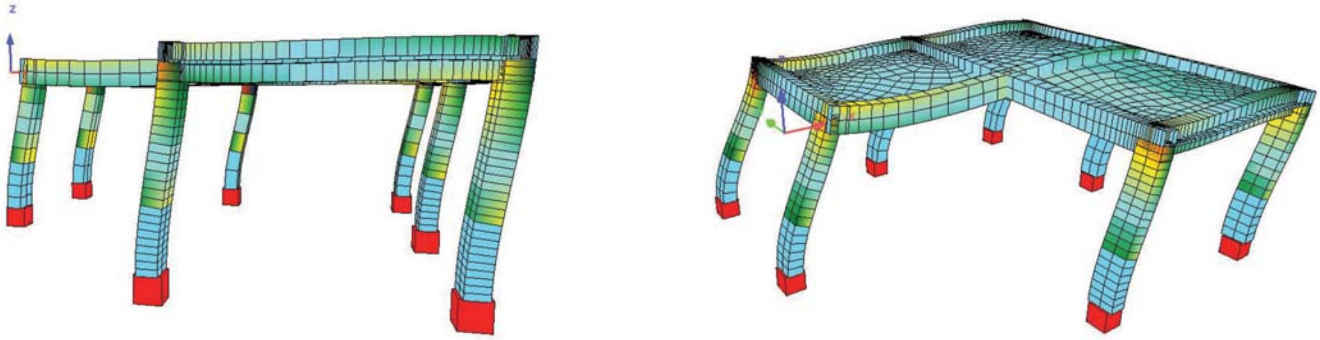
k | Bending moment diagram for lateral wind load.



m | Structural model of concrete frame structure: typical floor system



n | Stresses in the structure under dead loads: the secondary concrete slabs deflect in their plane, transferring the load to the intersecting primary frames (the structural movements shown are magnified).



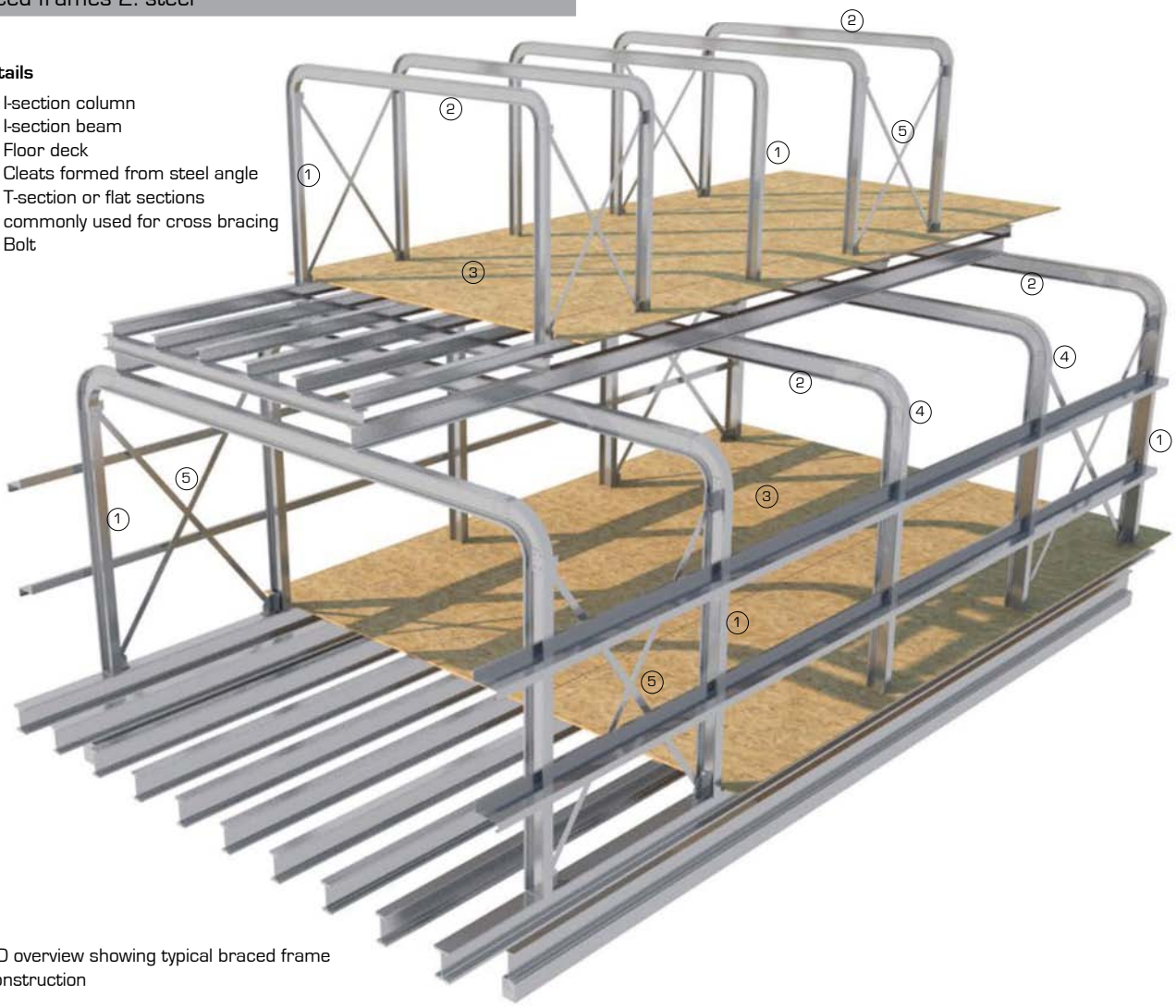
p | Considerable bending strength in the columns is required against lateral wind loading (the structural movements shown are magnified)

Reinforced concrete frames provide an integration of wall, roof, floors and columns into a single form of construction (e). Supporting walls and floors can be integrated into shell forms, as seen in the Science Park in Valencia by Santiago Calatrava. Concerns about the weathering capability of concrete have led to the material being covered by an additional weathering material, which can be thin metal panels or even an applied coating. Recent improvements in surface finishes, with honing and polishing used in precast concrete, have allowed a slow re-introduction of concrete as an expressed finish. An essential issue has been the thermal bridging associated with concrete structures, which has led to thermal insulation being set externally with an additional weathering material on the outside. The positioning of the insulation externally allows the environmental strategy within the building to benefit from the thermal mass of concrete. In recent years, with the enhanced weathering characteristics of precast concrete, the thermal insulation is set into the thickness of the wall, resulting in the construction being of diaphragm type rather than a single wall with a non-loadbearing skin set either internally or externally. In the diaphragm wall, the two halves of the wall are linked by either stainless steel ties or by reinforcing bars (g).

Regardless of whether concrete is formed in-situ or is precast, the material is cast in formwork. In-site formwork is typically made from plywood sheets but any material can be used. The material used for formwork leaves a strong impression on the concrete finish, often with a high degree of visible detail. This allows the concrete frame to have a wide range of finishes from timber boards, leaving a high degree of visible texture on the surface, to very smooth concrete where plastic laminate-coated plywood is used. Digital fabrication has had a modest influence over concrete construction, with the introduction of CNC-cut polystyrene forms that are set into the formwork to produce complex shapes in either precast or in-situ cast concrete. The ability of concrete to take up complex shapes using economic formwork has led to a gradual move to more sculpted forms in concrete frames, as seen in the work of Zaha Hadid and Santiago Calatrava. The visual continuity of openings in walls, roofs and floors within buildings gives a spatial continuity and fluidity which can be achieved without the need for elaborate decoration; the frame provides an elegant expression of form without the need for secondary finishes. The development of the reinforced concrete frame of columns and beams has seen considerable elaboration in the work of Calatrava, following visual principles of animal skeletons as well as drawing visual inspiration from equivalent steel structures. Reinforced concrete frames have shown the ability to move from being simple, rectilinear flat forms (m) to being visually rich structures of complex geometry of either curves or folds.

Details

1 | I-section column
2 | I-section beam
3 | Floor deck
4 | Cleats formed from steel angle
5 | T-section or flat sections commonly used for cross bracing
6 | Bolt



a | 3D overview showing typical braced frame construction

Steel frames are made from columns and beams that are fabricated in factories and workshops and assembled together on site. Unlike reinforced concrete frames, steel frames can be readily assembled with either rigid moment connections or with pin connections (a). Lateral stability is provided typically with either the cross-bracing of some bays, or with staircase enclosures, cores or shafts.

Steel frames are usually shot-blasted, cleaned and primed prior to erection. Frames that are not to be left exposed visually require no further painting. However, most steel structures require fire protection, which is provided typically with either concrete encasement, an intumescent paint or by enclosing the frame with fire resistant board. Steel frames not requiring fire protection, such as those used for roof structures only, are painted to avoid corrosion during construction and after the frames are assembled. Members which are to remain visible when assembled, such as in visible roof structures, are often delivered to site as pre-painted components that can be assembled on site and lifted into place by crane, avoiding the need for substantial scaffolding. Care is taken not to damage the surface finish, as the touching up of galvanizing and paintwork on site is slow, laborious and more difficult than in the factory.

Joints and connections

Joints in steel frames are bolted or welded (b). Bolted connections are the most commonly used, with either cleats or plates used as connectors. The advantages of a fast construction speed on site associated with steel frames is often continued into the configuration of the floor slab, which often uses trapezoidal-shaped floor deck instead of full concrete slabs. The profiled metal deck is used as both permanent formwork as well as having a structural role in composite action. Concrete is poured on top of the metal deck, which typically has shear studs or connectors to form a bond between the two materials. The profiled metal deck is set either on top of the steel beams of the structural frame, or is set on a continuous steel plate welded to the bottom flange of the steel beam. The advantage of the former method is its simplicity of construction, while the advantage of the latter is in reducing the overall depth of the structural floor zone, which can in turn reduce the overall height of the building with attendant savings in the cost of the external walls. In addition, the use of a composite concrete and steel deck provides essential properties of fire protection and acoustic separation.

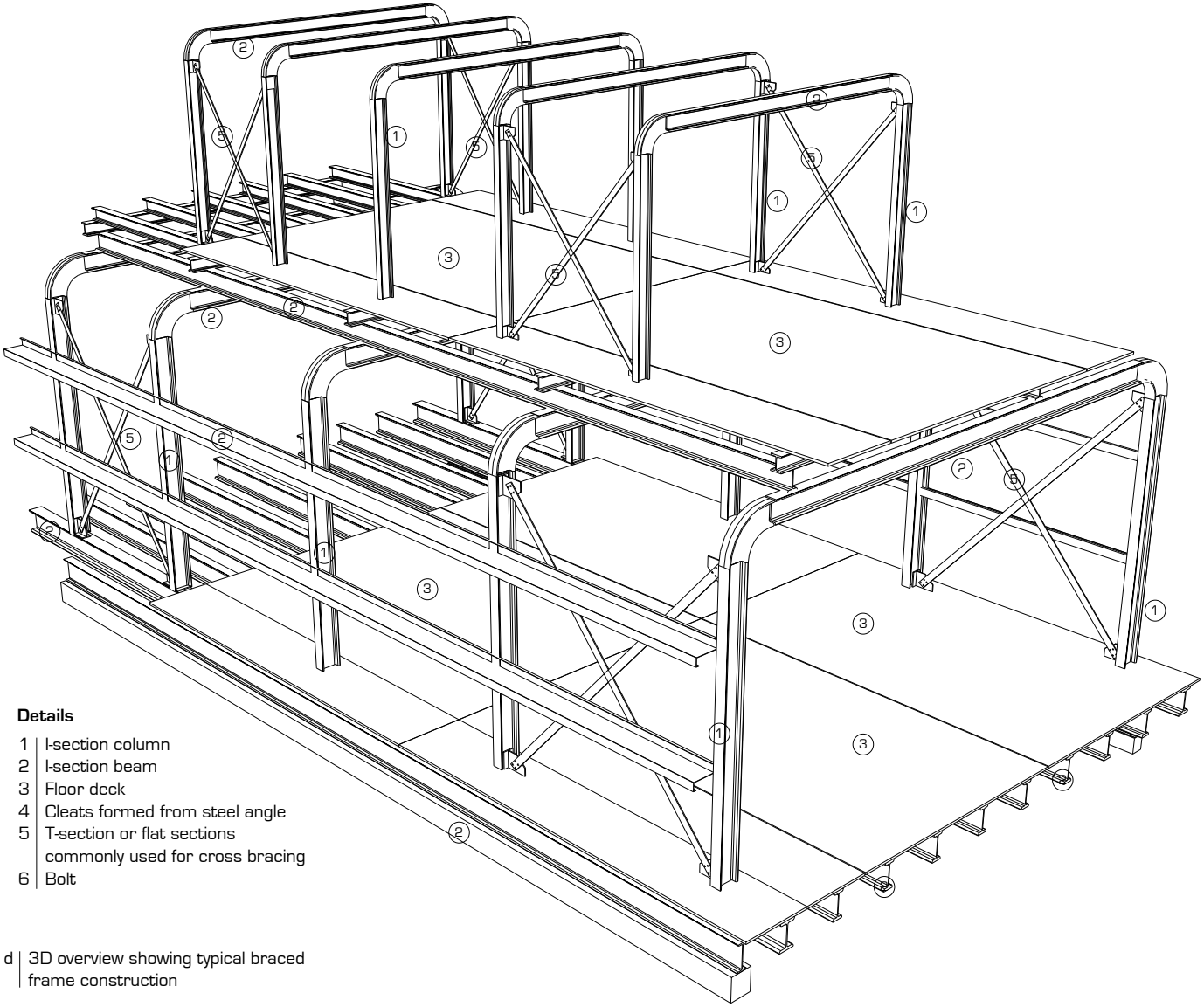
Movement joints are introduced to allow for thermal movement in the steelwork, which can be greater than that of concrete. These joints are breaks in the structure where each part of the structural frame must be independently stable of its neighbour. The corresponding movement joint on the external wall and roof is detailed so as to provide a continuity of waterproofing while creating a break in the structural support of the external wall across the joint. Movement joints in the external wall are typically up to around 20mm wide, so do not have a significant visual presence on the facade, but are usually designed to make them an intentional part of the language of construction.



b | 3D detail view showing steel connection plate detail



c | 3D detail view showing steel connection plate detail



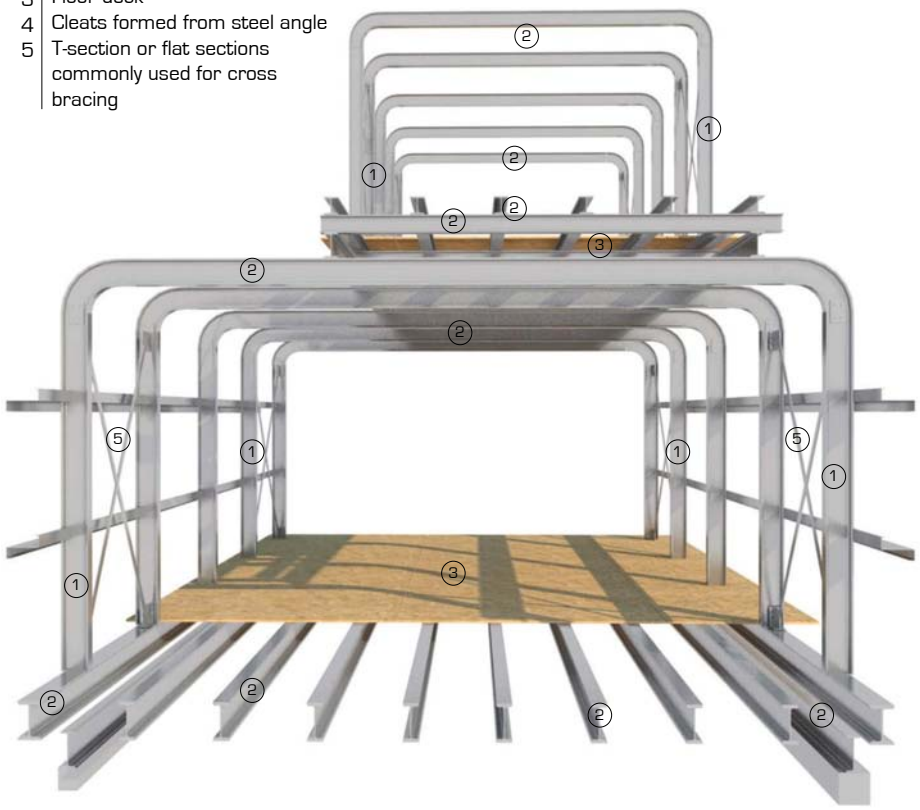
Details

1 | I-section column
2 | I-section beam
3 | Floor deck
4 | Cleats formed from steel angle
5 | T-section or flat sections commonly used for cross bracing
6 | Bolt

d | 3D overview showing typical braced frame construction

Details

1 | I-section column
2 | I-section beam
3 | Floor deck
4 | Cleats formed from steel angle
5 | T-section or flat sections commonly used for cross bracing



e | 3D overview showing typical braced frame construction



f | 3D detail view showing curved steel I-beam connection

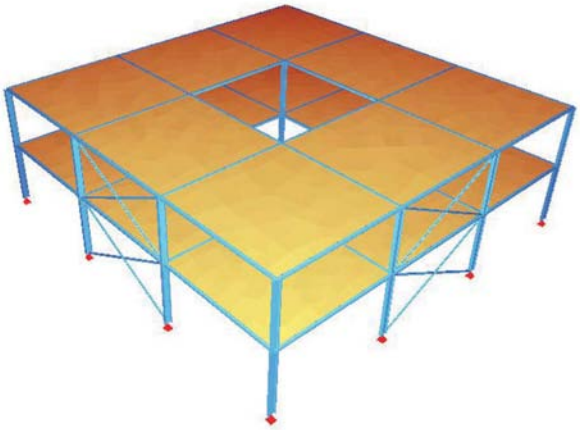
Smaller-scale steel frames for one or two storey buildings have the advantage of being possible to fabricate in the workshop as a 'kit of parts' for complex forms. Profiles can be cut, curved, welded and bolted in factory conditions for individual projects where the steel frame is visible from either inside or outside the building. This method allows welded joints which can be ground smooth and painted before being delivered to site in sections, where they can be bolted in place, achieving a level of workmanship that would be more difficult under site conditions.

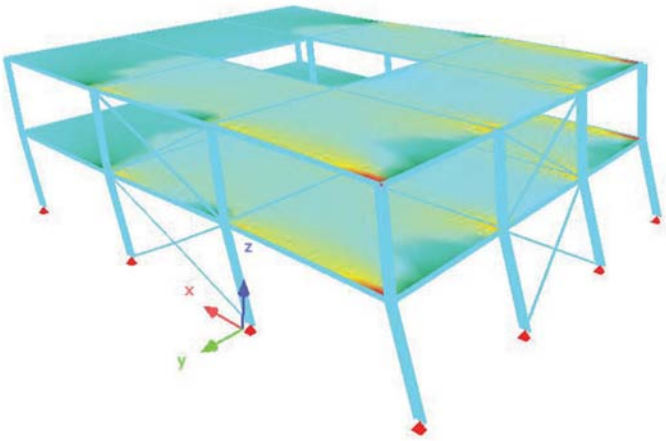
For short-spanning, lightweight steel frames, cold-formed sections can also be used (e). They have the advantage of being lighter to handle, forming frames which are more like a steel equivalent of the timber platform than a regular steel frame, with members at closer centres. The ability to mix hot rolled steels, capable of long spans, with cold-formed or 'pressed' sections provides a mixture of material systems in a single material, using a common method of fixing with screws and bolts. Small frames can benefit from the wide range of structural steel sections available, from I-sections to T-sections, box sections, tubes and flats, as well as specially fabricated sections of irregular shape (m). The introduction of irregular shapes has been made possible as a result of the development of digital cutting tools.

Interface with external envelope

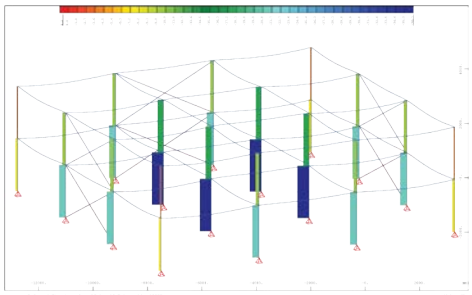
In common with reinforced concrete frames, steel frames can be either exposed outside the external skin or set inside the building; but when set externally, the frame is typically thermally insulated to reduce thermal movement of the frame. However the connection of the externally-set columns and beams to the floor slab through the external wall can be challenging. The need to create a weathertight seal around this junction requires special attention, as the seal is usually formed within a spandrel panel. More commonly, external walls are set on the outside of steel frames as cladding fixed to the edge of the concrete floor slab, sometimes with an additional backing wall set onto the edge of the floor slab. Sometimes facades are supported by brackets fixed to the outer face of the steel beam at the edge of the frame (f), but this can be difficult to achieve in practice due to the co-ordination needed between steelwork and facade away from site, which can be challenging from the point of view of sequence of procurement and construction.

Roofs in different material systems are set onto steel frames either directly, as in the case of a profiled metal deck, or with support brackets fixed to the steel framing members in the case of a glazed roof. The use of brackets that lift the roof system clear of the steel supporting members give a sense of visual separation, which can assist visually in the relationship between frame and covering.

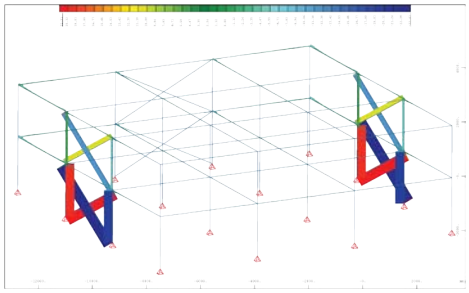




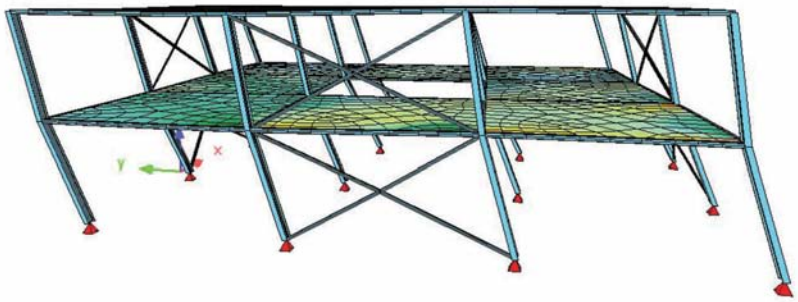
g | Structural model of a steel frame structure: concrete floor slabs provide horizontal stiffness.



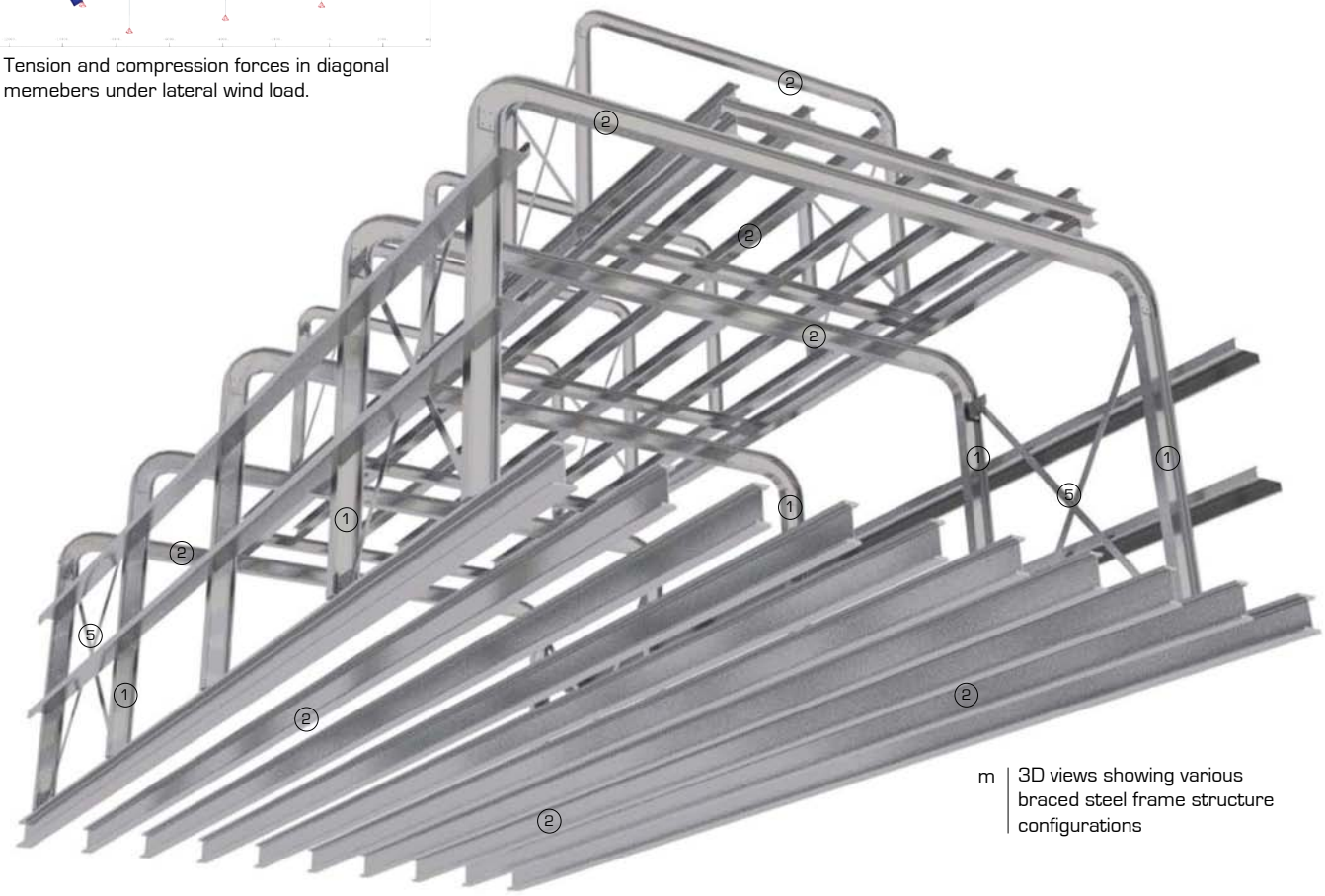
h | Column compression forces under dead loads.



k | Tension and compression forces in diagonal memebers under lateral wind load.



j | Diagonal bracing is necessary in steel frames for lateral wind and seismic loads (the movements shown are magnified)



m | 3D views showing various braced steel frame structure configurations



a | 3D views showing typical timber joinery and connection details



b | 3D cutaway view showing typical timber balloon frame on a masonry base

The platform frame

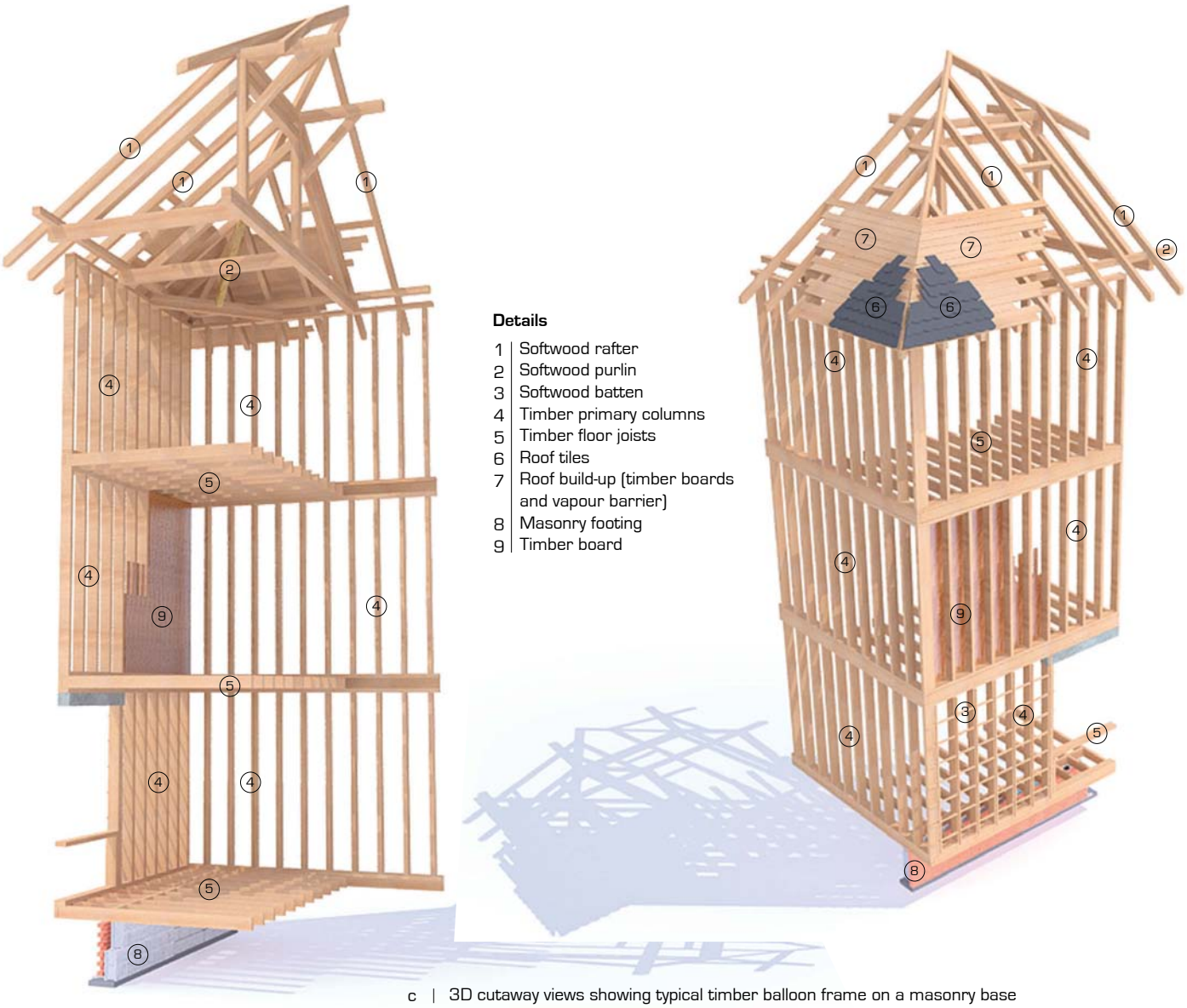
The platform frame consists of softwood timber studs, typically 100mm x 50mm, spanning vertically from floor to floor between horizontally-set timber sections called plates (b). The studs are set at close centres, typically 400mm as described in the section called 'Cladding to the platform frame' in the Walls chapter. Floor joists are aligned with the studs to transfer the loads efficiently from floor to wall. Timbers are butt-jointed and nailed, following the tradition of using simple techniques and relatively few tools to make a complete structural frame from cut timber sections that can be lifted by hand (a). The stability of the frame is provided by plywood sheets, which also form a substrate for a breather membrane and external finishes (c). Prior to the use of plywood, timber boards were the main form of sheathing for the frame. Floor spans are typically at up to around 3500mm to suit the ready availability of cut sections, but plywood-based floor joists can achieve longer spans depending on the design. Openings in walls, floors and roofs are easily formed and steel or engineered wood beams can be incorporated to increase floor spans. The walls to the platform frame are discussed in the Walls chapter, and timber floors are discussed later in this section.

Long-span timber frames

Larger frames can be made from either laminated timber or large cut sections which are connected pairs, spaced apart, to make larger components. These frames consist of columns and beams at 5-6 metre centres with infill panels between them to make walls. Floors are usually set on top of the beams. The large-scale nature of the frame makes it necessary to introduce cross-bracing or timber framed wall panels to provide lateral stability. These large-scale frames are increasingly being formed in cross-laminated timber, which have the ability to also be used as floor decks that have higher acoustic performance than timber joists and floor boards. Although sand pugging and layers of ceiling board can be added to the timber joist floor, their disadvantage has been to add mass without increasing the strength of the floor construction.

Hardwood timber frame

In recent years, there has been a revival in the UK in the use of timber frames that use large-size sections of hardwood such as oak, Douglas fir and larch to make frames that use traditional methods of frame construction rather than those of the platform frame. This method uses timber sections of around 300 x 300mm down to small-scale 100mm x 50mm sections in a hierarchy of primary, secondary and tertiary members, allowing most of the timber construction to be revealed rather than being concealed behind plywood sheathing and internal lining more typically associated with timber construction (d). Spans are modest, typically achieving those of platform frames.



c | 3D cutaway views showing typical timber balloon frame on a masonry base

Joints and connections

Where platform frames primarily use nails to fix the frame together, hardwood frames use knee bracing and wooden pegs at joints as an alternative to visible metal connectors (e). The use of larger size sections allows them to be cut to curves from single pieces of timber, or even to use traditional joints between large-scale sections which interlock as a result of their shape rather than relying on straight metal connectors.

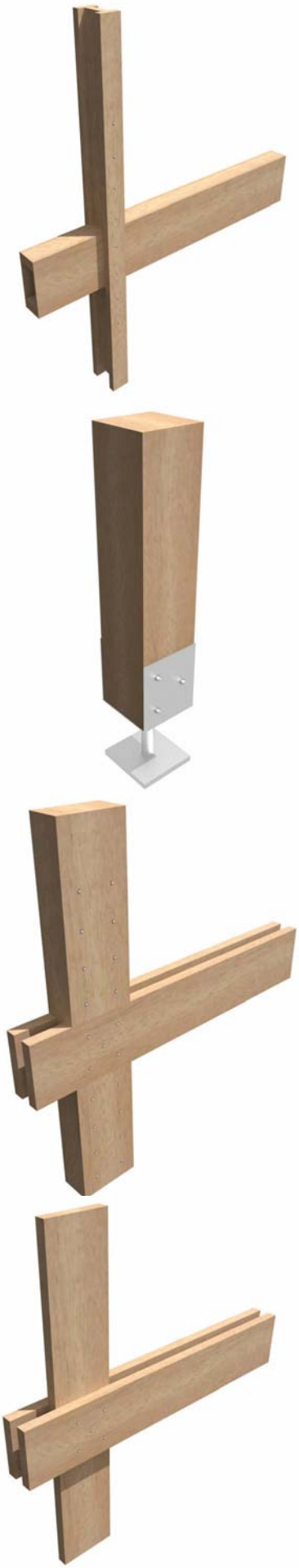
Long-span timber frames, connected in with timber blocks and bolted together, often form simple bolted connections with timber columns by setting the beams on the outside of the column, or vice versa to suit the structural design of the frame. However, this technique is being superseded by tight-fit connections that use CAD/CAM techniques to direct computer-operated machinery that can plane, rout or drill structural timbers. This new technique can provide economic connections that transfer loads more efficiently than traditional techniques do. Solid timber circular columns are increasingly being used to reduce the amount of fabrication required, and provide a substantial and smooth appearance. Timbers are fixed together using a set of tight-fit steel pins that are inserted into the connecting members. This type of connection is used as a tension joint, which is hard to achieve except by either bolting or by using split ring connectors.

Interface with external envelope

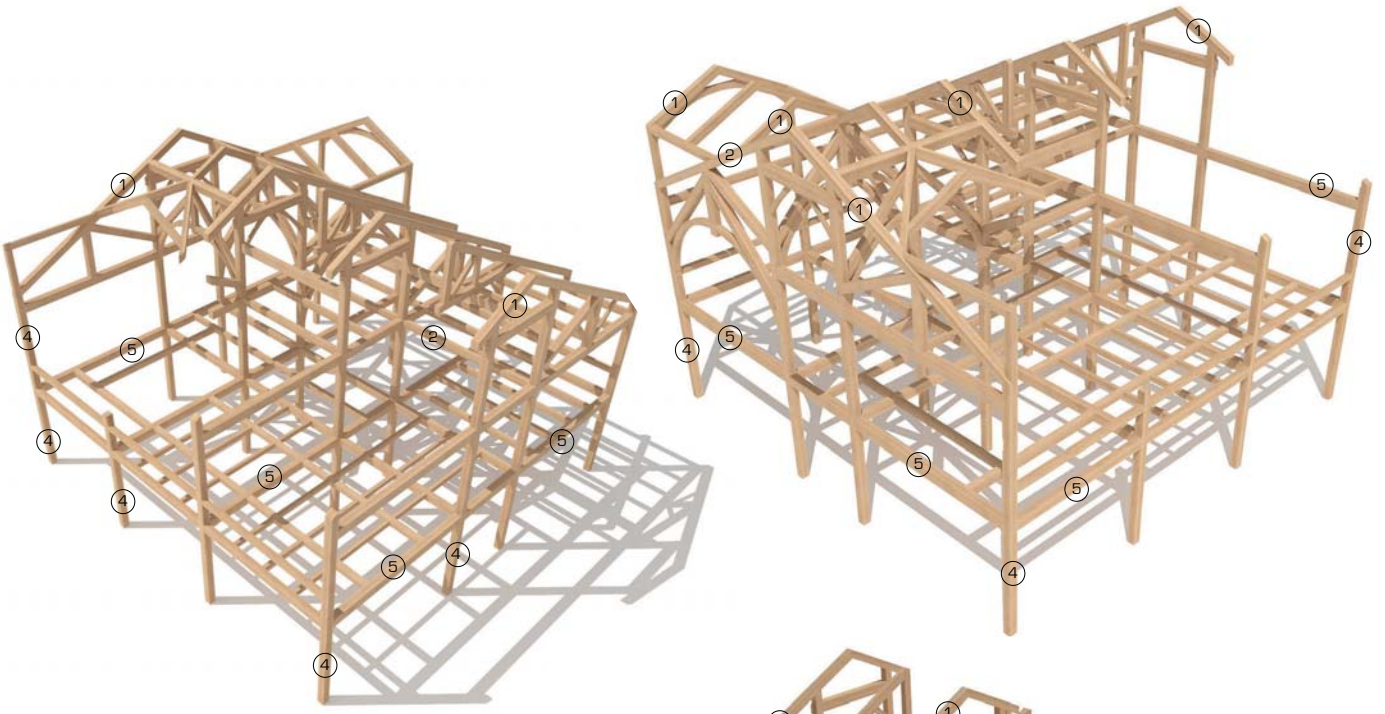
The use of the platform frame suits continuously supported, or short-spanning, cladding materials such as timber boarding and metal sheet. In the case of hardwood timber frames and long-span frames, the framing forms a primary part of the external walls, providing an opportunity to use infilling panels such as double-glazed units or low-energy materials such as straw bale and hemp, described in the Environment chapter. Roofs to hardwood frames follow traditional principles of keeping the structure dry within the building, with the roof covering the complete structure but allowing the frame to be fully visible within the building. A traditional issue of infill panels has been to assure a weathertight joint between a timber frame which undergoes structural movement, and an infill that is also subject to its own movements. The use of breather membranes and rainscreen construction has greatly improved this traditional technique to meet modern requirements. The timber frame can also be fully protected externally, typically with a breather membrane and rainscreen cladding to control moisture movement in the frame as well as providing ventilation to the construction where it meets the external wall. As with other forms of timber construction, timber frames are set onto masonry or concrete bases to keep them dry and ventilated, typically set a minimum of 150mm above external ground level, but subject to specific design requirements. The base wall follows the principles of that form of construction, typically a cavity wall in the case of brickwork or a waterproofed concrete wall with an additional outer skin to protect and conceal the membrane.



d | 3D sectional view showing typical timber balloon frame on a masonry base



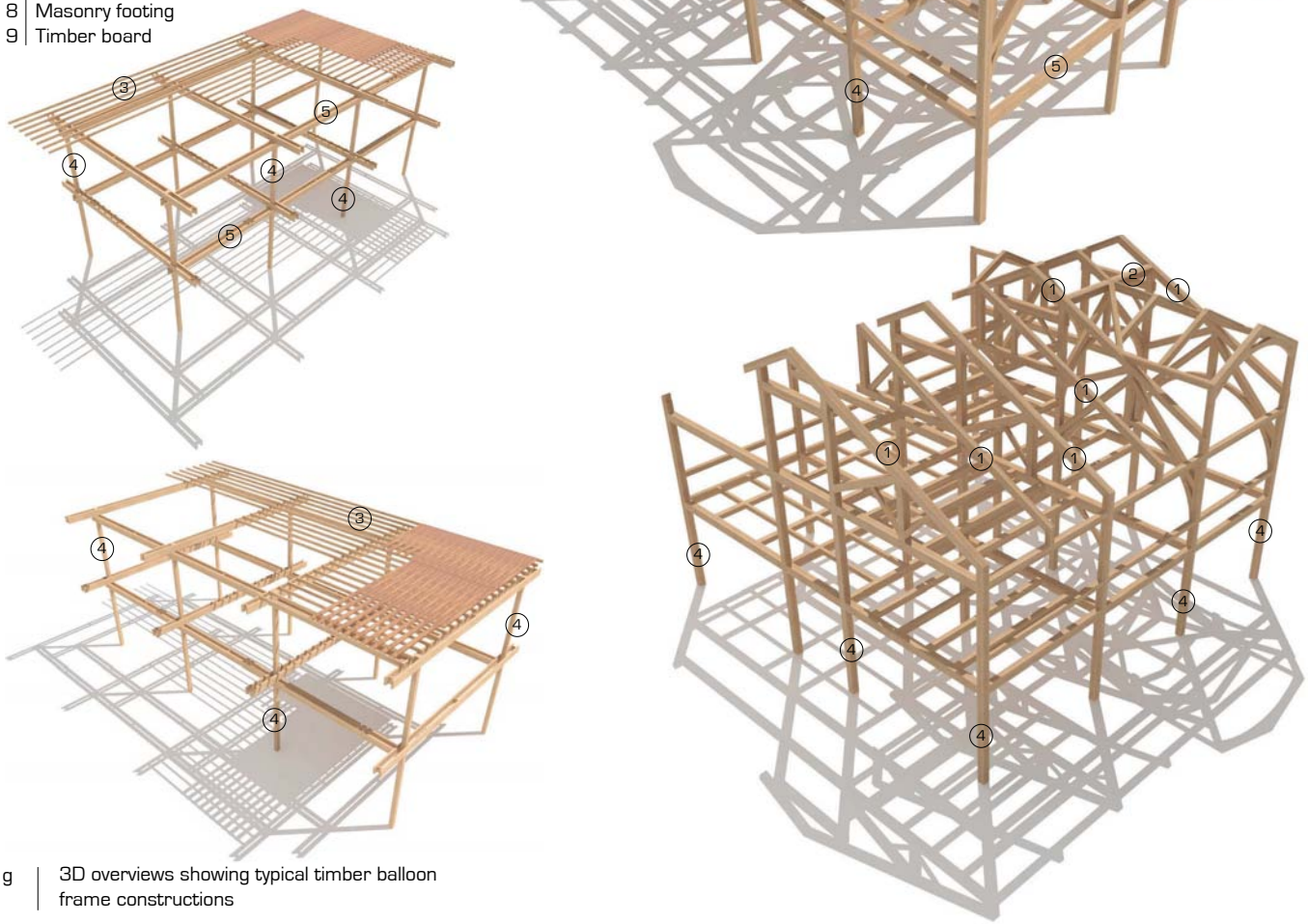
e | 3D views showing typical timber joinery and connection details



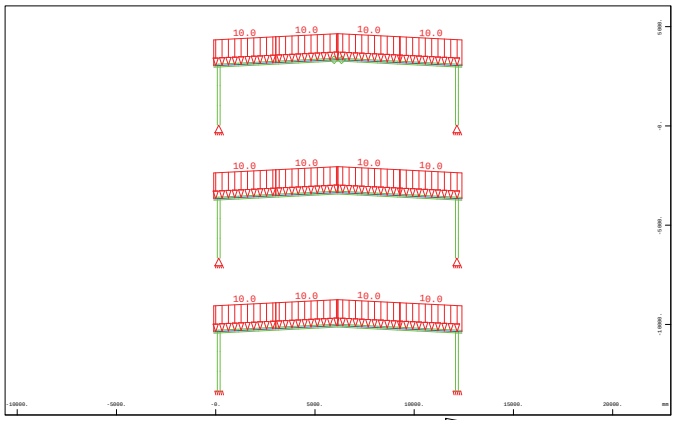
f | 3D overviews showing typical timber balloon frame constructions

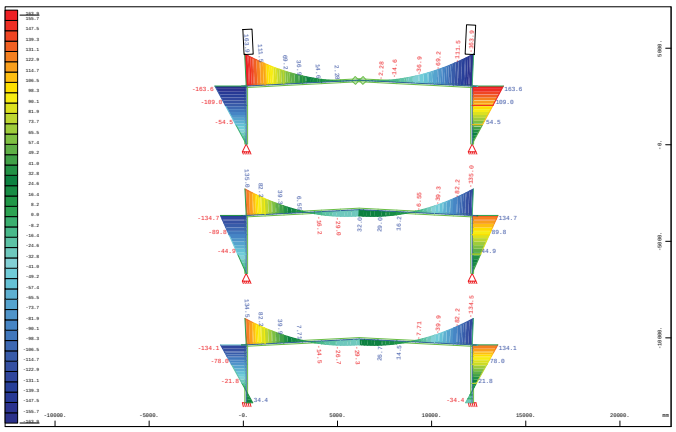
Details

1 | Softwood rafter
2 | Softwood purlin
3 | Softwood batten
4 | Timber primary columns
5 | Timber floor joists
6 | Roof tiles
7 | Roof build-up (timber boards and vapour barrier)
8 | Masonry footing
9 | Timber board

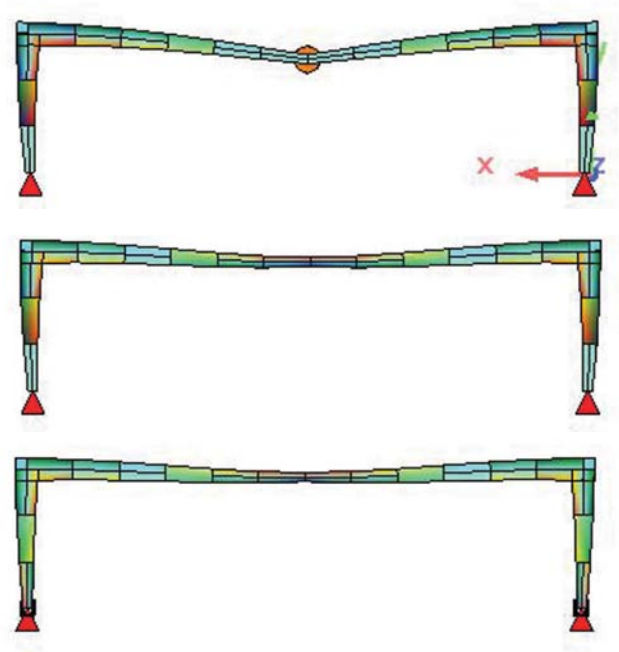


g | 3D overviews showing typical timber balloon frame constructions

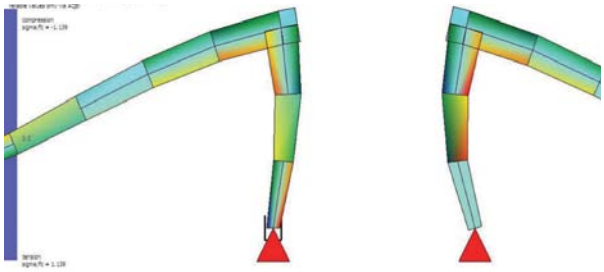




a | Under the same dead loads applied, the rigid frame shows the lowest bending moment values.



b | Structural model of typical timber portal frames



c | Different structural behaviour of pinned and clamped columns.

An essential characteristic of the portal frame is that it supports loads by bending at its primary joints rather than using the pin joints of other frame types (a). However, in practice portal frames are made in sections which are pin-jointed; typically at the top, in the centre and at their base. The frame is made stable in the plane of the frame as a result of the rigid moment connection between the column (or vertical member) and the rafter (or horizontal member) (c). Structural members are formed typically either as solid beams or framed trusses (d), and resist bending at their knee joint to form the moment connection by the use of rigid connectors. These connectors might be glued joints in laminated timber, metal connectors in framed timber members or welds in steel sections. An advantage of this structural type is in its economic use of material, combined with a simple construction technique. A wide range of structural components can be used, from trusses and trussed columns to I-sections. Although associated primarily with single-storey structures, the principle of the portal frame can be applied to multiple storey frames; though they are typically used to provide economic structures for long-span single-storey buildings with the benefit of their comparatively low weight.

Portal frames are typically made from steel, laminated timber and reinforced concrete (e). As is the case with arches, there are three types: the rigid frame, the two-pin frame and the three-pin frame. In the rigid portal frame, the structure uses the least material, with the rigidity of the joints being taken down as far as the base of the frame. The pinned types act in a similar way to arches but the loads in each member are resisted in bending (b). Portal frames are linked together with purlins to form linear arrangements at around 3000mm to 6000mm centres (f). Since the purlins alone do not usually provide sufficient rigidity in the transverse direction, the frames are stiffened with additional lateral bracing in a few of the bays, usually near the ends of the structure, but this depends on the scale of the structure and the specific design.

Joints and connections

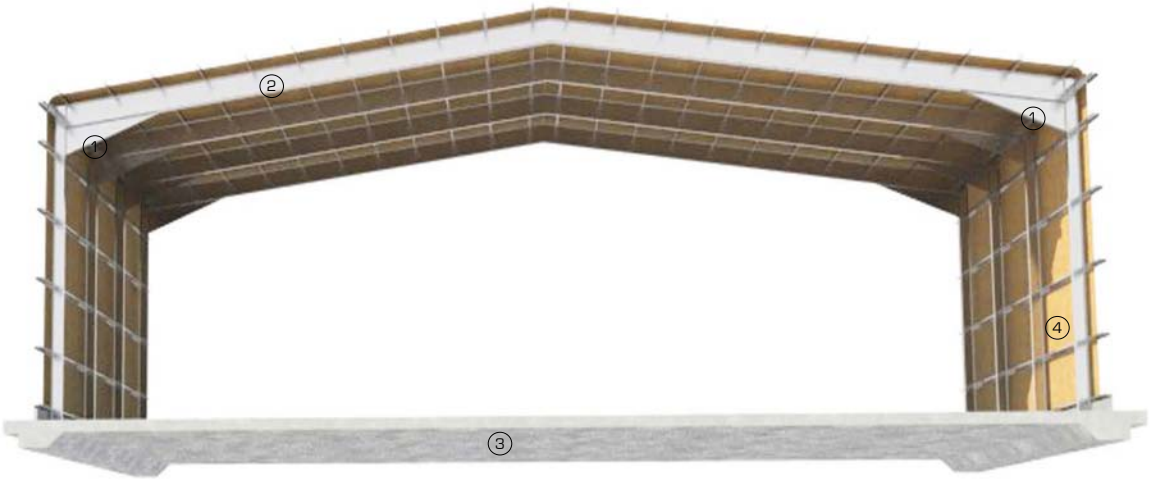
Moment connections are typically either welded or bolted with plates to form haunches (m). Some steel portal frames use specially fabricated connectors into which standard size box sections can be slotted and welded. Larger-scale connectors use castings for both moment and pinned connections, giving a visual continuity to the design, though they are used primarily on larger-scale projects where the benefits of making castings in high volume can be made economic. Pinned connections use types illustrated here (h). Smaller-scale portal frames can be fixed together in a way that gives them the appearance of being single components, but which are bolted or glued together on site. This can give the portal frame a more sculptural appearance, with the structure resembling more boat construction than traditional building. The use of digital fabrication tools such as CNC routers brings the opportunity for portal frames to be made in different sizes in order to form a more complex space within the building. The purlin members that connect the portal frames together are then cut at different angles on their



d | 3D view showing rigid reinforced steel portal frame

Details

1 | Portal frame
2 | Cladding
3 | Floor slab
4 | Timber board



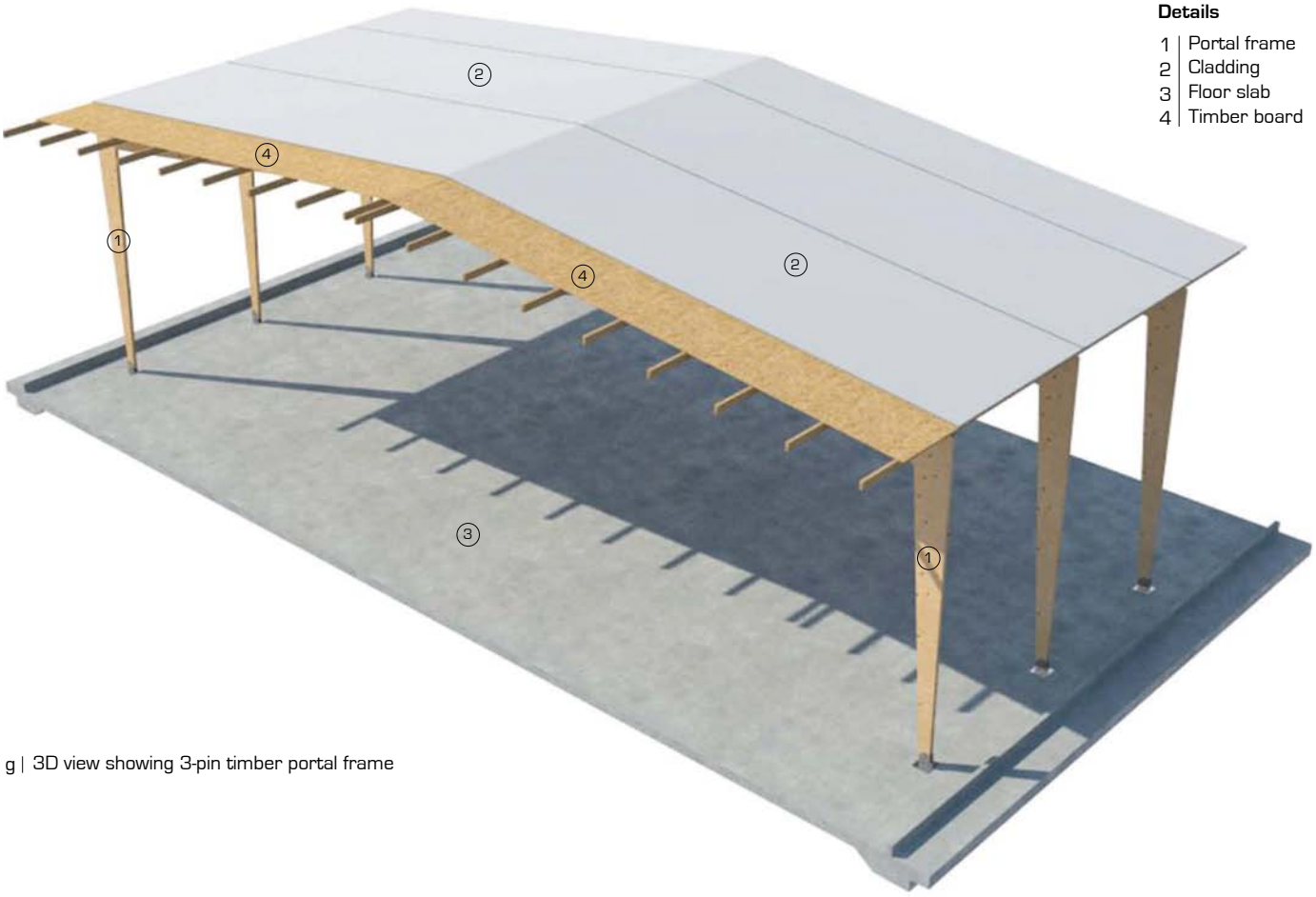
e | 3D view showing rigid reinforced steel portal frame

f | (Below) 3D view showing rigid reinforced steel portal frame

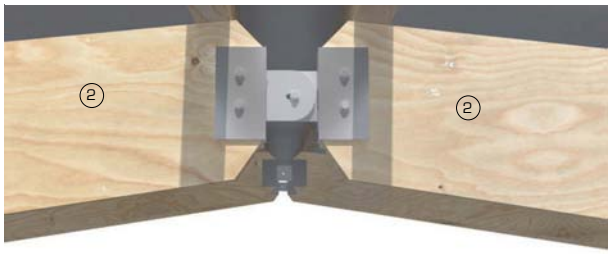


Details

1 | Portal frame
2 | Cladding
3 | Floor slab
4 | Timber board



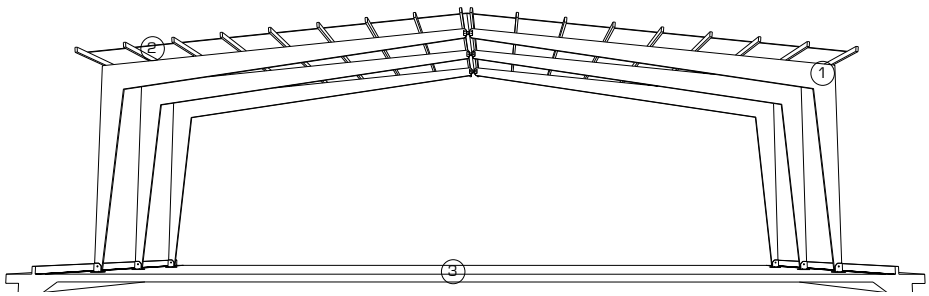
g | 3D view showing 3-pin timber portal frame



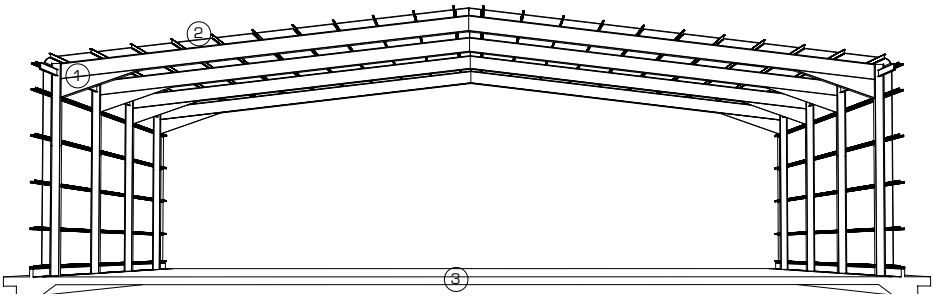
h | 3D view showing pin detail within timber portal frame



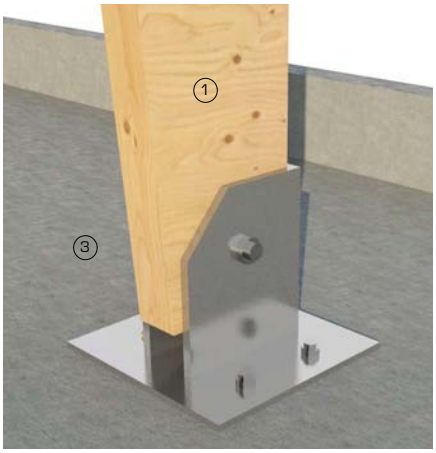
m | 3D view showing corner detail through rigid steel portal frame



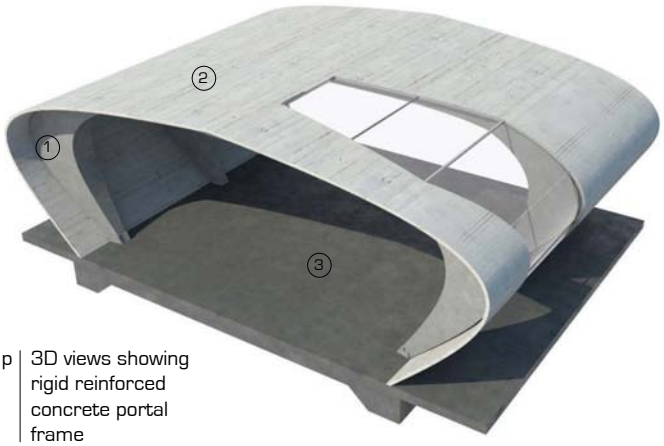
j | 3D view showing 3-pin timber portal frame



k | 3D view showing rigid reinforced steel portal frame

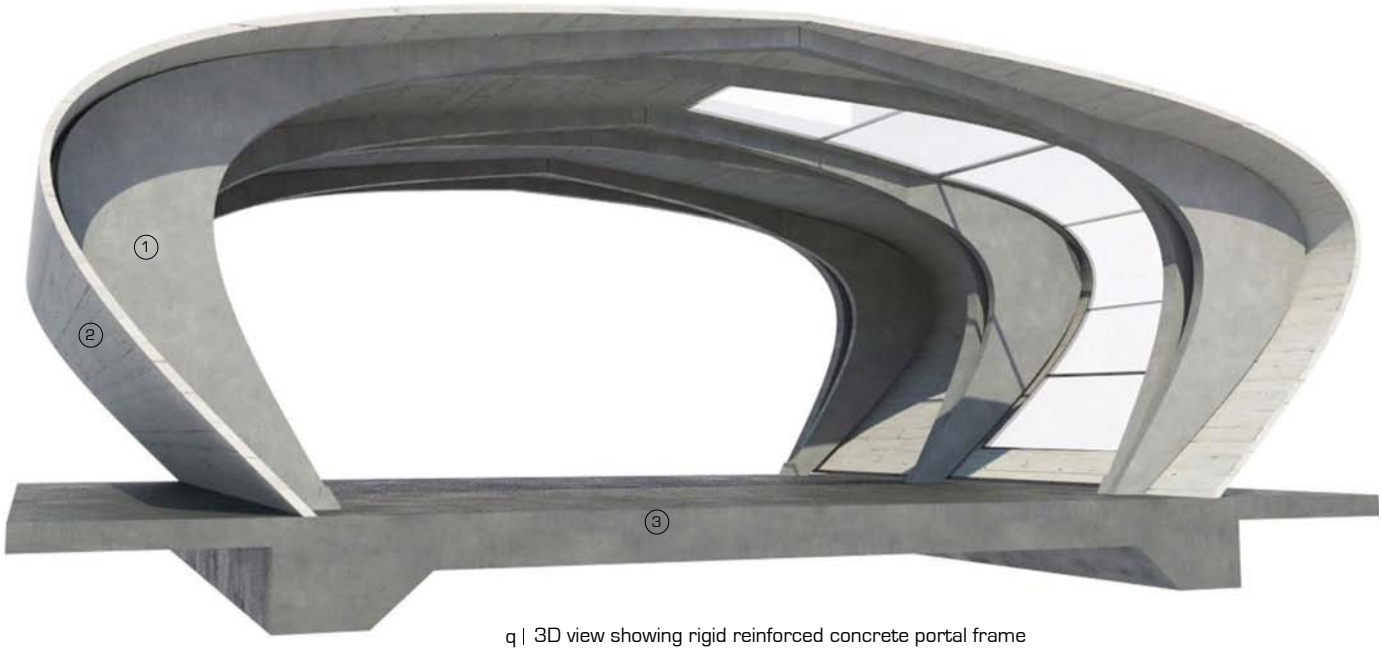


n | 3D view showing base plate acting as pin joint for timber frame





p | 3D views showing rigid reinforced concrete portal frame

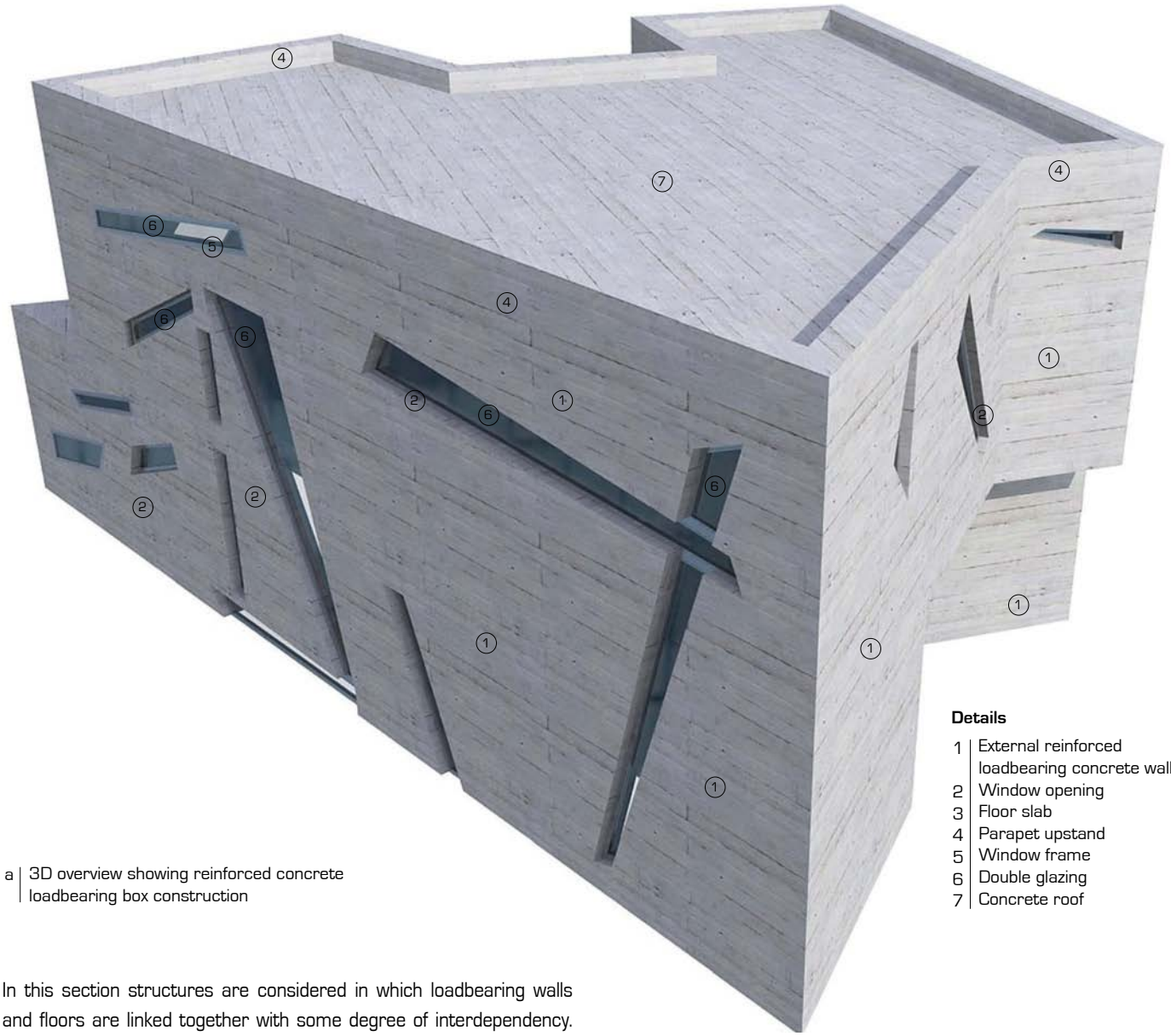


q | 3D view showing rigid reinforced concrete portal frame

ends in order to follow a particular line across the structure, which may be visible from inside or set in a staggered arrangement to suit the external roof and wall finishes. Portal frames are being increasingly associated with non-rectilinear structures due to their ability to form complex shapes with visually elegant connections (p). Large-scale portal frames can provide a visually elegant and more slender alternative to classic trusses, creating roof structures that more closely resemble shells than frames. A recent development is a hybrid of portal frame structures which is the use of a 'tree' like column arrangement of portal frame connections at the top of a structure that supports curved beams along its length.

Interface with external envelope

An advantage of portal frames is their ability to form a single surface for both walls and roof (q). In recent years, sheet metal roofs have been used with small-scale portal frame structures, with their ability to render the shape created by the structure. In other examples, the external skin is set between the portal frame members, revealing the shape of the frame and making the structure the visual expression of the design. The portal frames are weather-protected and thermally insulated, often using the same metal sheet system, but with the opportunity of setting glazed units between the portal frames in line with the adjacent covering for wall and roof. Purlins are used to support the external cladding. Where profiled metal cladding is used they are called sheeting rails. In common with arches, cladding is fixed to these purlins rather than directly to the portals in order to keep the connection type simple. The stiffness of junctions between walls and roof makes the transition in the external envelope straightforward and economic. Larger-scale portal frames require a gutter at the edge of the roof, which cannot always follow the geometry of the frame itself. A solution is to set the external envelope away from the portal frame, usually by setting the purlins on the outside edge of the portal frames, thus creating a gap between frame and envelope (k). This gap can then accommodate the shape of the gutter without interrupting the visual line of the roof / wall enclosure on the outside. The inside face of the external skin can also be lined to conceal the gutter if required. The base of portal frames typically has an upstand to provide weatherproofing at this point, dependent on the position of the portal frames; either at ground level or as part of a larger structure. The upstand provides a termination to the external envelope, forming a transition between wall and adjacent roof deck or ground conditions. The hybrid structures with their tree-like base use a range of curved and welded steel plate and cast connections to create complex forms that serve as moment connections which can contrast visually with adjacent pinned connections at roof level. Generally, the use of portal frame structures as single enclosures suggests a continuation of the interdependency of structure and envelope that is clearly visible in contemporary examples.



Details

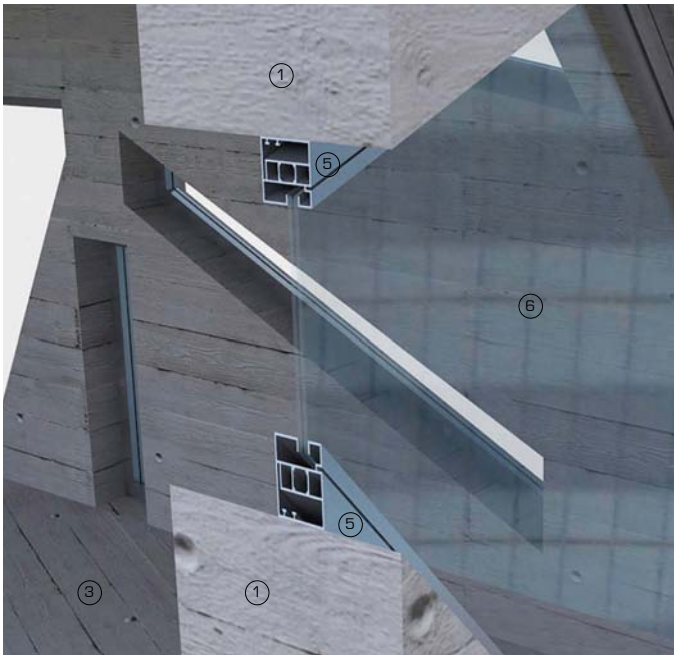
1 External reinforced loadbearing concrete wall
2 Window opening
3 Floor slab
4 Parapet upstand
5 Window frame
6 Double glazing
7 Concrete roof

a | 3D overview showing reinforced concrete loadbearing box construction

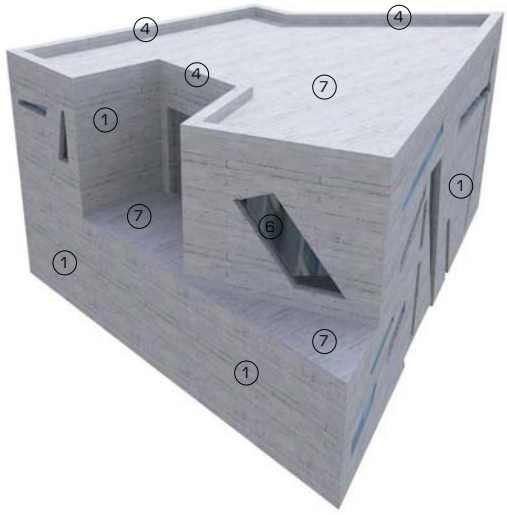
In this section structures are considered in which loadbearing walls and floors are linked together with some degree of interdependency. Although not strictly regarded as a structural system, techniques of loadbearing concrete wall and floor construction are very common in Europe for large-scale housing projects. Many European houses are built with loadbearing masonry walls having either timber or concrete floors that provide stability to the external walls.

Concrete loadbearing boxes

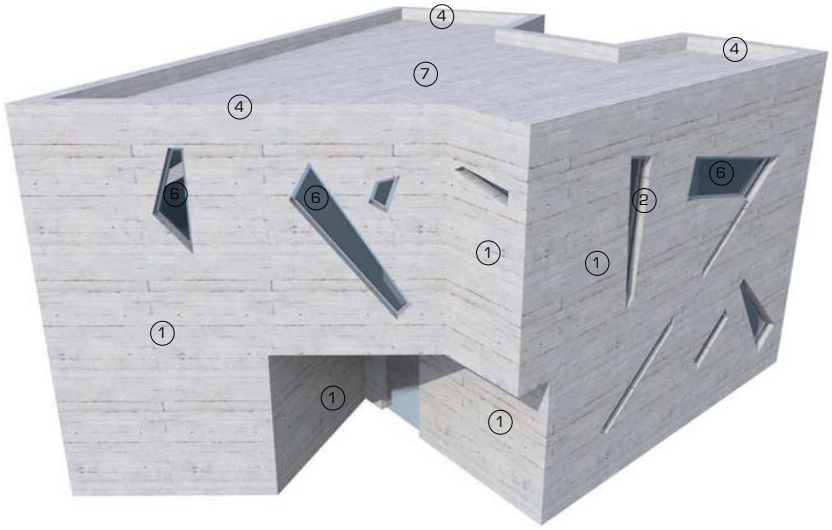
Loadbearing walls and floors made in reinforced concrete can be combined to make a complete monolithic structure (a). Both in-situ cast and precast concrete techniques can be used, though precast methods suit projects where a high degree of repetition occurs in panel types. Concrete loadbearing boxes have the advantage of high fire resistance combined with high sound insulation from both airborne and impact sound. Concrete can be used in conjunction with both steel and concrete structures. In-situ cast techniques generate a monolithic connection between floor and walls (j). Precast components are stitched together to form a similar connection. Since concrete is not regarded as vapour-proof, the outside of the concrete is either rendered or covered with a cladding system, typically a rainscreen. Measures to ensure thermal insulation, together with finishes, are discussed in the in-situ cast walls section in chapter 2 (MCH_146).



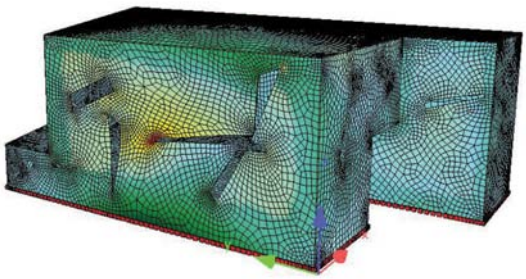
b | 3D detail view showing window opening in reinforced concrete loadbearing box construction



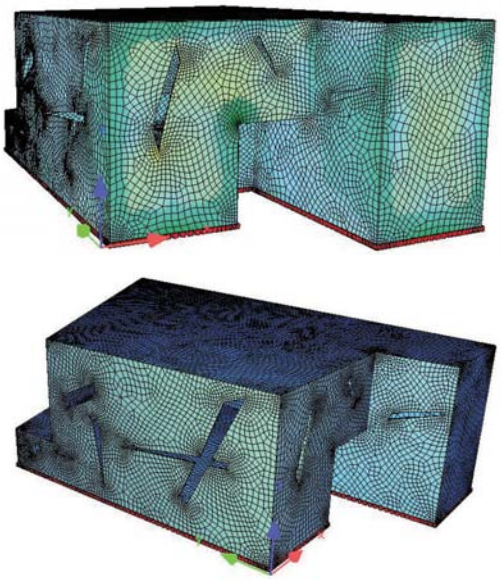
c | 3D overview showing reinforced concrete loadbearing box construction



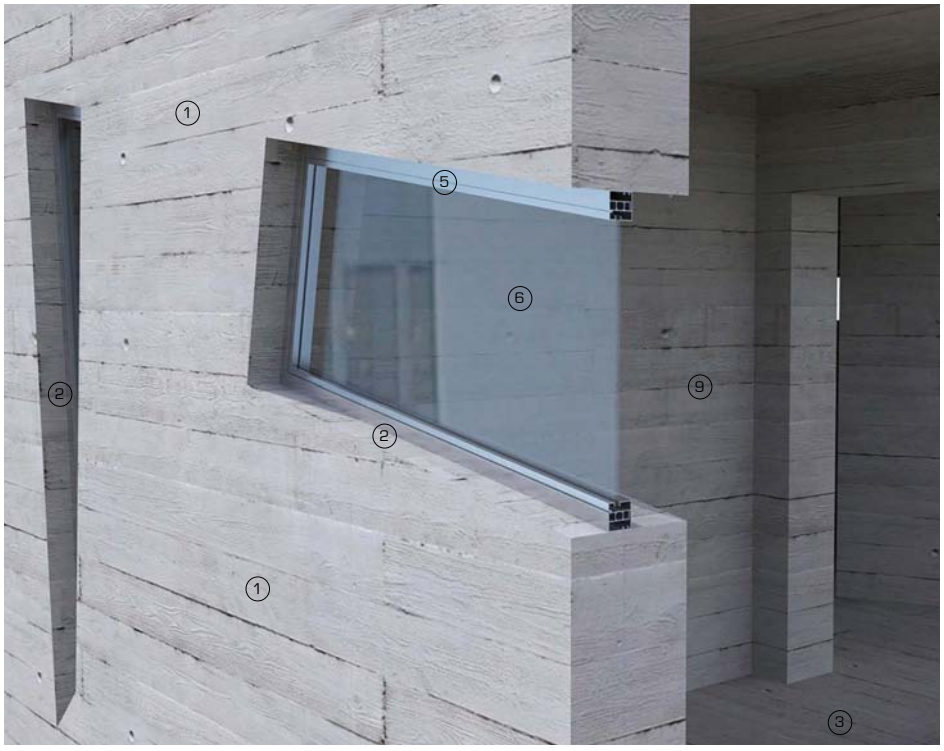
e | 3D overview showing reinforced concrete loadbearing box construction



d | Structural FE model of a loadbearing reinforced concrete structure.



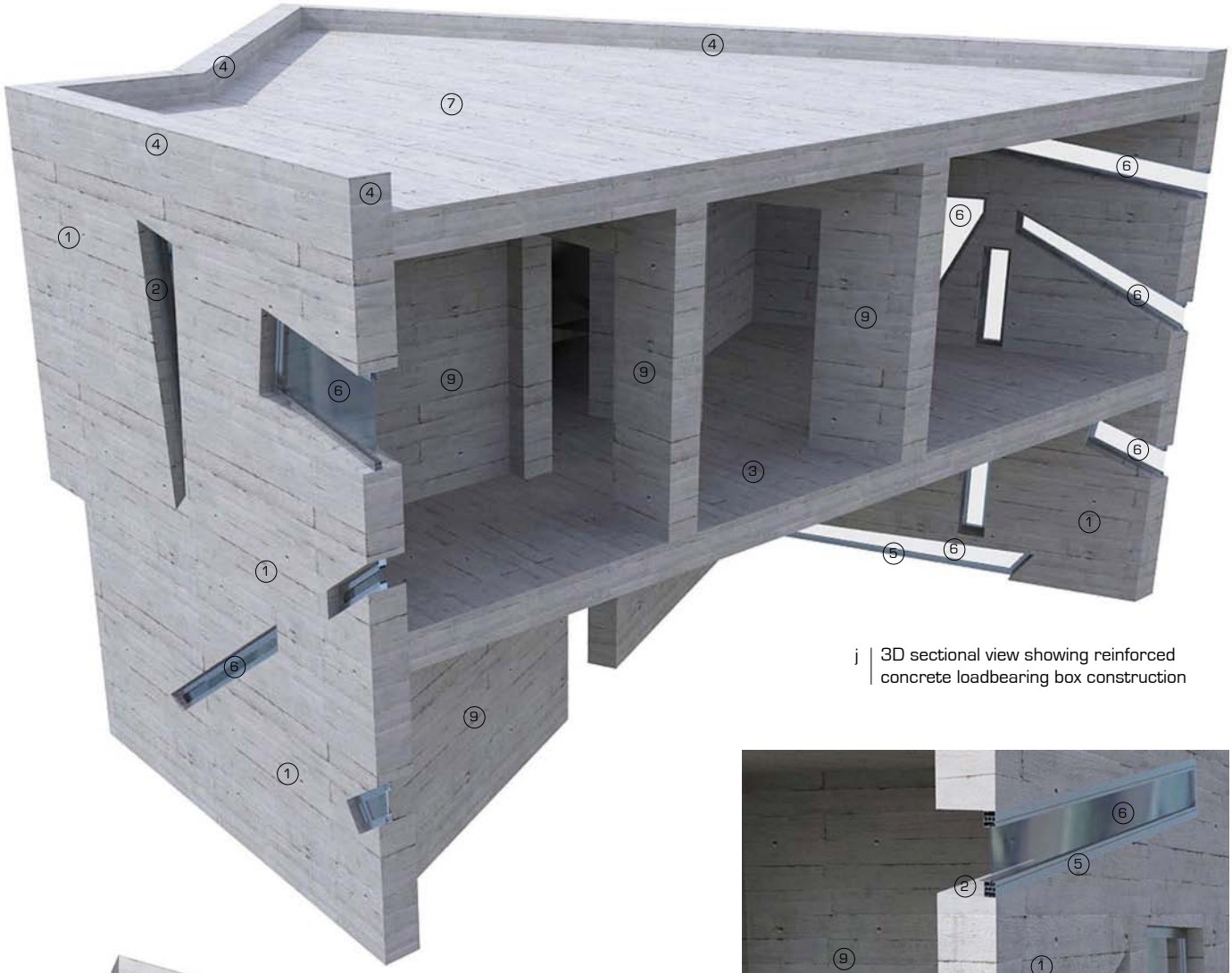
f | Stress distribution analysis for lateral wind loads (the movements shown are magnified)



g | 3D section view showing window opening in reinforced concrete loadbearing box construction



h | 3D view showing window openings of varying recess depths in reinforced concrete loadbearing box construction



j | 3D sectional view showing reinforced concrete loadbearing box construction



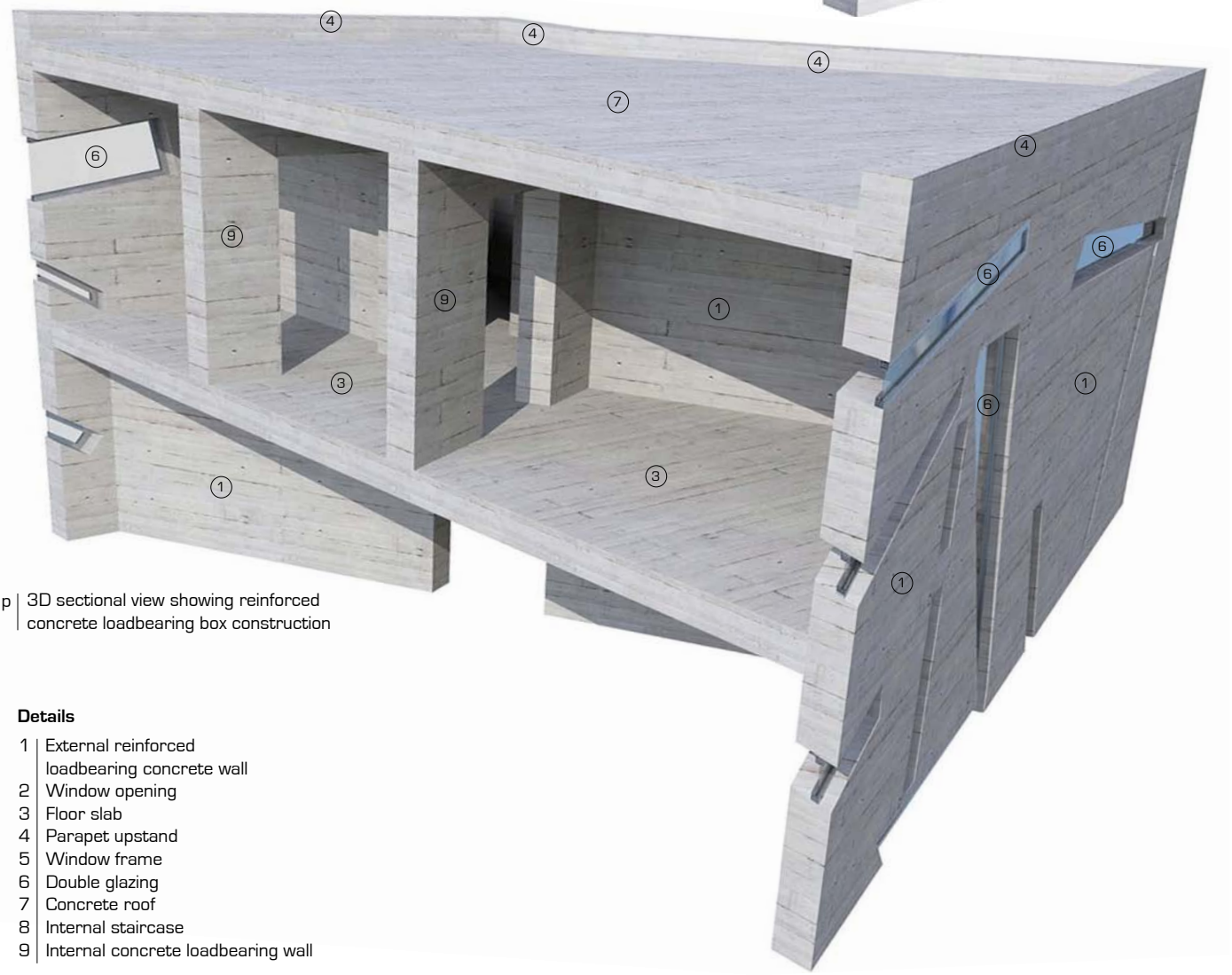
k | 3D overview showing various openings in reinforced concrete loadbearing box construction



m | 3D sectional view showing window openings of varying recess depths in reinforced concrete loadbearing box construction



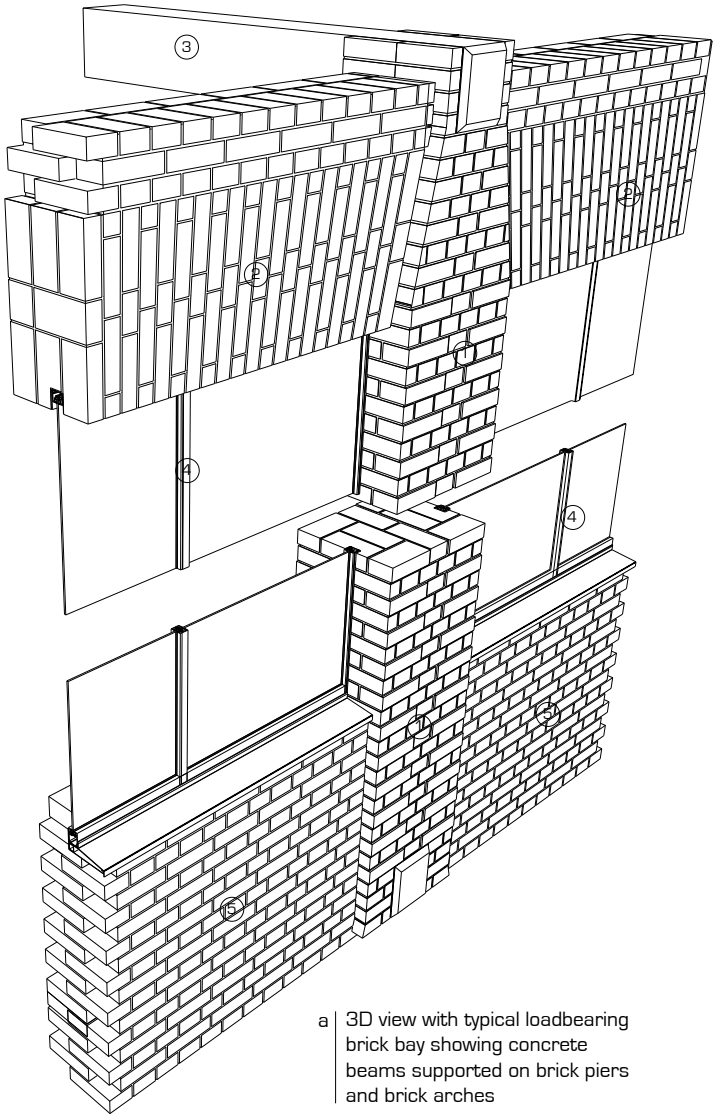
n | 3D sectional view showing reinforced concrete loadbearing box construction



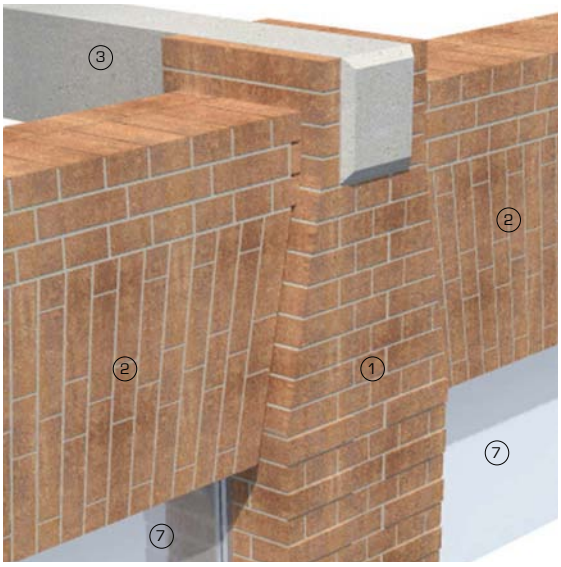
p | 3D sectional view showing reinforced concrete loadbearing box construction

Details

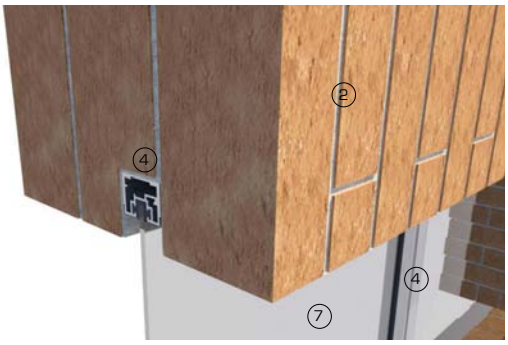
1 | External reinforced loadbearing concrete wall
2 | Window opening
3 | Floor slab
4 | Parapet upstand
5 | Window frame
6 | Double glazing
7 | Concrete roof
8 | Internal staircase
9 | Internal concrete loadbearing wall



a | 3D view with typical loadbearing brick bay showing concrete beams supported on brick piers and brick arches



b | 3D detail view showing typical loadbearing brick bay showing concrete beams supported on brick piers and brick arches



c | 3D detail view showing typical loadbearing brick bay showing concrete beams supported on brick piers and brick arches

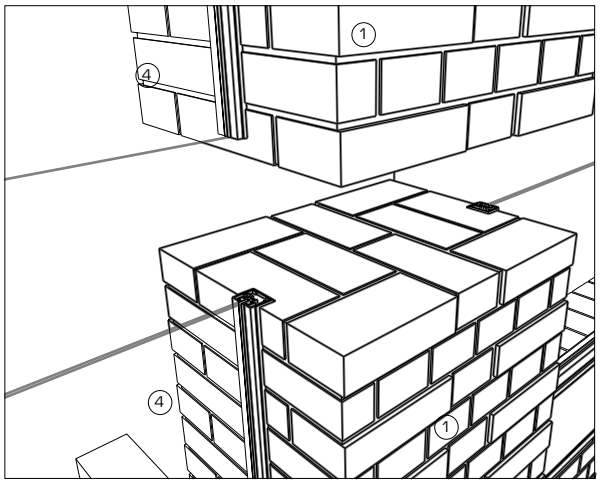
Loadbearing brick structures are rarely used in buildings in industrialised countries since they are more expensive than cavity walls, use more material and are slower to build. Traditionally, they have also been less efficient at excluding rainwater than contemporary cavity walls, with the separation of internal and external skins that has made cavity wall construction a technically accomplished and less expensive alternative to solid (a), loadbearing construction. Over the past 100 years, the design of brickwork has generally aimed towards increasing its strength through the use of higher strength mortars, though this results in a more brittle structure with reduced flexibility that was provided by the lime-based mortars. This has led to the need for movement joints in the material, usually at around 6.5 metre centres, with the effect that loadbearing walls become a series of linked panels. The gradual re-introduction of lime putty mortars, with their lower strength but greater allowance for movement, is set to change the nature of loadbearing brickwork, and its use is discussed in the Walls chapter (MCH_158).

The use of brick in these structures is restricted to the walls, since traditional vaulted brick floors have been superseded by timber or concrete floor construction, which can more easily achieve longer spans. Loadbearing walls are usually much thicker than their cavity wall equivalents, making the structure much heavier in order to provide sufficient waterproofing, since the brick absorbs rainwater near the surface and later dries out. Traditionally, openings in walls have been made with arches of the same material as the surrounding wall and in flat, curved or pointed variations (c). Flat arches require considerable skill to construct (f), and are often strengthened with bed reinforcement in the form of steel rod or expanded mesh. In common with other types of masonry construction, brickwork cannot be loaded, and will fail in tension.

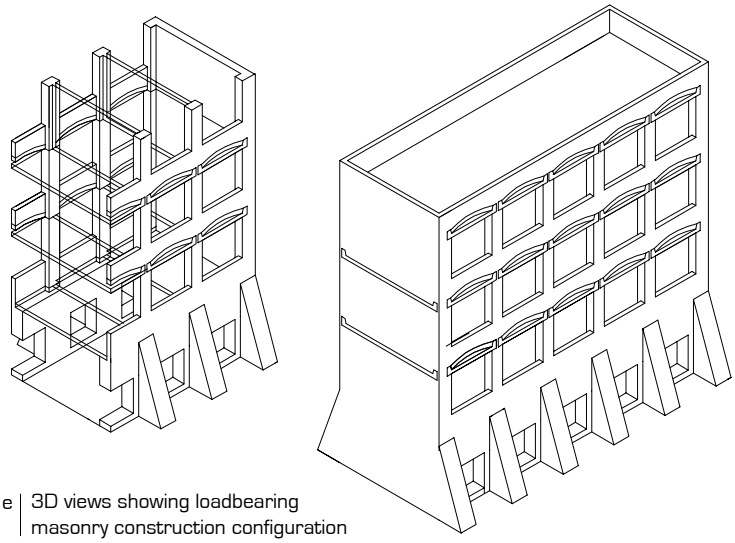
Loadbearing brickwork was used in the Indian Institute of Management at Ahmedabad, India (completed 1974) and part of the National Assembly at Dhaka, Bangladesh (completed 1983), both designed by Louis Kahn. The architect had previously used brick slips (thin brick tiles that imitate brickwork) to conceal openings formed in either steel or concrete. In these two projects, structural brick arches are used. Because of their large size, spanning up to approximately three metres, they were combined with reinforced concrete lintels as tied arches. The ends of the ties were specially formed to bond into the adjacent brickwork, thus avoiding the need for additional steel connectors.

Recent built example

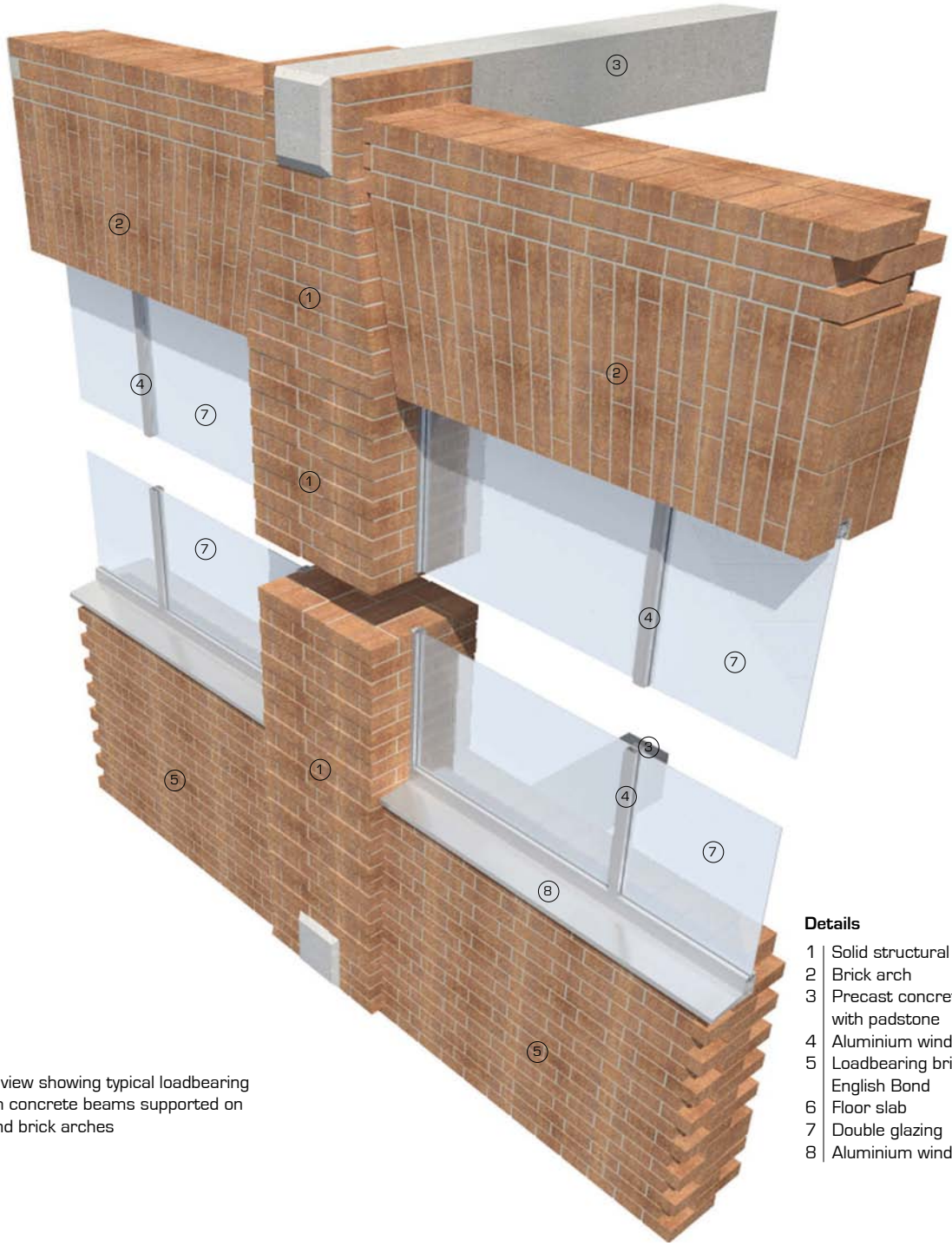
Glyndebourne Opera House in England has loadbearing brick walls which consist of two skins 220mm thick, with a 50mm cavity providing acoustic separation. The inner leaf supports the back of the balconies. The brickwork forms a loadbearing drum 33.7m in diameter and 17.7m high, truncated on one face where it intersects with the fly-tower. From



d | 3D detail showing window opening in loadbearing masonry construction configuration



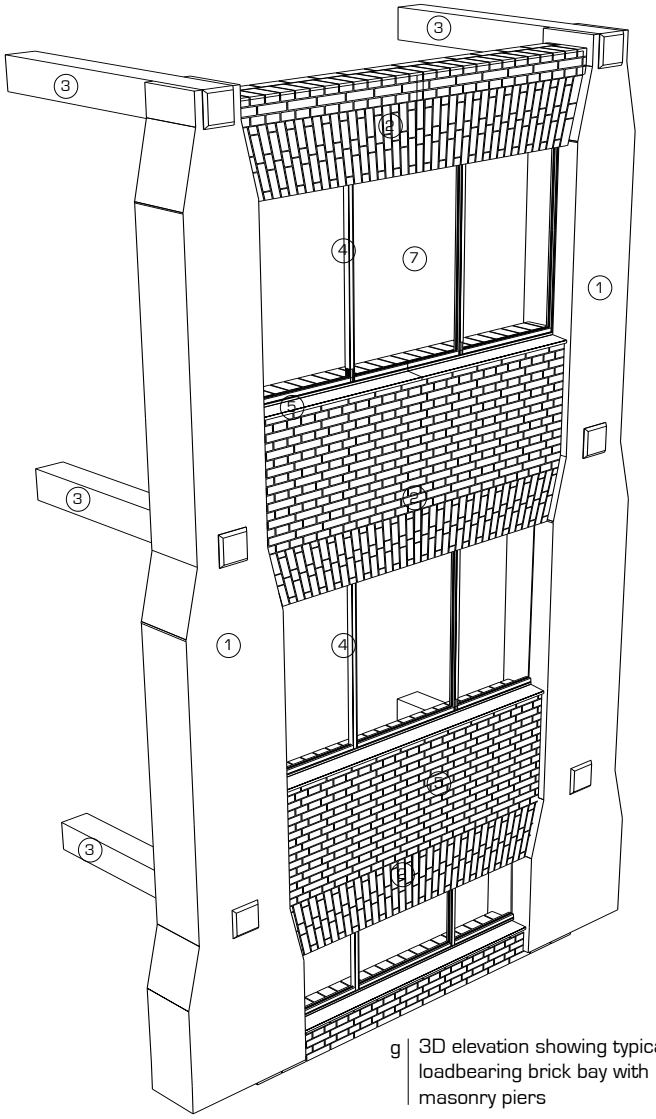
e | 3D views showing loadbearing masonry construction configuration



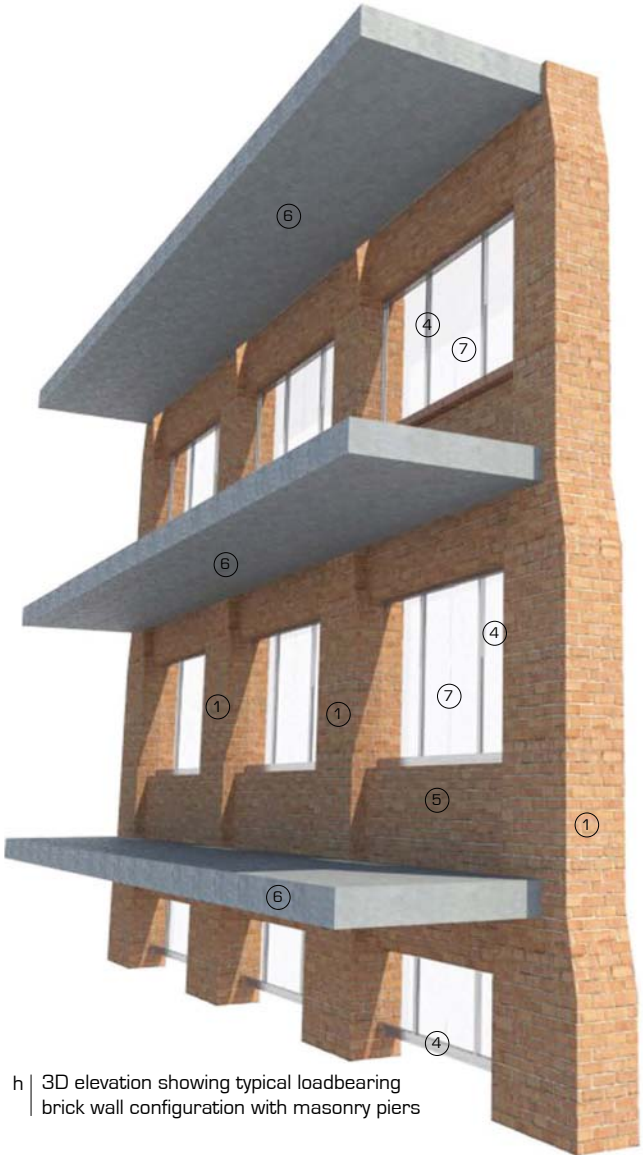
f | 3D sectional view showing typical loadbearing brick bay with concrete beams supported on brick piers and brick arches

Details

1 | Solid structural brickwork pier
2 | Brick arch
3 | Precast concrete floor beams with padstone
4 | Aluminium window frame
5 | Loadbearing brickwork wall in English Bond
6 | Floor slab
7 | Double glazing
8 | Aluminium window cill



g | 3D elevation showing typical loadbearing brick bay with masonry piers



h | 3D elevation showing typical loadbearing brick wall configuration with masonry piers

this wall radiates a series of precast concrete panels that form the soffit to the balconies and partially support the seating above. In-situ cast columns that are tied together with an in-situ cast topping and ring beam provide additional support. Where the structure runs alongside the side stages, the inner wall becomes an acoustic wall 220mm thick, but elsewhere it is less dense and where it is punctured by openings providing access to the auditorium, it becomes a series of piers (h). The walls supporting the balconies are 334mm thick continuous skin, supported by flat arches resting on gently tapering brick piers. The mix used for the lime putty mortar in the brickwork was a 1:2:9 (cement:lime putty:sand) ratio by volume. The cement gave early strength to the wall and slightly improved durability and weathering. The compressive strength of the bricks was 27.5N/mm2 and that of the lime putty mortar was 1.5N/mm2. This provided an overall compressive strength of 6.2N/mm2, which is less than half that of conventional brickwork at around 15N/mm2.

Current applications

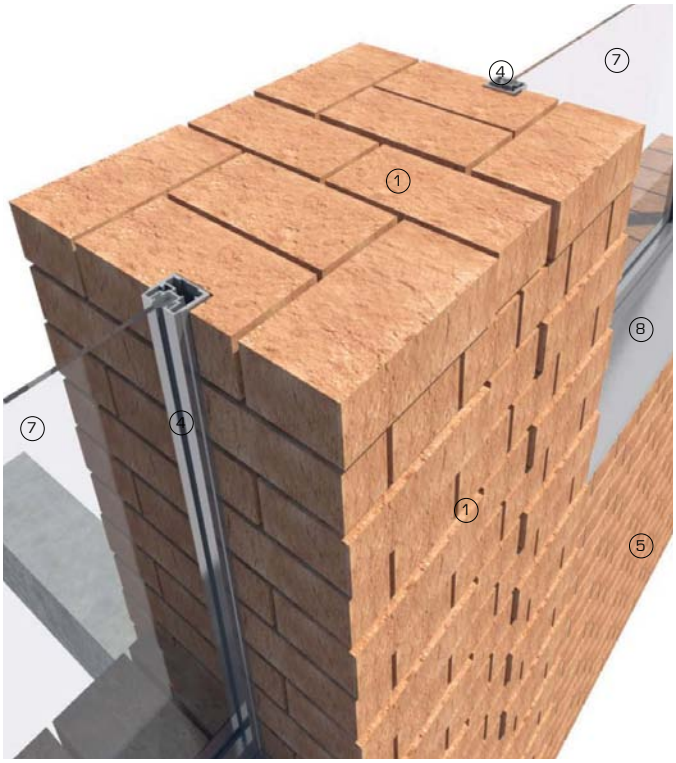
The use of loadbearing brickwork in recent economic applications has been mostly in situations where thermal insulation is not required, such as in walls set externally to form a screen wall to external spaces or semi-external spaces. Alternatively, the loadbearing wall is used in a hybrid condition where it supports itself in the manner of the outer leaf of a cavity wall, but is only connected at points to the floor slabs behind in order to reduce the thermal bridge through the material. Thermal insulation, when required, is set on the inside face of the wall, and is also set between slab and wall (n). These applications are set to revitalise the use of brickwork as they start to combine the authenticity of loadbearing walls with contemporary requirements for weatherproofing and thermal insulation. An advantage of loadbearing brickwork is its ability to vary in thickness to suit structural requirements without the need for the stainless steel fixings and supports associated with cavity brick walls, where any modelling of the surface of the wall is difficult to accommodate structurally due to the nature of its construction, which is to be non-loadbearing. Loadbearing brickwork is also able to use other materials in its construction, from cut stones forming pieces of loadbearing arches to precast concrete ties, lintels and cills as an integral part of the construction. The additional cost of this form of construction over that of cavity wall construction makes its application less widespread, but this may change with the possibility of prefabricating sections of the wall away from the site, and assembling the pieces on site in the manner of precast concrete construction, where speed of construction is a benefit. Some recent examples have set steel reinforcement into the depth of the wall so as to increase its strength and resistance to wind load without increasing its thickness beyond one and a half bricks thick, which is generally considered to be the minimum thickness of loadbearing walls which can exclude rainwater (though this is not always sufficient, of course). The use of steel reinforcement can help reduce the overall weight of the wall in order to remain within the loadbearing capacity of the wall.



j | 3D view showing window opening in typical loadbearing brick bay

Details

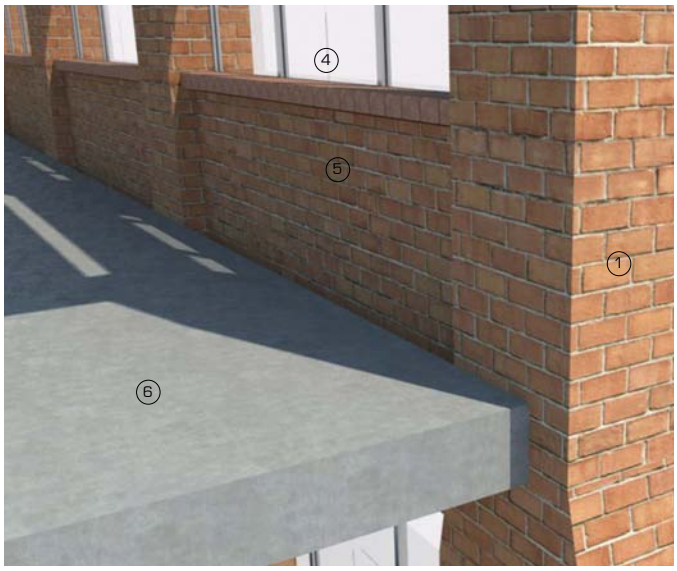
1 | Solid structural brickwork pier
2 | Brick arch
3 | Precast concrete floor beams with padstone
4 | Aluminium window frame
5 | Loadbearing brickwork wall in English Bond
6 | Floor slab
7 | Double glazing
8 | Aluminium window cill



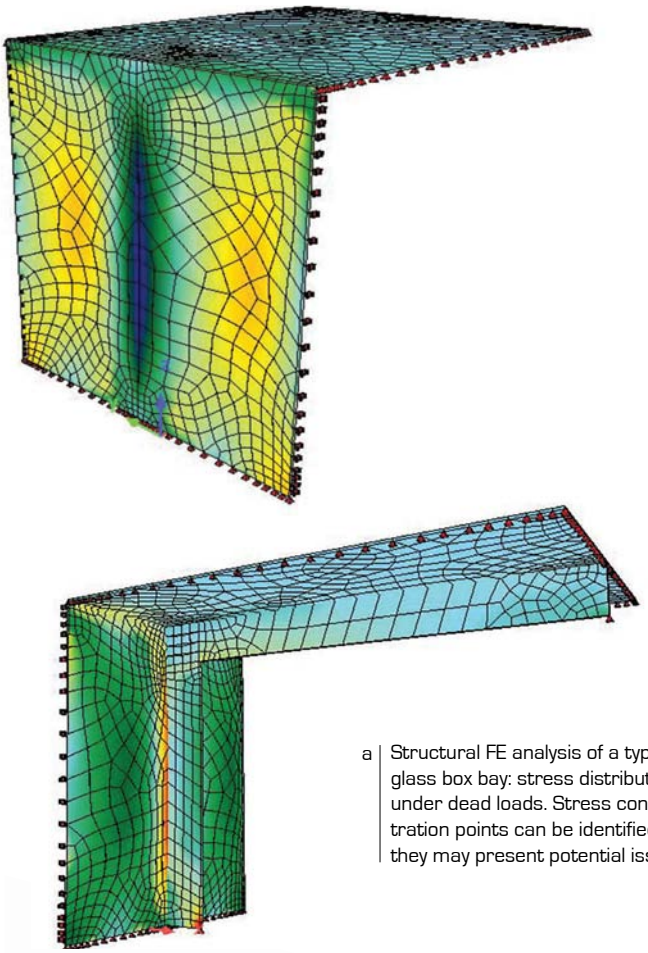
m | 3D view showing window opening in typical loadbearing brick bay at brick pier



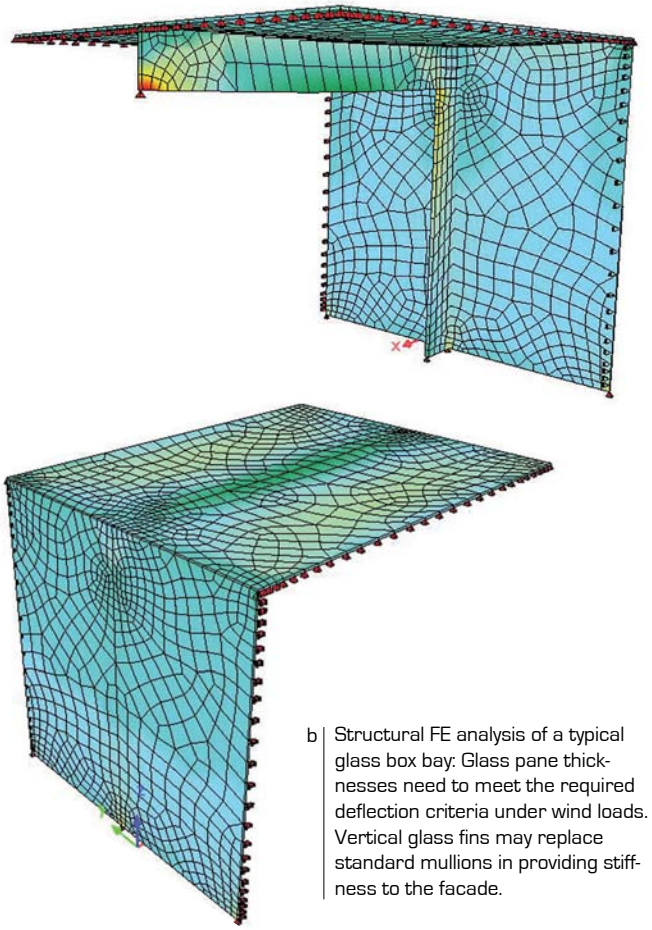
k | 3D view showing typical loadbearing brick bay



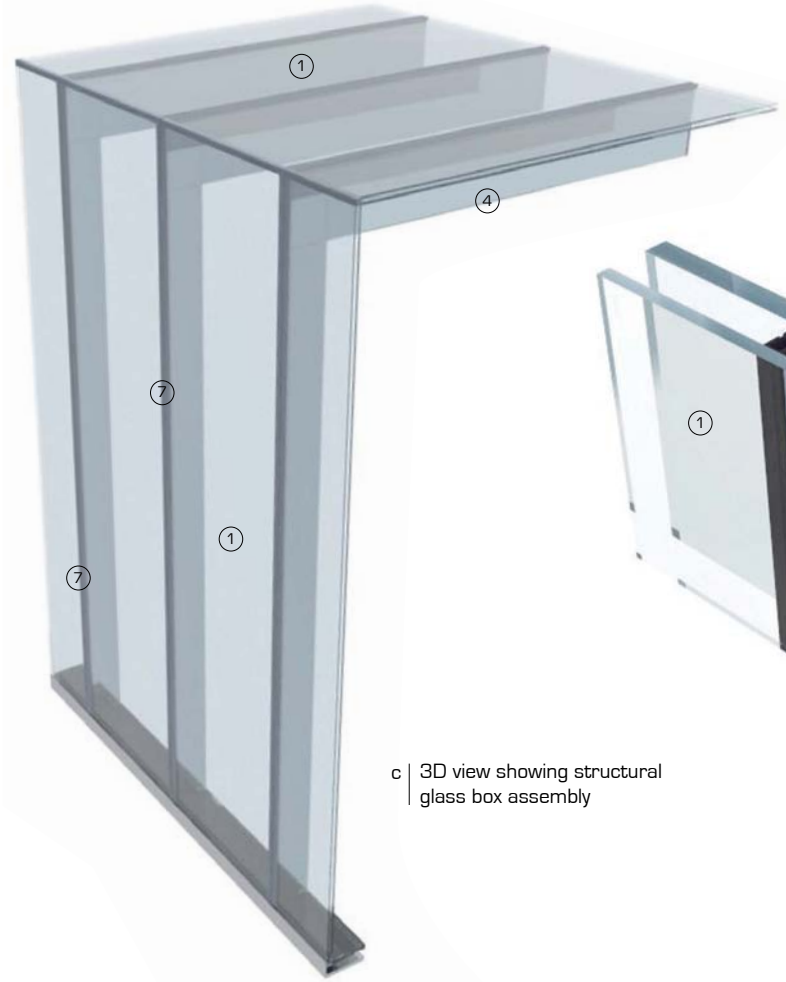
n | 3D view showing floor slab junction in typical loadbearing brick wall configuration



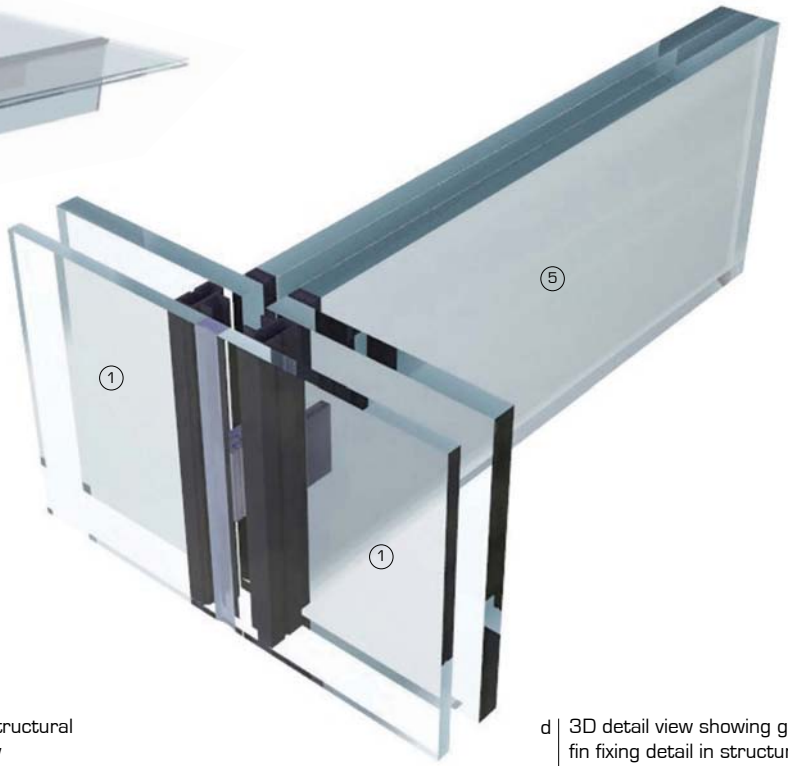
a | Structural FE analysis of a typical glass box bay: stress distribution under dead loads. Stress concentration points can be identified as they may present potential issues.



b | Structural FE analysis of a typical glass box bay: Glass pane thicknesses need to meet the required deflection criteria under wind loads. Vertical glass fins may replace standard mullions in providing stiffness to the facade.



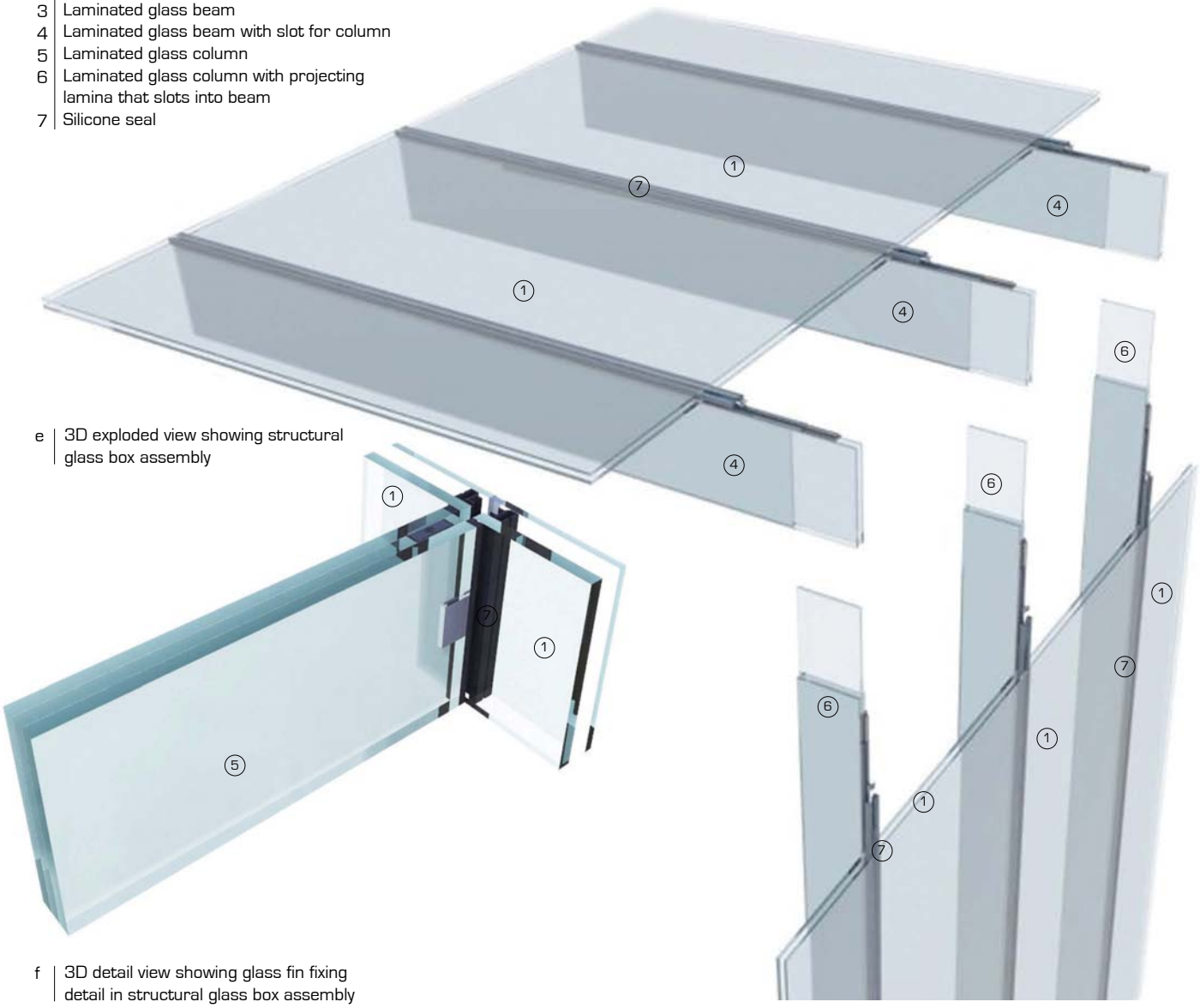
c | 3D view showing structural glass box assembly



d | 3D detail view showing glass fin fixing detail in structural glass box assembly

Details

1 | Double glazed unit
2 | Triple glazed unit
3 | Laminated glass beam
4 | Laminated glass beam with slot for column
5 | Laminated glass column
6 | Laminated glass column with projecting lamina that slots into beam
7 | Silicone seal

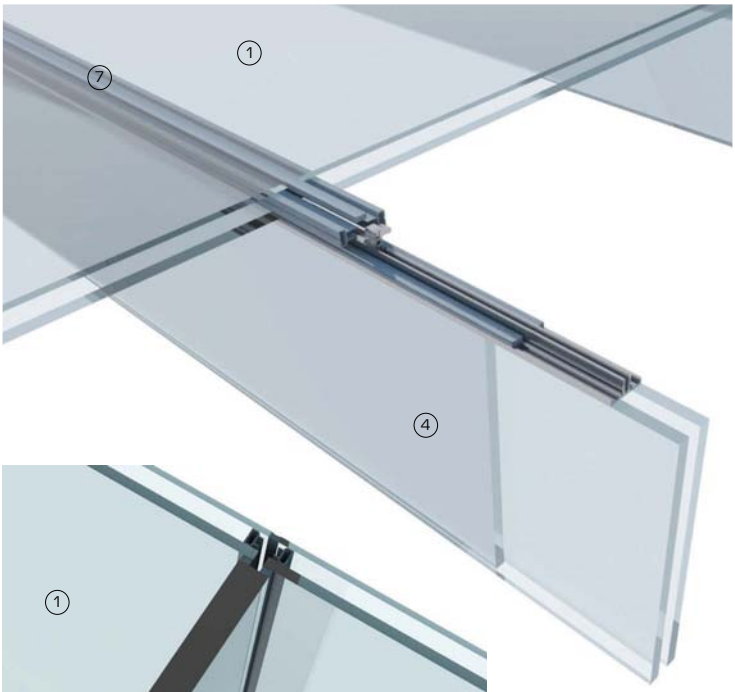


e | 3D exploded view showing structural glass box assembly

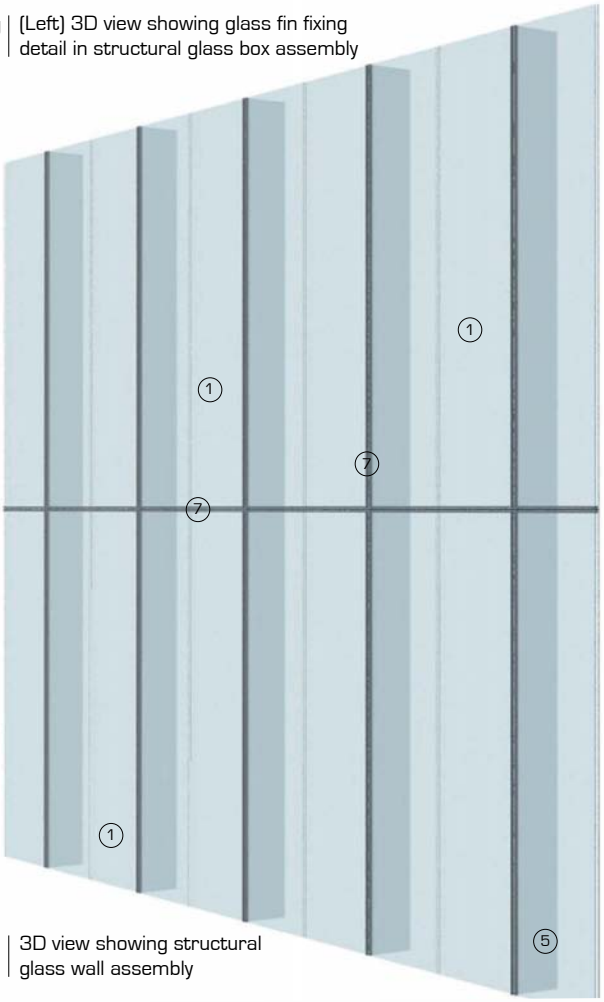
f | 3D detail view showing glass fin fixing detail in structural glass box assembly

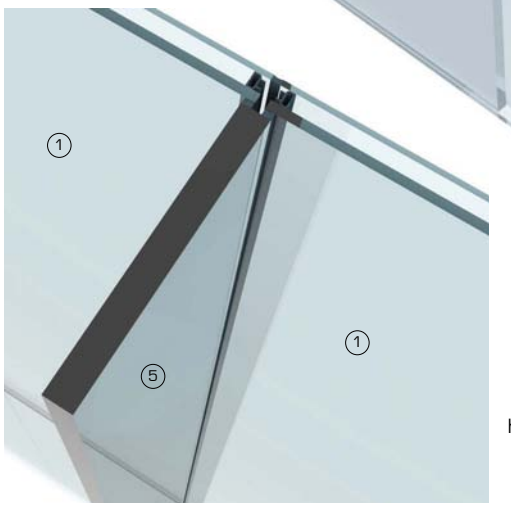
All-glass loadbearing structures are a recent development in the design of small-scale glass enclosures. Their intention is usually to maximise transparency, and their application on single-storey enclosures ensures that glass sheets can form walls without the need for aluminium or steel framing (c). Typically, double-glazed units are set vertically, with examples 1500mm wide x 3000mm high. These larger size panels require glass fins set vertically to take the place of glass mullions (d), but glass units 2100mm high sometimes do not require any glass fins, depending on the wind load (a). Double-glazed units are also used to form roof panels, set onto glass beams which are fixed to the vertical glass fins. Where no vertical fins are used, the glass beams can be fixed to stainless steel brackets or shoes which are bolt fixed to the double-glazed units forming the external wall. The beams, fins, wall panels and roof panels are bonded together, typically with silicone, to form an all-glass structure (e). In practice, most all-glass structures have additional mechanical fixings to secure all components (f), as a completely bonded glass structure has obvious risks associated with its design. A typical fixing might be a toggle-type fixing where a flat metal plate is used to hold double-glazed units in place. The double-glazed units have an edge spacer with a groove around the edge to which the toggle plate can be fixed. The silicone between double glazed units can then be silicone sealant rather than a silicone bond. The junction between vertical glass fins and glass beams supporting the roof panels may still use a silicone bond. The glass types used are a combination of tempered and laminated glass which is bonded or bolted together to form beam and column components. In common with bolt fixed glazing, an essential consideration in the design of loadbearing glass structures is the avoidance of any stress concentrations that might lead to glass breakage while the structure is under normal load conditions. Since the techniques used are very recent, no general principles for construction are set out here but two recent examples are shown. Sometimes a glass fin can be used at roof level only, projecting down the wall for a short distance and remaining above head height to avoid risk of injury to users.

All-glass enclosure, Broadfield Glass Museum, West Midlands, England. (MCH_283, f)
The architect was Brent Richards of Design Antenna working with



g | (Left) 3D view showing glass fin fixing detail in structural glass box assembly





h | (Left) 3D view showing glass fin fixing detail in structural glass wall assembly

j | 3D view showing structural glass wall assembly



k | 3D view showing structural glass wall assembly

structural engineers of Dewhurst MacFarlane. The enclosure is constructed without metal fixings or supports in any other material. It is 11m long, 5.7m wide and 3.5m high. The primary structure consists of glass beams 5.7m long x 300mm deep, at 1000mm centres. One end is supported by an existing masonry wall, whilst the other is supported on glass columns 3.5m high and 200mm deep.

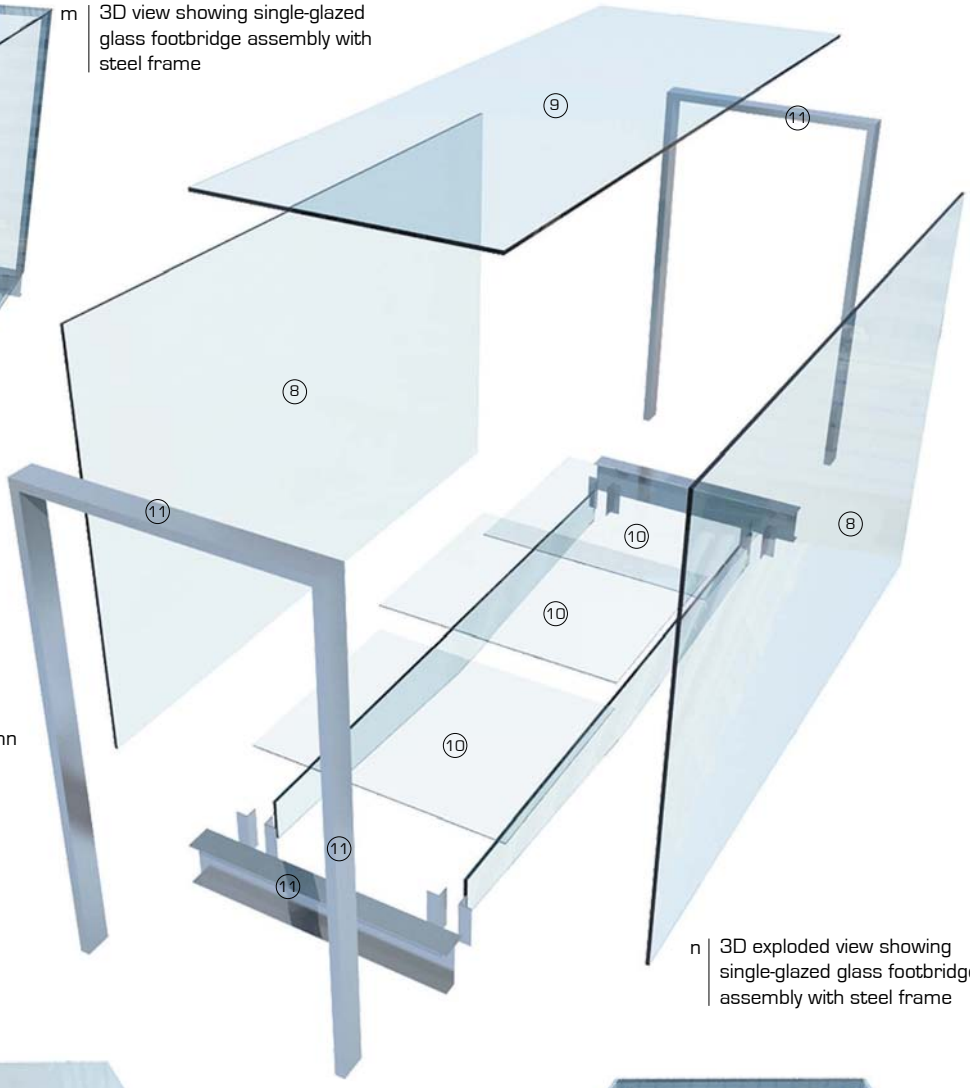
The beams and columns are made from three sheets of glass laminated together, making them 32mm thick. At the rear, the beams are secured by shoes in steel fixed to the wall, while on the glazed side they are connected to the columns in an interlocking of the glass layers. The junction was bonded on site with a catalyst-cured resin. The glass roof panels are bonded to the top of the glass beams. The double-glazed roof panels have an outer layer of 10mm thick toughened glass, a 10mm air gap and an inner skin of two sheets of 6mm glass laminated together. A silver film on the inner face of the upper sheet reduces solar gain, as does the ceramic fritting on the inside face of the panel.

The roof panels are bonded to the beams with structural silicone bead with a rigid foam backing. The gap between the panels is sealed using a silicone-rubber weather seal with a foam backing. The roof slope is 1.5º. The roof can be walked upon for maintenance, and supports expected snow loads. The front walls consist of 3.7 metre x 1.1 metre high double-glazed panels composed of two sheets of 8mm toughened glass with a 10mm air gap.

All-glass footbridge, Rotterdam, Holland (MCH_283, g)
This footbridge was designed by the architect Dirk Jan Postel of Kraaijvanger-Urbis, working with Structural Engineer ABT Velpe. The bridge spans three metres with floor plates of 15mm laminated float glass supported on two laminated glass beams made from float glass. The side-walls consist of double-glazed units made from 10mm and 6mm thick toughened glass sheet. In addition to being self-supporting, the walls support the glass roof, which has the same type of laminated construction as the walls (n). The all-glass components are fixed together with stainless steel brackets and plates. The use of stainless steel fixings does not noticeably reduce the transparency of the structure (q), instead adding a sense of visual refinement, while the curve of the beams supporting the floor deck contrasts with the rectilinear design of the glass enclosure. From a visual point of view, the all-glass design



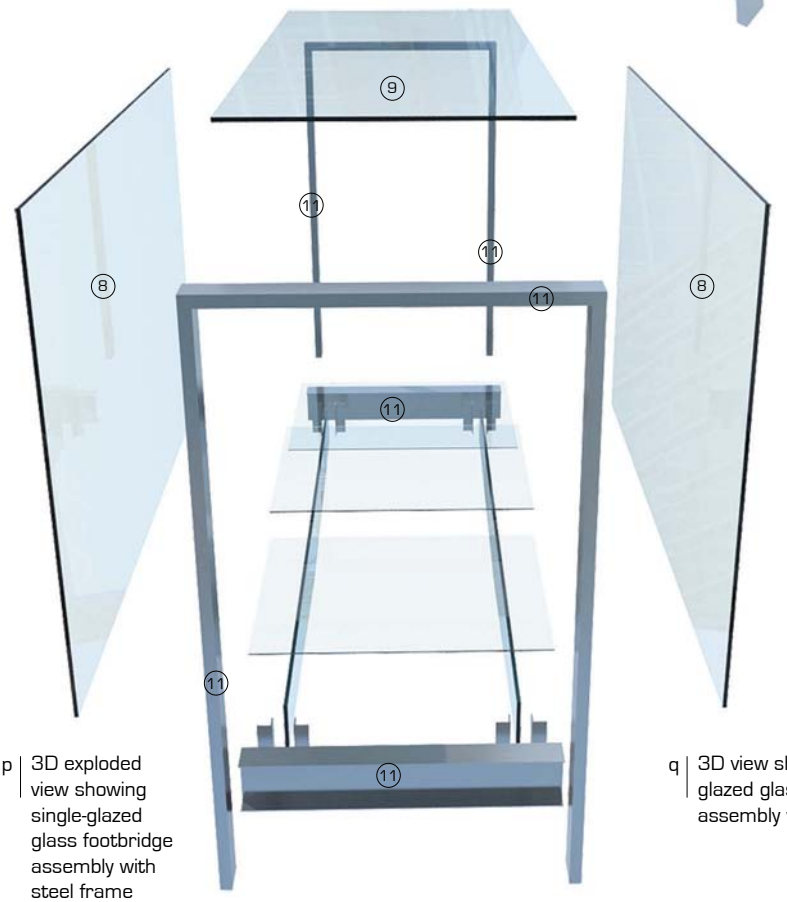
m | 3D view showing single-glazed glass footbridge assembly with steel frame



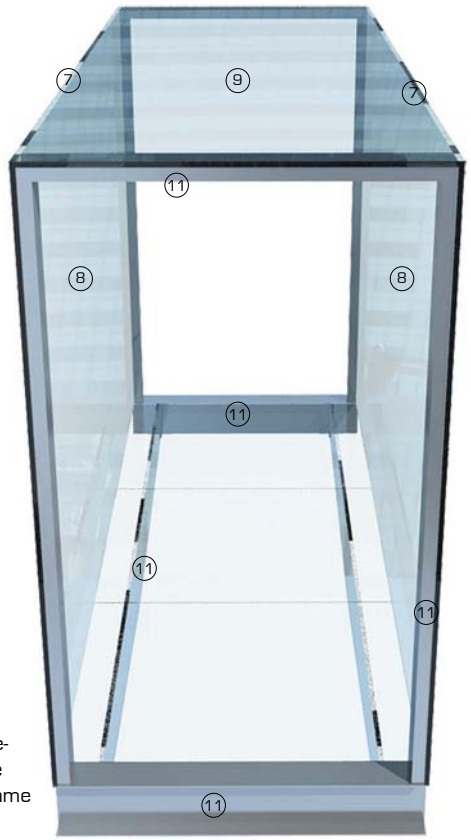
n | 3D exploded view showing single-glazed glass footbridge assembly with steel frame

Details

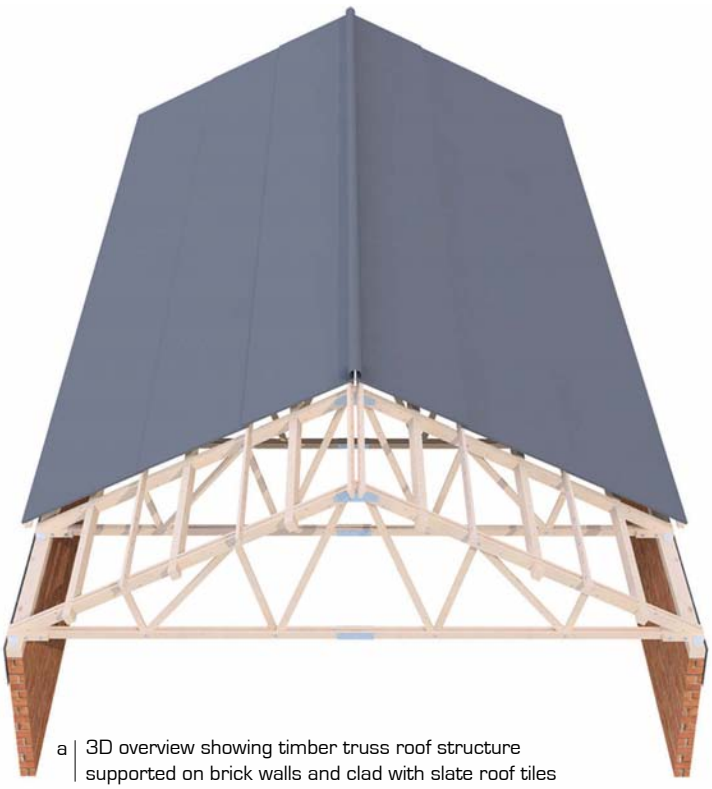
1 | Double-glazed unit
2 | Triple-glazed unit
3 | Laminated glass beam
4 | Laminated glass beam with slot for column
5 | Laminated glass column
6 | Laminated glass column with projecting lamina that slots into beam
7 | Silicone seal
8 | Single-glazed wall panel
9 | Single-glazed roof panel
10 | Glass as floor deck
11 | Steel frame
12 | Stainless steel bracket bolt fixed to beam and wall
13 | Bonded glass connection



p | 3D exploded view showing single-glazed glass footbridge assembly with steel frame



q | 3D view showing single-glazed glass footbridge assembly with steel frame



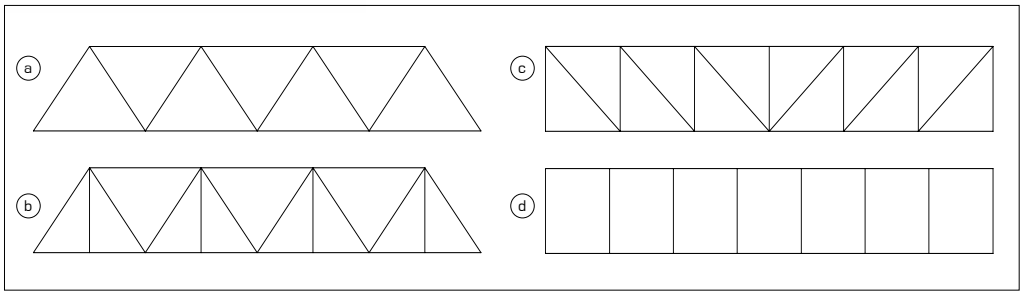
a | 3D overview showing timber truss roof structure supported on brick walls and clad with slate roof tiles



b | 3D detail views showing timber truss roof structure clad with slate roof tiles

Details

1 | Warren truss
2 | Modified Warren truss
3 | Pratt truss
4 | Vierendeel truss

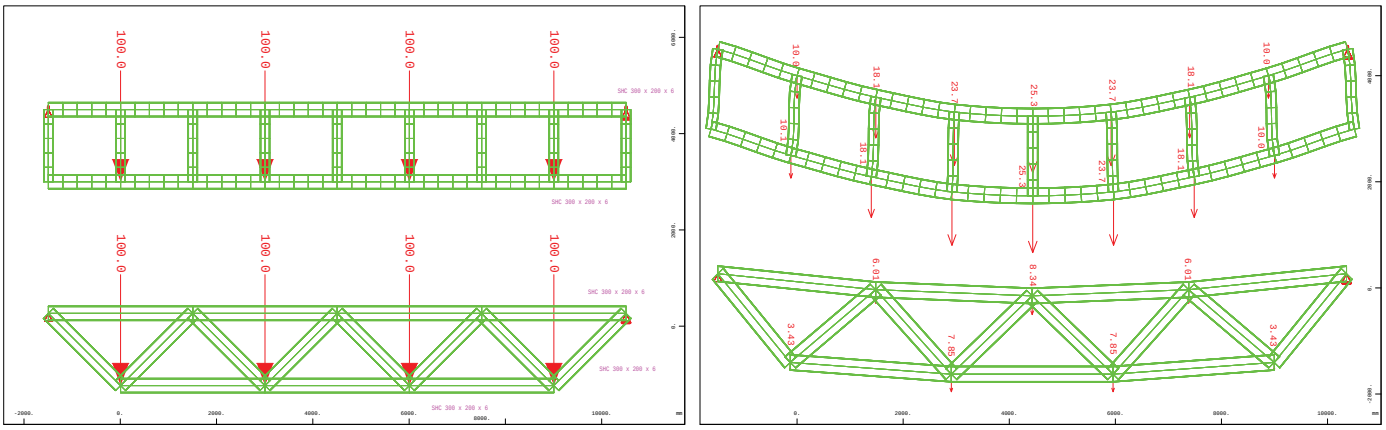


c | (Right) Traditional timber roof truss assembly types

Trusses are used for large spans where a solid girder would be at a disadvantage due to its self-weight. Instead of using a deep solid section, such as a girder, a more economic solution for larger spans can be provided by transmitting forces across a series of diagonally set and connected members to take up the vertical, horizontal and diagonal shear stresses (a). With the exception of the Vierendeel type, trusses use pin-ended members that utilise tension and compression in a series of ties and struts (c). While trusses bend along their overall length, local bending within the truss can be largely avoided if loads onto the truss are applied at the node points (d). Loading trusses away from the nodes introduces local bending into horizontal members with a resulting increase in their design size, as members now have to resist bending as well as axial loads, resulting in trusses that are heavier, usually less elegant and more expensive. The voids between members are often used to accommodate services and mechanical ventilation ducts. These structures maximise the lever arm between the compression and tension flanges to generate a greater moment of resistance in order to provide a greater loadbearing capacity while minimising weight. Simply supported trusses exert no thrust at their supports, allowing them to be easily supported on columns or supporting walls within a larger structure.

Truss types vary enormously in their design; the most common types being the Warren trusses, where loads are carried mainly as axial loads in the members, the 'N' truss which has vertical and diagonal members in a rhythm of alternating tension and compression, and the Vierendeel truss, which has an orthogonal rather than a triangulated series of members (c). In the Vierendeel truss, forces are transferred between members by localised bending, called Vierendeel action, with rigid connections between members. As such, it is not strictly a truss type. The bending makes members slightly larger than in an equivalent triangulated truss (e), resulting in their being heavier than a Warren truss spanning the same distance.

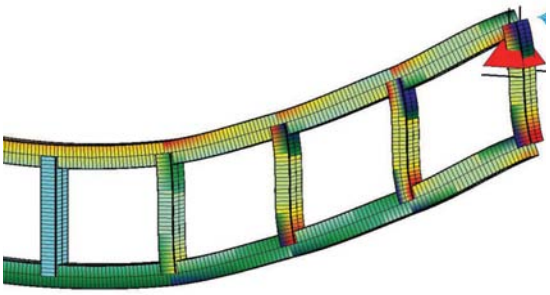
Whereas beam members are predominantly I-shaped to accommodate the bending effects, the cross-sectional shape for individual truss members can vary enormously, since truss members are generally subject to small direct forces. Consequently, T-sections and tubes can be used in steel trusses, for example, while a mix of timber and steel can be used in other types (f). Flat shaped sections make the connections easier to form than box sections, but this situation provides opportunities to design elegant connections, which can be one of the most significant considerations from a visual point of view.



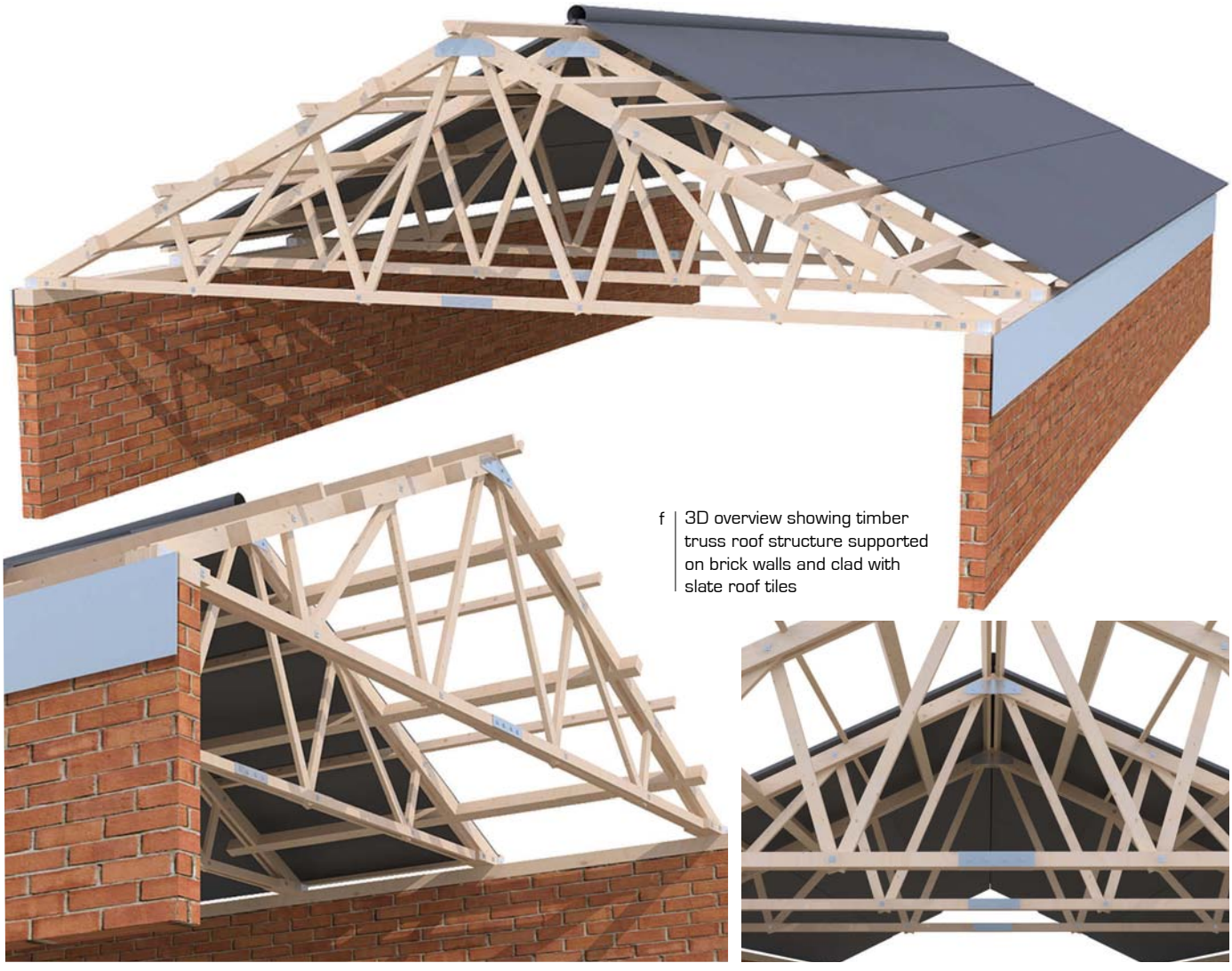
d | Comparative structural analysis: using the same member cross-sections and applying the same loads, the Vierendeel truss shows larger deflections.

Details

1 | Purlins spanning between trusses
2 | Roof covering
3 | Strut
4 | Tie
5 | Timber wall plate
6 | Bolted steel connection
7 | Steel connector plate



e | Structural behaviour of a typical Vierendeel truss: bending moments are carried by the rigid connections, which would normally be pinned in a braced truss.



f | 3D overview showing timber truss roof structure supported on brick walls and clad with slate roof tiles

g | 3D view showing timber truss roof structure supported on brick walls and clad with slate roof tiles

h | 3D detail view showing timber truss roof structure clad with slate roof tiles



j | 3D overview showing timber truss roof structure supported on brick walls and clad with slate roof tiles





k | 3D views showing timber truss roof structure supported on brick walls and clad with slate roof tiles

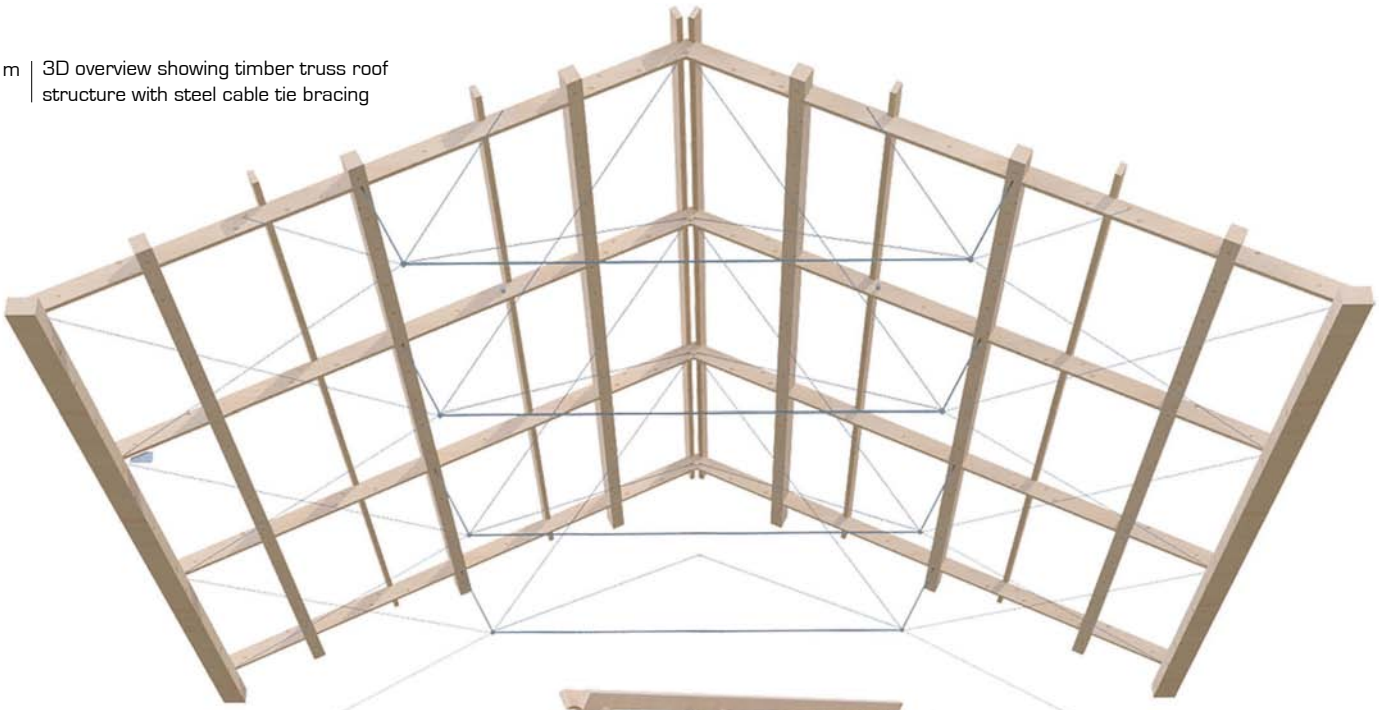
Details

1 | Purlins spanning between trusses
2 | Roof covering
3 | Strut
4 | Tie
5 | Timber wall plate
6 | Bolted steel connection
7 | Steel connector plate

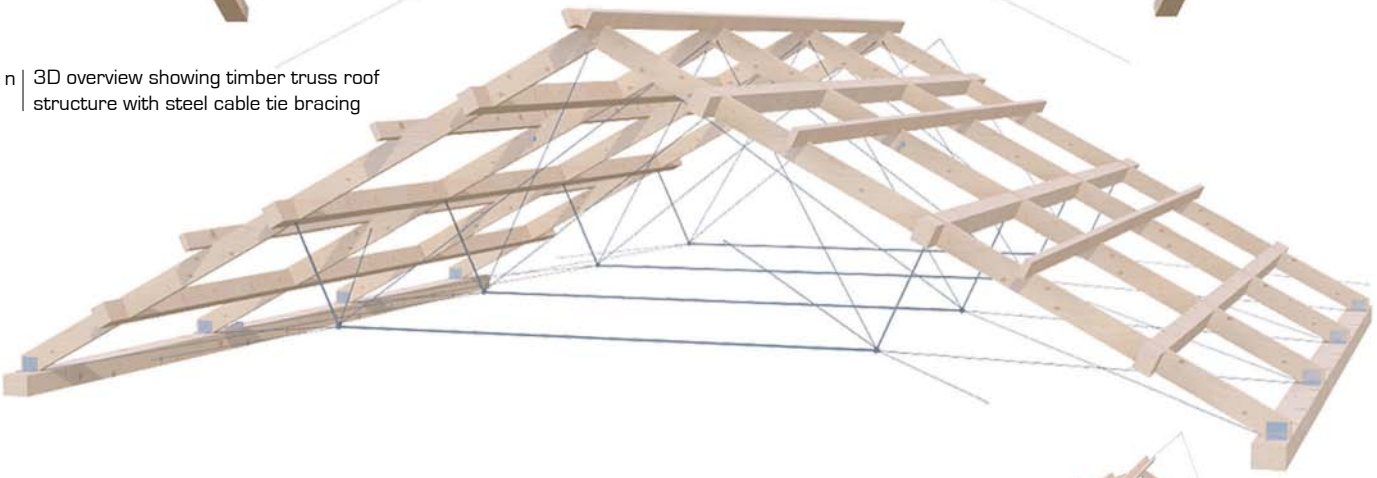
Joints and connections

Trusses are typically formed in timber, mild steel or a combination of the two materials (j). In trusses using mixed materials, steel rod or cable are used to form the ties, typically on the bottom chord of the truss, while steel tube might be used to form the central strut (m). Timber roof trusses are either large trusses set up to three metres apart, linked together with purlins or much lighter nail plate trusses set at around 450mm centres (k). Larger trusses often use double timber members forming the main rafters and joists that are spaced apart with secondary ties and struts linking the primary members. Timbers are bolted together using large steel washers that spread the load imposed by the bolt head and prevent it from crushing the timber locally as the connection is tightened. The exposed steel components are painted to avoid their corrosion. Timber trusses can also make use of ties made in steel rod where they are visible components (n). Smaller trusses are factory assembled with nail plates and split ring connectors, as described in the Materials chapter. Steel trusses can range from a modest set of angles bolted together with linking gusset plate connectors to welded tubular structures that can incorporate cast node connections to allow connections with complex geometries to be formed. These cast connectors allow the loads to meet at the intersection of the centre lines of members in order to minimise the diameter of the tubes. Modest steel trusses use angles set back-to-back and bolted together with gusset plates set between them to allow several members to be joined together at a single node. They are in widespread use as economic long-span supports to roof structures. Larger-scale trusses are made from laminated timber or LVL (laminated veneer lumber), which resembles plywood in its construction but is made in long lengths. These materials use similar bolted connections to smaller trusses, but typically with bigger metal connector plates. Truss members can be made from single lengths of LVL but for high loads; LVL is glue-laminated to make large cross-section members, typically square in profile. Reinforced concrete trusses are usually precast either as a series of prefabricated components which are stitched together or as a single completed component. They are much less commonly used than those in timber or steel due to their self-weight, which tends to reduce the lightness and economy associated with trusses in those materials.

m | 3D overview showing timber truss roof structure with steel cable tie bracing



n | 3D overview showing timber truss roof structure with steel cable tie bracing



Interface with external envelope

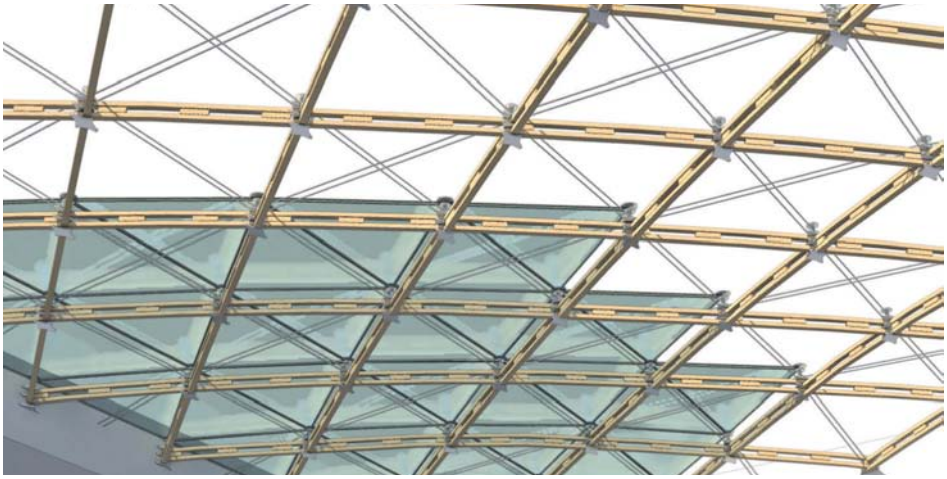
Trusses are connected at points to secondary members called purlins, set on top of the outer face of the truss in order to form a support for the build-up of the roof covering and to make a simple connection between truss and purlin (p). Purlins can have an internal finish applied, such as timber boards or dry lining in order to expose the trusses within the building, but this varies with the design of the trusses. In addition to avoiding local bending in truss members, the fixing of cladding to secondary supports permits the use of simple bolted or screwed connections that avoids any complexity in fixing to a primary member. The bases of trusses are set either onto a supporting structural frame or onto a supporting wall. The wall plate or purlin joining the base of the trusses is typically used to form an interface between roof covering and the external wall below, where a gutter is typically required. The arrangement of purlins is often adjusted to suit the needs of supporting the roof covering, which may range from profiled metal sheet to traditional roof tiling. Steel trusses also have brackets fixed to the top of the truss to provide connectors to the roof covering, typically with the aim of providing a visual separation between structure and roof covering.



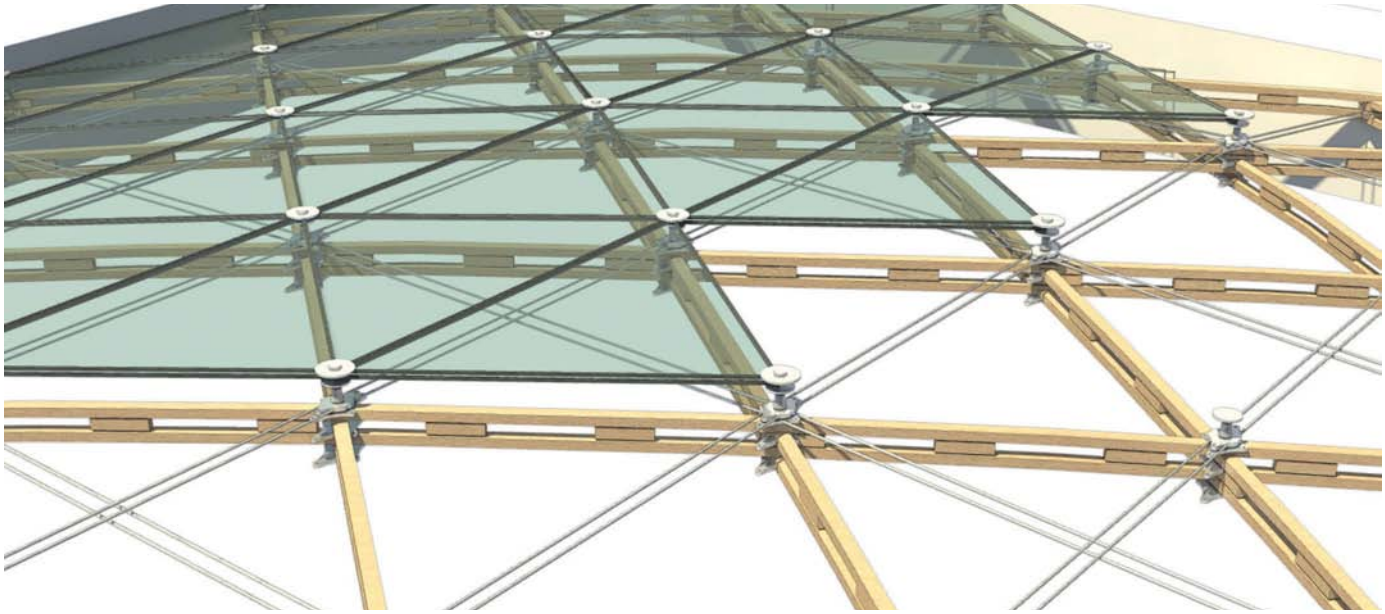
p | 3D view showing timber truss roof structure clad with slate roof tiles

Details

1 | Timber member
2 | Steel rod
3 | Steel node connector
4 | Doubled-glazed unit



a | 3D views showing timber shell structure with tension cable support and double-glazed roof



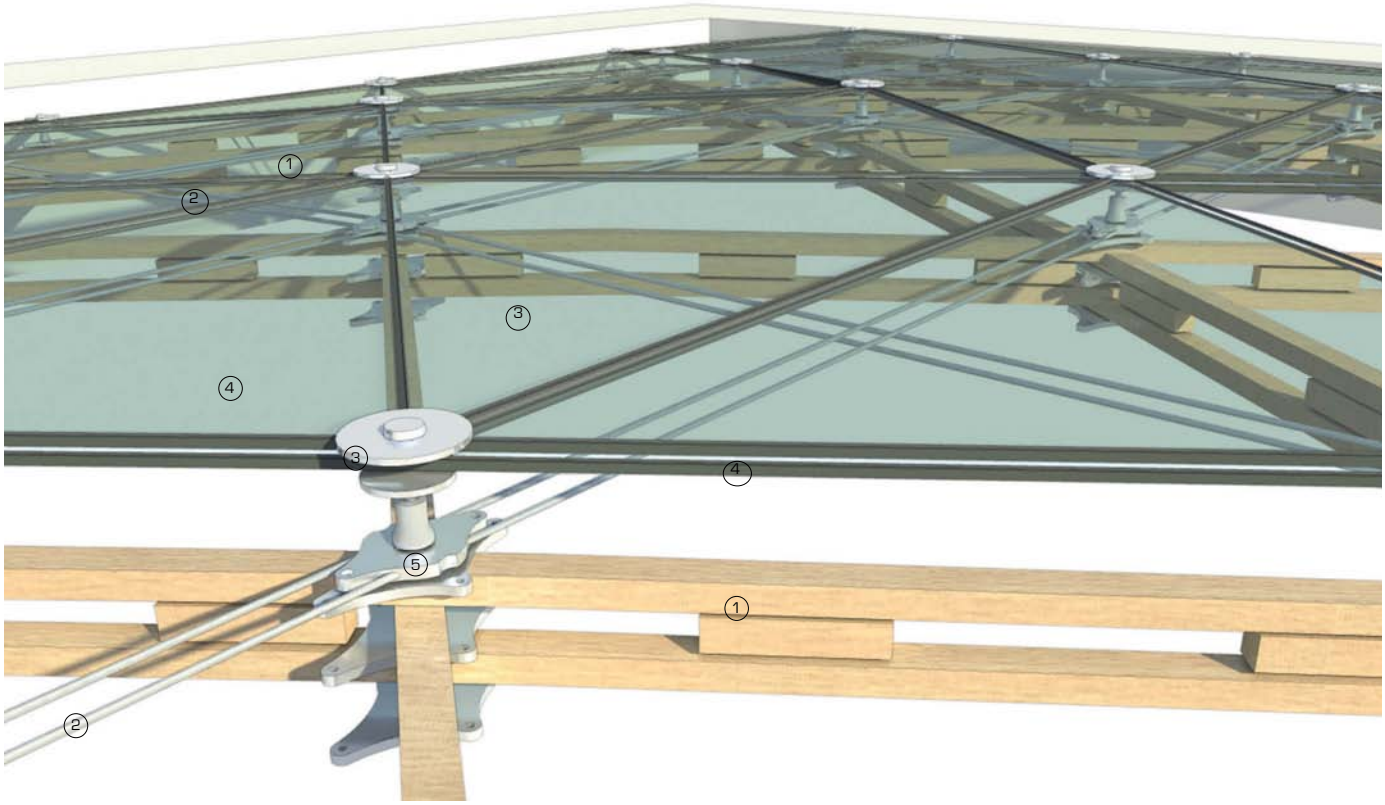
The essential concept of the arch is to support loads primarily as compression forces in the plane of the structure, with abutments at the base to resist the outward thrusts generated by its shape. Since arches exert outward forces at their bases, they require a tie such as a floor slab or beam, for example. This is quite different to some portal frames, which do not exert such forces at their base points. Consequently, a variation to this type is the 'tied arch', in which a tension member links the base points across the arch to resist these outward thrusts and control the spread of the arch. The three most common types used in modern construction are the rigid arch, the two-pin arch and the three-pin arch. These two-dimensional structures are linked together in bays with purlins to form a complete structure. Alternatively, the arch concept can be extended into three dimensions as a shell. Both arches and shells can be formed either from truss components as 'gridshells' (a), which are in increased use, or as monolithic structures in reinforced concrete.

Arches

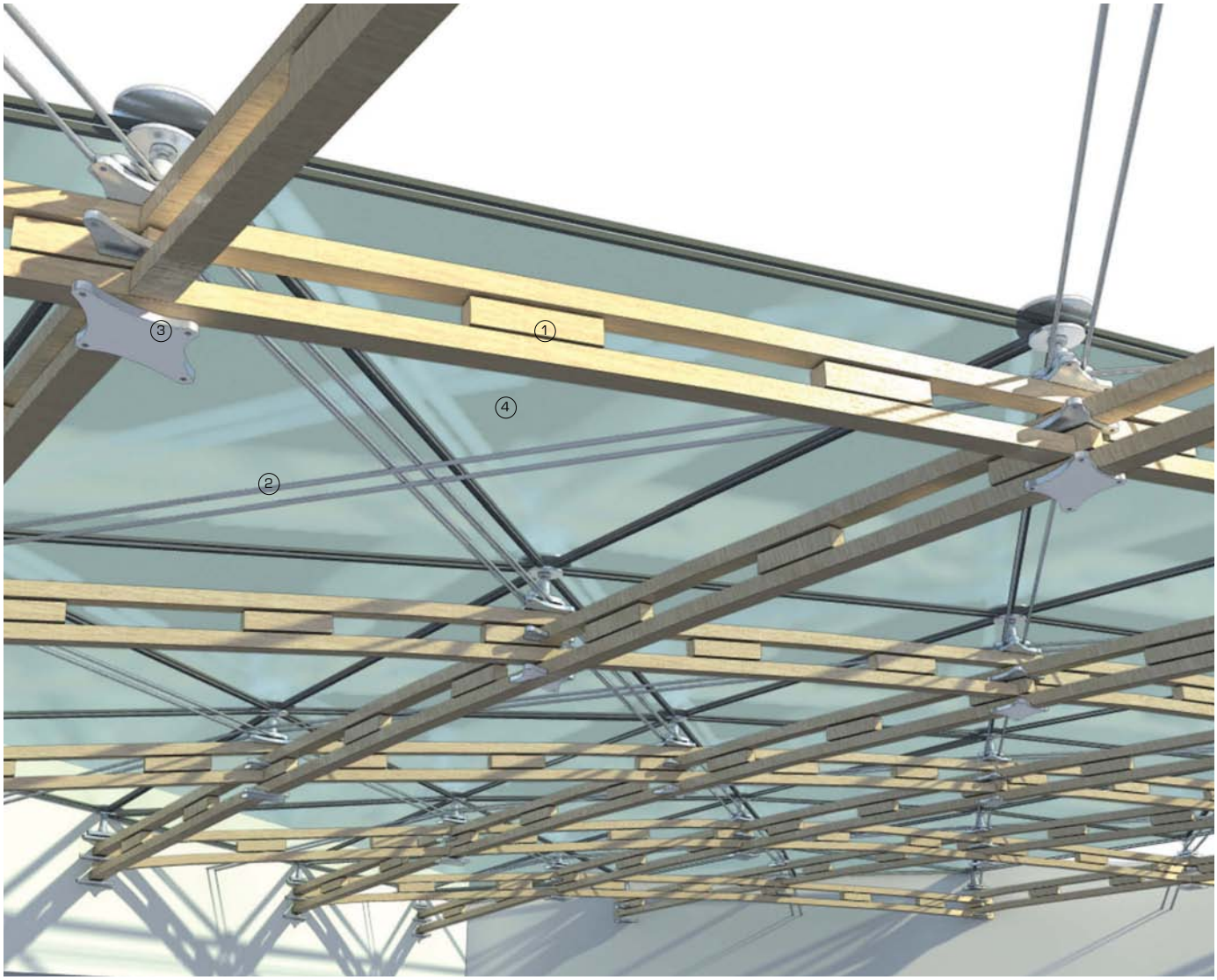
The rigid arch has no pin joints, but instead has rigid connections at both base points. This arch type is generally considered to be more economical than the two other types, but has bending moments at its base that are transmitted into the foundations, which may need to be linked by ground beams to resist the thrusts in the manner of a tied arch, unless the ground is sufficiently firm to withstand the thrusts without a beam. The two-pin arch has pin joints at the abutments only. It is more economical in use of material than the three-pin type, and bending moments are more evenly distributed than in the three-pin type, minimising the amount of material used. The three-pin arch is hinged at three points, which are at the apex and at the two base points. Bending does not occur at the pin joints, which behave as pivots or hinges. Bending moments away from the pins are greater than in other types. As with the traditional masonry arch, there are horizontal thrusts at the supports. Thrusts at the base of an arch increase as the arch profile becomes shallower. Both the three-point and two-point arches suit larger spans which would present difficulties for transport and handling if made in a single piece. The most common materials used are steel, laminated timber and reinforced concrete.

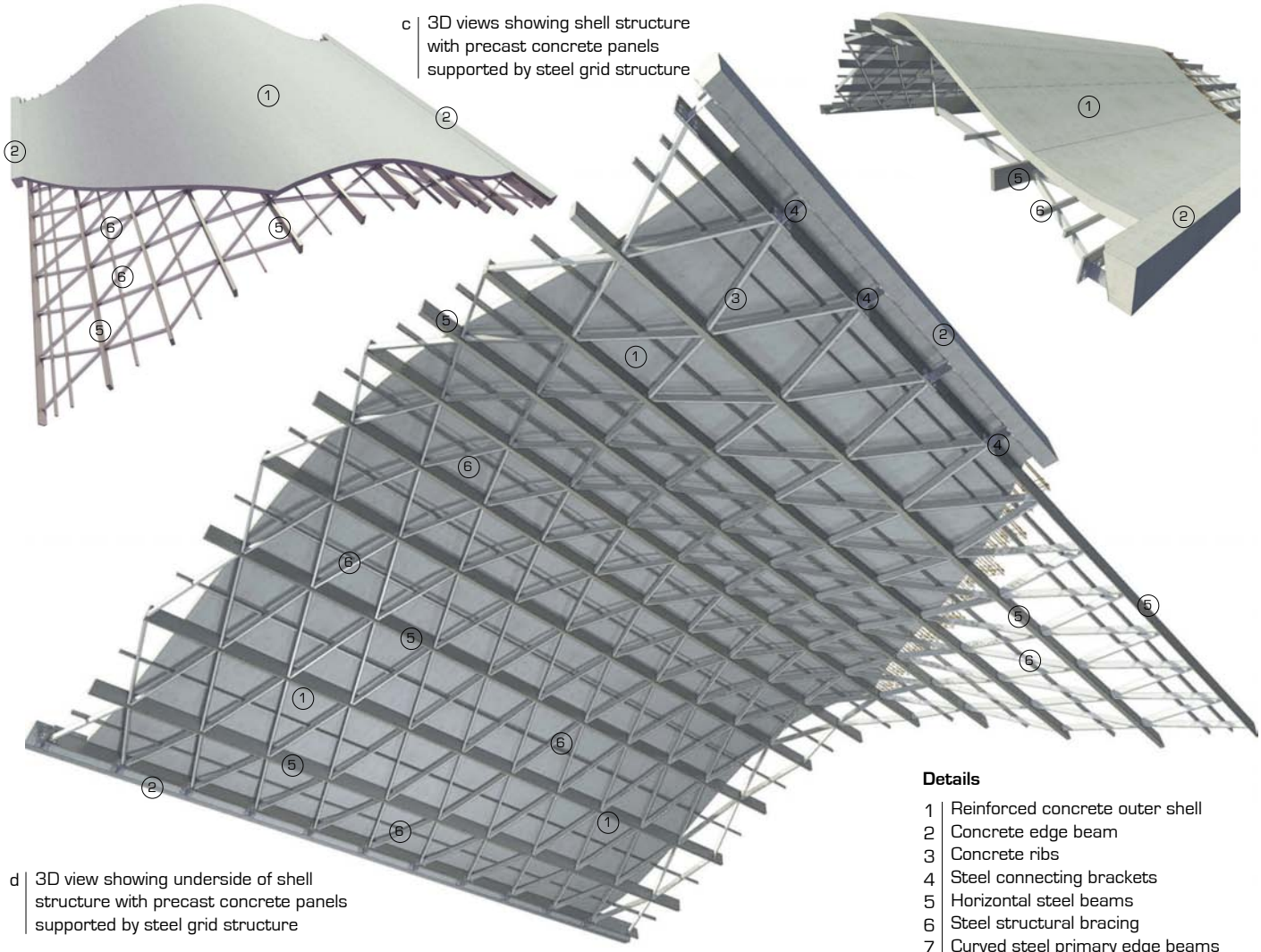
Shells

Shells are of two generic types; those made from framing members to which cladding is applied (b), and monolithic shells which are made either by casting concrete in place over complex formwork or as precast sections which are stitched together. In both cases, the loads are carried in the plane of the structure with the outward thrusts being taken out at the base. Shells constructed from framing members often have a ring beam at the edge to contain the effects of the outward thrusts. Monolithic concrete types may either follow the same principle or have a continuous abutment at their base to deal with the higher loads associated with concrete. Shells in which the structure and enclosure



b | 3D views showing timber shell structure with tension cable support and double-glazed roof





c | 3D views showing shell structure with precast concrete panels supported by steel grid structure

d | 3D view showing underside of shell structure with precast concrete panels supported by steel grid structure

Details

1 | Reinforced concrete outer shell
2 | Concrete edge beam
3 | Concrete ribs
4 | Steel connecting brackets
5 | Horizontal steel beams
6 | Steel structural bracing
7 | Curved steel primary edge beams
8 | Steel horizontal structural members

are combined in a single form, as is found in an egg shell, are referred to as monocoques. Shell forms vary enormously, from the relatively simple shell vault resembling an extruded arch to the complex ribbed structures resembling seashells.

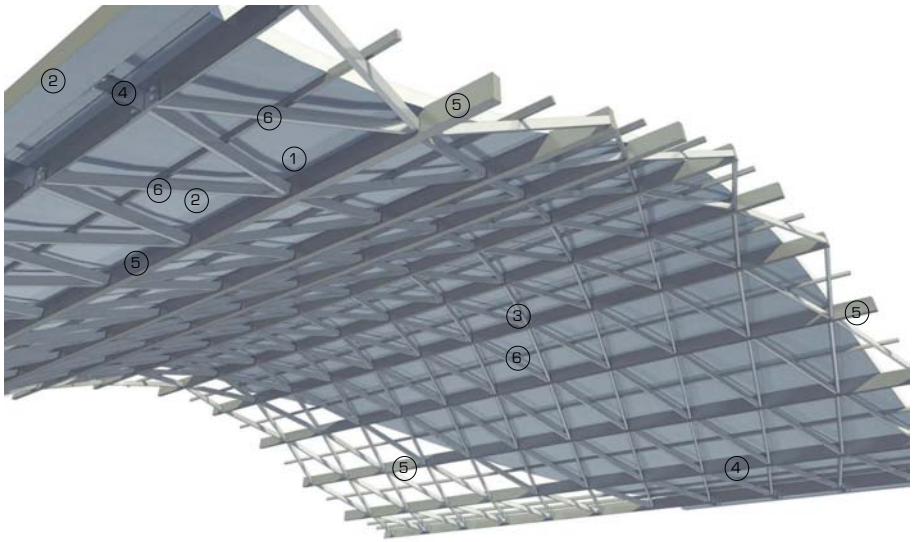
Joints and connections

Arches and shells made from framing members (rather than reinforced concrete) are formed using the pinned and moment connections associated with each material and are illustrated here (d). An interesting recent development has been in using a mix of materials to form shell structures, such as those in timber and stainless steel cables or rods (b). The mixing of materials has benefits in economy of weight, allowing forces in different members to be matched to a suitable material. An essential aspect of framed shells or 'gridshells', with their double curvature, is the connector node which is typically made in steel and which can also be used to support the roof covering (e). Where a single material is used for the gridshell, such as steel, node connectors are not required if regular cleat and bracket connections can be used economically. This allows the roof covering to be supported directly on the structural members. Shells can be supported at their base on a variety of supports, from columns to loadbearing walls or floor slabs. The choice of support may be related directly to the need to provide an economic weathertight seal at their junction, though structural ring beams are often needed to contain the outward thrust forces.

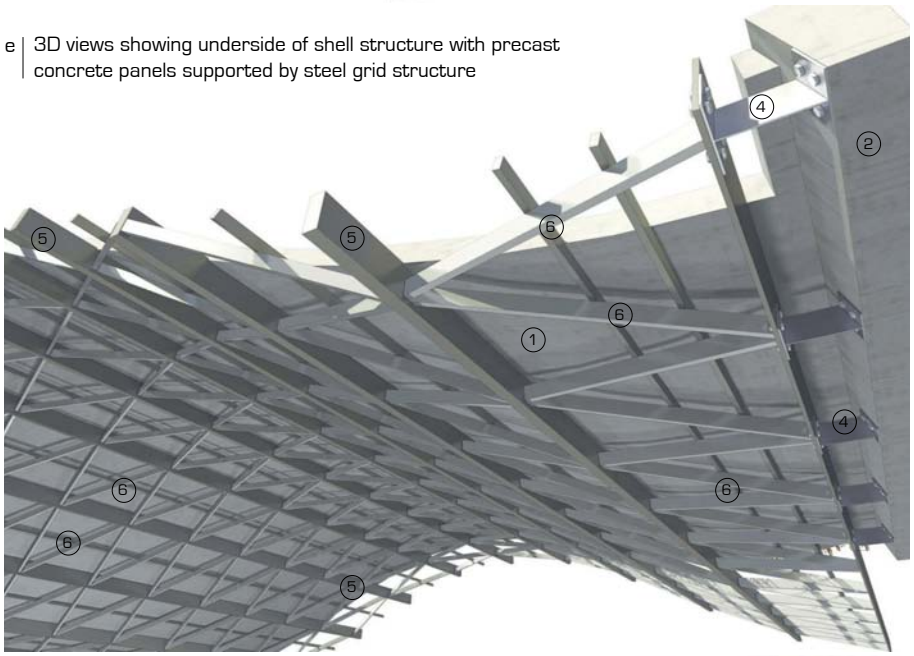
Interface with external envelope

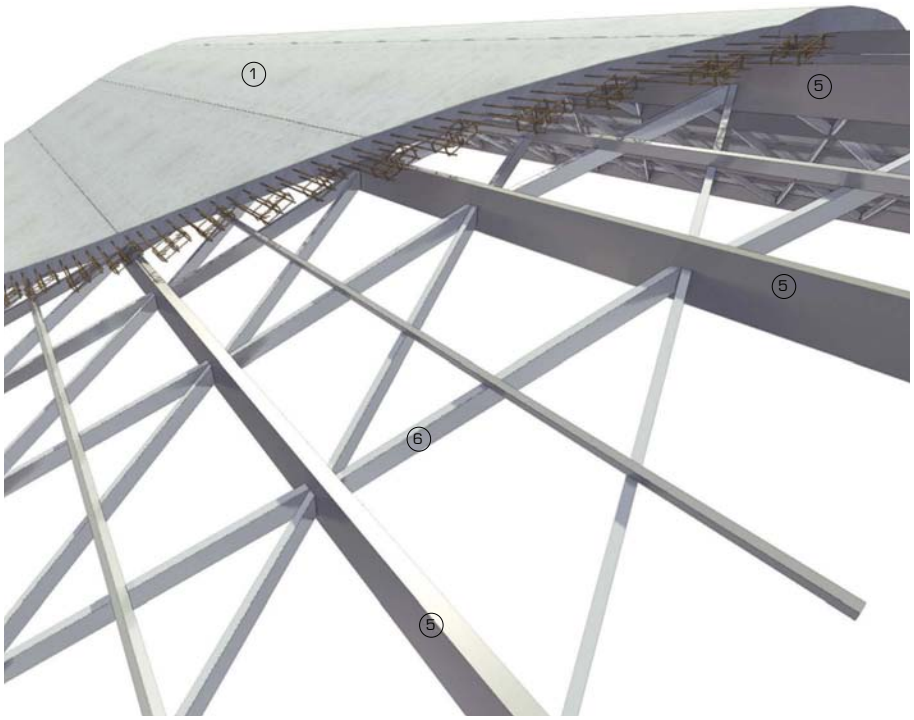
Monolithic arched structures and shells are covered externally in continuous membranes where rainwater is collected at the base of the structure. Membranes used vary from polymer-based types that are bonded to the structural substrate to standing seam metal sheeting.

Trussed arches and gridshells provide the opportunity for transparency where glazed roof systems can be used in addition to metal-clad roofs. Where metal is used, a covering of sheet metal or metal rainscreen panels are used, typically with a profiled metal substrate serving as a deck, though the double curvature of the shell can make it easier to form a substrate from triangles, which are always flat. Double-glazed units can be supported as clamped glazing supported at the node connector points, or alternatively from a secondary metal frame also connected at these node points. The external envelope is fixed in a way which allows the structural movements of gridshells (f), which can be higher than other types of roof structure, to take place without damage to joints in the roof covering. While movements can be more easily accommodated in metal roofs, glazed roofs require careful particular attention to detail to ensure that the support points for the glazed units do not experience significant amounts of movement. Consequently, the principles associated with point-fixed glazing are often used, even where part of the support system involves a metal supporting frame.

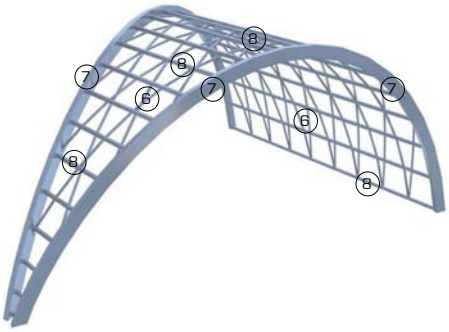


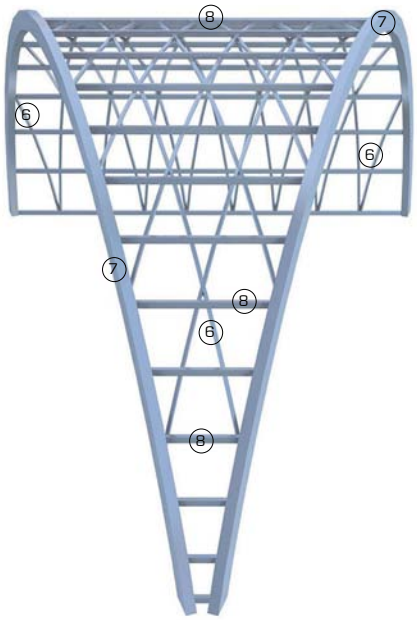
e | 3D views showing underside of shell structure with precast concrete panels supported by steel grid structure

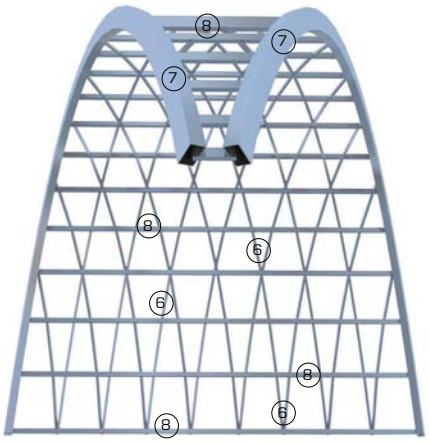


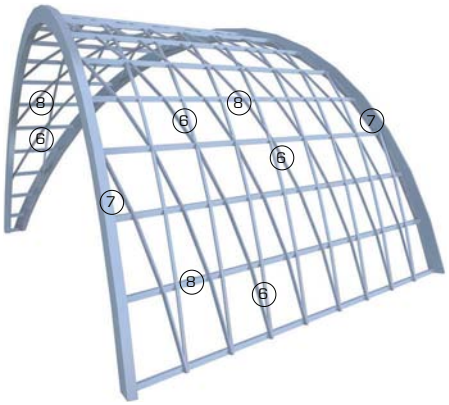


f | 3D cutaway view showing shell structure with precast concrete panels supported by steel grid structure

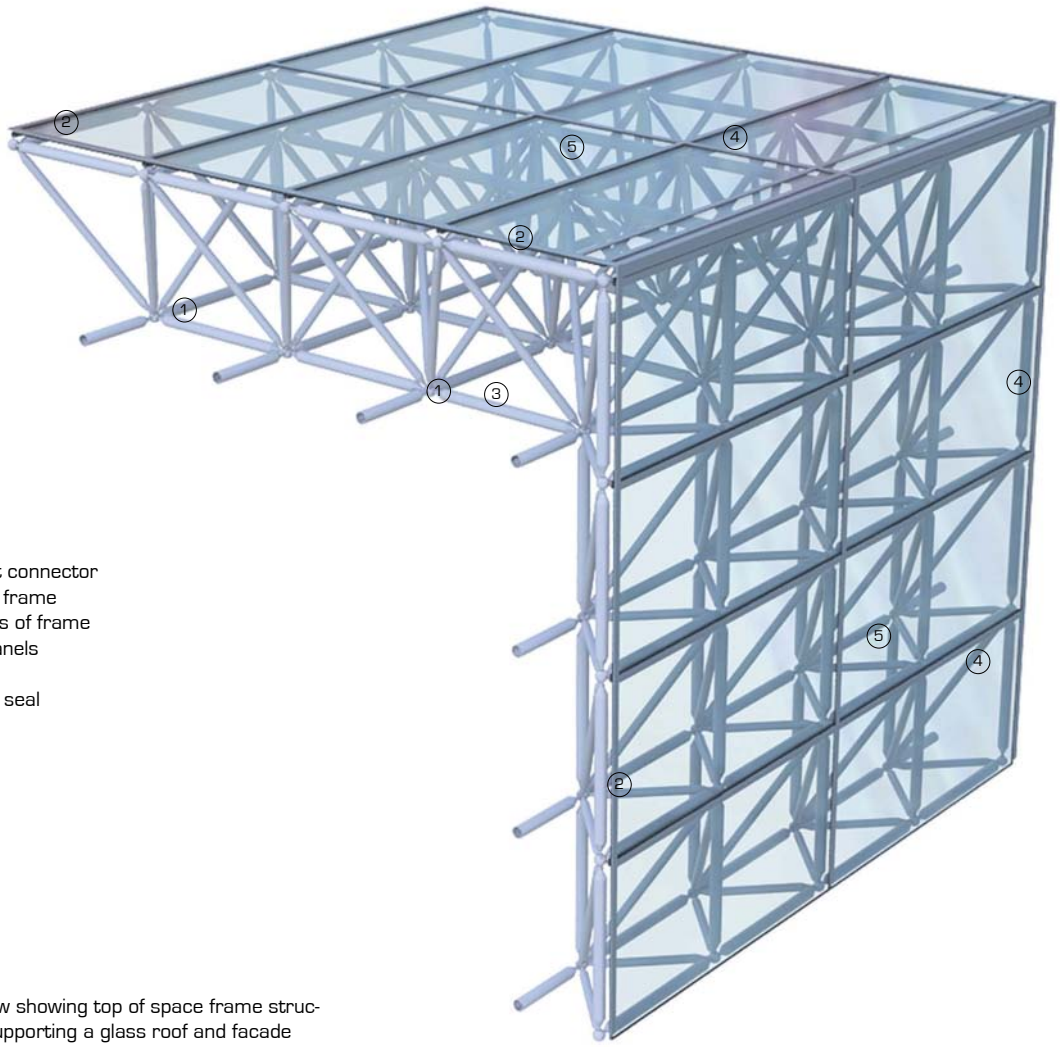








g | 3D views showing arched steel structural frame with diagonal cross-bracing



Details

1 | Spherical cast connector
2 | Top chords of frame
3 | Bottom chords of frame
4 | Glazed roof panels
5 | Glazing frame
6 | Rubber-based seal

a | 3D view showing top of space frame structure supporting a glass roof and facade

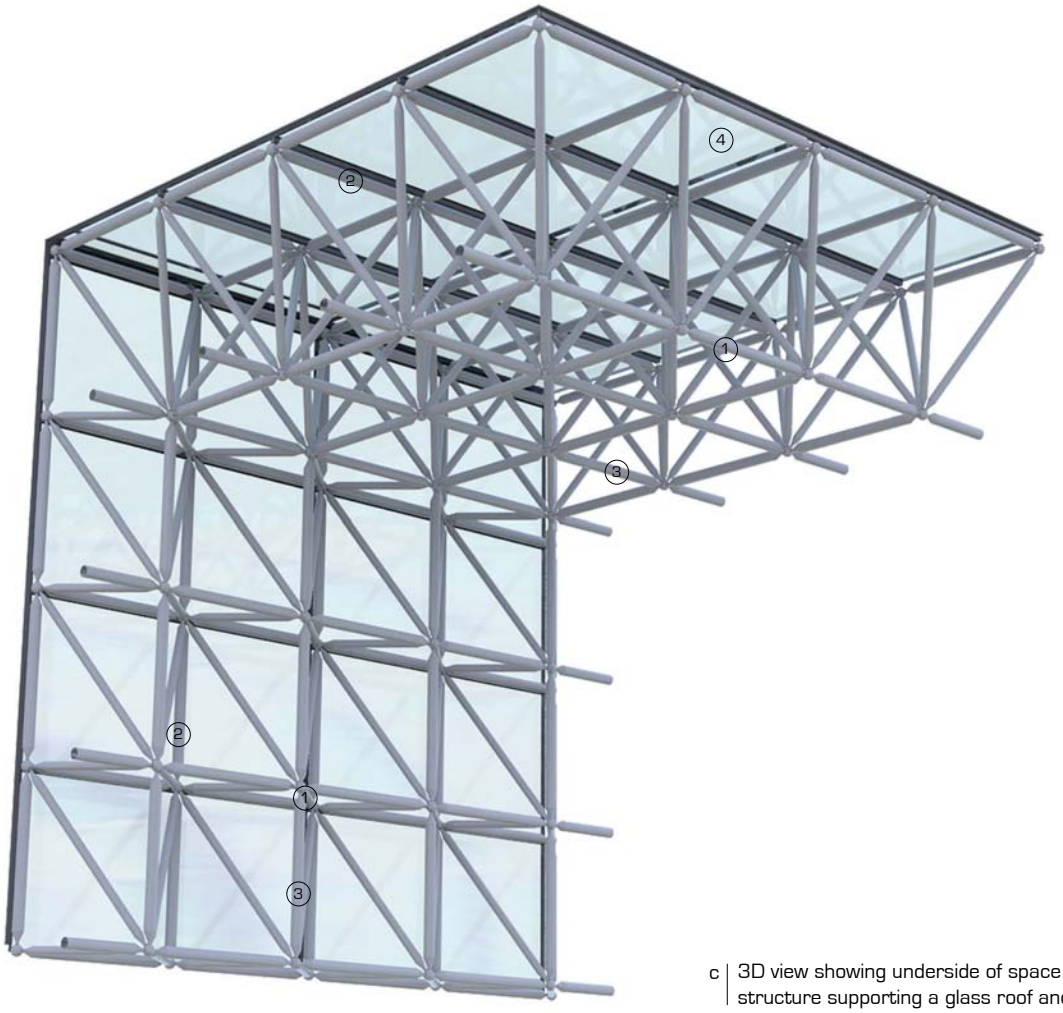
Space frames and geodesic domes are the most well-known types of space grid. They can be regarded, from a conceptual point of view, as being three-dimensional trusses. One of the earliest space frames was the Mero system designed in the 1940s by Max Mengeringhausen, and is still in use today, though much evolved from that time. A development by Konrad Wachsmann in the 1950s was based on the geometric form of the tetrahedron. The space frame comprises a series of triangulated members linked by node connectors that, effectively, form a series of linked trusses in directions perpendicular to one another (a). The material system is made economic and quick to install by using a single node type wherever possible, though different connectors may be used at the edges where they meet the external wall (b). Some geometries require a 'family' of connectors to form complex shapes, particularly those space frames that depart from the square, rectilinear format used until recently. An equivalent of the space frame for curved surfaces is the geodesic dome, originally developed by Richard Buckminster Fuller in the 1940s. Fuller believed that structures in nature behave such in a way that internal forces usually act in the direction of minimum effort with a maximum gain achieved for a minimum of energy input. Rather than apply this idea to the form of the plant leaf or the animal shell, Buckminster Fuller interpreted triangular crystalline forms found in nature, using triangulated frames. Like the space frame, the geodesic dome is essentially a continuous triangulated structure but its geometry often allows it to be used as a single-layer structure without the need for introducing triangulation into the depth of the structure. Space grids provide long-span structures for roofs and walls. They can take on a huge variety of forms from vaults to supporting structures for large glazed walls. Deflections in space frames are small due to the overall stiffness of the frame. Steel is most commonly used because of the strength and stiffness of the material combined with its comparatively low cost.

Joints and connections

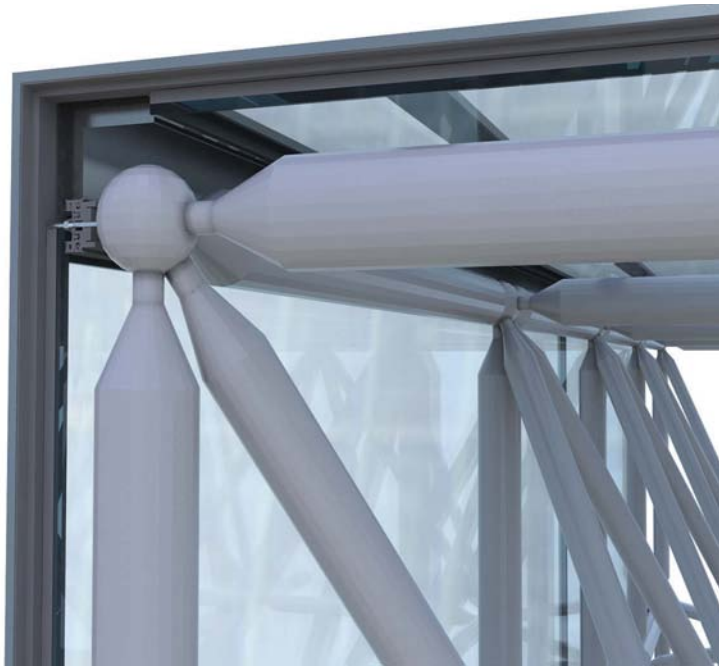
The 'base' component of space frames and geodesic domes can be considered as a square-based pyramid-shaped frame, assembled with rods or tubes connected by a single node connector (d). The early Mero systems used a spherical node, set with threaded holes into which eight connectors fixed to structural members forming the space frame could be connected. Four holes were set in order to allow members in the same horizontal or vertical plane to be connected together, with four additional holes at angles that allow triangulated members forming the depth of the space frame to connect to form the characteristic triangulated shape. More recent versions use square and polygon-based geometries to form the node connector, allowing triangular grids to be used rather than the square-based versions. The new generation of nodes can be used for single layer structures that are based more on the idea of gridshells than space frames, and allow more freedom



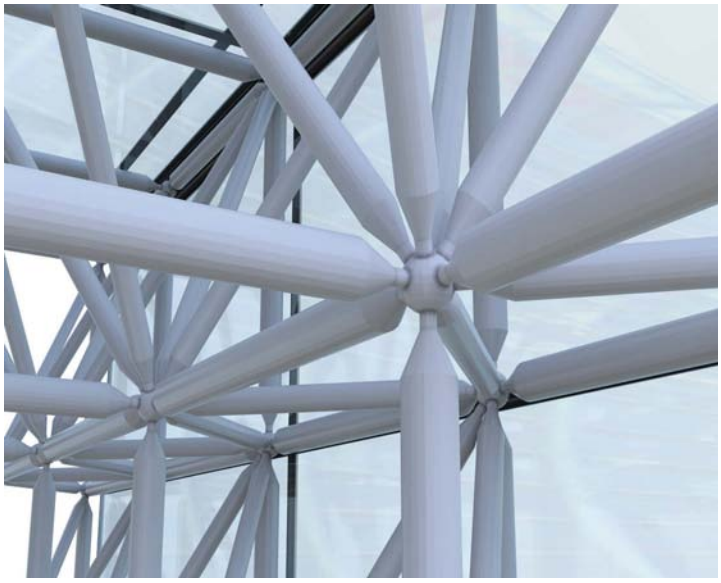
b | 3D view showing space frame structure supporting a glass roof and facade



c | 3D view showing underside of space frame structure supporting a glass roof and facade

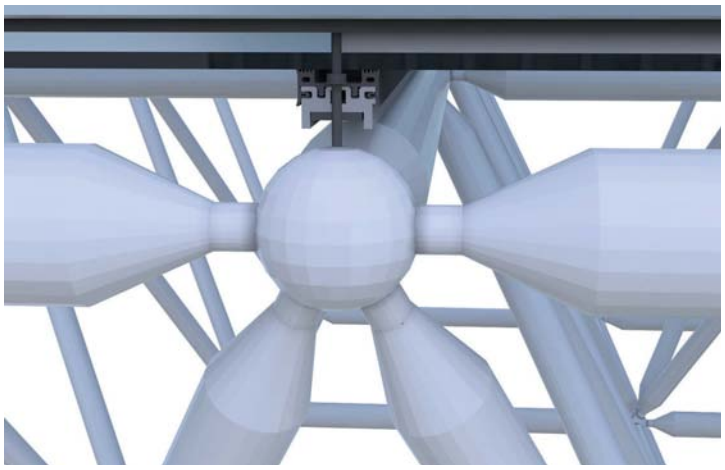




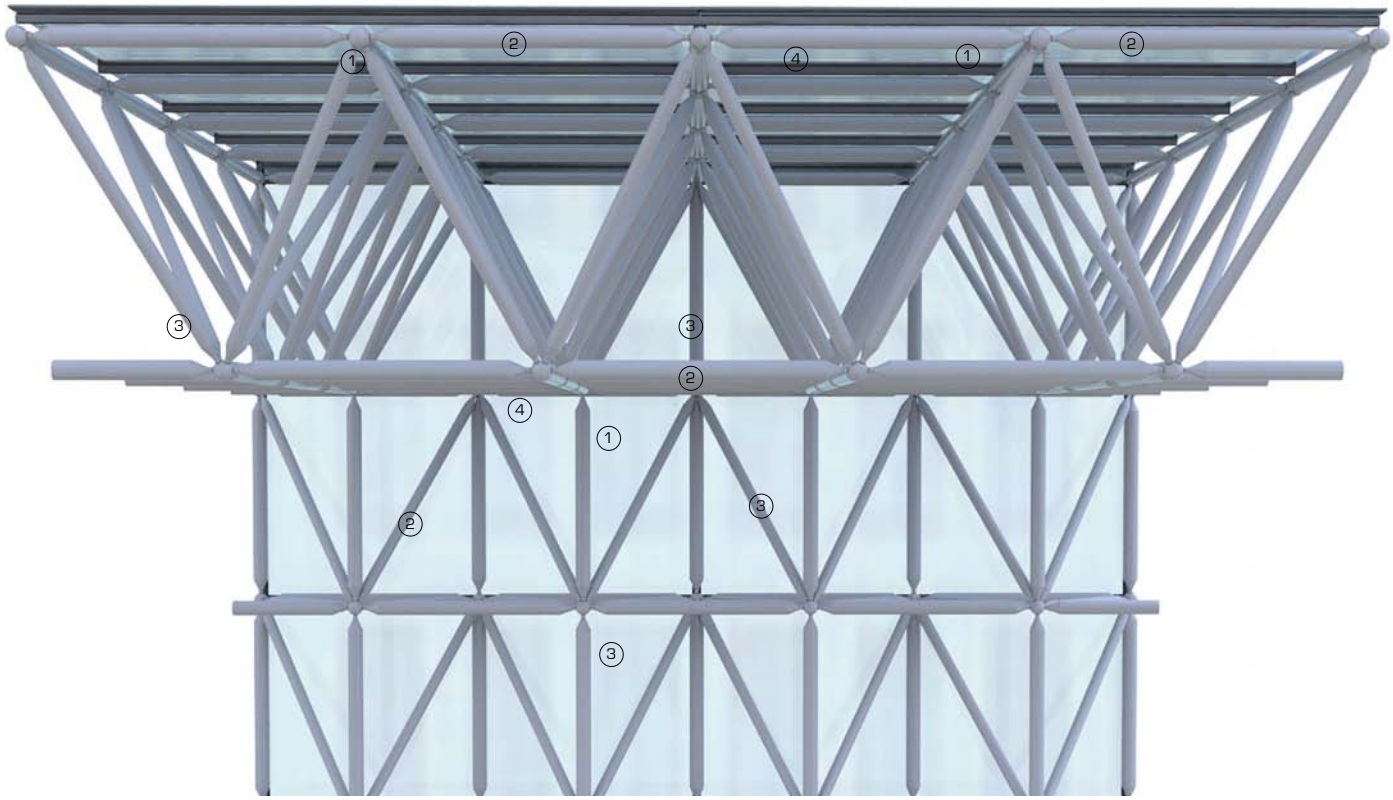




e | 3D views showing typical nodes and chords of a space frame structure



d | 3D views showing typical nodes and chords of a space frame structure



Details

1 | Spherical cast connector
2 | Top chords of frame
3 | Bottom chords of frame
4 | Glazed roof panels
5 | Glazing frame
6 | Rubber-based seal

f | 3D view showing space frame structure supporting a glass roof and facade

in the range of angles that can be accommodated in order to allow more geometric variation in the form of the grid. The design of nodes is currently moving towards this preference in design for a wider range of forms than are afforded by the rectilinear frame arrangement.

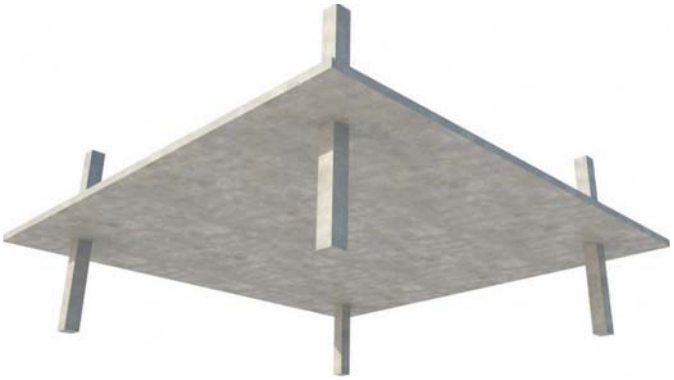
The node connector is the essential component of the space grid. Very simple types with simple geometries use a flat plate connector to which steel angles are bolted in the manner of a truss. Complex geometry types use a cast or machined node that has threaded holes to receive the ends of the threaded connectors of the ties and struts (e). These form part of proprietary systems designed by manufacturers.

Interface with external envelope

An essential advantage of the space grid is that cladding panels can be fixed directly to the structure without the need for additional rails or purlins (f). For glass roofs, a typical distance of 1500mm between horizontal structural members in the space frame allows economic sized double-glazed units of the same size to be used. Where a profiled metal desk is used, there is greater flexibility in the size of the structural bay, as the decking can span up to around 3500mm with standard profile depths. Roof cladding or glazed panels are fixed either with lugs or brackets welded to the structural members, which may be tubular or rectangular. Alternatively, the roof covering can be fixed to the node connectors where the node is designed for this purpose. More typically, the nodes are used as structural connectors only. Where a rectangular hollow section is used, cladding can be fixed directly to structural members without the need for welded lugs, provided that the potential corrosion caused by penetrating the tube is taken into account.

Point-fixed glazing is also suitable for space grids since the connectors for the glazing can be fixed directly to the structural node. Cladding conditions can vary from flat to inclined to curved, following the geometry of the supporting structure to which they are fixed. In conditions where the roof is horizontal, the roof covering can drain into gutters set between roof panels, following the direction of structural members beneath. In conditions where the roof is inclined, the roof covering is drained like a glazed roof, with water running across the roof surface to gutters at the edges. Glazed roofs in most geometric conditions use glazing which is toggle-fixed or point-fixed, with a single silicone-based seal set flush with the surface of the glass, in order to allow rainwater to run freely across the roof (f).

Junctions between wall and roof in glazed space frames typically use either a glass-to-glass joint, or one where an insulated metal panel is used to form the junction (b). The choice is largely based on design preference and the visibility of the glazed edge.



1. Flat slab



2. Slab with downstand beams



3. One-way spanning ribbed slab



4. Two-way spanning ribbed slab

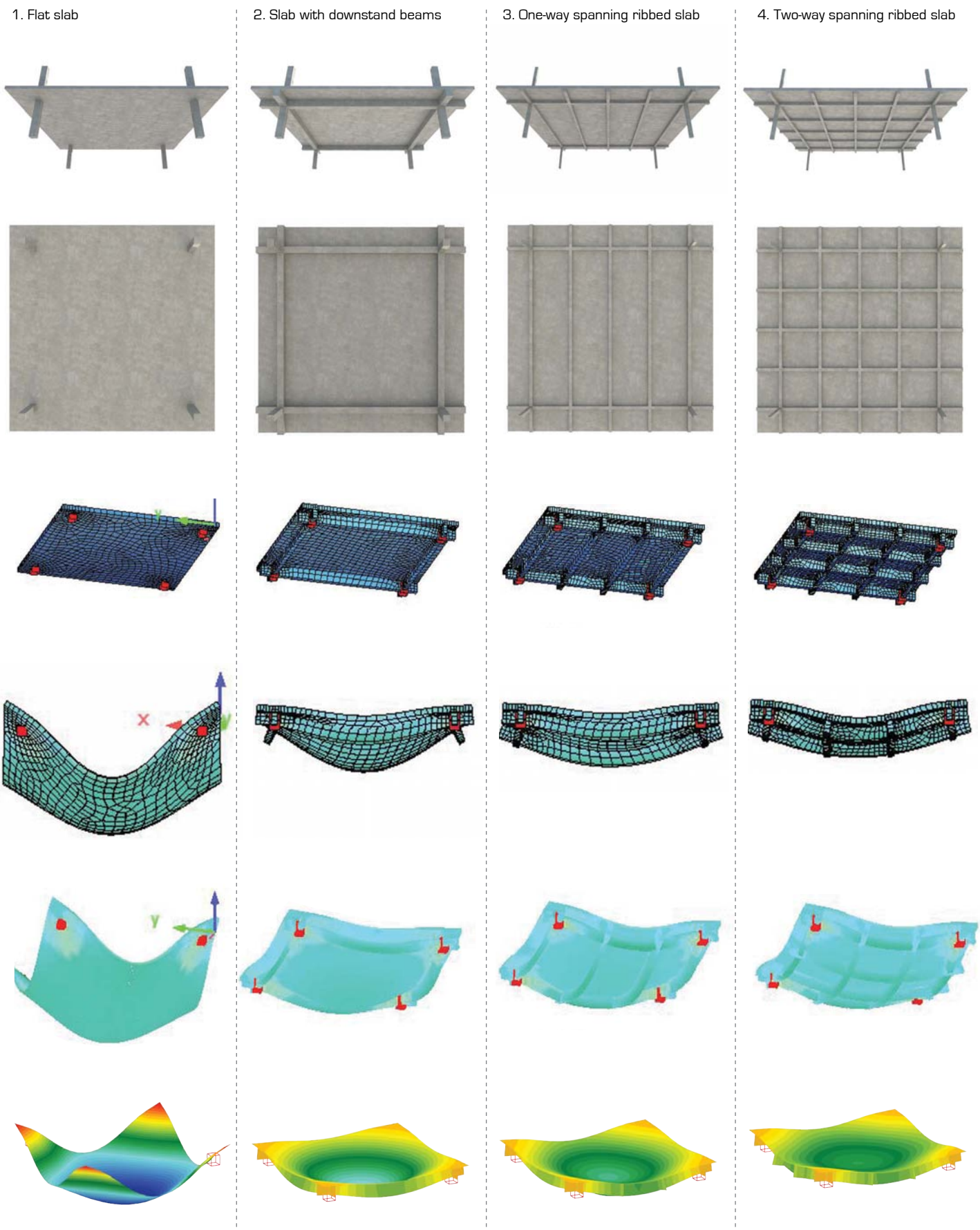
a | 3D views showing various in-situ cast concrete floor slab configurations

The flat slab is the simplest type of cast-in-place floor and is suitable for spans of up to around nine metres. It can be used in a one-way or two-way span, approximately 300mm deep, depending upon span and loading (a). In a one-way span, steel reinforcement is introduced into the bottom part of the slab and the floor is designed to span in one direction only, like a beam. In a two-way slab, the reinforcement is laid in a perpendicular grid so that the total load of the floor is more evenly distributed at its perimeter as the floor spans in two directions. Reinforcement is concentrated on the lines between columns to create beams connecting columns within the depth of the slab. The soffit is flat, providing a smooth ceiling and allowing a straightforward type of formwork to be used. Providing the tops of columns with protruding caps where the transfer of forces is concentrated can reduce the depth of flat slabs. These caps provide greater rigidity for the structure and reduce the span of the slab between columns.

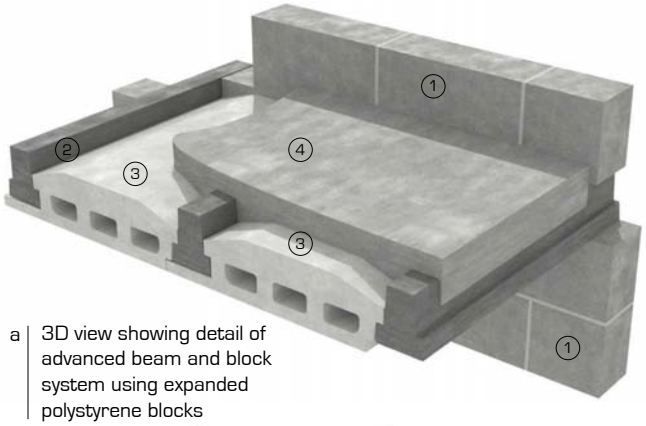
Floor spans can be increased economically from six metres to 15 metres by forming a series of downstands in the floor soffit to create a ribbed floor. Steel reinforcement in the bottom of the ribs makes this type of floor lighter than the flat slab because of the structurally efficient ribbing, but the formwork is more complex.

The two-way coffered floor slab is a ribbed floor for large spans of up to around 17 metres in two directions. The hollow coffers are often used to house lighting and service outlets. The floor structure gives better resistance to shear when the beams are set diagonally to the structural grid of columns but as with ribbed floors, the formwork must be specially made (b).

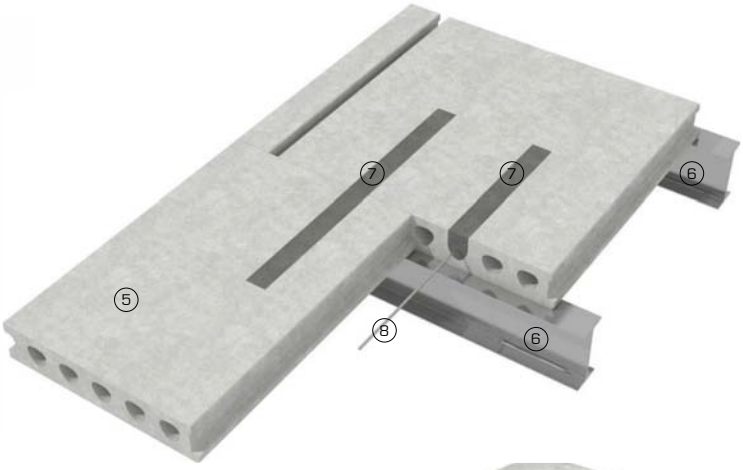
Ground-bearing slabs may be either reinforced or poured as mass concrete, depending on the degree of strength and rigidity required. Where ground-bearing conditions permit, they are supported directly by the ground beneath. Where the ground is too soft, a suspended floor is used. Ground-bearing slabs can be designed either as a raft or as a slab supported by separate foundations beneath. Ground slabs are laid on a compacted base of hardcore (gravel), which provides a level and well-drained base. The hardcore is blinded with a smooth layer of sand onto which is laid a damp-proof membrane (DPM: vapour barrier). The sand prevents the DPM, usually a thick polythene sheet, from being punctured by the hardcore. The DPM prevents moisture rising up through the slab. The concrete is poured directly over the DPM. In addition, a DPM can be laid between the concrete slab and the screed. A liquid material is used to provide a bond to the surface of the slab. This results in a loss of bond between the screed and the slab, and a thicker screed (about 75mm) is used. The DPM is joined to the wall DPC (damp-proof course: vapour barrier) to provide continuity of damp-proofing . A DPM laid on top of the concrete, usually in the form of a liquid-applied layer, is used as an alternative where sealing the underside and edges of the slab is not practical. Distribution bars (reinforcing mesh) are set near the reinforcing bars in order to avoid cracking in the underside of the slab due to its being in tension under load. Reinforcement used in concrete floors can be either conventional reinforcement bars or welded mesh fabric.



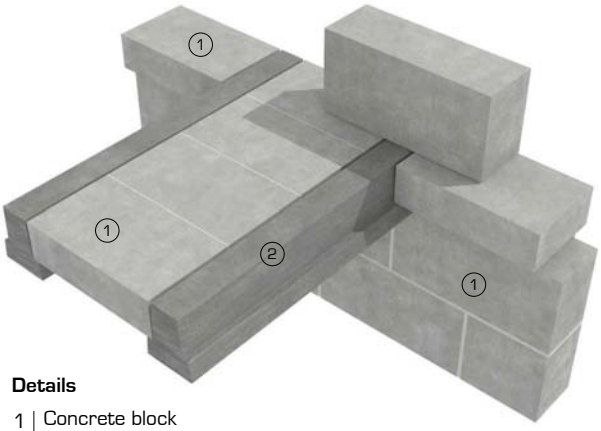
b | Finite element analysis of different concrete slab systems showing the effect of adding structural ribs.

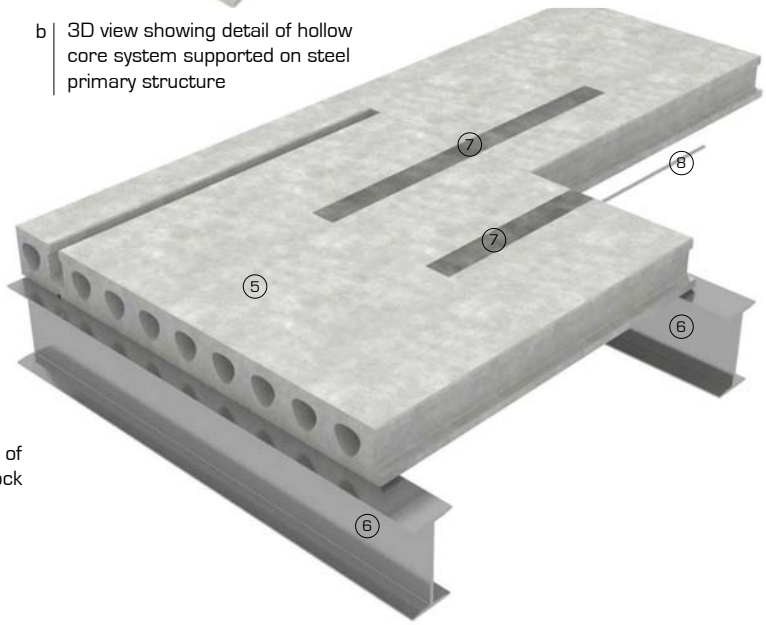


a | 3D view showing detail of advanced beam and block system using expanded polystyrene blocks



b | 3D view showing detail of hollow core system supported on steel primary structure





c | 3D views showing detail of traditional beam and block floor system

Details

1 | Concrete block
2 | Prestressed concrete beam
3 | Expanded polystyrene block
4 | Structural concrete topping
5 | Hollowcore slab
6 | Primary steel structure
7 | Structural concrete infill
8 | Reinforcement tie

Precast concrete floors consist of prefabricated planks or beams connected together to form a deck (d). Proprietary systems provide longer spans than in-situ-cast concrete floors, but they span in one direction only. Precast floors that span two ways have been developed for specific projects such as the Richards Medical building shown here, and go beyond the constraints imposed by standard systems (e).

Proprietary systems

The generic types produced by manufacturers are as follows:

1. Hollow core slab, spanning to around 12 metres (b)
2. Beam and block, spanning to around 7.5 metres (c)

These are all essentially prestressed beams which are stitched together to form a complete deck. Ends are supported either on beams or by a loadbearing wall typically forming part of an overall precast concrete construction, which has the advantage of a rapid rate of construction. All types can be left either exposed, as is sometimes the case with parking garage constructions, or be topped with a layer of concrete to form a composite structure. Openings for service runs need to be fixed at an early stage, since the size and position of openings in precast floor systems is much more constrained than is the case for cast-in-place floors.

Beam and block system

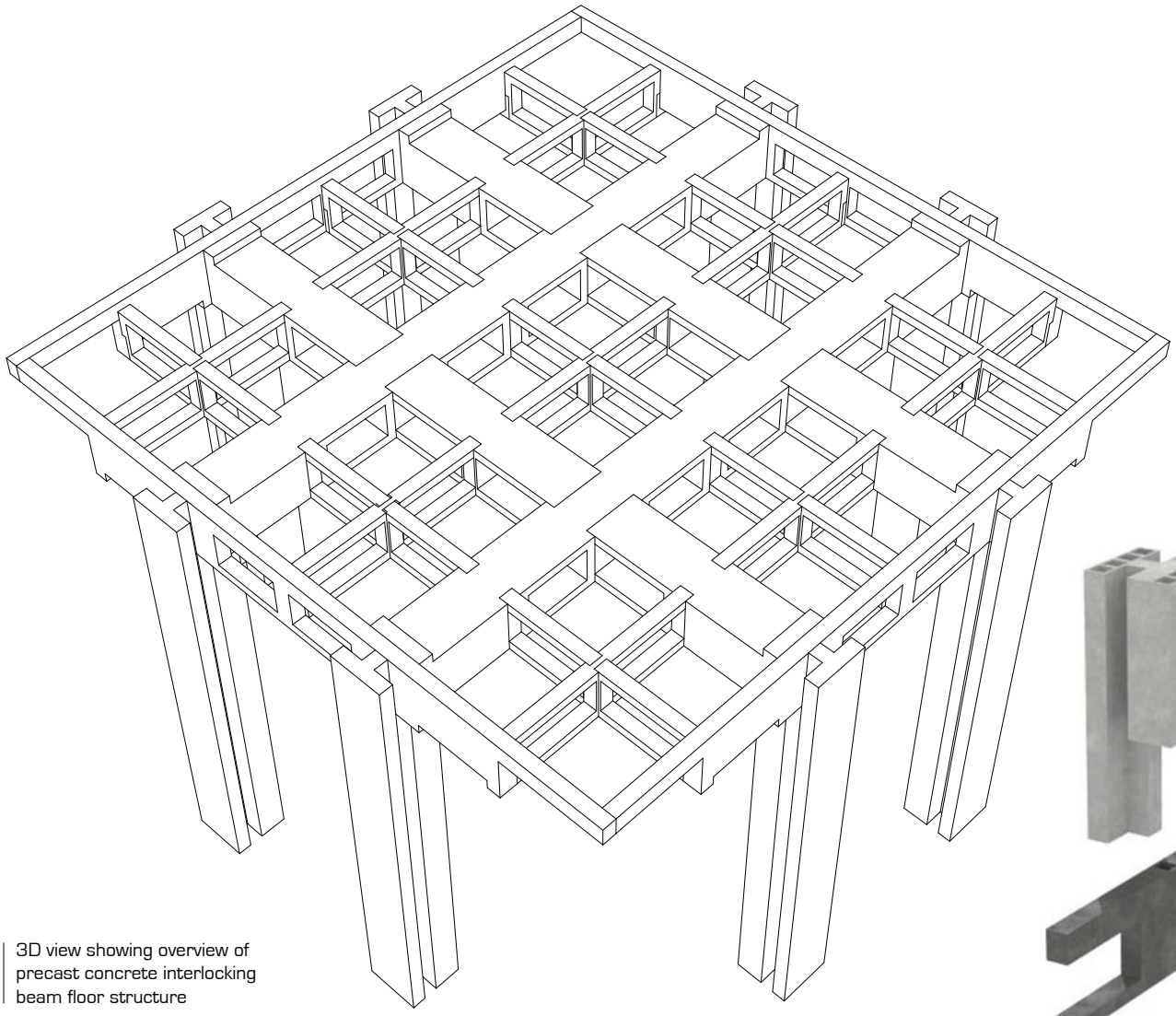
A traditional beam and block floor uses pre-stressed concrete beams to support aggregate concrete blocks. The beams are spaced at various centres depending on the applied loads and internal plan configuration. Beams may need to be staggered or doubled up to support internal walls.

After the blocks have been positioned, a grout consisting of a mixture of sand and cement is brushed across the floor to ensure all joints are evenly filled. The use of expanded polystyrene blocks in the place of concrete blocks eliminates the need for additional sheet insulation within the floor system (a). Prestressed concrete beams are placed at 620mm centres before the polystyrene blocks are fitted between them. A structural concrete topping adds strength to the system and provides a smooth topping to which internal finishes can be applied.

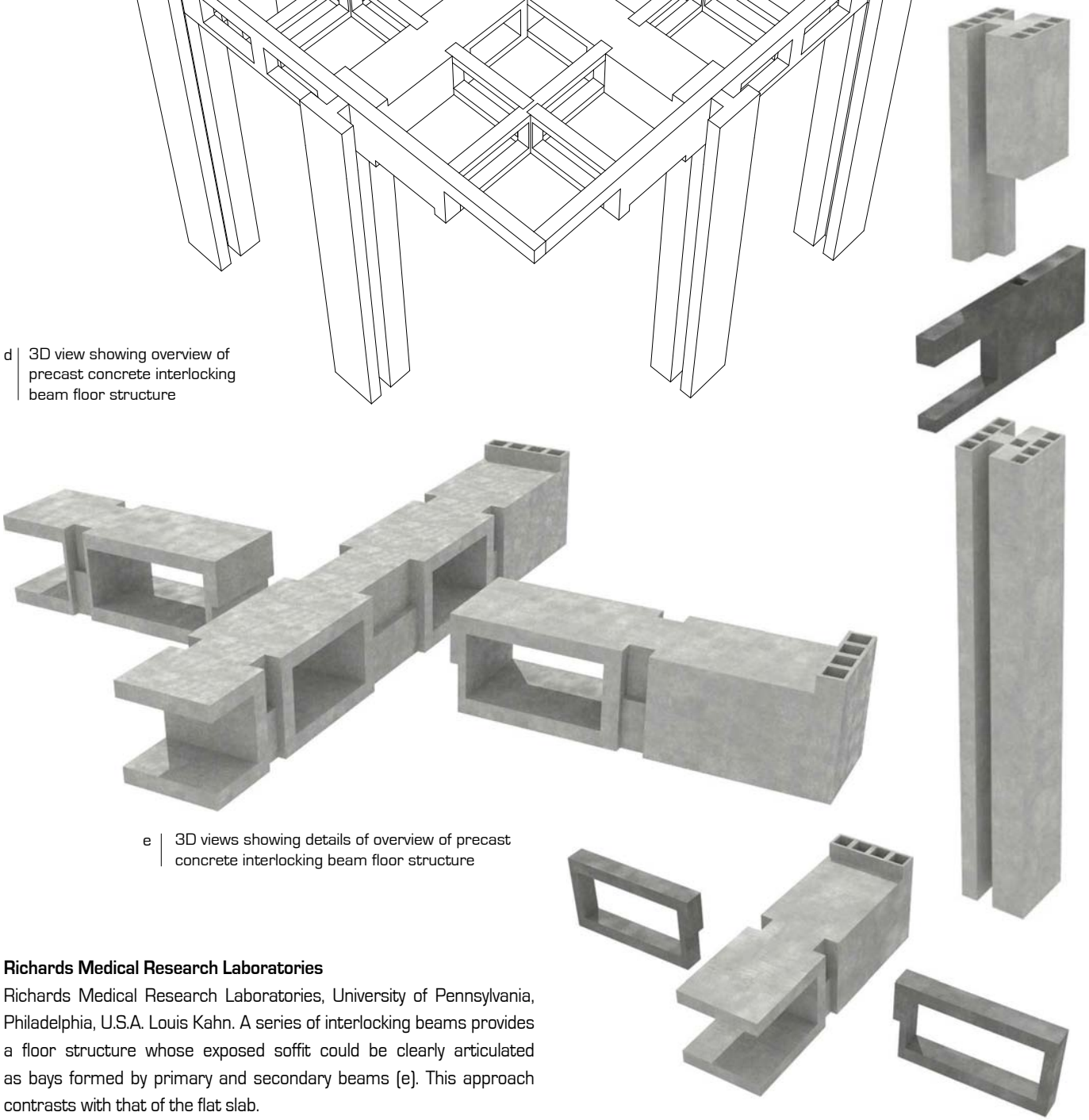
Hollowcore systems

Hollowcore flooring systems use large precast slab elements supported from a structural frame to create large clear-spanning floor systems (b). The hollowcore system can be used with the majority of structural framing systems including masonry, steel and concrete. Masonry bearings need to be in the region of 100mm, whereas 75mm is needed for bearings on steel or concrete.

Hollowcore slabs can span up to 12 metres, and panels are typically tied over supports with a tie reinforcement and structural concrete infill. Holes smaller than 100mm should be drilled on site. Larger holes can be formed during manufacture and may need steel trimming supports.



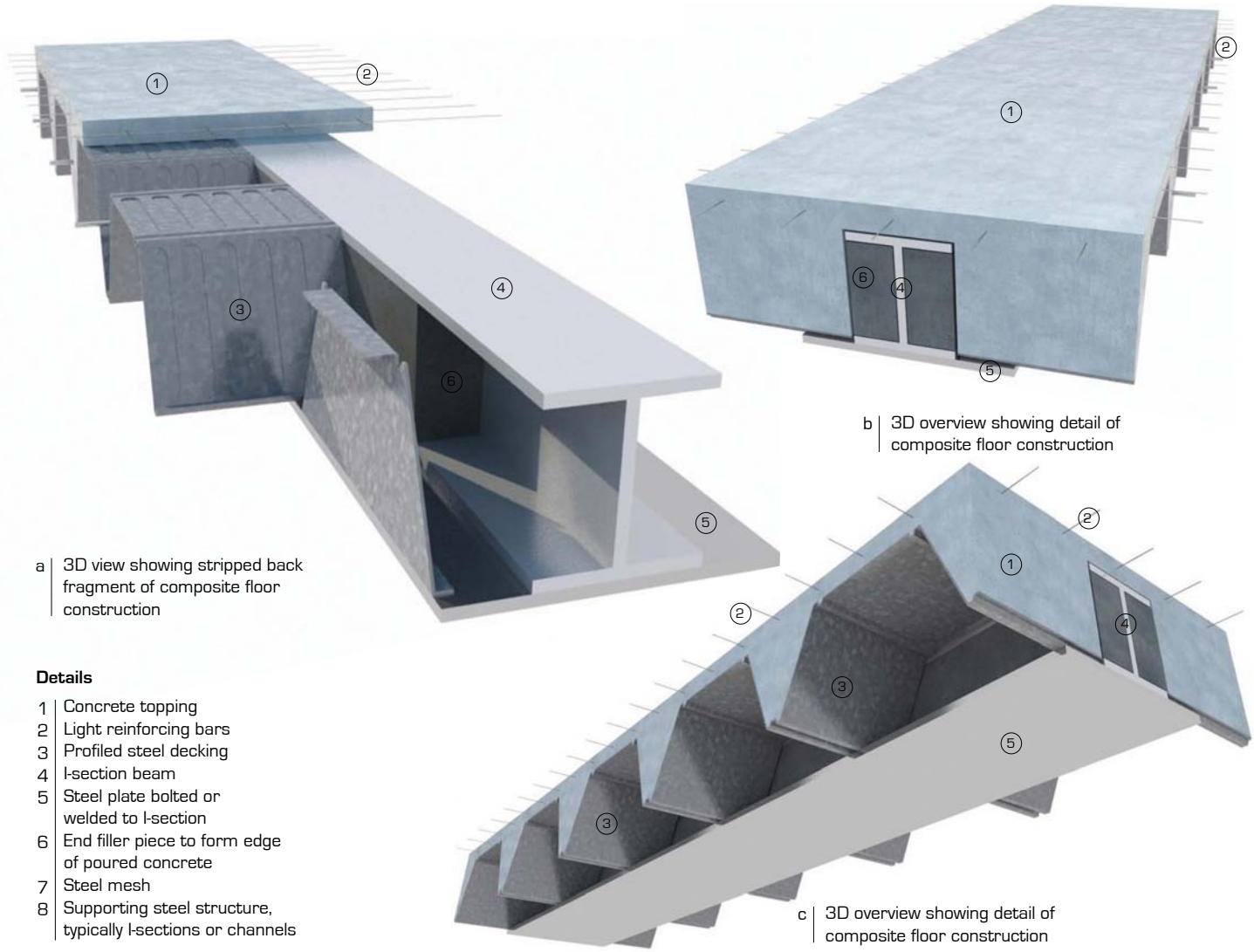
d | 3D view showing overview of precast concrete interlocking beam floor structure



e | 3D views showing details of overview of precast concrete interlocking beam floor structure

Richards Medical Research Laboratories

Richards Medical Research Laboratories, University of Pennsylvania, Philadelphia, U.S.A. Louis Kahn. A series of interlocking beams provides a floor structure whose exposed soffit could be clearly articulated as bays formed by primary and secondary beams (e). This approach contrasts with that of the flat slab.



a | 3D view showing stripped back fragment of composite floor construction

b | 3D overview showing detail of composite floor construction

c | 3D overview showing detail of composite floor construction

Details

1 | Concrete topping
2 | Light reinforcing bars
3 | Profiled steel decking
4 | I-section beam
5 | Steel plate bolted or welded to I-section
6 | End filler piece to form edge of poured concrete
7 | Steel mesh
8 | Supporting steel structure, typically I-sections or channels

Although it is possible to make an all-steel floor, in practice it is structurally inefficient and difficult to provide the necessary fire resistance, impact resistance and sound insulation. In addition, the amount of steelwork fabrication required would make it very expensive. The use of all-steel floors is restricted to steel grating in areas that are not required to provide fire resistance. All-steel floors in sheet and plate are most commonly used in industrial buildings.

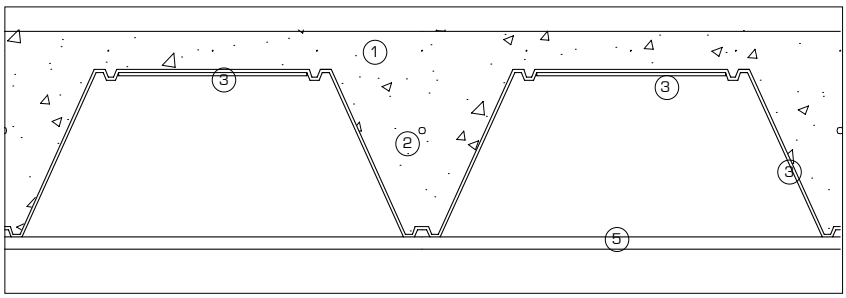
Steel composite floors

An alternative to precast concrete floors is to use a composite deck made from deep profiled steel sheet with concrete poured on top (a). During construction, the profiled decking provides permanent formwork to the concrete. Since the steel deck requires little or no temporary propping when the concrete is cast, construction time is reduced in comparison to other cast-in-place techniques. The steel deck and concrete perform structurally in a composite action where, in a simply supported situation, the concrete is in compression and the steel is in tension (c).The economic use of this type of floor is limited by its span. Over large distances, the supporting beams become very deep, resulting in an increased floor-to-floor height.

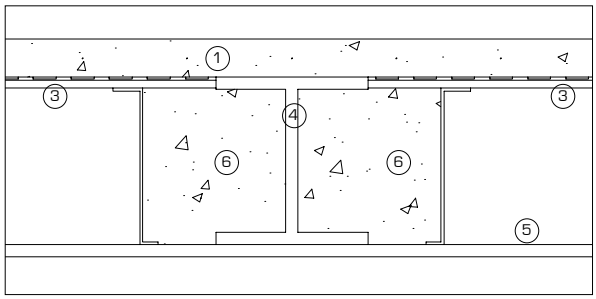
The profiled decking is fixed to the supporting steel beams with shear studs which provide the composite action between slab and beam. The concrete grips the shear studs, transmitting the shear forces through the metal deck to the supporting structure. The bond between the profile and the concrete is improved by the additional ribbing on its surface (h). The profiled sheet can be set either onto the top flange of the beam or onto a plate projecting from the bottom flange (e). The second method reduces the overall structural depth of the floor, with a consequent reduction in floor-to-floor heights; it also stiffens the web of the beam, increasing its performance.

Steel mesh floors

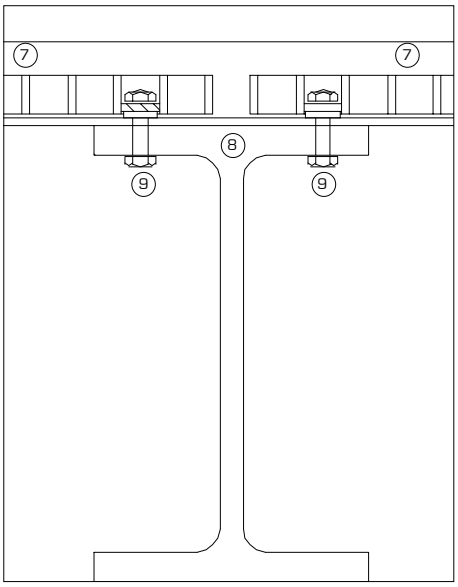
Steel grating is used primarily in industrial buildings and on maintenance access decks in other building types such as offices. It provides a lightweight, economic deck material that allows rainwater to drain off it immediately, making it less susceptible to corrosion when painted or galvanized (j). Steel grating is used to make structural decks by making a span between supports of up to about two metres (6ft), depending on the depth of the grating. The choice of grating depends upon the spacing between the bars and their depth. Steel grating is made by one of two processes: welding or pressing. Lightly loaded small panels are manufactured by welding flats and rods together. Larger panels are made by a process that involves pressing together rows of notched flat bars positioned at right angles to one another to form a grid.



d | Vertical section 1:10. Composite steel floor - section through slab



e | Vertical section 1:10. Composite steel floor - section through steel beam



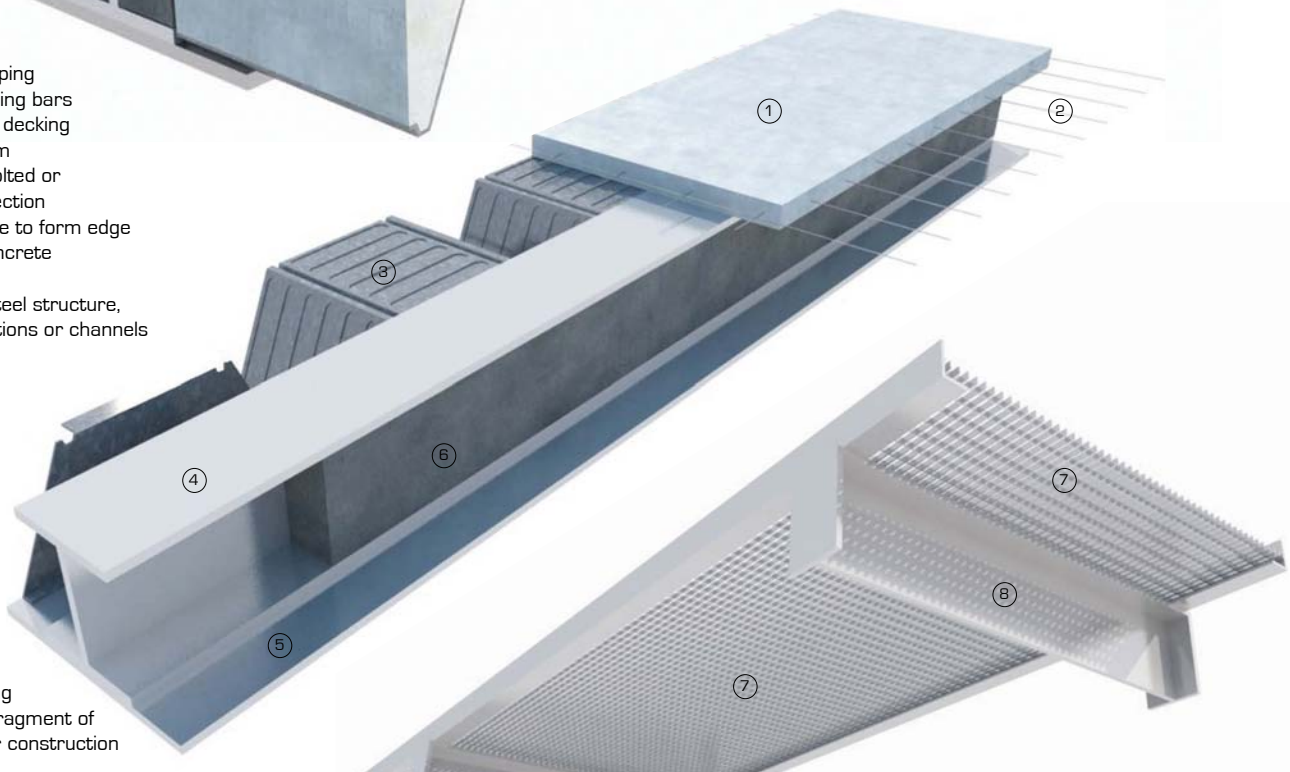
f | Vertical section 1:5. Steel mesh deck and support



g | 3D overview showing detail of composite floor construction

Details

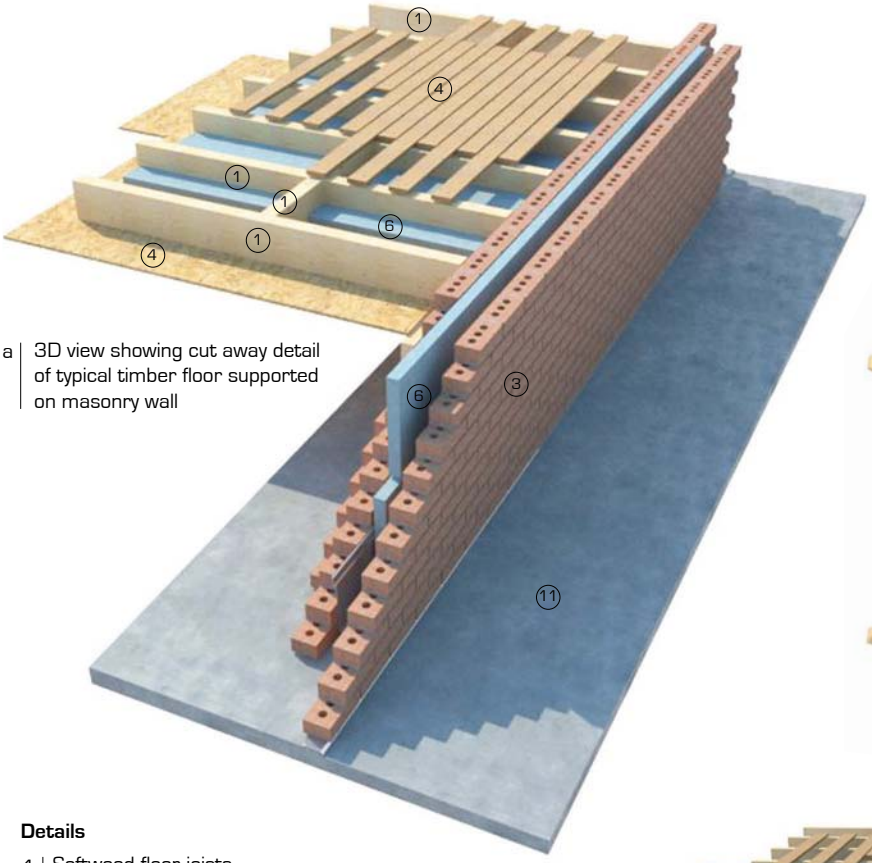
1 | Concrete topping
2 | Light reinforcing bars
3 | Profiled steel decking
4 | I-section beam
5 | Steel plate bolted or welded to I-section
6 | End filler piece to form edge of poured concrete
7 | Steel mesh
8 | Supporting steel structure, typically I-sections or channels



h | 3D view showing stripped back fragment of composite floor construction



j | 3D view showing detail of underside of steel mesh deck



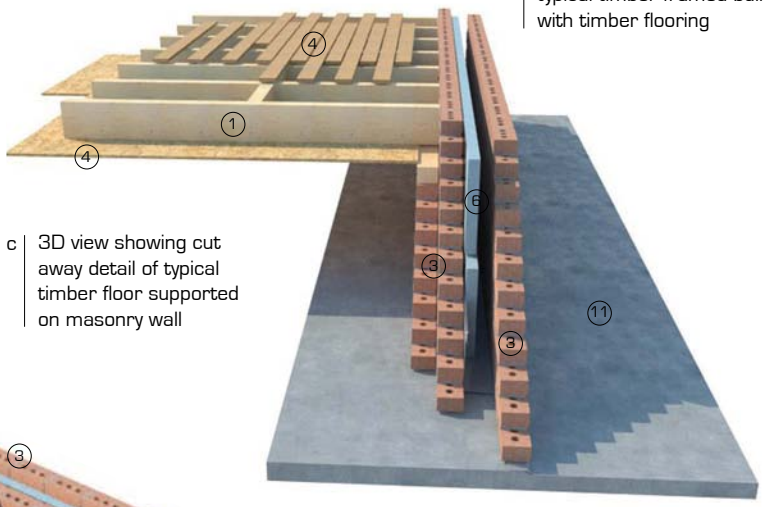
a | 3D view showing cut away detail of typical timber floor supported on masonry wall



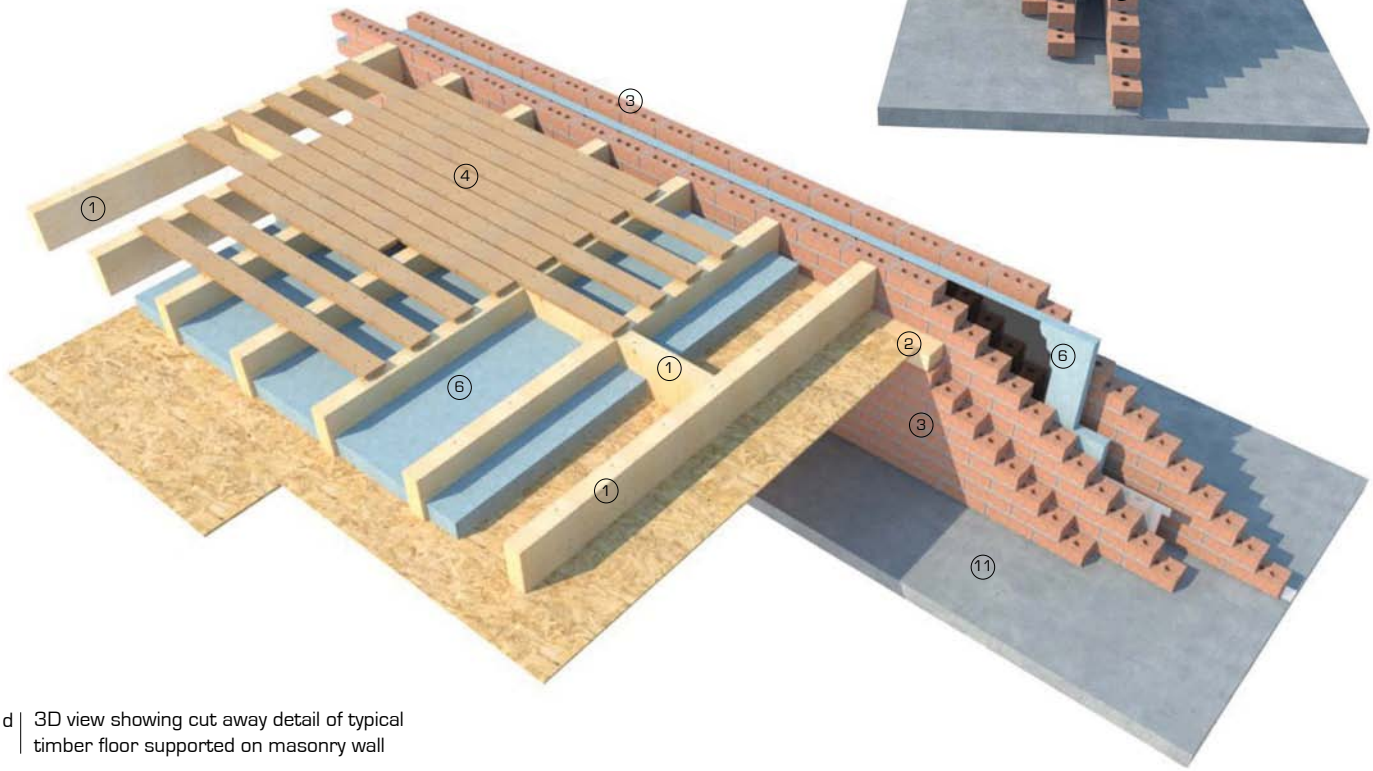
b | 3D view showing cut away of a typical timber framed building with timber flooring

Details

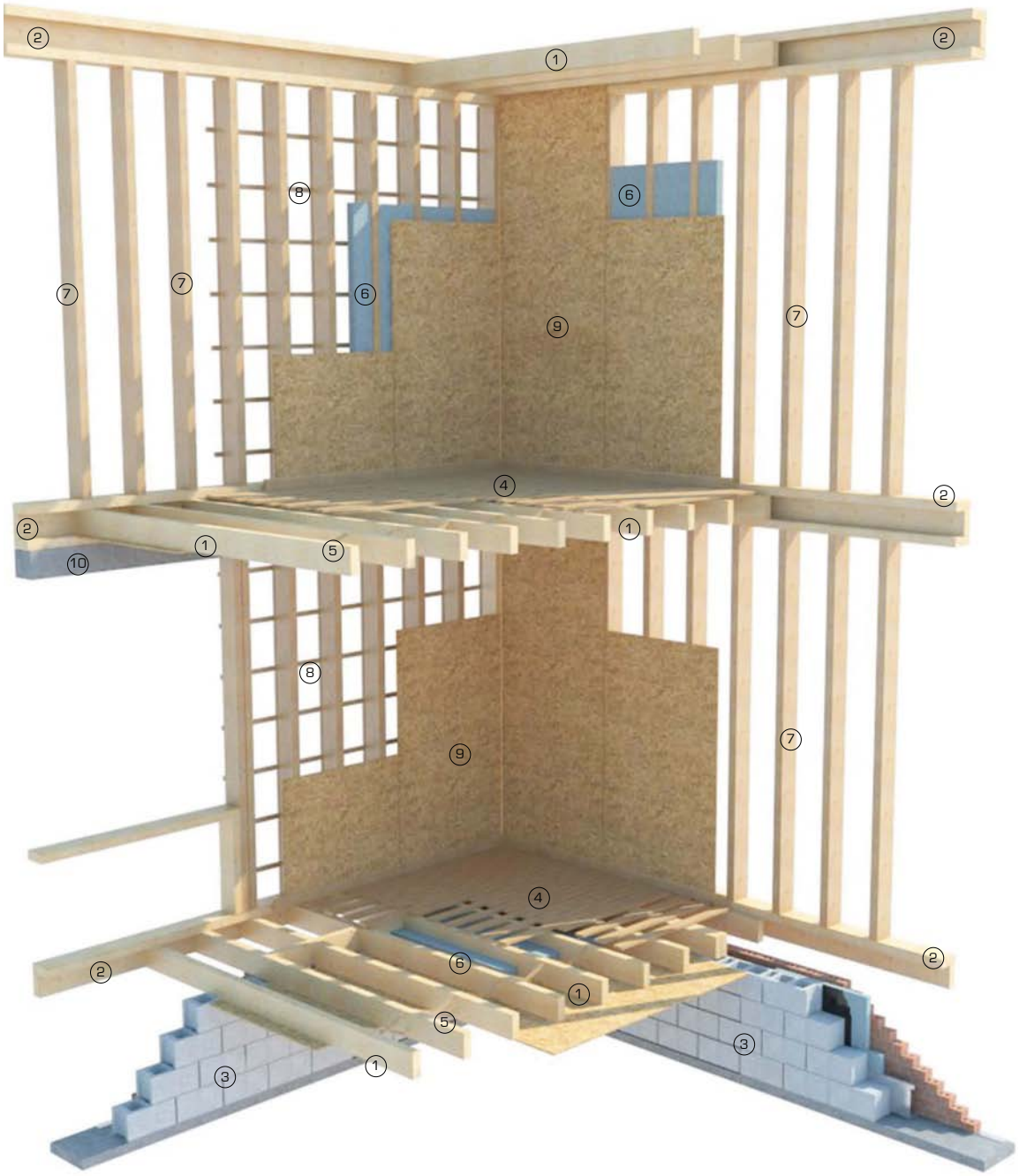
1 | Softwood floor joists
2 | Softwood floor plate
3 | Loadbearing wall
4 | Floor boards or plywood/chipboard
5 | Strutting to stiffen floor construction
6 | Insulation
7 | Timber wall studs
8 | Timber battens
9 | Plywood/chipboard wall boards
10 | Concrete lintel
11 | Concrete foundation



c | 3D view showing cut away detail of typical timber floor supported on masonry wall



d | 3D view showing cut away detail of typical timber floor supported on masonry wall



e | 3D view showing cut away of a typical timber framed building with timber flooring

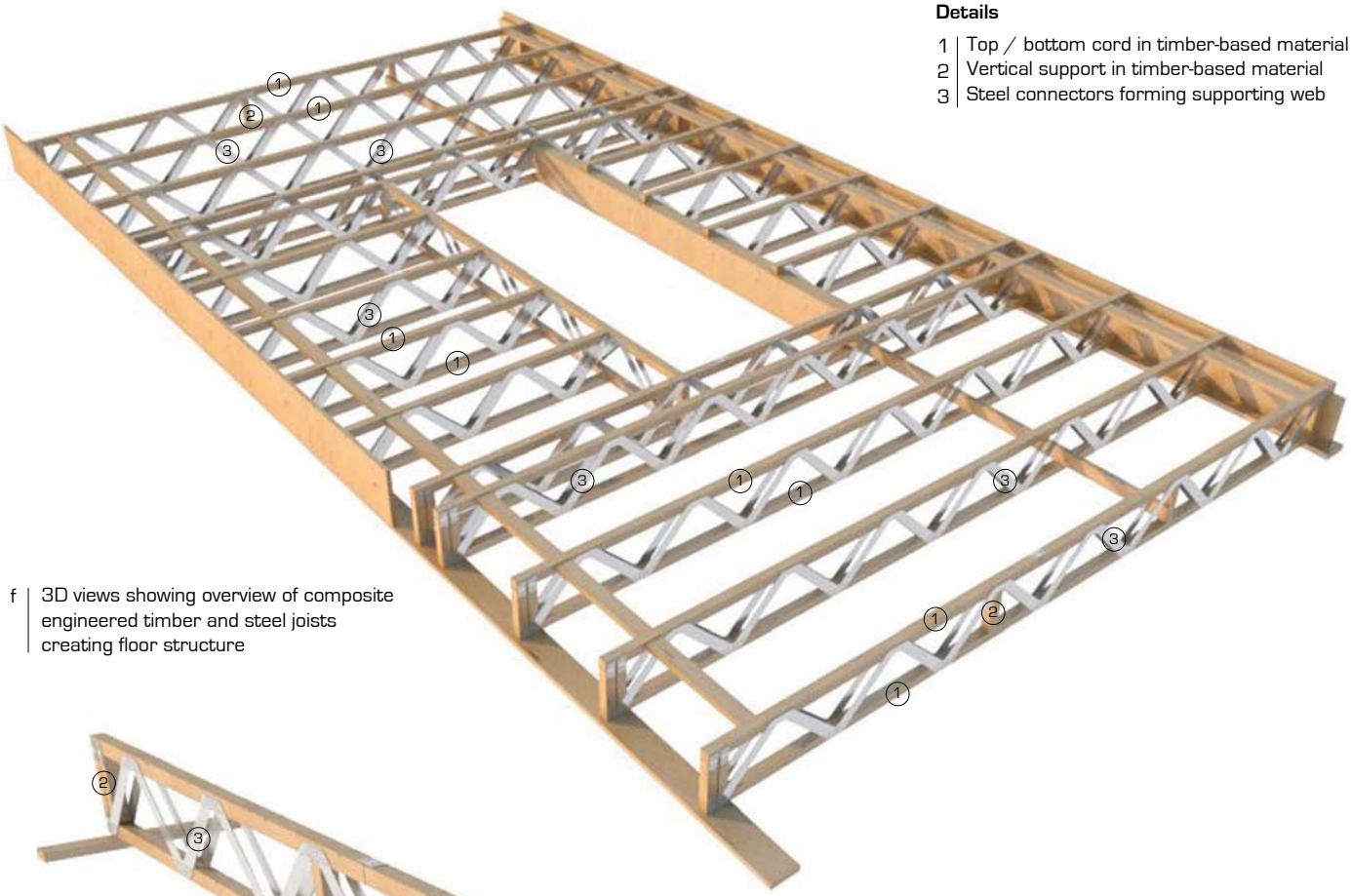
Timber floors are used typically with either loadbearing masonry walls, usually in cavity construction (a), or as part of a timber-framed structure (b). A typical floor for residential use, spanning up to around 3500mm, might consist of softwood joists supported at each end by galvanized metal shoes or timber plates. Timber struts provide lateral stability and rigidity. Softwood boards are typically used as decking which is either butt-jointed or tongue-and-grooved (d). Alternatively, thicker boards are used, which have the advantage of bracing the floor structure horizontally. Plywood sheet provides superior stiffening action but its use makes access to the void beneath more difficult, particularly if the floor void is used for the passage of services (e). Additional stiffness is provided by herring-bone strutting set into the depth of the floor joists at centres to suit the span and design of the floor.

A recent development has been the introduction of 'engineered joists' in timber as an alternative to cut timber sections. They make use of a combination of cut timber sections and timber composites that combine wood or wood fibre with adhesives. The main composite materials used in the joists are mainly LVL (laminated veneer lumber) or OSB (oriented strand board).

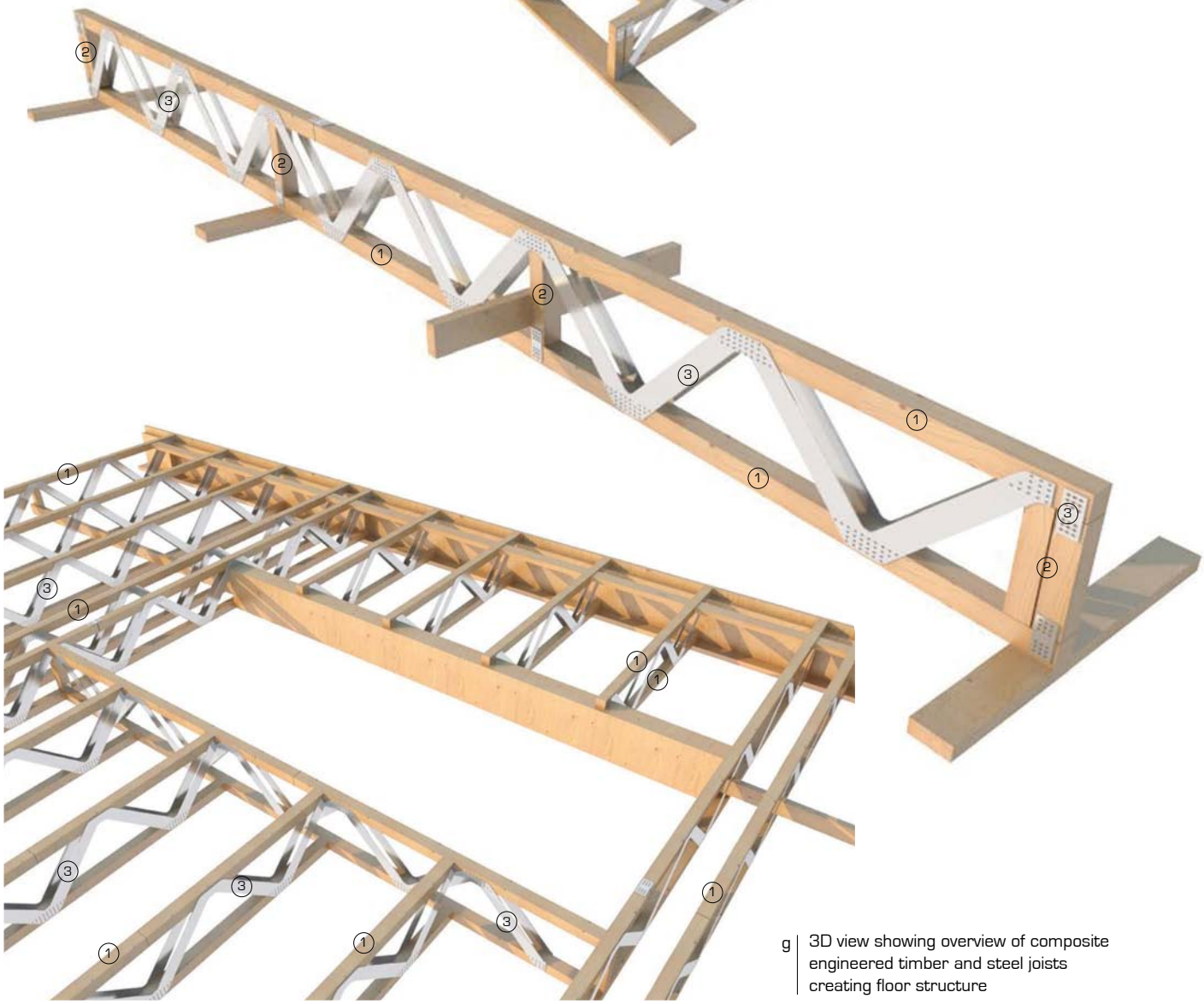
Engineered joists are of two generic types, those which resemble the form of a steel I-beam and those which resemble open web trusses (f). The solid joist I-beam type is made from top and bottom chords in timber which are connected by a solid web made in wood-based products such as LVL or OSB. The open web types often have a series of V-shaped and triangulated connectors forming the equivalent of truss members with narrow timber flanges top and bottom connected by a vertically

Details

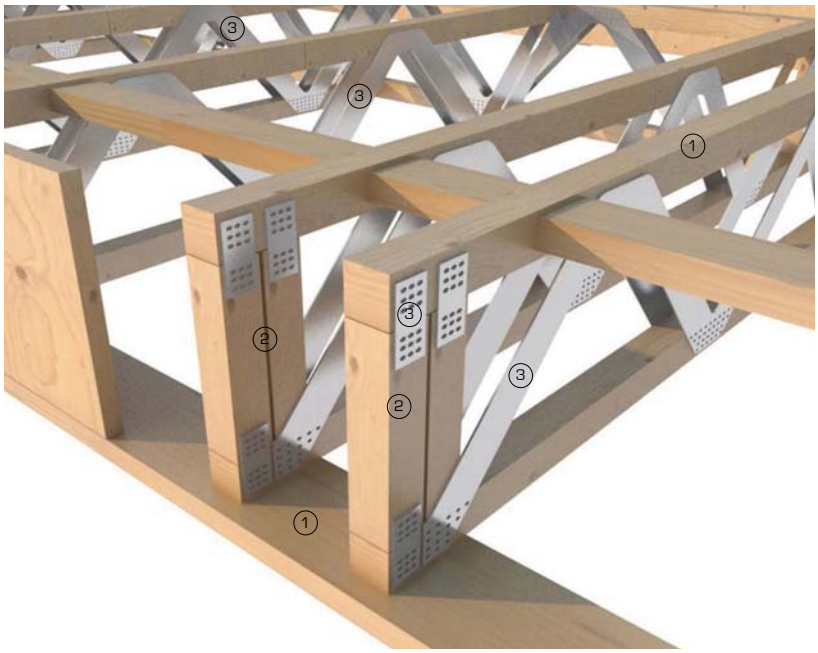
1 | Top / bottom cord in timber-based material
2 | Vertical support in timber-based material
3 | Steel connectors forming supporting web



f | 3D views showing overview of composite engineered timber and steel joists creating floor structure

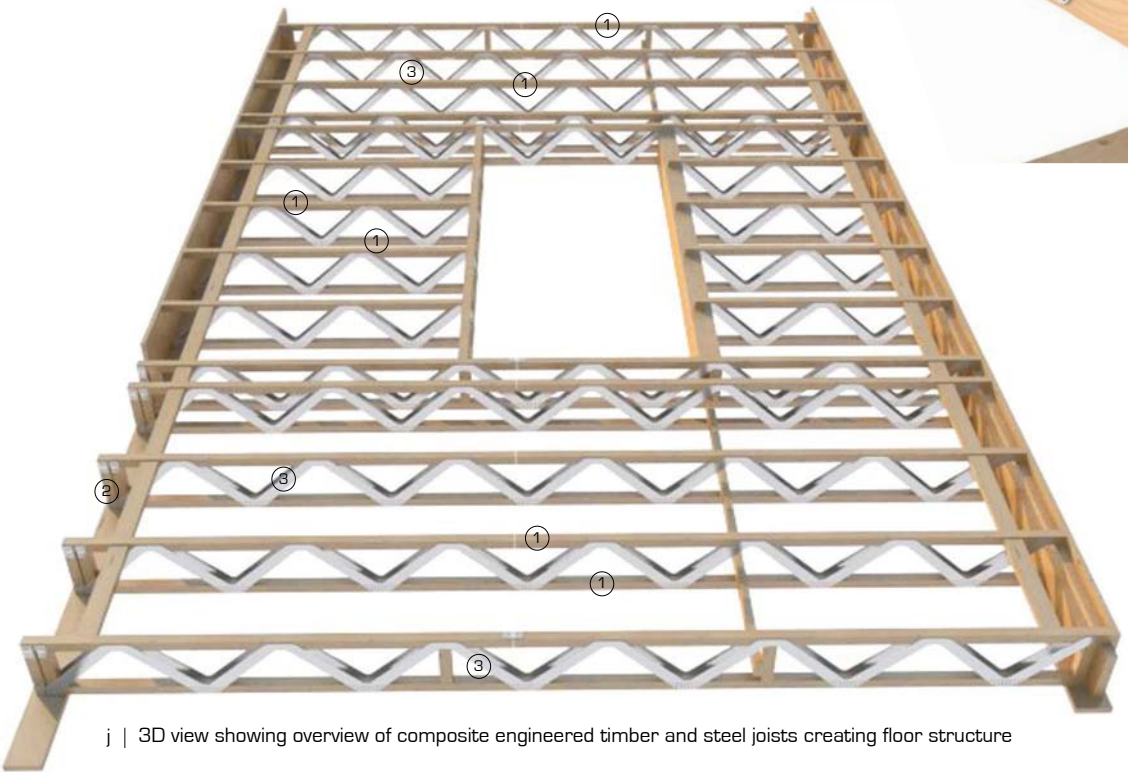


g | 3D view showing overview of composite engineered timber and steel joists creating floor structure



h | 3D view showing detail of composite engineered timber and steel joists creating floor structure

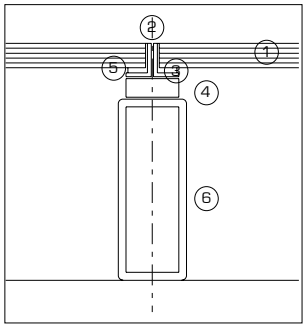




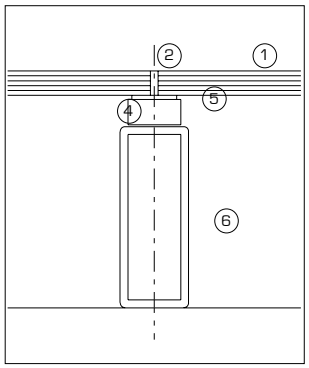
j | 3D view showing overview of composite engineered timber and steel joists creating floor structure

set timber-based board material to form a structural web (g). These V-shaped connectors are made as proprietary products with fixing systems to suit a factory-based manufacturing process rather than for assembly in a small workshop. The idea of these engineered joists has been taken further by joining them into prefabricated floor panels, also called 'cassettes'. These are made in standard modules to suit reduced construction time on site, and where there is sufficient repetition to suit prefabrication methods. Panels arrive on site with a timber deck and soffit lining attached, as well as thermal insulation when used as panels for roof decks.

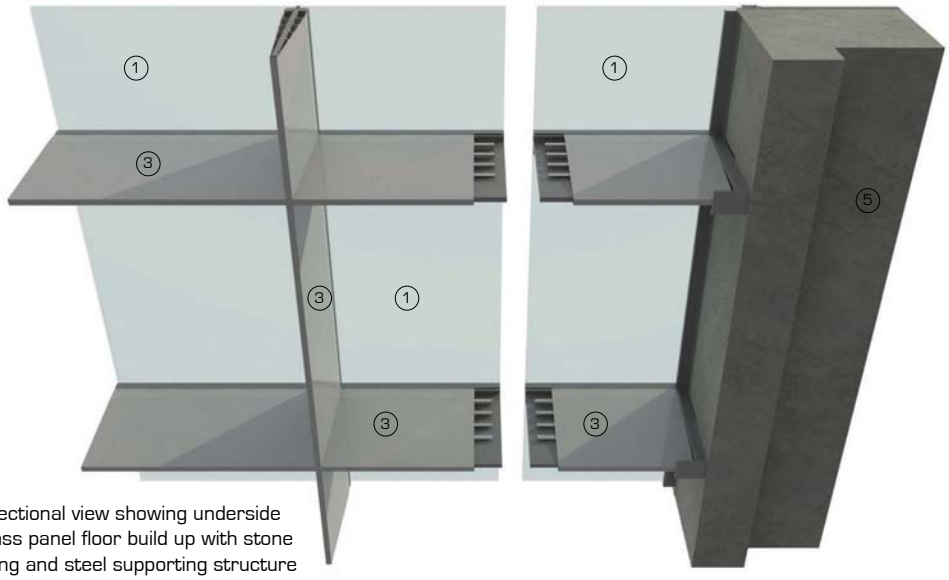
An advantage of engineered joists is their ability to form longer spans than sawn timber sections, with spans of up to 12 – 14 metres depending on the proprietary system used. The open web joists also have the advantage of being able to pass service ducts and cables through the depth of the floor construction, which is an advantage in mechanically ventilated buildings. These new forms of floor construction are finding a use in commercial buildings as well as their use in the more obvious application in domestic construction. Engineered joists also have the advantage of using less material than an equivalent solid timber joist (j), which is also typically heavier than the engineered type. The lower moisture content of the materials makes it less susceptible to moisture movement and reduces the risk of squeaking noises associated with timber floors.



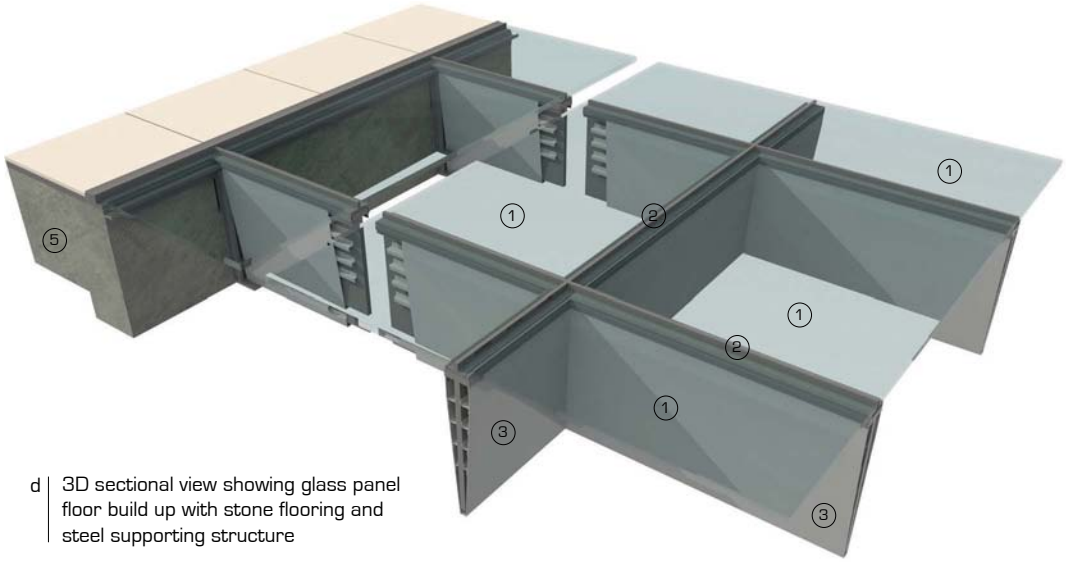
a | Vertical section. Alternative fixing method



c | Vertical section. Alternative fixing method



b | 3D sectional view showing underside of glass panel floor build up with stone flooring and steel supporting structure



d | 3D sectional view showing glass panel floor build up with stone flooring and steel supporting structure

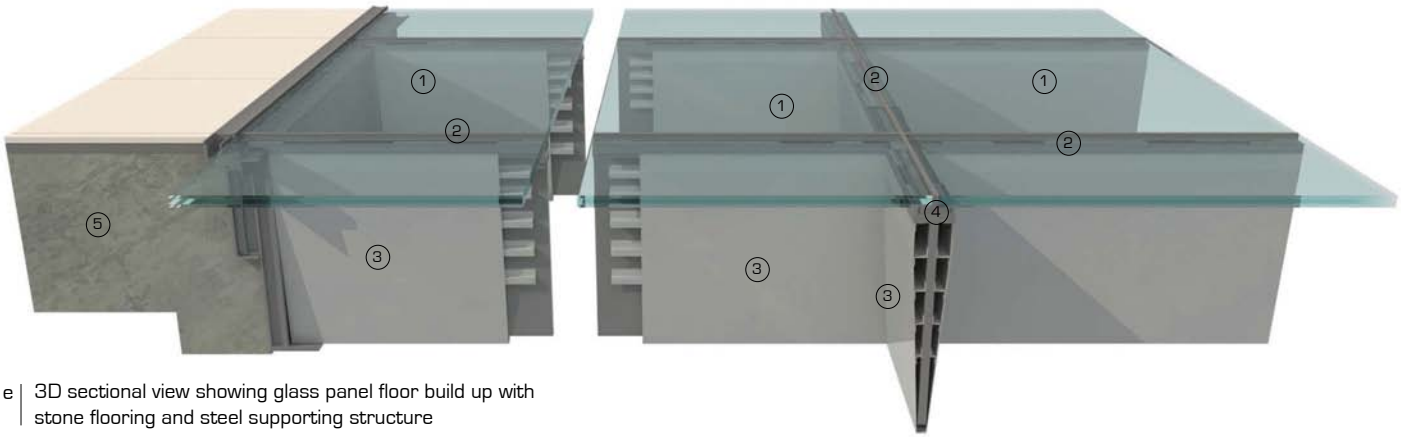
Details

1 | Laminated glass sheet, single-glazed or outer layer of double-glazed unit
2 | Silicone seal
3 | Stainless steel angle
4 | Spacer
5 | Supporting structure

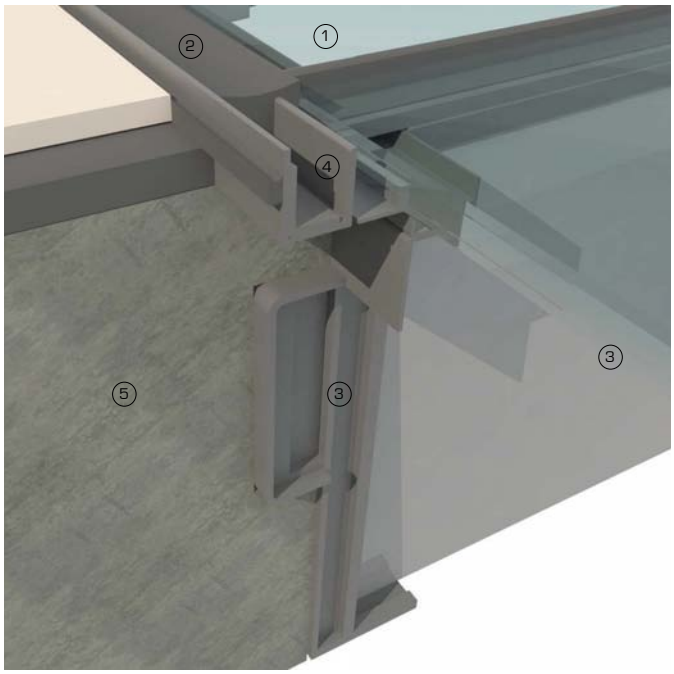
Glass floors are used to enhance naturally lit spaces by allowing light to pass through to spaces below. The primary material used is typically either glass sheet or glass blocks. Where glass sheet is used, laminated glass is set into a steel frame, giving it as much lightness and transparency as possible (b). Where glass blocks are used, they are set into a supporting frame of steel or concrete with reinforcing bars (j). Each block is individually supported, which has the effect of limiting the effects of lightness and transparency (n).

Economic spans for glass sheet are currently in widths of one metre, but panel sizes of 1200mm by 2600mm can be achieved at significantly higher cost. The glass is usually bedded within the frame on a flexible, rubber-based material such as neoprene or EPDM, or alternatively bonded to the frame with silicone (c). This allows the supporting structure to move independently of the glass, as well as allowing each to move with thermal expansion. Junctions with the frame are closed with a silicone sealant. Sandblasting grooves into the glass can provide transparency and slip resistance. In addition, a translucent laminated interlayer can be used to control views through the glass. Sheet glass floor panels are currently restricted to relatively low loadings. Supporting structures can be in either steel (e) or reinforced concrete. If the supporting structure is constructed to the correct height and fall, then the laminated glass sheets if used externally can be bonded directly to it rather than setting them into a steel sub-frame. Steel frames to support the glass use T-sections in order to provide a bearing for the glass at the top, but avoid a bottom flange to the supporting beam that would make the frame appear wider (g).

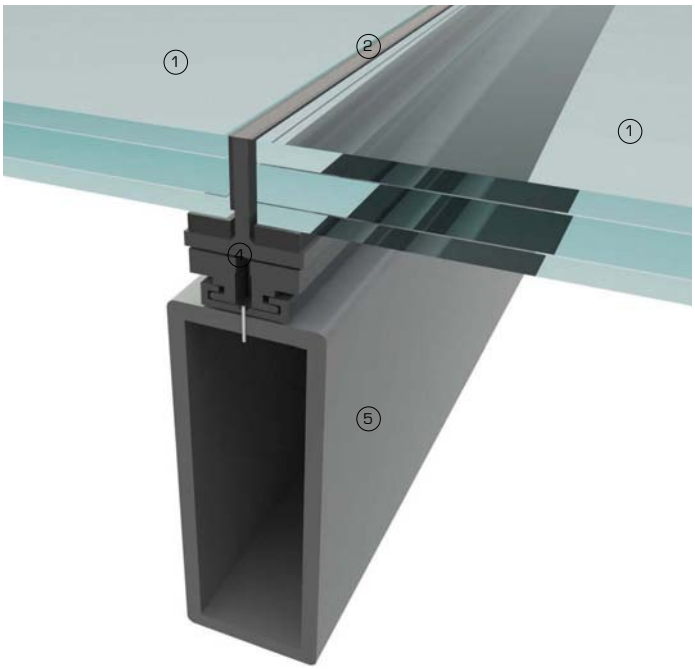
Glass blocks with textured or ribbed surfaces are often used as they have good slip resistance. This type of construction has a high resistance to shock, and is capable of very high loadings. Because each glass block requires support, the number of junctions in the frame becomes very high (m). Since joints in materials are usually expensive to form in relation to the cost of components, junctions are kept as simple as possible. For this reason, frames are often made as castings, where the material is poured in place to form a frame. Cast iron, cast steel and reinforced concrete are commonly used (f). An advantage of concrete is that it can be cast directly against glass blocks which become a permanent formwork. Reinforcing bars are laid in a grid in the joints between the blocks.



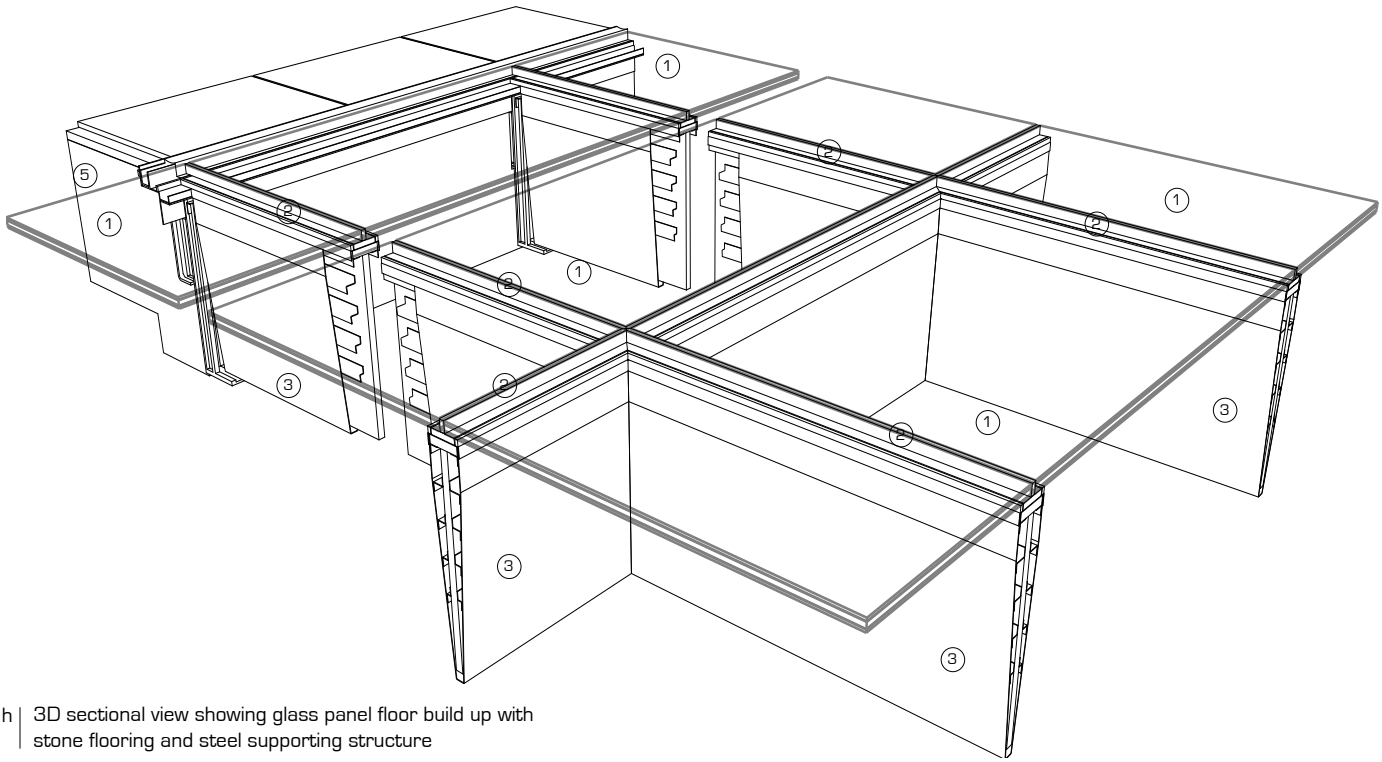
e | 3D sectional view showing glass panel floor build up with stone flooring and steel supporting structure



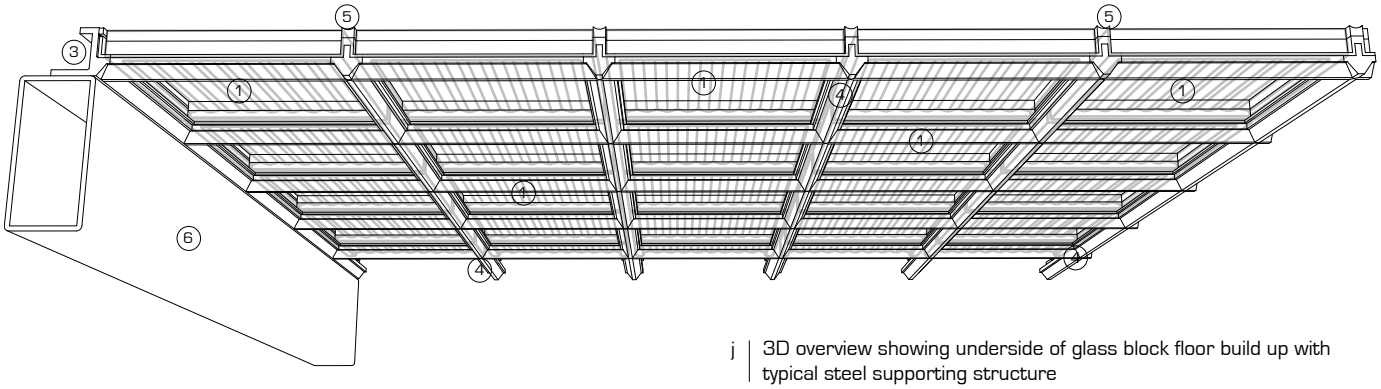
f | 3D detail view showing glass panel floor build up with stone flooring and steel supporting structure



g | 3D detail view showing glass fixing method for glass floor



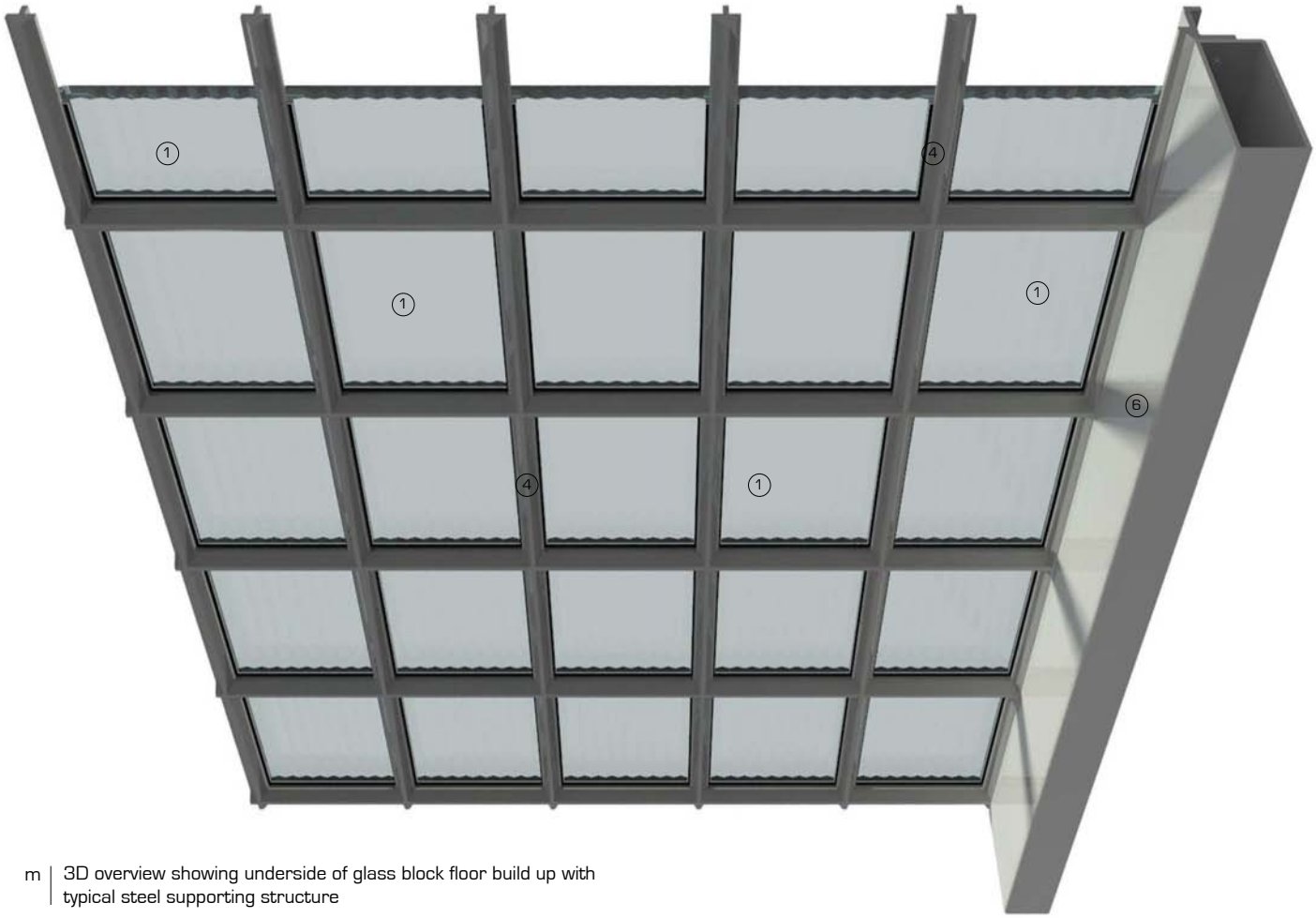
h | 3D sectional view showing glass panel floor build up with stone flooring and steel supporting structure



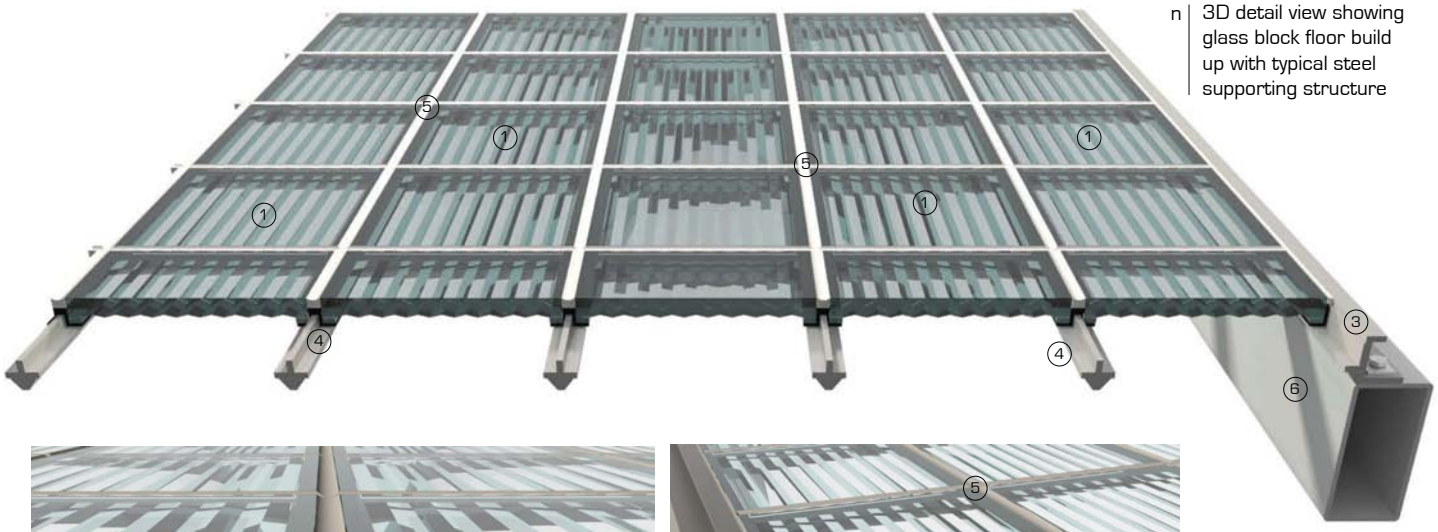
j | 3D overview showing underside of glass block floor build up with typical steel supporting structure



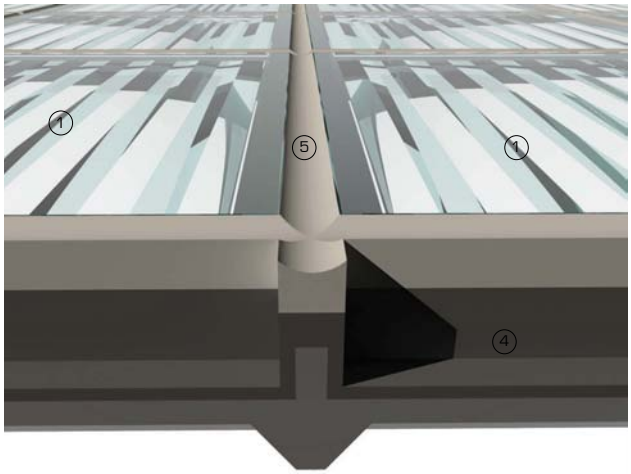
k | 3D detail view showing glass block floor build up with typical steel supporting structure



m | 3D overview showing underside of glass block floor build up with typical steel supporting structure



n | 3D detail view showing glass block floor build up with typical steel supporting structure

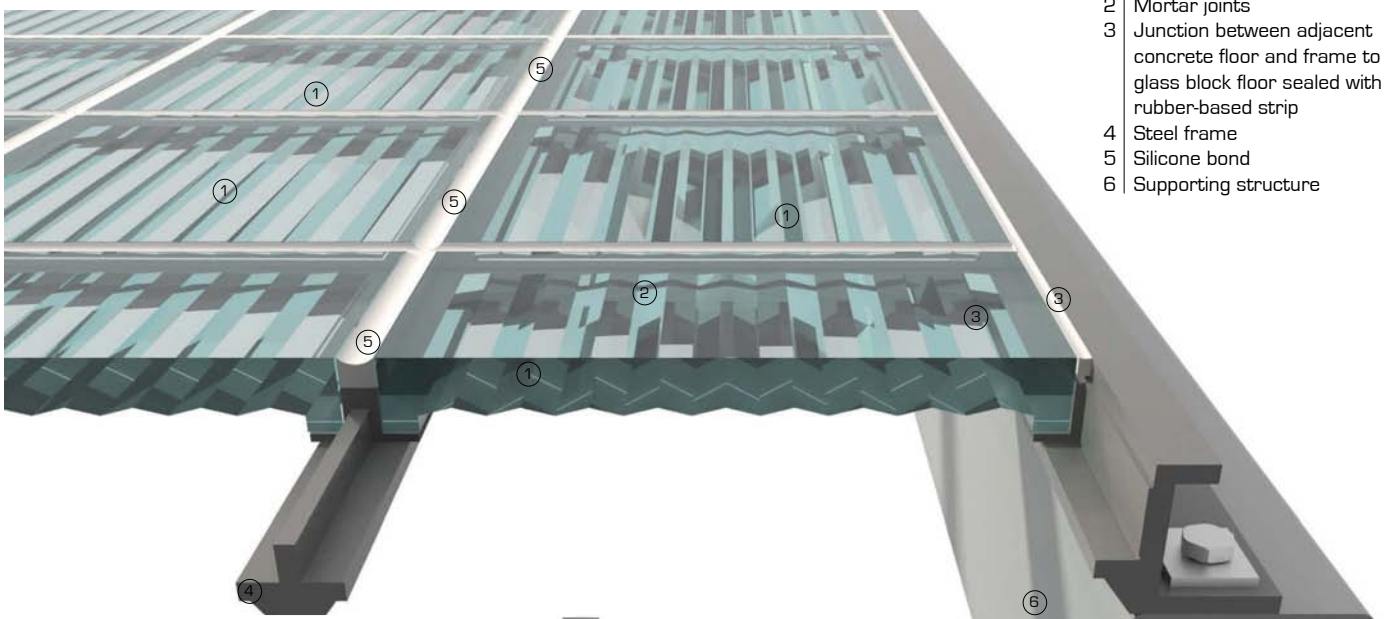




p | 3D detail views showing glass block floor build up with typical steel supporting structure

Details

1 | Glass blocks
2 | Mortar joints
3 | Junction between adjacent concrete floor and frame to glass block floor sealed with rubber-based strip
4 | Steel frame
5 | Silicone bond
6 | Supporting structure

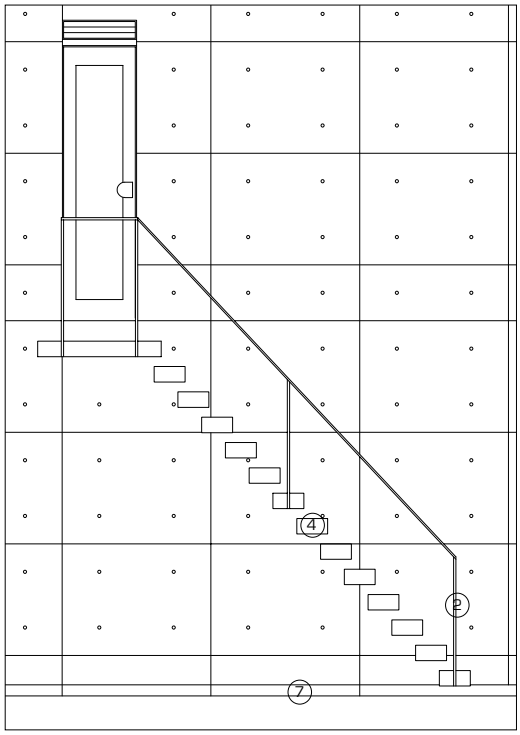




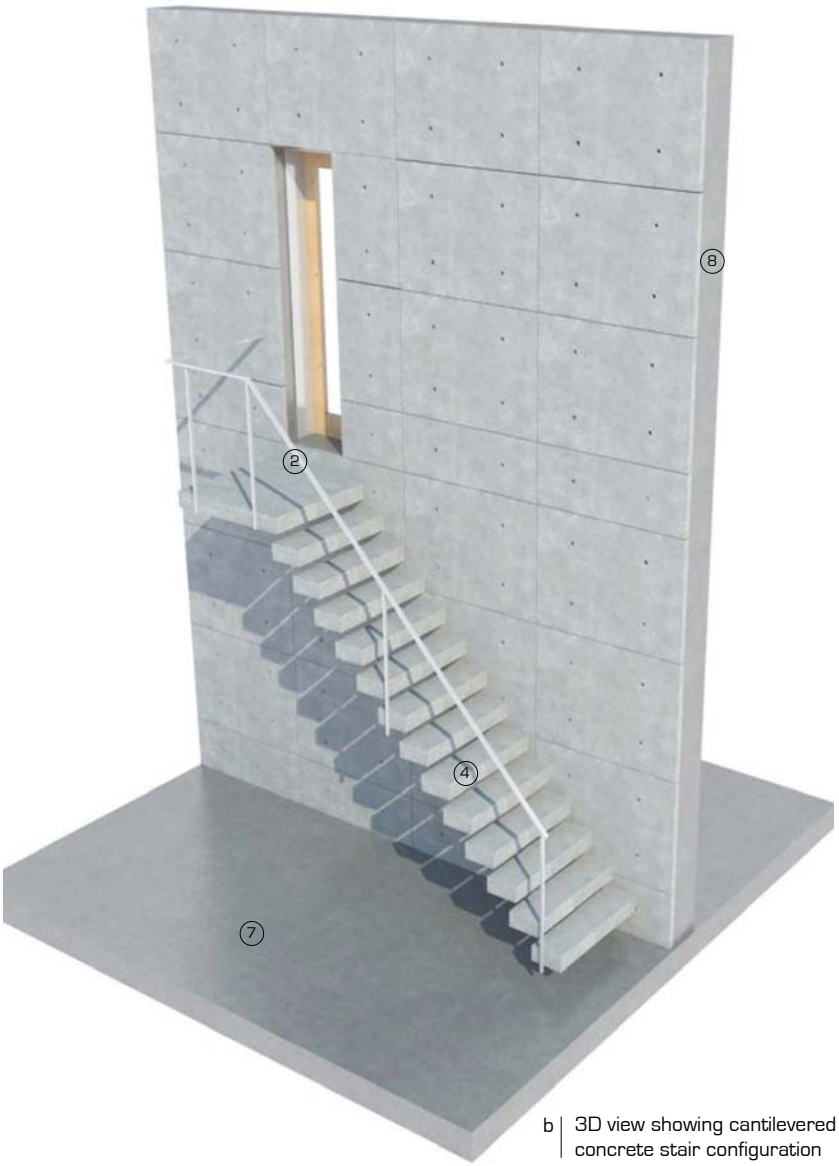
q | 3D detail views showing glass block floor build up with typical steel supporting structure

Details

1 | Guarding
2 | Handrail
3 | Staircase
4 | Treads projecting from concrete wall
5 | Cast-in-place staircase
6 | Precast staircase
7 | Floor slab
8 | Loadbearing concrete wall



a | Part elevation of concrete cantilever stair



b | 3D view showing cantilevered concrete stair configuration

Concrete stairs have the advantage of good fire resistance combined with the ability to absorb impact sound. Concrete can be used in conjunction with both steel and concrete structures (b). Stairs can be of cast-in-place or precast types, but the type used must be compatible with the overall type of construction used.

In-situ cast concrete

In-situ cast concrete stairs are made by setting steel reinforcement into reusable steel or timber formwork. A screed is added afterwards to provide a smoother and more exacting finish to the exposed surfaces. The screed can be used as a self-finish, when used internally, but the dusty nature of concrete walking surfaces often leads to the use of floor paint, polishing the concrete, or inserting treads in another material such as timber. Where the screed is used as a self-finish, anti-slip nosings are added. They can be recessed or surface fixed. Where the stair is exposed to view, the formwork into which the concrete is cast has to be designed and built carefully to reflect the quality of the finish demanded.

The junction at stair landings is often designed to create a single arris line across the soffit (f). This allows handrails on different flights to be properly aligned, achieved by offsetting flights by a distance equal to one tread width.

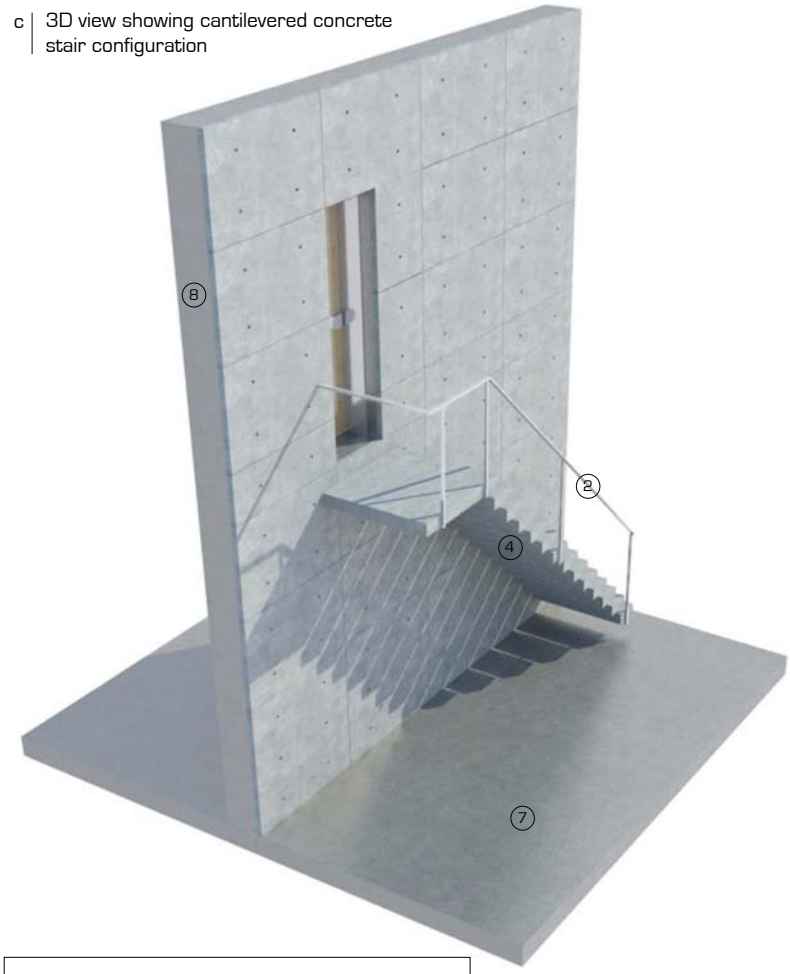
Precast concrete

Precast stairs are manufactured either as complete flights, sometimes with a landing attached to one end (d), or as individual treads which are fixed together on site (g). Precast stairs are used primarily where there is a large number of stairs of the same design used in a single project, and where a shorter construction time is an important factor. These stairs also assist in the construction process itself by providing convenient access. This is particularly important if the design of the stair is complex, where the cost of precast staircases can be considerably more than the cast-in-place type.

Guardrails

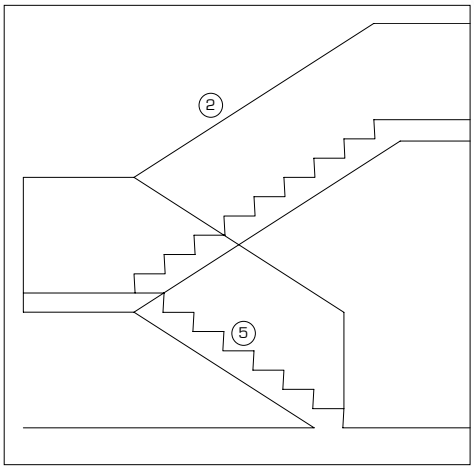
Guardrails on concrete stairs are most often pre-fabricated in parts, typically in steel, and then grouted into slots or holes drilled into the sides or treads of the stair (e). Alternatively, they can be fixed to the side of the stair with steel brackets. Handrails in metal are either integral with the guardrails or fixed to an adjacent wall.

c | 3D view showing cantilevered concrete stair configuration





d | 3D view showing precast concrete stair

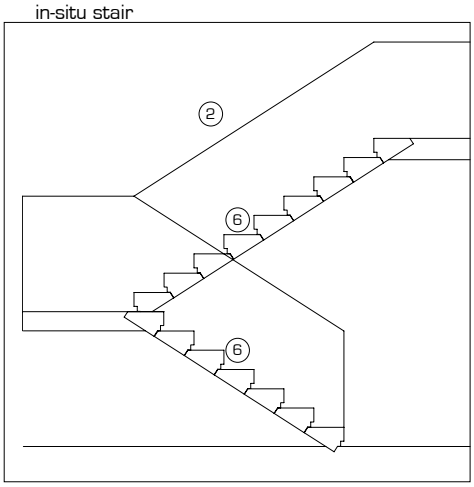


f | Elevation showing cast in-situ stair

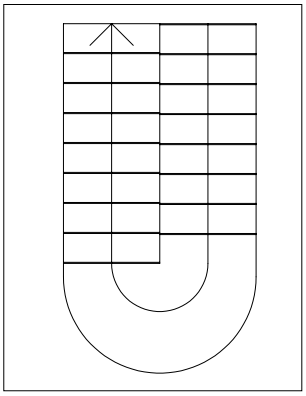


e | 3D views showing cantilevered concrete stair configuration





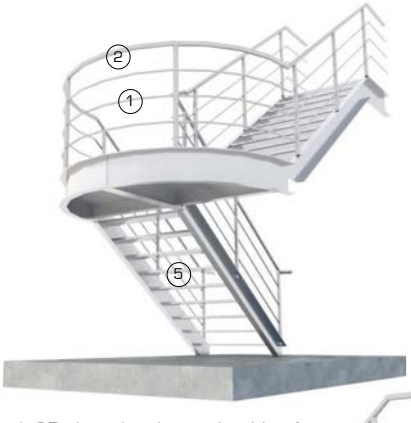
g | Elevation showing precast stair with individually cast treads



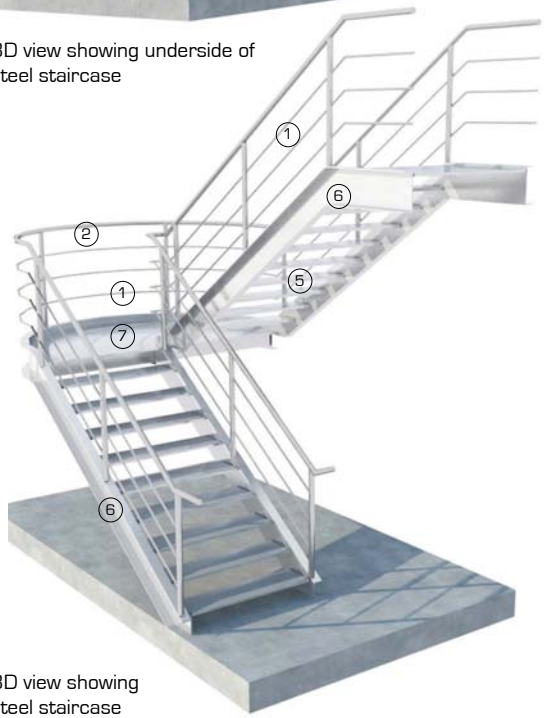
h | Plan view of stair

Details

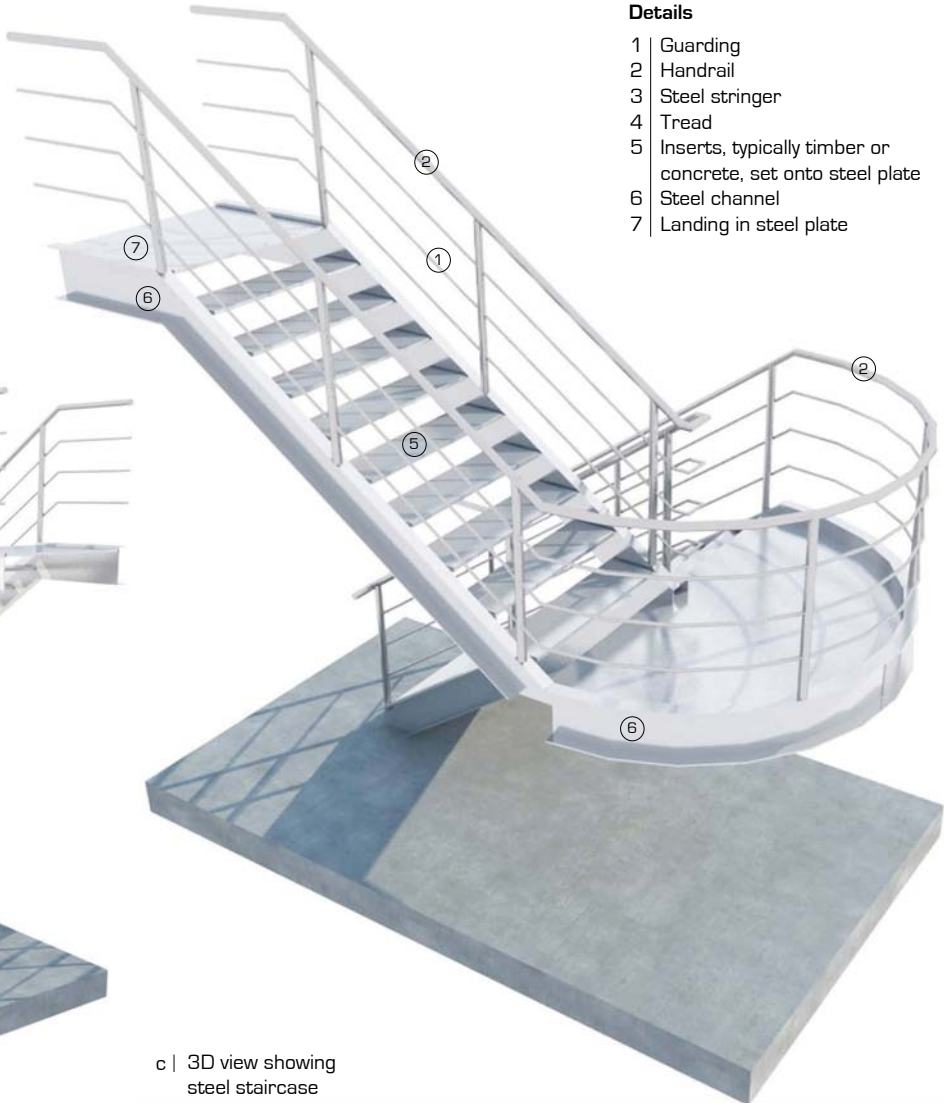
1 | Guarding
2 | Handrail
3 | Steel stringer
4 | Tread
5 | Inserts, typically timber or concrete, set onto steel plate
6 | Steel channel
7 | Landing in steel plate



a | 3D view showing underside of steel staircase



b | 3D view showing steel staircase



c | 3D view showing steel staircase

Steel stairs have the advantage of being lighter in weight, allowing them to be prefabricated and delivered to site as completed sections of flights and landings (a). They can be lifted into place more easily than concrete stairs, but lack the high fire resistance associated with that material. There are two generic types, with either treads as plates set between stringers (e), or with folded sheet set between stringers (d). In addition, spiral stairs in cast iron and steel are available as proprietary products in a range of standard sizes. These comprise a central post to which radiating treads are fixed.

Flat plate type

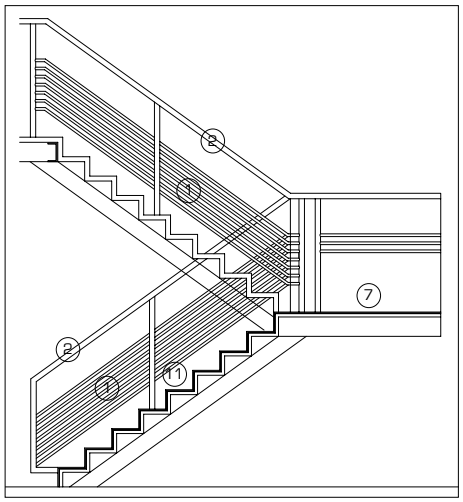
Stairs with plate set between stringers are made by bolting or welding treads formed from either smooth- or checker-plate. Stringers, which form the beams at the sides of the stair, are usually made from steel channel which provides a straight vertical face to which the treads can be fixed (b). The position of the treads within the depth of the stringer is critical in order that stringers can be aligned neatly where they intersect at landings (c). Bolted or welded connections are made to be sufficiently stiff so that the stair does not rattle or experience any significant movement while in use. Depending on their width, treads may need to have either their edges folded to provide stiffness which can accommodate an additional finish such as a decorative timber tread, or formed as a composite steel tray with a concrete fill. An alternative method of stiffening treads is to weld a vertical steel plate to their underside to form a T-section.

Folded sheet type

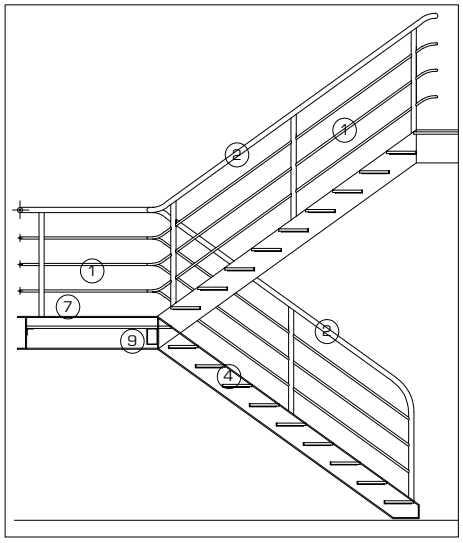
Stairs can be formed by folding a steel sheet and supporting it, either on stringers set at the sides or by a single central stringer set beneath the plate (j). The inherent rigidity of the folded sheet allows a wide range of economic solutions for the arrangement of the stringers. As with the flat plate type, the assembly can be either bolted or welded, and decorative inserts in other materials such as timber can be added. Both stair types can be finished in a variety of coatings from galvanizing to painting to polyester powder coating. Softer coatings such as PVDF are rarely used due to their poorer wearing qualities. In addition to visual considerations, the choice of finish is determined by the required degree of durability and appearance.

Guardrails

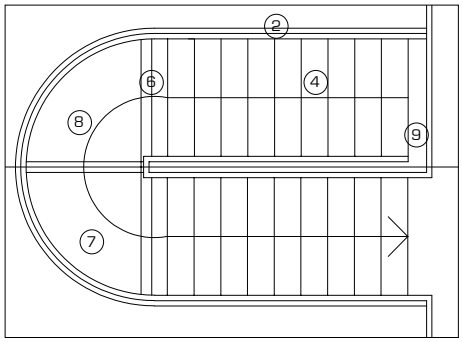
Steel guardrails are prefabricated but are not often fixed to staircases before delivery to site in order to make the stair both easier to install and to make it easier to align the guardrails with adjacent walkways or enclosing walls (k). Guardrails are usually finished before delivery to site. If a paint finish is used, the guardrail will at least be prepared and primed before arriving on site where finish coats can be applied after its installation.



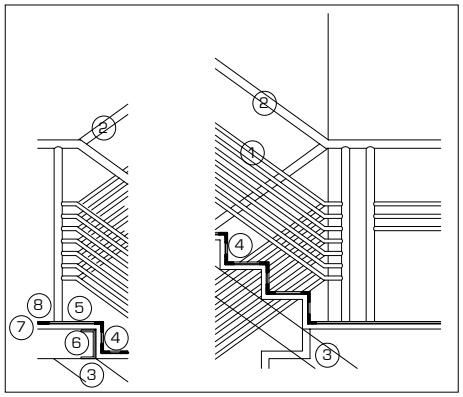
d | Vertical section through treads



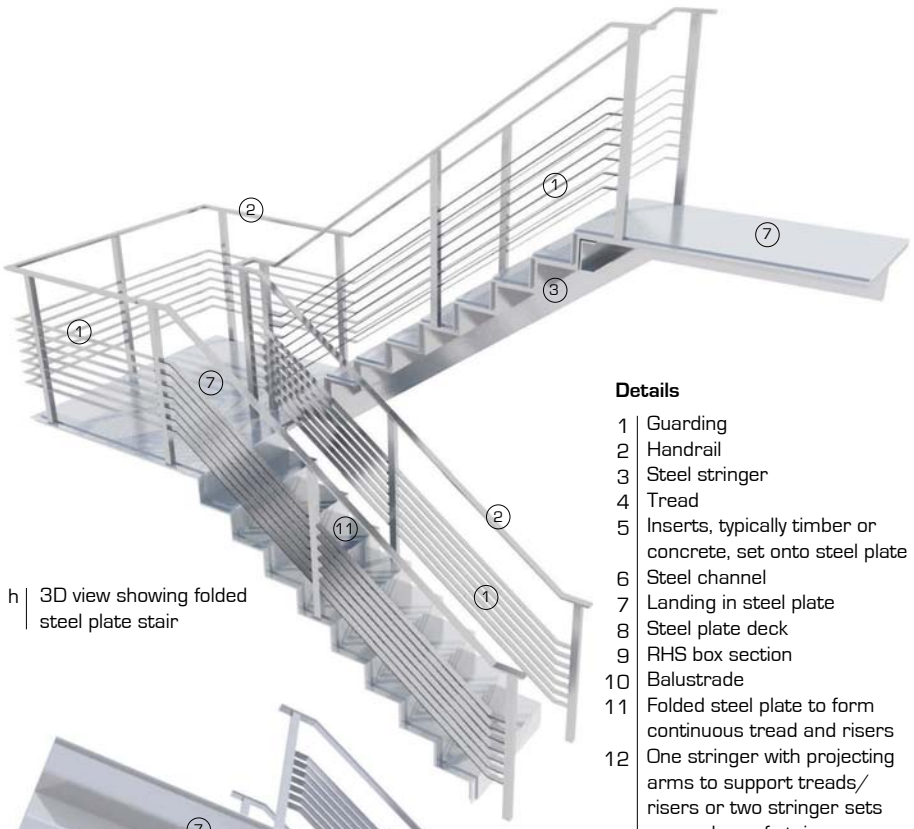
e | Vertical section through treads



f | Horizontal section



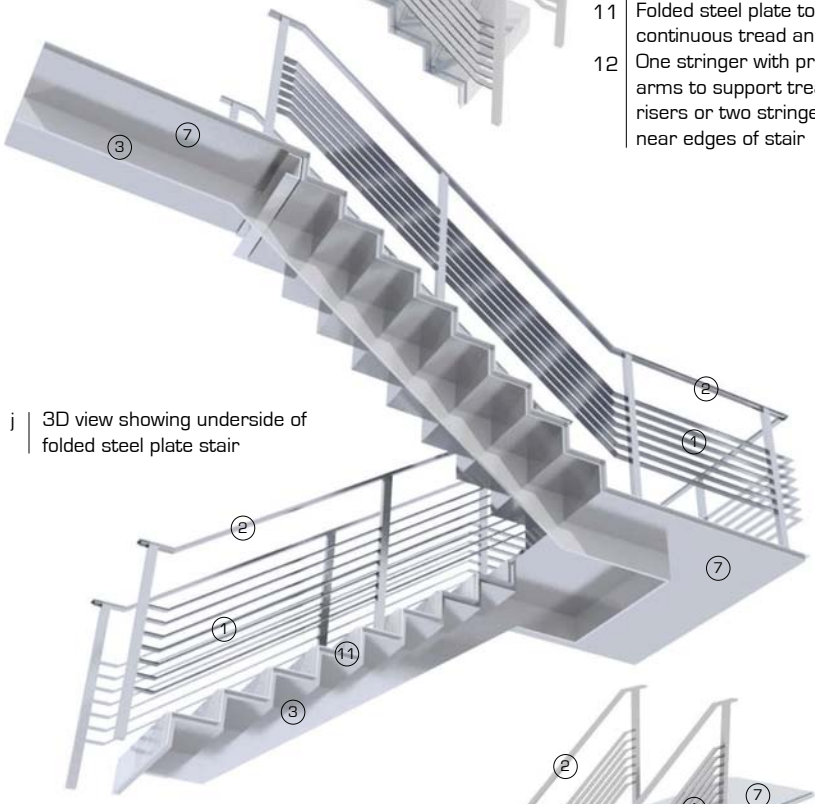
g | Vertical section



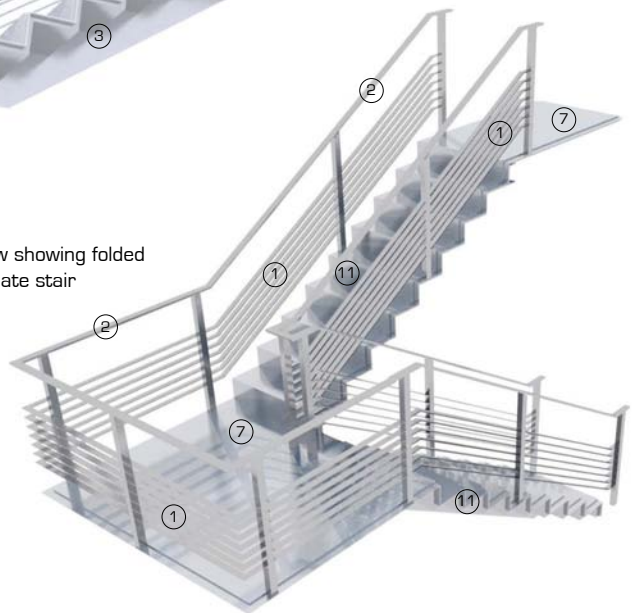
h | 3D view showing folded steel plate stair

Details

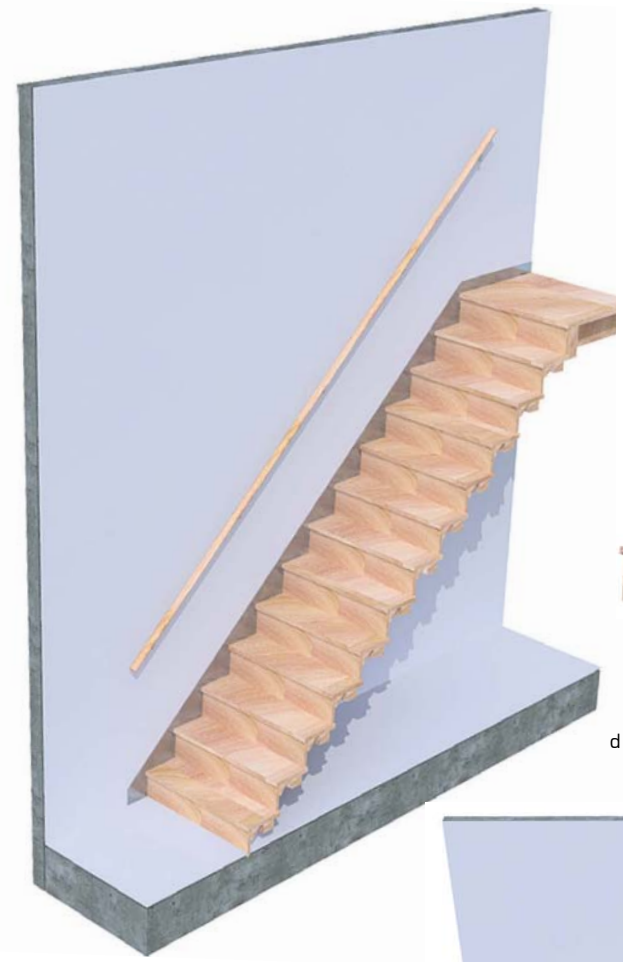
1	Guarding
2	Handrail
3	Steel stringer
4	Tread
5	Inserts, typically timber or concrete, set onto steel plate
6	Steel channel
7	Landing in steel plate
8	Steel plate deck
9	RHS box section
10	Balustrade
11	Folded steel plate to form continuous tread and risers
12	One stringer with projecting arms to support treads/ risers or two stringer sets near edges of stair



j | 3D view showing underside of folded steel plate stair

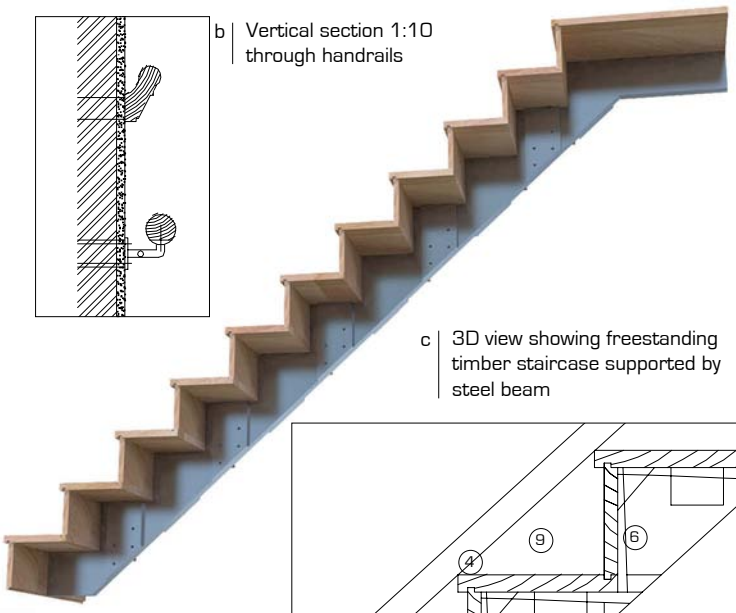


k | 3D view showing folded steel plate stair



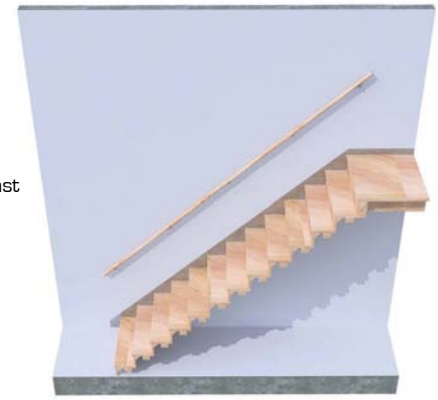
a | 3D view showing timber staircase against in-situ cast concrete wall

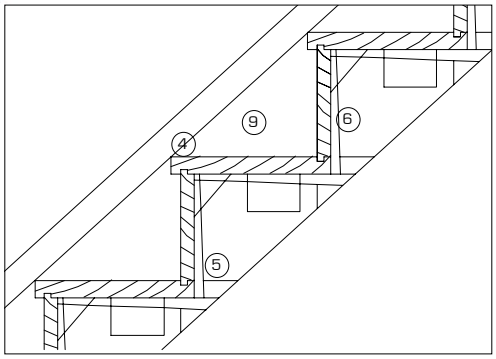
b | Vertical section 1:10 through handrails



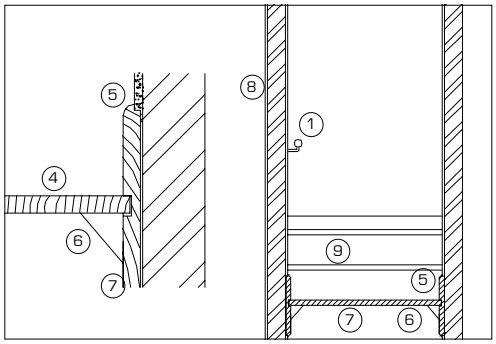
c | 3D view showing freestanding timber staircase supported by steel beam

d | (Below) 3D view showing timber staircase against in-situ cast concrete wall





e | Vertical section 1:10 & 1:50 through stair



f | Vertical section 1:10 through treads

Details

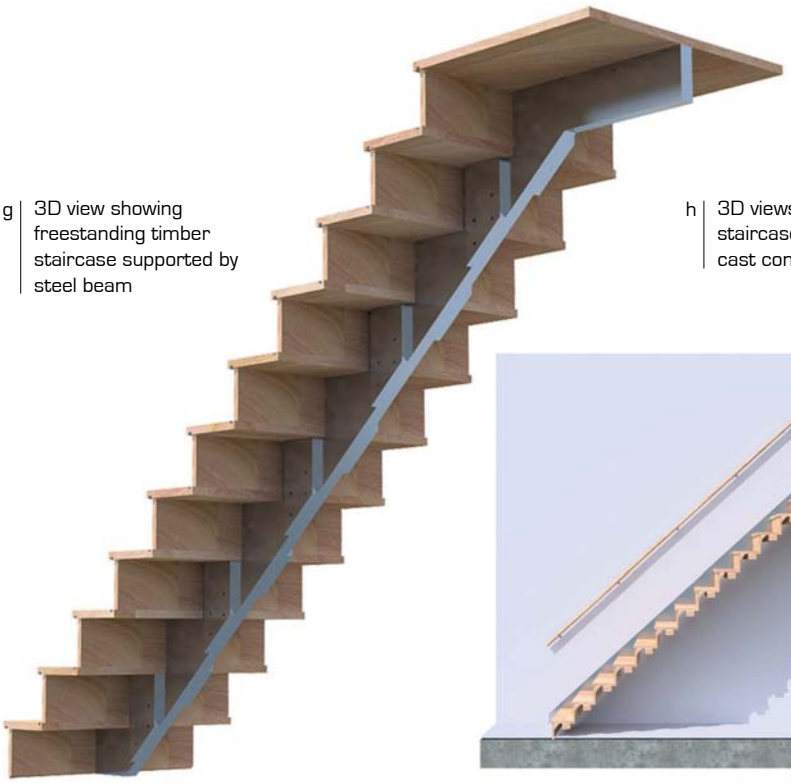
1	Handrail	7	Bracket
2	Balustrades	8	Wall
3	Timber beam	9	Riser
4	Tread	10	Newel post
5	Carriage	11	Trimmer joist
6	Wedge		

An advantage of timber staircases is that they can be integrated easily into adjacent timber construction and can be modified easily on site in a way that is very difficult to achieve in an equivalent steel or concrete construction. Timber stairs consist of stringers or carriages, which support the stair to which treads and risers are fixed (c). Several carriages may be positioned between stringers as loading demands.

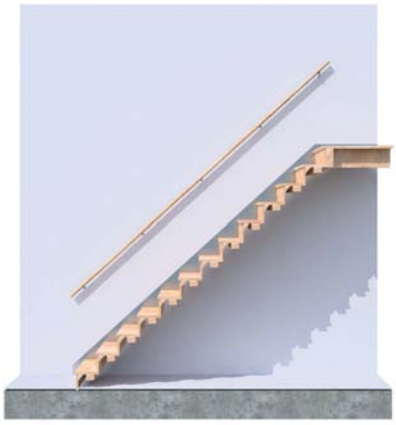
The stair is generally delivered to site as a complete structure secured with timber wedges, avoiding the need for visible fixings. Relatively small pieces of timber are used. The thin timber sections are prone to shrinkage and creep unless they are locked together. Because timber stairs have poor fire resistance, they are often restricted to residential use. Treads and risers are fixed together with tongue-and-groove (or rabbeted) joints that provide a tight fit and avoid creaking when the stair is in use (e). Both treads and risers are fitted into rebated slots cut into the stringers where they are wedged to provide the correct alignment of treads (f). Trimmer beams are sometimes added at the top and bottom of the staircase to stabilise it and provide fixing points to the adjacent floors, which are typically also of timber construction.

An alternative approach is to use heavy timber sections to form staircases that resemble those in steel. Steel brackets that are bolted into the timber sections connect the stringers and separate treads together (g). They can easily accommodate steel guardrails which are bolted through the large stringer sections. Timber guardrails follow the traditional use of balusters at close centres, typically set 100mm apart (j). The lack of large structural members in timber stairs makes the use of balusters at wider centres, as used in steel or concrete construction, less suitable. Timber connections are more fragile than those in steel; they must also accommodate more movement due to moisture. Balusters at close centres allow imposed loads on the guardrail to be spread evenly along the length of the stair stringers.

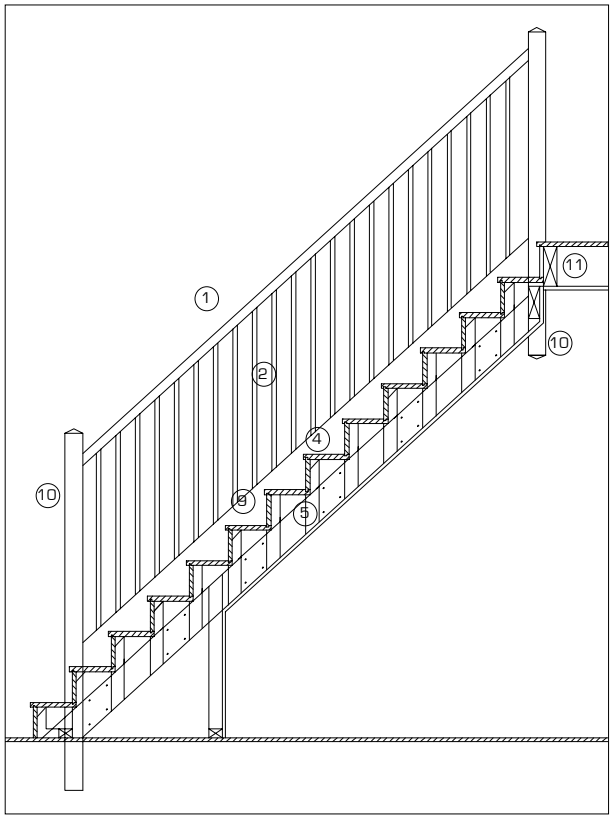
g | 3D view showing freestanding timber staircase supported by steel beam



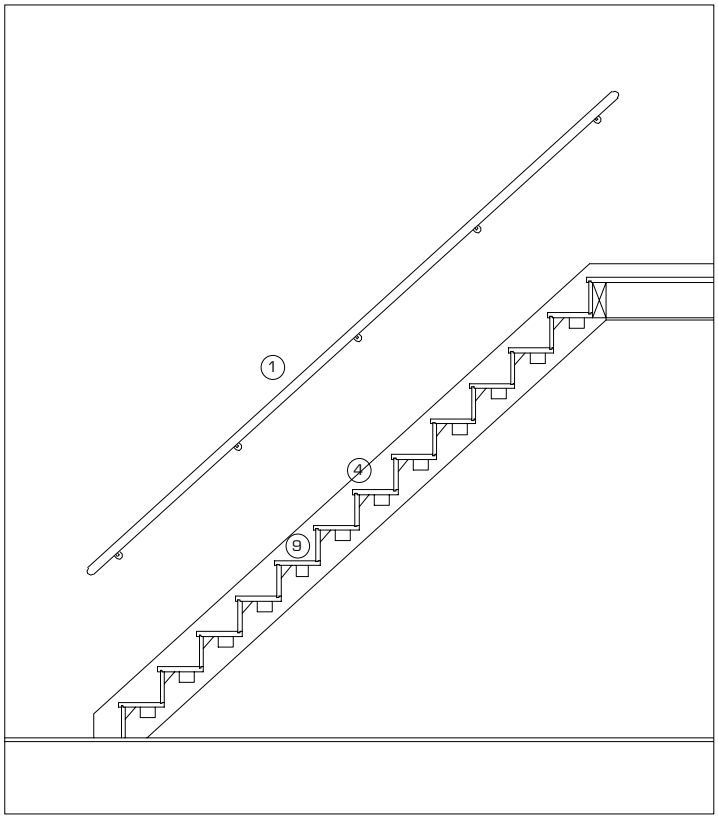
h | 3D views showing timber staircase against in-situ cast concrete wall



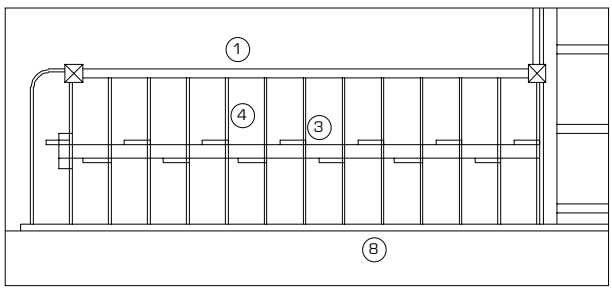




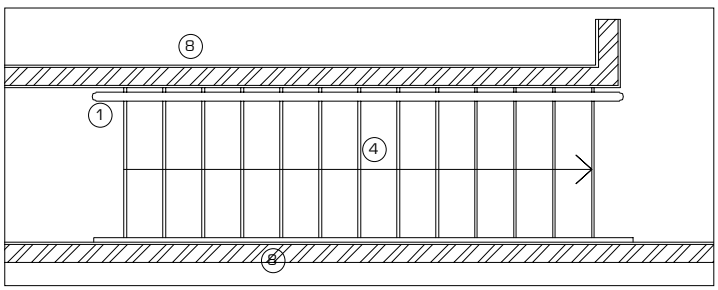
j | Vertical section



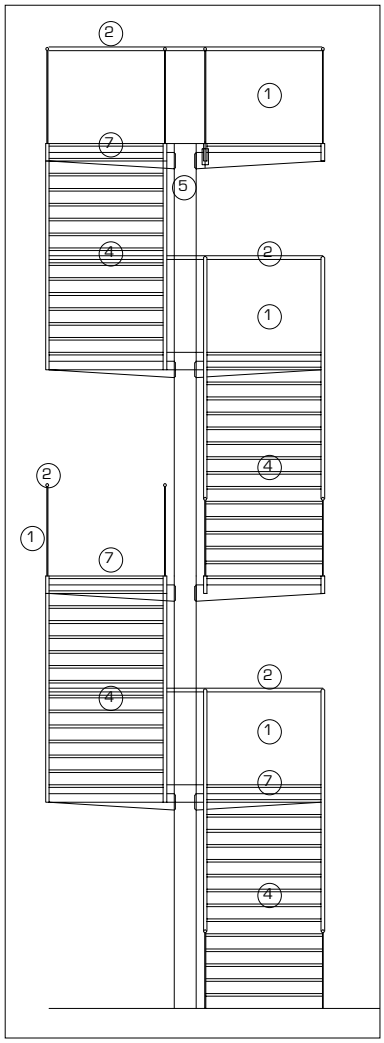
k | Vertical section



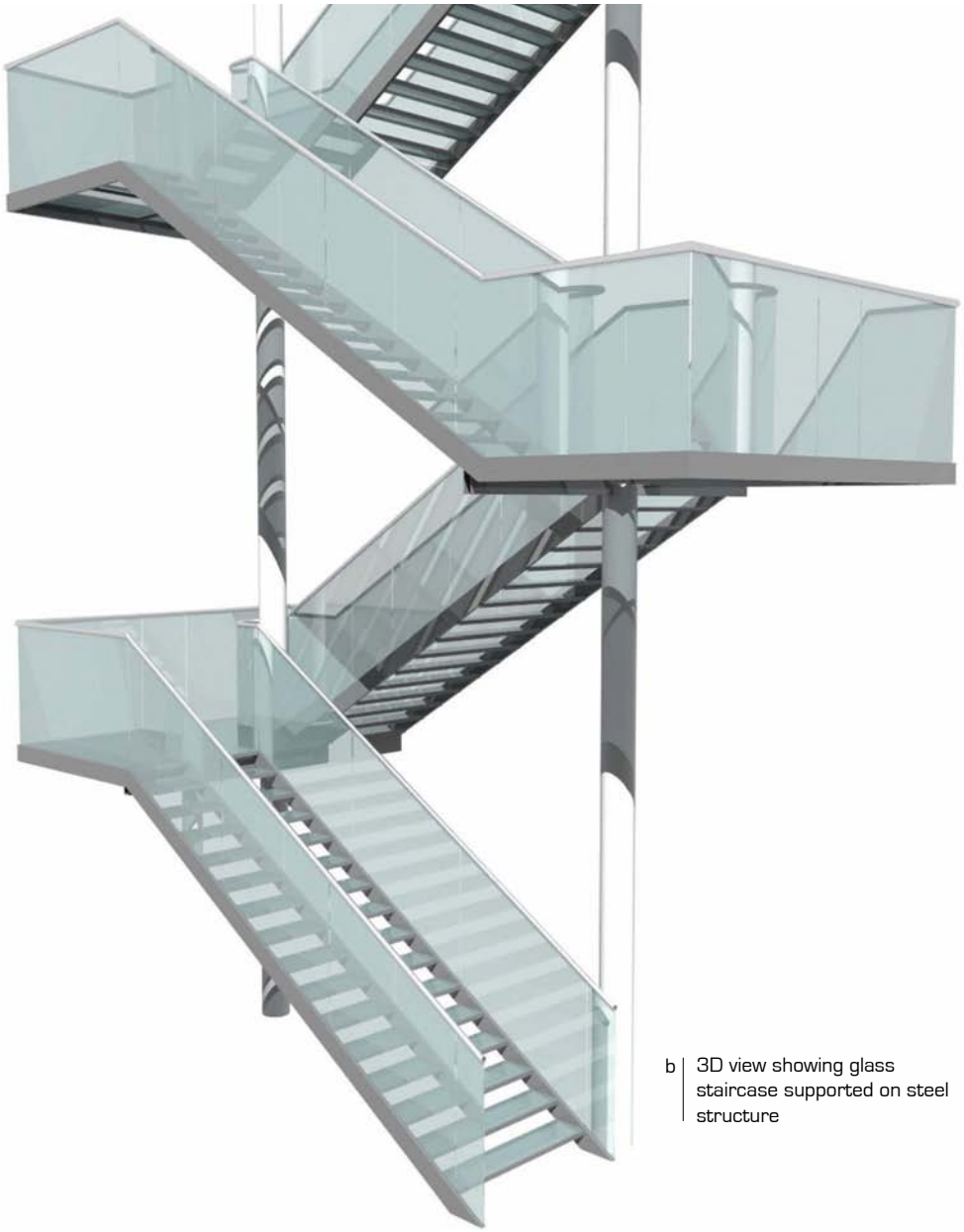
m | Horizontal section



n | Horizontal section



a | Vertical section 1:50



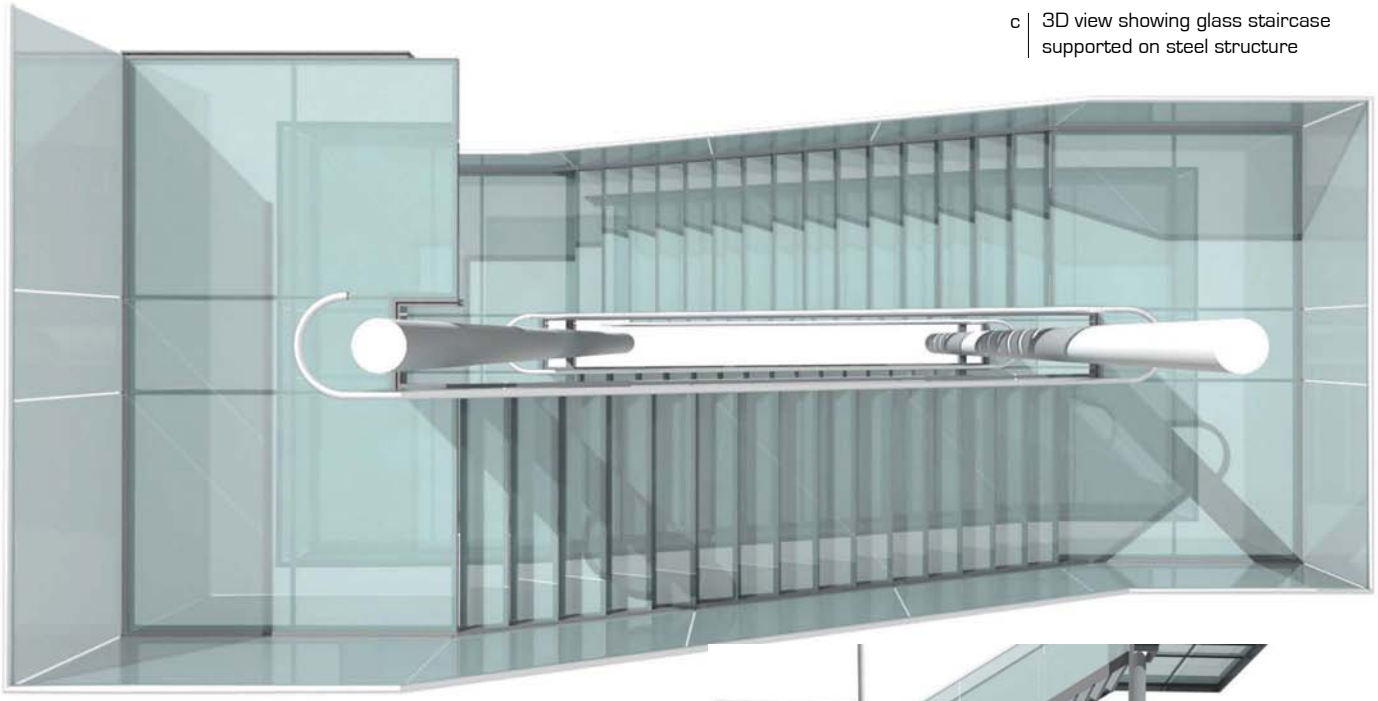
b | 3D view showing glass staircase supported on steel structure

Stairs with glass treads have the advantage of transparency, allowing light to penetrate down the stair enclosure (b). The glass used is usually a thick laminated glass which can be made of two sheets of float glass with a thin interlayer (g), or toughened glass with a more robust interlayer that stays in place if the two toughened sheets are broken. Glass treads can be supported either within a steel tray which provides support on all edges, or be two-edge supported (d). An alternative is to bolt-fix the glass using techniques taken from their primary application in glazed walls (MCH_126). This method allows the stair to be suspended from cables, a technique still in the early stages of use. The tread assemblies are then usually supported by steel stringers, though concrete can also be used.

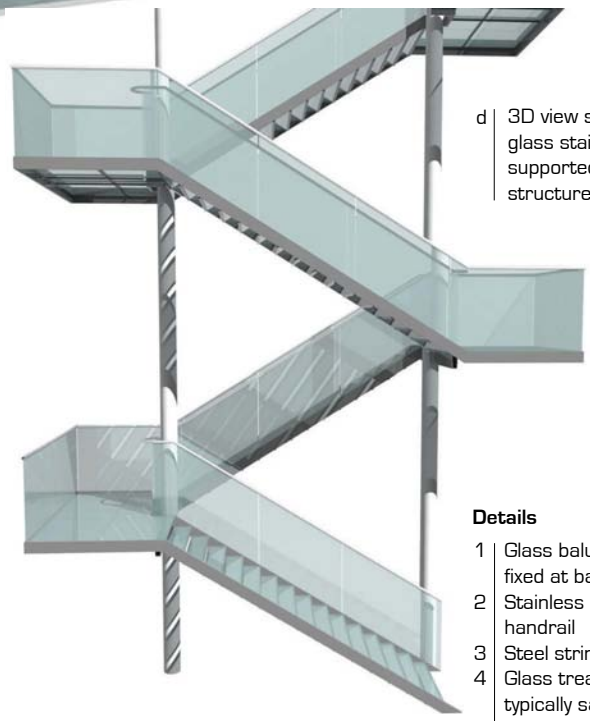
Where glass treads are set within a steel supporting tray, the laminated glass sheet is set directly onto a silicone-based bedding. In addition to holding the glass in place, the bedding provides both a cushion and a method of ensuring that the glass is evenly supported along all the edges and is fixed level (h). An additional weather seal is used on the sides of the glass between the glass and frame, if the stair is to be used in external conditions. Treads often have a surface treatment to provide slip resistance. Sandblasting, etching or the addition of a carborundum coating, typically in strips, is used for this purpose.

Guardrails

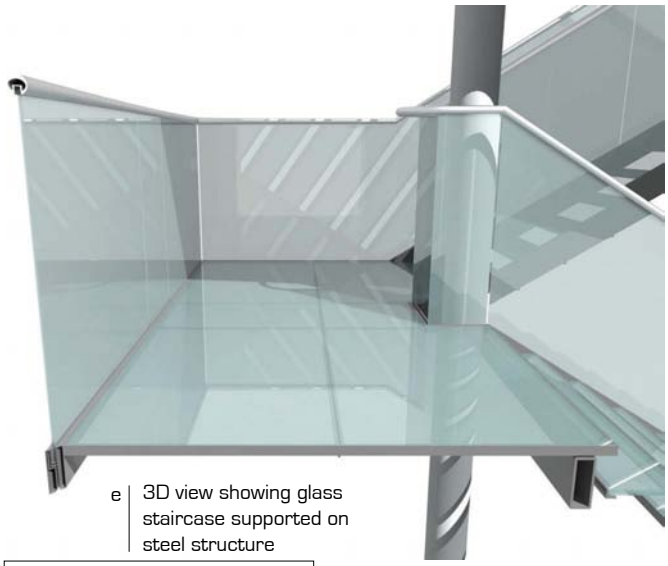
All-glass, or structurally glazed, balustrades can be constructed with sheets of toughened or laminated glass and used with a stair built in another material. They comprise sheets of toughened or laminated glass fixed at floor level with either a clamped plate secured by bolts or by bolt fixings directly through the glass (e). The glass must be sufficiently strong and rigid to span vertically without additional vertical support. A 12mm thick sheet is typically used. A handrail can be added by introducing a rebate into the handrail section and setting it directly onto the top of the glass guardrail. An alternative method is to form a guardrail from steel posts that support a handrail, with laminated or toughened glass sheets used as infill panels. The glass can be fixed with clamps or be bolt fixed back to the posts. Glass sheets are set with a vertical gap of around 10mm between them which is filled with a translucent or transparent silicone seal.



c | 3D view showing glass staircase supported on steel structure



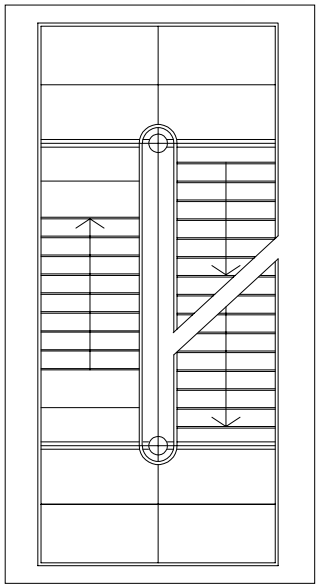
d | 3D view showing glass staircase supported on steel structure



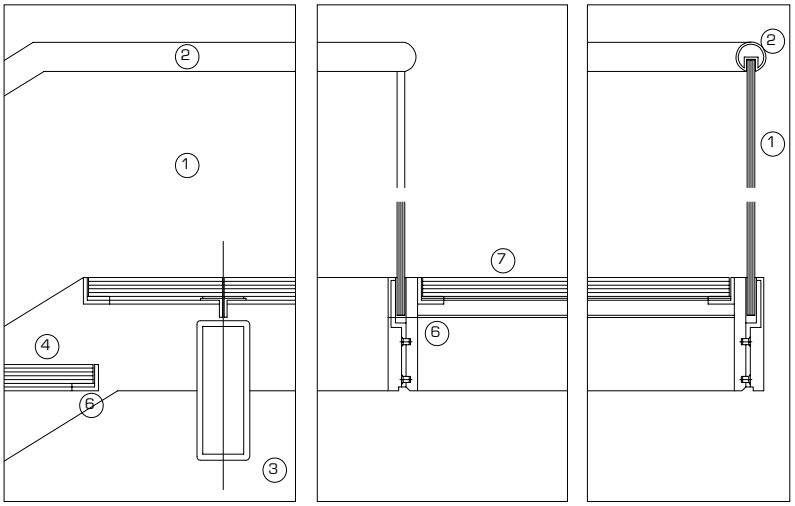
e | 3D view showing glass staircase supported on steel structure

Details

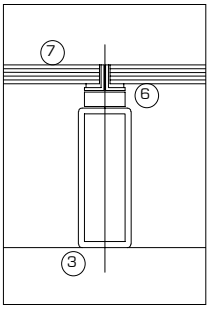
1 | Glass balustrade fixed at base
2 | Stainless steel handrail
3 | Steel stringer
4 | Glass treads, typically sandblasted to provide friction
5 | Steel tube support frame
6 | Steel angle
7 | Glass landing in steel plate



f | Horizontal Section



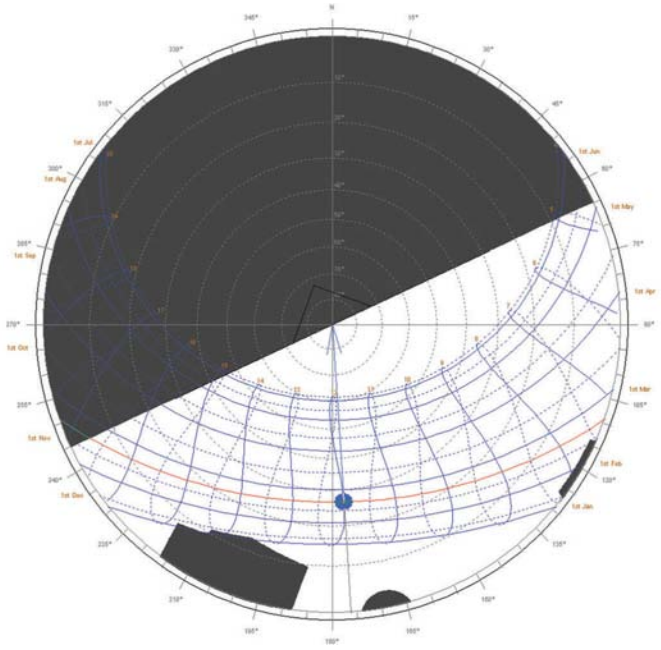
g | Vertical Section



h | Horizontal section 1:10

05
ENVIRONMENT

	Environmental studies for envelopes
	Analysis for design
1	Solar radiation
2	Daylight
3	Thermal performance
4	Wind
5	Solar shading
6	Double skin facades
7	Natural ventilation
8	Thermal mass
	Low-energy material systems
1	Embodied energy
2	Green walls
	Active design
1	Liquid-based heating/cooling systems
2	Mechanical heating/cooling systems
3	Electrical lighting
4	Raised floors
5	Internal ceilings
	Support services
1	Sanitation and drainage
2	Maintenance and cleaning
3	Lifts
	Performance testing
1	Facade material systems
2	Roof material systems



a | Sunpath diagram for southerly facade



b | Study of shading design on glazed facade

This chapter discusses environmental design in terms of passive and active methods that can be used to modify environmental conditions within a building. Active controls are provided mostly by mechanical ventilation systems that are used to heat, cool and ventilate spaces. Passive controls can be provided by natural ventilation, solar shading, passive heating and even by the use of the building fabric as a thermal mass to slow down the rate of heating and cooling. A combination of these methods helps to reduce the energy consumed by buildings in use. This chapter also looks at the rise of natural building materials in construction and the reduction of embodied energy within building projects.

In the past, combinations of structure and cladding were generally limited to the use of materials that were constructed either from the same base material (steel, concrete or timber) or from materials having compatible amounts of thermal movement. The expression of structure and construction (particularly of joints) was considered one of the primary architectural intentions in cladding design; however this situation is slowly changing. More buildings are clad externally with insulation and use a rainscreen cladding system to conceal it from view. Rainscreens allow a simplified approach to be taken to movements in the primary supporting structure of the building. A continuous, uninterrupted appearance can be achieved with a consistent gap between panels that extend across movement joints in the building structure. Both movement joints and breaks in the construction need not be 'registered' on the facade. Where they are visible they serve only as a decorative device. These innovations have led to a much wider range of structure/cladding combinations being used in construction which has allowed a greater focus on the use of materials with low embodied energy. It has also allowed buildings to exploit the thermal mass of their structural elements to slow down the rate at which the building heats up and cools down.

While thermal and structural movement were once the main issues in detailing, the idea of 'energy' is considered important today and detailing has become more complex in response to these changing priorities.

Protection vs comfort.

Over time, the concept of the building as a means of protection from natural elements and predators has slowly given way to control and modification of the natural climate to create a comfortable environment for an increasing range of human activities. The challenge for the design team is to develop strategies for creating buildings that create an effective filter between man and his natural environment.

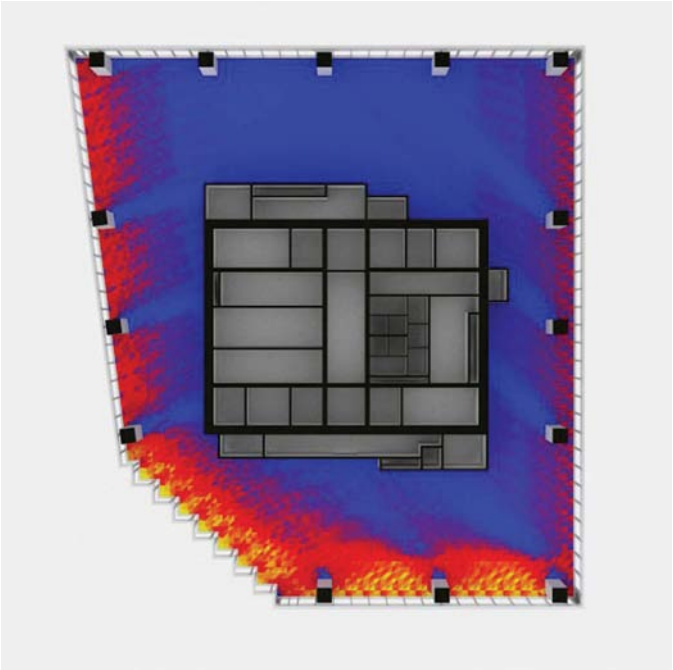
The last century saw a tendency for designers to focus on the problems associated with climate. Their challenge was to develop methods for dealing with the effects of hot or cold climates, mitigating the impact of high solar gain risks or counteracting other inhospitable conditions. This focus resulted in the creation of buildings with increasingly artificial environments and high energy costs in an attempt to minimise their interaction with the external climate. As building technology developed, designers could aim for improved comfort conditions in increasingly hostile climates without compromising design philosophies that were often at odds with the local vernacular.

Over recent years there has been a move to reverse this thinking and work instead to exploit the potential benefits that the climate offers. For example, facades with high solar exposure can harness the sun's energy through photovoltaic cells to contribute to the energy demands of the building. This shift has seen a change in design emphasis towards buildings that minimise their impact on the environment whilst ensuring they provide acceptable comfort conditions for the occupants.

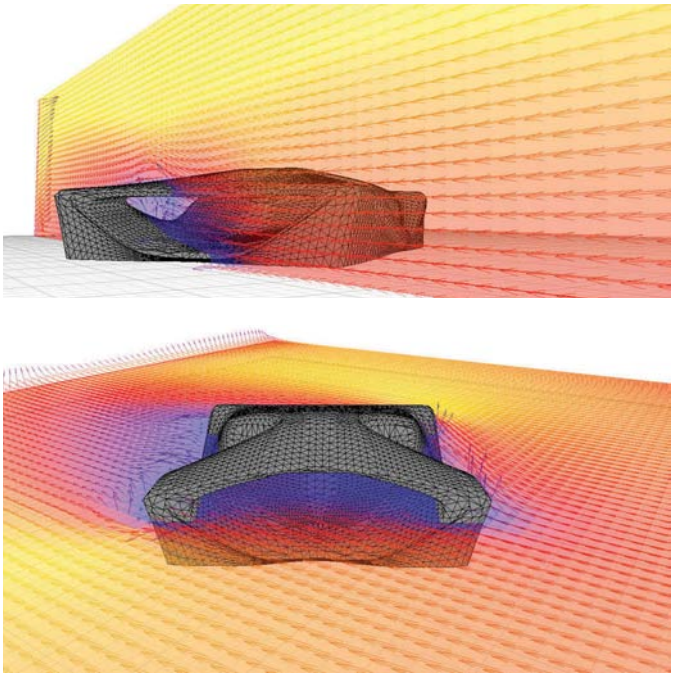
Since humans spend most of their time inside buildings, the drive for improved comfort standards is important to maintain the health and wellbeing of each individual.

Human comfort

The environmental conditions conducive to human comfort are not absolute. They can vary based on the individual's metabolism, the tasks



c | Study of sunlight penetration into office floor plate



d | CFD analysis of air movement around a building

they are trying to accomplish or their perception of the environment they are in. In brief, the definition of comfort can be defined as the absence of discomfort. During the design of most new projects, a series of environmental parameters will be presented as a means of providing comfortable conditions within the building. However, comfort is more of a holisitic concept based on the interaction of many factors and the individual's ability to alter those variables. Since everyone has different criteria for comfort, it is often measured by the percentage of occupants who report they are satisfied with the conditions. In terms of the built environment, this can be categorised into 3 areas:

Thermal comfort – The user experiences discomfort if they are too hot or too cold. This occurs when the temperature, humidity, airflow and radiant sources within a space are not kept within an acceptable range. The exact balance of these factors will vary depending on what activity is occurring within the space and at what intensity, as well as what the occupants are wearing.

Visual comfort – A space becomes uncomfortable if there is insufficient light to undertake the task required by the user. This level will vary depending on the activity. Laboratories, for example, will require higher light levels than classrooms to maintain user comfort. Natural light tends to create the most comfortable environments, but artificial lighting has the advantage of maintaining a constant illumination. Visual comfort is also based on offering occupants a good view. This gives users a sense of connection with their surroundings and helps promote a sense of wellbeing.

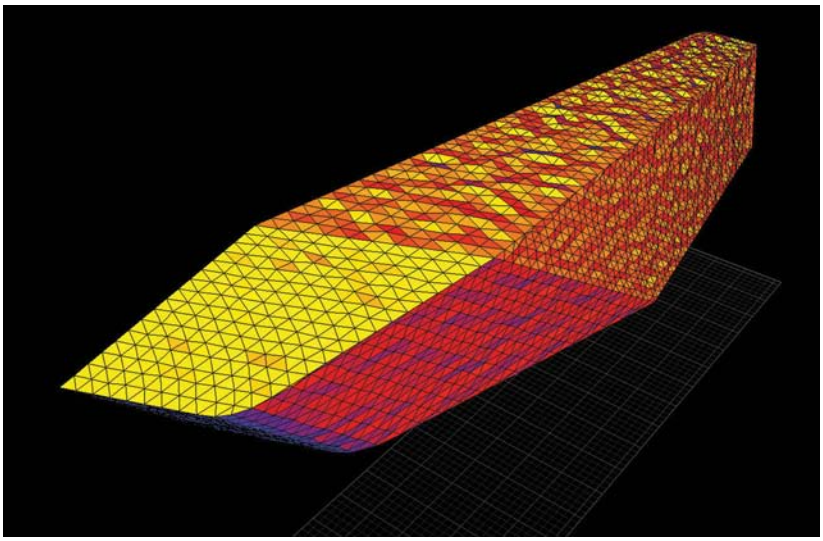
Acoustic comfort – This is achieved by ensuring the user has the right level and quality of noise to use the space as intended. Depending on the environment, control of decibel level, reverberation times and sound reflection can aid user comfort.

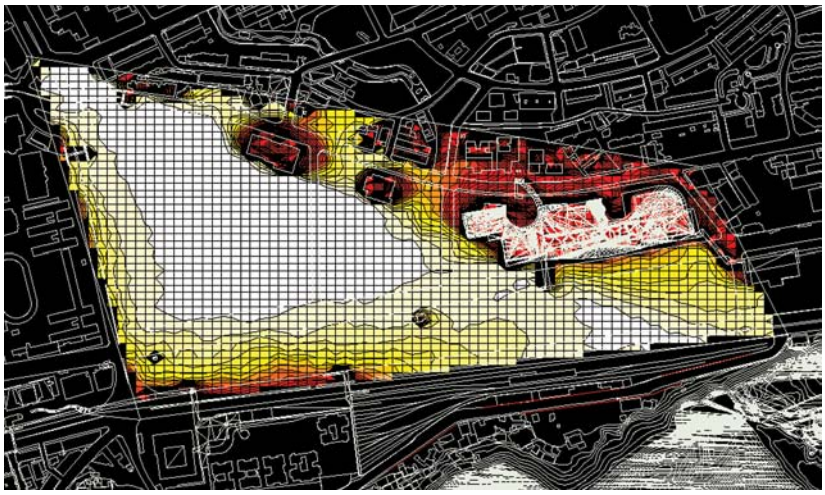
Environmental analysis in design

The design team can use environmental analysis throughout the design process to study how a building is likely to perform when in use by predicting how a building affects, and is affected by, its local environment. This allows the designer to respond to, and develop solutions to, potential problems before construction is completed. This analysis can be performed at various stages of the design process through to building use, with equal benefit. At the earliest stage of the project, analysis of the local environment can help to inform the project brief, identifying natural climatic factors that can be exploited within the design as well as highlighting potential challenges to occupant comfort (a).

During the design process itself, proposals can be tested to establish their effectiveness at responding to the challenges of the local climate in order to inform future design development (b). Once the building is in use it can be assessed to see how it is performing. The results of these assessments can be studied and the lessons learnt can be fed back into the pre-planning stage of future projects. Assessment at this stage can also help to develop strategies for improving the comfort of occupants through modifications to the building.

The following pages look at some of the concepts of environmental design focusing on solar control (c), daylight, thermal performance, wind (d) and natural ventilation. This is followed by case studies which show how these concepts can be applied in the context of building design.







e | (Above & top left) Solar insolation analysis of complex forms

f | (Left) Exposure study for urban site

Decisions made early in the design process have considerable influence over the environmental performance of the completed building. Designers need no longer rely on 'rules of thumb' to create energy efficient buildings during the early stages of design. The use of computer software can also allow designers to be more independent of specialist consultants during the early stages of design, without ignoring the essential issues of environmental design. Specialist consultants too often become involved in a building design only after the conceptual stage of the design process is complete.

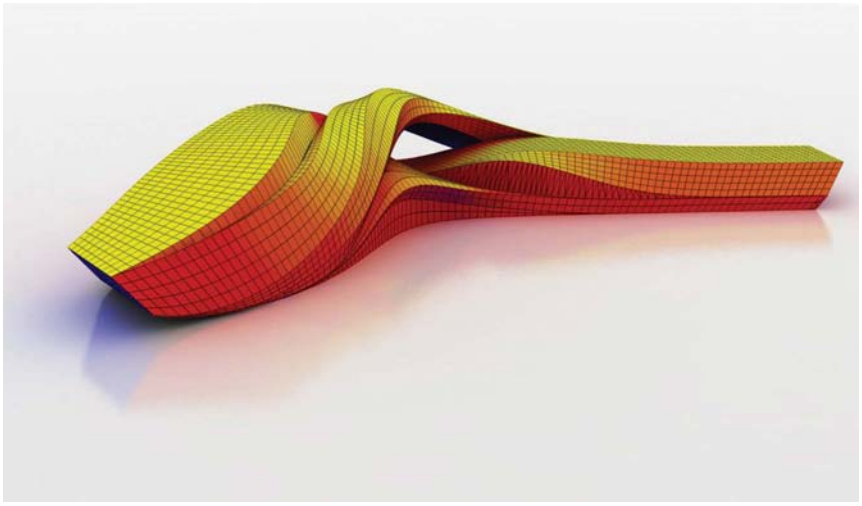
Computer software has developed to the point that many 3D CAD design applications have some form of environmental analysis tools built into them. Most applications will allow the designer to project shadows both onto, and created by (d), the building being designed. Some more advanced software applications will provide an analysis of solar gain (e), calculate approximate daylight levels and give information about the thermal properties and embodied energy of construction materials.

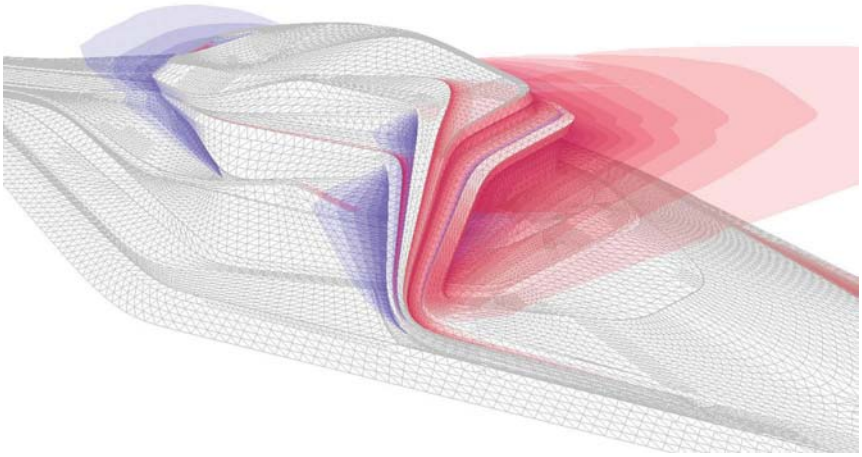
If designers both use and respond to these opportunities for analysis, it allows them to keep step with the specific environmental demands of their building. This helps the design team keep the overall project design in balance rather than having to accept 'features' being added to the final design as consultants try to alleviate problems caused by a lack of environmental input at the early stages. Digital analysis also allows the design team to understand the performance of their building without having to invest significantly in mock-ups or time-consuming calculations undertaken by hand.

One of the major benefits of computer-based analysis is that it can be used to inform design decisions at all stages of the design process. Data is displayed in a graphic manner that is easy to understand and interpret, and also aids discussion with other project consultants. At the earliest stages of a project, environmental analysis can help inform decisions about the orientation and specific geometry of the external envelope. Analysis can be carried out on a digital model of the 'empty' site to help the designers build up a picture of the microclimate they are dealing with and ensure that appropriate design responses are formulated at the earliest stages of the project (f). Information about annual sunpaths, temperature ranges, humidity and prevailing winds can be used to identify key issues that need to be addressed during schematic design (a).

This analysis becomes even more important when dealing with projects in parts of the world unfamiliar to some in the design team, and will







g | (Above & top right) Solar insolation analysis of complex forms

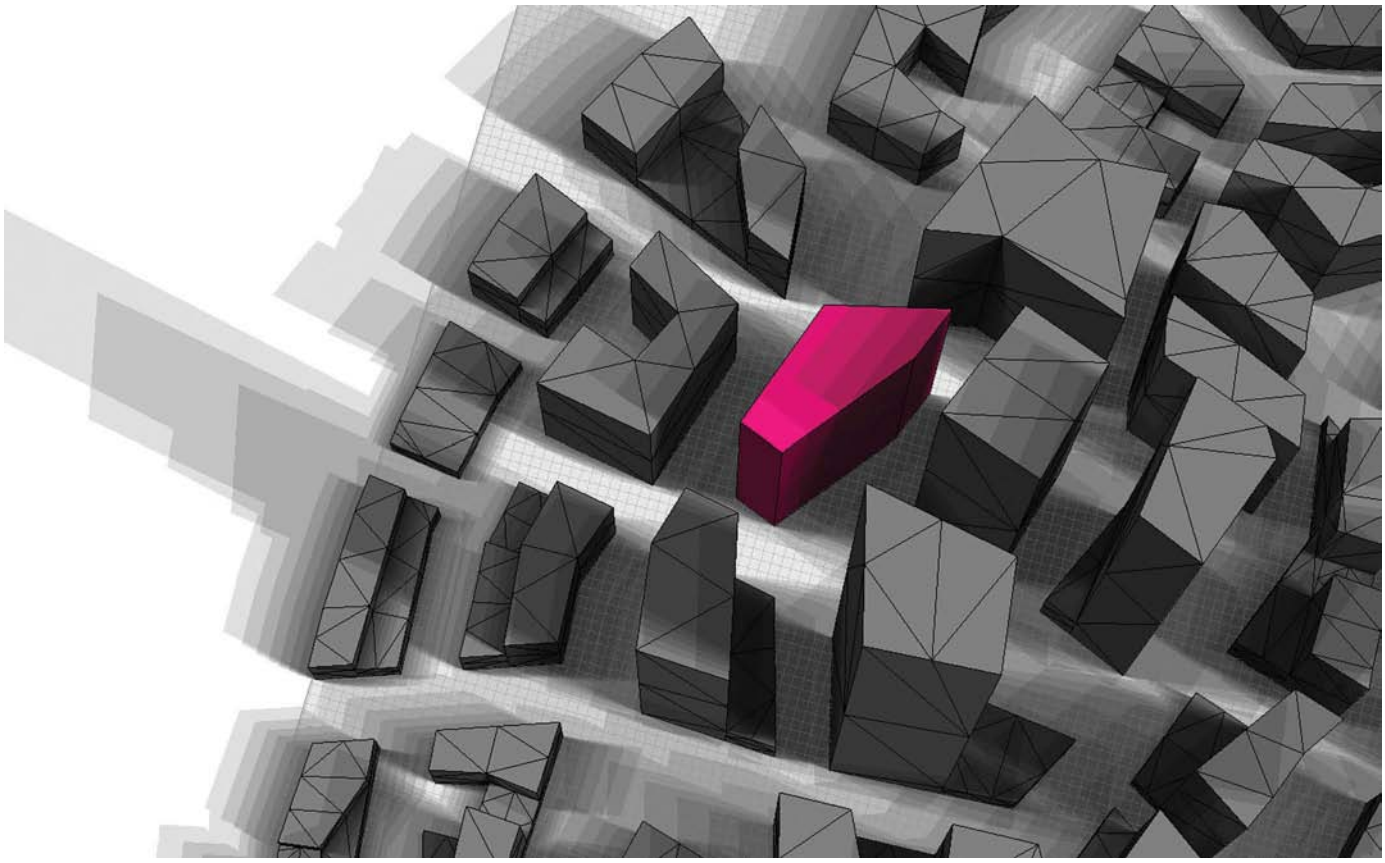
h | (Right) Cumulative shadow projection for a complex form

help identify how design solutions which are considered to be 'standard' may need to be modified to meet specific environmental conditions. As the design process develops and more information can be input into the software programme, more detailed environmental analysis can be carried out on the project. This analysis can help inform decisions about geometry optimisation, window placement and shading design. Throughout the design process the impact of design decisions can be analysed and their consequences evaluated. This process is conducive to an iterative design process where many options are proposed, analysed, modified and analysed again. Because the resulting data is displayed in such a graphical way, it is easy to compare the results and identify the most successful solutions to the design brief.

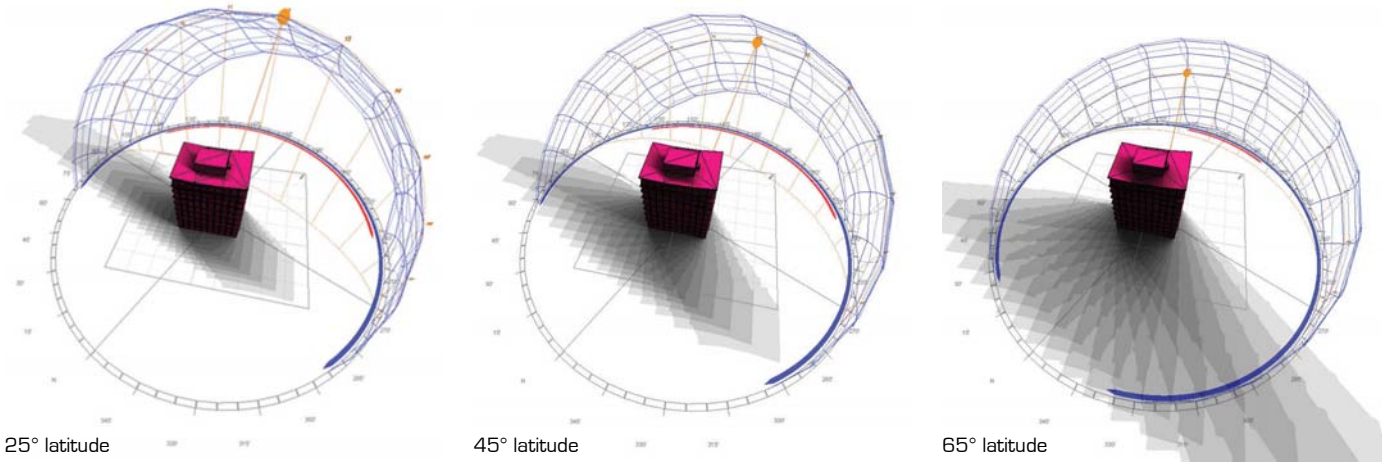
Over recent years, digital tools have made the design and construction of complex forms more achievable. Conventional rules of thumb regarding environmental design becomes harder to implement once the building geometry deviates from traditional shapes, and with complex geometry it can be difficult to know where to focus the attention of environmental design since the worst case conditions are not always obvious. Environmental analysis software can harness a computer's ability to carry out complex calculations in an iterative manner to allow the evaluation of the whole building in a relatively short period of time. This can help the designer to identify areas of the building that require further development, for example areas of a facade that are subject to particularly high levels of incident radiation or whether the building will cast unwelcome shadows over its surroundings at a particular time of the year.

As computers become more powerful and software algorithms more efficient, the use of real-time analysis will become more prevalent in building design. The ability to change parameters such as window size and location within a facade, and receive instant feedback on the impact on daylight levels or solar gain, will allow design teams to see the consequences of design changes as soon as they are made. The ability to embed this parametric interactivity within a shared 3D model will allow designers from all disciplines to see the impact of design changes on the performance of the building as a whole.

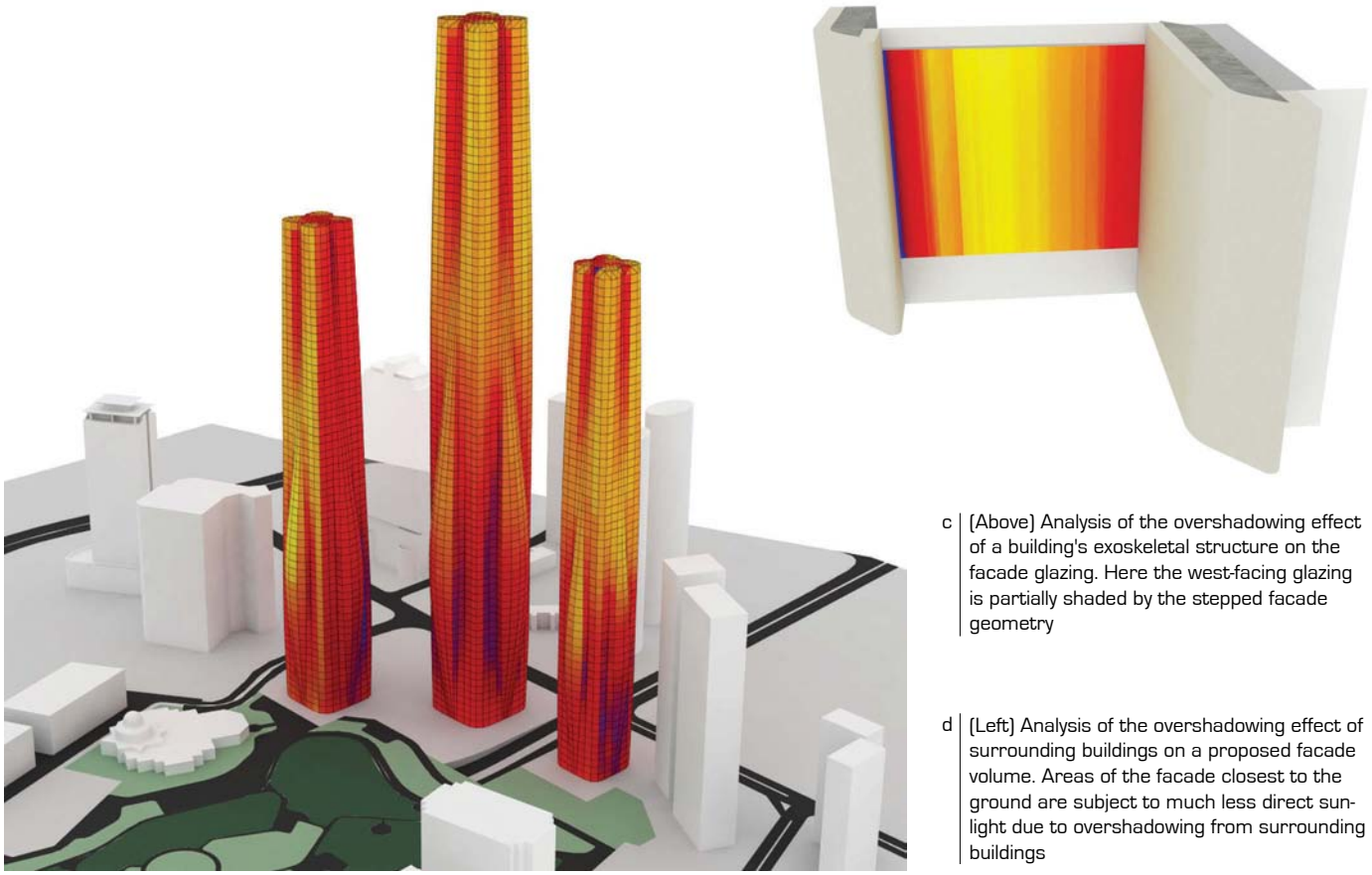
As with all analysis tools, a certain understanding of the subject is required to interpret the results effectively. The risk with digital analysis is that the wealth of data available can overwhelm the design team. Similarly, the software will only present the results of analysis in relation to its inputs. The user is still required to evaluate the results and decide on their relevance to the design process.



a | Overlaying shadow projections for one day helps evaluate how the building's shadow tracks across the site.



b | Comparison of sunpaths at different global latitudes and the effect on shadow projections



c | (Above) Analysis of the overshadowing effect of a building's exoskeletal structure on the facade glazing. Here the west-facing glazing is partially shaded by the stepped facade geometry

d | (Left) Analysis of the overshadowing effect of surrounding buildings on a proposed facade volume. Areas of the facade closest to the ground are subject to much less direct sunlight due to overshadowing from surrounding buildings

Sunpath

An awareness of how the sun moves around a building at different times of the year can assist with the design of solar shading for a building. In most situations the specific design aim would be to exclude some of the effects of the sun during the summer months, when solar gain is at its most intense, but potentially to allow some spaces behind the facade to enjoy the effects of solar gain during the winter to take advantage of its warmth.

Sunpath diagrams offer the most visual way of assisting this understanding and most 3D CAD design software will allow the user to evaluate the sun's position in real time for any time of day at any location in the world (b).

Shadow projection

The sunpath features in 3D CAD design software also enable the user to evaluate shadows falling across the model. This allows real time analysis of the sun's penetration into buildings, aiding the designers with the placement of windows as well as the design of the electrical lighting. This analysis also allows the designer to visualise the overshadowing effect of surrounding buildings as well as the extent to which the proposed building will, in turn, overshadow its neighbours. This is particularly important for urban sites where maintaining rights of light may be a significant aspect influencing the building's design (a).

Mapping how building shadows track across the site throughout the day helps with the design of outside space. Cafe terraces can be sited in areas which attract the sun and external landscape features can be positioned based on their planting requirements.

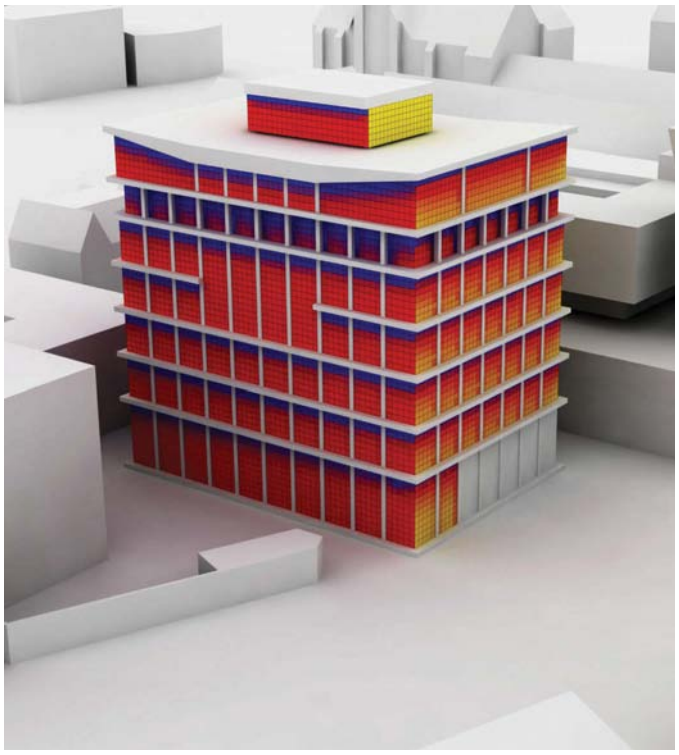
Sun path analysis can help to identify problems with reflections from the building's facade. This is more of a problem in built-up areas, since the glare from the sun on occupants of surrounding buildings can cause significant discomfort. Digital analysis can help to alleviate these concerns by projecting the path of building reflections throughout the year.

Overshadowing

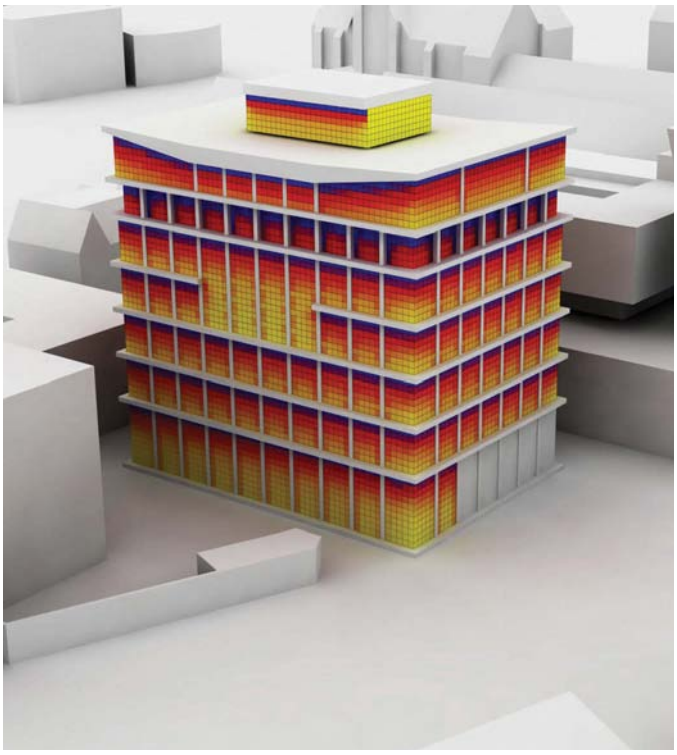
In urban areas, the effect of overshadowing from adjacent buildings may have a significant impact on certain aspects of design (d). Areas of the facade that are in shadow for most of the day will not require the same shading design as areas that are more exposed. Traditional analysis techniques would treat all areas of a facade in the same manner, based on 'worst case' environmental conditions. Digital analysis allows the designer to take overshadowing into account to produce optimised shading solutions. This type of analysis can also be applied to smaller facade modules to assess whether overhangs, projections or other envelope details will have an overshadowing effect (c).

Solar exposure

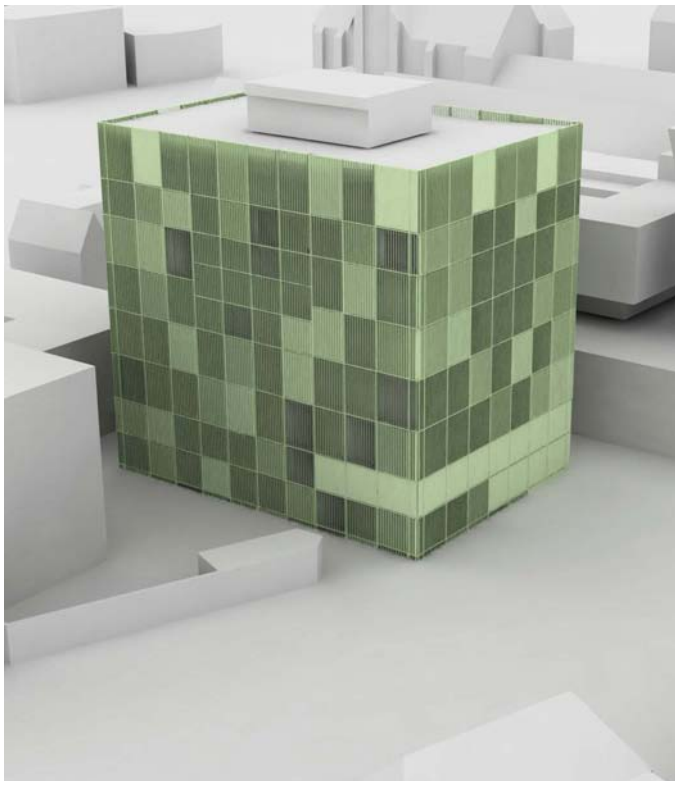
Digital environmental analysis can help to identify areas of high solar exposure over a building and assist with the placement of solar panels on the facade. With more detailed analysis it is possible to calculate how much energy these solar panels can generate over the course of a year.



e | Study of cumulative solar radiation incident on a building facade over the course of 1 year



f | Study of peak solar radiation incident on a building facade over the course of 1 year



g | Based on the solar radiation analysis, along with a study of internal program requirements, a louvred facade shading system helps to keep internal comfort levels within an acceptable range by minimising solar gain and sunlight penetration.

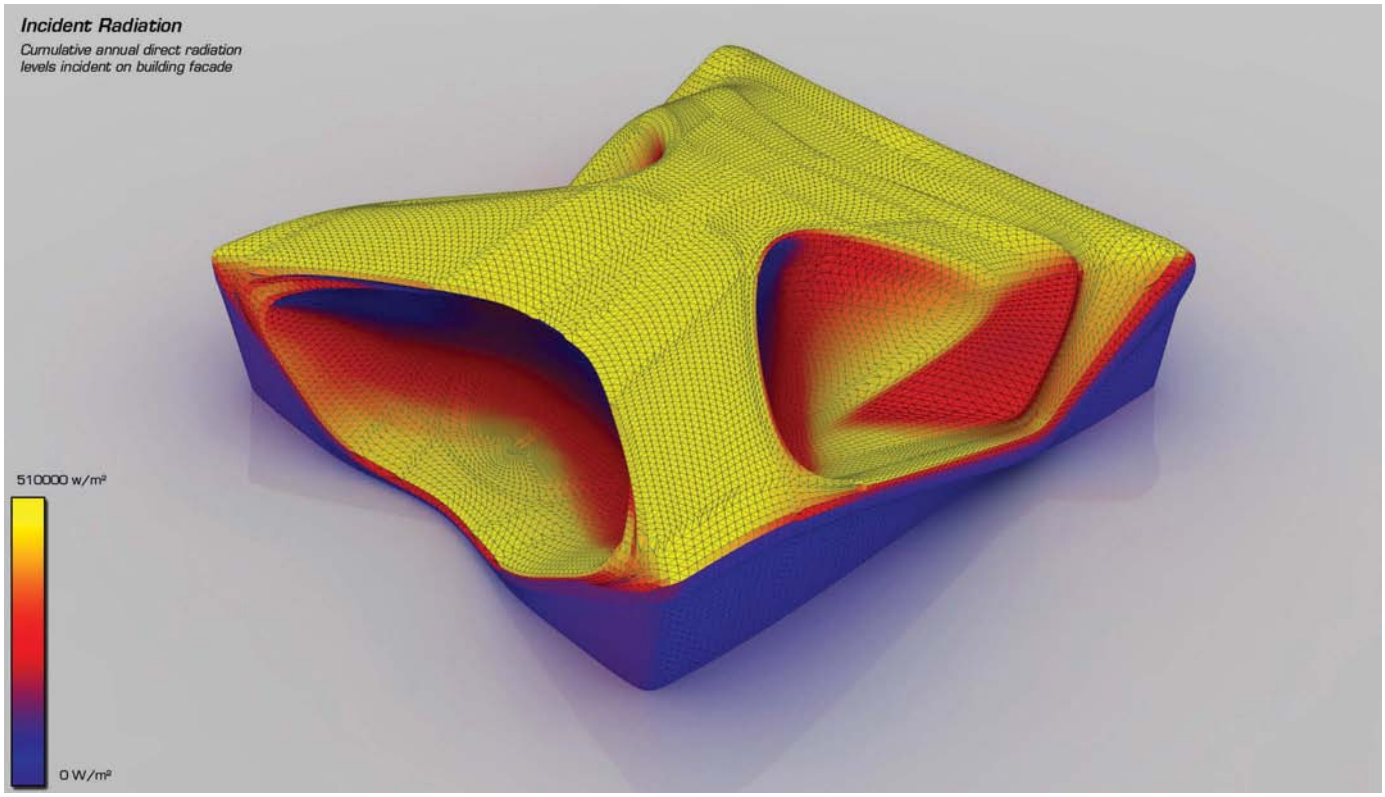
Solar gain

Solar gain can be defined as the increase in temperature of an internal space due to the absorption of the sun's energy by the building fabric. In most situations it is necessary to minimise solar gains, especially during the summer; though in cooler climates solar gain is sometimes encouraged as a means of reducing internal heating loads. In buildings where natural ventilation systems are being considered, it is important to ensure that solar gains match natural cooling capacity to ensure that spaces in the building do not overheat.

The sun is at its strongest towards the middle of the day when it is also at its highest. At this point the sun is incident on vertical facades at quite a steep angle; depending on the time of year and geographical location, the proportion of heat energy transferred is relatively low. Roofs and atria, which face the sun more directly, are particularly vulnerable to solar gain during this period of the day. Either side of its peak, the sun's strength reduces but is incident on the facade at a more direct angle, transferring a high proportion of its energy to the cladding.

Environmental digital modelling can help to indicate the distribution of solar radiation across the facades of a building and build up a picture of which areas inside the building are particularly at risk from overheating (f). This information can be used to help inform decisions about window placement and material systems.

There are a number of ways of controlling the effects of solar gain. Solar control glazing can help to reduce the amount of solar transmittance through windows and glazed facades. Shading systems are an effective means of controlling solar gain since they limit the amount of solar



h | Analysis of incident radiation on complex building form to assess areas which are at highest risk of problems from solar gain.

radiation that penetrates the facade. External shading is far more efficient at controlling solar gain than internal shading, but requires cleaning and maintenance as well as the ability to be removed in the event of facade components being replaced. Careful choice of other cladding materials also helps minimise heat transmittance through the facade.

In hot climates it may not always be possible to control solar gain by passive means. In this case, mechanical ventilation systems will be needed to provide additional cooling inside the building. By analysing the peak annual radiation values for the facades, it is possible to design mechanical systems to cope with the effects of overheating. In this situation it is still beneficial to use passive solar control systems as this will reduce the average energy use of the mechanical systems.

Sunlight penetration

Solar exposure analysis identifies the number of hours facade elements are in direct sunlight (h). When read in conjunction with an analysis of solar radiation distribution, solar exposure analysis can help create a more complete picture of how the sun is impacting on solar gain across the facades.

Solar exposure analysis can also be carried out for the landscape surrounding buildings in order to inform decisions about hard landscape design, planting schemes and irrigation requirements.

Within buildings, solar exposure analysis can help to understand how sunlight will penetrate through facades. It provides a more quantitative measure of solar access which may be of use when designing internal fit-outs, helping to identify areas where computer screens or sensitive equipment should be placed, for example. In conjunction with computer software-generated renders, the study can help to build up a more complete picture of how sunlight penetrates the building.

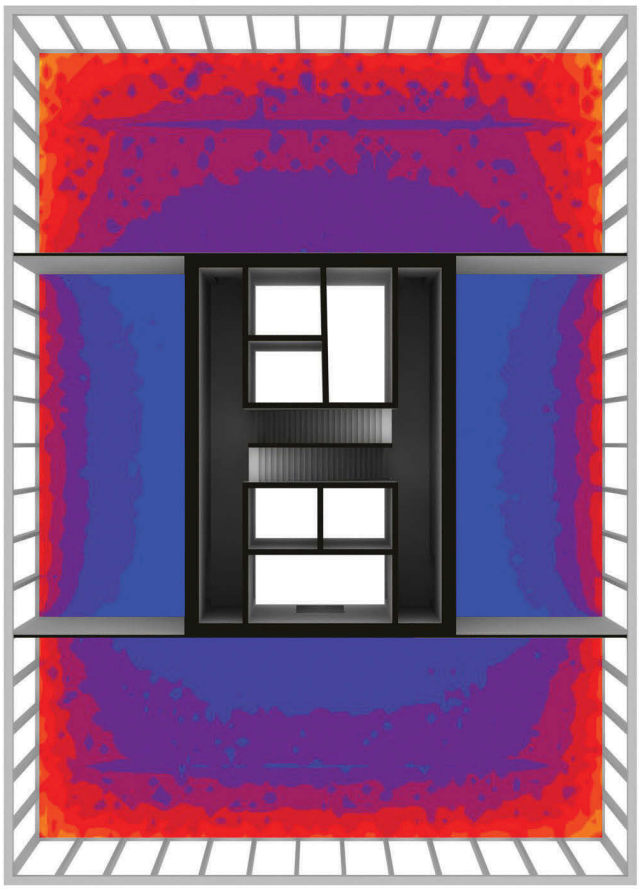
Shading design

The use of external shading can significantly reduce the amount of energy needed to cool buildings in summer months in either temperate climates or hot climates. External shading prevents solar energy from passing through a facade by absorbing, then radiating and convecting solar energy outside the building envelope. In contrast, internal shading has much less effect on controlling solar gain since the solar energy has already passed through the facade and is radiated and convected back into the room, having been absorbed by the internal shades.

In the northern hemisphere, typical guidelines suggest horizontal shading devices are generally effective on south-facing facades to deal with high-angle sun, whilst vertically set systems on the east and west facades are generally efficient at dealing with low-angle sun.

In the design of buildings it is not always possible to follow these guidelines, but detailed digital analysis can help designers derive more specific systems suited to both the building's geometry and location.

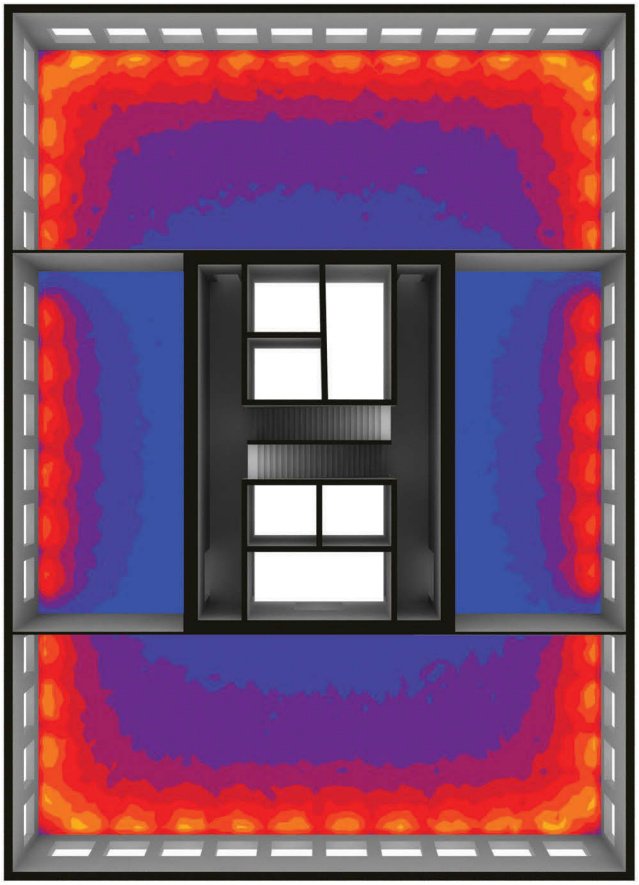
Iterative design techniques help to assess the effectiveness of different shading systems (g). This allows shading systems that may be considered as more visually unconventional, but very effective, to be developed with the confidence that they will function effectively.



Scale
(Daylight factor)

0%	6%	12%	18%	24%	32%	38%	44%	50%

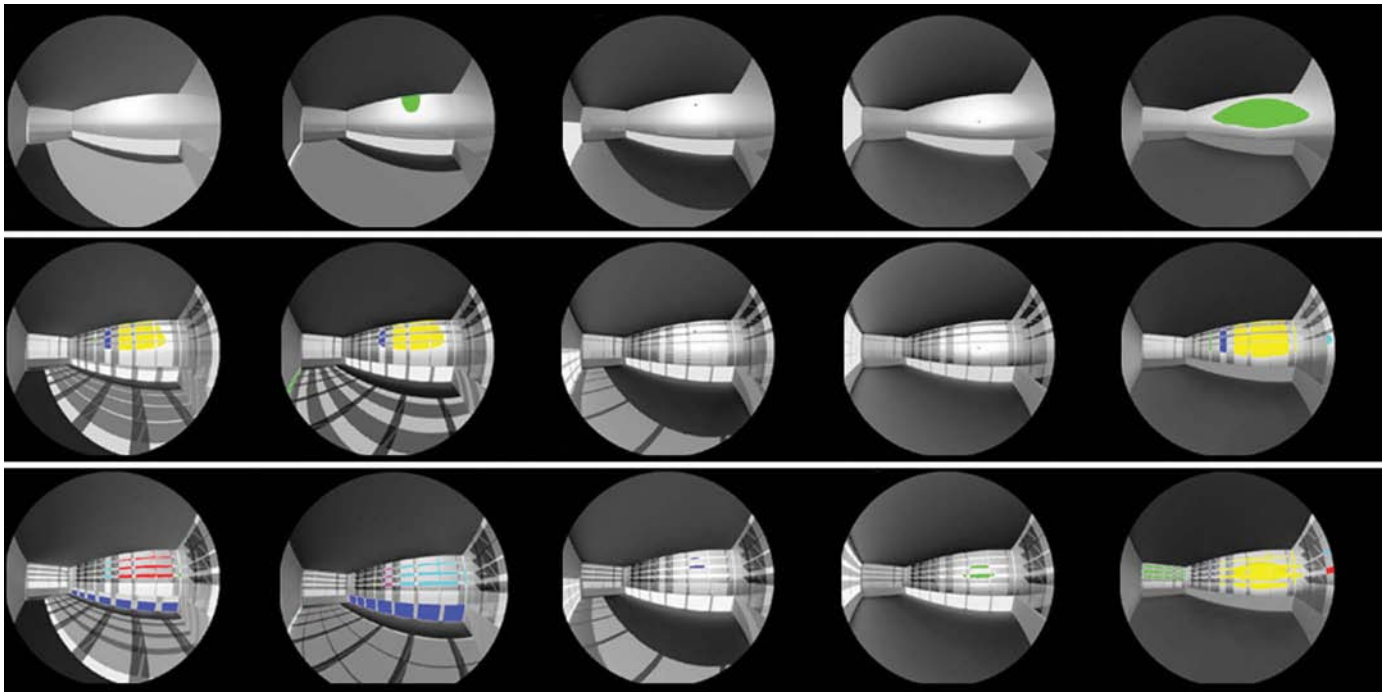
a | Daylight analysis of a fully glazed curtain wall facade: this results in high levels of daylight penetrating the office zones. Since the entire wall is glazed, an even spread of daylight is achieved in the space. Highest light levels occur at the corners of rooms where light is allowed to enter from 2 sides. In these areas, glare may cause discomfort for the user.



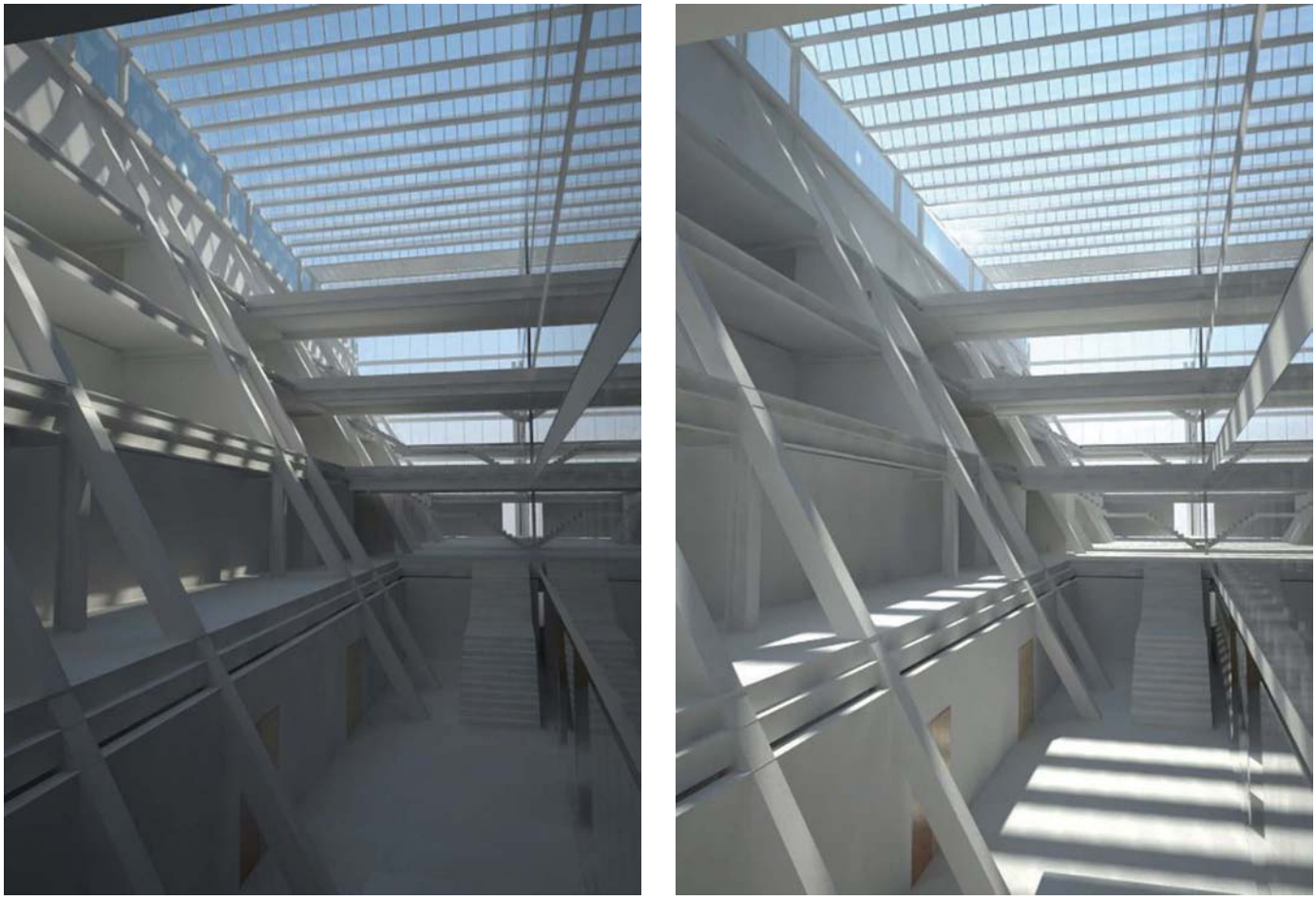
Scale
(Daylight factor)

0%	2%	4%	6%	8%	10%	12%	14%	16%

b | Daylight analysis of a solid facade with punched windows: this results in significantly reduced light levels within the office zones. Higher light levels occur close to windows; however the distribution through the rest of the space is still fairly even. Although the back of the office areas may experience low daylight factors, they may still be within an acceptable range for the tasks undertaken within the space.



c | Glare studies of a room highlighting areas of high contrast between daylight levels inside in the room and at the window for a series of shading designs.



d | By comparing rendered views it is possible to build up a picture of how light levels fluctuate throughout the day.

Levels of daylighting in buildings have increased in recent years in building types that consume a high level of energy through electrical lighting; mainly office buildings. An increase in daylighting, accompanied by a control of glare and solar energy from external shading, has led to a reduction in the energy used in electrical lighting, particularly near the glazed walls.

Daylighting levels are expressed as a daylight transmission factor, measured in terms of the percentage of daylight passing through the glazed facade (a). Daylight transmission factors of 70% to 80% are common in double-glazed units. For daylighting levels in buildings and their accompanying levels of electrical light to either supplement this or provide electrical lighting during hours of darkness, the amount of light required is defined for different tasks. Lighting levels are expressed in terms of lux, with office spaces having 250 lux, depending on how detailed the work needs to be and how the lighting is distributed between general lighting from the ceiling, and task lighting usually provided on desks, which can give up to 400 lux.

Analysis is typically carried out on the working plane of the room, typically 700mm above floor level, as this is where light levels have most impact on the occupants. Analysing a space in section is also beneficial as it can highlight areas of particularly high contrast between light and dark spaces (b).

Analysis method

The calculation of internal daylight levels requires considerable data input to achieve accurate results. Changes in minor elements of the design such as internal finishes can have a significant effect on the daylight factor within a given space.

Computer rendering can be used as a simpler alternative to digital analysis if quantitative results are not important. Care must be taken when treating rendered images as accurate representations of actual lighting conditions, as what appears dark in a given image may actually be adequate in a working environment (d). When used in comparative analysis, rendered images can help to assess the quality of light within a space over the course of a year.

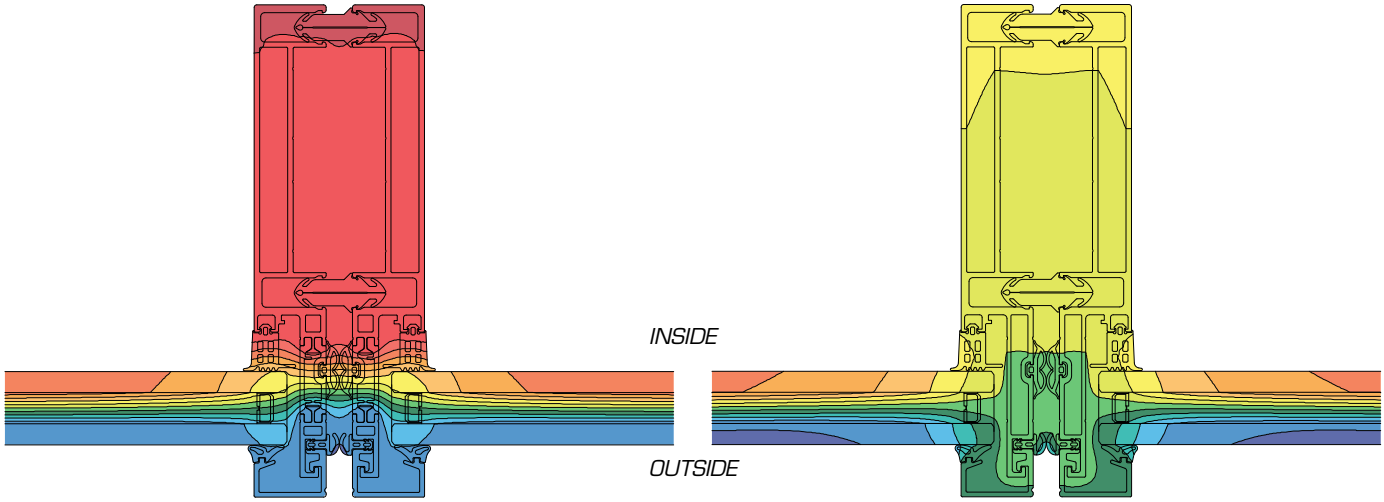
If quantitative daylight analysis is undertaken, it is essential to construct the digital model as accurately as possible with regard to window openings, floor and ceiling profiles and proposed furniture.

Daylight vs solar gain

An environmental study can investigate what daylighting levels are provided by a facade and suggest ways of modifying the design to balance daylight with heat gains and energy losses.

When designing shading systems, a balance needs to be struck between providing an appropriate shading response and maintaining natural light levels within the building.

In climates where light levels outside the building are particularly high, it is necessary to reduce the amount of open area on the facade to reduce glare and create comfortable working conditions for the occupants (c). In this situation shading elements can help to reduce the overall transparency of the facade.



a | Diagram of thermal performance of a unitised curtain wall mullion with an integrated thermal break. Isotherms show areas of equal temperature within the mullion in a design case that specifies an exterior temperature of -18°C and an interior temperature of 24°C. The low conductivity of the thermal break component reduces the heat transfer between the outside and inside.

b | Diagram of thermal performance of a untised curtain wall mullion system without a thermal break. The absense of a thermal break results in an inside temperature of close to 0°C, compared to around 15°C for the thermally broken mullion.

Controlling the rate at which heat energy is exchanged with its surroundings is an important factor in maintaining a constant temperature within a building. Keeping heat inside buildings in cold climates reduces the energy demand for mechanical heating in cold climates. In warmer climates, keeping heat out of buildings will help to reduce the energy costs associated with mechanical cooling. Another benefit of good thermal insulation is the reduced risk of surface condensation, which is unsightly and can damage the building envelope.

A thermal insulator is a material which opposes the transfer of heat between areas of different temperature. Thermal conductivity (λ) is the rate at which heat is conducted through a particular material and is a measurement that allows the comparison of how well different materials conduct heat. It is measured as the heat flow in watts across a thickness of 1m of material, for a temperature difference of 1 degree Kelvin and a surface area of 1m². The unit is W/mK. Resistivity is an alternative method of defining the conduction of materials and is expressed as 1/λ with the unit mK/W. Values for the thermal conductivity of common materials can easily be found in manufacturers' data tables.

U-values

A U-value is the measure of the overall rate of heat transfer through a particular section of the building envelope. Each layer of material will conduct heat at different rates depending on its resistivity, whilst cavities will allow heat transfer through conduction and convection. In addition, the inside and outside surfaces of the wall or roof will radiate heat to their surroundings. The U-value is regarded as a combined thermal transmittance coefficient and is measured as the rate of heat flow in watts through 1m² of a structure where there is a temperature difference across the structure of 1 degree (Kelvin or °C). It is expressed in W/m²K.

U-values are calculated from the thermal resistance of the parts making up the envelope construction. Each element of the wall or roof will oppose the transmission of heat by varying amounts depending on their material. This is referred to as its thermal resistance or R-value.

Thermal resistance falls into three catagories:

Material Resistances – The thermal resistance of each layer of material depends on its conductivity and its thickness. It can be calculated using the following formula:

$$R=d/\lambda$$

Where

R = thermal resistance of element (m²K/W)
d = thickness of material (m)
λ = thermal conductivity of material (W/mK)

Surface Resistances – At the surface of the building envelope, the air in contact with the building skin forms a stationary layer that opposes the flow of heat. Surface resistances can be obtained from tables of design standards.

Airspace Resistances – The thermal resistance of an airspace or cavity depends on the nature of conduction, convection and radiation within. These can vary depending on the thickness of the airspace or the flow of air through it. Typical values can be found by consulting published standard values.

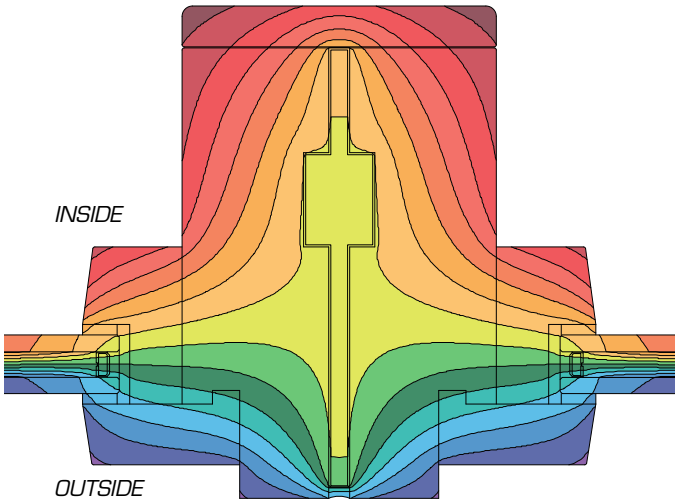
The total thermal resistance can be calculated as the sum of the thermal resistances and the external surface, of each component, including air cavities, plus the internal surface and air cavities.

$$R_T = R_{SO} + R_1 + R_2 + R_3 \ldots + R_n + R_{SI}$$

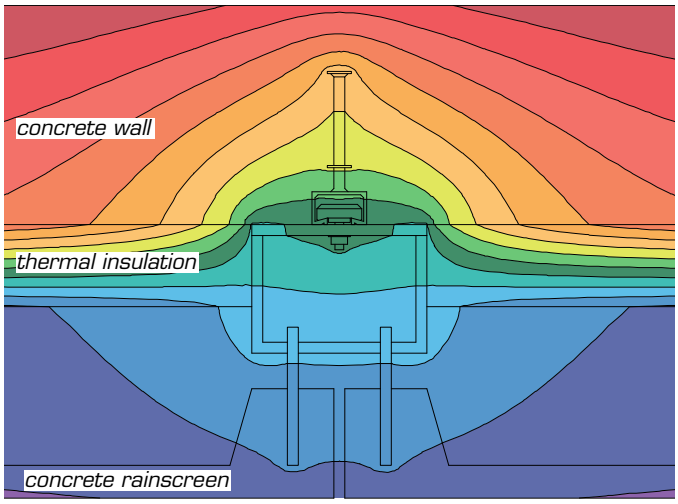
The U-value is expressed as the reciprocal of the total thermal resistance:

$$U=1/R_T$$

Typical U-values for solid wall and roof build-ups are around 0.2 - 0.35 W/m²K. For glazed assemblies an overall U-value of around 0.15 W/m²K can be achieved although the glass unit itself may have a U-value of up to 1.0 W/m²K.



c | Diagram of thermal performance of a timber framed window. This has a thermal performance comparable to a thermally broken aluminium system. The resistivity of timber reduces heat transfer through the profile, and despite the presence of a steel insert between the frames, the interior temperature of the frame is around 15°C



d | Diagram of thermal performance of a rainscreen cladding system. In this system, thermal insulation is used to limit the transfer of heat from inside to outside. The weak link of the system is the fixing bracket and the diagram above shows how the temperature levels distort around the cladding support

Where a particular part of the building envelope contains more than one construction system, for example a window in a wall, the overall U-value can be calculated by assessing the relative areas of each construction and relating their specific U-value to each proportion:

$U_{average} = (A_1 U_1 + A_2 U_2 + ...) / (A_1 + A_2 + ...)$

Where A_1, A_2 etc are the areas of each construction and U_1, U_2 etc are the U-values associated with each component.

Air temperatures within buildings are kept at between around 18°C and 25°C, with the surface temperature of facades being a few degrees either side of this temperature for the internal face. Isotherm diagrams are used to investigate and check variations of temperature across facade systems (a), and these also serve to detect and check thermal bridges across facades. Isotherm diagrams are also used in conjunction with thermal calculations or thermal models of a building, including its facade. The diagrams above show isotherm projections for a number of different facade systems in a cold climate (c). Poorly performing systems result in cold surfaces on the interior surfaces of the facade, which will in turn affect how the interior temperature of the building is maintained (b).

Humidity levels are significant in the transition from inside to outside, particularly when linked to extremes of air temperature. The relative humidity inside buildings is set in the region of between 30% and 70%, depending on the internal air temperature. Dew point diagrams are used to determine where condensation will occur for the most demanding or extreme conditions experienced by the facade. This might be done in summer when, for example, it is hot and humid at 45º outside, while internal conditions are air-conditioned at 18º. It is essential to know where the dew point will occur to see if condensation forming at the dew point will cause any damage to the construction, and whether vapour barriers are needed in particular locations or whether it is better to allow parts of the construction to be ventilated to either the inside or the outside.

While data for established forms of construction is usually easily available, and is used by manufacturers, unusual designs or significant variations from established facade systems will need to be checked from first principles.

Thermal properties of glass

In glazed areas the U-value of the construction must be evaluated in conjunction with the potential for heat transfer through solar gain to understand its overall thermal performance. The performance data for glazed assemblies often refer to the following properties:

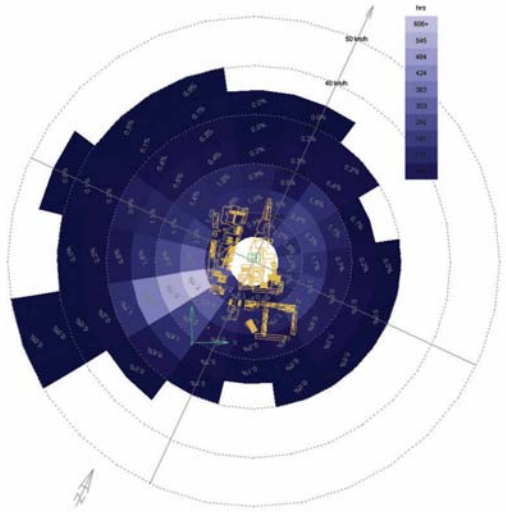
G-value – The coefficient used to measure the solar energy transmittance of glass. It is expressed as a value between 0 and 1, where low values represent low thermal transmittance. The g-value is sometimes referred to as the Solar Factor and is expressed as a percentage (for example a g-value of 0.35 is equivalent to a Solar Factor of 35%).

Solar Heat Gain Coefficient (SHGC) – The solar energy transmittance of a complete glazing assembly including glass, frame, opaque inserts and external shading.

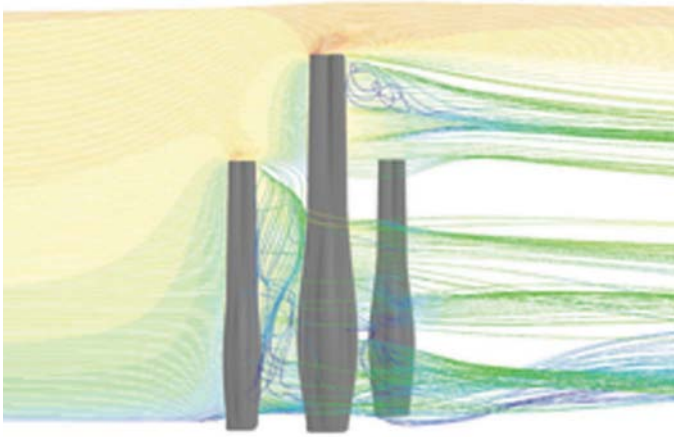
Shading Coefficient – The ratio of the solar energy transmitted by a particular glass combination to that transmitted by a reference glass, usually 3mm or 4mm thick clear glass.

Light Transmission – The percentage of light that passes from the outside of the glass assembly to the inside. This is often expressed as a percentage with lower values representing lower levels of light transmission.

When calculating U-values of glazed assemblies it is important to consider taking an averaged value that takes into account the thermal transmittance of each element. An averaged U-value of a glazed assembly would include the individual values for the glass, the frame and any insulated spandrel panels that may be present.



a | Wind rose for U.K. site



b | CFD analysis of air movement around a collection of tall buildings

Airflow in and around buildings can have a large impact on their design and the way people experience it. At a large scale it is important to understand how prevailing wind conditions (a) will affect building performance and in turn how it will impact its surroundings. Loads imparted on the building will affect the design of the structure, cladding and weathertightness which means that an understanding of the prevailing conditions will allow the design team to minimise potential problems during the design process. The size and form of a new building development will have an impact on wind paths, which could cause problems for neighbouring structures and reduce pedestrian comfort.

Airflow studies within buildings can help to assess the effectiveness of ventilation systems, identify areas of stagnant air within buildings and even predict the spread of heat and smoke should a fire break out in certain locations. All of these factors will have an impact on the levels of comfort experienced by the users, and identifying potential problems early in the design process will save costly remedial work at a later stage.

Wind and the urban environment

In built-up areas, wind speeds are often accelerated at pedestrian level due to the particular aerodynamic configurations associated with buildings (b). This is particularly problematic with tall buildings which can induce downdraughts at their base due to the pressure variations created by velocity differences at the top and bottom of the building. It is direct exposure to the wind rather than the height of the building that causes the problem of downdraughts, which means that they will only induce high wind speeds at lower levels if a significant part of them is exposed to direct wind flows. If a building is significantly taller than its surroundings, this effect can be exaggerated further.

Where buildings are positioned adjacent to one another, the channelling of wind flows between them can induce horizontally accelerated airflows at ground level. Similarly, openings through the base of buildings can induce high wind speeds due to the difference in pressure between the front and back of the building. To the average person, these accelerated wind speeds are no more than a discomfort, but in extreme conditions they can affect pedestrian safety. During the design process, pedestrian comfort studies can help to understand wind conditions at street level (c). For each test location, a wind speed is established and evaluated to determine whether it is considered comfortable. The definition of comfort depends on the activity that the space is designed for. This falls into four main catagories:

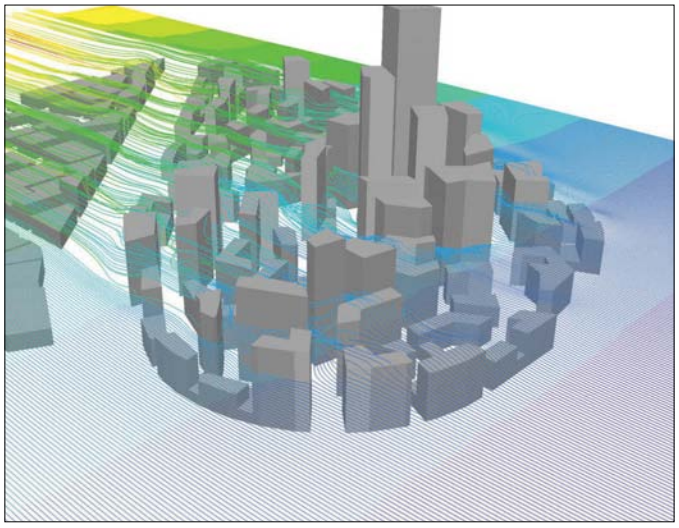
Long stationary – areas in which a person will spend more than 10 minutes in a stationary activity such as sitting. In these areas wind speeds of up to 10m/s are considered comfortable: during which a person can read a newspaper without it blowing away. This is recommended for outdoor seating areas and other areas that promote long-term sitting.

Short stationary – areas in which a person may spend no more than 10 minutes in a stationary activity such as queuing or waiting. Examples include building entrances or bus stops, where people will linger but not sit for prolonged periods. Wind speeds of up to 14m/s are considered comfortable for these locations; a level that will rustle leaves.

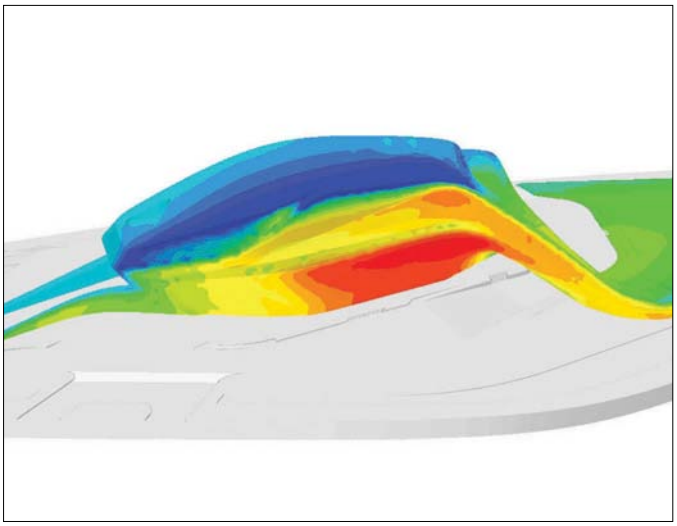
Recreational motion – areas where the average person will be walking at slow speeds or involved in recreational activities such as frisbee. Wind speeds of up to 19km/h are considered comfortable for these locations; a level that would lift leaves and disturb loose clothing.

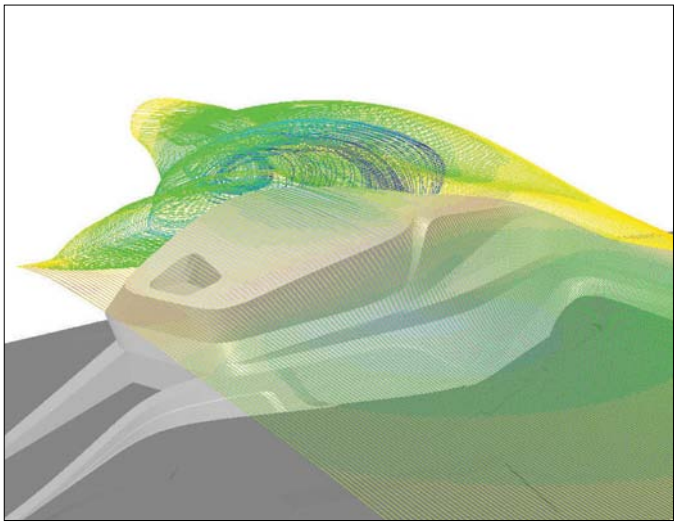
Transitory motion – areas where the average person will be active and receptive to some degree of wind movement. Examples include pavements, playing fields or plazas. Wind speeds of up to 25m/s are considered comfortable for these locations, a level that would lift loose paper.

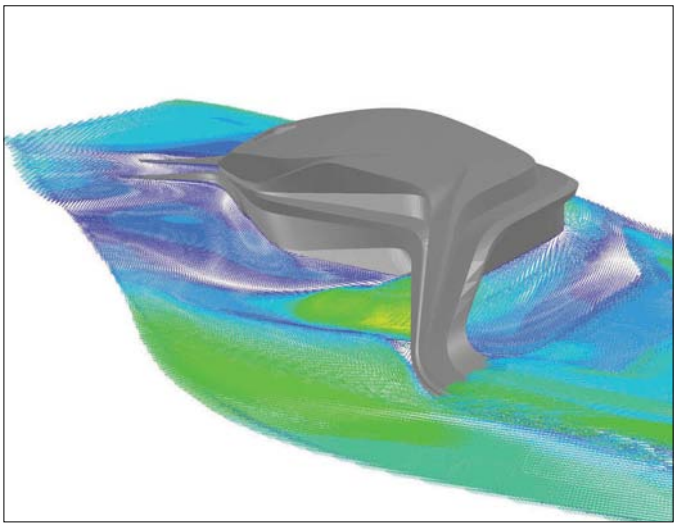
The criteria above include both average wind speeds and peak wind speeds, which take into account the fact that there will always be a few days in the year when wind speeds are particularly high. Wind conditions are considered comfortable if they are within the specified range for at least 80% of the time. The exact values may change depending on local climate and the expectations of the potential user groups.



c | Study of windflow in an urban environment







d | CFD studies looking at the effect of local topography on the proposed building. Wind from different directions has different effects on the cladding pressures due to the overshadowing effect of the hillside.

The analysis highlights the accelerating effect of the tail component geometry, especially at ground level which could compromise pedestrian comfort.

This analysis helps to develop structural and environmental responses during the design process.

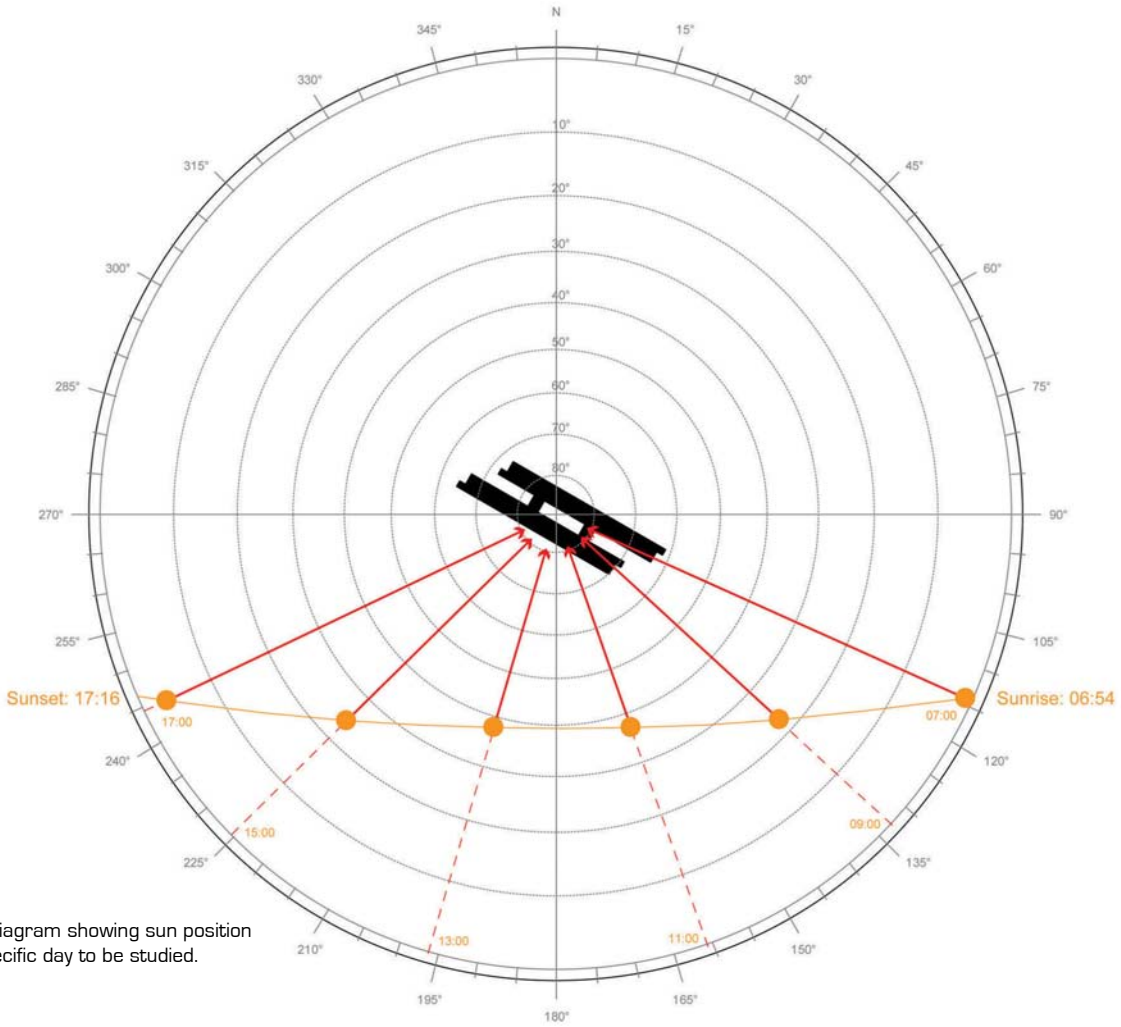
Wind speeds above 25m/s are considered uncomfortable in most situations. The effects vary from small trees swaying to walking becoming an inconvenience. Gusts of wind above 88 km/h are considered dangerous if they occur regularly. Gusts of this speed can significantly affect pedestrian balance and cause slight structural damage to buildings.

Once potential problems have been identified, modifications to the building's design can help to reduce their impact. Curved buildings, for example, generally promote lateral airflows and behave much better than angular buildings in terms of pedestrian level winds. Canopies or skirts at the base of tall buildings can prevent downdraughts from reaching ground level, whilst balconies or alcoves in the building facade can diminish downdraught effects at pedestrian level. In each case, however, such measures may simply transfer the problem to another part of the building or across the street.

Testing methods

Pedestrian comfort studies have traditionally been performed using wind tunnels. In these tests a scale model is used to assess the impacts of wind from different angles and at different speeds. Sensors record wind speeds at critical areas to give accurate and reliable predictions of the building performance. Since measurements can only be taken at discrete points on the model, it is not possible to form a complete 3D view of wind flow around the building. More sensors will result in more accurate analysis: however, this has added expense and increases the risk of the sensors themselves interfering with wind flows and corrupting the data.

Advances in computer power and digital technology have allowed for an alternative approach called Computational Fluid Dynamics (CFD) to become a viable alternative to wind tunnel testing. CFD analysis allows designers to investigate the whole modelling domain to build up a detailed picture of airflows, velocities and pressures which can be presented in an easy-to-understand graphical form (d).



a | Sunpath diagram showing sun position on the specific day to be studied.

The relative position of the sun is a major factor in the heat gain of buildings, and understanding how the sun moves across the sky is crucial in preventing unwanted solar gain through building facades. The term 'sunpath' relates to the apparent positional changes of the sun as the earth rotates and orbits the sun. The position of the sun in the sky changes continually throughout the day and is also subject to seasonal variation. Sun position is very location-dependant and the latitude and longitude of the site is required before accurate sunpath data can be produced.

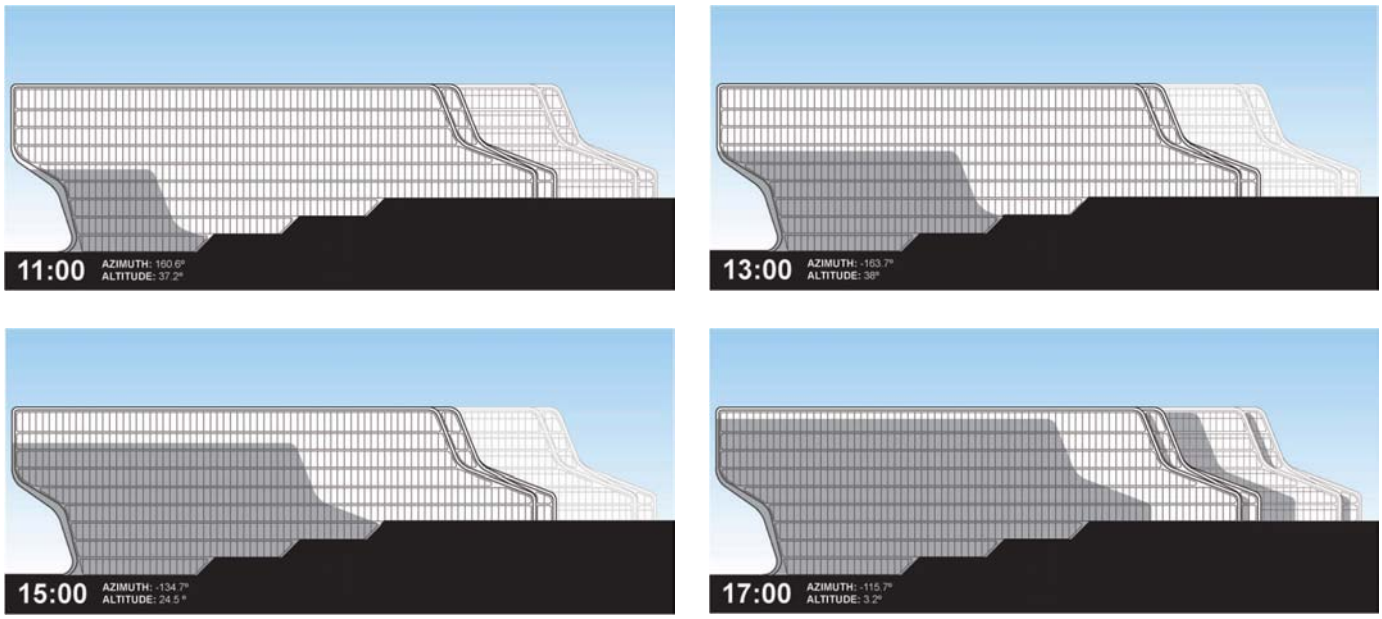
A sunpath diagram, such as the one shown above (a), is a method of displaying the annual changes in sun position in an easy-to-interpret 2D diagram. For any given time of the year, data for the azimuth (horizontal sun angle relative to north) and altitude (vertical sun angle relative to horizontal ground plane) can be evaluated and used to develop effective shading systems.

The diagram above shows the sunpath for a single day and highlights the sun's position at regular intervals as well as showing the times of sunrise and sunset for the specific site location (a). The sun is at its highest between 11am and 1pm when it reaches an angle of 50°.

The amount of radiation incident on the building facade is governed by the Lambert cosine law which states that the relative intensity of radiation on a surface is equal to the cosine of the angle of incidence, and that the relative area over which it is distributed is equal to the inverse of this value. Therefore high-angle sun, whilst stronger, imparts only a fraction of its energy on a vertical facade, whilst low-angle sun imparts a greater percentage of its energy. For this reason, horizontal facades in equatorial climates where sun angles are high are more prone to solar gain than vertical facades.

Within a building the effect of sunlight penetration can have a dramatic effect on user comfort. This is affected by a number of factors such as the occupancy of the space and the tasks that the users are undertaking; for example direct sunlight in an atrium or circulation space may be desirable, whereas in an office environment it may become problematic. Similarly, sunlight entering a building early in the morning before the building is in use may not be considered a problem.

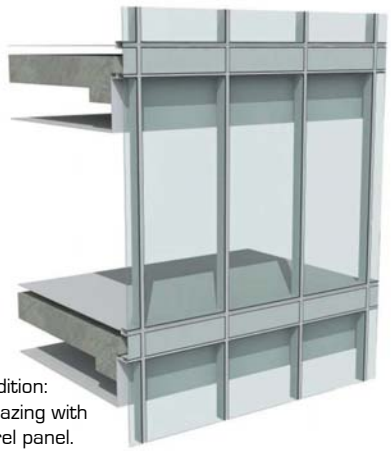
Shadow studies on the interior of the building can help to build up a picture of how direct sunlight enters the building over time (c). These can be used to analyse the impact of shading devices or overshadowing elements of the surrounding site, and identify the need for additional shading systems such as blinds or screens to block sunlight completely.



b | Shadow projection of surrounding buildings on the glazed office facade at different times of the day.



c | Study of sunlight penetration into the office space throughout the day to assess the impact on internal working conditions.



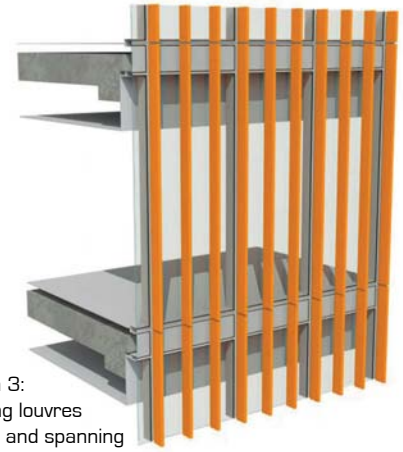
d | Unshaded condition: Floor-to-floor glazing with opaque spandrel panel.



f | Shading option 1: Small horizontal louvres equally spaced over full extent of glazing



e | Shading option 2: Single, large louvre positioned at spandrel level



g | Shading option 3: Vertical shading louvres equally spaced and spanning floor to floor.

The need to control the amount of sunlight that penetrates the building facade is based on a number of design considerations. In warm, sunny climates, excess solar gain may result in high cooling consumption to keep the internal temperature at a comfortable level. In cold climates, winter sun entering the building can contribute to passive solar heating and help reduce the winter energy consumption. Sunlight penetration into buildings can also have a detrimental effect on human comfort as the impact of glare can easily make a space unsuitable for carrying out certain tasks. For this reason shading devices can also be used to improve the user's visual comfort by controlling glare and reducing contrast ratios.

The design of any shading device will depend greatly on the path of the sun through the sky at the building's location as well as the orientation of a particular building facade. Thus, a shading system developed for a building in Europe may not be suitable for an equivalent building in the Middle East. The following concepts hold true for most shading applications:

Horizontal shading – protects from high-angle sun and is typically used on facades that are equator-facing. For locations with high sun angles, a single louvre at floor level can shade a whole storey of glazing (e). A more dense shading arrangement may be required in locations with lower sun angles (f).

Vertical shading – Generally used on east and west-facing facades to protect against glancing sun angles (g). Vertical shades are also useful on pole-facing facades to protect against low-angle sun in the early morning and late evening.

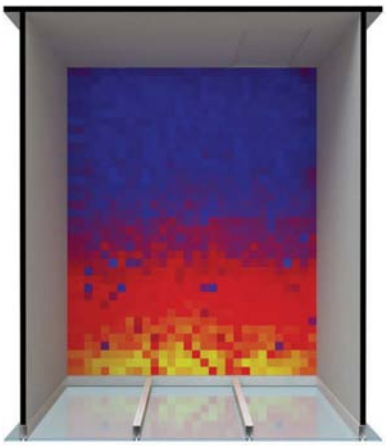
Shading screens – Perforated screens on the outside of the building reduce the amount of direct sunlight that hits the facade. The effectiveness of shading screens is dependent on their opacity and has a significant impact on the amount of daylight entering the building.

Interior devices – Blinds, curtains and other interior shading devices have limited ability to control solar gain; however they can help to control the penetration of low-angle sun into the building as well as reducing the impact of glare. Interior devices tend to be controlled by the user, which gives occupants a sense of control over their environment.

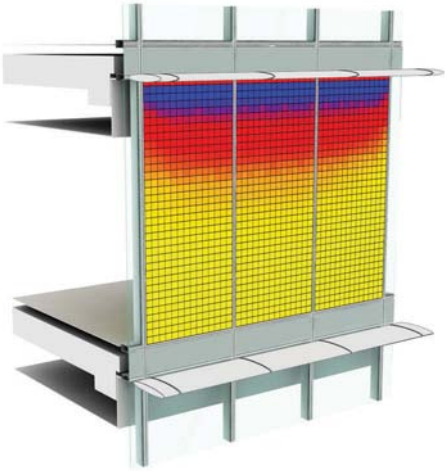
The development of high-performance glazing products with low shading coefficients has led to buildings being less reliant on shading systems; however they allow significantly less light to enter the building. External shading systems allow more transparent glass to be used without compromising the overall performance of the facade.

The studies on this page show a comparison of the shading performance of different louvre configurations alongside their impact on daylight levels within the building (j)(k)(m). An unshaded glazing bay is used to provide a reference case for the shading systems to be compared against (h).



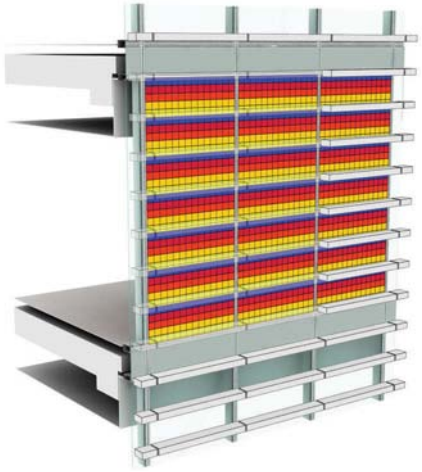


h | The unshaded facade sets the benchmark for exposure levels. This configuration allows high levels of daylight to penetrate the space.



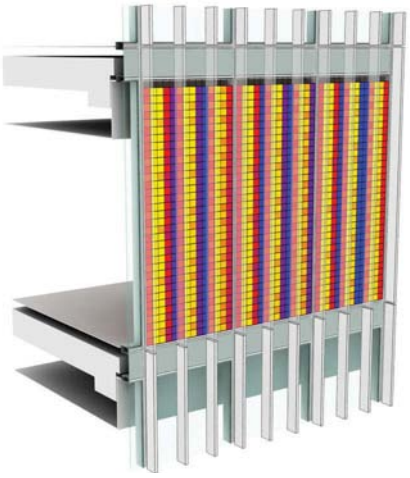


j | A single horizontal shade stops high-level sun from hitting the facade. It has little effect on daylight levels and in some cases it may even increase daylight penetration as a result of reflecting light into the space



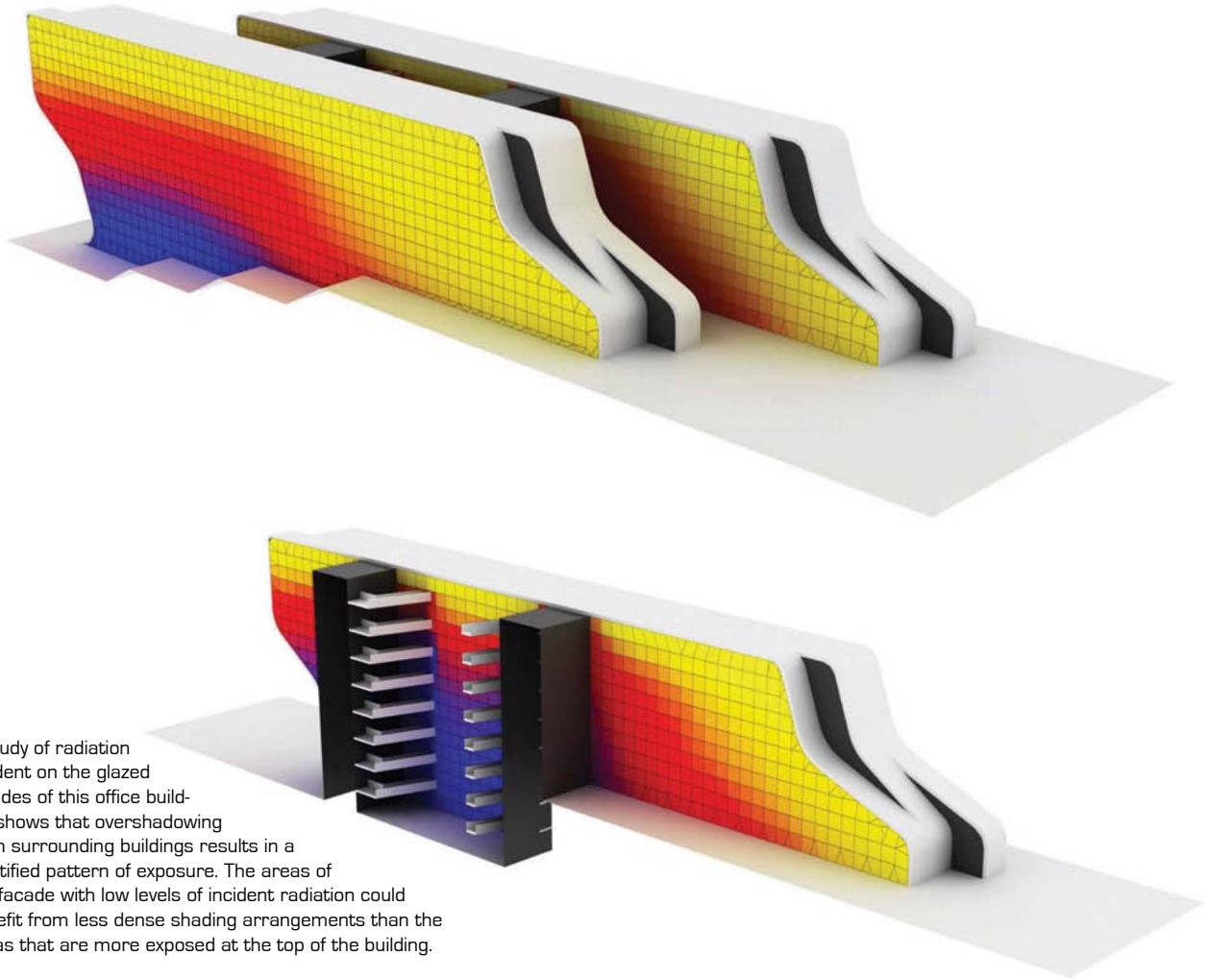


k | Evenly-spaced horizontal louvres have a greater shading effect but result in lower daylight levels inside the space.





m | Vertical louvres protect against low-angle sun hitting the facade at glancing angles but have little effect on high-angle sun. Daylight levels are similar to the horizontal layout.



n | A study of radiation incident on the glazed facades of this office building shows that overshadowing from surrounding buildings results in a stratified pattern of exposure. The areas of the facade with low levels of incident radiation could benefit from less dense shading arrangements than the areas that are more exposed at the top of the building.

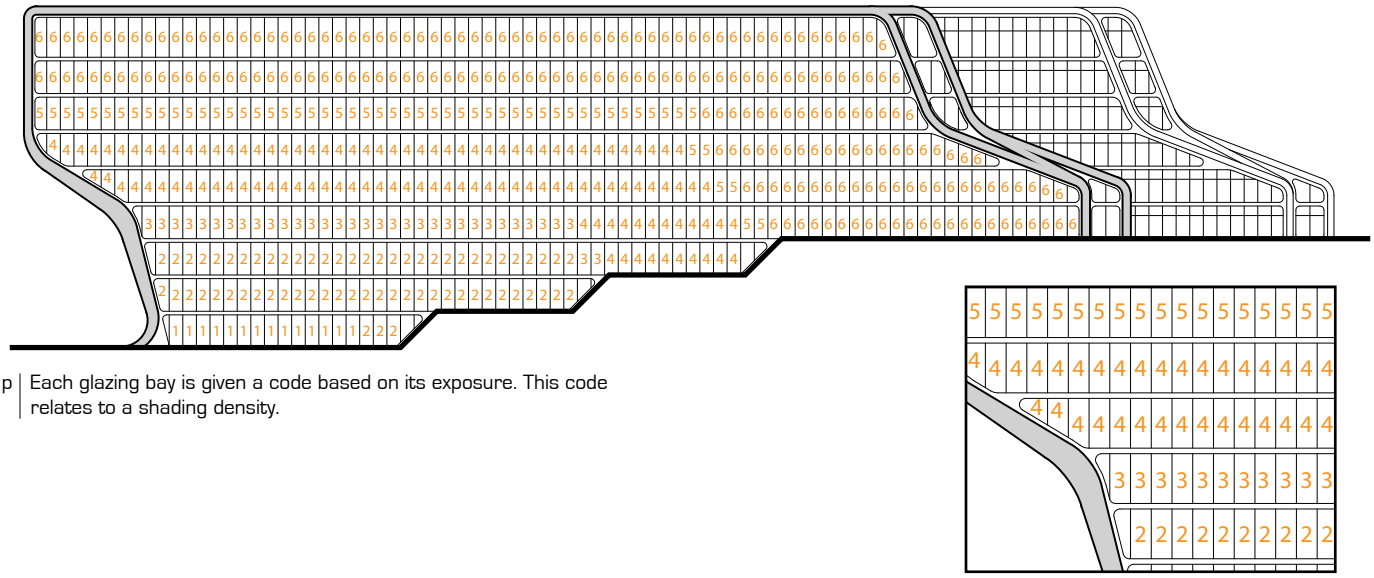
Shading devices can have a dramatic impact on building appearance and the earlier they are considered in the design process the more likely they are to become a well-integrated part of the project. With the increased use of digital analysis software, there has been a trend in recent years to develop whole building shading strategies that assess the shading demands of each part of the facade and develop specific solutions. This strategy allows the shading effects of the building geometry, the surrounding buildings and environmental features such as trees or hedges to be taken into account when defining the shading requirements of the building.

One of the many advantages of this philosophy is an improved relationship between the external climate and the internal space. Designers can consider the shading requirements of the space based not only on its orientation but also its function, and shading solutions can be developed that meet the building's specific needs. Location-specific shading solutions help to maintain visual comfort levels for users by allowing improved views out of the building whilst also ensuring higher levels of natural daylighting inside the space. Bespoke shading solutions also allow designers to differentiate building facades from one another, adding interest and human scale to even the most functional of buildings.

The case study on this page shows the development of a whole building shading system for an office building in Egypt. There was a need to design a shading system for the building to prevent the office spaces from overheating due to solar gain, but there was a desire to take advantage of the overshadowing effect of the building's geometry to limit the amount of shading louvers.

A digital analysis of the facade's exposure to direct sunlight identified that the upper floors of the building were in direct sunlight for large parts of the year, whilst the lower floors were less exposed (n). The design team was keen to avoid designing a shading system to the 'worst case' scenario and applying it uniformly across the facade. Instead, there was a desire to express the stratification of the exposure analysis and a decision was made to use a shading system that could be adapted to give many shading densities.

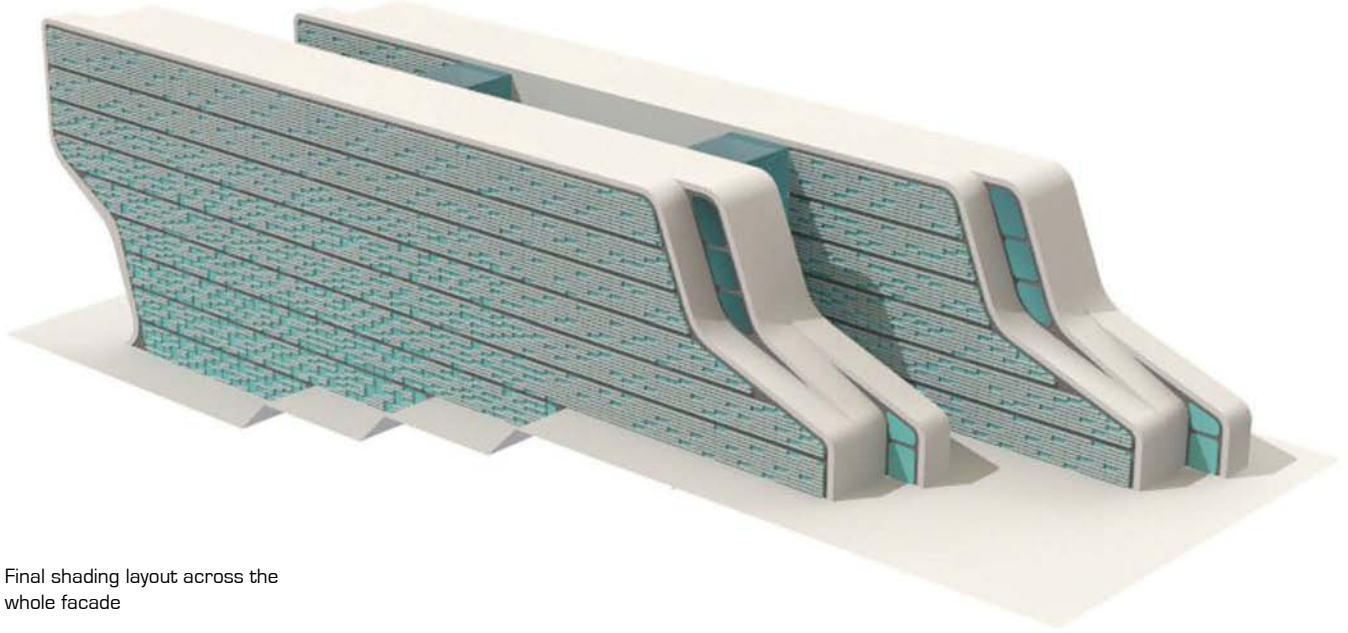
The digital study was mapped onto the facade so that each glazing bay was given a numeric value to represent the level of shading required to prevent the space behind from overheating (p). Earlier studies had identified that horizontal louvers were the best performing system for the climate and a series of louvre layouts were generated and mapped to the facade based on this shading level required (q). The result was a gradual increase of shading density across the facade which not only protected the interior from unwanted solar gain, but also maximised the amount of daylight entering the ground level spaces (r).



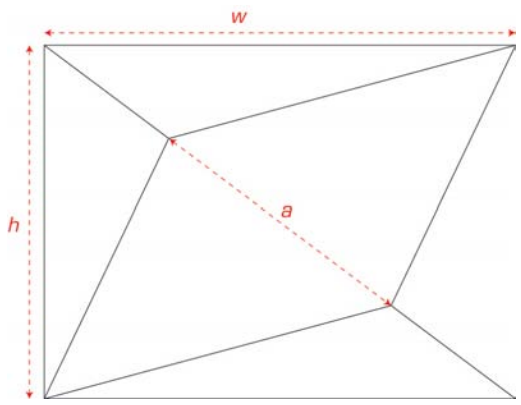
p | Each glazing bay is given a code based on its exposure. This code relates to a shading density.

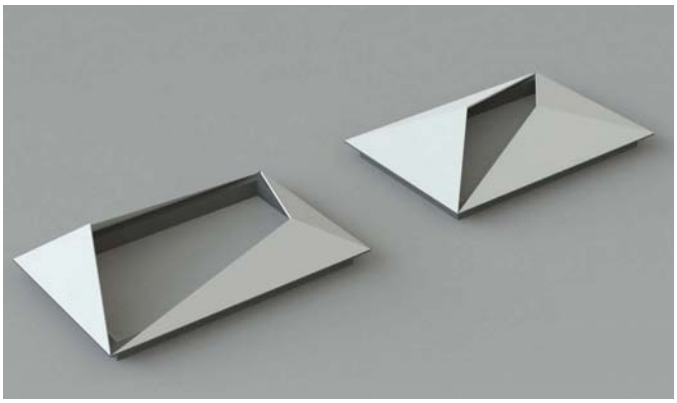


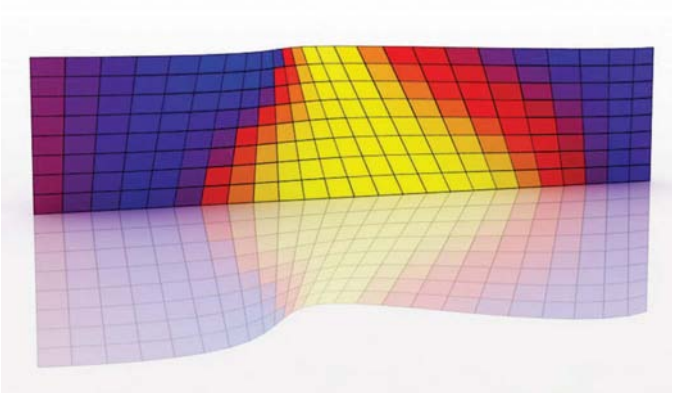
q | Different shading layouts of varying densities are set up.

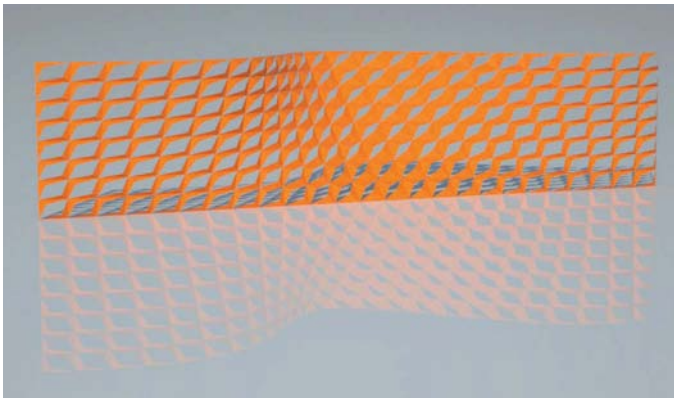


r | Final shading layout across the whole facade









s | A shading component designed to have a variable aperture, with the opening sized in relation to the amount of radiation incident on the facade at each particular location. In this case, distance 'a' is linked to the exposure value from an environmental study of a curved facade resulting in small apertures in highly exposed locations and larger apertures in locations with lower exposure.

Well-designed shading systems will protect a facade from the worst effects of solar gain and keep internal conditions at a comfortable level, but their static nature means they will never be able to protect against all sunlight conditions. In recent years there has been a rise in the deployment of adaptive shading systems which change their shading performance based on their location on a building facade. Adaptive shading systems fall into two main catagories; static systems and kinetic systems.

Static systems

These use fixed elements that have been shaped to suit the particular shading requirements of their location. The example above shows a component of a set width and height with a geometry that creates an aperture at the centre (s). The size of the aperture 'a' can vary to restrict the amount of sunlight that can penetrate, with small apertures used where facade exposure is high. A digital exposure analysis of the facade identifies exposure levels which can be used to size the aperture. The result is a shading system that relates directly to the site conditions.

Kinetic systems

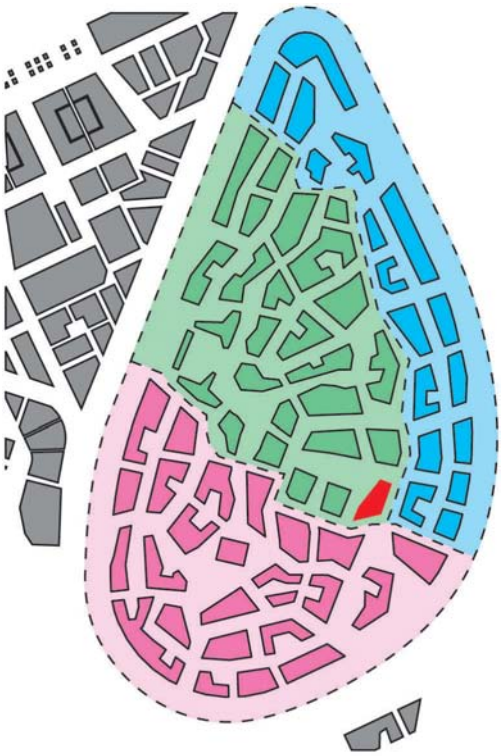
These systems use moveable elements which allow building facades to respond to a number of changing factors:

Sun position – Shading elements move based on the movement of the sun providing shading when needed, and when out of use can move to a position that maximises daylight into the building and provides unobstructed views out.

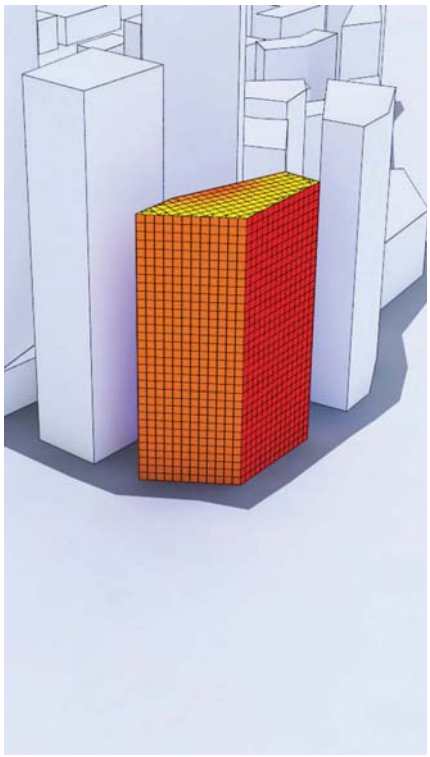
Context – Constant urban renewal means that the nature of the buildings surrounding a new development may change over its lifetime. The overshadowing potential of neighbouring structures cannot be relied on to be present for the lifetime of the building, and moveable systems allow the shading potential to alter over the life of the facade.

Function – The change in function of a building, or parts of buildings, may require changes in shading performance over the lifetime of the building. Moveable systems allow the shading components to be reconfigured based on the changing demands of the building.

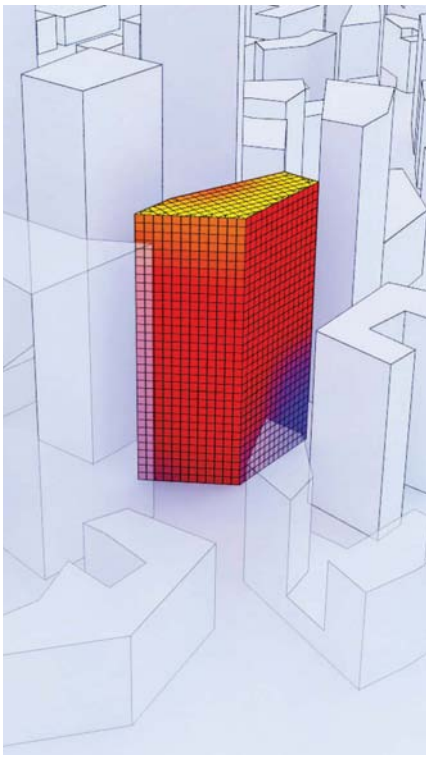
The example opposite shows a tower built as part of a master plan in the Middle East. The building was on the edge of the first phase of the development and the south facade was exposed to direct sunlight for much of the day (t). The latter phases included further development to the south with new towers overshadowing the facades of existing towers (u). A shading system was proposed with the potential for change over the lifetime of the building as the site developed. At the beginning of the building's life, the shading system would be working at its hardest to prevent solar gain from the south facade. As new buildings are constructed on the neighbouring plots, the moveable parts of the shading system reconfigure themselves to allow more daylight into the building with the overshadowing from surrounding buildings helping to control solar gain (v).



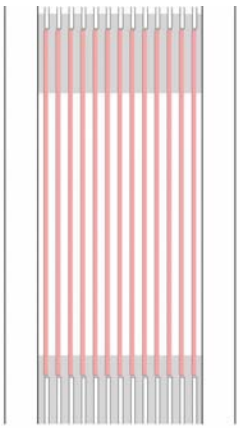
Development Phase 1
Development Phase 2
Development Phase 3
Building Study

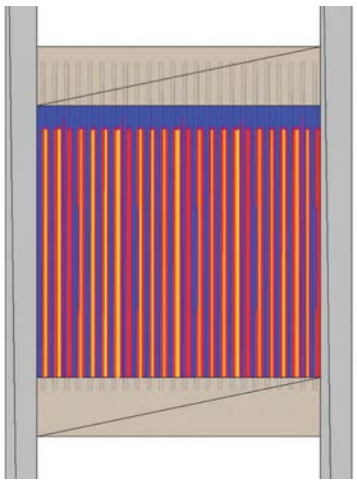


t | Facade exposure of building study after completion of Phase 1. South facade is highly exposed to direct sunlight

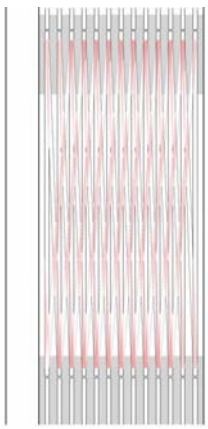


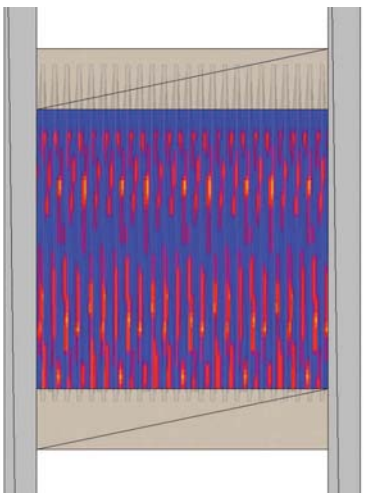
u | Facade exposure of building study after completion of Phase 2. Surrounding buildings offer a degree of shading to the lower floors on the south facade





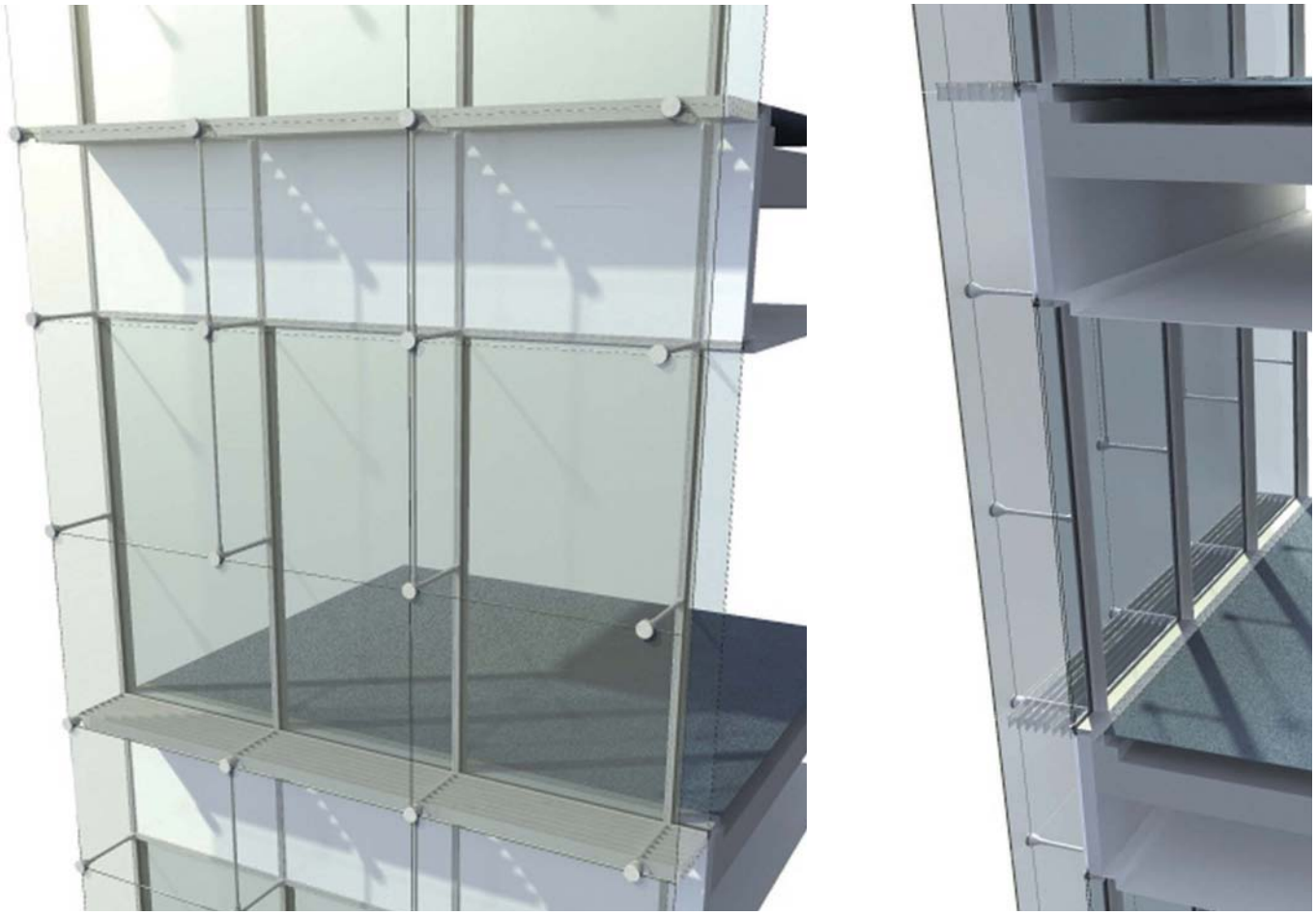








v | Study of sunlight penetration through moveable vertical shading system in two different positions to adjust the amount of daylight entering the building



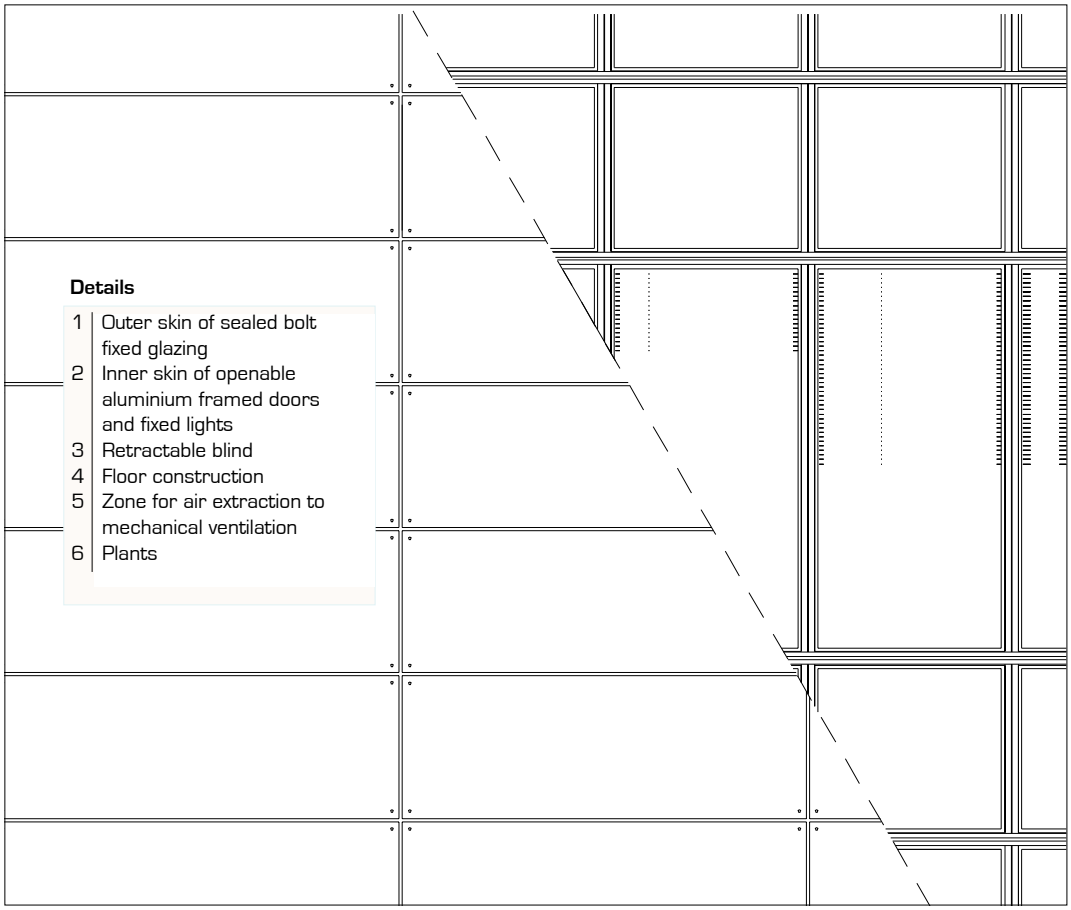
a | 3D views of corner-clamped double-skinned facade system

Double skin facades

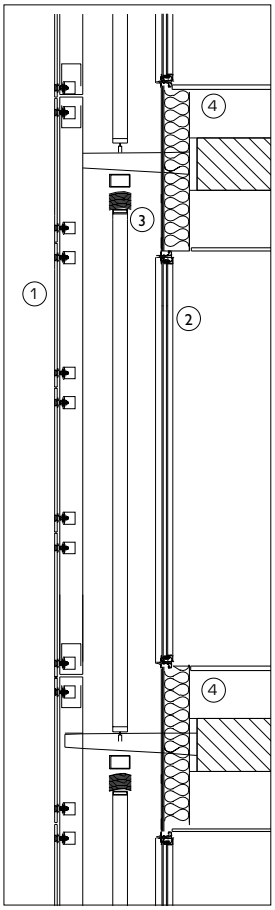
A recent development in facade technology has been the introduction of double skin facades, which present a solution to increasing requirements for natural ventilation, increasing daylighting and the use of thermal mass for night-time cooling. The use of double skin facades can provide energy savings of up to 50% in the mechanical ventilation of a building. External shading is useful in buildings with single skin glazed facades where there is a risk of high solar gain, resulting in overheating inside the building. When located externally, fixed shading systems are considerably cheaper than those with moveable screens or louvres, but they are unable to respond to the changing angle of the sun during the day, and throughout the year. Internal shading does not perform as well, as mentioned in the following sections. However, in double skin facades the solar shading is installed in the void between inner and outer skins, where the blinds are better protected. Conventional single layer glazed walls tend to introduce conflicting performance requirements into a single layer. Solar control films or layers have the effect of reducing the transparency of external walls, which increases the amount of electrical lighting required internally. Layered facades separate out functions of waterproofing, solar control and ventilation in different configurations. In double wall facades these have become two generic types: thick walls and thin walls.

Thick walls

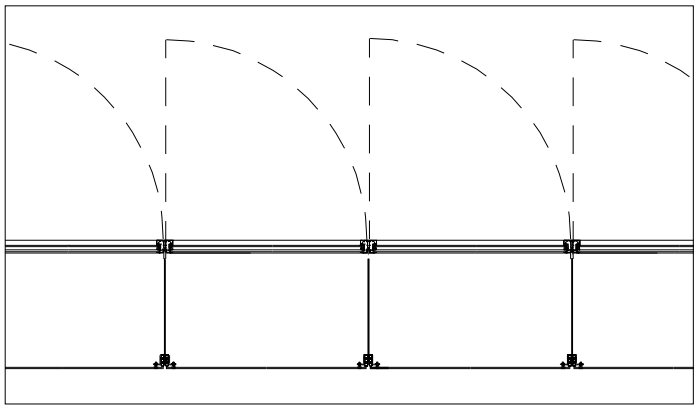
In thick double skin walls, an outer layer comprises a single skin of glass, typically a single-glazed bolt fixed glazed wall (a). This is separated from the inner wall by a gap of between 750mm and 1000mm. The wide cavity is required primarily for maintenance access (c). The inner skin is typically a standard double-glazed curtain wall system using either stick or unitised systems, with opening windows (d). Because the outer wall is protecting the inner wall from windblown rain, materials other than metal and glass can be used to form the inner wall. Fresh air is allowed to pass through the outer wall into the zone between the two skins. This is achieved either by having open-jointed, or partially-open joints in the outer glazed wall, or alternatively metal flaps or louvres at floor level that are operated mechanically to admit air at different times of the day and at different times of the year (q). This latter method provides a more controlled way of regulating air intake into the void between the two skins, but is considerably more expensive than the open joint method. Once air has entered the void its wind speed drops dramatically, allowing the inner glazed wall to have opening windows to introduce fresh air. This method is particularly useful in taller buildings over three storeys, where the wind speed is often too high to allow windows to be opened safely, particularly in office buildings and public buildings. A walkway is set into the void, usually at the same level as the internal floor to provide easy access to it and ensure that the walkway does not obscure views out of the building (f). The walkway allows the glass surfaces facing into the void to be cleaned and maintained easily. Depending on the height of the facade, the natural ventilation provided by this configuration uses external wind pressure to provide fresh air into the void. It uses the stack effect to allow the heat gained within the void, in warm weather,



b | Elevation 1:25



c | Vertical section 1:25



d | Plan 1:25



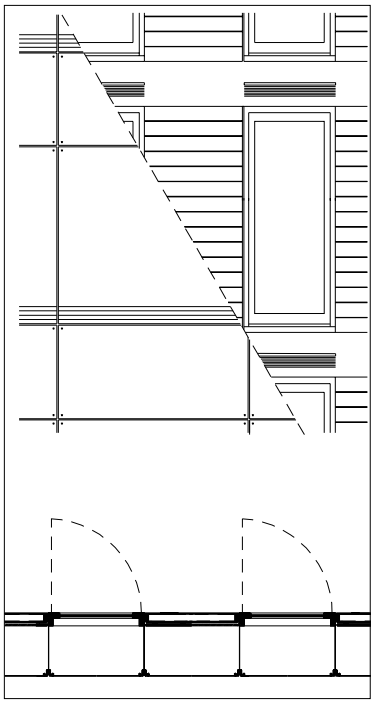
e | 3D view of twin wall from inside



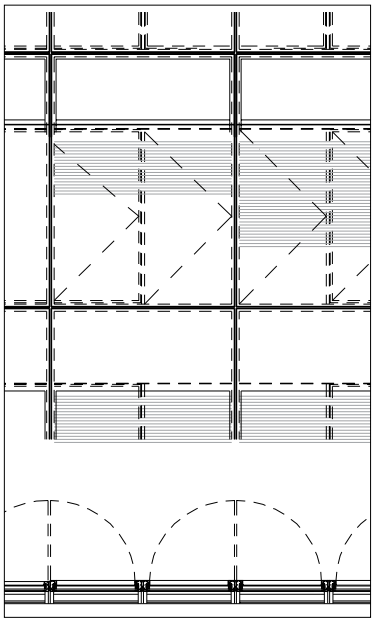
f | 3D view of twin wall cavity



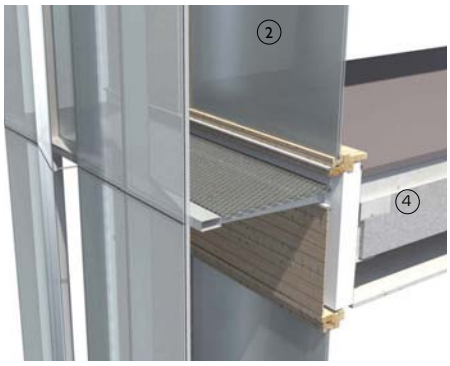
g | 3D view of vertical section through stepped twin wall facade system



j | 1:50 Plans and elevations. Thick wall with ventilated outer screen



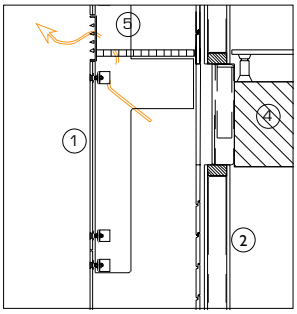
k | 1:50 Plans and elevation. Thin wall with out sealed glazed unit

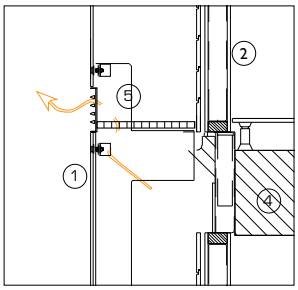


m | 3D section cut through double skin system with openable screen



n | Plan view of twin wall with openable screen





p | Vertical section 1:25 through thick twin wall system



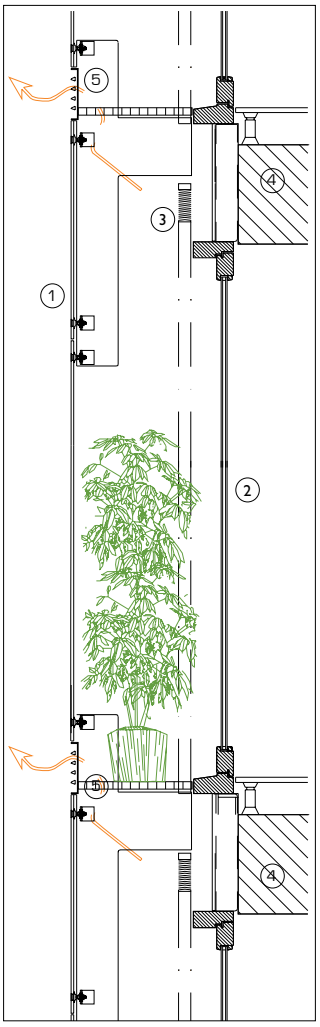
h | 3D view of double skin system with openable screen

Details

1 | Outer skin of sealed bolt fixed glazing
2 | Inner skin of openable aluminium framed doors and fixed lights
3 | Retractable blind
4 | Floor construction
5 | Zone for air extraction to mechanical ventilation
6 | Plants









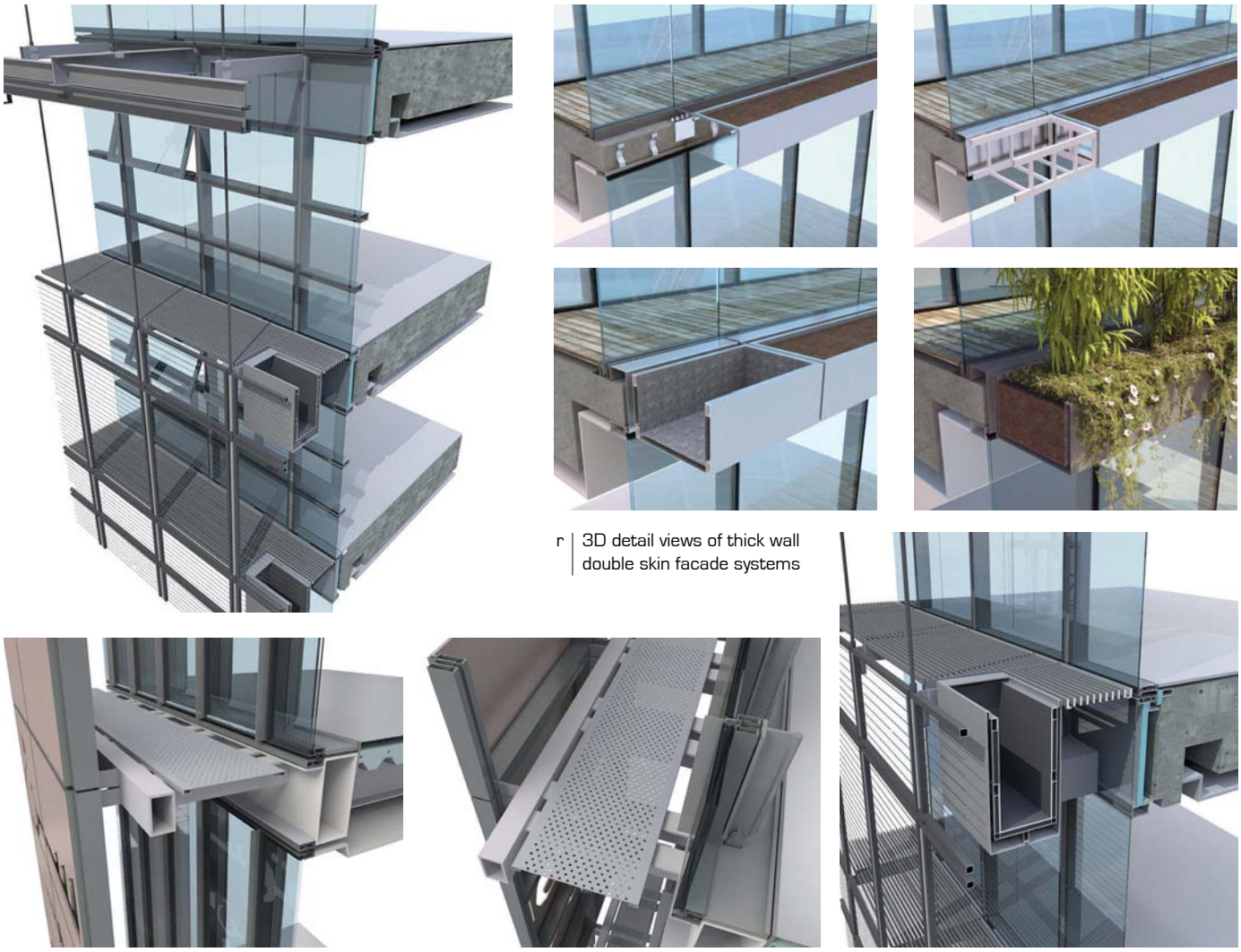
q | Vertical section 1:20 and 3D views through double skinned facade with plant in cavity

to escape to the outside (p). In winter, where solar gain is a much less significant issue, in open jointed methods of ventilation the outer skin can suffer from cold air being allowed to enter the void, which can act as a winter 'buffer zone'. The method of using metal flaps and louvres allows the quantity and frequency of fresh air entering the void to be more closely controlled. This helps to regulate the temperature of air passing through the inner wall, by ventilation or by opening windows. Air in the void between the two skins will be warmed in winter by heat transmitted through the facade as well as by any solar gains incident on the facade. The cavity within a double skinned facade acts in a similar way to that of a greenhouse. This area becomes ideal for the growth of many plants. The plants can not only enhance the appearance of the facade but also enhance the environmental benefits of the double skin system (q). Double skins help insulate the building, absorbing the heat of the sun during summer and retaining warmth during winter. Plants, it has been shown, are more efficient in controlling these environments than traditional blinds and other solar devices and can provide very efficient shading to interior spaces. In addition to this they can provide sound attenuation as well as providing potential crops or food growing areas in buildings.

Thin walls

Thin wall facades comprise two skins of glass set closely together, with a cavity in the region of 100mm wide (s). The cavity is mechanically ventilated, allowing it to be considerably smaller in depth than the naturally ventilated thick wall design. Air can be drawn up through the cavity from outside or from inside. Air drawn from outside needs to be relatively free of dust and pollution, since this makes the cavity dirty quite quickly. In this system, the air drawn through the facade is separate from the mechanical ventilation for the building. The inner skin has a series of opening doors to allow access into the cavity for cleaning and maintenance. Blinds are usually set into the void in order to provide solar shading. Solar energy absorbed by the blinds is radiated into the cavity where it is drawn away by air rising in the cavity. The warmed air is then ejected at the top of the panel.

In winter, warm air extracted from the inside of the building is drawn through into the facade at floor level or in the void below floor level and is drawn up through the external wall to reduce the amount of heat loss through it (u). When air is drawn through the facade from inside the building, the wall becomes an integral part of the mechanical ventilation system for the building. The air is drawn through a heat exchanger to be used in heating the space in cooler months, or is ejected from the building through the mechanical ventilation system. In summer, air drawn up the cavity from inside the building passes over the solar shading blinds, which are dropped down in place to provide solar shading. The heat from the blinds, as a result of the solar energy, is drawn away and is ejected from the building through the mechanical ventilation system. When the air into the cavity is provided from inside, the facade is completely sealed, and requires only occasional access to the void for cleaning and maintenance.



r | 3D detail views of thick wall double skin facade systems

As previously mentioned thin double skin walls, formed as unitised (prefabricated) panels, comprise two skins of glass set apart, forming cavity in the region of 100mm to 300mm wide. Panels are either ventilated from the outside with fresh air or are internally ventilated by the mechanical ventilation system. The construction of the panel is based usually on unitised glazing, where each panel usually from 1500mm to 3000mm wide (s). In contrast, wide double skin walls can be constructed as two stick-built facades, or as a mixture of stick and unitised glazing (r). Combined systems of ventilating from both the outside and the inside are not used to date due to the conflicting requirements of the position of the double-glazed units which need to be one side of the panel (either inside face or outside face) to suit either internal ventilation or external ventilation. The cavity can be either mechanically ventilated or naturally ventilated to suit performance requirements. Air is drawn up through the cavity either from the outside or inside and is expelled at the top of the panel, typically at each floor level.

Thin double skin panel ventilated to the outside has a single-glazed outer skin and a double-glazed inner skin. The inner skin is openable from inside, as opening doors, in order to access the cavity for cleaning and maintenance. Fresh air is introduced from outside at the base of the panel, admitted through slots at the bottom and expelled at the top (t). The solar shading blind is fixed at ceiling level, where it is usually left visible when in the closed position. The void above the blind, in the floor/ ceiling zone, is closed off by a metal faced spandrel panel on the inside skin. Air is drawn up to the top of the cavity, which helps to avoid heat build-up in the void which is highly insulated at this point.

Thin double skin panels ventilated on the inside are formed with a double-glazed unit on the outside and a single-glazed panel on the inside face, with the inner panels opening for cleaning and maintenance. Tempered air from inside the building is drawn into the void of the facade panel at floor level, or in the void below floor level, and is drawn up through the cavity to provide a thermal buffer. The air is extracted internally and drawn through a heat exchanger to be used in heating the space in cooler months, or is ejected from the building through the mechanical ventilation system (u). In summer, air drawn up the cavity from inside the building passes over the solar shading blinds, which are dropped down into place to provide solar shading. The heat from the blinds, as a result of the solar energy, is drawn away and passed through the mechanical ventilation system. When the air into the cavity is provided from inside, the external skin of the facade is sealed while the inner skin is openable. The cavity between the glass skins requires cleaning from the dust drawn into the cavity between the two glass skins. The set of doors on the inner skin provides access for cleaning the two faces of the cavity, but the external face of the wall of both types requires cleaning from outside, typically from a cleaning cradle. An advantage of the blinds being in a cavity rather than on the outside is that they can be made to be moveable without the need to have motorised equipment outside, where it is more vulnerable to deterioration in the external environment.



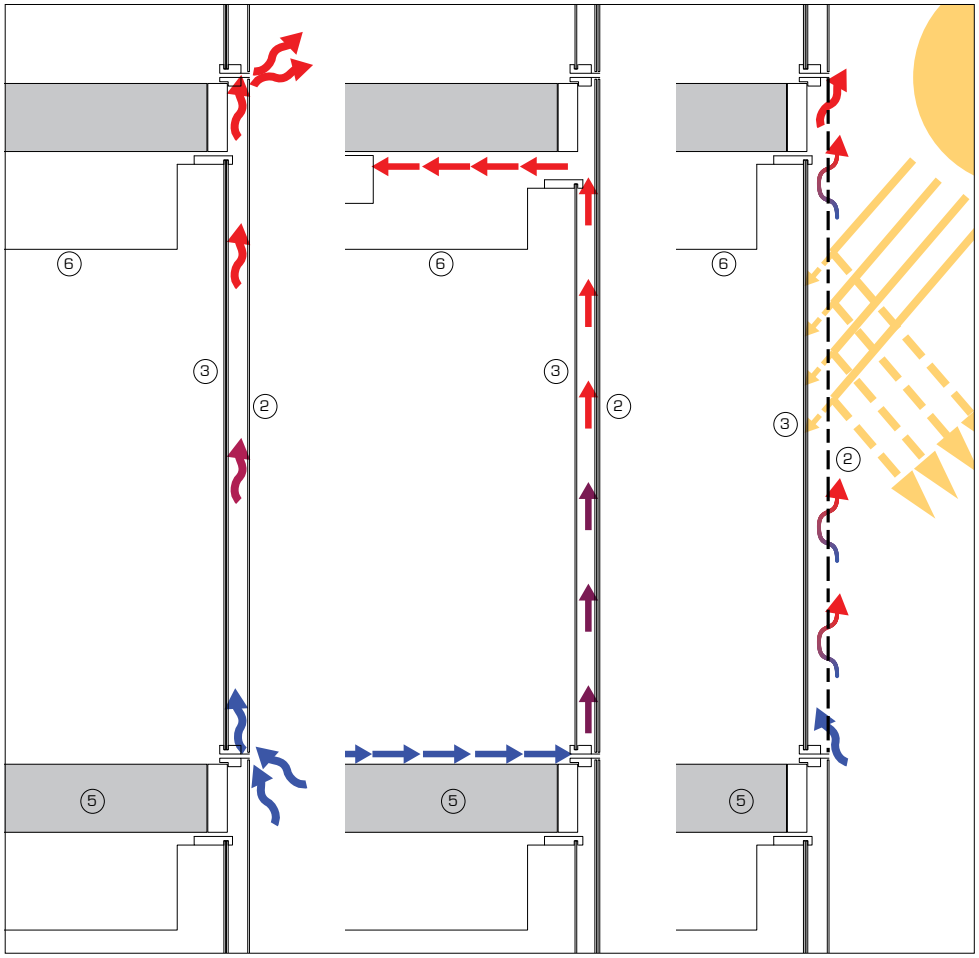


Details

1 | Unitised double skin facade panel
2 | Outer glazed wall
3 | Inner glazed wall
4 | Floor finish
5 | Floor slab
6 | Ceiling finish



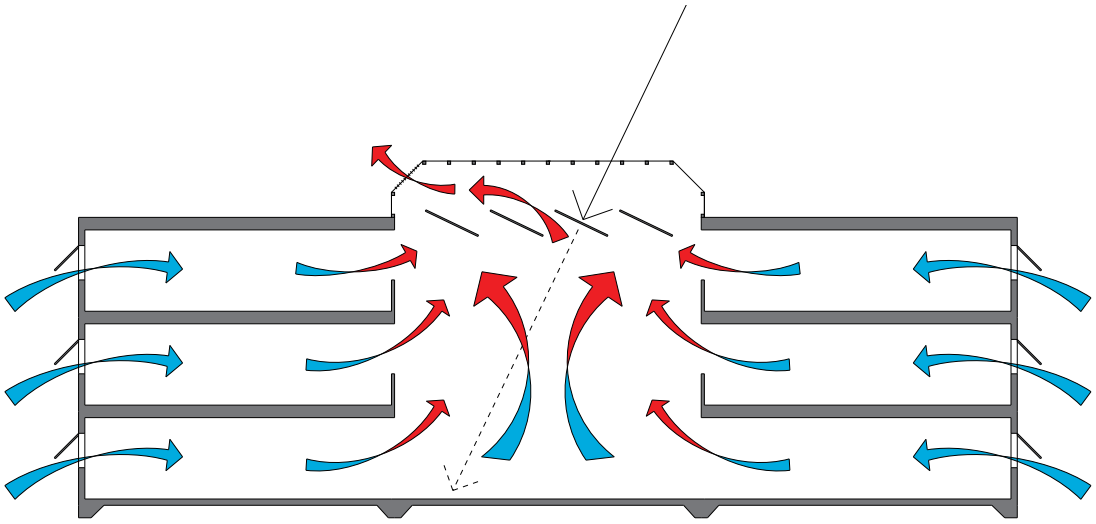
s | 3D views of unitised double skin facade system



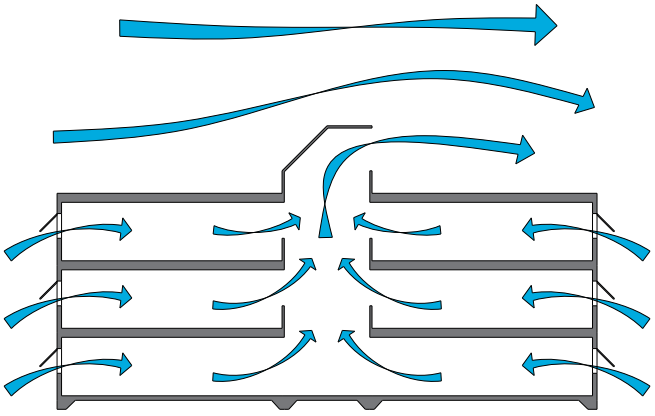
t | (left) Externally ventilated
Internal double-glazed unit with single-glazed external skin.
Cavity ventilated with outside air by buoyancy.
Cavity needs to be of adequate dimensions to optimise stack effect.
System can be mechanically driven to increase effectiveness during thermal peaks.

u | (center) Internally ventilated
External double-glazed unit with single-glazed internal skin.
Cavity is ventilated with return room air which is extracted from the room at floor. level and returned to the air handling unit.
Shading devices in cavity absorb solar radiation which is then expelled via the moving air.

v | (right) Externally shaded
External perforated metal or mesh screen with double-glazed internal skin.
Outer screen acts as shading element for inner skin in addition to benefits of externally ventilated approach.
Cavity ventilated with outside air by buoyancy.
Cavity needs to be of adequate dimensions to optimise stack effect.



a | Stack effect ventilation: As sunlight heats the atrium space the air temperature increases. Hot air rises to the top of the atrium pulling air from the office spaces. The resulting pressure change draws cool air into the building from outside.



b | Wind driven ventilation: Wind flowing over a chimney creates areas of low pressure which draw air from the shaft below. This in turn draws air into the building from outside.

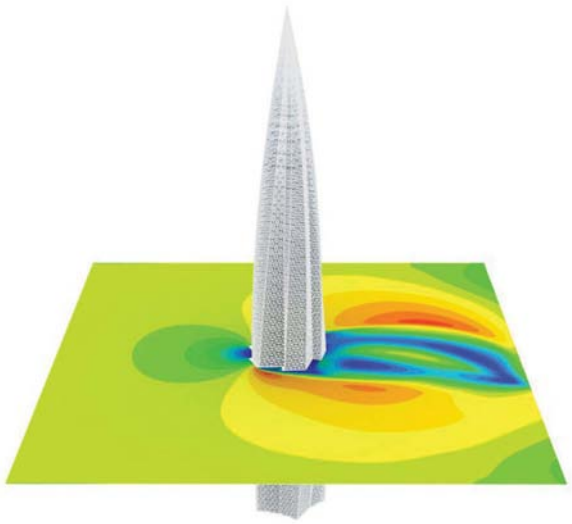


c | Ventilation chimneys on the Ionica building in Cambridge, U.K.

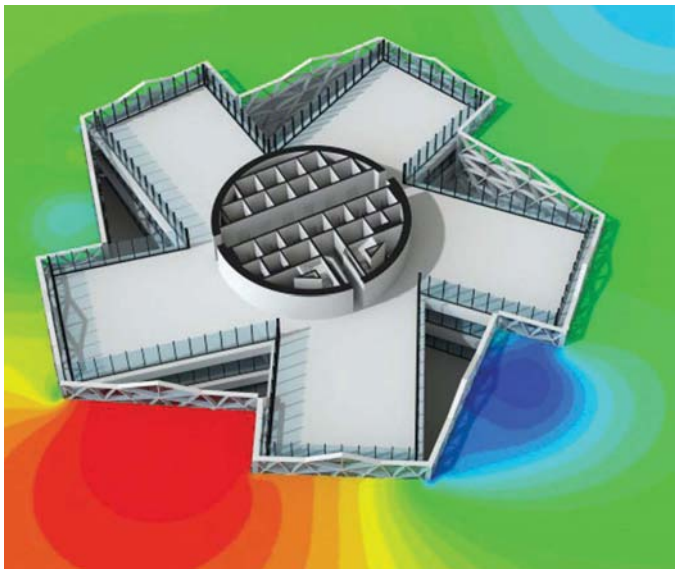
The return to natural ventilation in buildings, and away from dependency on mechanical ventilation (including air conditioning), has gathered momentum in recent years. This has come about through the desire to reduce both the energy consumption in buildings and the wider issue of carbon dioxide (CO_2) emissions from the primary energy generation through to building use. The link between global warming and the build-up of greenhouse gases has yet to be conclusively proven, but the circumstantial evidence seems convincing. Nearly half of CO_2 emissions generated in the U.K. alone arise from energy consumed within buildings. The reduction of energy consumed in buildings has a huge benefit for future generations. The decline in the supremacy of air conditioning can also be linked to 'sick building syndrome' due mainly to systems dependant on the re-circulation of used air in buildings.

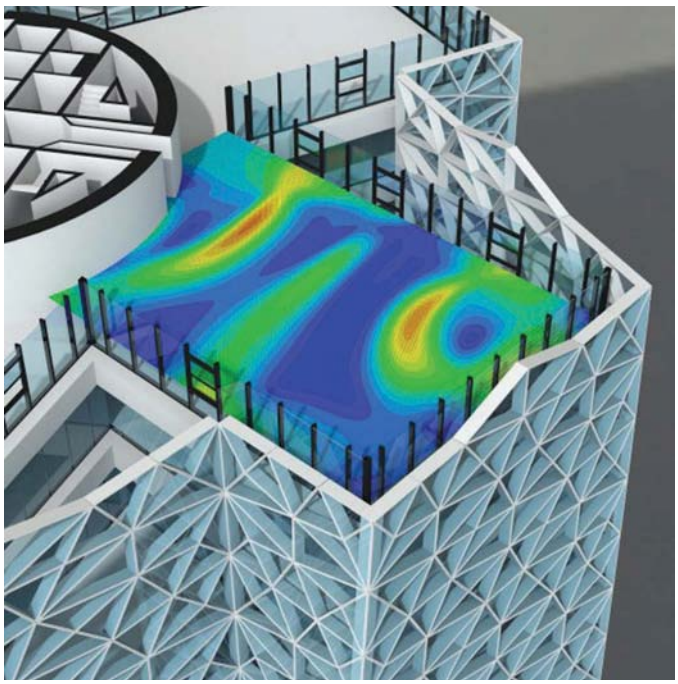
This has resulted in the increased use of opening panels and window systems. Previously, building types other than housing were often designed as hermetically sealed boxes which aimed to provide a constant temperature and steady rate of ventilation. In addition, air conditioning systems would control humidity as well as temperature. This high degree of environmental control led to very high energy consumption from running the equipment. In urban areas, the use of operable windows to provide natural ventilation is often considered inappropriate due to high levels of noise and atmospheric pollution. This has led to the development of 'layered' systems in which functions of sound insulation, weatherproofing and air infiltration are separated.

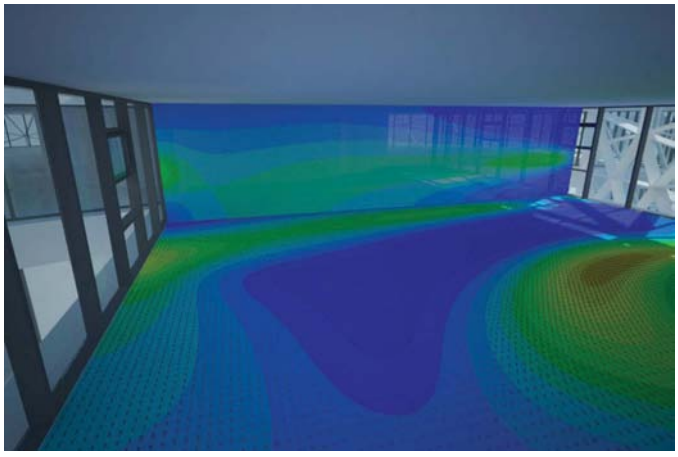
Natural ventilation in buildings is generated either by wind or by a 'stack effect'. In most buildings a combination of both occurs. As air flows across a building, a difference in air pressure will occur as a result of varying wind pressure (e). This difference in pressure causes the air in the area of higher pressure to flow towards the area of lower pressure. Provided openings are appropriately located in these pressure regions, the movement of air creates a natural ventilation flow through the building (b). 'Stack effect' ventilation is caused by a difference in the



d | The CFD study showing the variations in wind speed around a tower and the impact that the complex geometry has on the design of the framing that supports the glazed panels.







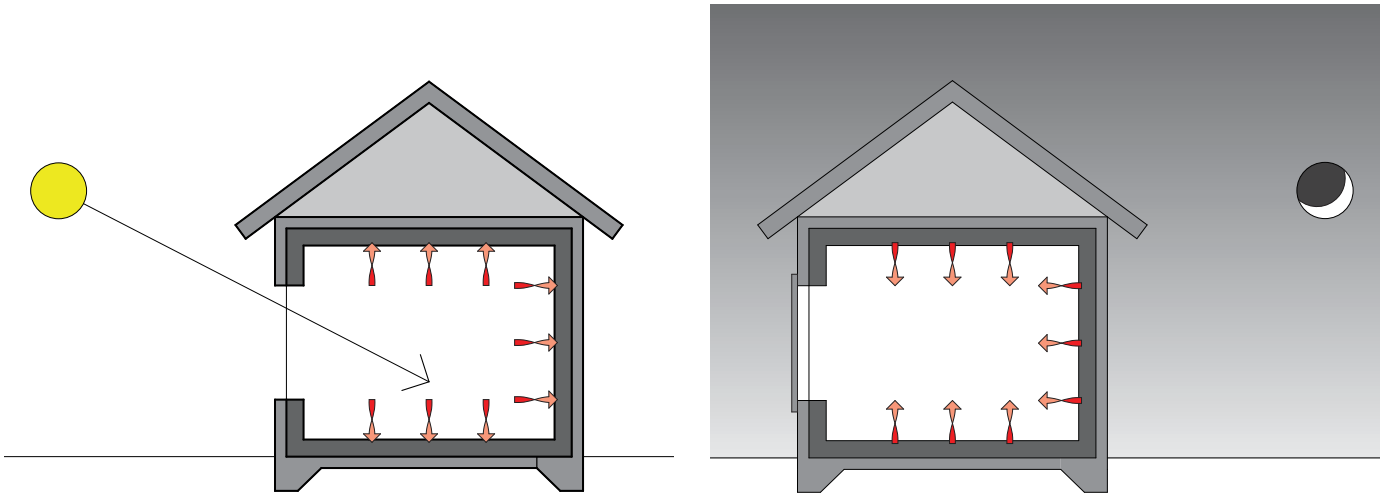
e | Study showing pressure differences across the facade, these create ideal conditions for a pressure driven natural ventilation strategy. In this building inlets in the outer skin create areas of varying pressures in the atrium spaces which drives cross ventilation of the office floor plates.

density of air due to internal heat input from casual and solar gains to the ventilating outdoor air. The temperature, and consequently the density difference between indoor and low level supplied outdoor air results in an upward flow (buoyancy) (a). Air moves from low level to high level in a building with a higher temperature than that outside, whilst the reverse will occur if the air in the building is cooler than that outside.

There are a number of advantages to using natural ventilation strategies over mechanical systems. Perhaps the most significant is the reduced energy consumption of the building during its operation, which in turn helps to reduce the operational costs of the building during its lifetime. Since there are fewer ducts, filters, pumps and other mechanical equimpent, maintenance costs for the building are also reduced. The reduction in mechanical equipment has the added benefit of reducing ceiling zones in commercial buildings, which can allow additional floors to be added to multi-storey buildings without compromising ceiling heights.

Most natural ventilation systems require some manual operation which offers a psychological benefit to users, since occupants are able to control their own environment. The air entering the building is also regarded as healthier as it has not passed through ducts and filters which could potentially harbour diseases.

There are a number of potential problems with implementing natural ventilation strategies; in particular noise control. The requirement for large openings and open plan spaces may conflict with acoustic separation between spaces and may not be suitable to particularly noisy locations. It is also important to ensure that the air flow patterns within the building as a result of natural ventilation do not create areas of stagnant air or air that moves too fast to be comfortable (d). This is particularly problematic in tall buildings where double skin facades are often used to provide a cavity to extract air from, rather than pulling air directly from outside.



a | During the day, exposed thermal mass within the building absorbs heat resulting from solar gain which helps to keep the room at a comfortable temperature.

b | At night, the heat energy stored within the thermal mass radiates back into the room, helping to maintain a comfortable temperature and reducing the need for nightime heating.

Thermal mass is a term used to describe the ability of the building fabric to absorb excess heat. Materials with a high thermal mass are able to absorb heat, store it and then release it at a later time. Since these materials take a long time to heat up and cool down, they can be effective at regulating temperature fluctuations within a building and help to keep the internal temperature at a comfortable level throughout the year.

Heavyweight materials such as concrete and brickwork store a large amount of heat and can be regarded as having high thermal mass. Lightweight materials such as timber and metal do not have the capacity to store a great deal of heat and therefore have a low thermal mass. A table of the heat capacity of typical building materials can be found below:

Material	Heat Capacity (kj/m³°C)	Specific heat (kj/kg°C)
Fibreboard	300	1.0
Hardwood	900	1.23
Gypsum plaster	1050	1.10
Lightweight concrete	1000	1.0
Brick	1360	0.80
Dense concrete	1760	0.84
Stone (marble)	1500	0.88
Water	4200	4.2
Air	1.2	1.0

When used in conjunction with an effective passive solar design strategy, thermal mass can help to reduce energy use in mechanical heating and cooling systems, reducing the running costs of the building. Large thermal mass can be a disadvantage in winter if the building is not in constant use or has intermittent heating as it will take a long time to heat the building up.

Climate and thermal mass

The application of thermal mass in construction is dependent on the local climate. In cold or temperate climates, thermal mass can be used to absorb heat energy from low-angle winter sun which is then released back into the space at night. In the summer thermal mass within a building can absorb excess heat as a result of solar gain and occupancy, limiting the temperature rise within the room (a). At night cool air from outside is allowed into the building and flows across the surfaces that have absorbed the heat during the day, purging that energy and allowing the process to start again the next day (b).

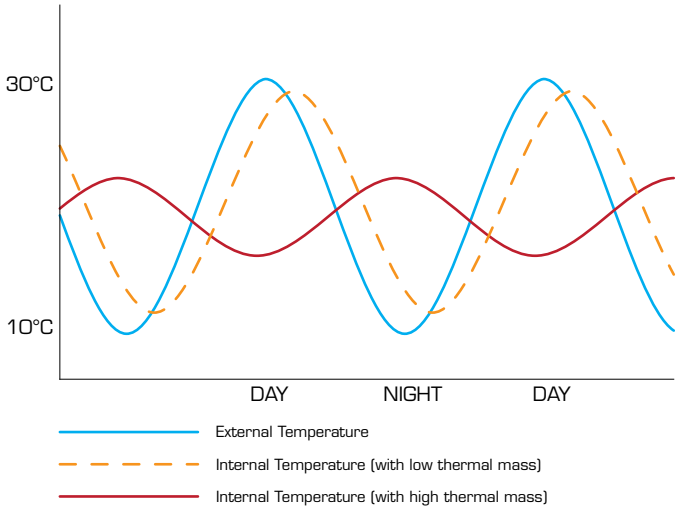
In hot climates thermal mass is used to regulate the high diurnal temperature variation. The building fabric absorbs heat during the day, keeping the internal temperature at a comfortable level (c). At night when temperatures drop significantly, this heat is then re-radiated back into the room.

Thermal mass in offices

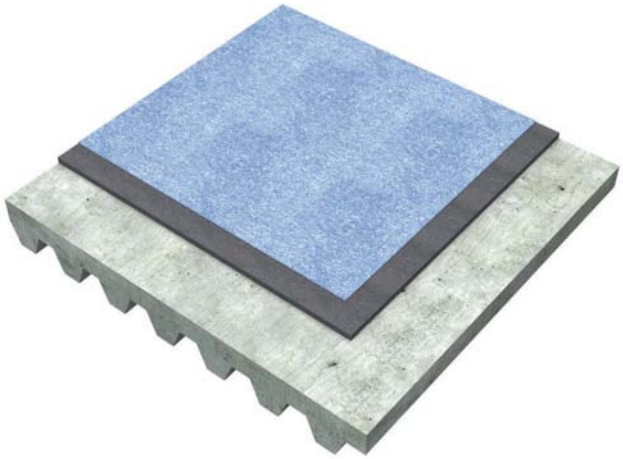
Office and commercial buildings which have specific occupancy periods can make use of thermal mass to control internal temperatures during the day. The thermal mass is typically provided by concrete floor slabs with either an exposed soffit or underfloor ventilation system. The slab acts as a heat sink which absorbs excess heat generated from electrical lighting, equipment loads, occupancy loads and solar gain; and since the material has a relatively low radiant temperature, a comfortable internal temperature can be maintained. As well as reducing the peak internal temperature, a building with high thermal mass is able to delay the temperature peak by up to six hours (c). In an office environment this will typically occur in late afternoon, after the occupants have left. At night cool air is allowed to enter the building to remove the heat stored in the slabs in preparation for the process to begin the following day.

Floor slab configurations

Exposed slab – The quickest and simplest way of providing a high degree of thermal mass in a building. When used in conjunction with natural ventilation, this form of construction can provide around 15-20 W/m² of



c | Graph showing impact of thermal mass of internal temperature. With high thermal mass the temperature fluctuations are less extreme and the peak temperature is delayed by up to six hours.



d | Exposed slab: Underside of slab is exposed and absorbs heat from the roof below. Night purging uses cool air from outside to remove heat.

cooling. Profiled or coffered slabs have an increased surface area which improves convective heat transfer and improves thermal performance. Profiled slabs have a cooling capacity of around 20-25 W/m² (d).

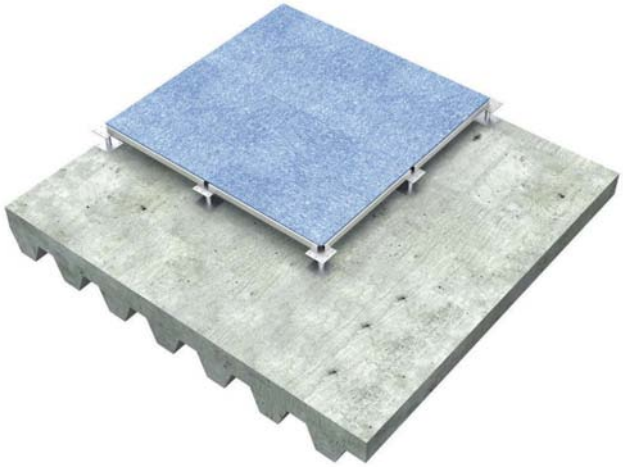
Exposed slab with underfloor ventilation – Raised floors are common in office environments with the primary function of routing power and communication cables. This configuration system can also be used to provide ventilation via floor outlets via a mechanical system or through natural cross flow. Since air is in contact with both the upper and lower surfaces of the slab, the thermal mass of the whole slab can be exploited and can provide an overall cooling capacity of around 25-35 W/m² (e).

Exposed hollowcore slab – Precast hollowcore slabs have tubular voids extending through their length. Air is passed through these voids at low velocities, allowing it to be in contact with the concrete for a prolonged period and increasing the transfer of heat to the slab (f). A cooling capacity of up to 40 W/m² can be achieved with this system.

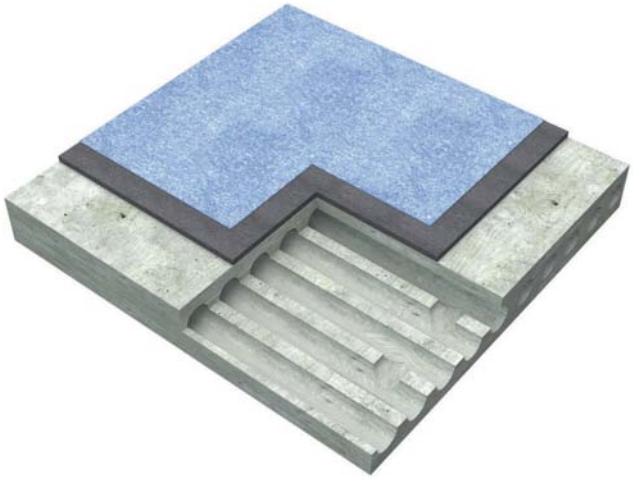
Exposed slab with water cooling – The use of water rather than air to cool floor slabs enables higher cooling capacities to be achieved by increasing the rate of heat transfer. Typical systems use a plastic tube embedded within the concrete slab through which water is circulated. This application is particularly suited to buildings whose occupancy patterns or local climate do not allow for night-time cooling as a constant flow can be maintined if necessary. A cooling capacity of around 60-80 W/m² can be achieved with this system and it is equally suited to providing winter heating solutions by running warm water through the slab.

Locating thermal mass

For maximum effect, thermal mass should be located inside a building and insulated from external temperatures. Brick walls offer little thermal mass benefit as the brick material is on the outside of an insulated cavity. Similarly, thermal mass within a building loses its effectiveness if it is isolated by lightweight finishes such as dry linings or suspended ceilings.



e | Raised floor: Both faces of the floor slab are exposed to the air which increases the transfer of heat. Cool air can be circulated beneath the floor to cool the slab at night.



f | Hollowcire slab: Cool air is passed through voids in the slab to remove heat either at night or during occupancy.





a | An example of a building designed with an emphasis on low embodied energy materials: The Centre for Alternative Technology, Wales, U.K.

An introduction to embodied energy

The energy consumed in the manufacturing of construction material, its transport, its installation and ultimate renovation or demolition is almost always in the form of non-renewable fossil fuel which produces carbon dioxide (CO_2) emissions as a result of these processes. Atmospheric emission levels are widely regarded as one of the most significant considerations associated with the production of building material, and particularly the emission of CO_2 as the chief contributor towards climate change.

The energy embodied in a building material can be considered as the sum of the energy used in the manufacture of its components, transportation, assembly on site, together with its ultimate demolition and associated recycling. This embodied energy must be seen in relation to the overall amount of energy expended by a building during its lifetime. The total energy consumption of a building can be considered as the sum of its embodied energy and its operational energy consumed in using the building during its lifetime. Embodied energy currently accounts for only around 10% of the lifetime energy expenditure of a building, based on a 50-year period. However, levels of the operational energy component are set to reduce significantly. This will be done by improving thermal insulation and by a mixture of passive and active controls that regulate ventilation heat loss and solar heat gain. This would make the embodied energy component in a building even more significant.

Since reductions in the operational energy component are currently being researched, the relationship between embodied energy and operational energy is not discussed here. Instead, this text focuses on how typical forms of construction might best be combined to create buildings of low embodied energy, regardless of the individual levels of embodied energy in the materials used.

Embodied energy values

The figures for embodied energy used in this chapter are those quoted by The Institution of Structural Engineers of the United Kingdom in their publication 'Building For A Sustainable Future: Construction Without Depletion', which lists the total embodied energy for seventy-one materials including transportation but excluding demolition or recycling. These figures are consistent with an earlier U.K. Steel Construction Institute's publication, 'A Comparative Environmental Life Cycle Assessment of Modern Office Buildings' by K J Eaton and A Amato. Precision in measuring embodied energy is difficult when the amount of energy used in the production, transportation to site and installation of the material varies between locations.

Levels of embodied energy in building materials

Current research has focused on levels of embodied energy in individual materials used in buildings rather than on specific types of construction which use a combination of materials. The body of research reveals that natural materials such as stone have low EE (embodied energy). Reinforced concrete, bricks, concrete blocks, timber elements and other wood products such as laminated timber and plywood have higher EE values. Timber, excluding transportation, has a very low embodied energy but much of the timber used in highly industrialised countries is imported, which forms a relatively high proportion of the total embodied energy level of this material. The embodied energy of steel is higher still, with aluminium having by far the most embodied energy of the common building materials. These findings have led to an assumption that natural materials are more sustainable.

Comparisons of embodied energy in typical forms of building construction

In order to compare levels of embodied energy, two worked examples have been taken for comparison. The first example is a set of options for the structural frame of an office building. Similar spans and loadings are used for a wide range of buildings in the U.K., from offices to educational buildings and hospitals. The structural frames investigated use either steel or reinforced concrete. Timber was not considered as it is not economical for large spans with high loadings. The second example comprises a set of options for wall cladding in different materials. The two sets of examples could be used as part of the same building. Either a steel or concrete frame could be used with any of the cladding options. The examples were intended to be used to find out how materials for both structure and external wall might best be used both separately and





together to achieve low levels of embodied energy in their construction. Examples of roofs were not used since they would have broadened the scope of investigation too widely into comparisons of construction methods for pitched and flat roofs in various configurations.

The effect of thermal insulation on levels of embodied energy in the wall cladding options was investigated as a separate exercise. Since most forms of thermal insulation can be used with most forms of building construction, a comparison was made between the use of a material with very high levels of embodied energy (expanded polystyrene) and one with very low levels of embodied energy (mineral fibre insulation). Taking the 3x3 metre bay with a 1x1 metre window used in the cladding options, it was found that expanded polystyrene accounted on average for 15% of the overall embodied energy of the wall panel. Mineral fibre insulation accounted for on average less than 1% of the overall embodied energy. Since the type of insulation used with a particular form of construction has such a large effect on the level of embodied energy, it was decided to omit thermal insulation from the following worked examples.

Example 1: options for an office-building frame

The level of embodied energy in a 6000 mm wide x 16000 mm long bay with intermediate columns was calculated for each option. Four options were examined: in-situ concrete flat slab with concrete columns; prestressed precast concrete hollowcore (wide plank) deck on a steel frame; light gauge steel floor cassette on a steel frame; composite concrete steel deck on a steel frame. The structural options are based on alternative designs for a typical office building. For each option the weight of structural components was multiplied by the embodied energy (GJ/m^2). Embodied energy levels for each material were then added together to find the overall value for the complete structural assembly. Fire protection was added to the steel options to make them as closely comparable as possible. For each option, the total embodied energy was derived from the summation of the calculated embodied energy for each component. In all options an alternative has been calculated using multi-cycle steel (steel that will be recycled at the end of the building's life) and recycled steel reinforcement bars (recycled from an Electric Arc Furnace as is common practice) from figures published in The Steel Construction Institute's 'A Comparative Environmental Life Cycle Assessment of Modern Office Buildings'. Crushed concrete can replace up to 20% of aggregates in structural concrete, but the embodied energy would not change substantially as aggregates have a low embodied energy, therefore this option was not considered. The columns in all options have been omitted, as their contribution is deemed insubstantial.

The results are as follows:

1a) In-situ concrete flat slab (virgin steel reinforcement) 1.73 GJ/m^2
1b) In-situ concrete flat slab (recycled steel reinforcement) 1.41 GJ/m^2
2a) Precast concrete hollowcore floor / steel beams (virgin steel) 1.27 GJ/m^2
2b) Precast concrete hollowcore floor / steel beams (multi-cycle steel) 1.05 GJ/m^2
3a) Light gauge steel floor cassette / steel beams (virgin steel) 1.46 GJ/m^2
3b) Light gauge steel floor cassette / steel beams (multi-cycle steel) 1.20 GJ/m^2
4a) Composite concrete steel deck / steel beams (virgin steel) 2.28 GJ/m^2
4b) Composite concrete steel deck / steel beams (multi-cycle steel) 1.78 GJ/m^2

It is clear from this information that the construction technique with the highest embodied energy is the composite concrete steel deck. The lowest figure was for the prestressed precast concrete hollowcore floor supported off a steel frame, closely followed by the light gauge steel floor cassette supported off a steel frame. The embodied energy for the composite concrete steel deck solution is 80% greater than the prestressed precast hollowcore solution and 56% greater than the light gauge steel cassette solution. The four options were re-examined using multi-cycle structural steel and recycled reinforcement bars. The results remained similar, with the exception that the embodied energy for the light gauge steel cassette solution was only very marginally greater than the precast





a | Examples of wall systems

concrete hollowcore solution. In conclusion, the options with the greatest degree of material efficiency and prefabrication resulted in solutions with the least embodied energy. The present popularity of preassembled modular construction appears to be in tune with sustainable construction.

Example 2: options for wall cladding

The level of embodied energy (EE) in a 3000 x 3000 mm (10ft x 10 ft) bay of a facade was calculated for each option. Since thermal insulation has been omitted from the calculations, the U-value of each construction is not considered here. For each cladding panel option, it was assumed that each panel would be supported by a floor slab/perimeter beam both top and bottom. Components within each panel were sized accordingly. Like the structural options, levels of embodied energy were calculated based on the weight of each material used in the assembly multiplied by the EE value for each.

The results are as follows:

1) Timber framed wall+double-glazed window	0.48 GJ/m²
2) Timber framed curtain walling	0.82 GJ/m²
3) Reinforced concrete panel+dg window	0.70 GJ/m²
4) Facing brick cavity wall+double-glazed window	2.33 GJ/m²
5) Facing brick cavity wall with steel shelf angle	2.54 GJ/m²
6) Aluminium framed curtain walling	2.48 GJ/m²
7) Steel framed curtain walling	1.26 GJ/m²
8) Bolt fixed glazing	0.80 GJ/m²

The wall configuration with the lowest embodied energy is the timber framed wall. The highest are the aluminium framed curtain walling and the facing brick cavity wall. When steel is used for the framing solution, the embodied energy of the curtain walling drops to approximately half the level of aluminium. Among the options for opaque walls with a 1 metre square window, levels of embodied energy are relatively similar between timber and reinforced concrete but the brick cavity wall has almost five times the embodied energy of the timber framed wall. Among the glazed curtain wall options, levels of embodied energy are higher for steel than timber but bolt fixed glazing provides the lowest solution. With the obvious exception of aluminium and brick cavity, the levels of embodied energy are relatively similar for a given configuration of opaque and glazed areas.

The EE level of facing brick is nine times that of concrete block and twice that of common brick. Bolt fixed glazing minimises the use of materials, using glass as panels which are unrestrained along their edges. The use of aluminium framing results in there being three times as much embodied energy in the frame as in the glass. The use of steel framing is much better, using 60% more embodied energy compared to the bolt fixed glazed units. Nevertheless, from a performance point of view, there are problems to overcome concerning thermal breaks in steel.

What are the best mixes between high and low embodied energy materials in typical forms of construction?

In the examples, the combinations of materials consuming the least EE tends to be those using the materials most efficiently. A building constructed from a high embodied energy material, such as a steel framed building clad in glazed panels, uses far less material than an equivalent design in reinforced concrete and has a lower level of embodied energy. What is surprising is the comparison between different types of glazed walling and cavity brick construction. An uninsulated cavity wall with regularly spaced windows and a shelf support angle has three times as much embodied energy as double-glazed bolt fixed glazing, but both forms of construction have a similar U-value.

The exercise suggests that low levels of embodied energy can be achieved using mixed methods of lightweight and heavyweight construction in a single building. From the above examples, the best combination might be a timber clad precast concrete solution or a bolt fixed glazed facade with a light-gauge steel cassette solution. The worst combination would be a brick clad composite concrete steel deck solution, but this building combination has been extensively constructed in recent years.

This puts greater emphasis on the need for an efficient use of material where high embodied energy materials are used. Aluminium seems to be a very extravagant material in terms of energy. This is mainly





because when used in building components, aluminium is required to have high rigidity as well as high strength. The material is used for the precision of its extrusions and castings rather than for any real qualities of lightness. This is not the case where aluminium is used in other industries. In aircraft design, aluminium is used for its strength and lightness. Rigidity is much less important, as part of the aircraft can deflect without significantly impairing performance.

Recycling and sustainability

In attempting to reduce the embodied energy level in the construction of a building, the levels of EE in different materials might suggest that prestressed concrete and timber are preferable to steel and aluminium. However, these criteria must be seen within the overall context of recycling non-renewable resources and a sustainable approach to the use of renewable resources.

Bricks and blocks can be re-used, but are not used in many parts of the world where the ready supply of timber, for example, can provide a more appropriate material. Steel and aluminium, with much higher embodied energies, are more easily recycled. Once manufactured, these metals are in a fairly 'closed' cycle of re-use. Aluminium is one of the easiest materials to recycle and at a reasonable cost. Energy savings are made by recycling the material. The conversion of scrap aluminium back to high-grade metal requires only about 5% of the energy needed to make the same amount of metal from bauxite.

The manufacture of building materials has a direct impact on our environment. Removing raw materials from their natural environment can cause long-term damage to the environment. The extraction of ores to make steel and aluminium leaves holes in the ground. Mining areas can be re-instated. Trees cut down as a result of timber production can and should be replanted and replaced. The cost of this work will have to be added into future calculations of embodied energy. Care should be taken to establish the source of timber. An area of tropical forest corresponding to the size of the United Kingdom is being destroyed or seriously degraded every year. Therefore, timber should be selected from an audited and sustainable forest or from plantations already established on degraded land. Planning the life of the building as appropriate in environmental terms will become a higher priority. This might lead to the pre-assembly of shop-constructed components which can be readily adapted to suit changing needs using a kit of parts, or can be dismantled and reassembled as the need arises. This might lead to a scenario where modern high embodied energy buildings will be demolished and recycled rather than maintained, but masonry buildings of heritage may be allowed to remain without fear of being recycled.

In conclusion, a well conceived light steel structure with bolt fixed glazed facades or a prestressed precast concrete structure with a timber facade may provide an optimised solution for low embodied energy, and hence provide a sustainable construction. Both solutions rely on a high degree of specialist prefabrication and preassembly. This is good news and bad news for traditional construction. The focus should be on prefabrication and efficient use of carefully selected materials. It appears that prefabrication and preassembly can provide the means to a future in construction that is flexible, adaptable and sustainable.

Embodied energy values used	GJ/tonne
1) Aluminium alloy	200 GJ/tonne
2) Synthetic rubber	150 GJ/tonne
3) Structural steel	26.8 GJ/tonne
4) Steel used in windows	31 GJ/tonne
5) Float glass	15 GJ/tonne
6) Softwood	13 GJ/tonne
7) Plasterboard	2.7 GJ/tonne
8) Facing bricks	11.7 GJ/tonne
9) Mortar	0.84 GJ/tonne
10) In-situ concrete structure above ground	1.09 GJ/tonne
11) Steel reinforcement	26.8 GJ/tonne
12) Plywood	17 GJ/tonne
13) Concrete block	1.31 GJ/tonne
14) Wall insulation	35 GJ/tonne
15) Plastic	150GJ/tonne



a | Modular system with soil substrate: Eco Store, London, U.K.



b | Tensioned wire green wall, Heathrow Airport, U.K.



c | Modular planting casette element

Green wall design

Green walls are living, self-regenerating cladding systems that allow building facades to be covered completely with vegetation. The concept has been in existence for centuries. In the Mediterranean, plants are often trained over facades to act as a natural means of climate control. Fruit plants in particular thrive in this situation since the heat stored in the backing wall is particularly conducive to plant growth.

In recent years, however, the use of 'living walls' has expanded into the public realm to the extent that vegetation can now be seen adorning the facades of museums, shops, community centres and offices.

Living walls can help to link buildings with their natural environments. In cities, large planted facades have a dramatic visual effect and can act as an oasis of nature within what may otherwise be barren and industrial surroundings. While climbing plants can be seen as temporary additions to buildings (b), technological advancements have enabled living walls to become fully integrated facade systems in new developments (a).

Advantages and disadvantages

Living walls offer a number of environmental benefits: Planted facades can help regulate internal temperatures. In the summer the vegetation shades the wall from the sun and can reduce daily temperature fluctuations by up to 50%. In the winter an evergreen facade will provide insulation not just by trapping air between the planted zone and the wall, but also by reducing the wind chill on the facade.

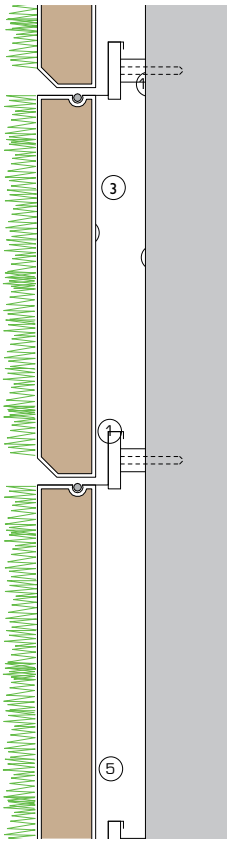
Living walls can also benefit the surrounding environment by altering the local microclimate. Vegetation helps with noise absorption and can lead to an improvement in the atmosphere through the dust trapping effect and its absorption of CO_2. Planted facades also help with the retention of rainwater after heavy rainfall. They reduce intense local heat gains experienced in cities and create a cooling effect as a result of evaporation.

Living walls are an excellent way of introducing biodiversity into urban environments although the presence of mice or insects may cause problems.

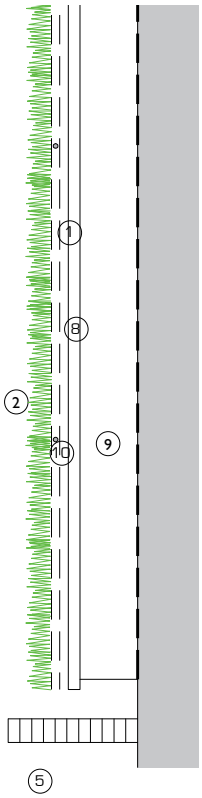
Without proper planning living walls can cause building damage. Planting systems can impose additional loads on external walls. They can also affect the structural balance of the building. Roots and tendrils can break through waterproof seals or force their way behind cover strips and window abutments and without regular maintenance, leaves and other dead matter can block gutters and rainwater pipes.



d | Modular system with rockwool substrate:
Paradise Park Childrens Centre, London, U.K. Architect: DSDHA



e | Vertical section of modular green wall system



f | Vertical section of hydroponic green wall system

System overview

Living walls fall into two main categories: Individual point plantings and planting beds. Individual point plantings require almost no supporting structure and therefore provide the simplest method of installation to both new buildings and existing facades. Plants are grown in individual containers and trained across trellises or wires fixed back to the facade (b). Because plants grown in this manner will have a maximum height to which they will grow, it is often necessary to distribute many containers across the facade to achieve growth beyond this range. It can take many years to achieve a dense, homogeneous coverage.

Planting beds, laid vertically on the facade, allow for full surface coverage. Plants grow horizontally out from the wall rather than vertically up it and this allows for a wider range of plant types to be used.

Living wall systems fall into two categories, distinguished by their method of plant cultivation:

Modular systems

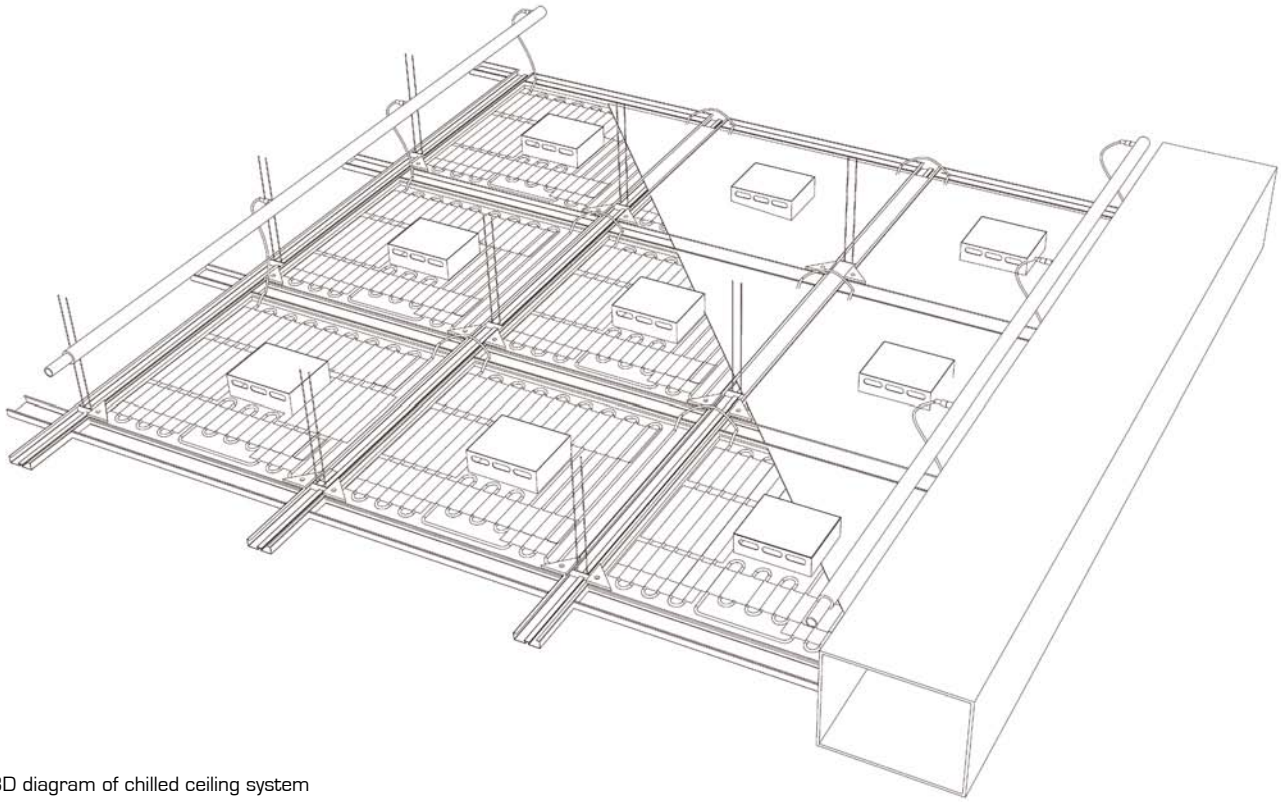
Modular systems use cassette elements (c) filled with a soil substrate that plant roots draw nutrients from. The modular units are usually cultivated off-site until they reach maturity. These modules can then easily be fixed to a supporting structure on site to complete the facade (e). Because of their modular nature, substrate walls often take on a chequerboard pattern, however it does give great flexibility and allows panels to be replaced individually if necessary.

Hydroponic walls

Hydroponics is a method of growing plants without the need for a soil substrate. An irrigation system distributes nutrient-enriched water droplets across the facade which are absorbed directly by the roots.

Hydroponic walls have a much reduced constructional depth and impose significantly reduced loads on the building facade (around 30kg/m²) when compared to substrate systems (f).

The standard form of construction provides felt pockets in which plants can be individually located. Roots spread radially within the felt and can support plant growth of up to six metres. Horizontal irrigation pipes run along the outer edge of the felt at the top of the facade. The supply of water is computer-controlled to ensure the regularity of operation is in keeping with external conditions. The exact calibration of the system needs to be calculated prior to installation taking into account the facade dimensions, plant types and local climate, to ensure an adequate supply of nutrients to all plants. With correct cultivation and maintenance living walls have a lifespan of around 30 years.



a | 3D diagram of chilled ceiling system

Liquid based heating systems are provided mainly by radiators, convectors or underfloor heating. Commonly used liquid cooling systems are chilled ceilings, chilled beams and related items which are mainly used in office buildings, where heat loads from building occupants and equipment impose cooling requirements for much of the working year even when solar gains are minimal.

Radiators

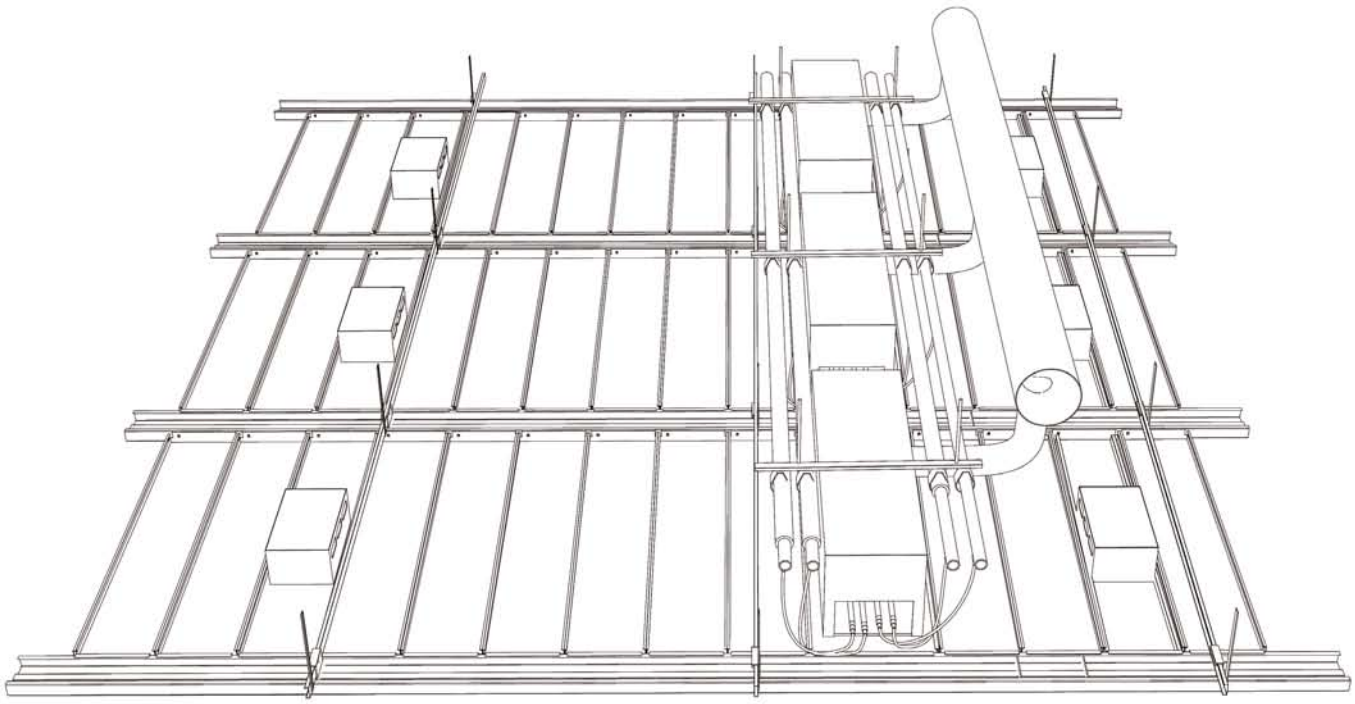
Radiator systems pump low-pressure hot water through a pipe circuit, and distribute the heat through radiators which have a large surface area to radiate and convect heat. Heat is generated by boilers, usually fired by gas or oil. The pressed steel radiator, which has generally replaced the traditional cast iron type, is made from pressed metal sheet welded together and has become the most commonly used type. They are generally ribbed to encourage convection currents, many have fins on their rear surface to enhance performance and panels can be supplied as single, double or even triple to match duties required. Most of the heat is given off as convection, the remainder as radiation. Radiators are positioned to maximise convection currents and minimise pattern staining. They can be individually temperature-regulated with either a manual or thermostatic type valve on a constant temperature circuit or linked on a compensating distribution system, which automatically varies heat supplied to different facade orientations and adjusts in response to ambient variations.

Fan and passive convectors

Fan convectors are used where air needs to be heated very quickly, such as in countering downdraughts adjacent to large areas of glazing or above building entrances. Passive convectors are more static and are generally used where the loads are more stable. Convectors utilise a constant temperature low-pressure hot water pipe circuit. They are also used in conjunction with mechanical ventilation systems. Convectors consist of thin metal fins radiating from a central pipe supplied with circulating hot water. The fins are enclosed in a metal casing to increase the effect of convection, caused by the movement of air around the fins. Convectors can be floor or wall mounted and, like radiators, they are positioned to maximise air currents. When used in conjunction with glazed walling they are often recessed into the raised floor. Fan-assisted units distribute the air more quickly, but can create noise. Convectors are generally controlled by valves operating in response to temperature sensors and, because they require less water than radiators, react more quickly to changes in temperature if thermostatically monitored. A convector type used in conjunction with mechanical ventilation systems is the fan-coil unit, used primarily for cooling.

Underfloor heating

Underfloor heating is another alternative to radiators. Heat is radiated from PVC pipes set into the screed of a concrete slab or located within the void in a timber floor. Insulation is laid under the pipes to minimise heat loss and, in the case of multi-storey buildings, avoid heating of the



b | 3D diagram of chilled beam system

floor below. Water in the pipes is kept at a constant temperature of about 50ºC, which is only warm to the touch. This system is often used as low-level background heat or where large floor surfaces in materials such as stone which would be cold to the touch.

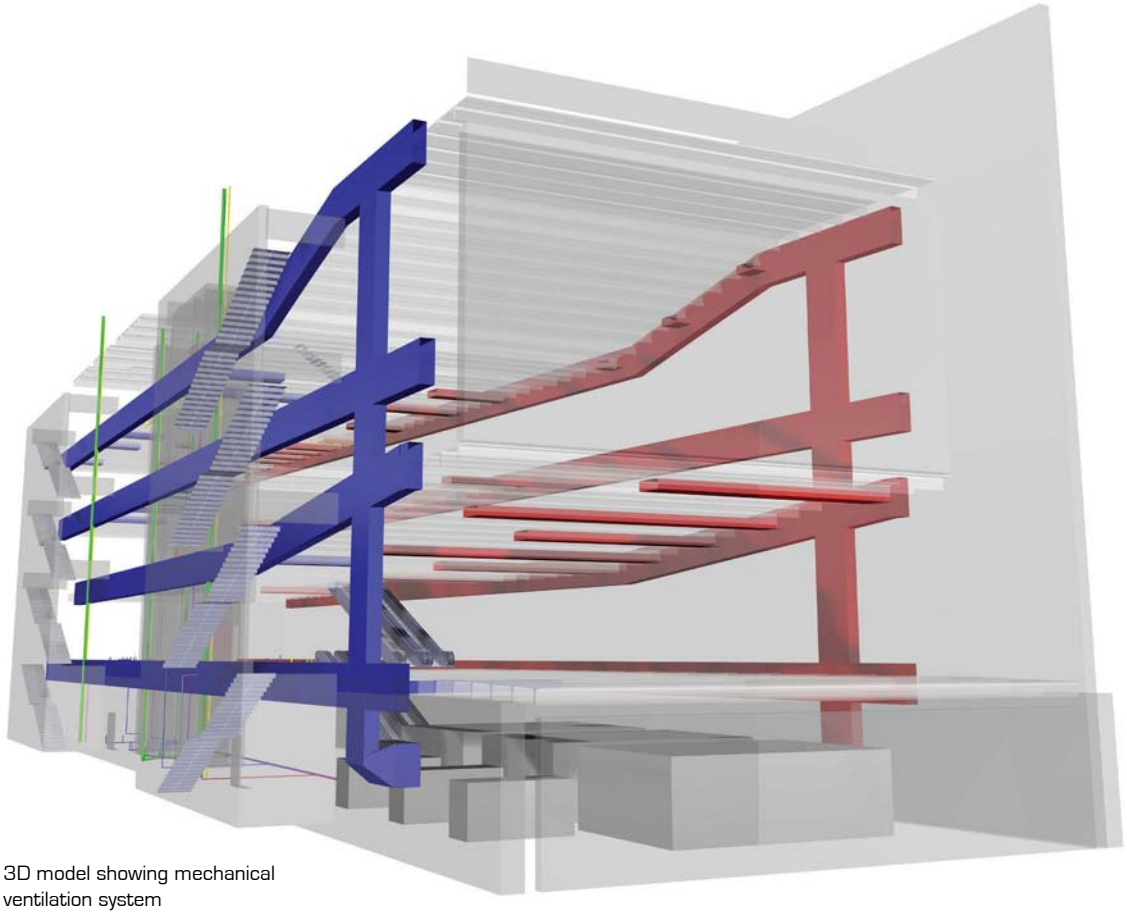
Chilled ceilings

Passing air through a building during the night at outside temperature can help to cool the building structure (MCH_380). When a building is designed for this strategy, the structural soffit is exposed to the occupied zone providing a passive cooled ceiling to the space, thereby slowing the rate of rise in internal resultant temperatures. However, this approach is hard to control and is dependant on reliable diurnal temperature differences during warm summer periods.

Chilled ceilings have been developed to provide a controllable means of achieving overhead static cooling. These systems consist of chilled radiant panels, cooled by a chilled liquid, which are fixed to ceilings providing cooling by both convection and radiation (a). There are a number of types but generally chilled water is circulated in very small diameter pipes connected to panels which act as the heat exchanger to the internal space. As cooling is provided, the temperature of the water rises as it flows through the panels. The water is pumped back to a refrigeration plant or heat exchanger. Chilled ceilings are used as an alternative to full air-cooling and are used in conjunction with ducted mechanical fresh air ventilation systems.

Chilled beams – active and passive

These devices are often grouped with chilled ceilings, but they are quite different in operation. Active chilled beams are supplied directly with treated fresh air to induce added convection across the heat exchanger surfaces and generally provide greater cooling capability than a chilled ceiling system. Passive chilled beams rely on warm room air from the surrounding volume creating a downward flow as it is cooled when in contact with the beam heat exchanger surface; they provide considerably less cooling at the same density when compared to active beams. With passive beams, the ventilation air is often provided by an underfloor or displacement system. A chilled liquid, normally water, cools both types of chilled beam (b).



a | 3D model showing mechanical ventilation system

Mechanical ventilation systems use ducted air that is heated or cooled either by a central plant, or at the point of use, or by a combination of these two methods (a). Mechanical ventilation is used primarily for its ability to provide fresh air to large areas within a building where natural ventilation cannot be used successfully. This is often due to the need for closer temperature control, or because of a deep floor plate where natural ventilation would be less effective, or where windows cannot be opened due to external noise and/or air pollution. Air from a central plant is ducted in prescribed volumes, based on either the number of people or the room thermal load, to where it is needed around the building. Air conditioning modifies the state of the ventilation air, which can include re-circulated air, primarily changing the temperature and humidity of the ducted air. As is the case with radiator systems, the air temperature can be modified at the point of delivery. Simpler systems are available wherein local air supply units are used which deliver the air directly into the space.

There are two basic approaches to mechanical ventilation, which are as follows:

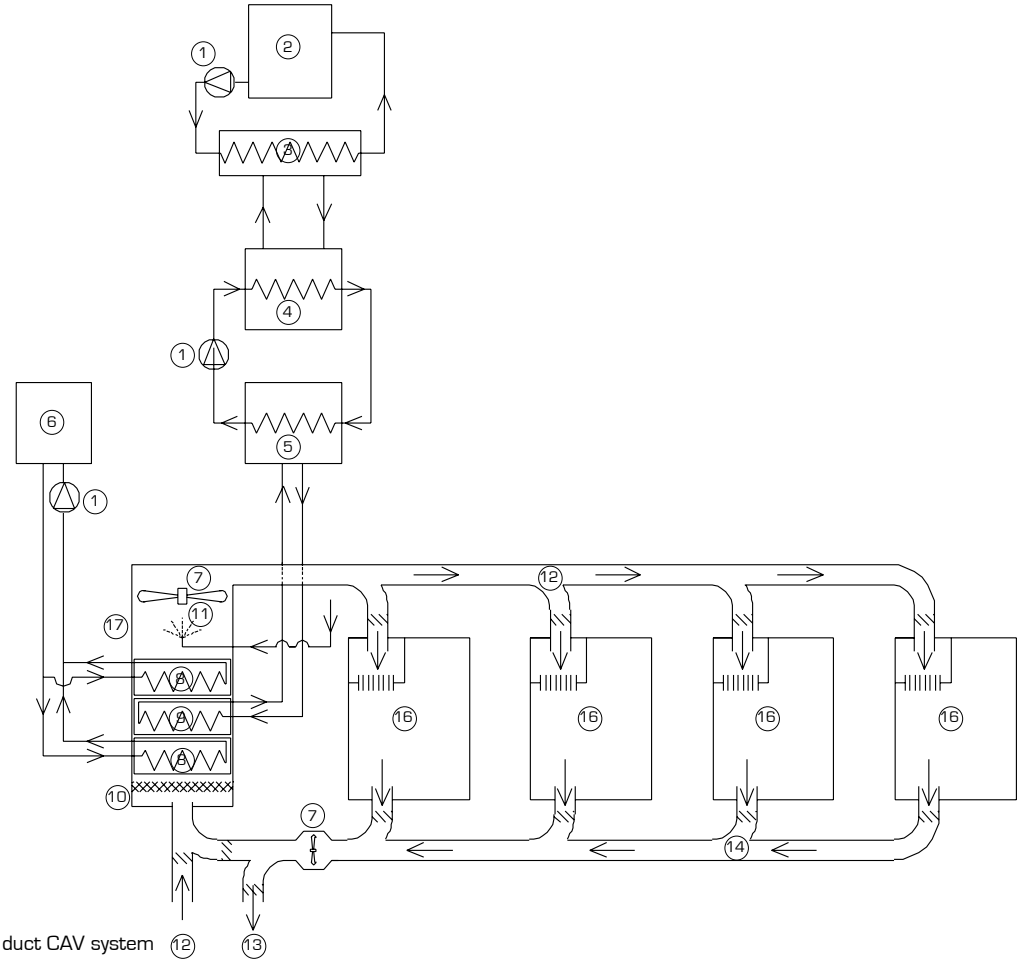
- Constant air volume (CAV) system, in which the temperature of the air is altered.
- Variable air volume (VAV) system, in which the volume of air delivered is altered.

Constant air volume (CAV) system

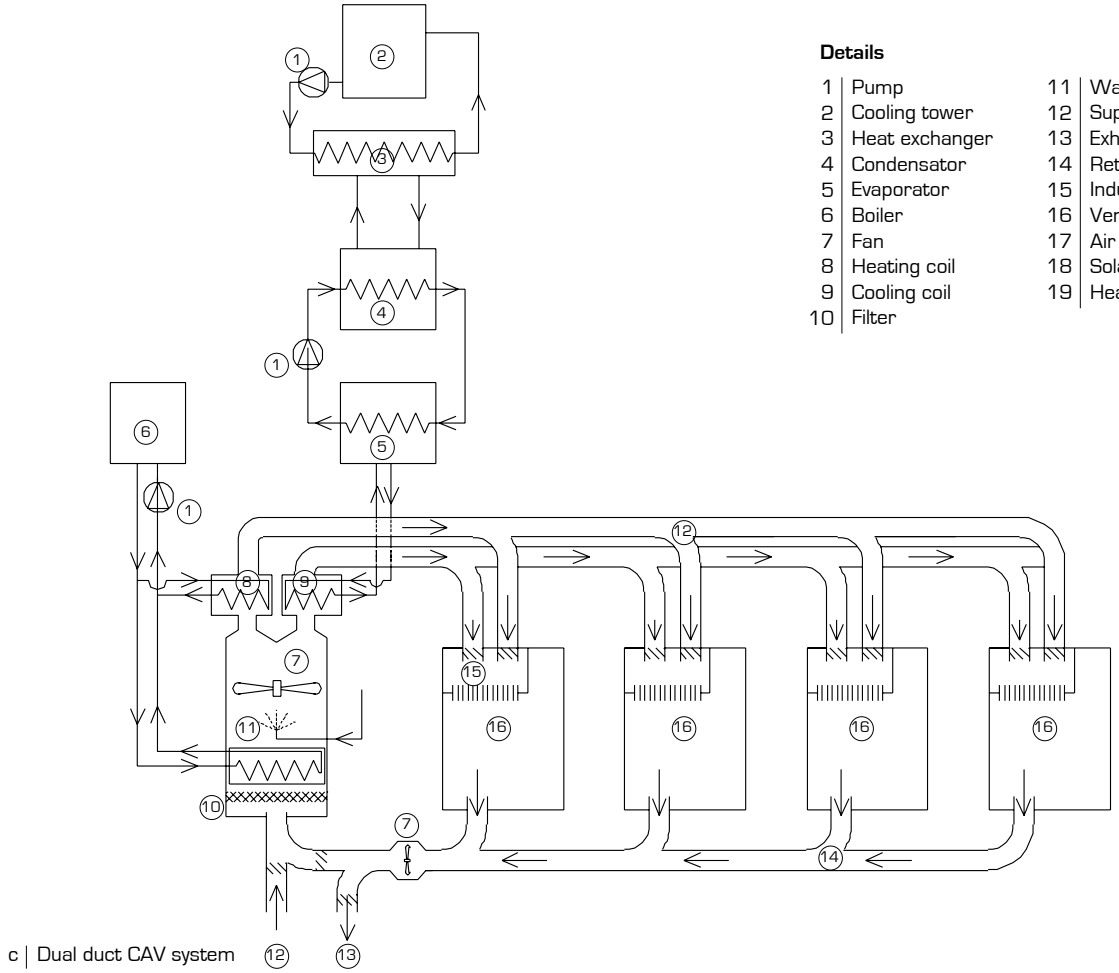
The constant air volume (CAV) system delivers air to a space with no variation in volume regardless of load change. As various parts of a building have different heating and cooling requirements at any given time, in theory separate CAV systems are required for each zone. This causes problems in large developments with multiple zones so a central supply system is used with local temperature adjustment. Traditionally these systems relied on the central plant supplying a premixed volume, of return air and fresh air, treated to a level that coped with the highest sensible heat gain in summer or lowest net heat loss in winter. Re-heat coils in the terminal ducts cater to local variations in load in response to room temperature sensors (b). This type of system fell out of favour during the energy-conscious nineties due to the waste of energy inherent in cooling the air centrally, only to re-heat it locally.

The dual duct system allows air at varying temperatures to be supplied to different zones. Separate ducts supply heated and cooled air, which is mixed at the point of delivery in response to room temperature sensors (c). This enables a much greater degree of control, but it is much more expensive than the single duct system and requires much more space in the building services zones.

The constant air volume system utilises air-handling units that supply either warm or cool air. Some units can supply both hot and cold air simultaneously by dividing their supply. One half is warmed and the other cooled, after which they are remixed to provide the required temperature. Ducts supplying different zones can be connected separately to the air-handling units, with the required temperature controlled by dampers.



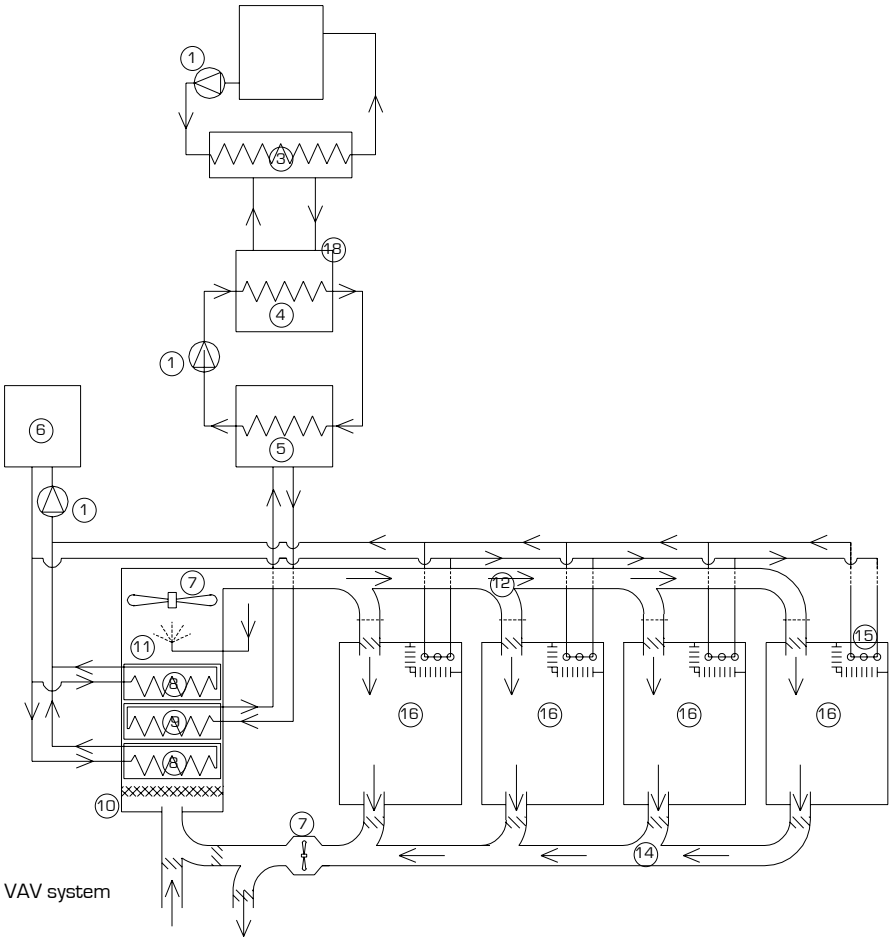
b | Single duct CAV system



c | Dual duct CAV system

Details

1	Pump	11	Water spray
2	Cooling tower	12	Supply air
3	Heat exchanger	13	Exhaust air
4	Condensator	14	Return air
5	Evaporator	15	Induction unit or fan coil unit
6	Boiler	16	Ventilated space
7	Fan	17	Air handling unit
8	Heating coil	18	Solar heat gain
9	Cooling coil	19	Heat loss through fabric
10	Filter		



d | VAV system

Details

1 Pump
2 Cooling tower
3 Heat exchanger
4 Condensator
5 Evaporator
6 Boiler
7 Fan
8 Heating coil
9 Cooling coil
10 Filter
11 Water spray
12 Supply air
13 Exhaust air
14 Return air
15 Induction unit or fan coil unit
16 Ventilated space
17 Air handling unit
18 Solar heat gain
19 Heat loss through fabric

Variable air volume (VAV) system

The variable air volume system (VAV) is used where the heating and cooling requirements differ within the same building, or even within the same treated volume. VAV systems use a single supply duct distributing air at a constant temperature (d). It responds to different temperature requirements in different spaces by altering the volume of air supplied. For example, the air volume supplied to a space will be increased if the temperature begins to rise, whilst the reverse occurs for dropping temperatures. The system provides local temperature control without the need either for separate air-handling units, or for water to be supplied to terminal units to warm or cool the air. The heating of perimeter spaces can be provided for by a liquid perimeter heating system. It is important when designing these systems to ensure that the blend of fresh air to return air is sufficient to maintain adequate fresh air at a minimum volume setting for ventilation purposes.

Air supply to each space is controlled by variable volume terminal units which adjust the volume supplied whilst maintaining adequate velocities for mixing. Variable speed electric fans are used in the central plant to maintain constant duct pressures, thus ensuring that terminal units can maintain volume control.

Mechanical ventilation equipment

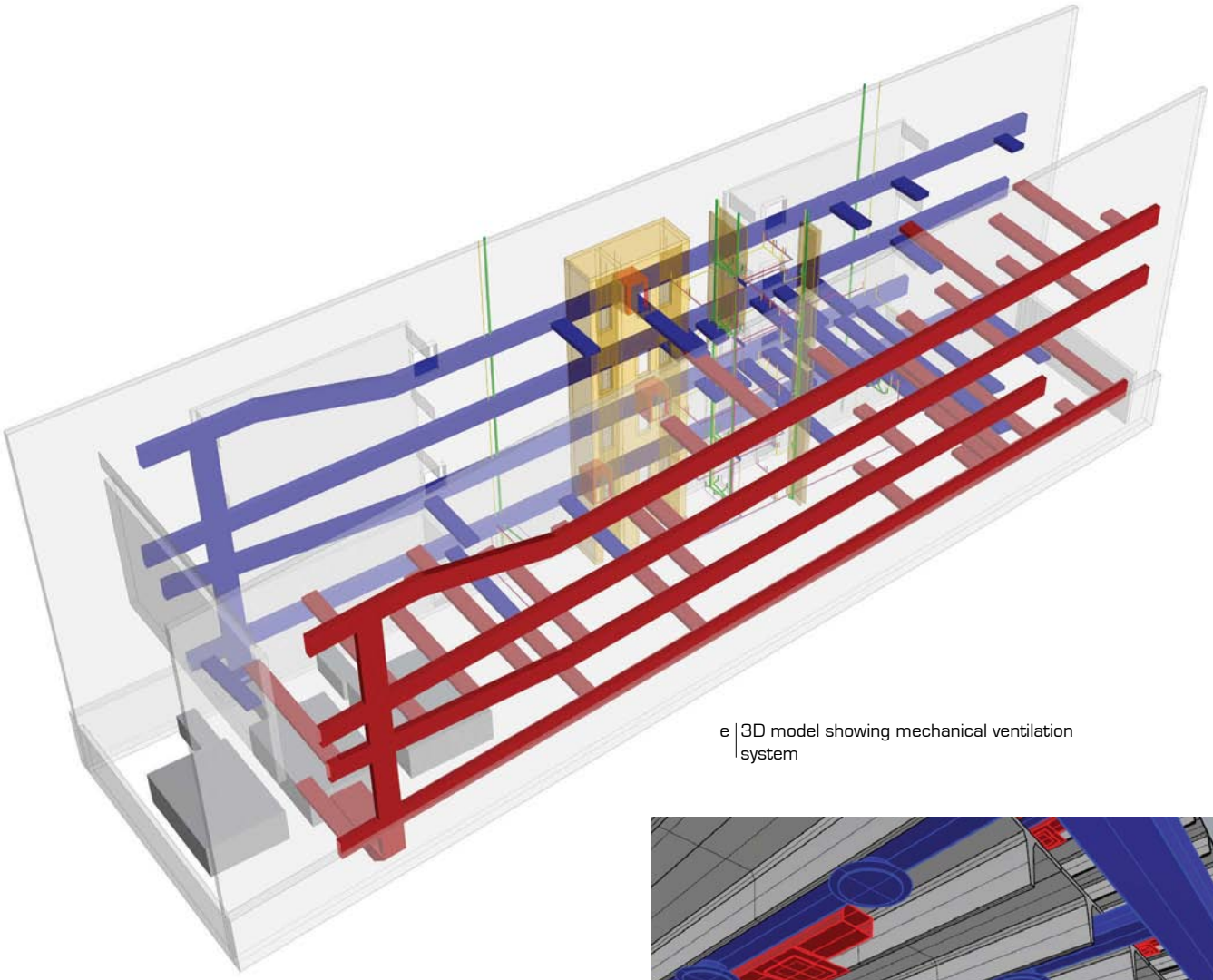
Mechanical ventilation equipment consists of an air handling plant and a network of supply and extract ductwork (e). Air is blown through supply ducts from the air-handling unit to a series of supply grilles or diffusers and returned via extract grilles or from a ceiling void (f). Air that is recovered in extract ducts which return it back to the air handling unit can be filtered and partially re-circulated, depending on the system and time of day or year. The remainder is discharged to the outside. Air is usually re-circulated because the quantity of air required for cooling or heating is often several times greater than that required for ventilation.

Air-handling units

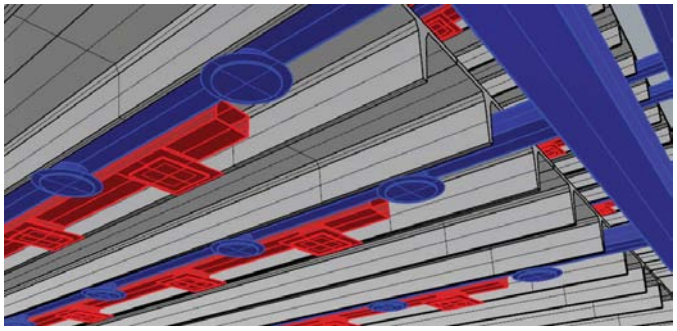
An air-handling unit draws outside air in through a filter using an electric fan, where dust particles are removed. The air is then warmed or cooled to the required temperature for distribution. The temperature and relative humidity of the air can be controlled by a combination of warming, cooling and humidifying devices. The air is warmed by drawing it through a heating coil, which is heated by heating fluid, or through a heat recovery device, heated by the return air stream. To cool the air it is drawn across a cooling coil cooled either by a cooling fluid, by water or directly by a refrigerant. The humidity of the air can be controlled by spraying water into the air stream to increase its humidity, or by de-humidifying it as it is cooled. Air-handling units are either installed in a plant room or are self-contained, waterproof package units that are located externally.

Heat pumps

Heat pumps are used in a wide range of applications. The heat pump is a device that makes use of both the evaporation and the condensing stages of a vapour compression cycle. The refrigerant in the cycle absorbs the heat when vaporised (evaporator) and releases it when the gas condenses (condenser). These heat pumps can be reversed to deliver either heating or cooling to the same air stream or directly into the space.



e | 3D model showing mechanical ventilation system



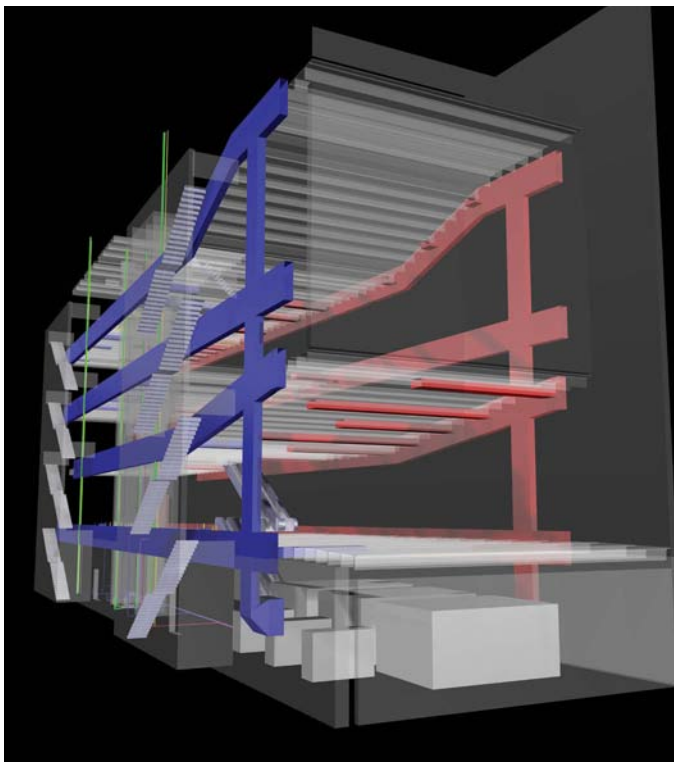
f | 3D view of mechanical ventilation system in exposed ceiling

Heat recovery

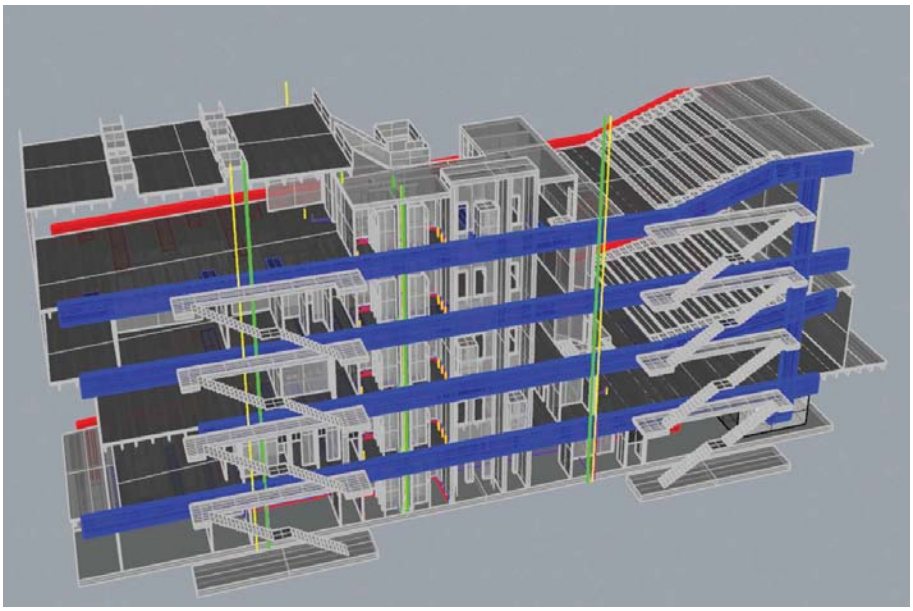
Heat recovery is an important aspect of low-energy design for ventilation systems. There are a number of methods of heat recovery used which generally transfer heat from the return air to the supply stream, which are as follows:

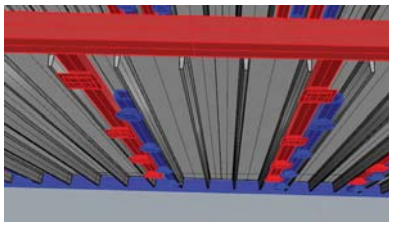
- Run around coil, capable of up to 50% efficiency.
- Recuperators or cross-over plate exchangers, capable of up to 65% efficiency.
- Thermal wheel, capable of up to 80% efficiency for dry heat using the non-hygroscopic type and 65-90% total heat recovery (latent and sensible) for the hygroscopic type.
- Heat pipes capable of 50-65% efficiency.

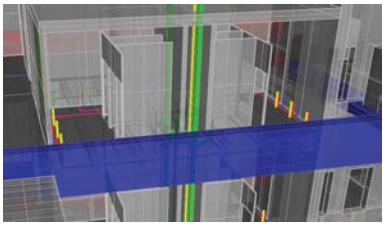
Run-around recovery consists of a series of coiled pipes with water circulating in them, set into the extract duct, usually near the exhaust air outlet. The water absorbs heat from the extract air and releases it into the supply duct. The thermal wheel consists of a wheel made from metal blades that spins in an enclosed jacket between the supply and extract ducts. The wheel absorbs heat from the extract duct and releases it to the supply duct. The same principle applies in the cooling mode although with less benefit, where heat from the warm incoming air stream can be slightly pre-cooled by exchanging heat with the exhaust air from the extract duct. Heat pumps can also be used to recover heat from exhaust air, helping to reduce energy costs. They are often used in swimming pool ventilation applications.

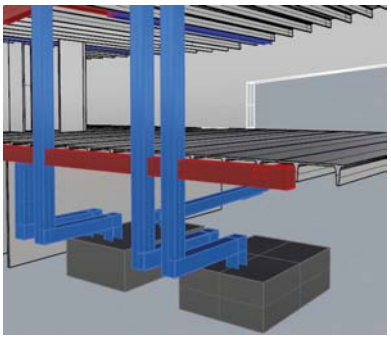


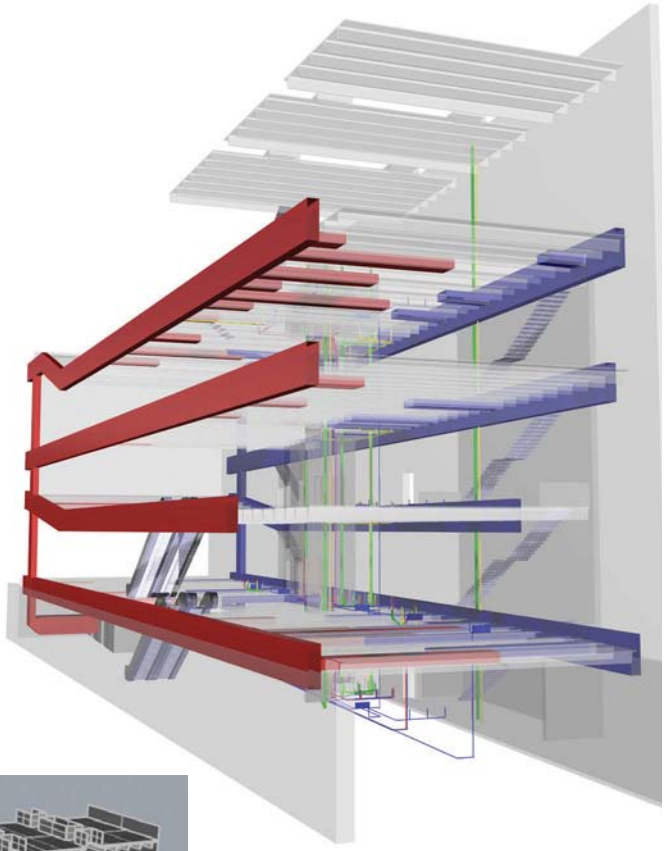
g | 3D model showing mechanical ventilation system

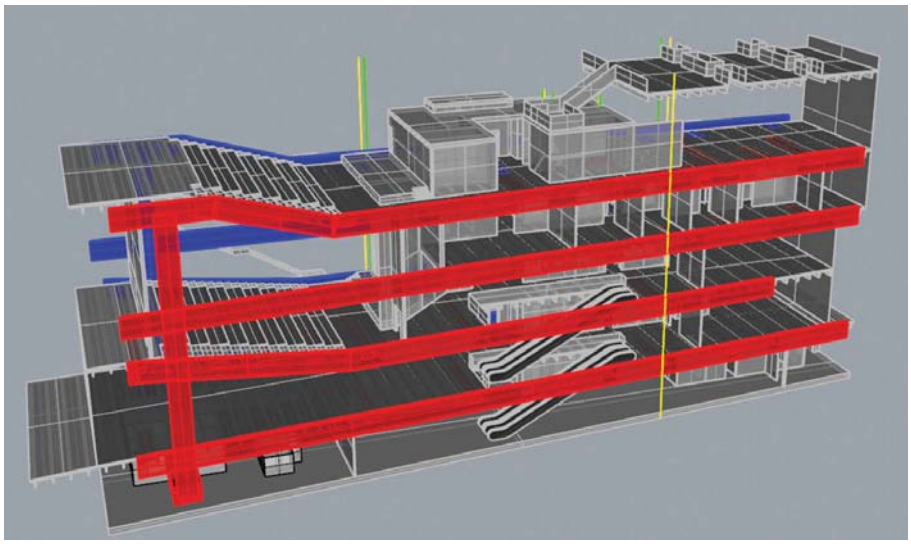




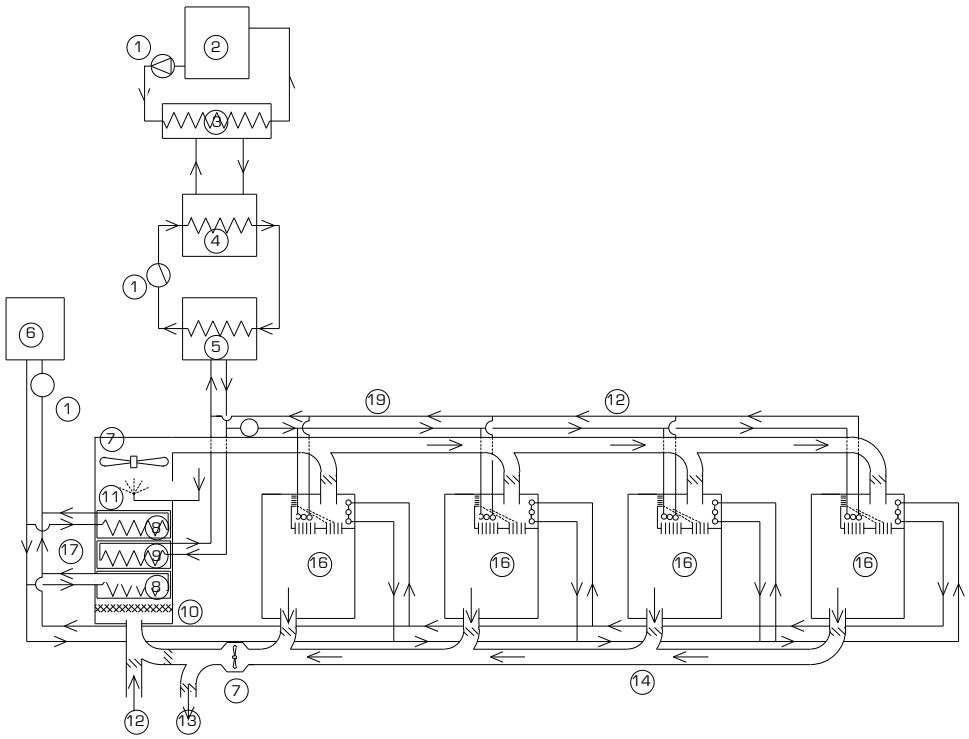








h | Views from 3D model showing mechanical ventilation system



Details

1	Pump
2	Cooling tower
3	Heat exchanger
4	Condenser
5	Evaporator
6	Boiler
7	Fan
8	Heating coil
9	Cooling coil
10	Filter
11	Water spray
12	Supply air
13	Exhaust air
14	Return air
15	Induction unit or fan coil unit
16	Ventilated space
17	Air handling unit
18	Warmed water supply/return
19	Chilled water supply/return

j | 4 pipe system for use with fan coil or induction unit

Ducting

Air is circulated in ducts of galvanized sheet steel (h), used because of its ease of fabrication, light weight, smooth internal finish to assist air flow and is economic. Ducts are usually insulated externally in order to reduce heat loss, or gain, and to prevent condensation forming on the outside of the duct when cold air is circulating. Circular ducts have the least surface area and the lowest frictional losses; however rectangular section ducts are more commonly used in commercial developments due to the fact that they require less depth when fitted above suspended ceilings and are economic. Square sections perform better than elongated sections; the maximum normally accepted depth/width ratio being 1:3. Flat oval ducts are also used in certain applications as they offer an advantage over rectangular ducts in being able to handle the same volumes with smaller sections due to lower frictional losses. Flat oval ducts are however more expensive to manufacture and require more specialised fabricators than circular or rectangular. The cross-sectional size of a duct is a balance between volume of air required, pressure drop and air velocity. Small volumes of air can be delivered at high speed or, alternatively, larger amounts of air can be delivered at lower speeds all with the same pressure drop using the same duct size.

Supply and extract plenums

The need for extract ducting can be reduced where the void provided by a suspended ceiling or raised floor is used as a supply or extract plenum. When used as a plenum, the ceiling or floor void can house air-handling equipment that recirculates air at the required temperature. Alternatively, extract air can be drawn back to the central plant for treatment. Sometimes light fittings are used as air extracts to draw away the heat they produce. Extracted heat from these fittings can be recirculated, or exhausted from the building as required, which helps to reduce the direct impact on room heat gains due to lighting.

Package units

Package units do not require a network of ducts. They are essentially air handling units which draw air from outside and either cool or heat it, releasing the treated air directly to the space served. Due to its relatively small capacity the package unit is unsuitable for large spaces, since too many units would be required.

Fan coil units

Fan coil units (FCUs) work in conjunction with a central fresh air plant. Generally, the fresh air required is treated at a central air handling plant and supplied at a constant temperature and volume either directly to the FCU or into the room/space served (j). The FCU is normally provided with cooling and heating coils and an inlet filter for the return air. The heating coil can sometimes be an electric coil if low usage is anticipated or no heating fluid is readily available. The fans inside these units can be speed regulated, normally by step changes; they simply draw room air in, mix this with fresh air where directly supplied, and distribute the air at the required temperature and volume to the space served.

FCUs can be either horizontally mounted above a false ceiling or vertically mounted, concealed or exposed against a wall. They are sometimes concealed below a raised floor working as part of a floor supply system.

Induction units

Induction units come in a variety of forms, although they are less popular nowadays. The most commonly used units were perimeter mounted, normally part of a perimeter office cabinet section. They are supplied with high-velocity, centrally treated fresh air which discharges via supply nozzles within the units, inducting room air from a low level to be drawn across cooling and/or heating coils, then mixed with the fresh air and discharged vertically into the room.



a | Kitakame Canal Museum, Japan. Architect: Kengo Kuma and Associates.



b | Furniture House, Yamanashi Prefecture, Japan. Architect: Shigeru Ban.

Electrical lighting

The two main types of electric light source are tungsten filament lamps or incandescent lamps and discharge lamps.

Incandescent filament lamps

These lamps produce light by passing a current through a thin tungsten filament in a glass bulb containing either a partial vacuum or an inert gas. The filament glows and produces a mixture of light and heat. When an inert gas such as a halogen is used, the lamp runs more efficiently as more of the electrical power is converted into light rather than heat.

The most common lamp is the general lighting service (GLS) light bulb. It has clear, coloured or pearl glass and its shape can vary from the common bulb form to spherical or linear. Some bulbs have their end silvered to reflect light upwards, reducing glare. The bulb used for spotlights or floodlights is the internally silvered reflector, or IS lamp. Its characteristic shape is designed to reflect light in a particular direction. A bulb with better directional focus, due to a reflector and a lens at the front, is the parabolic aluminised reflector, or PAR lamp, which is particularly suitable for spotlights and floodlights. Some lamps have dichroic filters in front of the bulb to reduce the amount of heat projected forward of the fitting. PAR lamps are also produced in a tungsten halogen type.

All these three lamps run on mains power (house current). The GLS and IS types last approximately 1,000 hours, while the PAR lamp lasts up to 2,000 hours.

Another type, called low-voltage tungsten halogen lamps, run off 12 volts and require a transformer. They produce sharply directional beams of light, making them useful for illuminating displays. They can last up to 4,000 hours. They are also used for car headlights.

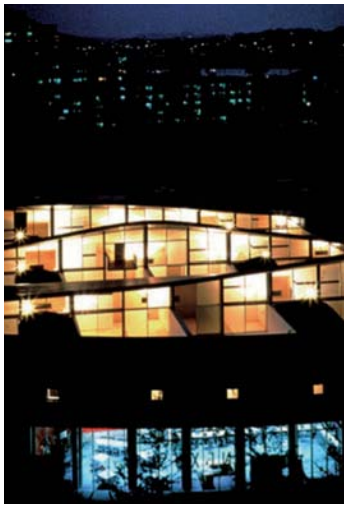
Discharge lamps

These lamps work by discharging an electric current through a gas or vapour in a sealed glass tube or bulb, which causes it to glow. These produce more light and less heat than a tungsten lamp for the same amount of power. The most common type is the fluorescent tube, which is filled with low-pressure argon and a proportionally small amount of mercury. The tube is coated with a fluorescent powder, and lengths vary between 320mm to 2400mm (13in to 96in). There is no standardisation in the production of these tubes, and each manufacturer designs lamps to their own specification. Tubes can last up to 10,000 hours, but their efficiency is slightly diminished with use. The low-pressure sodium discharge lamp is another common type used in many countries for road lighting, which has a characteristic yellow colour. It is extremely efficient and lasts approximately 12,000 hours.

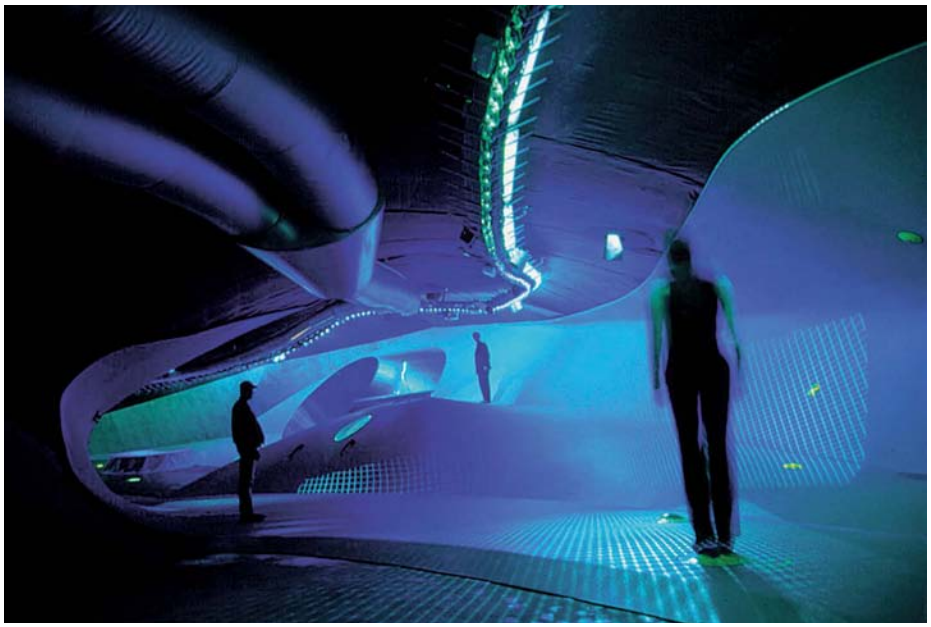
High-intensity discharge lamps have a wider range of colour rendering, use much less electricity and last longer than an equivalent tungsten filament lamp. Mercury vapour lamps are used for lighting large spaces, such as factories, where colour rendering is not a determining factor as they have a yellow/blue colour. Metal halide lamps have excellent colour rendering and are commonly used in all types of buildings from commercial offices to public buildings. Both types of lamp last approximately 10,000 hours. Compact fluorescent lamps, which are used as a substitute for GLS and are compatible with tungsten fittings, offer significant energy savings as a direct substitution for incandescent fittings.

Luminaires

Luminaires are used both to hold the lamp and to direct light to the point of use. They are used for both incandescent filament and discharge lighting. A huge range of luminaires is available; each suited to its intended use, location and method of directing light by diffusion,



c | International Housing Exhibition, FU.K.uoka, Japan. Architect: Rem Koolhaas, Office for Metropolitan Architecture.



d | Freshwater Pavilion, Neeltje Jans, Holland. Architect: NOX.

reflection or absorption. Manufacturers' catalogues use polar curves to plot the intensity of light radially around a cross-section or long-section through a light fitting. This helps the design team to understand how light from a single fitting will be directed.

Ceiling-mounted types

Luminaires on ceilings are either pendant (hanging), surface-mounted or recessed. The pendant is the most flexible, allowing light to be thrown up, down or a mixture of both. Surface-mounted luminaires can direct light to the side (d) or downward. Recessed fittings throw light downward by concealing the lamp and luminaire behind the ceiling plane. Pendant luminaires are often used where there is no suspended ceiling. They can be fixed directly from the ceiling or housed in a track that is attached to the soffit. Huge varieties of ceiling tracks are available and some incorporate both fluorescent strips and tungsten filament spotlights in a single length.

Ceiling fittings are often co-ordinated with low-energy mechanical features such as chilled ceilings and beams. Fittings suspended from a thermally exposed soffit can be designed to incorporate acoustic absorbent material to help address reverberation. Ceiling light fittings can also form part of integrated servicing fingers, often used to service exposed soffit areas, incorporating sprinklers, air supply, chilled beams and high-level electrical services.

Wall-mounted types

Luminaires on walls can also be pendant, surface-mounted or recessed. Pendant fittings are mostly used in conjunction with a track hung from the wall on a cantilevered bracket. Most wall-mounted fittings are surface-mounted which can direct light in all directions away from the wall, either directly or by reflection. Recessed wall lights have either a diffuser in front of the lamp or a reflector to avoid glare.

Floor-mounted types

Freestanding floor-mounted uplighters are often used in offices to provide or supplement office lighting. They are generally better for glare control than ceiling-mounted lights. Energy efficiency is lower with this type of fitting as the light has to be reflected from the soffit to illuminate the space.

A recent development in luminaire design is the recessed floor type. These have a cover that is strong enough to walk on and which is designed to minimise glare when looking down at the floor (a). This type has to be capable of dissipating its own heat generated in use, and as a result the casings are often made from metal alloys with high thermal conductivity, such as brass.

Exterior luminaires

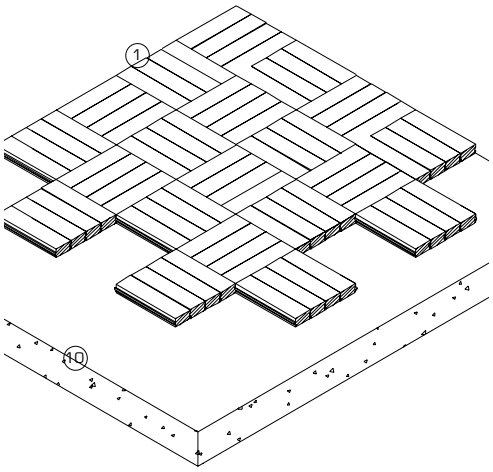
Exterior lighting utilises all of the above fixings. Luminaires must be either waterproofed or sheltered from the weather and power supplies must be planned well in advance so as to incorporate cable ways and access boxes into the external works.

Emergency lighting

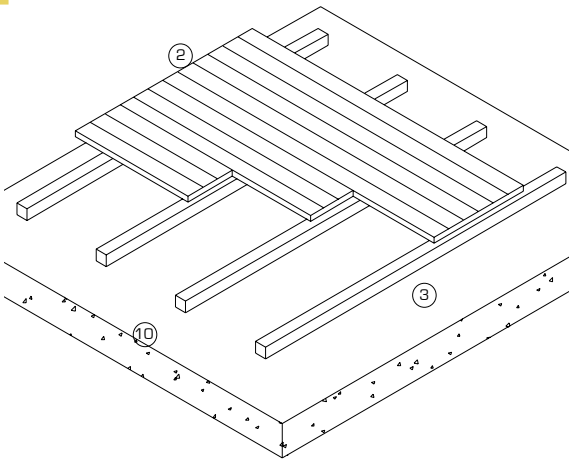
Emergency lighting allows escape routes and stairs to be sufficiently illuminated in the event of a fire or other emergency. The lighting can be permanently illuminated or switched on automatically by a fail-safe system in the event of a power failure. Both tungsten filament and discharge lamps are used. Power to emergency lighting is normally supplied by batteries charged continuously by the mains using separate circuits. Emergency generators should be used in buildings where mains failure can affect life safety and other essential equipment. Batteries are usually housed within plant rooms.

Details

1 | Timber flooring block
2 | Timber boards
3 | Timber battens
4 | Ceramic tile
5 | Stone
6 | Compressible seal
7 | Compressible backing
8 | Stainless steel angle
9 | Bedding compound
10 | Concrete floor



a | Timber block floor finish



b | Timber strip floor finish

Fixed floor finishes are those which are not intended to be accessible or demountable and form a permanent part of the building. Floor finishes are usually harder and more resilient than the floor structure, or substrate, beneath. Since the properties of finishes and substrates are usually different, the finish used must be laid in a way that allows both it and the substrate to move together or be separated in order to avoid cracking in the floor finish. Where there are movement joints in the floor structure, the floor finish is usually broken to allow expansion and contraction. As a result, the finish can influence the design of the substrate. For example, a cast-in-place concrete slab may require contraction joints at centres which do not correspond to the module of a proposed tiling layout, but which should be adjusted to suit the design of the floor finish.

Concrete

Concrete can be used as a self-finish to a floor slab, with its surface sometimes polished to provide a smooth, dust-free finish, either as a screed or as a power-floated finish to a floor deck. Grains of carborundum can be added to improve the wear of the floor. Concrete floors can be coated with floor paints which have improved enormously in recent years to provide fairly hardwearing surfaces that will last up to 5 years, but are not suitable for very heavy use which can cause the paint to wear away quickly. An epoxy coating is used where a harder surface finish is needed for heavy foot traffic, particularly for industrial applications. This polymer coating has excellent resistance to abrasion but is a very hard surface to walk on. A softer surface is provided by rubber-based compounds which are used in indoor sports facilities, but they have less abrasion resistance. Both epoxy and latex coatings, together with variations such as polyester resins, are referred to as poured floor finishes due to their ability to be poured in place to provide a self-levelling joint-free floor finish. They are poured over large floor areas to produce thicknesses of up to 6mm (1/4in). Made by mixing a resin with a curing agent, they provide a hard, smooth finish which can be coloured and is resistant to chemical attack.

Terrazzo is a hardwearing floor finish that is applied to a concrete substrate. It consists of crushed marble aggregate mixed with cement. The material is applied as wet mix to a thickness of between 15 and 25mm (5/8in to 1in) depending on whether it is bonded directly to the screed or concrete slab beneath. Terrazzo is bonded by laying it on the concrete substrate while it is curing (but hard enough to walk on). It is laid in bays formed by movement joints (expansion and contraction joints) in the concrete substrate. The bays are separated by stainless steel, brass or bronze angles in a very similar way to ceramic tiles. Terrazzo is finished by grinding and polishing.

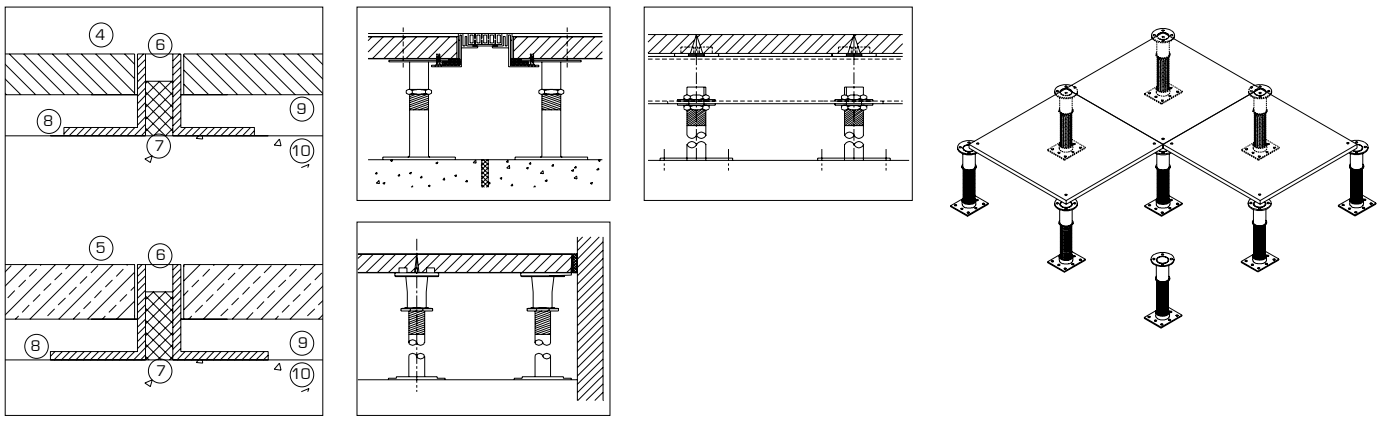
Stone

Stone is used as a fixed floor finish in the form of paving slabs that are bedded in a sand-cement screed and can be used both internally and externally. The thickness used depends on the strength and thickness of the stone and the size to which the stone can practically be cut from blocks. The most common thickness is 20 - 30mm (1in to 1 1/2in) with slab sizes adjusted to allow it to be carried by hand and laid in place. A common size is a module of 500 x 500mm (20 x 20in) or 600 x 600mm (2ft x 2ft) slabs, which allows 10mm for the joint between them. For small applications, stone can be ordered from choosing a sample, but for large areas the material is cut to order and the architect should visit the quarry to choose the material. In common with other natural materials, it is difficult to define precise visual qualities since its natural formation produces an enormous variety of appearance. The usual method is to define 'extremes' of quality between the most and least marked, and the lightest and darkest in a set of sample slabs. Because stone has little strength in tension, the substrate must be firm, with very little structural movement or deflection.

Stone floors are ground before being laid to provide different surface finishes. They can be polished, using fine sanding wheels, or honed, using rougher grinding wheels. Floor sealers are often not recommended for some stones since some slabs will be more absorbent than others, resulting in exaggerated colour differences across a floor surface.

Timber

Timber flooring can be used as a floor finish on concrete, timber or cold-formed steel framed floors. In all three instances, the substrate is sealed with a vapour barrier to avoid the timber rotting. The timber is either loose-laid as solid strip flooring, fixed on bearers resting on the substrate, or bedded in mastic or bitumen as block flooring. Strip flooring has traditionally been used with timber strips less than 100mm (4in) wide (b), while boards indicate anything wider up to a limit of around 150mm (6in). Nowadays strip flooring refers to all sizes of hardwood



c | Vertical sections of raised floor systems

d | 3D view of fully accesible raised floor system

tongue and groove board. Thicknesses range from 9 to 38mm (3/8in to 1 1/2in). Almost all types are proprietary systems that are either fixed to supporting battens as a sprung floor, typically used in sports halls, or are held together by pressed steel clips as a continuous material that rests on the substrate. Beech and maple are the most common hardwoods used, having a light-coloured appearance. A gap between the floor and the wall is left to accommodate movement in the wood due to changes in temperature and humidity. This gap is typically 10mm (3/8in) for a four metre (13ft) wide bay of strip flooring.

Wood block flooring consists of small hardwood blocks that are bonded with bitumen to a concrete floor (a). Block sizes vary from 25 to 100mm (1 to 4in) wide and 150 to 300mm (6 to 12in) long. Depths vary from 19 to 38mm (3/4 to 1 1/2in). Blocks are bonded directly to the concrete with a bitumen-latex adhesive. Simple rectangular patterns or herringbone patterns are the most common ways of laying blocks. Both strip flooring and block flooring require a surface seal, such as polyurethane sealer, to avoid dirt being trodden into the grain. This is re-applied every few years depending on the amount of wear experienced by the floor.

Floor tiles

There are two types of tiles for flooring; these are ceramic and quarry tiles. Ceramic tiles are manufactured from refined clays, while quarry tiles are made by extruding or pressing natural clays. Whereas the former are available in a wide range of colours, the latter are produced only in their natural colours of reds, browns and blues.

Floor tiles are made in many sizes and thicknesses. They are laid either on a bed of sand-cement mix or adhesive. Each bay of tiles is edged with a 6mm (1/4in) wide movement joint, which can be filled with a flexible seal such as polysulphide. Maximum bay size is usually six metres x six metres (20 x 20 ft). The bay size depends on whether the area is reached by sunlight and/or moisture. Metal edging strips, or a rigid sealant such as epoxy-polysulphide, is used to protect bay edges in large areas of tiling.

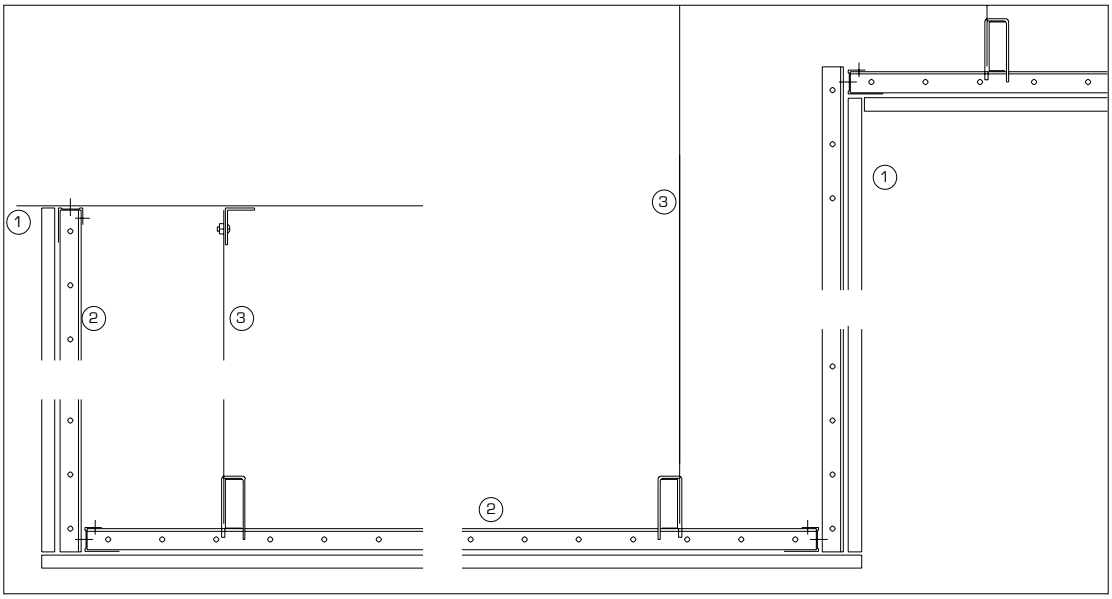
Raised Floors

Raised floors were first used as computer floors to provide a zone for electrical cables and air handling ducts for large computers housed in a separate room. They are now used throughout office buildings as a means of providing a zone for mechanical and electrical services including ventilation, as either a complement or replacement for those used in suspended ceilings. Raised floors are used as a method of bringing electrical cables under the floor to a large number of points while allowing tiles to be moved to accommodate changing servicing requirements. Completely open voids can also be used as an air plenum to supply or extract air in a mechanical ventilation system.

Raised floors are manufactured as proprietary systems with different loading capabilities, designed to be either fully accessible or semi-accessible, depending on the ease of use and frequency of access required to the floor void beneath. Fully accessible types have a much greater range of void depth, ranging from 100mm (4in) to around 2000mm (6ft). Semi-accessible types are restricted to low floor voids of around 150mm (6in). The fully accessible types are generally steel composite panels with a concrete-based infill, supported on variable height pedestals (c). Semi-accessible types are generally made from timber composite panels supported on concrete pads or timber battens. The two types have varying degrees of rigidity in their framework to suit the degree of accessibility required. In some systems, the structural stability of the frame is lost if too many modules are removed for maintenance access.

Fully accessible floors are made with a variety of construction methods. Some are made as a support framework with legs beneath. The panels fit into the frame to be supported on all four sides. Others have self-supporting panels supported on an adjustable leg in each corner (d). Semi-accessible systems vary even further in their design. Some comprise a single precast concrete tray with integral legs. These are laid side by side directly onto the floor slab. Others are very similar to the timber sprung floors used in sports halls, consisting of a rectilinear grid of softwood battens resting on acoustic pads to prevent sound transmission. Timber composite boards are screwed down to the frame.

Ventilation grilles and electrical socket boxes can be incorporated into all types. Floors typically have carpet tiles loose-laid on top, to provide both a comfortable walking surface and for acoustic purposes. Carpet can be separately bonded to each tile or be loose-laid off the grid to conceal joints in the floor beneath.



a | Vertical section through suspended ceiling

Suspended ceilings are used primarily to provide a service void between a ceiling plane and the underside (soffit) of the structural slab above. This zone is used to house recessed light fittings, ducts for mechanical ventilation and associated equipment. There are two generic types of suspended ceiling. The fixed version is used where a continuous plastered surface is required and where there is no need to access the ceiling void from below. Accessible types are used primarily in office buildings where they integrate with a modular layout of partitions. They are designed to suit both cellular office layouts and open office areas requiring individual lighting and mechanical ventilation.

Fixed suspended ceilings consist of either layers of plasterboard sheets or wet-applied plaster on metal laths which are supported on a frame suspended from the soffit of a structural slab or floor on either wires or galvanized steel strips (a). They can be designed as a simple timber or metal supporting frame, or be specified as proprietary manufacturers' systems.

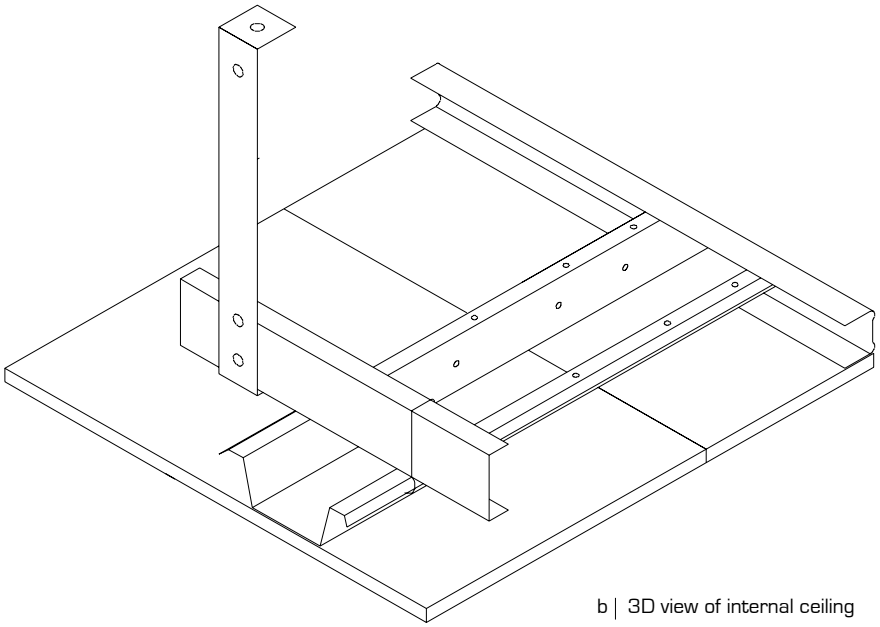
Fixed ceilings create a smooth, continuous soffit for recessed lighting and a ceiling plenum for ducts that do not require access (d). They can also provide a fire-resistant layer where this is not provided by the supporting floor structure. Access hatches can be used but are difficult to conceal. Fixed suspended ceilings can be used to form single direction curves by bending plasterboard around a modelled frame.

Complex shapes can be formed with metal laths. Fibrous plaster is often used, which provides a smooth surface that is easy to work but lacks the strength of other plasters. As a result, it is applied onto a reinforcing mesh in a very similar way to ferro-cement. Fibrous plaster is used where curves are required in two directions as well as in repetitive decoration, where items can be made in a workshop and later fixed to the ceiling.

Accessible ceilings use a supporting grid in steel or aluminium. The two most commonly used types are the T-section and the spring clip. Both are designed to be as light as possible with varying degrees of strength and rigidity, which are defined by the loads imposed on the ceiling by services from above and by partitions fixed to it from beneath. In some manufacturers' systems, the dimensional stability of the frame is lost if too many tiles are removed during maintenance access. The T-section uses an inverted T-shaped aluminium extrusion which holds the ceiling tile in place. The tile either sits directly on the section, creating an exposed grid, or is set hanging partially below the frame in a semi-concealed grid (c). The spring clip system allows the tile to be slotted into the support grid from beneath in a concealed system. The support grid can also be concealed by fixing the tile onto a T-section grid from beneath. This is done where aluminium or steel sheet is countersunk screwed to the support frame. Noise control within a room, or between adjacent spaces, is achieved by setting a sound-absorbent board or quilt onto the upper face of the ceiling tiles. The tiles are usually perforated to allow sound to pass through to the insulation behind.

The most common support grids are the one-way grid and the two-way grid. The one-way system has identical sections set parallel, at centres corresponding to the width of the tiles (d). Tiles are supported on two sides and span between the sections of the grid. Partitions beneath can be supported continuously in one direction but are supported only at points in the other direction. The reduced flexibility makes the system economical. A two-way system uses either metal cross tees that span between the main runners, or by using the same sections set perpendicular to one another to create a full grid. The latter type is made by half-jointing the main runners where they cross. The increased flexibility of the two-way system makes it more expensive. The frame is fixed back to the soffit with members of varying rigidity: wires, rods and angles. Suspension wires are not usually appropriate if partitions are fixed in such a way as to exert pressure from below.

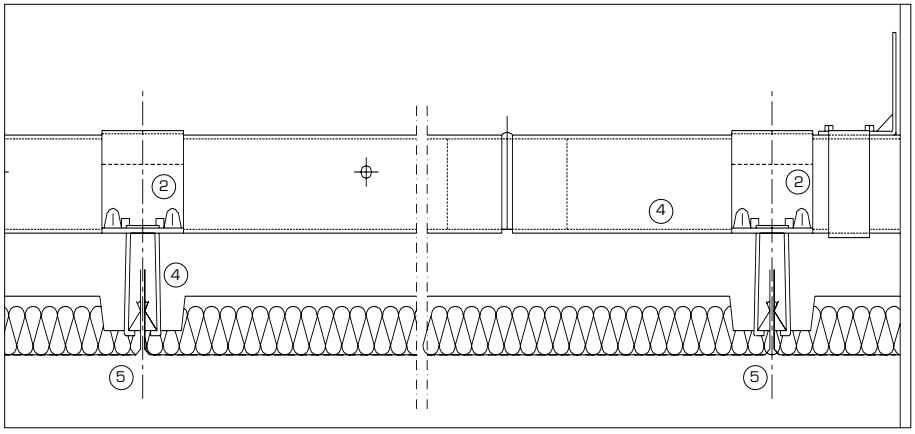
Like their supporting grids, ceiling tiles are designed to be lightweight. The most economical generic tile is mineral fibreboard, which provides high acoustic insulation but is limited to smaller spans due to its lack of rigidity. Greater thicknesses of board add considerably to the weight of the ceiling. The typical grid size in this material is 600 x 600mm (2ft x 2ft). Larger tiles are made from perforated steel trays. Since steel is a poor absorber of sound, it is perforated to enhance its acoustic performance, and in addition can be lined on the upper face of panels with either thin mineral quilt or an acoustic pad. Ceiling grids up to around 2000 x 3000mm (6ft 6in x 9ft 10in) are possible. Aluminium sheet can also be used but it requires a greater depth of vertical edging to attain the spanning capability of steel. This increases the overall depth of the ceiling.



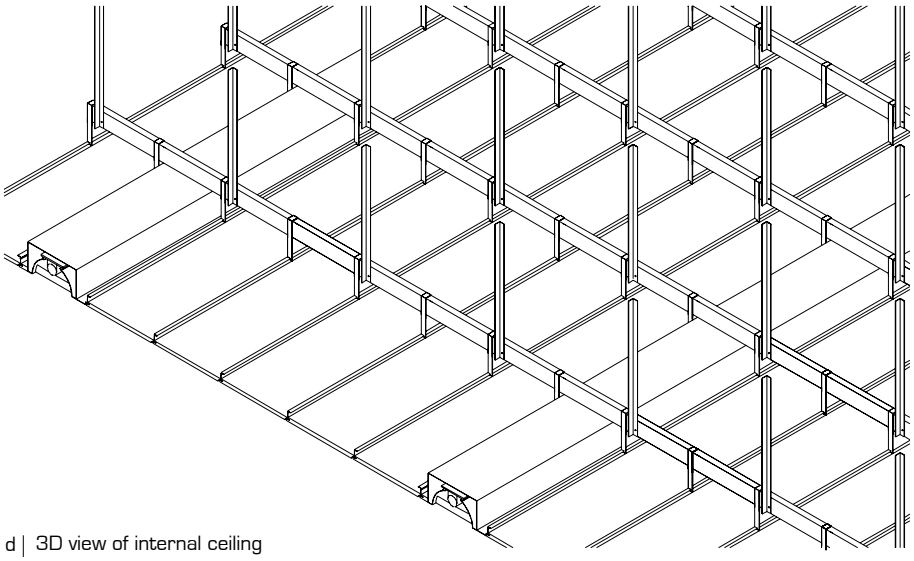
b | 3D view of internal ceiling

Details

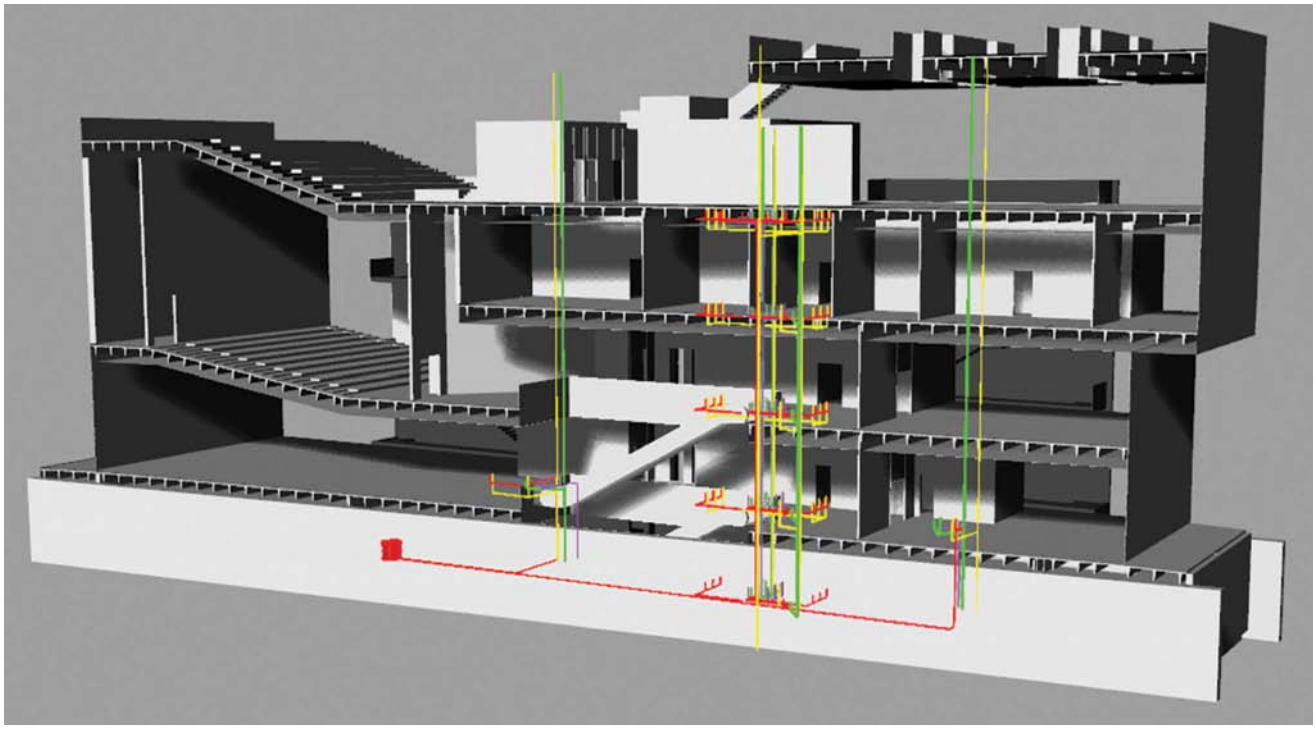
1 | Plasterboard/drywall
2 | Fixing rails
3 | Suspension rod, wire or pressed metal strip
4 | Clip to secure panel
5 | Ceiling panel (perforated metal panel with acoustic lining shown)



c | Vertical section through internal ceiling



d | 3D view of internal ceiling



a | 3D model showing water supply and associated drainage

Drainage below ground

Drainage is the second half of the supply cycle. Drainage can be provided by a separate surface water (storm water) and foul (sanitary) drainage system, or combined so that rainwater is drained with the foul water. In some areas, particularly towns, the separate arrangement is preferred so that during storms rainwater does not overload the drainage system, preventing the discharge of foul water from buildings.

Underground drainage is laid to falls in straight lines to allow for ease of cleaning by rodding (a). Access points are provided either where there is a change of direction or where pipes join, as blockage tends to occur at these points. Rodding eyes or inspection chambers are provided for this purpose. Inspection chambers are also provided along the length of the pipework. They consist of a brick, plastic or concrete-lined box. The top is sealed with a removable cover. The upper halves of the pipes in the chamber are cut away to provide access for cleaning by rodding. The connecting pipes in the chamber do not need to be at the same level. This allows pipework to follow levels and gradients which suit other parts of the drainage layout and meet at different levels. The lowest level at which the water runs is known as the invert level of the manhole. Ladder steps are provided if the chamber is deeper than approximately 600mm (2ft). Where a pipe runs below a building and an inspection chamber is required, special measures, in particular double-sealed chamber covers, are taken to prevent foul air escaping. Not all pipe intersections require inspection chambers. An alternative is to provide sufficient rodding points along the length of the drainage run.

Pipework below ground consists of a series of pipe lengths with a spigot at one end and a socket at the other. The pipes slot into one another, and are sealed with rubber rings. Sometimes separate sleeves are used to connect pipes instead of sockets. The rubber rings also provide a degree of flexibility for movement. Pipes are made from vitreous clay, concrete, plastic (UPVC) and cast iron. Pipes are laid in trenches on a well-compacted surface. Concrete is sometimes used depending on the local ground-loading conditions. They are enclosed in gravel wherever excessive movement is expected and rocker pipes, short lengths of pipe with connections at both ends, are used to allow movement to occur.

Septic tanks

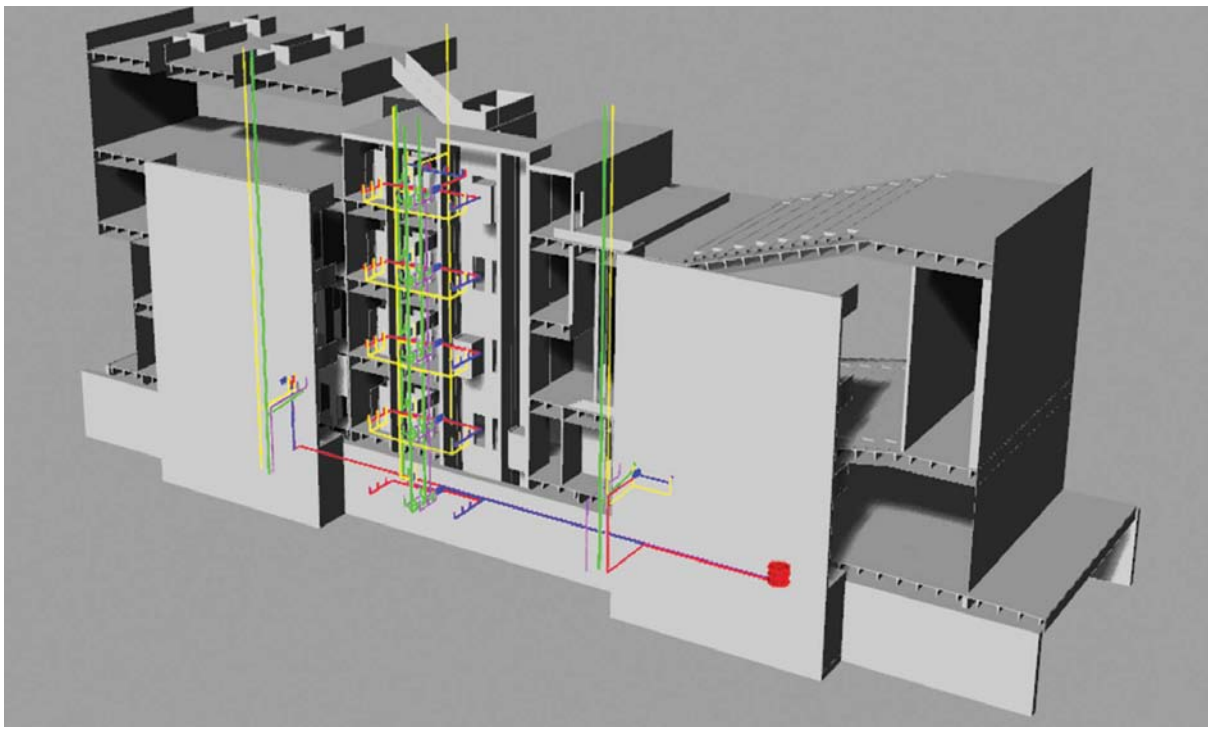
Septic tanks are used where there is no local sewer system. These can be set either at or below ground level. They are manufactured as complete units prior to installation on site and consist of a series of chambers which separate solid from liquid waste. The liquid waste is allowed to leach back into the soil through a series of perforated pipes called a 'leaching field'. The solid waste is periodically emptied into tankers and removed for off-site treatment.

Soakaways (drywells)

These are a method of providing surface water drainage directly to permeable ground adjacent to the building. Soakaways are used in rural areas where there is no benefit in draining away rainwater into the sewer system. They consist of a large pit into which the surface water drain discharges, permeating the rainwater into the surrounding soil. The most common type is a concrete tank made from a set of stacked rings. Simpler versions consist of a pit filled with hardcore (gravel) that prevents it from collapsing, whilst allowing the water to drain away.

Sanitation and drainage above ground

Water in a building is drained as either soil or waste. Both are drained either separately in a two-pipe system or together in a single-pipe system. The drainage is usually installed and connected to the below ground drainage from inside the building to avoid the pipes freezing and to avoid multiple street sewer connections.



b | 3D model showing water supply and associated drainage

Water closets (WCs) and urinals are drained to a soil pipe. Sinks, basins, baths and showers are drained to a waste pipe. Rainwater is drained separately. Below ground, the soil and waste pipes combine as foul water drains. Rainwater either drains into separate surface water drains or it joins with the foul water via a special trap forming a combined system. These pipes run below ground to the main sewer. In areas not served by a sewer network, a septic system can be installed for soil and wastewater treatment.

Air from these pipes is prevented from entering the building using traps fitted to each sanitary and waste appliance. Pipes slope downward to the sewer, since they work entirely by gravity. Pumps are only occasionally used where adequate falls cannot be provided. For this reason, pipes with smooth internal bores are used to reduce friction. Falls in soil pipes below ground are normally around 1:60, depending upon location, design flow rate and size.

Balancing the system

Water flows down the inside surface of vertical pipes, leaving an air gap in the middle. In horizontally laid pipes, the water runs down the bottom or invert of the pipe due to a shallow fall. The air inside the pipework is designed to remain at atmospheric pressure to equalise air pressures on either side of traps. If the pipe bore is filled with water then air cannot balance the system, causing traps to pull due to the siphon effect, or blow through their water seal due to over-pressure. Consequently, pipes are designed to be large enough to accommodate a percentage of air and are ventilated to the outside air, close to the sewer outfall and at the top end of the drain stacks.

Single-pipe system

This system, also called the single stack system, combines the soil and waste pipes. Each sanitary and waste appliance is connected to a single pipe, one above the other in a stack. The pipe used is generally larger than in the two-pipe system, helping to avoid pressure fluctuations that might cause the traps to lose their seal. The use of a straight stack: that is, without bends above ground level, ensures a controlled flow of soil and waste, allowing air to move freely in the pipe. Lengths of waste pipes from appliances to the stack are limited to approximately two metres (6ft). Beyond this distance, the trap to the sanitary appliance is fitted with a separate vent pipe known as an anti-siphon pipe.

Rainwater

There are a number of rainwater systems in use today, the choice of which is based on the type of areas being drained. Large areas, where space for high-level-collection rainwater pipework is limited, can be drained using siphonic drainage systems. These systems are designed to create a suction pressure within small-bore horizontal rainwater pipework and use specially designed outlets. Large glass roofs are often drained by flat channel systems that have special tapering outlets to cope with the large flow rates needed to drain the roof efficiently. Insulation is applied to rainwater pipework where it passes within internal areas to avoid condensation.

Rainwater is generally collected below ground into either a combined or a separate drain, which is then connected to the combined foul-water-and-surface-water sewer or a surface-water-only sewer. In both cases, the connection is made via a vented intercepting trap. Rainwater is sometimes collected into storage tanks for reuse in irrigation applications or as a supplement to grey water systems. Bypass pipes are needed to avoid overfilling storage tanks.



a | Cleaning gantry allowing underside of roof to be cleaned and maintained without cleaning platform from below.
B8 offices, Daimler Chrysler Projekt, Potsdamer Platz, Berlin, Germany. Architect: Richard Rogers Partnership.

Roof-mounted facade cleaning systems

With the increased use of metal, glass and composite materials in facade design, there has been a greater requirement for cleaning and maintenance. Building facades 30 years ago were detailed with low levels of maintenance envisaged; with the use of brick, concrete, stone and timber dominating architectural design. Facades would be cleaned only rarely, with details that would weather well with the passage of time. Windows in masonry walls were detailed to be openable, partly to admit fresh air for ventilation and partly for cleaning access. With the increased use of sealed facades without openable windows came an increased requirement for cleaning equipment.

Facade cleaning systems for twinwall facades (MHC_372) are often provided in the form of walkways set at each floor level. Most systems, however, are roof-mounted and are required to be integrated into the roof design (a), usually with a minimum of visible equipment. These roof-mounted types are discussed here. Most facades are cleaned with either davits, monorails or trolley systems mounted at roof level, with larger buildings having a mixture of these systems on a single roof.

Davit systems

A davit is a jib or scaffold-shaped frame from which a cleaning cradle is hung. A single cleaning cradle, holding one or two persons, is usually hung on cables from a davit at each end of the cradle (b). Davits are moveable and when in use are secured to bases in fixed positions near the roof edge. Davits are very useful for roofs where the permanent visual presence of a monorail or trolley system is not the preferred solution to facade maintenance.

Davits are usually made of mild steel or aluminium tube and are moved with wheels at their base. This makes them sufficiently lightweight and mobile to be handled by one or two people when they are moved into position and fixed for use. Davits are usually dropped into position onto a set of bolts projecting up from the roof surface, typically as either plinths in the form of short columns, or as a recessed box below the level of the roof finishes where the bolts are concealed from view, as on an accessible roof terrace. The davit is lifted into position, usually by a person pulling it up with a rope secured to the top of the post. The arm of the davit can be swung outward once it is fixed in place. Cables, secured to the end of the davit arm before it is lifted into position, are lowered down the facade to be attached to the cleaning cradle below, at the base of the facade (c). The cradles usually have wheels which enable them to be moved to suit each new pick-up position for the davits as they are moved to each new fixing point on the roof. The cables are connected to the cradle, allowing it to be raised up the facade. The cradle is fitted with an electric winding mechanism and rubber fenders to avoid direct contact with the facade. There is no winding mechanism at the level of the davit, whose function is to support the cables only. The electrical power supply for the cradle motors is from points either at roof level or at the base of the facade, supplied to the cradle by a power cable. In the event of a power supply failure, a manual system in the winch allows the cradles to be lowered to the ground. Various proprietary systems of winch motors and lifting equipment are available, all with different safety features.

When one vertical strip of facade is cleaned by a cradle that is raised and lowered from a pair of davits, the cradle is moved to its next position by descending to its lowest level and disconnecting the cables. The davits are then unbolted and lowered from their bases before being moved to



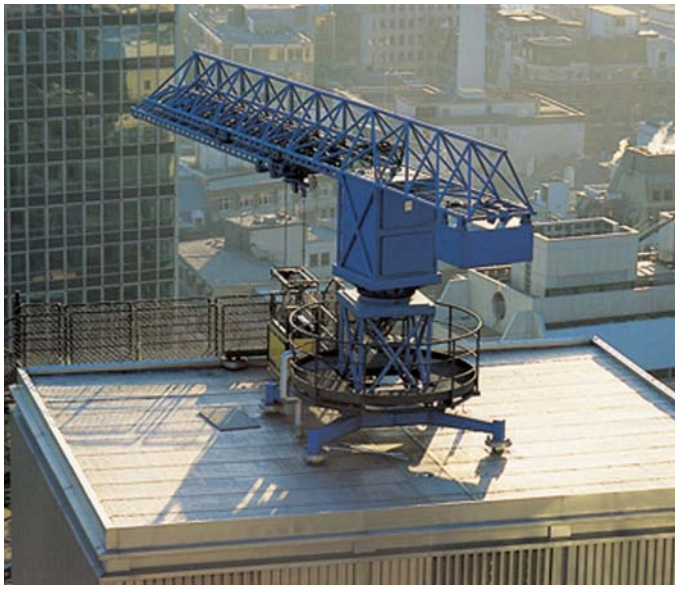
Details

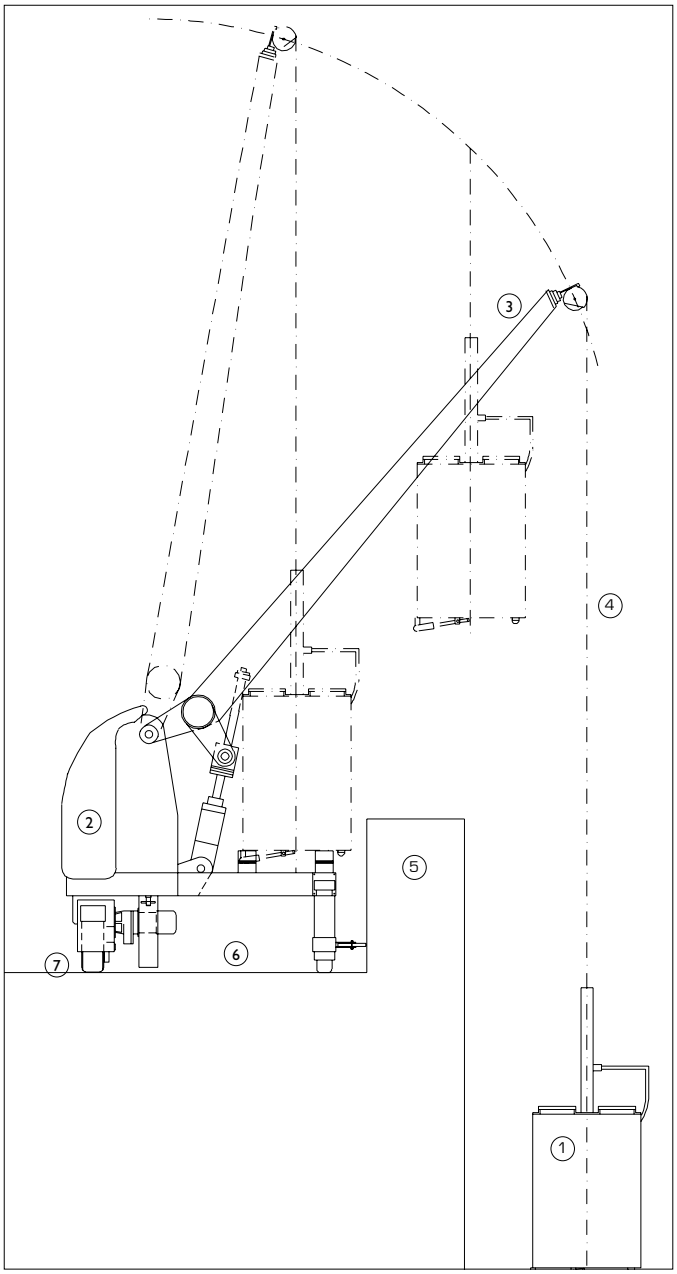
1 | Cleaning cradle
2 | Motor and counterweight
3 | Hydraulically operated arm
4 | Steel cable
5 | External wall parapet
6 | Roof surface
7 | Wheels or guide rails

b | (Above and below) Cleaning equipment, Lloyds Building, London, U.K.
Architect: Richard Rogers Partnership

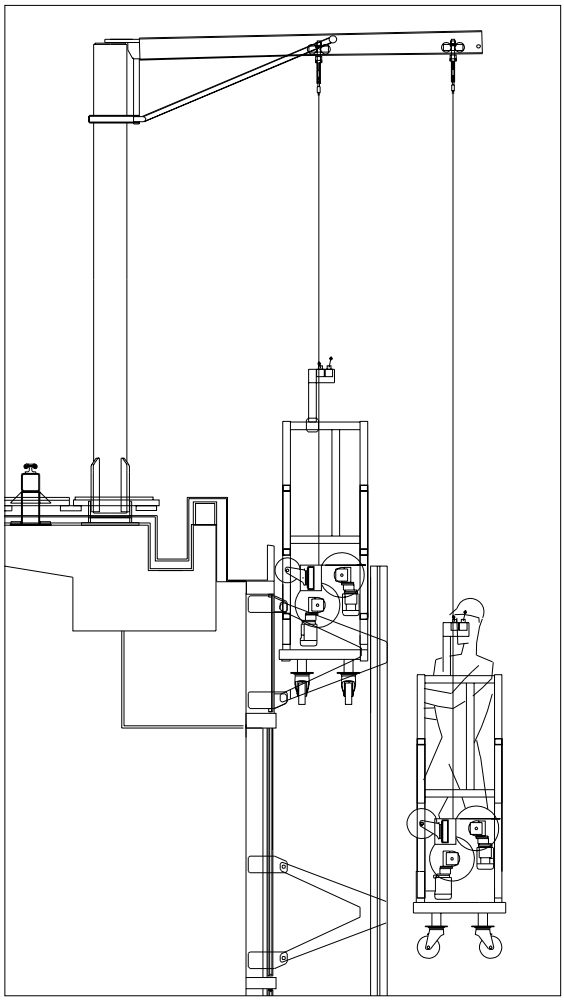
Cleaning equipment on this building has been specially designed and integrated into the overall architectural aesthetic being highly visible at all times from the surrounding city streets



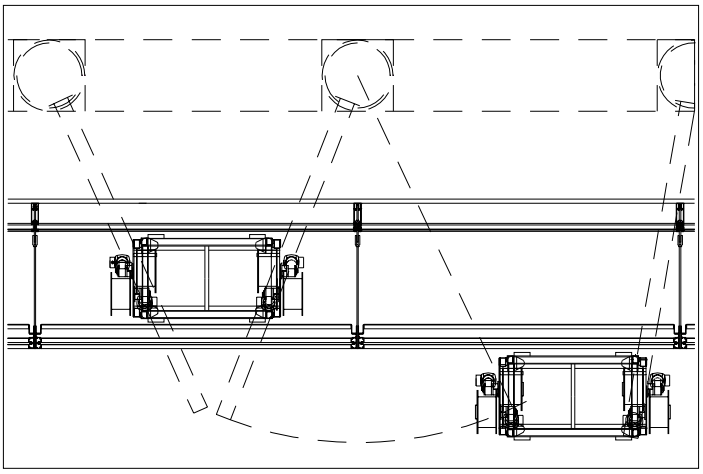




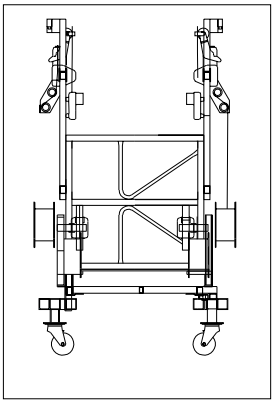
c | Section 1:50 Roof-mounted cleaning crane



d | Section 1:50 Davit supporting cradle in two positions



f | Plan 1:50 Davit supporting cradle in two positions





g | Elevation 1:50 and 3D view of typical cleaning cradle

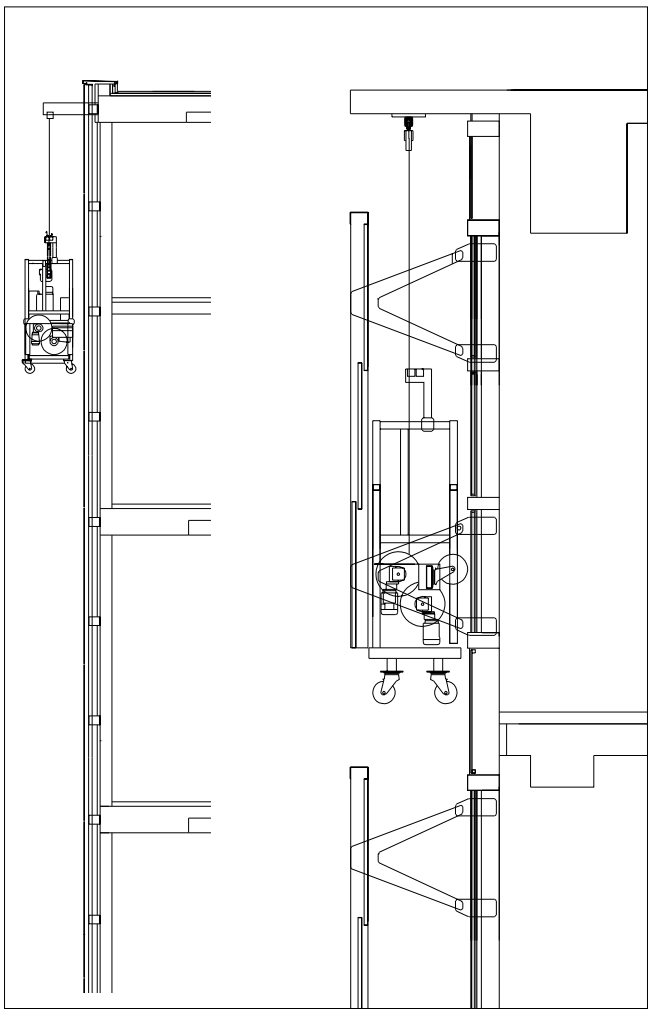




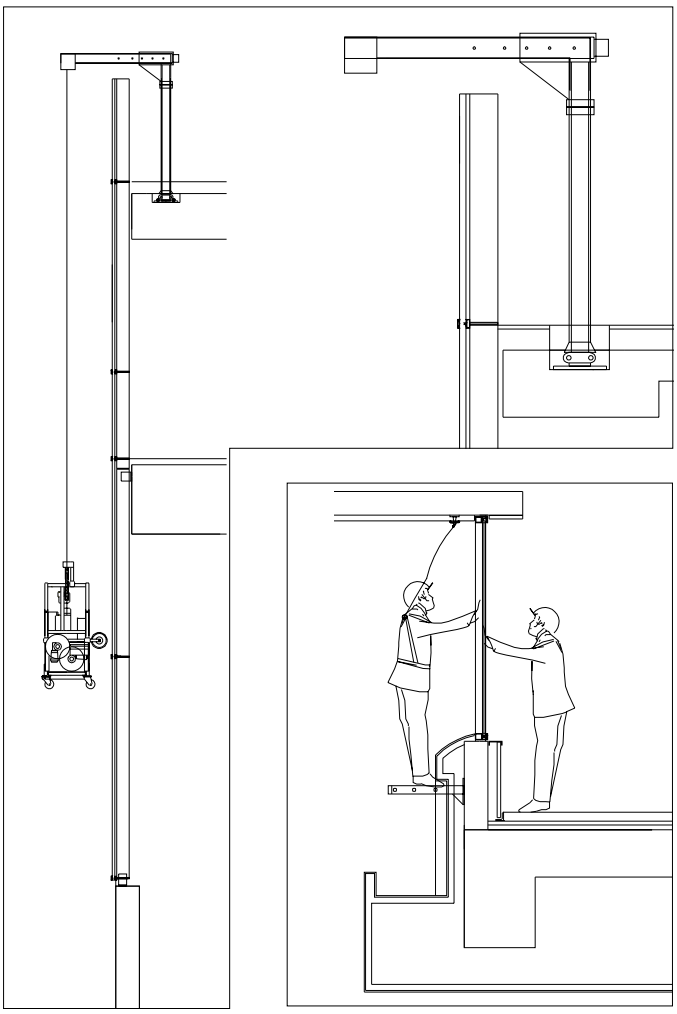
e | 3D views of typical cleaning cradle on facade



h | Cleaning cradle on glazed facade



j | Section 1:100 and 1:50 monorail supporting cradle from cantilevered brackets / beam



k | Section 1:100 and 1:50 davits supporting cradle

m | Section NTS cleaning with harness on a platform

the adjacent base positions for re-connection.
While this is a relatively slow process involving erecting davits, setting up the cables and cradle then disconnecting the parts and moving the davits again, this method avoids a permanent and visible cleaning system being mounted on the roof. The davit system is most commonly used where the roof is used as an accessible roof terrace or garden, and where a permanent cleaning system would not be visually desirable.

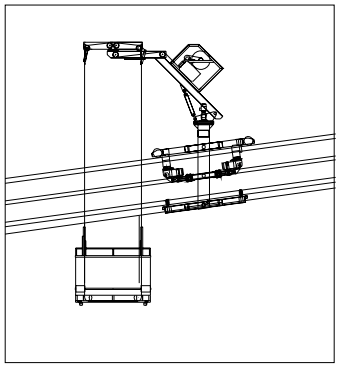
Monorails

In the monorail system, a continuous single rail is fixed at roof level, from which a cleaning cradle is hung from a cable at each end. The monorail is set around 500mm beyond the edge of the roof to allow the cradle to hang slightly forward of the facade, typically on brackets cantilevered from the roof structure as shown in (j). The monorail is a visually strong element that is integrated into the overall design at the edge of the roof. An alternative to cantilevered fixing brackets is to cantilever the edge of the roof out by around 500mm. The rail is usually made from mild steel which is painted or enclosed in a decorative metal cover, usually in folded aluminium sheet. Where cantilevered support arms are used, these can be castings or standard structural steel sections to suit the design. The monorail, set horizontally, is usually formed as a channel-shaped section that allows a pair of wheels to run inside the rail. Sets of wheels are operated either by sliding the cleaning cradle beneath manually, or by electrical power for larger installations. As with the davit system, cables are connected from wheeled pulleys which travel inside the monorail. The cables are lowered down and connected to the cleaning cradle, which is set at the bottom of the facade. As each vertical strip of facade is cleaned, the cradle is moved along the facade, usually when it is at roof level just below the level of the monorail. When manually operated, the cradle can be moved when at the bottom of the facade if maintenance personnel are assisting at roof level. The monorail offers a visually discreet method of providing a permanently fixed cleaning system at roof level.

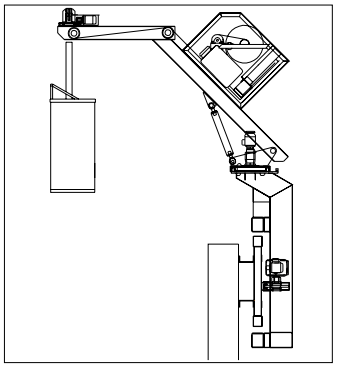
Where the monorail is hung from the underside of a balcony or slab soffit, it can be concealed with cladding panels set on either side of the rail. From below, only a single continuous groove is visible. A gap of around 20mm is provided between the monorail and the adjacent panel to allow for movement of the monorail itself when in use. This joint is either left open or closed with a flexible seal, typically EPDM sheet.

Trolley systems

Where a facade is required to be cleaned from a roof which is either sloping or has a stepped profile in elevation, a horizontal monorail is a much less practical solution for supporting cleaning cradles. Davits are usually difficult to handle on sloping roofs. Trolley systems are better adapted to reaching facades from a sloping roof, and where the facade itself is of complex geometry. Trolleys are typically mounted on wheels and are secured to a continuous track, which may be beneath the trolley as roof-mounted rails, or set vertically. The trolley usually has arms



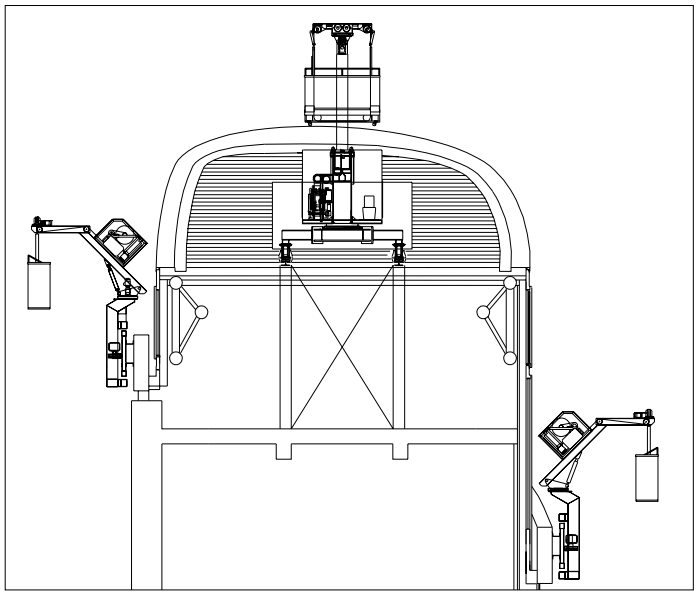
n | Elevation 1:200 trolley supporting cradle



p | Elevation 1:100 trolley on vertically set rails



q | Cleaning cradle on trolley around Swiss Re building, London, U.K. Architect: Foster and Partners



r | Elevation 1:200 trolley supporting cradle



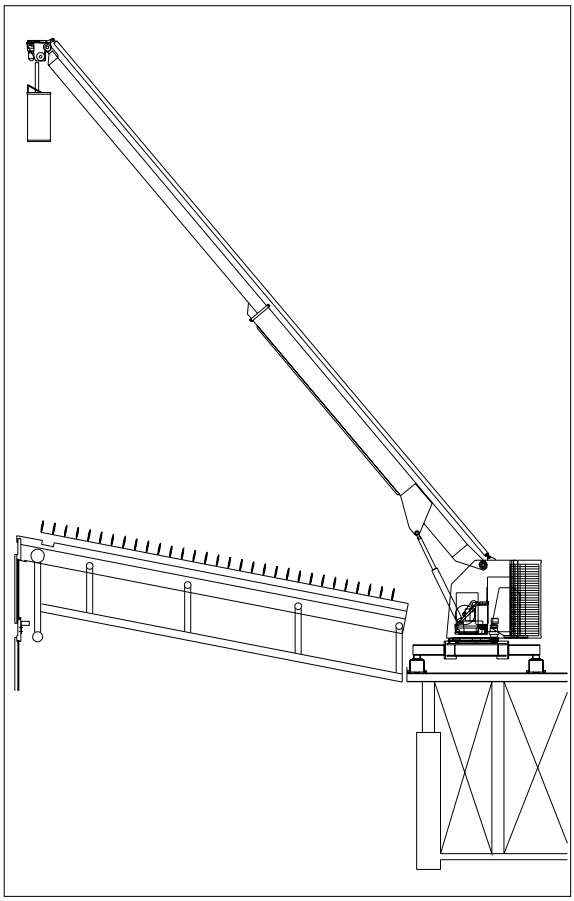
x | Cleaning cradle

which project out over the edge of the roof and support a cleaning cradle from cables fixed to the ends of the arms (p). The arms are sometimes telescopic (hydraulically operated) in order to reach either the facade or, for example, solar shading panels in front of the facade. The arms are usually raised or lowered to bring the cradle in and out from the facade and to bring it to rest at roof level (r). The trolley itself houses the motors for both moving the equipment along its rails, moving the arms, and raising and lowering the cradle itself. The trolley is usually controlled from within the cradle, allowing it to move both vertically and horizontally.

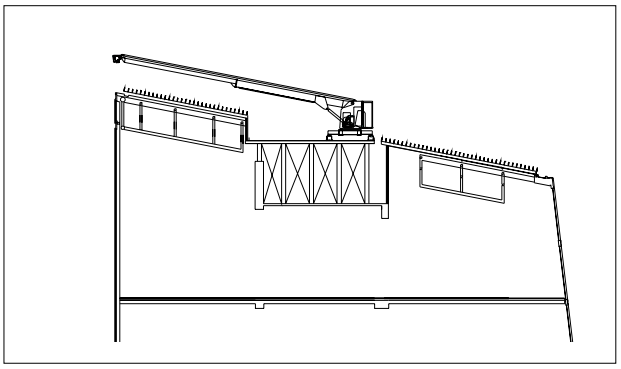
This system is not usually suited to roofs which are fully accessible to building users due to the presence of rails or a dedicated path, as well as the visual presence of the trolley itself. As the trolley is controlled remotely, safety at roof level is a critical consideration. Where roofs are required to be accessible, rails are mounted above the roof, but their dominant appearance may deter this solution in practice. Where the trolley can be seen from below, it is usually concealed behind a screen or in a small enclosure allowing it to be protected from the effects of the weather. Trolley systems are well-suited to being mounted on sloping or curved roofs (q) where they climb steep slopes, typically up to around 45°.

Where facades step in at a lower level, the cradle can be offset from its supporting cables by the use of counterweights attached to the cleaning cradle. The cradle can be moved by an arm fixed directly to the supporting cables. As the arm moves from a vertical position to the horizontal, the cradle swings away from its cable. The movement is balanced by a counterweight at the other end of the arm which keeps the cradle level and stable. This method is useful in facades that either step outwards as they rise up or are inclined outwards through their height. The mixture of a trolley system and cradles allows complex facade and roof forms to be cleaned and maintained from a single cleaning cradle. With facades and roofs of complex geometry, the trolley rails can be concealed in a gutter at roof level where facade and roof form a single and continuous form.

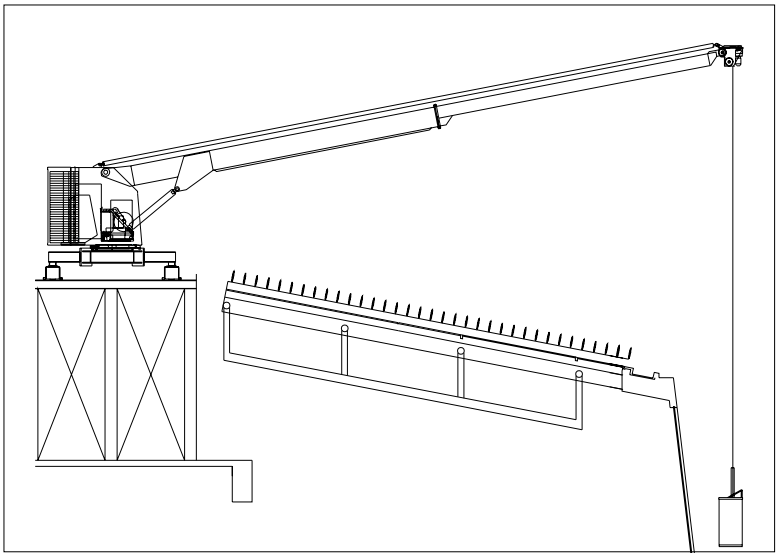
In the example above (s), a trolley is set behind a parapet formed by solar control louvres. It is set on a track that forms a continuous loop to suit the shape of the building. As the trolley moves around its circuit it is able to reach all parts of the facade. The trolley is able to reach the facades with telescopic arms that can be adjusted both in length and height to suit the facade being cleaned. A single trolley is usually provided for a single building, but more than one may be required; working on the same track to suit different facade geometries beneath. Not all large-scale trolleys require tracks to restrain them. Trolleys with wheels that move on a raised portion of roof deck are also used.

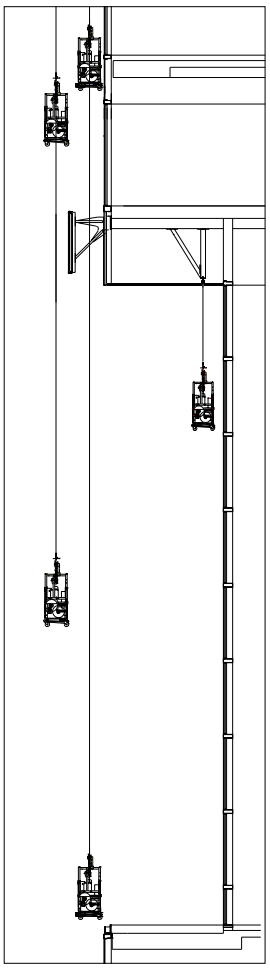


s | (Left and right) Elevation 1:200 trolley with reach over adjacent facades

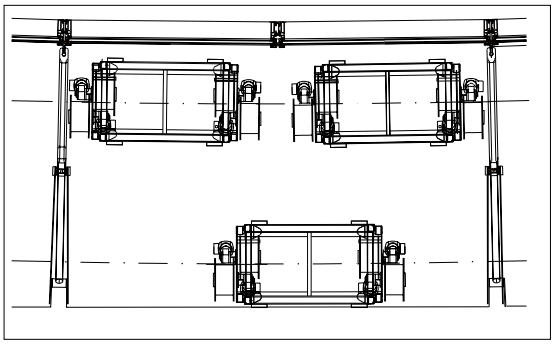


u | Elevation 1:500 trolley with reach over adjacent facades





t | Section 1:200 cradles hanging from trolley and monorail



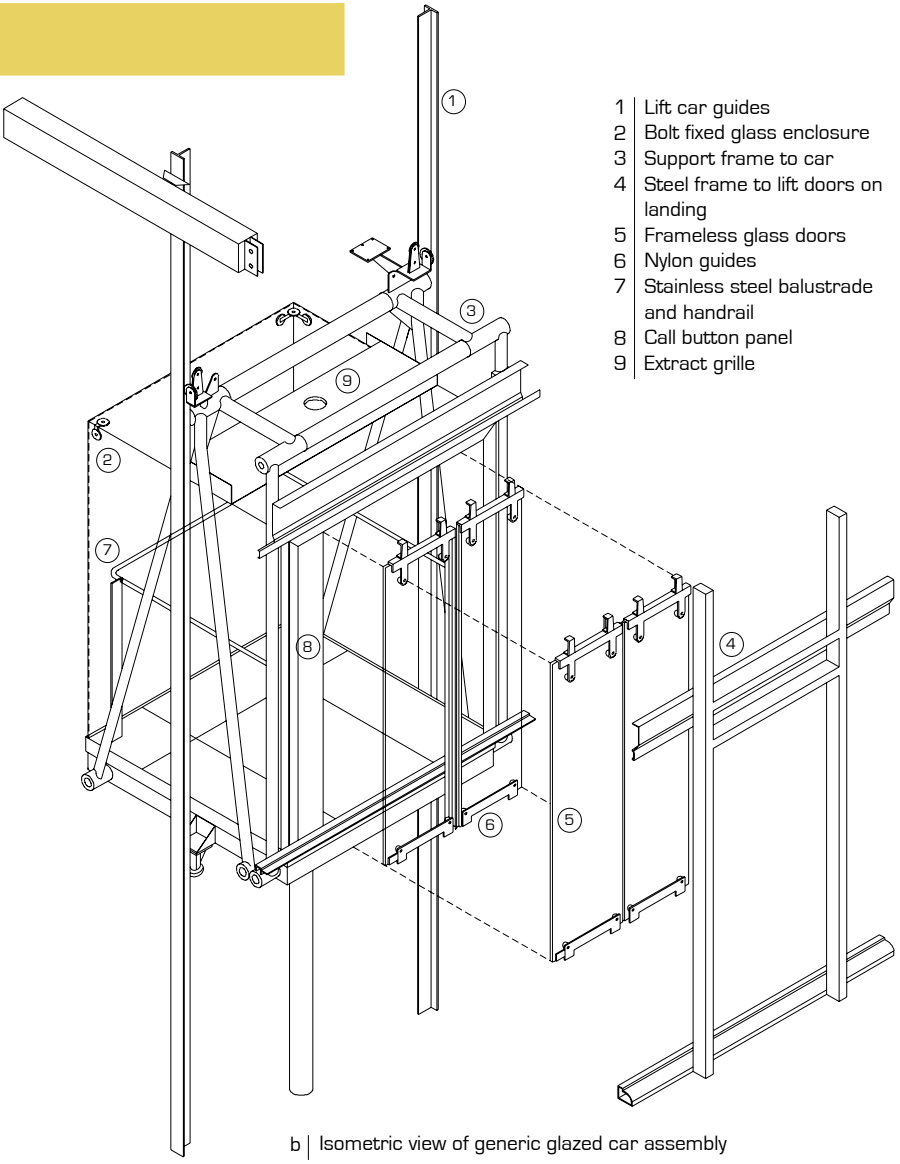
v | Plan 1:50 cradles hanging from trolley



w| Cleaning cradle



a | 88 Wood Street, London, U.K.
Architect: Richard Rogers Partnership.



b | Isometric view of generic glazed car assembly

There are two generic types of elevators: traction, where the elevator car is suspended on cables with counterweights, and hydraulic, where the elevator car is fixed on a ram which is sunk into a shaft. In both cases the elevator cars run on vertical guides which are attached to the inside of an elevator shaft or, in the case of open wall-climber elevators, directly to the edge of floor structures. It is common in tall buildings to use fast elevators that stop every ten floors. Intermediate floors are accessed from separate elevators that run between the fast elevators.

The type and number of elevators for any installation is established by the following criteria:

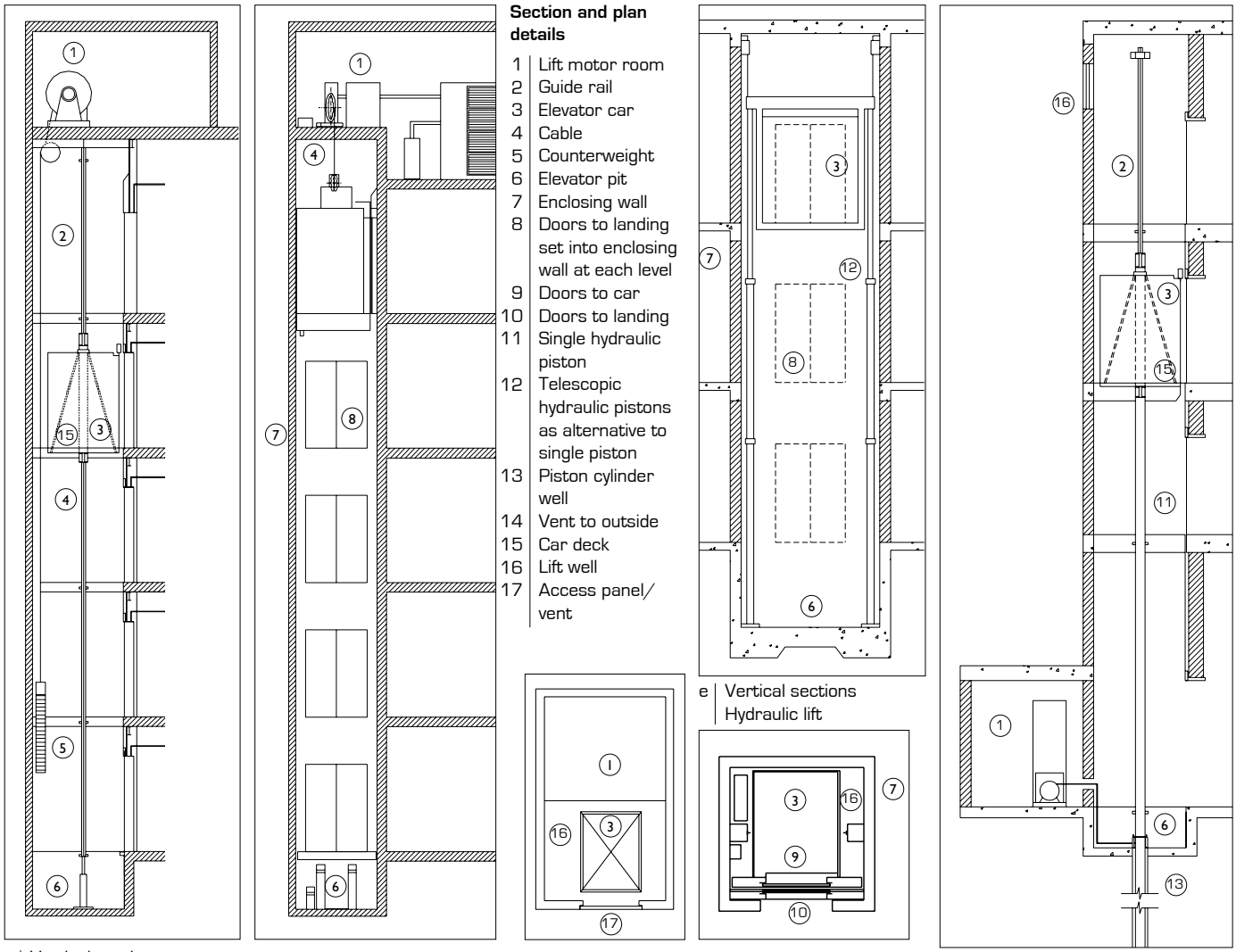
- Approximate passenger load
- Maximum acceptable waiting time
- Number of persons each car will carry
- Elevator speed
- Expected passenger load at peak times

Elevator cars consist of metal frames clad with solid or transparent panels (b). Doors to the elevator cars can be single or double, sliding on either one or both sides of an opening. Width restrictions, particularly where elevators are set side by side, may mean that doors are set off-centre to the elevator car or that twinleaf doors are necessary.

At each level served there are elevator landing doors, which can be solid or transparent. These doors open only when engaged by the elevator car doors. When the elevator is in an open shaft there is a need to protect people on each landing from the moving parts of the elevator mechanism. In this case, each floor is provided with landing screens which are incorporated into the elevator landing doors. Where the elevator is in an enclosed shaft, the risk of fire spread from floor to floor must be taken into account. In such a case, the elevator landing doors may need to be fire-resistant. Call buttons are located on each floor. In larger installations, calls are registered by the control gear and automatically dealt with in sequence. Banks of elevators have co-ordinated control systems that respond to calls in a given sequence.

Hydraulic elevators can carry a maximum of around thirteen passengers. In theory, there is no limit to what a traction elevator can carry. For cars carrying up to thirteen people, the same-sized well can be used for both traction and hydraulic elevators. An eight-person elevator is usually the smallest which can comfortably admit a wheelchair. The minimum door width is usually 900mm.

Traction elevators are electrically powered. Cables, running over pulleys and balanced by counterweights in order to minimise the efforts of the elevator motor, support cars. Both car and counterweight move in vertical steel guide rails (c). Traction elevators have advantages over



Section and plan details

1 Lift motor room
2 Guide rail
3 Elevator car
4 Cable
5 Counterweight
6 Elevator pit
7 Enclosing wall
8 Doors to landing set into enclosing wall at each level
9 Doors to car
10 Doors to landing
11 Single hydraulic piston
12 Telescopic hydraulic pistons as alternative to single piston
13 Piston cylinder well
14 Vent to outside
15 Car deck
16 Lift well
17 Access panel/ vent

c | Vertical section Traction lift

d | Horizontal section Traction lift

e | Vertical sections Hydraulic lift

f | Horizontal section Hydraulic lift

hydraulic elevators with their higher speed and hardwearing qualities. Speeds vary from 0.5 metres per second for smaller installations to 6.0 to 7.0 metres per second for tall buildings.

Traction elevators have an over-run space at the top of the shaft. This protects anyone working on top of the elevator should the car travel to the top floor accidentally. The overrun also allows cables to run over the pulley to the motor. The overrun space also accommodates the cable pulleys. Motor rooms house the elevator motors and ancillary equipment that drives the cars (d). These are usually located at the top of the shaft, adjacent to the overrun. The motor room can also be positioned to one side of the elevator pit at the bottom of the shaft, but this requires more sophisticated cabling. Motor rooms require ventilation because of heat generated by the machinery.

A pit is located at the bottom of the elevator shaft. It is usually about two metres deeper than the lowest floor served in order to accommodate the underside of the elevator car. The top of the elevator shaft is vented to the outside to ensure that air is drawn up the shaft and out of the building in the event of fire (c).

A hydraulic elevator consists of a piston cylinder set into a well beneath the elevator pit, which accommodates the underside of the elevator car at the lowest floor level. The piston can be a single or telescopic tube. If it is a single tube, the well must be deep. The hydraulic piston is fixed to the bottom of the shaft and connected to the elevator car. The ram is activated by hydraulic oil which is forced into the cylinder well under high pressure, which then moves the elevator car (e). Hydraulic elevator mechanisms are suited to installations serving up to five floors. They are usually slower than traction elevators, with speeds ranging from 0.63 to 1.00 metres per second. The motor room can be located a short distance away from the elevator shaft, rather than next to it, either at the bottom or the top, which is an advantage in small buildings (f). Hydraulic elevators are also useful where an overrun cannot be accommodated easily at the top of the elevator shaft.

The machinery room can be independent of the elevator shaft, and may be located up to five metres away. Machine rooms are smaller than those of traction elevators and contain pumps, motors, fluid storage tanks and control equipment. Machinery rooms require ventilation due to heat generated by the equipment. Hydraulic elevators have an overrun at the top of the elevator to protect anyone working on the top of the car, in case it accidentally rises to the top of the shaft (e). Like traction elevators, the top of the shaft is externally vented to ensure that air is drawn up and out of the building in the event of fire.



a | Movement transducers are fixed to structural supports that are not affected significantly by the wind pressures created by an aero engine. Transducers are calibrated and checked to ensure their reliability during testing.



b | The digital types shown provide a continuous set of readings during a dynamic air pressure water penetration test. The wall sample is checked visually throughout the duration of the test to check for any signs of water penetration.



c | An array of water spray nozzles around a glass rooflight is used to check the water tightness of silicone-sealed joints.



d | A test rig with additional architectural elements added to combine a performance test mock-up and visual quality mock-up as a single item.

Performance testing of facade material systems

The performance testing of facade systems is undertaken for a number of reasons; the most important usually being the weather-tightness of the system. Whereas for twin wall facades and external solar shading devices form a part of the system, overall stability under wind load forms an important part of the testing. A range of tests simulate the worst conditions, and combinations of conditions, that can be expected to occur during the life of the facade. Performance testing is a check of the design approach, both visually and technically. It also assists the fabricators in understanding the complexities of making the components and assemblies, as well as assisting the installers by familiarising them with the system and allowing them to make adjustments during the construction of the mock-up at the laboratory. The test mock-up also serves as a way of agreeing on how to achieve the required quality of construction, which may range from the flatness of glass to the smoothness of welding and surface textures. The test mock-up for a facade is both a vehicle for learning during its assembly and a tool for checking of the required performance during its lifetime. Along with test results, which it is hoped will show the design to have been successful, there is much information that can be accumulated about ease of construction, avoiding surface damage and the visual checking of components that can inform the complete facade installation on the actual building.

The test rig

Test rigs are assembled at test laboratories that are specially equipped to deal with building facades, and so are partly a simulated building site and partly a scientific laboratory. Facade panels are set into a test rig, comprising a well-sealed chamber usually made from a steel frame clad in steel sheet and plywood, accessed through a door in the chamber that can be sealed. The test panel is fixed with its external face outwards and is supported by a rigid steelwork frame, usually of I-sections designed to simulate the actual fixing conditions of the facade to the primary structure (d). The facade panel is erected at the test facility and is enclosed and sealed into the chamber.

A measurement of static pressure is taken inside the chamber, with readings taken in a position that is not affected by the velocity of air supply into, or out of, the chamber. A fan, usually connected to ductwork, is fixed to the test rig to create positive or negative pressure in the chamber; that is, higher or lower than atmospheric pressure. The fan provides a constant airflow at fixed pressure for the duration of the tests.

A wind generator, usually a propeller-type aircraft engine, is used to create positive pressure differentials during dynamic air pressure water tightness testing (j). It is mounted in front of the external face of the facade panel. A positive pressure differential is where the pressure against the external face of the facade panel being tested is greater than that against the interior of the chamber.

The effect of rain is simulated by a water spray system with nozzles spaced at regular centres, both vertically and horizontally, usually around 700mm (2ft 3in) apart and set 400mm (1ft 4in) from the face of the test panel (c). The nozzles have a wide angle spray to cover the facade panel with water as evenly as possible. A hydraulic jack is used to displace the test rig support beam to simulate structural movements in the supporting structural frame or backing wall.



e | An impact resistance test on a glazed panel.



f | A site-based hose test to check the performance of the tested system when installed in a building.

g | A pull-out test on a balustrade checks that the unusual design will not generate a significant deflection when installed.



h | Bolt torques of facade assemblies are checked on-site to ensure that components can accommodate expected structural movement.



Deflection transducers are used to measure the deflection of principal framing members to within an accuracy of around 0.25mm (a). Transducers are telescopic-like devices where a rod is held in a sleeve and is pushed in or out as it is held against a facade panel. Gauges are installed on a separate support frame in order not to be influenced by the application of pressure or loading to the facade panel.

Air infiltration and exfiltration

Measurements of airflow are taken at a positive pressure differential of 600 Pa (Pascals). The first test has the chamber sealed to determine the chamber leakage. Joints in the facade are taped up in order to provide a reliable seal. The test is repeated with the tape removed, but with any opening lights sealed. The difference between the two readings is the airflow through the facade. The average flow rate for fixed glazing at 600 Pa should not exceed 1.1m^3 per hour per m^2. For opening lights the figure is 1.4m^3 per hour per metre length of internally visible joint.

Static air pressure water penetration

Water is sprayed continuously at a rate of 3.4 litres/m^2/minute – if internationally recognised ASTM standards are applied – onto the facade panel, with a pressure differential of 600 Pa applied across the panel and maintained for 15 minutes. Throughout the test, the interior face of the panel is checked for water penetration (b).

Dynamic air pressure water penetration

Deflection measurements are taken on several cladding members at a positive static air pressure differential of 600 Pa. A wind generator is mounted adjacent to the exterior face of the facade panel. The generator output is adjusted so that the average deflections of the member matches the deflections measured at the previous 600 Pa pressure differential. Water is sprayed onto the facade panel at a rate of up to 3.4 litres/m^2/minute for 15 minutes, depending on the standards used. The interior face of the facade member is checked for water penetration.

In both static and dynamic tests the aim is to check that no water has penetrated through to the inside face of the panel that could stain or damage any part of the building. Any water entering the system should be contained and drained to the exterior. If the test is unsuccessful, then remedial work is done to the design and to the test mock-up.

Impact resistance

Impact resistance is measured with a soft body impactor, which consists of a canvas bag, in a hanging spherical or conical shape filled with glass balls. The weight of the bag is usually 50kg and is suspended from a cord around 3 metres (10ft) long. The impactor is positioned so that it hangs at rest in a position that just touches the facade panel (e). For horizontal or inclined facade panels, the impactor may be dropped vertically onto the facade panel. The bag is swung from the top of the rope. In either case the impact energies are the same and are usually set at 120Nm, for a drop height of 0.25m for serveability and 350Nm for a drop of 0.71 metres (2ft 4in) used for safety. In the serveability test, for a test to be successful there must be no damage to the panel, and air and water penetration performance must not be reduced. In the safety test, no components can become detached from the system and the impactor must not pass through the wall. The impact resistance test is performed on joints and panels in materials other than glass.



j | An aero engine generating strong air movement is set in front of a rack of water spray nozzles that simulate wind and rain at different pressures.



k | An opaque glass rainscreen wall has projecting glass fins which are being tested for their rigidity.



m | A bolt fixed glazing system has high expected deflections when compared to a framed system.

Wind resistance serviceability test

In this test, instruments are positioned to measure deflections of representative framing members (m). A positive or negative pressure differential of 50% of the positive or negative design wind pressure, held for 10 seconds, is applied to the panel. After a recovery time of one or two minutes, the displacement transducers are set to zero. A positive pressure differential is then applied to the panel and held for 10 seconds, in order to take the readings at 50%, 75% and 100% of the positive or negative design wind pressure. After a recovery time of 1-5 minutes, readings are taken for any remaining deflections. In a successful test, no permanent damage will have occurred at both positive and negative applications of peak test pressure, set at the design wind pressure. In addition, the maximum deflections will not exceed the following figures, which are given for general guidance only:

General framing members: 1/175 of clear span, to a maximum of 19mm
Glazing framing members: 1/240 of span
Framing members when finished material is attached: 1/360 of clear span
Framing members for support of natural stone: 1/500 of clear span

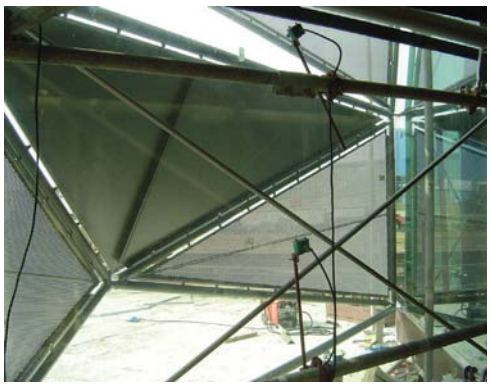
At 1.5 times design wind pressure, for both positive and negative pressures, there must be no permanent damage to framing members, panels or fixings. Glazing beads and copings will have remained in place and gaskets not displaced. Permanent deformation to wall framing members will not have exceeded 0.2% of span up to one hour after loading has been removed.

Seismic building movement test

A mid-height support beam is displaced horizontally and then back to its original position. At each stage, visual observations are made, with the test being conducted three times. Displacements, in terms of mm, are determined as 'probable' or 'credible' displacements. In the 'credible' test, there must be no permanent damage to the framing members, panels or fixings. Glazing beads and cappings must be held securely and gaskets not displaced. In the probable test, no racking or distortion of members occurs. The panel must then pass the subsequent air and water penetration tests.

Inter-storey movement

The mid-span point of the mid-height support beam is displaced by a fixed distance vertically downwards then back to the centre, tested three times, during which no racking or distortion of the members is allowed to occur. The panel must pass the subsequent air and water penetration tests.





n | Mock-ups are designed and fabricated from parametric models with three purposes in mind for each assembly: visual approval by the design team; using the actual fabrication method proposed for the project to see how this can be made more cost effective; performance testing for essential weather resistance under dynamic conditions as proof-of-concept.

Wind resistance safety test

Instruments are positioned to measure the deflection of representative framing members. One positive or negative pressure differential pulse of 75% of the positive or negative design wind pressure, held for 10 seconds, is applied to prepare the panel. After a recovery time of 1-5 minutes, the displacement transducers are set to zero.

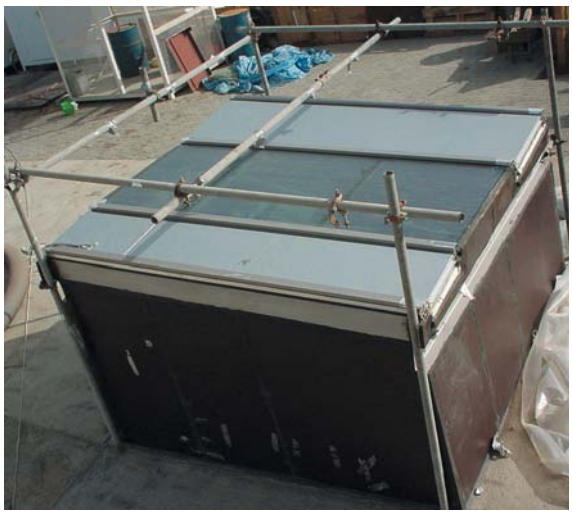
One positive or negative pressure differential pulse of 150% of the positive or negative design wind pressure is applied and held for 10 seconds. After a recovery period of 1-5 minutes, readings are taken for any remaining deflections. At both positive and negative application of peak pressure, there must be no permanent damage to framing members, panels or fixings. For a glazed wall test panel, for example, pressure plates and decorative cappings must remain securely held and gaskets must not be displaced. Permanent deformation of wall framing members must not exceed 1/500 of the span, which is measured between the fixing points, usually measured one hour after the loading has been removed. At the end of tests, the facade panel is dismantled in controlled conditions to check that it complies with the design drawing. In the event of test failure, any water that has penetrated into the system is recorded.

Site hose test

In addition to laboratory tests, a facade system can be checked on site with a controlled hose pipe test. This test is conducted using a nozzle that produces a solid cone of water droplets with a spread of approximately 30°. The pressure is around 220 kPa (30-35 psi) at the nozzle with a flow rate of around 22 litres per minute (f). Typically, water from a hose is directed at the area of completed facade on site, perpendicular to the face of the wall. The direction of water from the hose is set 300mm (1ft) away from the wall and is directed in a linear direction across 1500mm (5ft) of the wall for 5 minutes. The test starts from the bottom of the wall upwards to determine when leaks start to occur within the system. The inside face is continuously checked for leaking. If no leaks are found, the hose moves on to the next adjacent area of facade being test. If leaks occur, the system is allowed to dry out then is completely taped up at the joints. Starting again at the bottom, the tape is gradually removed while applying water from the hose again until the location of the leak is found.

Post-test conclusions

In addition to verifying the performance of the facade system, any adjustments required during the mock-up must be carried out on site. The quality of construction for the mock-up can also be used as a 'benchmark' or quality control sample for the completed facade. This can avoid many later on site difficulties, where the earlier expectations at the drawing stage can mature at the mock-up stage before installation commences, allowing all parties on the building project to agree on visual appearance and quality of assembly before proceeding to production (n).



a The testing of a roof system is undertaken typically with a small test panel which contains the full range of joints that comprise the system as well as the maximum span that the system can accommodate. This is to ensure that adequate weatherproofing can be provided while the system experiences maximum deflections from both positive and negative wind pressures.

Performance testing of roof material systems

Testing of water tightness of mock-ups has until recently been restricted mainly to facades. Roof structures are usually tested in a specialist laboratory when they differ technically from standard systems, or have an unusual combination of standard systems. Testing is usually restricted to systems in metal, glass and plastics. Concrete, timber and fabric do not usually require test mock-ups, since their performance is well-established both in the systems used and as industry-wide specifications. Test rigs determine the ability of the mock-up to remain watertight and airtight when the various design loads are applied to the mock-up. In addition, the effect of a falling object onto the roof is tested when it is considered essential to withstand the load to protect building users beneath when they are at possible risk; from higher buildings adjacent to the roof, for example. A test that is particular to roofs and is not undertaken in facades is the flood test. An area of roof is filled with water up to a level anticipated in the event of rainwater outlets being blocked, and left standing for up to several days. This is usually undertaken on flat roofs where there would be standing water in the event of blocked outlets, and applies to pitched roofs only at gutters or drainage points. This test is usually undertaken on site, typically for single membrane roofs on a flat roof deck in either concrete, steel or timber.

Mock-ups for performance testing have the added benefit of revealing the installation problems inherent in the system, particularly if some innovation is involved, and of allowing the design team to see how the roof will appear before proceeding with the work in the workshop or on site. The mock-up can also be used to establish an accepted level of quality of construction, particularly with regard to the visual crispness of assembly, flatness of materials, visible joint widths, finishes and colour.

The workshop usually has at least one panel or set of joints that covers an area sufficiently large to provide full structural deflections of framing members, as well as internal ventilation and drainage in the case of glazed roofs (a). There is little point in testing a panel 300mm x 300mm in size that includes only one joint, since the overall effects of movement under full design wind load cannot be determined unless a full panel is tested. The test mock-up panel is set at the same angle at which it is to be used in the completed installation. Where a range of angles are encountered, the most vulnerable or extreme angles are taken to form the mock-up. The roof mock-up is set 1500mm to 2000mm above ground level to allow the underside to be inspected easily, and set typically on a concrete slab. The roof sample is usually supported on a steel frame at its edges in a way that simulates the structure used in the building. The space beneath the roof is then enclosed, usually with plywood sheets which are sealed at the interfaces with the mock-up and with the floor slab or deck beneath to provide as air-tight an enclosure as possible. A door is provided into the chamber which is able to be clamped shut during the testing.

The test chamber is pressurised with an air supply in order to establish the amount of air infiltration through the system. The air supply is provided usually by a flexible hose that passes through an opening in the plywood chamber enclosure. The hose is connected to a centrifugal fan which can either supply air to, or extract air from, the test chamber.

The largest external component in the testing is an aero engine with propellers which acts as a generator for the wind pressures applied to the test mock-up. A grid of water spray nozzles is set above the mock-up in order to simulate rainfall onto the roof.

A canvas bag filled with small-diameter glass spheres is provided for the soft body impact test, which is typically dropped from a mobile platform or temporary scaffolding tower set next to the test sample.

Air infiltration test

In order to establish the rate at which air filtrates through the assembly, the mock-up is first subjected to a single positive pressure 'pulse' which is held for 10 seconds, which corresponds to half of the design pressure for the roof system. This is done in order to pressurise the test chamber and ensure that the chamber has been properly sealed. This is done



b | The test chamber, which is capable of being fully sealed, is fitted with an air supply to provide both positive and negative air pressures on the internal face of the roof sample panel.

before testing commences. The pressure inside the chamber is now increased to a difference of 600 Pascals between inside and outside. The roof sample is first sealed with tape to determine chamber leakage, and measurements of airflow are taken which, for fixed rooflights, should not typically exceed 1.1 m^3 per hour per m^2. The airflow test is repeated with the tape removed. The difference between the two readings indicates the air infiltration rate through the roof sample.

Water penetration tests

These tests are conducted both under static air pressure; that is, with no significant wind blowing across the sample, and at dynamic air pressure, where an aero engine blows air onto the sample. In the first test, the static air pressure water penetration test, water is sprayed from the nozzles onto the roof mock-up at a rate of at least 3.4 litres/ m^2/minute. The water spray nozzles are set out on a grid so that the nozzles are no more than 700mm apart, and are fixed at around 400mm from the face of the sample (b). This ensures that all parts of the roof sample are sprayed with water. A pressure differential corresponding to 600 Pascals is applied across the sample for 15 minutes. The interior face of the mock-up is checked for any water penetration. The test is repeated at the same pressure with a propeller-type aero engine to provide the same 600 Pascal pressure difference across the sample. The underside of the mock-up, inside the chamber, is checked to ensure that no water drops are visible as a result of penetrating the roof assembly.

Wind resistance tests

In these tests, pressure transducers are fixed to the inside face of the roof sample in positions where the deflectors are most critical, such as at the centre of framing members or the centre of panels. Transducers are telescopic gauges that measure deflections, usually to an accuracy of 0.25mm. Readings are taken digitally at a distance from the test chamber. The transducers are set by applying a positive pressure 'pulse' of 50% of the positive wind pressure for 10 seconds. After a recovery period of up to 5 minutes, the pressure transducers are set to zero to establish a 'zero' level for the test. A positive pressure is then applied to the roof mock-up and held for 10 seconds at different pressure deflections. Readings are taken at 50%, 75% and 100% of the positive design wind pressure. After a period of up to 5 minutes, any remaining (or permanent deflections) in the sample are recorded. This process is repeated for negative wind pressure, where air is drawn out of the test chamber. The test starts again from the beginning, with a 50% pulse held for 10 seconds in order to establish a 'zero' level for the transducers.

These two sets of tests for positive and negative wind pressures establish whether the mock-up deflects within the limits set out in the design, at the design wind pressure (typically 1400 Pascals). These two tests are repeated at 1.5 times the design wind pressure in a safety test. The pressure is then increased to a maximum of 2.0 times design wind pressure to examine what would happen in the event of failure if this limit is not reached. Typically, failure occurs in a seal in the roof assembly, or a glass panel may break in a rooflight, but this occurs usually when the 2.0 times design wind pressure is exceeded.

Impact resistance test

The ability of a lightweight roof, typically a glazed or plastic-based rooflight, to withstand an object falling on it is simulated with a canvas bag 400mm in diameter, filled with the glass balls already described, to a mass of around 50kg. The bag is dropped from a height of around 750mm to simulate an impact energy of around 350 Nm in a safety test. The test is performed on joints and panels to establish that the complete roof assembly would not fail under these impact energies.

Dismantling of sample

When the tests are complete, the roof mock-up is dismantled to ensure that the mock-up was built exactly in the way it would be applied on the roof of the finished building. In the event of a test failure, this dismantle assists the design team in understanding how to resolve the matter, in preparing the mock-up for a second round of testing if required.

06
APPLICATIONS

1 Working with industry
2 Triangular panels for twisted facades
3 Twisted panels with flat glass for curved facades
4 Solar shading louvres
5 Double-skin facades
6 Precast concrete panels for facades of complex geometry
7 Exoskeleton facades of complex geometry
8 Diagrid structures
9 Hybrid systems forming facades of complex geometry
10 Opaque cladding interface with full-height glazing
11 Complex curved glazed roofs
12 Large-scale glazed facades
13 Panelisation of complex building surface geometry
14 Opaque rainscreen cladding
15 Full-height glazing with GRP-clad structural frame
16 GRC cladding interfaces
17 Full-height entrance glazing
18 GRP louvres on stick glazing system
19 GRC cladding
20 Windows in GRC cladding
21 Windows and unitised glazing with GRC cladding
22 Unitised glazing with GRC cladding
23 Complex glazed roofs with supporting steel structure
24 Glazed roofs with complex geometry
25 Louvres and stick glazing



a | Construction of full-size visual mock-up panel



b | Reverse of visual mock-up panel



c | Visual mock-up of facade panel

The relationship between the design team of architects and engineers and those that construct facades is defined by whether fabrication work is done on site or off site. Facade construction work that is conducted on site, such as in-situ concrete, masonry cavity walls and timber walls to the platform frame, are fabricated and installed with materials delivered directly from a materials supplier to the building site. With on-site fabrication, the building site becomes the workshop for facade assembly from its constituent components. Work is done by building contractors who buy their components not directly from manufacturers, but from building suppliers. This is because building contractors for brick cavity walls or in-situ concrete or timber walls, for example, are involved in constructing with a wide range of construction technologies, with construction conditions changing from job to job. As a result, they do not generally form close ties with particular manufacturers, but are instead involved with a large number of individual suppliers for a large range of components, some of which will have been specified by the design team at the tender stage. Architects and designers work through development, mock-ups and performance testing in the same way as for factory and workshop-based companies that use a high degree of prefabrication.

Facade fabrication done off-site in factories and workshops involves the design and assembly of proprietary components and systems. Examples are glazed curtain walling, metal walls, plastic-based cladding and precast concrete which are designed and fabricated off-site, then installed in the building. Off-site fabrication involves manufacturers, fabricators and installers. Some manufacturers supply systems for others to assemble; while other companies design, manufacture and assemble systems, allowing others to install the facade assemblies on site. Architects and engineers can work independently with all three groups of manufacturers, fabricators and installers.

Manufacturers do not install their own systems but instead focus on the design and manufacture of systems and their components. Each company usually has a set of installers with whom they have an agreement. The manufacturers supply the facade systems together with technical support for their application, while the fabricator provides the skills required to assemble them. The manufacturer supplies facade systems in varying amounts of fabrication; for example standing seam sheet metal systems are supplied as either sheet in rolls, sheet with standing seams pre-formed and folded, or as coiled metal with a forming machine for use directly on site. If the sheet is pre-formed, then the manufacturer will have very specific requirements for fixings which will be conveyed to the installer. If the sheet is delivered to the site as a roll, then much more expertise for forming and fixing is required of the installer. In the case of composite metal panels, the panels are manufactured for installing on site with very specific requirements for fixing provided by the manufacturer. This may involve a detailed installation manual by the manufacturer, with some training provided for the installer. The architect or designer must be aware of how a particular product is procured so that an appropriate input to the detailed design can be made.

For glazed systems, specialist items such as windows and doors are usually assembled by the manufacturer. Other materials such as glass, metal sheet, timber sections and stone are obtained from other manufacturers. Architects and engineers work increasingly with both manufacturers and fabricators throughout the design development stages, with greater emphasis on working with installers as the project progresses towards the construction phase. The manufacturer designs the systems, while the installer assembles them in place from project to project. In some cases manufacturers buy the raw material from the supplier, while in other cases they manufacture the raw material as well. Examples are steel or aluminium companies which both manufacture metal and roll, profile or extrude it for immediate use in facade systems, usually where manufacture of the primary material is their core business. Similarly, glass manufacturers sell their material on to companies who make double-glazed units. Systems provided by manufacturers are fully designed and tested. While architects can use the systems in ways prescribed by the manufacturer, there is relatively little scope for changing them, or even adapting them for use on a particular building, except in large-scale projects. This happens because the systems are manufactured as a set of standard components which are made especially to deal with a range of options available within the system. In addition, the test certificates obtained for their use are specific only to the standard system. Deviation from the tested systems adds both time and cost to a project, the implications of which are weighed up before incorporating these changes into the tested system. Some manufacturers have their own test facilities which can speed up the process of testing variations on standard systems, while others use independent test facilities which can take longer to obtain results. If the modified design does not successfully complete testing, then additional modifications will need to be made, adding further time to the design programme. Testing is primarily concerned with structural rigidity, infiltration of air and water, thermal and acoustic insulation, and fire resistance.

Standard systems from manufacturers are not necessarily optimised solutions. They are in constant development and become 'frozen' for



d | Construction of full-size visual mock-up of facade panel



e | 3D detail view showing facade panel



f | Construction frame-work for visual mock-up of facade panel

manufacture at a particular stage of development, subject to their achieving a given technical and aesthetic performance. Some installers do not only erect facade systems supplied by a single manufacturer or a range of suppliers. The large companies, which operate all around the world, also develop designs with architects and engineers in order to provide specific solutions for individual buildings, usually those of a larger scale. This method of working with large facade contractors can make use of parts of systems by specific manufacturers, or be developed from designs developed for use on previous building projects.

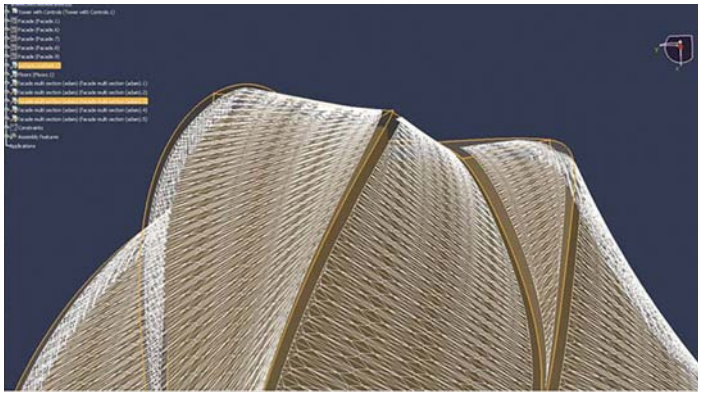
As a building project develops at the design stage, the question arises as to when facade manufacturers, fabricators and installers should become involved with the project. All groups will give informal advice at this stage of the project, though the amount will vary from company to company, as well as what agreement, if any, has been made about their involvement in tendering for the project. Large-scale projects will usually have access to a more significant input from manufacturers and fabricators before tender. Involvement from these two parties will ensure that the facade design being developed for tender will fall roughly within the budget. This avoids unpleasant surprises after the tender evaluations have taken place.

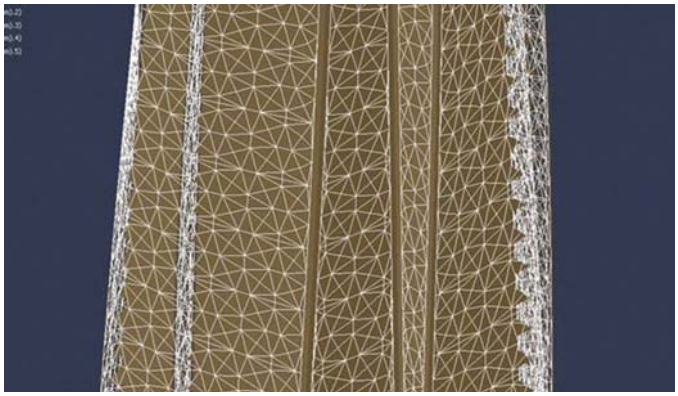
Facade designs and details drawn in too generic a way do not interact with what manufacturers can produce reasonably economically, so an understanding of the constraints of each facade type is essential to being able to design for a non-specific manufacturer, fabricator or installer, thus providing even-handed tender documents. On the other hand there is always a risk of working too closely with one manufacturer or fabricator at the design stages before tender, only for that party to be unsuccessful at the tender stage. This results in both the tenderer having spent considerable time and resources on a project only to be disappointed, and leaves the design team with a solution that does not conform to the approach of the successful tenderer. An even-handed approach ensures that none of the parties become involved in too rigid an approach.

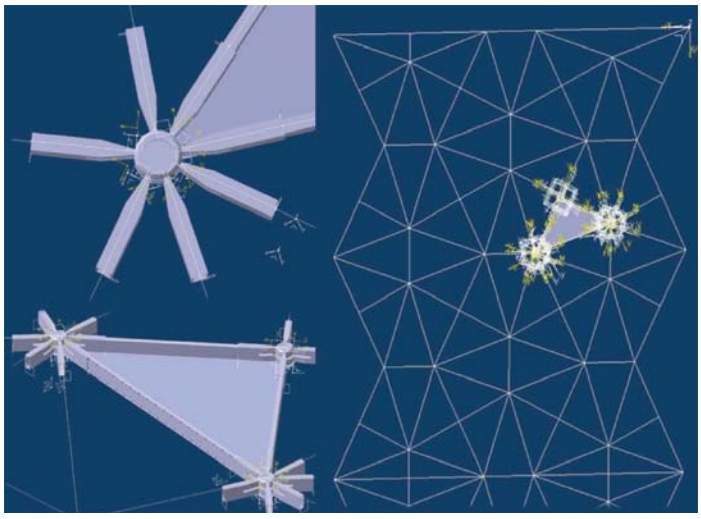
An alternative approach for the design team is to develop a facade system, or set of systems for a project, to a detailed stage without assistance from manufacturers or fabricators. This is particularly appropriate if the building design involves a new facade technology that is an essential component of the success of the design. A team of architects and engineers can develop a facade system to tender stage with a comprehensive set of structural calculations in place to determine the section size of the most important components. The system will be designed to a stage where a set of full-size visual mock-ups (c) and a performance mock-up for testing can be constructed immediately after the tender is awarded. During the tender stage each tendering company is invited to comment on the proposed system, and to either accept the system or modify it until they find it compatible with their own approach. Tenderers may also propose their own facade system if it meets the performance requirements of the proposed system, and abandon the proposed solution altogether.

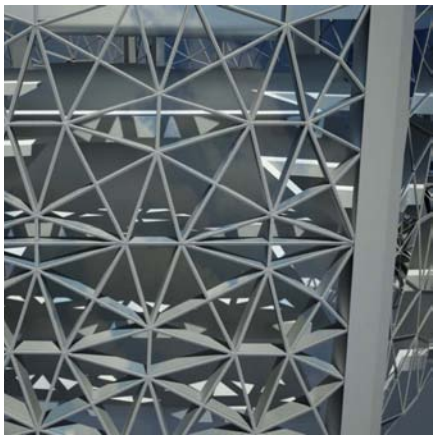
In some projects, the building owner or client may have a specific company, or set of companies, with whom they like to work. This approach gives greater scope for working with a single manufacturer / fabricator team that can proceed more quickly to a detailed design with visual mock-ups and results from previous performance testing on related systems. Regardless of how the design team develops a project to the tender stage, it is essential for the design team to visit the facilities of all potential tenderers at the earliest possible opportunity. This allows the designers to understand the range of systems, skills and experience of each manufacturer / fabricator and to understand the working method of each company. These visits help the design team to understand how materials are made, worked and formed into components, and how they fit together into the final assembly. This method also helps the designers to appreciate the level of quality produced by each company.

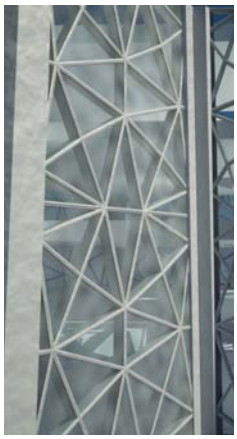
These factory / workshop inspections are also vital immediately after tender, when the successful tenderer can again show how the facade systems or components will be made. This is very useful during the workshop drawing phase, when the design team can work with designs from the manufacturer, fabricator and installer to give the best possible result on site. It is far easier to exert influence in the factory at this stage than it is on site, where changes and modifications to systems are very difficult to make. In prefabricated systems it is usually too late to push for higher quality on site, since this work has already been done in the factory. The same is true of site-based work such as in-situ concrete and sheet metal cladding, where visual mock-ups and performance testing mock-ups, as well as visual mock-ups of important junctions, should be considered at the stage immediately after tender. Site inspections for facades should focus on the correct setting out, replacement of damaged items and the fine tuning of a few interfaces that may not have been considered during the production phase in the factory. It is essential that dialogue and co-ordination occur at the appropriate time of the project and not be left to a late stage of the project.





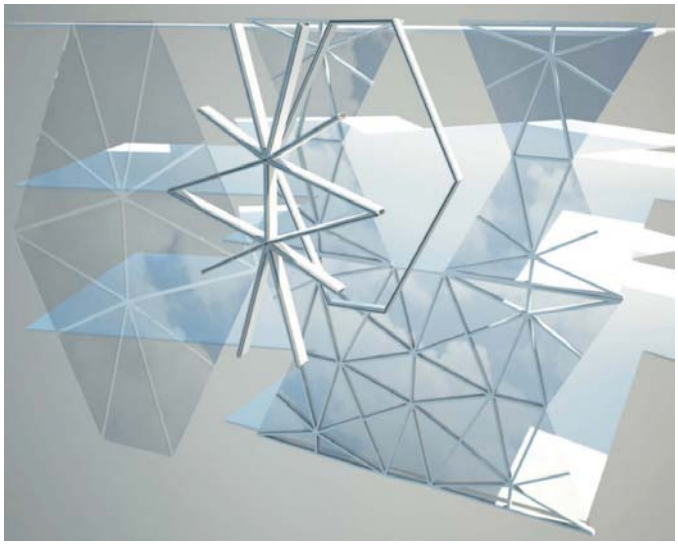


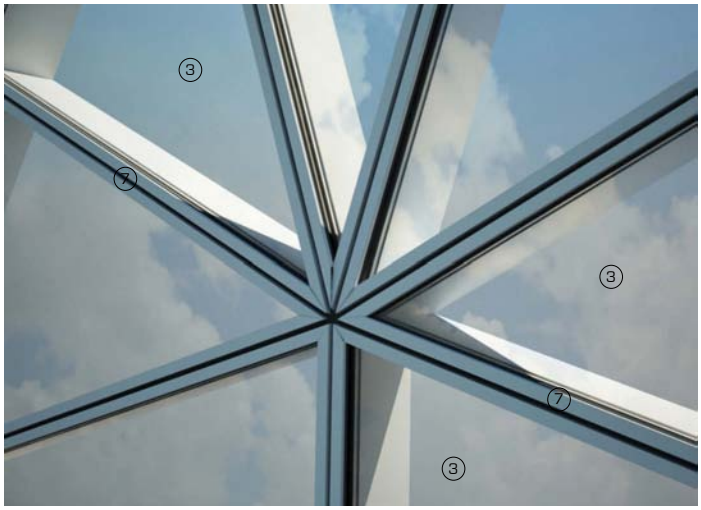




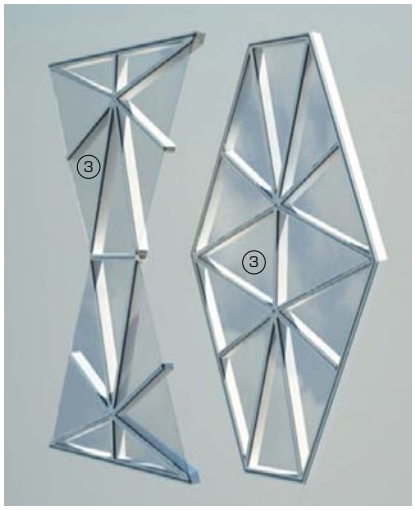
a | Working digital models of triangular unitised glazing panels for twisted facade







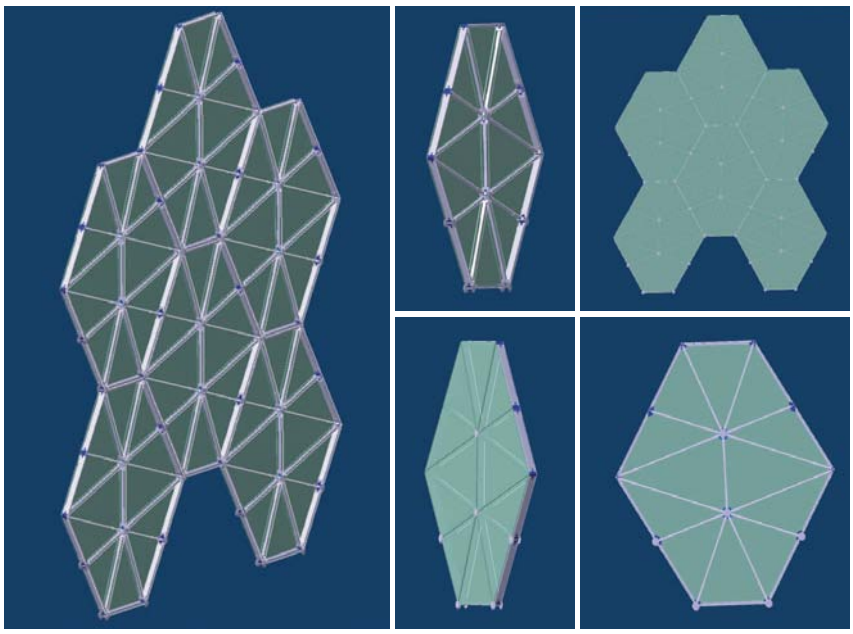
b | 3D detail views showing triangular unitised glazing panels for twisted facade



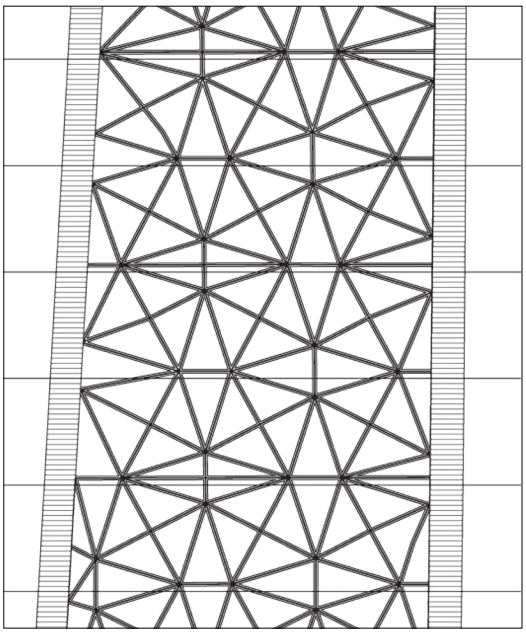
c | 3D views showing triangular unitised glazing panels for twisted facade

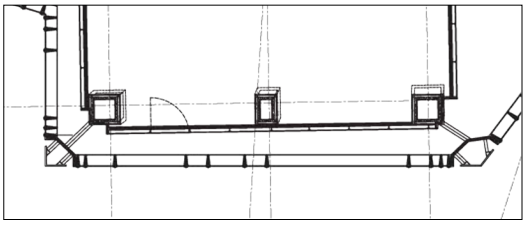
Details

1 | Primary steel structure
2 | Primary concrete structure
3 | Aluminium unitised double-glazed panel
4 | Floor slab
5 | Cladding for primary structure
6 | Silicone seal
7 | Glazing frame cap
Internal floor finish



d | Working digital models of triangular unitised glazing panels for twisted facade



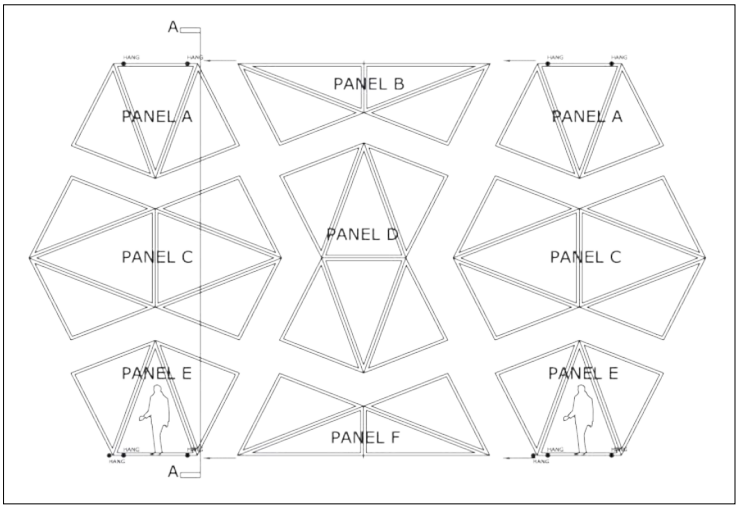


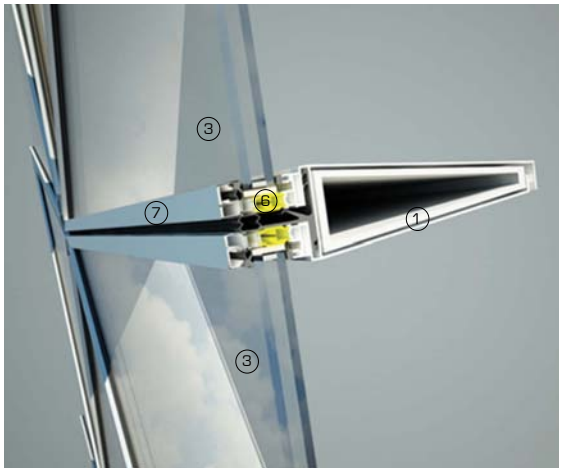
e | Elevation and horizontal section. Triangular unitised glazing panels for twisted facade

Details

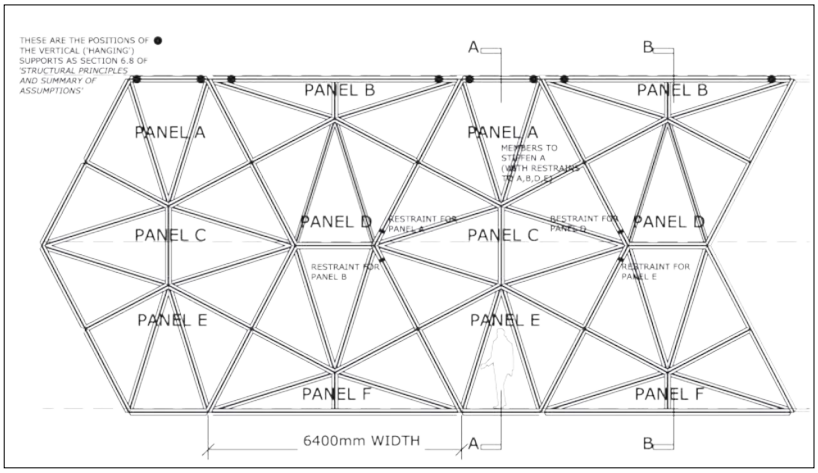
1 | Primary steel structure
2 | Primary concrete structure
3 | Unitised aluminium glazing frame
4 | Floor slab
5 | Cladding for primary structure
6 | Silicone seal
7 | Glazing frame cap
8 | Internal floor finish







f | 3D sectional detail views showing triangular unitised glazing panels for twisted facade



g | 2D layout. Triangular unitised glazing panels for twisted facade



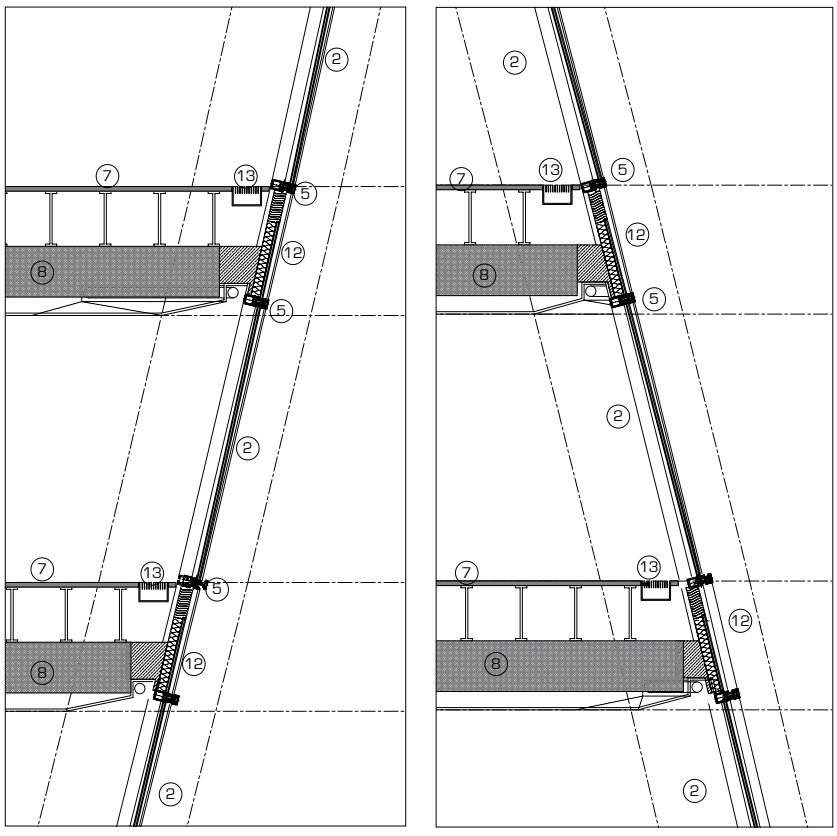
a | 3D views of unitised glazing panels with twisted frame and flat glass to achieve curvature and externally-fixed louvres

Details

1 | Primary steel structure
2 | Unitised double-glazed facade panel
3 | Outer glazed wall
4 | Inner glazed wall
5 | Perimeter frame to panel
6 | Intermediate horizontal framing member
7 | Floor finish
8 | Floor slab
9 | Ceiling finish
10 | Structural column
11 | Metal cap pieces fixed to front of unitised frame
12 | Insulated opaque spandrel panel
13 | Gutter
14 | Double glazing

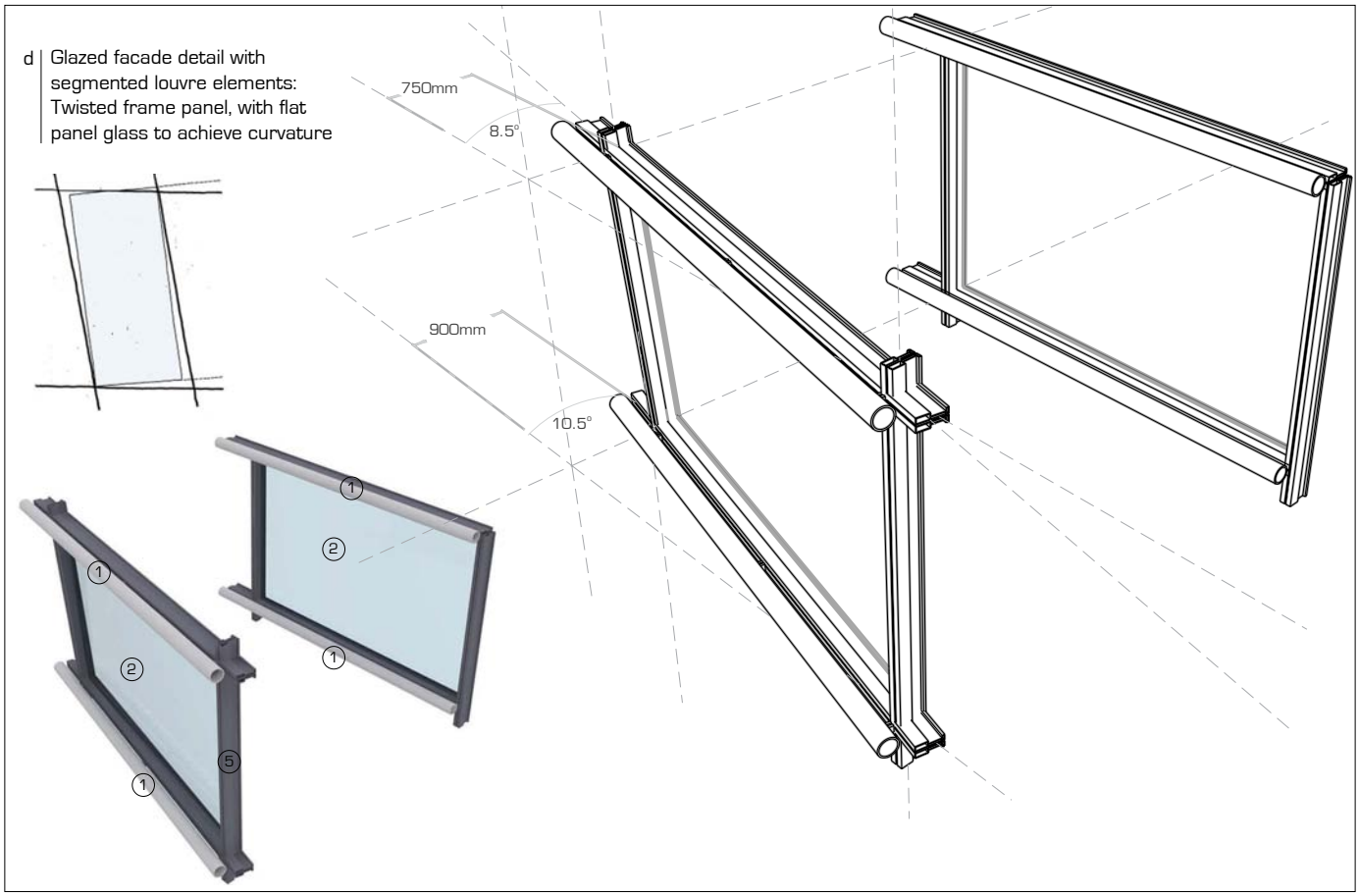


b | 3D views showing unitised glazing panels with twisted frame and flat glass to achieve curvature and externally-fixed louvres



c | Vertical sections. Unitised facade panel system with opaque spandrel panels at floor level

d | Glazed facade detail with segmented louvre elements: Twisted frame panel, with flat panel glass to achieve curvature

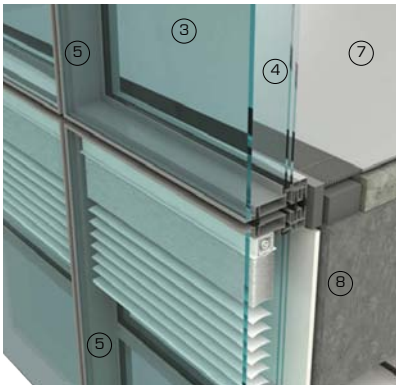


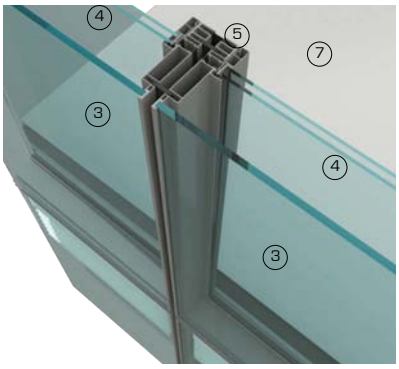
e | 3D overviews of unitised glazing panels with twisted frame and flat glass to achieve curvature and interface with twisted opaque facade segments

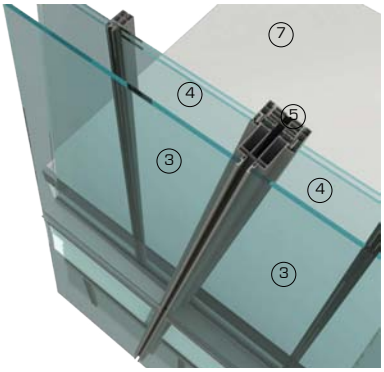
f | 3D views of unitised glazing panels with twisted frame and flat glass to achieve curvature



a | 3D fragment view showing unitised double-skin glazed facade panel system for twisted facade







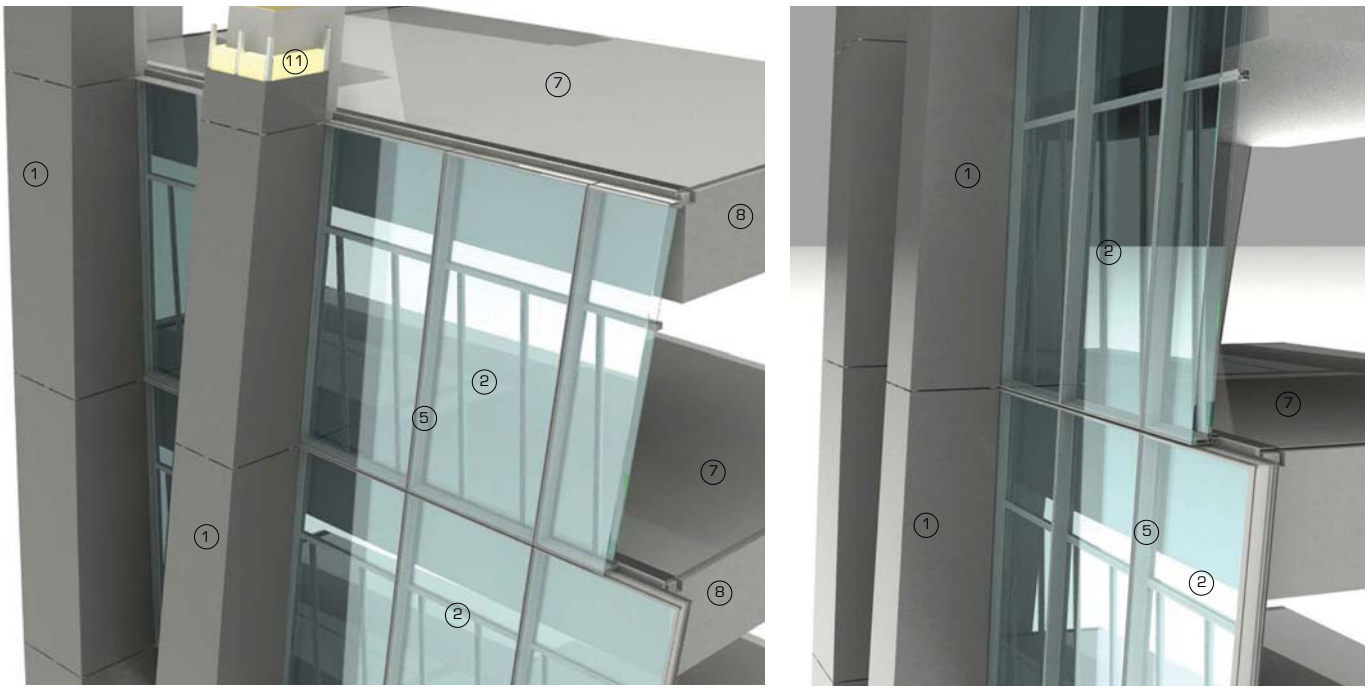
b | (Below) 3D overview showing unitised double-skin glazed facade panel system for twisted facade

c | 3D detail views showing unitised double-skin glazed facade system for twisted facade



Details

1 | Metal cladding to exoskeleton structure
2 | Unitised double-skin facade panel
3 | Outer glazed wall
4 | Inner glazed wall
5 | Perimeter frame to panel
6 | Intermediate horizontal framing member
7 | Floor finish
8 | Floor slab
9 | Ceiling finish
10 | Structural column
11 | Thermal insulation
12 | Double glazing
13 | Opaque spandrel panel



d | 3D sectional views showing unitised double-skin glazed facade panel system for twisted facade





e | 3D views showing unitised double-skin glazed facade panel system for twisted facade



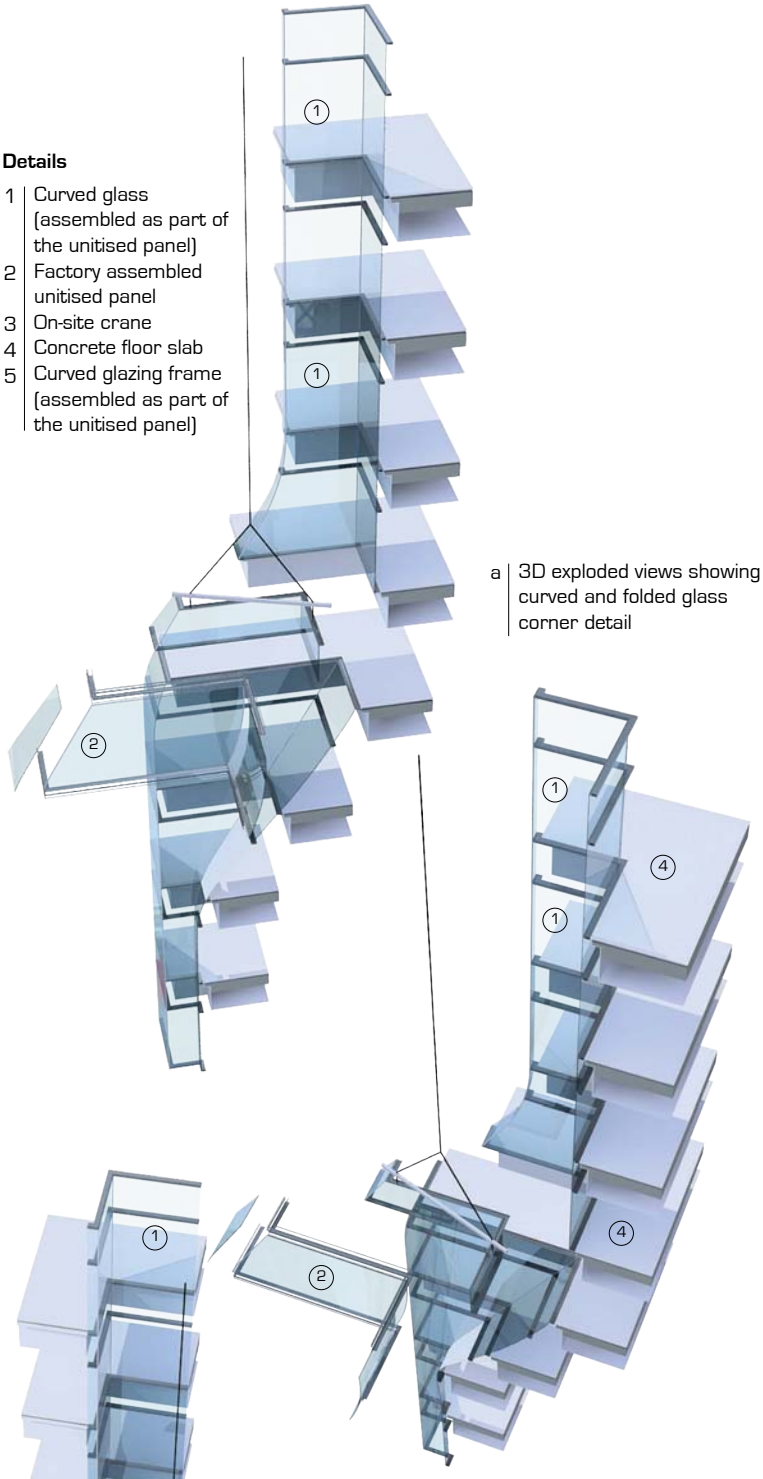


f | (Above) 3D exploded view showing unitised double-skin glazed facade panel system for twisted facade

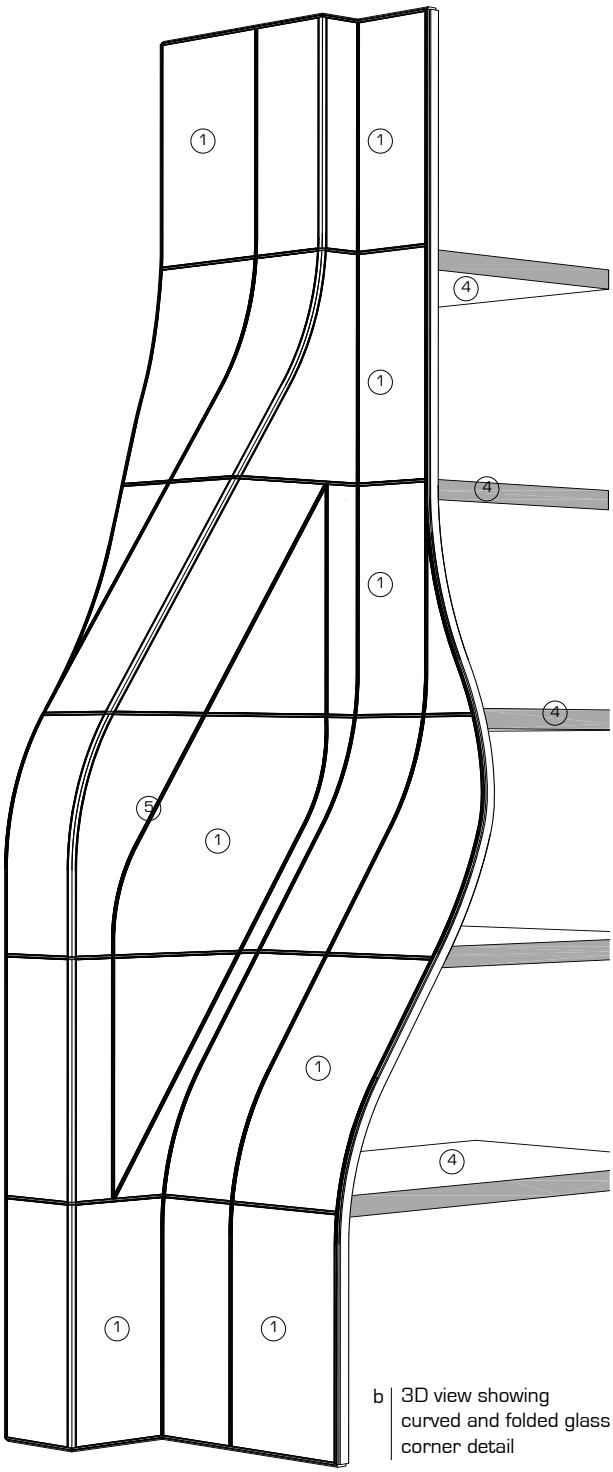
g | (Left) 3D view showing unitised double-skin glazed facade panel system for twisted facade

Details

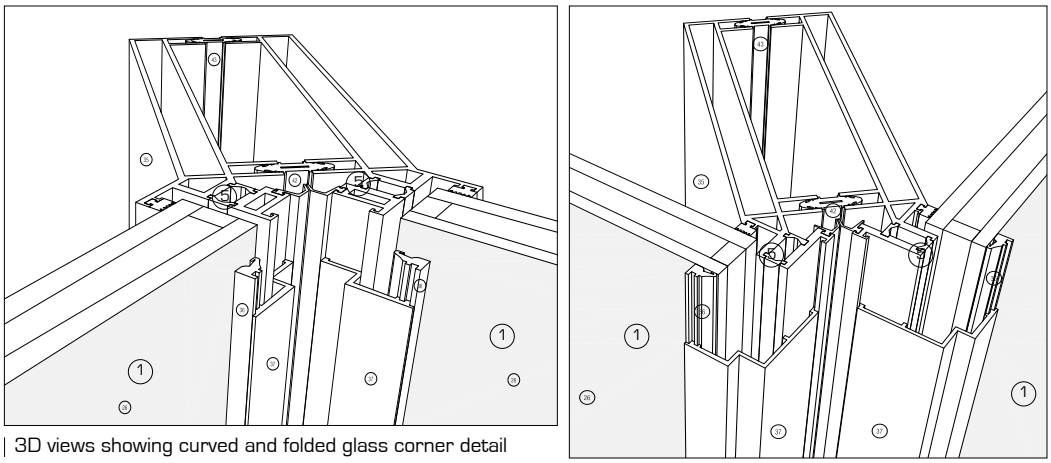
1 | Curved glass (assembled as part of the unitised panel)
2 | Factory assembled unitised panel
3 | On-site crane
4 | Concrete floor slab
5 | Curved glazing frame (assembled as part of the unitised panel)



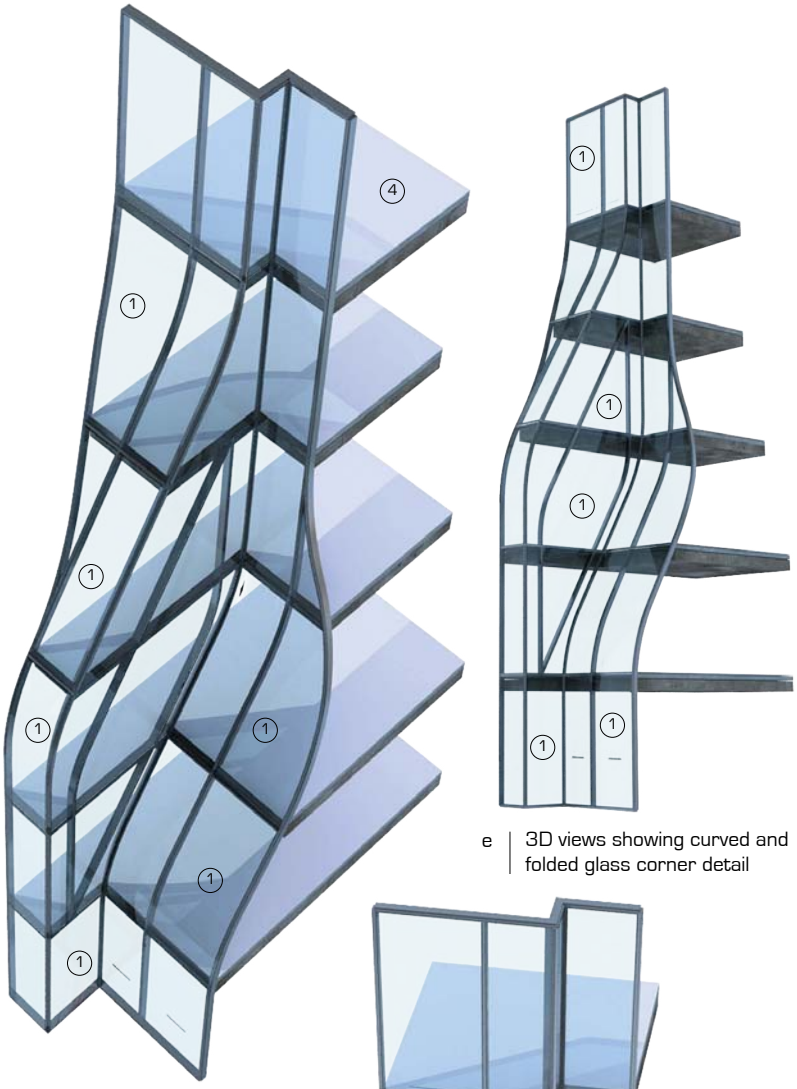
a | 3D exploded views showing curved and folded glass corner detail



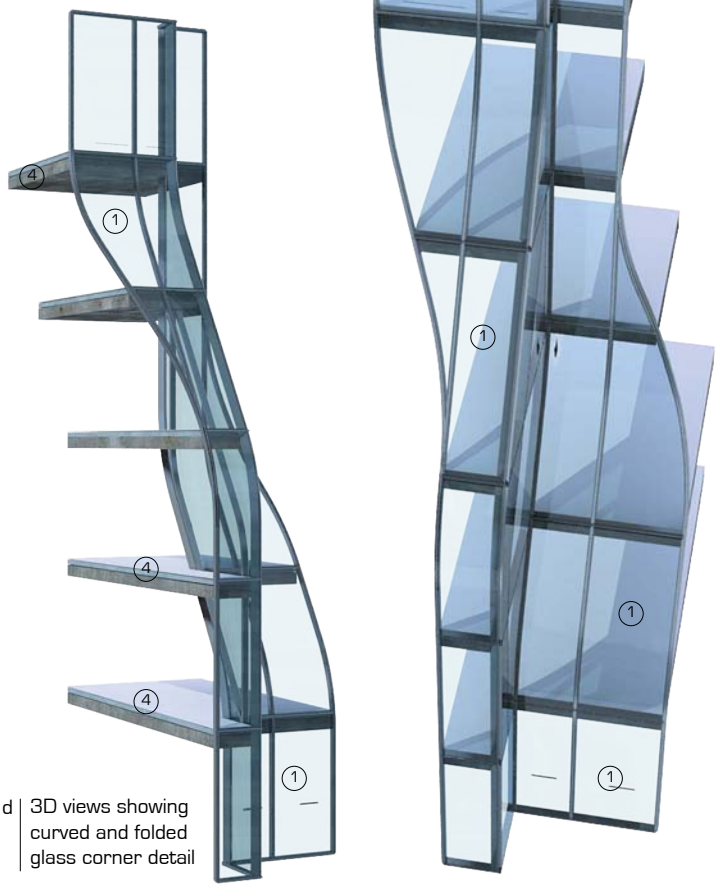
b | 3D view showing curved and folded glass corner detail



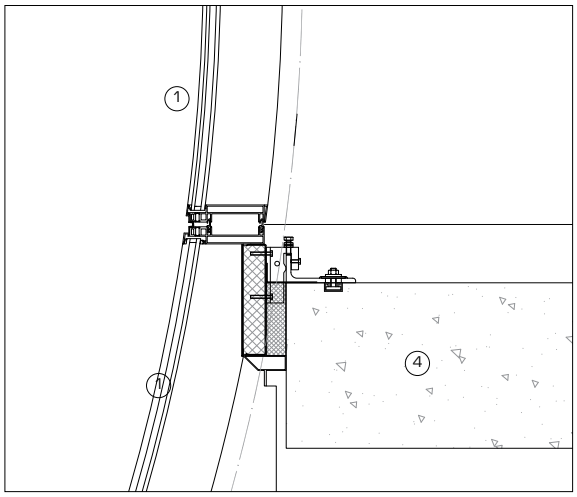
c | 3D views showing curved and folded glass corner detail



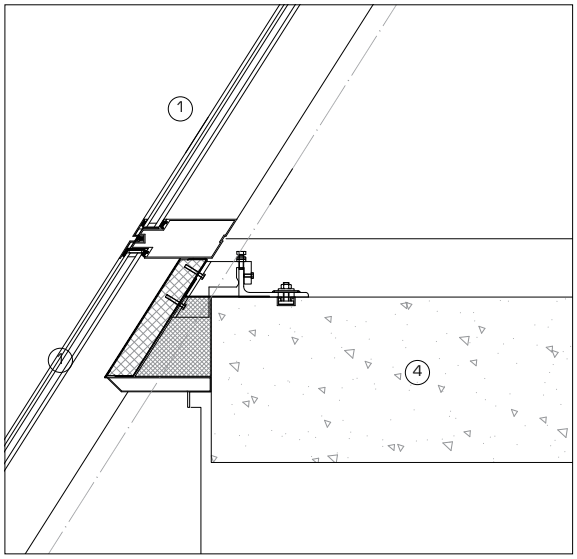
e | 3D views showing curved and folded glass corner detail



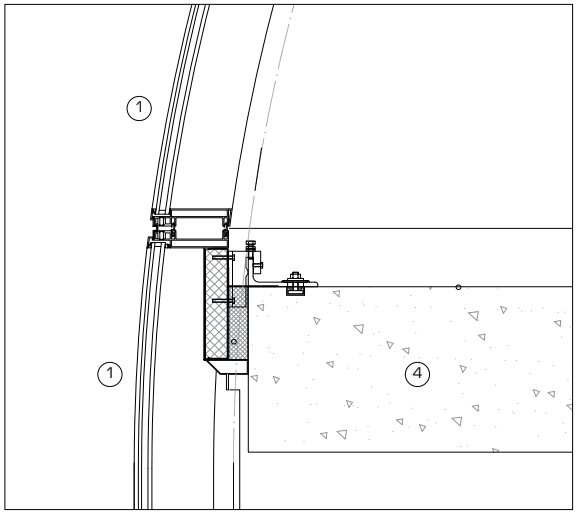
d | 3D views showing curved and folded glass corner detail



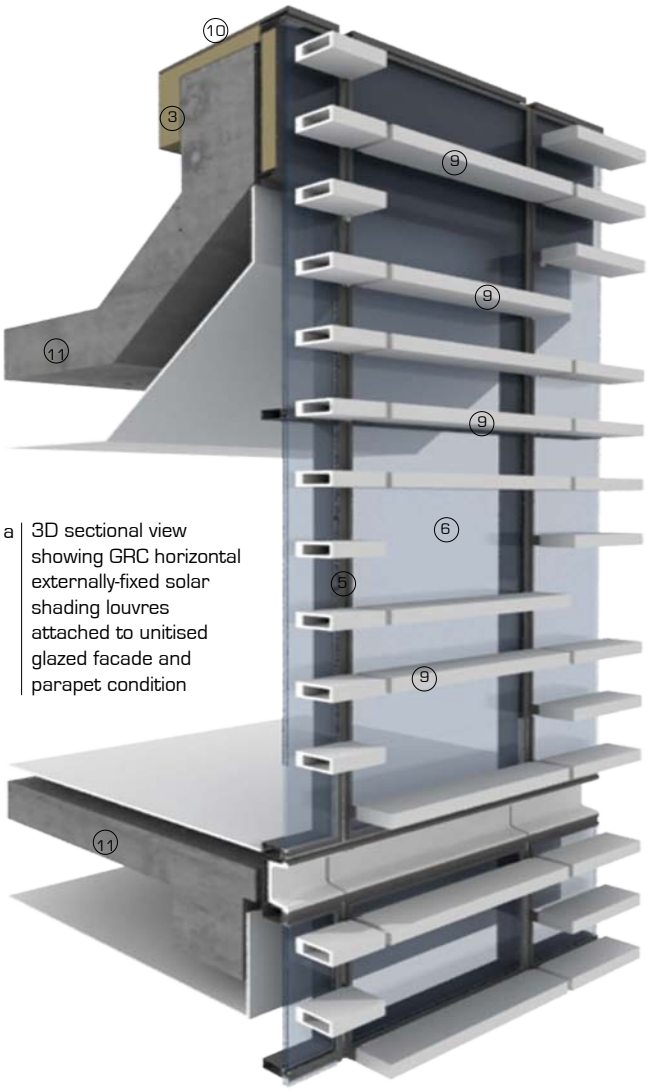
f | Vertical section. Curved unitised glazing at floor-slab junction



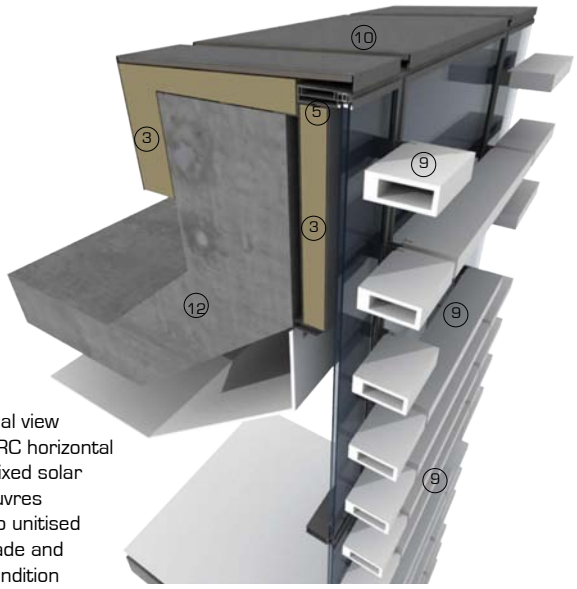
g | Vertical section. Curved unitised glazing at floor-slab junction



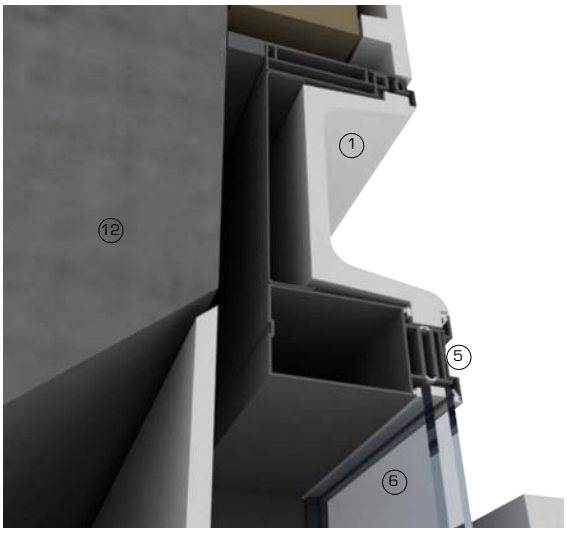
h | Vertical section. Curved unitised glazing at floor-slab junction



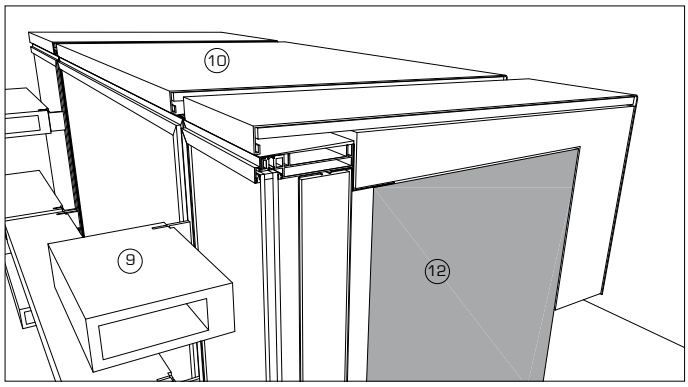
a | 3D sectional view showing GRC horizontal externally-fixed solar shading louvres attached to unitised glazed facade and parapet condition



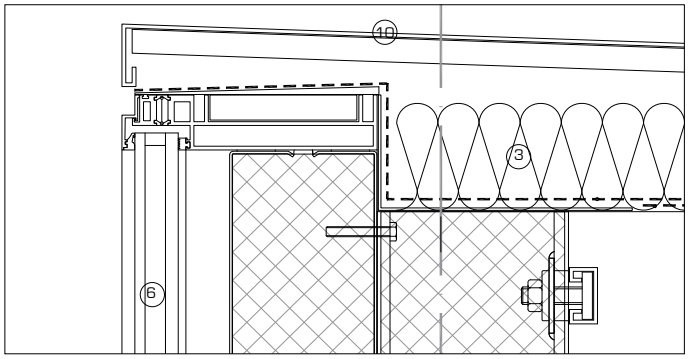
b | 3D sectional view showing GRC horizontal externally-fixed solar shading louvres attached to unitised glazed facade and parapet condition



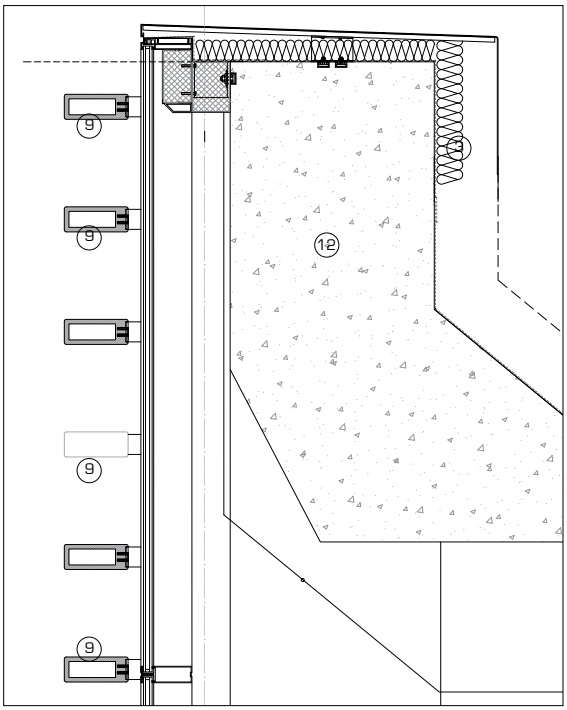
c | 3D sectional view showing GRC horizontal externally-fixed solar shading louvres attached to unitised glazed facade at floor slab



d | 3D sectional view showing GRC horizontal externally-fixed solar shading louvres attached to unitised glazed facade and parapet condition



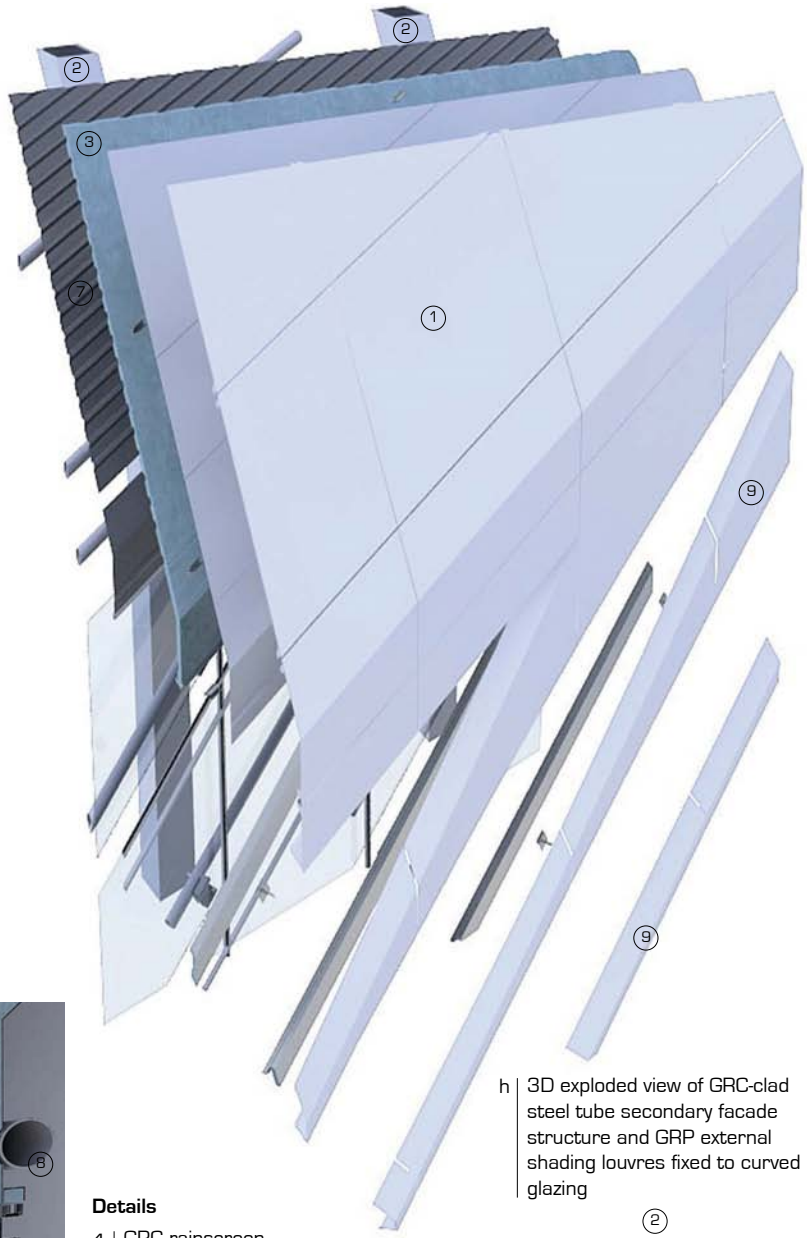
e | Vertical section. GRC horizontal externally-fixed solar shading louvres attached to unitised glazed facade at parapet condition



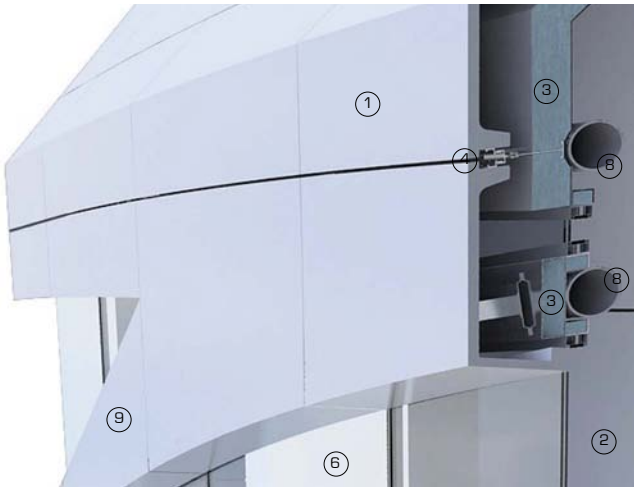
f | Vertical section. GRC horizontal externally-fixed solar shading louvres attached to unitised glazed facade at parapet condition

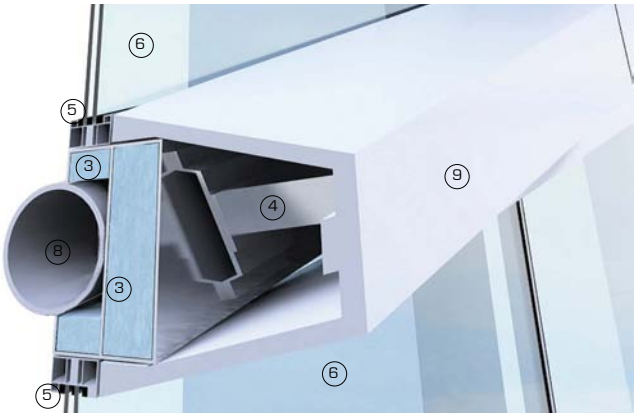


g | 3D sectional view showing GRC-clad steel tube secondary facade structure and GRP external shading louvres fixed to curved glazing



h | 3D exploded view of GRC-clad steel tube secondary facade structure and GRP external shading louvres fixed to curved glazing

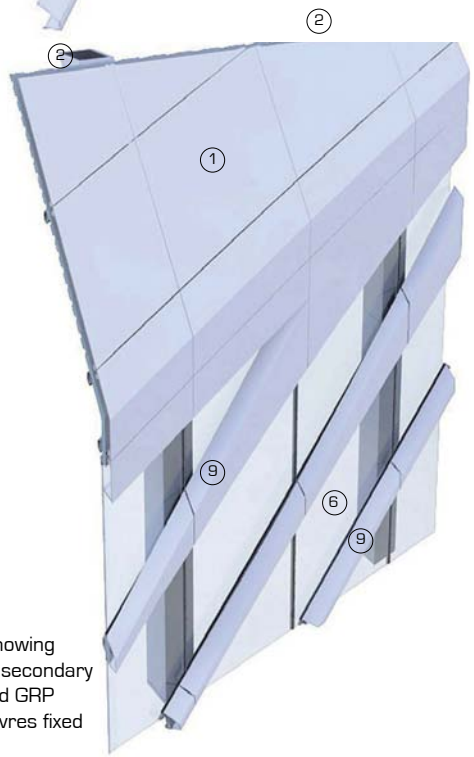




i | 3D detail views showing GRC-clad steel tube secondary facade structure and GRP external shading louvres fixed to curved glazing

Details

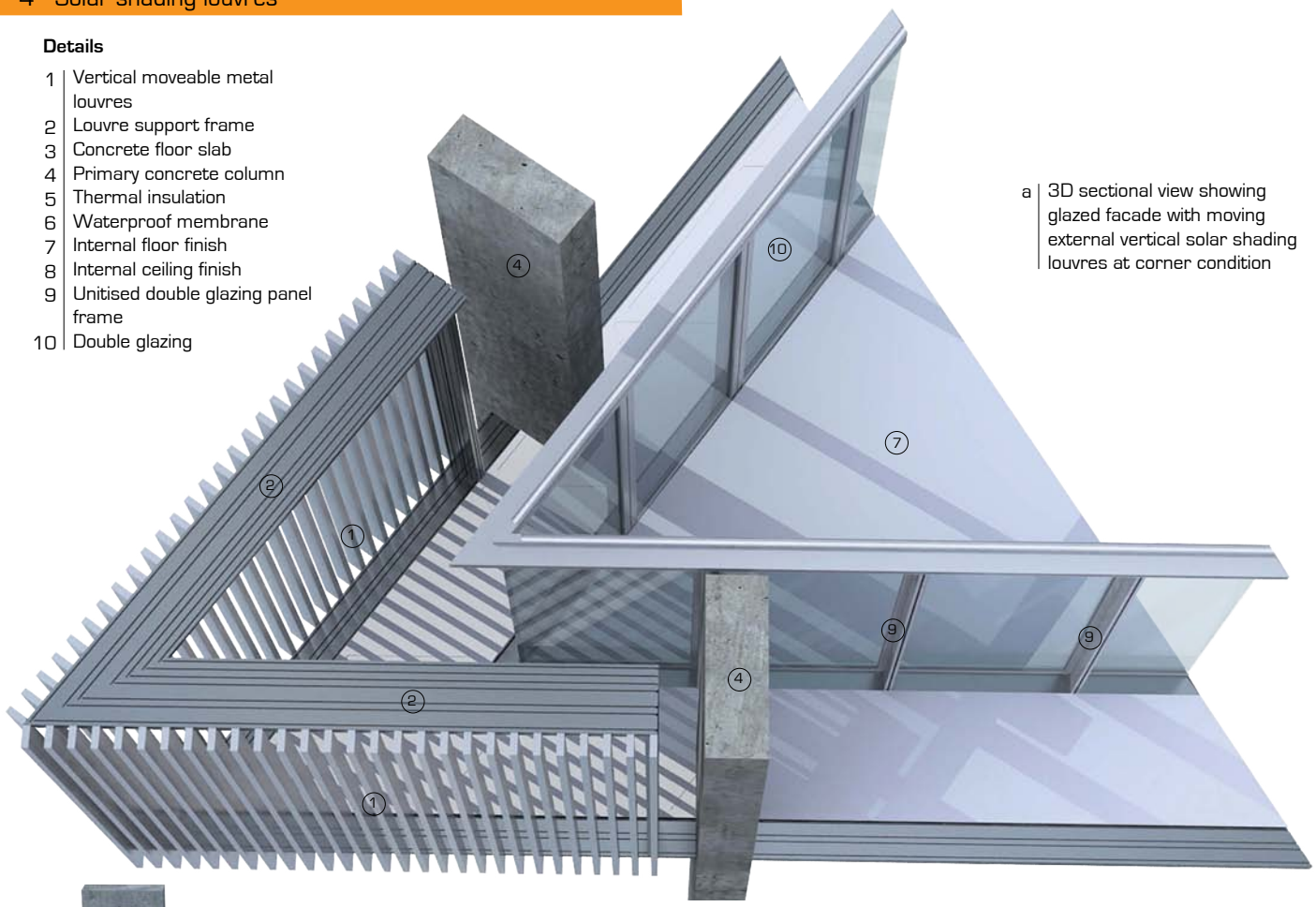
1 | GRC rainscreen cladding
2 | Primary steel columns (insulated and faced)
3 | Thermal insulation
4 | Rainscreen panel fixing system
5 | Glazing frame
6 | Double glazing
7 | Profiled metal deck
8 | Steel tube secondary facade support structure
9 | GRC external shading louvres
10 | Parapet cladding
11 | Concrete floor slab
12 | Concrete primary structure



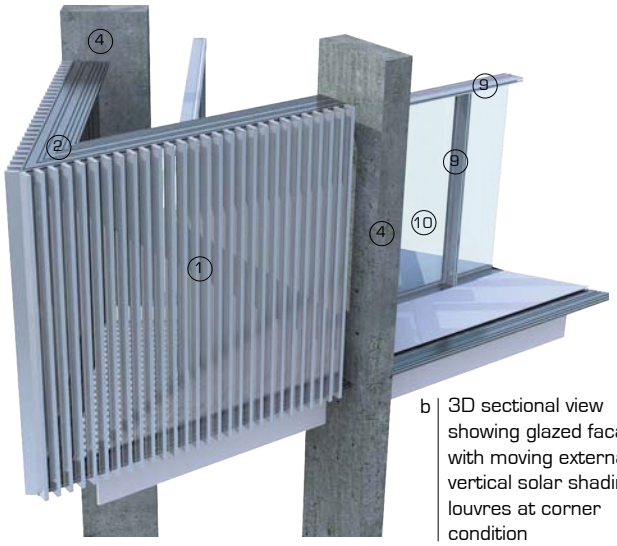
j | 3D sectional view showing GRC-clad steel tube secondary facade structure and GRP external shading louvres fixed to curved glazing

Details

1 | Vertical moveable metal louvres
2 | Louvre support frame
3 | Concrete floor slab
4 | Primary concrete column
5 | Thermal insulation
6 | Waterproof membrane
7 | Internal floor finish
8 | Internal ceiling finish
9 | Unitised double glazing panel frame
10 | Double glazing



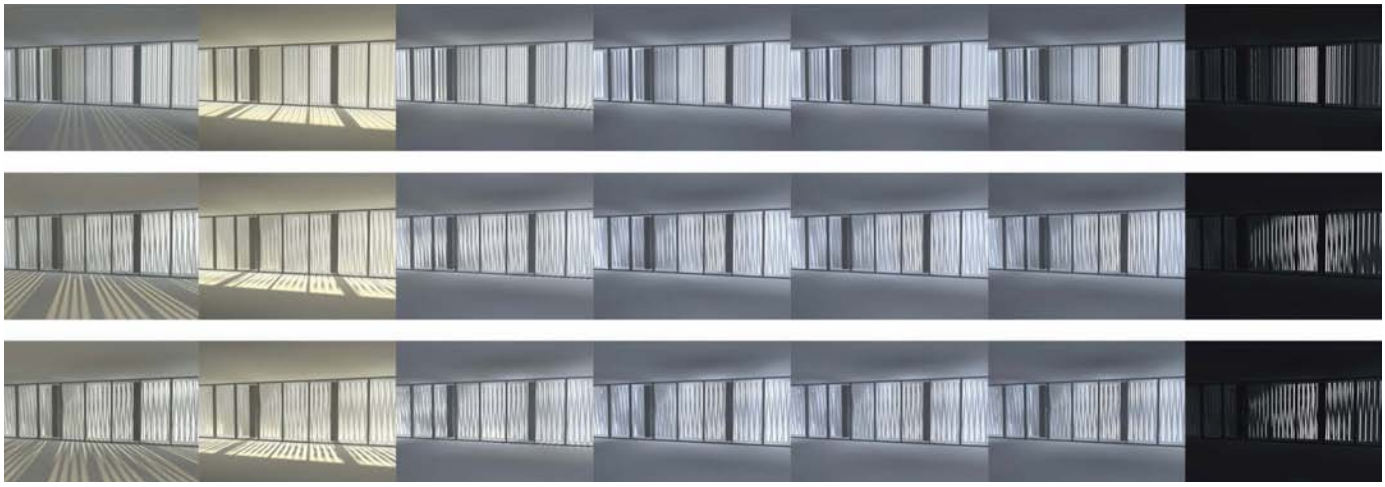
a | 3D sectional view showing glazed facade with moving external vertical solar shading louvres at corner condition



b | 3D sectional view showing glazed facade with moving external vertical solar shading louvres at corner condition

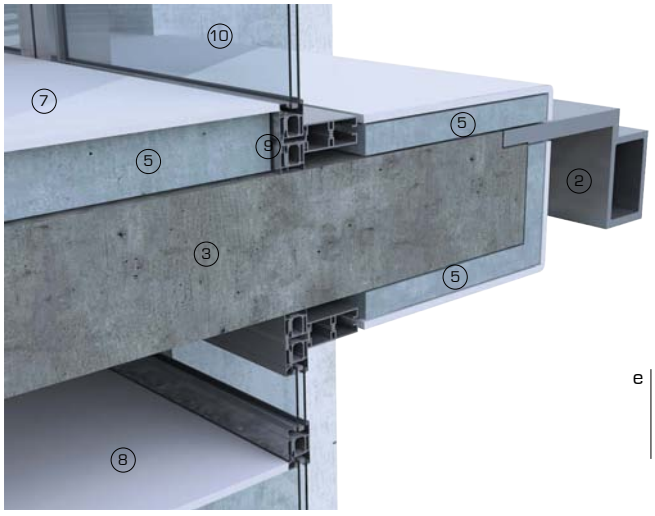


c | 3D internal view showing glazed facade with moving external vertical solar shading louvres



d | 3D internal views showing effects of external vertical shading louvres throughout the day

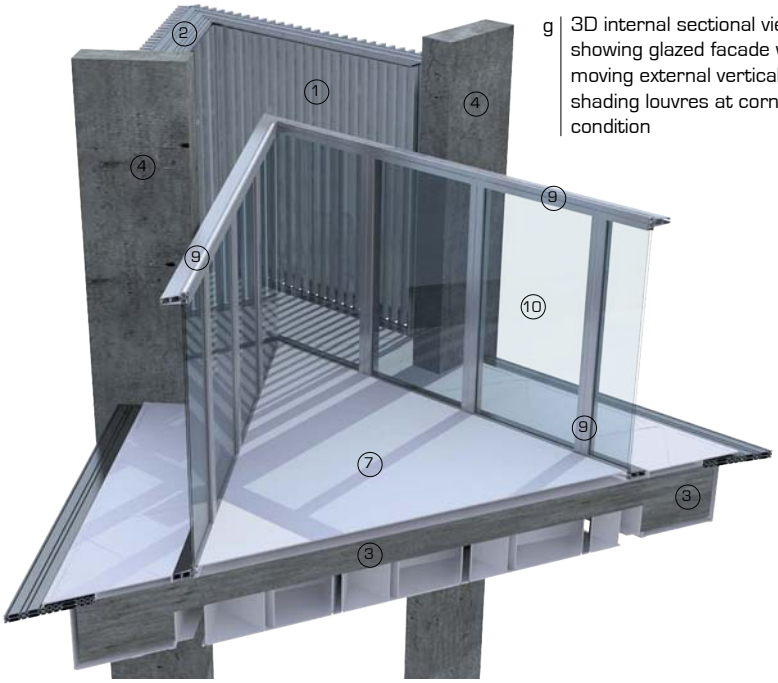




f | 3D detail sectional views showing glazed facade with moving external vertical solar shading louvres



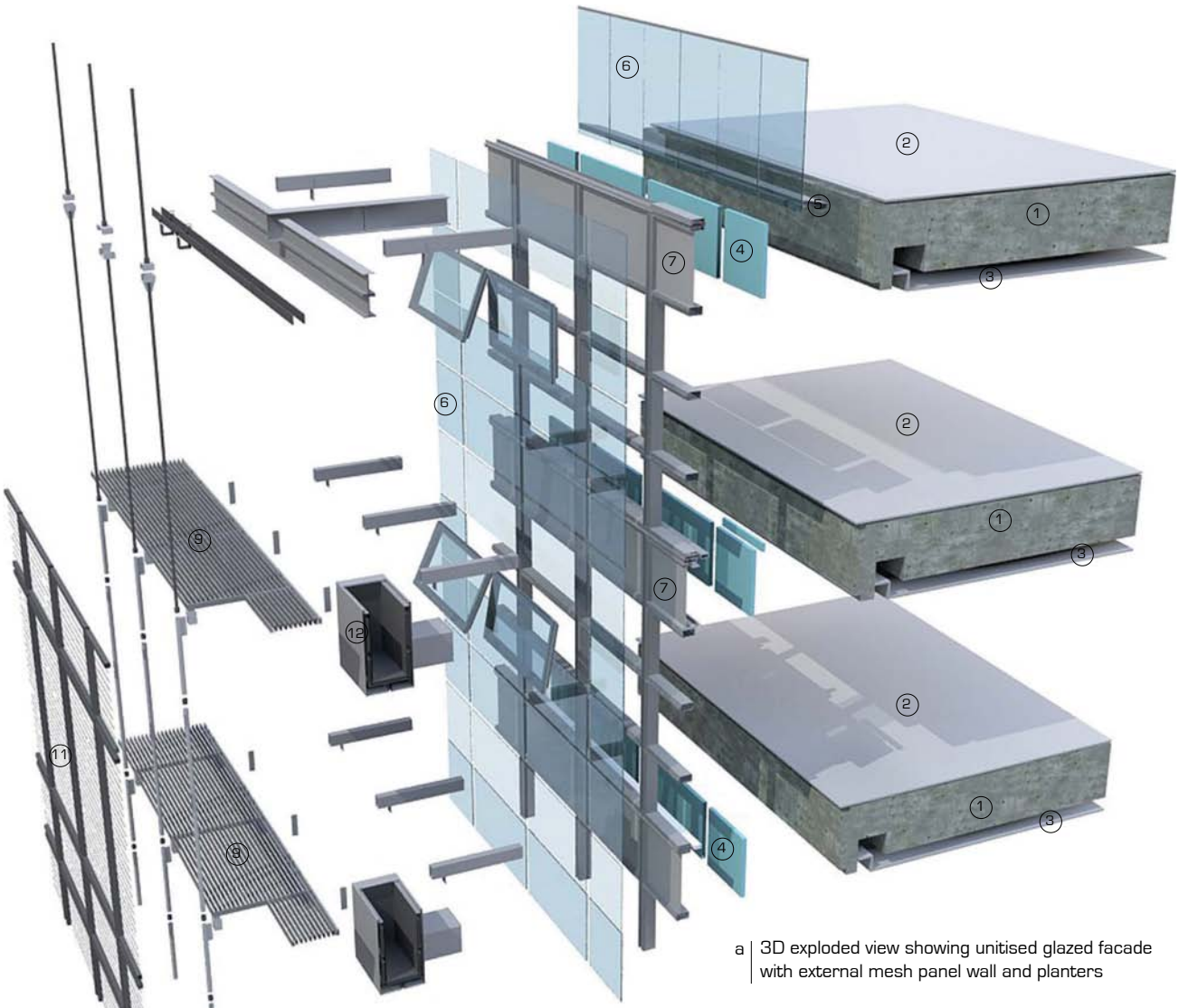
e | 3D sectional view showing glazed facade with moving external vertical solar shading louvres



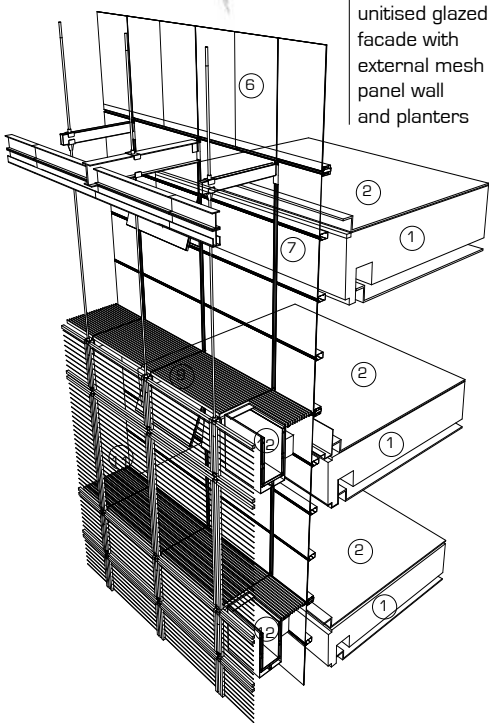
g | 3D internal sectional view showing glazed facade with moving external vertical solar shading louvres at corner condition



h | 3D detail sectional view showing glazed facade with moving external vertical solar shading louvres



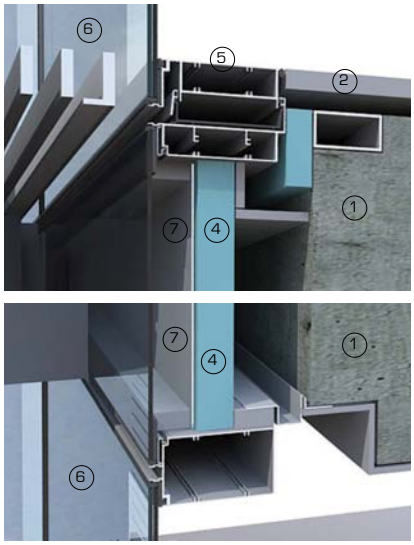
a | 3D exploded view showing unitised glazed facade with external mesh panel wall and planters



b | 3D view showing unitised glazed facade with external mesh panel wall and planters

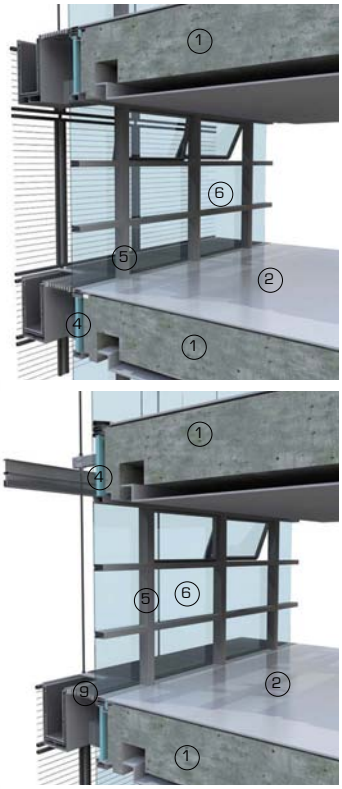


c | 3D detail views showing unitised glazed facade with external mesh panel wall and planters at floor slab interface



d | 3D views showing unitised glazing details on full-height glazed facade

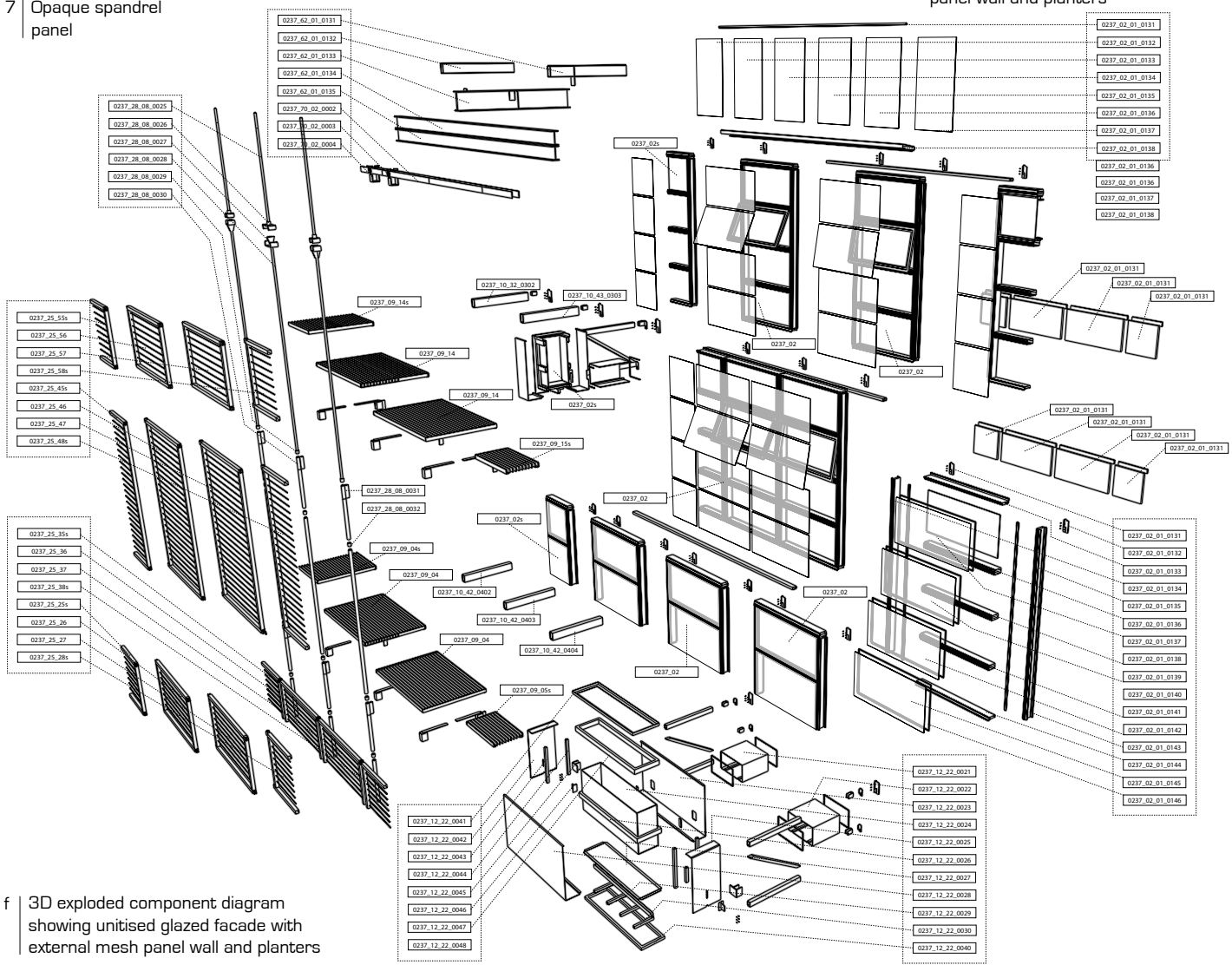




e | 3D sectional view showing unitised glazed facade with external mesh panel wall and planters

Details

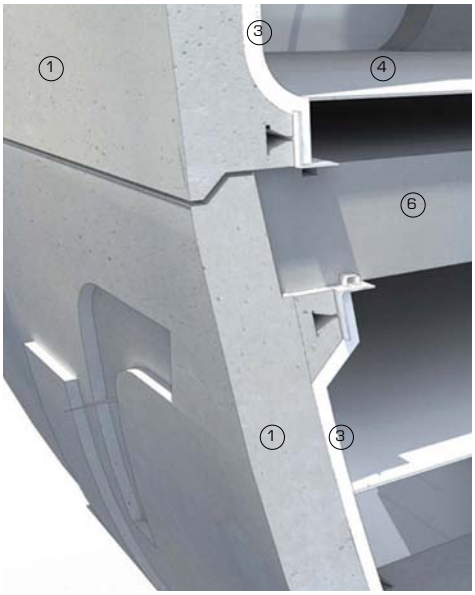
1 | Floor slab
2 | Internal floor finish
3 | Internal ceiling finish
4 | Thermal insulation
5 | Unitised glazing frame
6 | Double glazing
7 | Opaque spandrel panel
8 | Cleaning cradle
9 | Perforated metal walkway
10 | Metal bracket
11 | Metal mesh panel (external)
12 | Planter

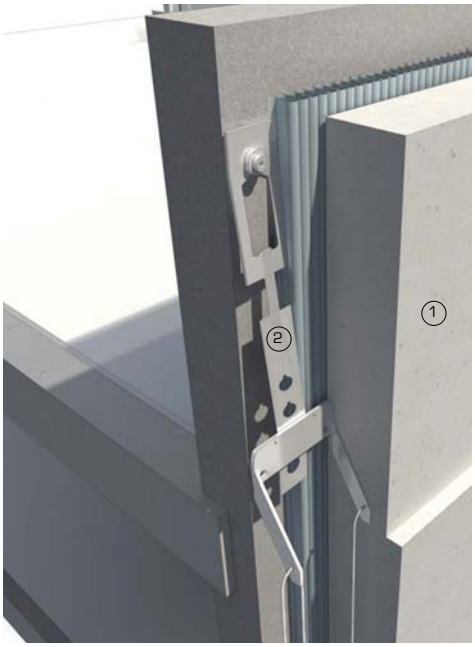


f | 3D exploded component diagram showing unitised glazed facade with external mesh panel wall and planters



a | 3D views showing large precast concrete cladding panels with moulded surface relief and cast-in window openings





b | 3D sectional views showing fixing system for large precast concrete cladding panels with structural reinforced concrete wall behind



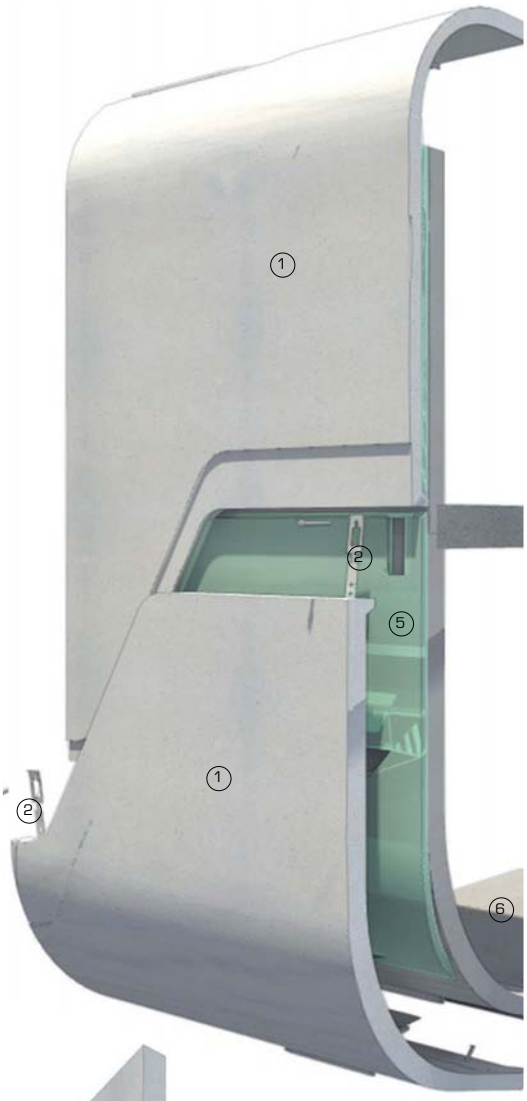


c | 3D exploded, sectional view showing fixing system for large precast concrete cladding panels with structural reinforced concrete wall behind

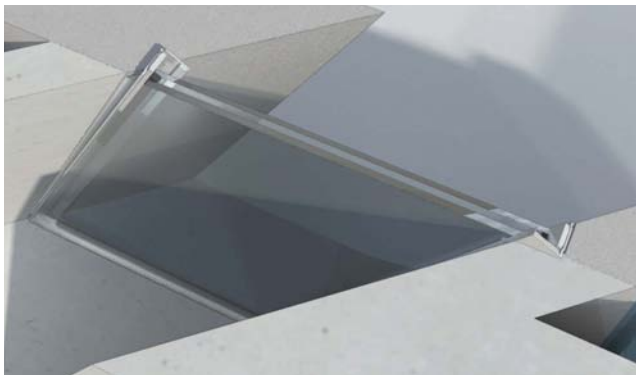
Details

1 | Precast concrete cladding panel
2 | Concrete cladding panel lifting hooks (cast-in)
3 | Internal wall finish
4 | Internal floor finish
5 | Thermal insulation
6 | Concrete floor slab
7 | In-situ cast concrete structural backing wall
8 | Unitised double-glazed window panel





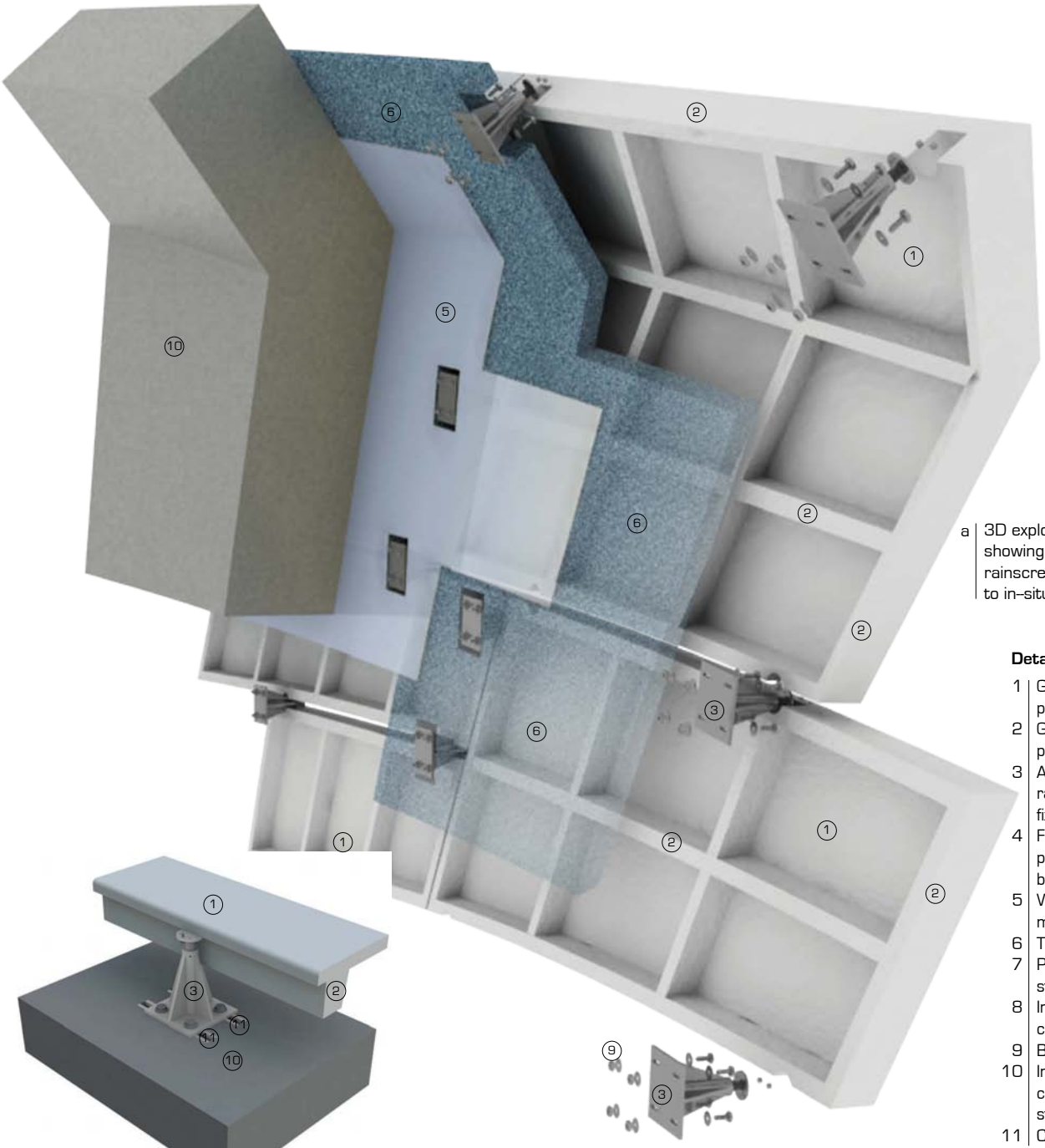
d | 3D exploded sectional views showing fixing system for large precast concrete cladding panels with structural reinforced concrete wall behind





e | 3D sectional views showing window within large precast concrete cladding panel facade system (with structural reinforced concrete wall behind)

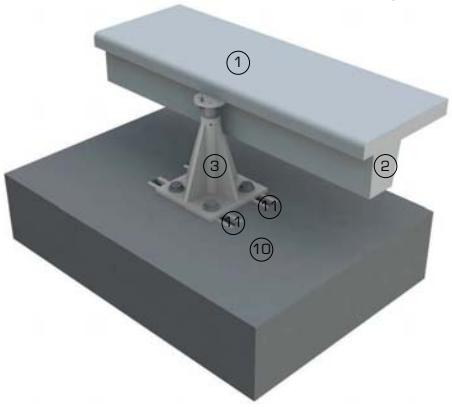




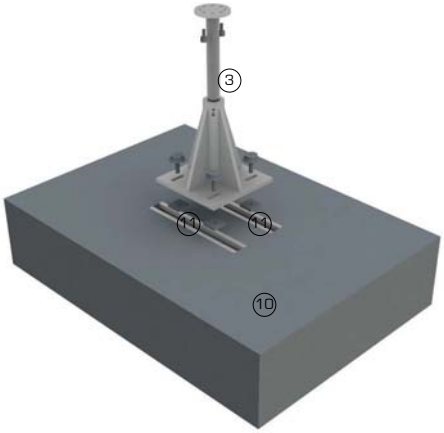
a | 3D exploded view showing GRC rainscreen panels fixed to in–situ cast concrete

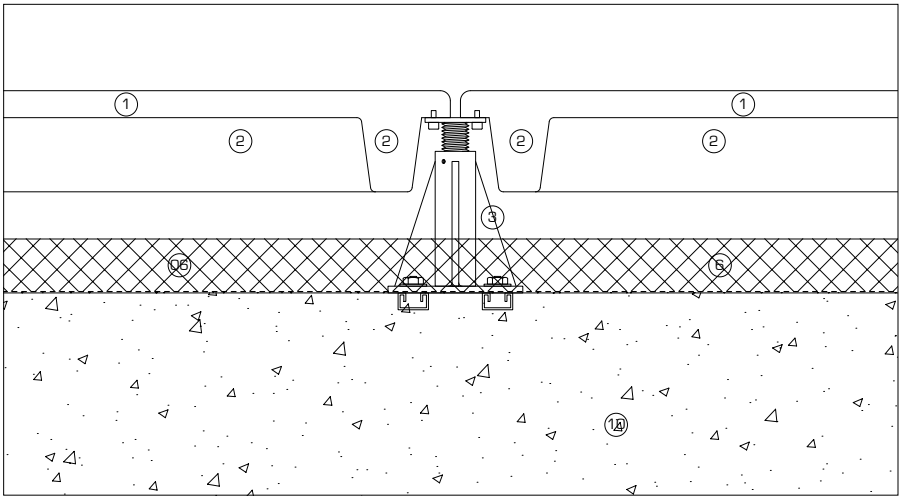
Details

1	GRC rainscreen panel
2	GRC rainscreen panel rib
3	Adjustable rainscreen panel fixing bracket
4	Fixed rainscreen panel fixing bracket
5	Waterproof membrane
6	Thermal insulation
7	Primary steel structure
8	Internal wall/ ceiling finish
9	Bolt
10	In-situ cast concrete primary structure
11	Cast-in channels

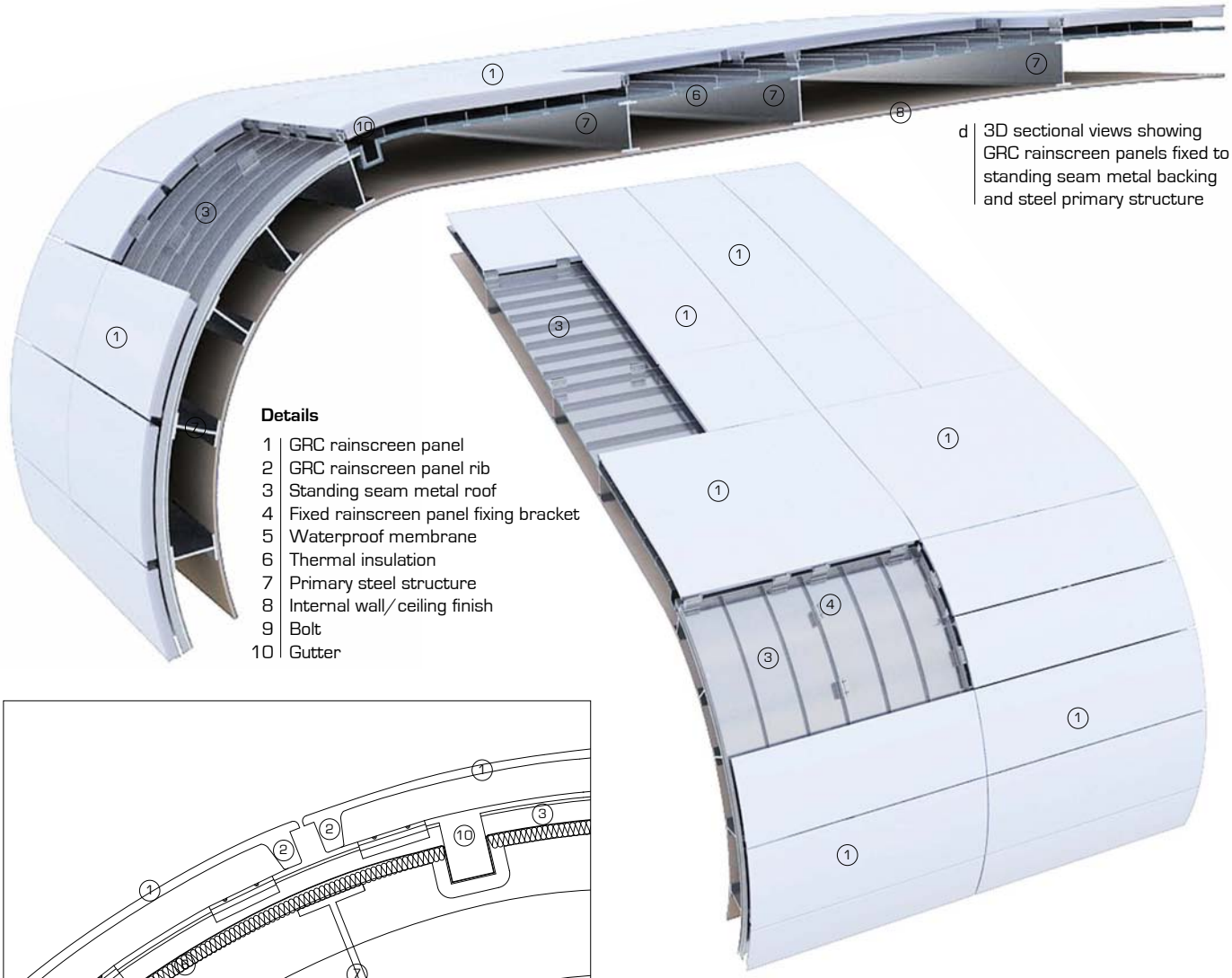


b | 3D fragment views showing GRC rainscreen panels fixed to in–situ cast concrete with adjustable fixing bracket





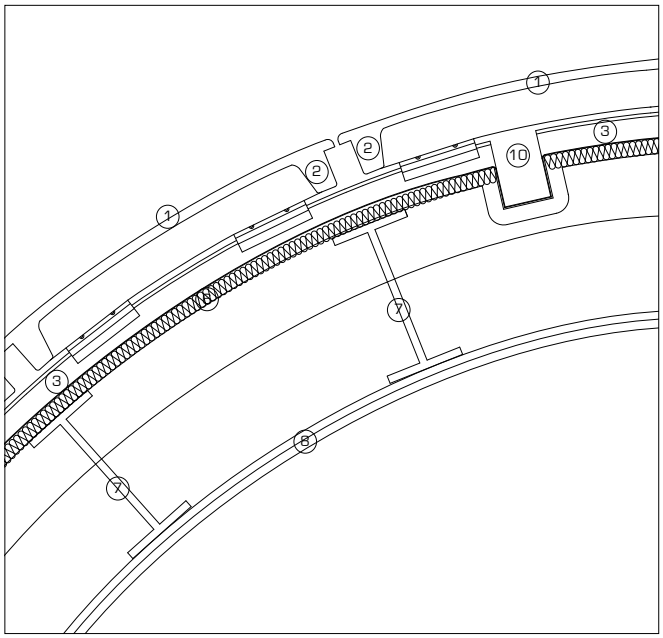
c | Vertical section. GRC rainscreen panels fixed to in–situ cast concrete

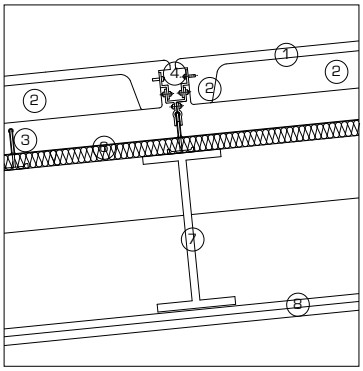


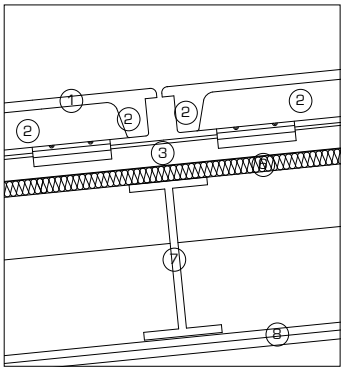
d | 3D sectional views showing GRC rainscreen panels fixed to standing seam metal backing and steel primary structure

Details

1	GRC rainscreen panel
2	GRC rainscreen panel rib
3	Standing seam metal roof
4	Fixed rainscreen panel fixing bracket
5	Waterproof membrane
6	Thermal insulation
7	Primary steel structure
8	Internal wall/ceiling finish
9	Bolt
10	Gutter

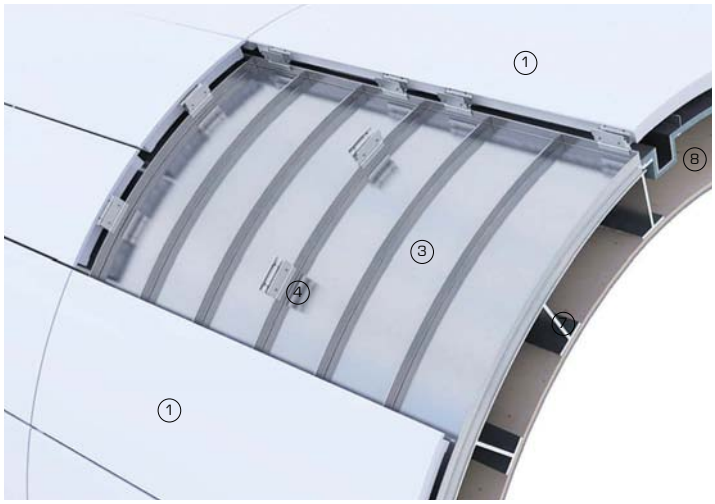






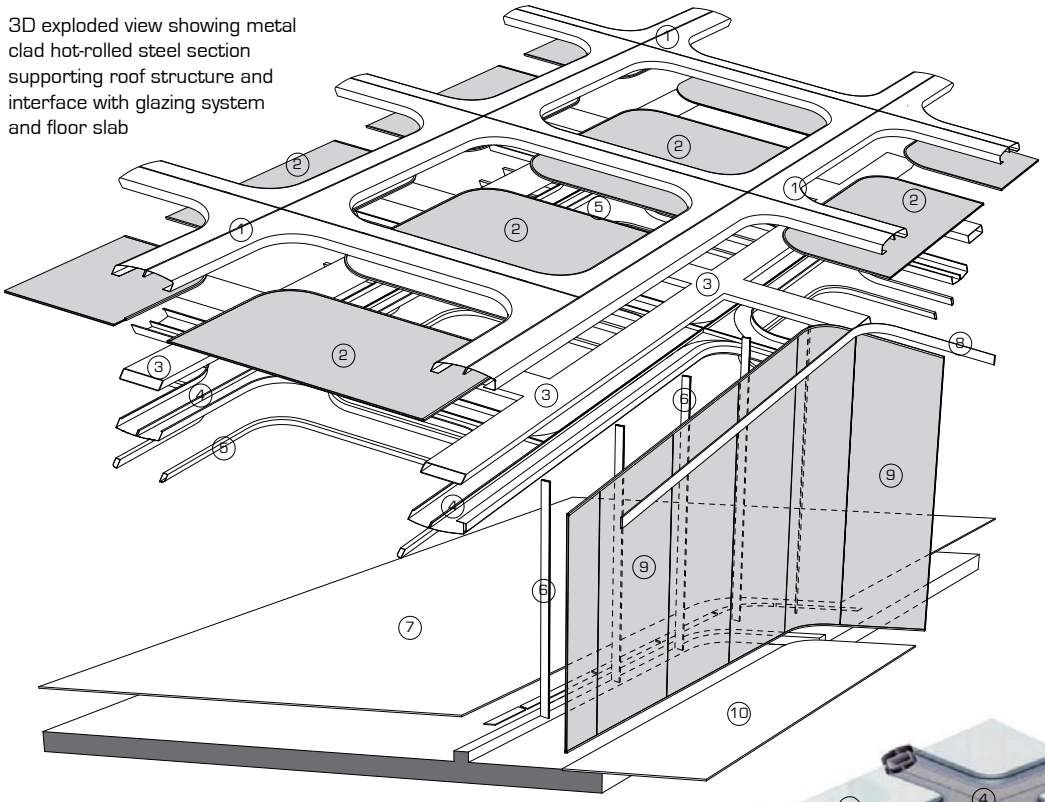
e | Vertical sections. GRC rainscreen panels fixed to standing seam metal backing and steel primary structure





f | 3D detail views showing GRC rainscreen panels fixed to standing seam metal backing and steel primary structure

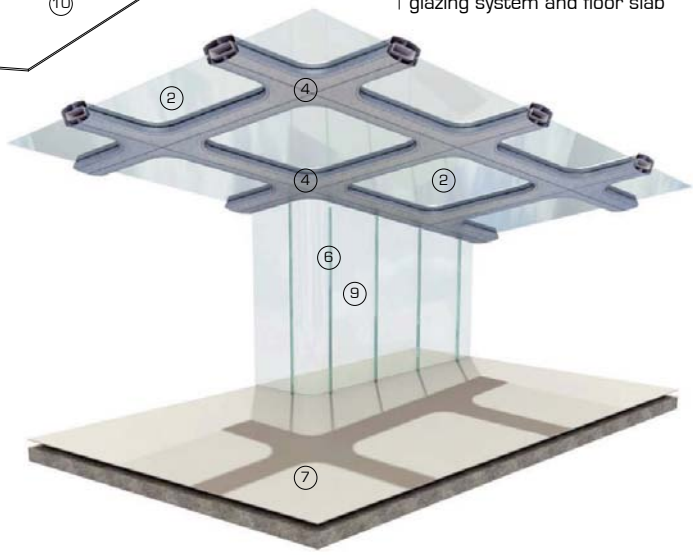
a | 3D exploded view showing metal clad hot-rolled steel section supporting roof structure and interface with glazing system and floor slab

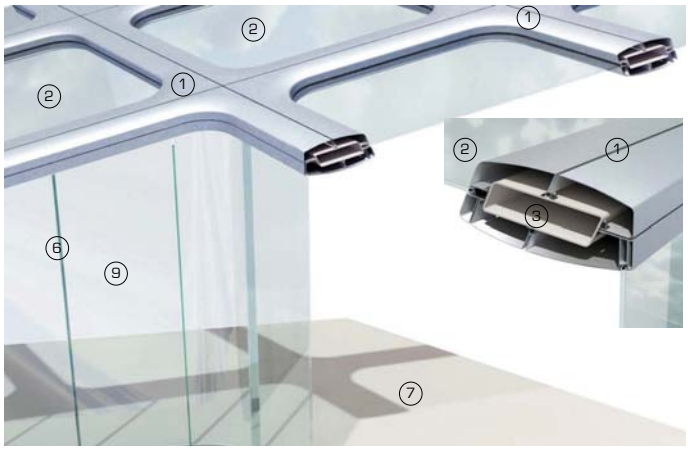


Details

1 | Metal outer cladding
2 | Double-glazed unit
3 | Hot-rolled steel section
4 | Inner metal cladding
5 | Glazing frame
6 | Glass fin
7 | Internal floor finish
8 | Pressure plate
9 | Toggle-fixed glazing supported on vertical glass fins
10 | External floor finish
11 | Concrete slab
12 | Precast concrete outer cladding panel
13 | Precast fascia panel
14 | Supporting steel structure
15 | Seal between precast concrete elements

b | 3D sectional view showing metal clad hot-rolled steel section supporting roof structure and interface with glazing system and floor slab



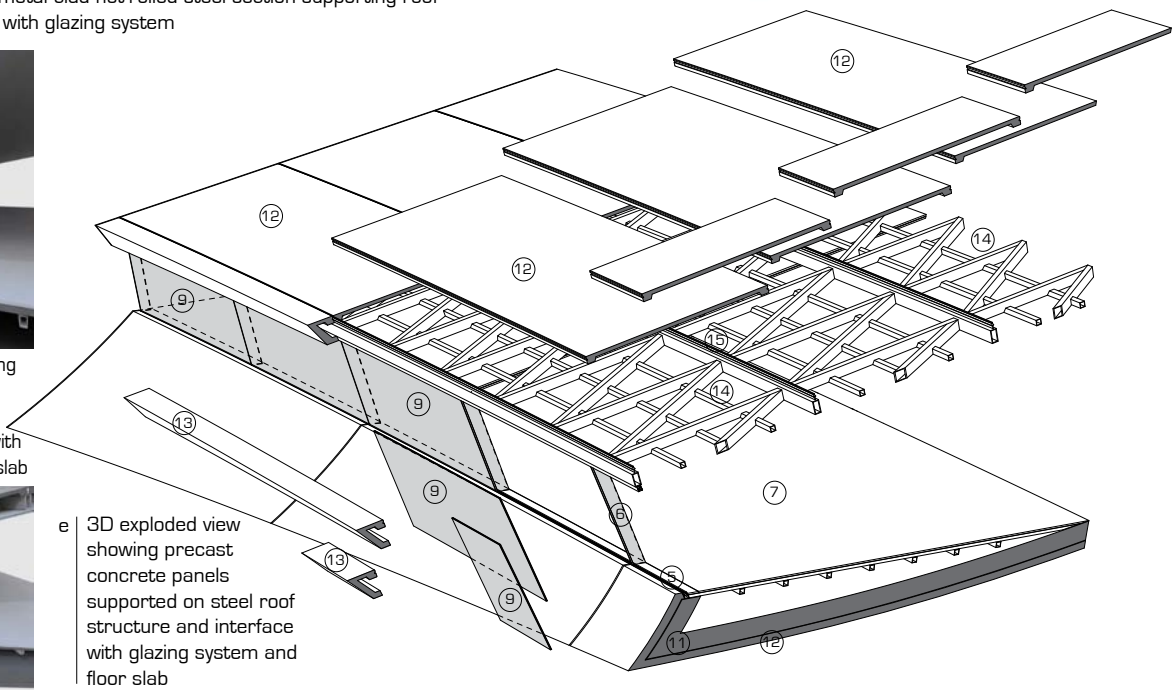


c | 3D detail view showing metal clad hot-rolled steel section supporting roof structure and interface with glazing system

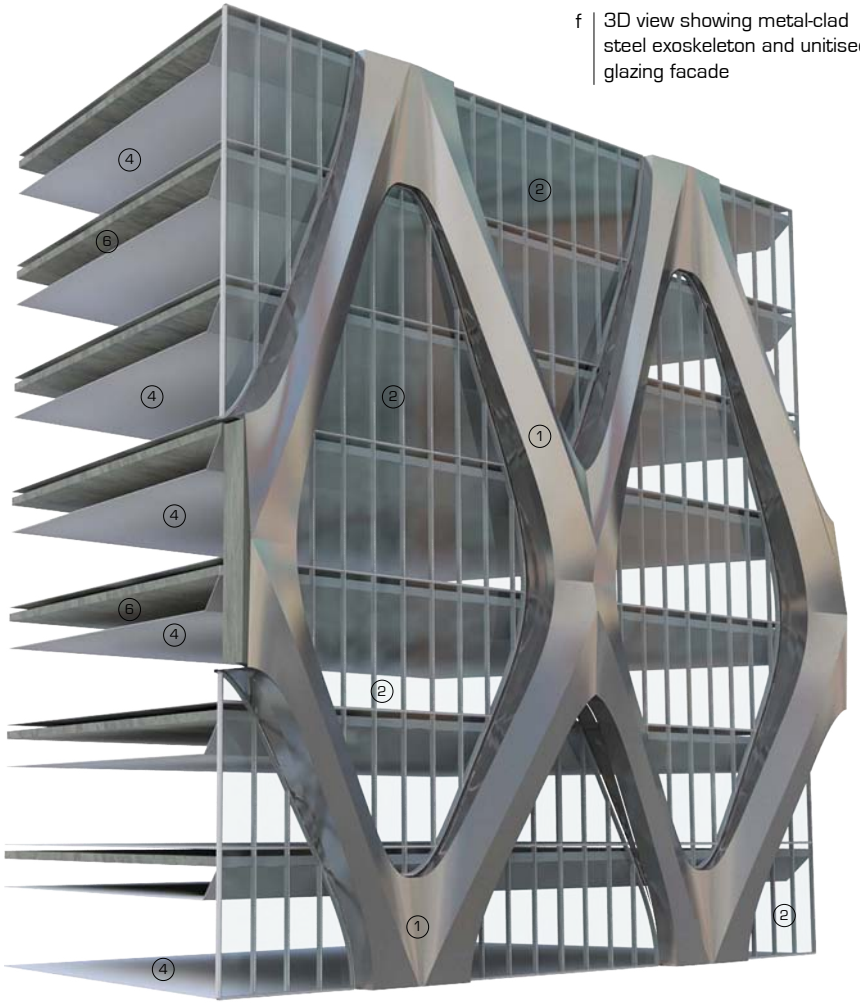


d | 3D sectional views showing precast concrete panels supported on steel roof structure and interface with glazing system and floor slab

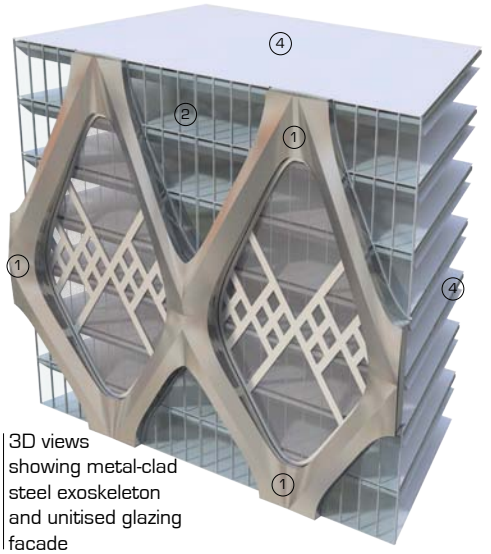




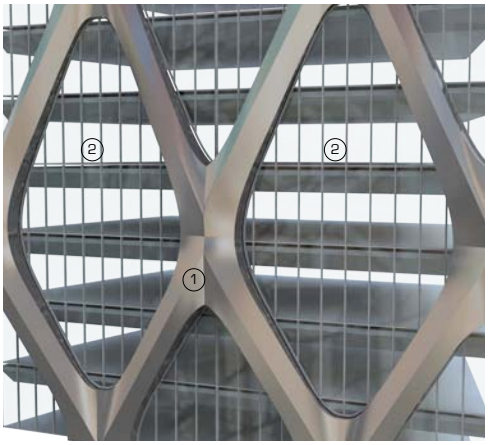
e | 3D exploded view showing precast concrete panels supported on steel roof structure and interface with glazing system and floor slab

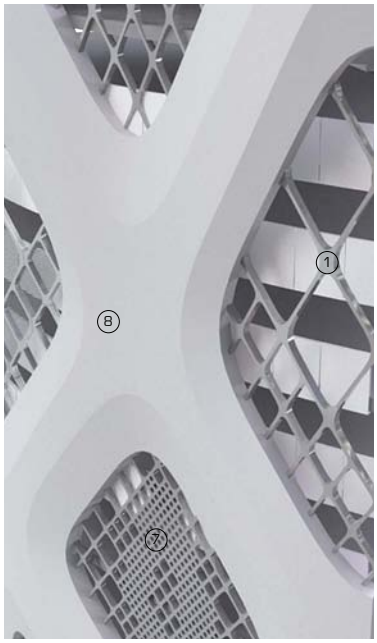


f | 3D view showing metal-clad steel exoskeleton and unitised glazing facade

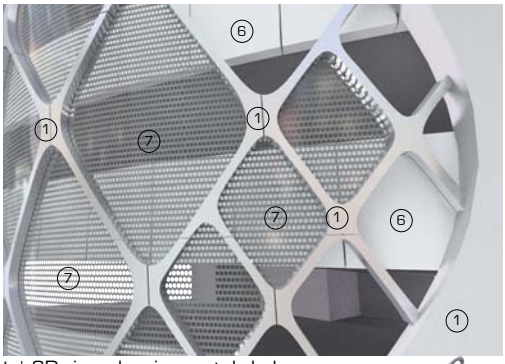


g | 3D views showing metal-clad steel exoskeleton and unitised glazing facade

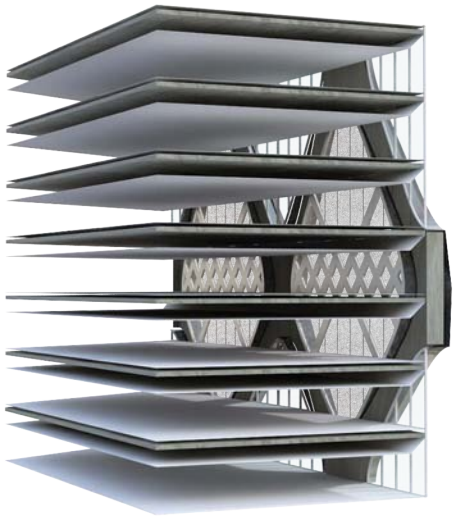


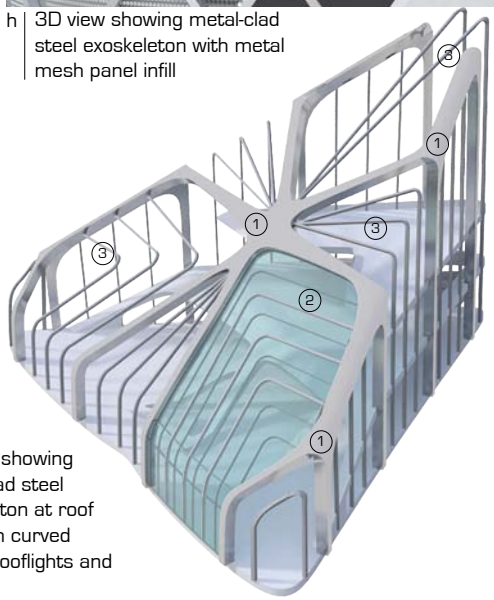


j | 3D view showing GRC-clad steel exoskeleton with metal mesh panel infill



h | 3D view showing metal-clad steel exoskeleton with metal mesh panel infill



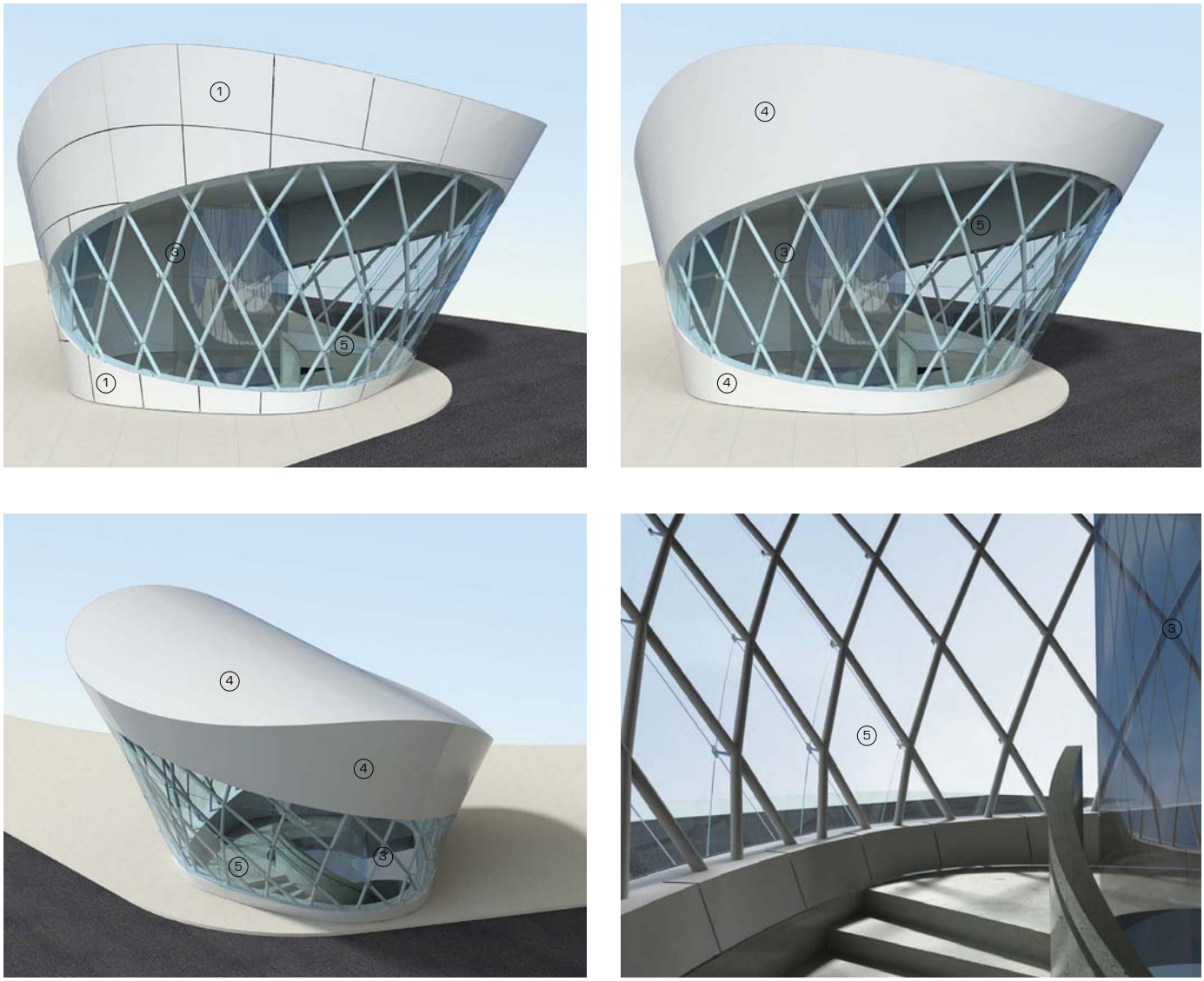


k | 3D view showing metal-clad steel exoskeleton at roof level with curved glazing rooflights and facade

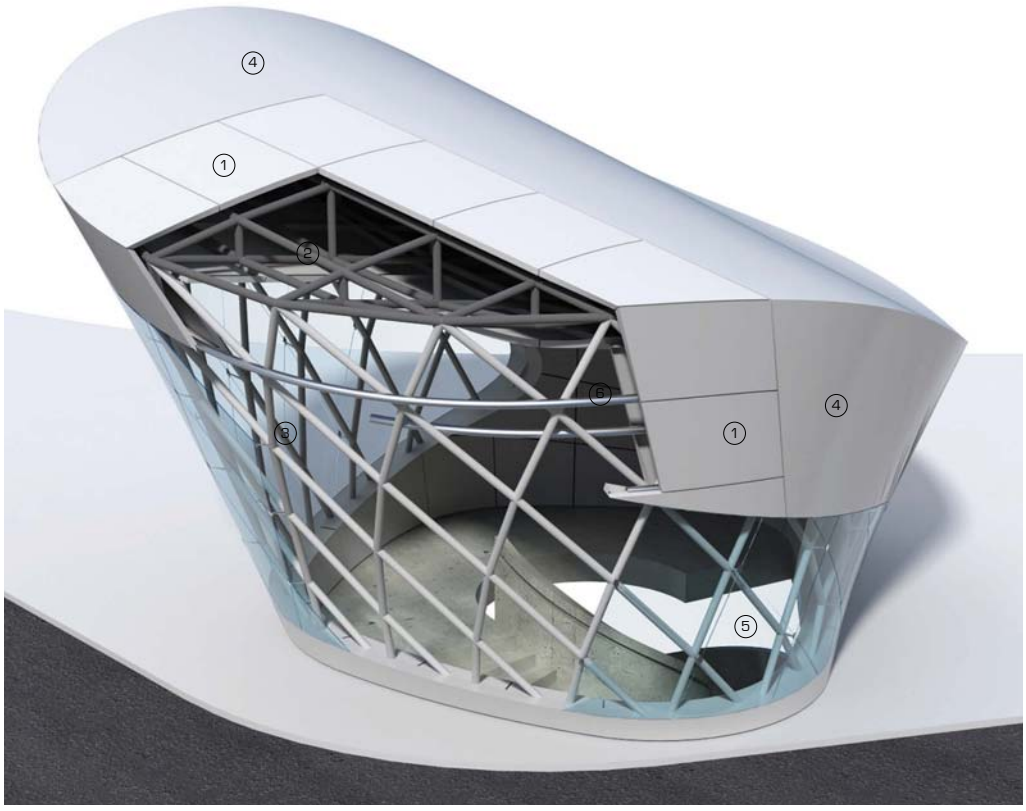


Details

1 | Metal outer cladding
2 | Double-glazed unit
3 | Glazing frame
4 | Internal finish
5 | Internal floor slab
6 | Concrete slab
7 | Metal mesh panels
8 | GRC outer cladding

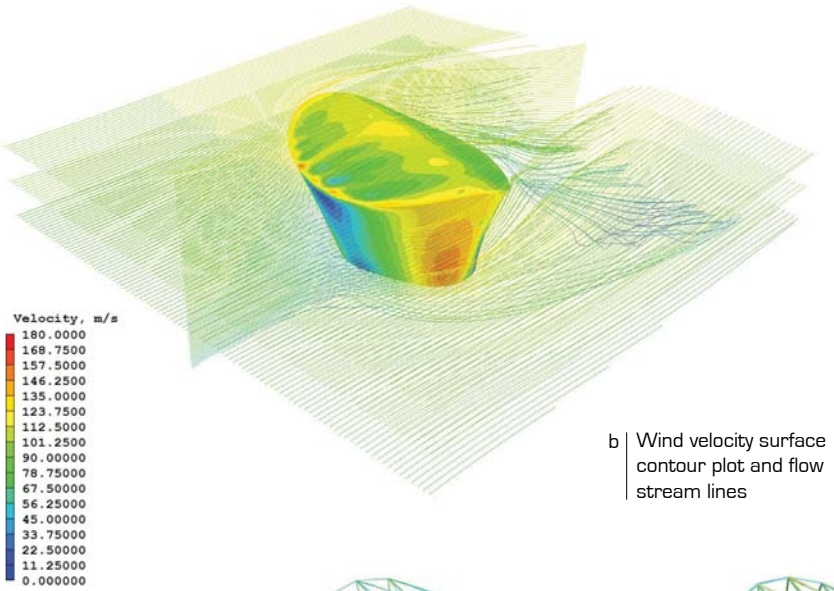


a | 3D views of diagrid structure

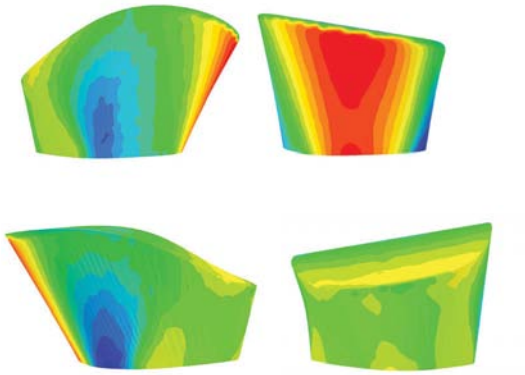


Details

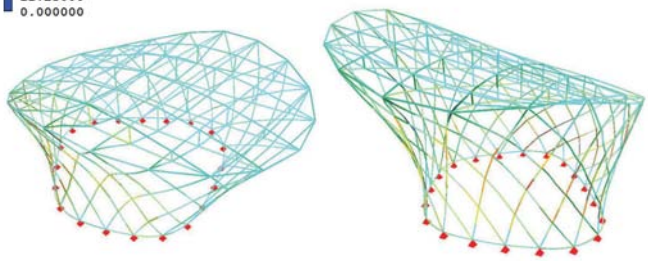
1 | Opaque panel
2 | Roof structure
3 | Wall structure
4 | Opaque panels with joints filled and coating applied
5 | Secondary structure
6 | Glazed panels



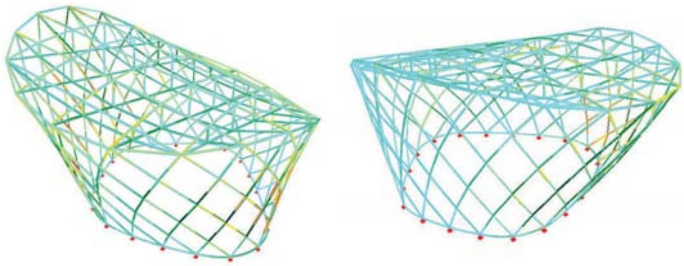
b | Wind velocity surface contour plot and flow stream lines



c | Wind pressure surface contour plot

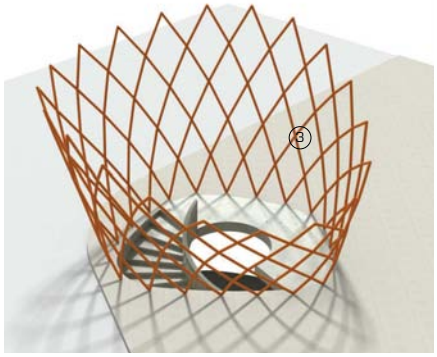


d | Wind – front on (left) and lateral (right)
The diagrid structure distributes forces through the frame in an even way, reducing peak loads in individual members. The pavilion form reduces the impact of wind uplift since there are no overhanging roof elements.

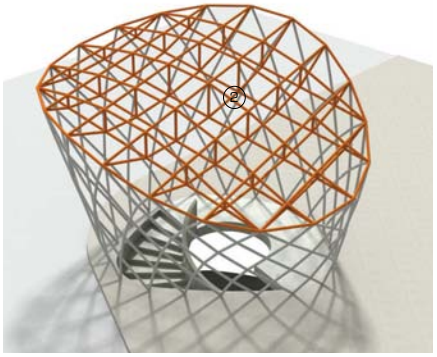


e | Self weight
The diagrid structure distributes the stresses in an even way which reduces areas of high stress in the frame. The need for ring bracing needs further investigation.

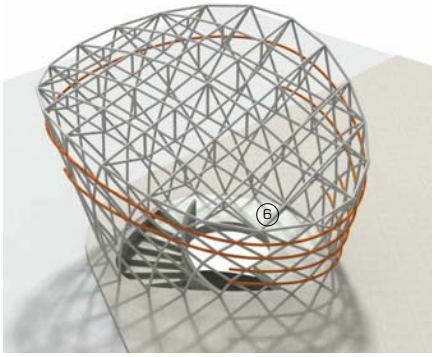
f | Torsion
The diagrid offers a higher degree of stiffening against torsional moments since the forces are distributed throughout the frame.



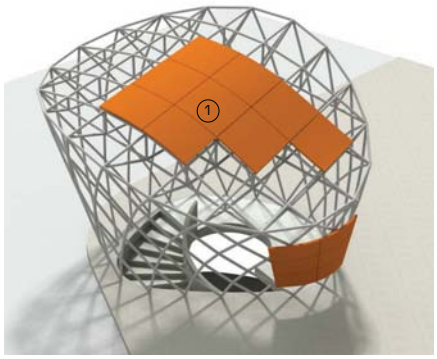
g | Diagrid structure erected to form rotunda form.



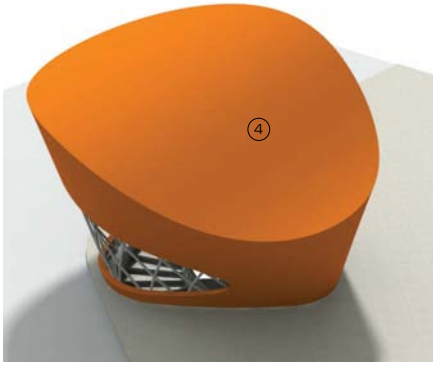
h | Roof trusses supported on ring beam at top of diagrid.



j | Secondary steelwork for cladding support fixed to primary structure on inside and outside of pavilion.



k | Opaque cladding panels attached to secondary structure



l | Joints between panels are filled and coated to form a smooth surface

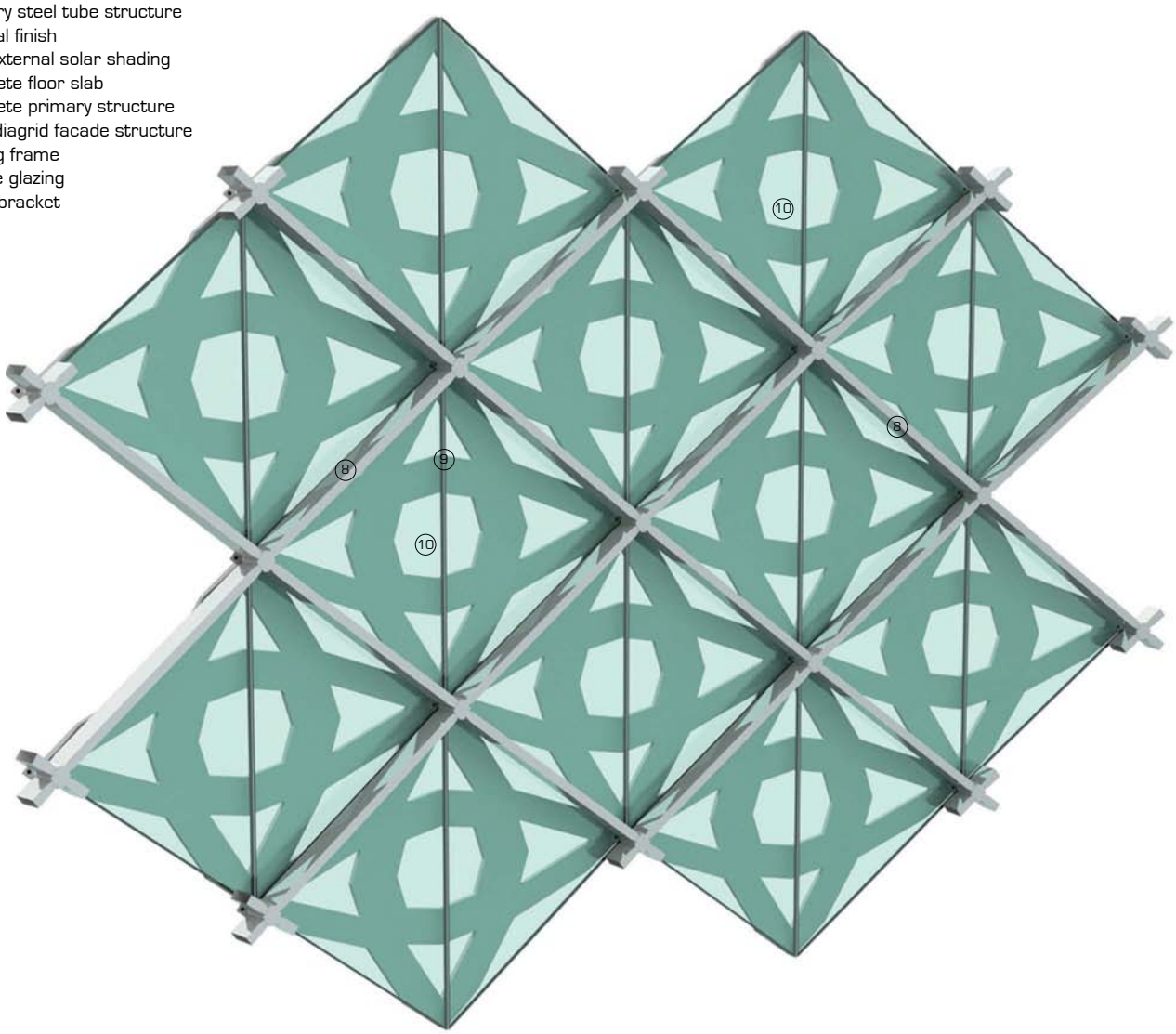


m | Glazing panels fixed to diagrid structure using point fixings

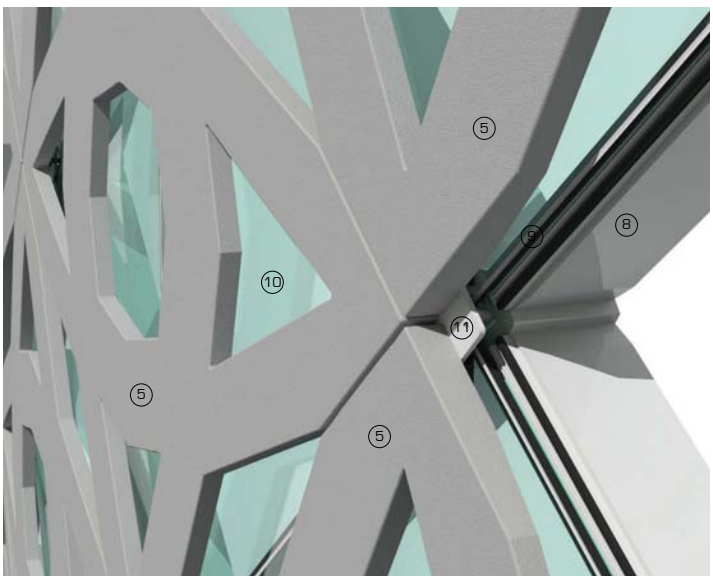
Details

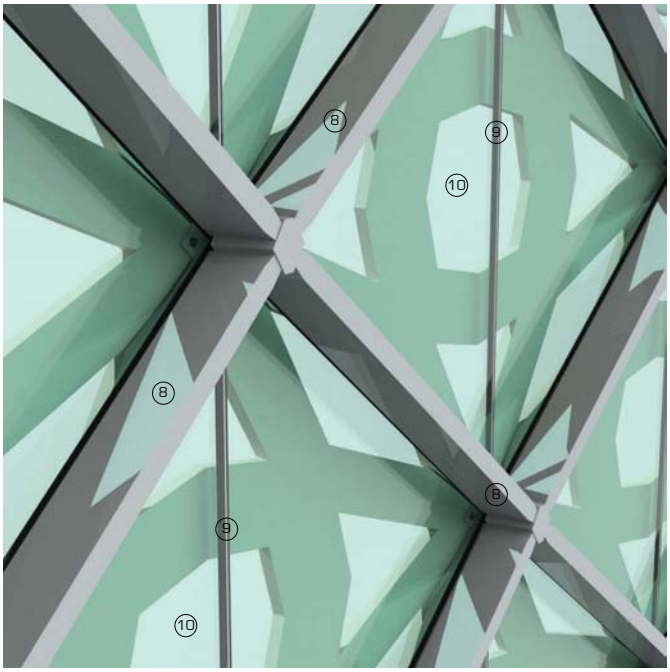
1 GRP rainscreen cladding
2 Thermal insulation
3 Primary steel tube structure
4 Internal finish
5 GRP external solar shading
6 Concrete floor slab
7 Concrete primary structure
8 Steel diagrid facade structure
9 Glazing frame
10 Double glazing
11 Fixing bracket

a | 3D sectional view showing GRP-clad undulating steel tube primary facade structure, and GRP external solar shading fixed to curved glazing supported on steel diagrid structure



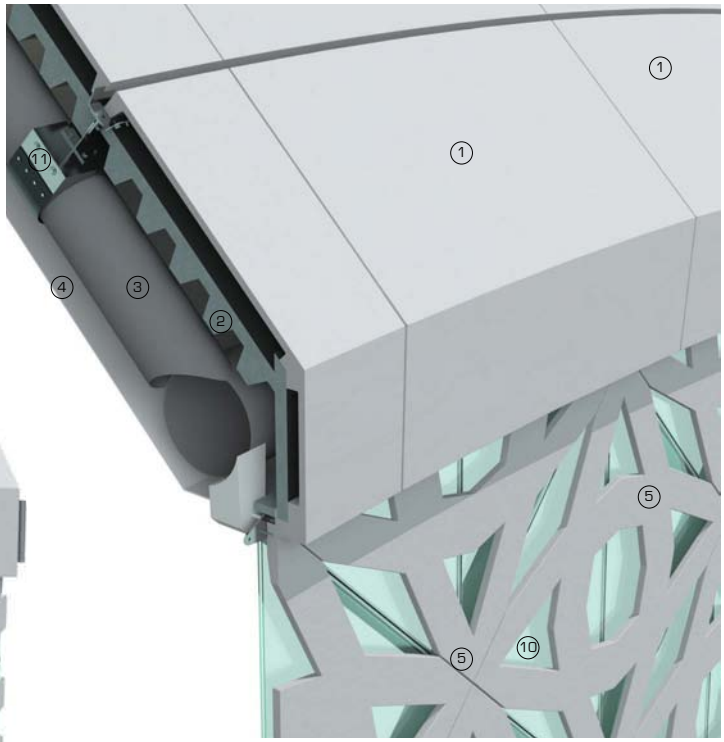
b | (Below) 3D detail views showing GRP external solar shading fixed to curved glazing supported on steel diagrid structure



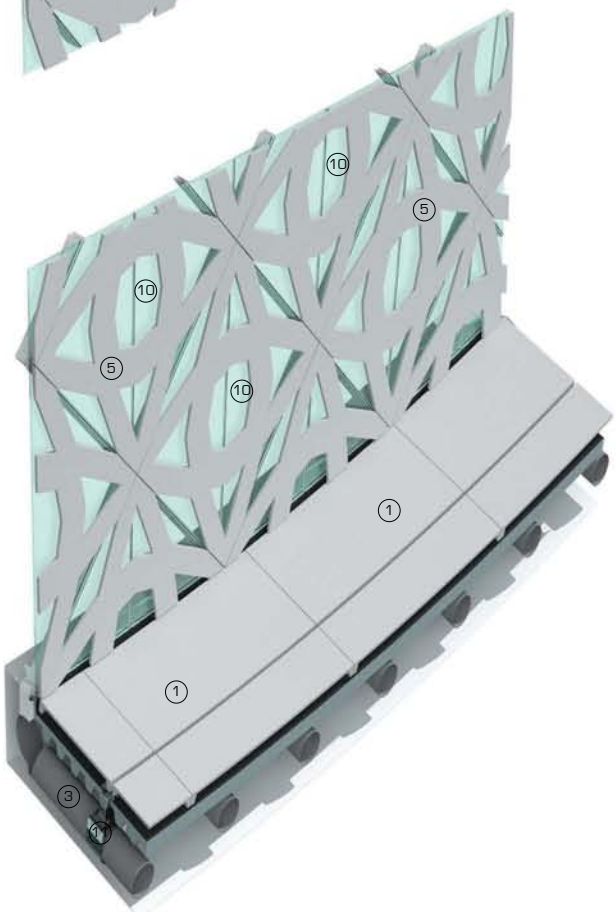


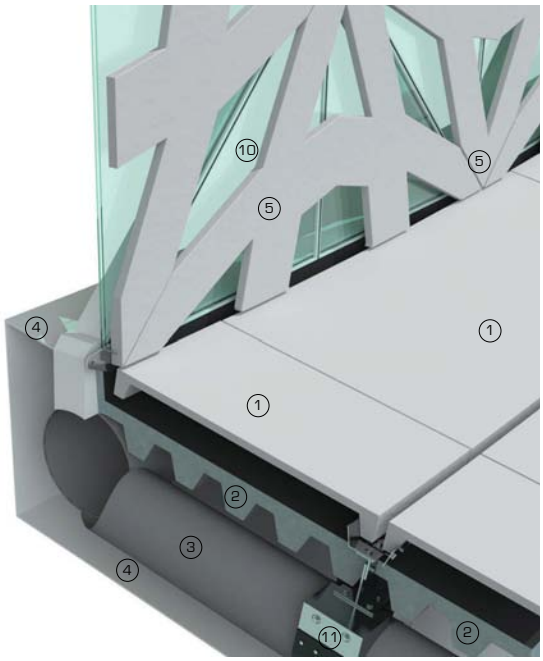
c | 3D sectional detail views showing GRP-clad undulating steel tube primary facade structure, and GRP external solar shading fixed to curved glazing supported on steel diagrid structure

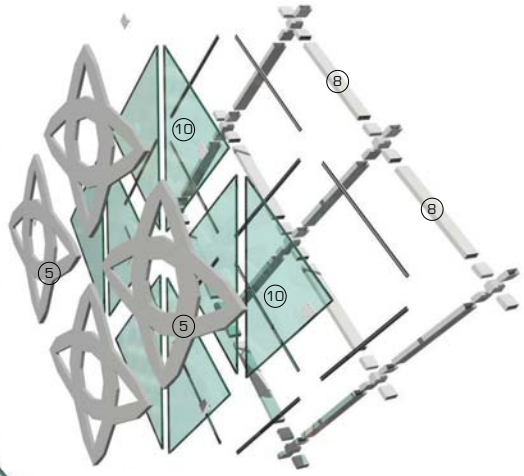




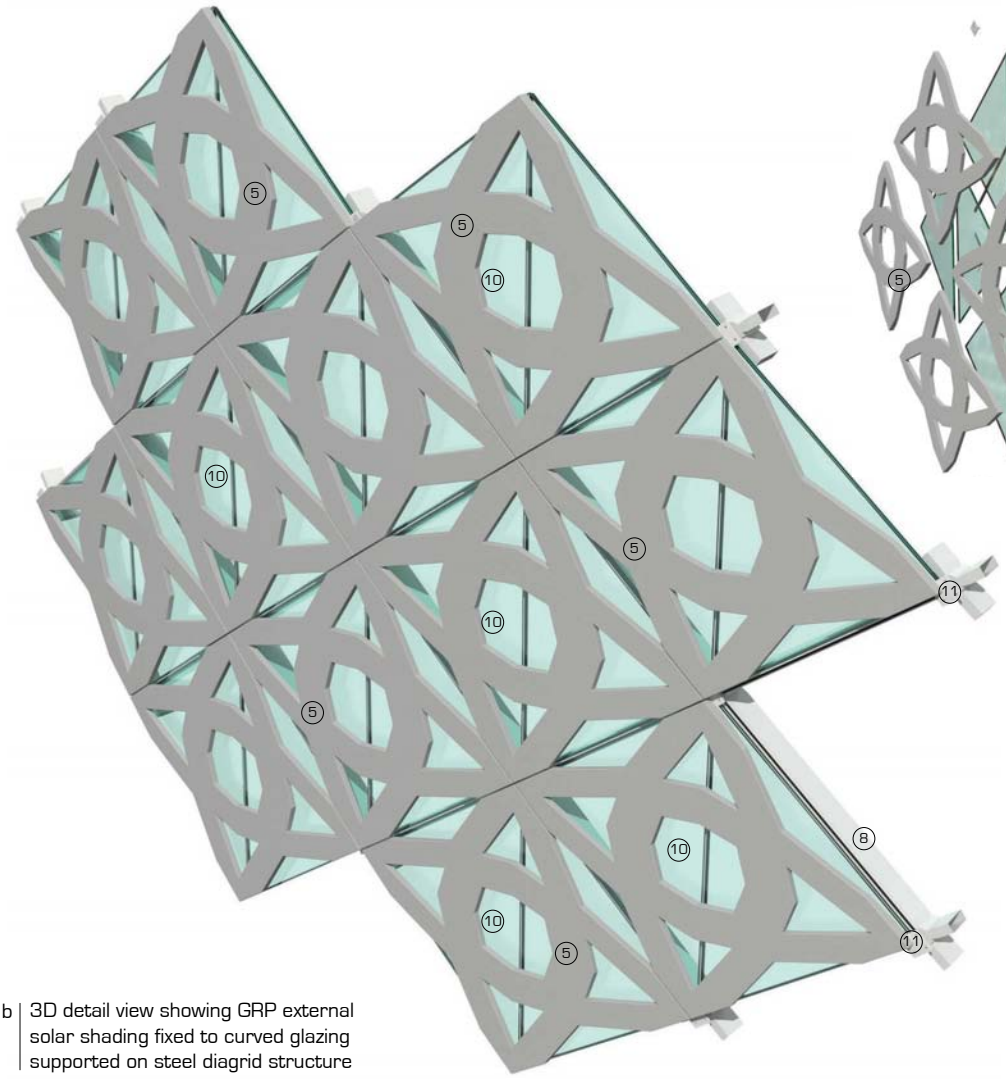








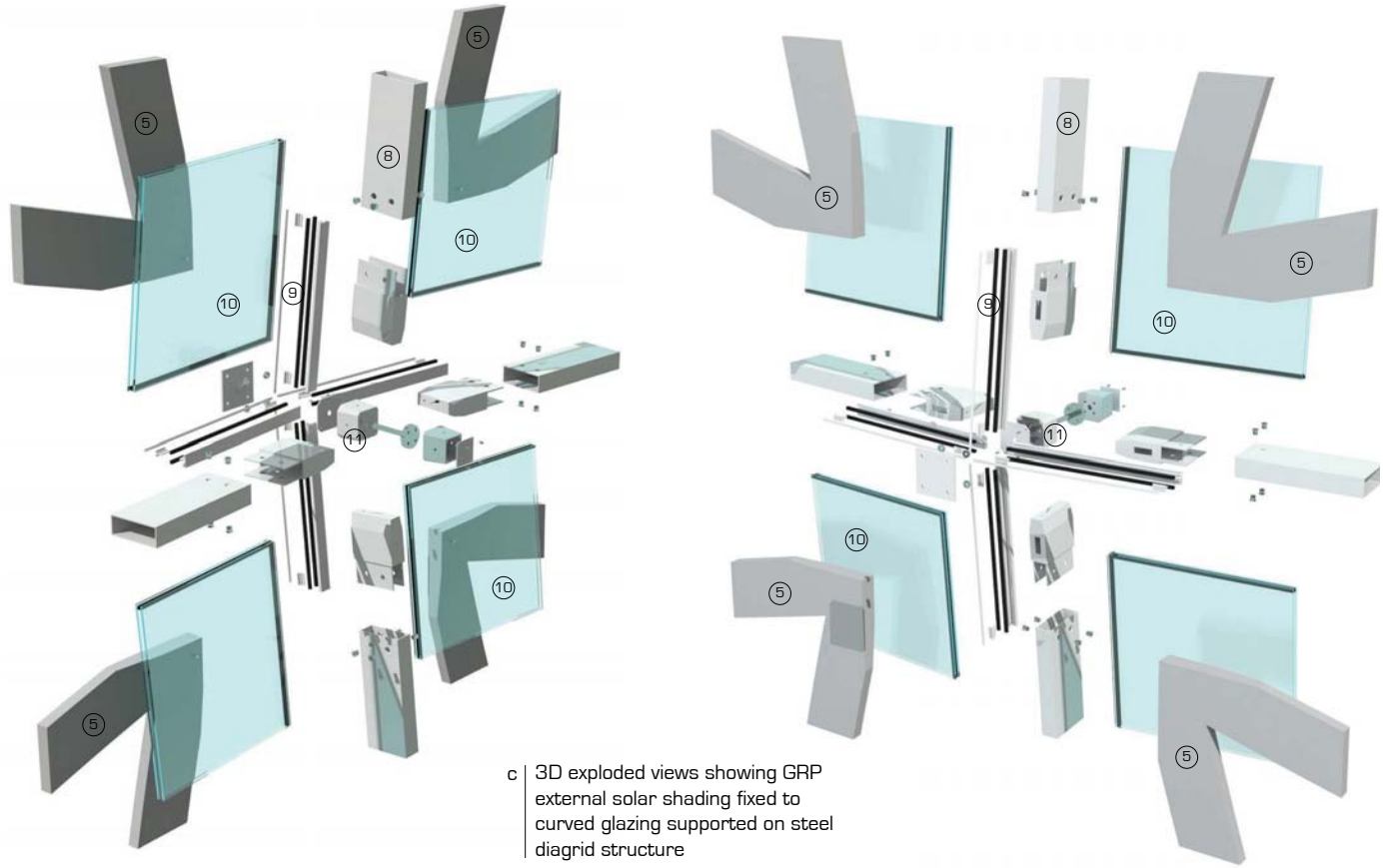
a | 3D exploded views showing GRP external solar shading fixed to curved glazing supported on steel diagrid structure



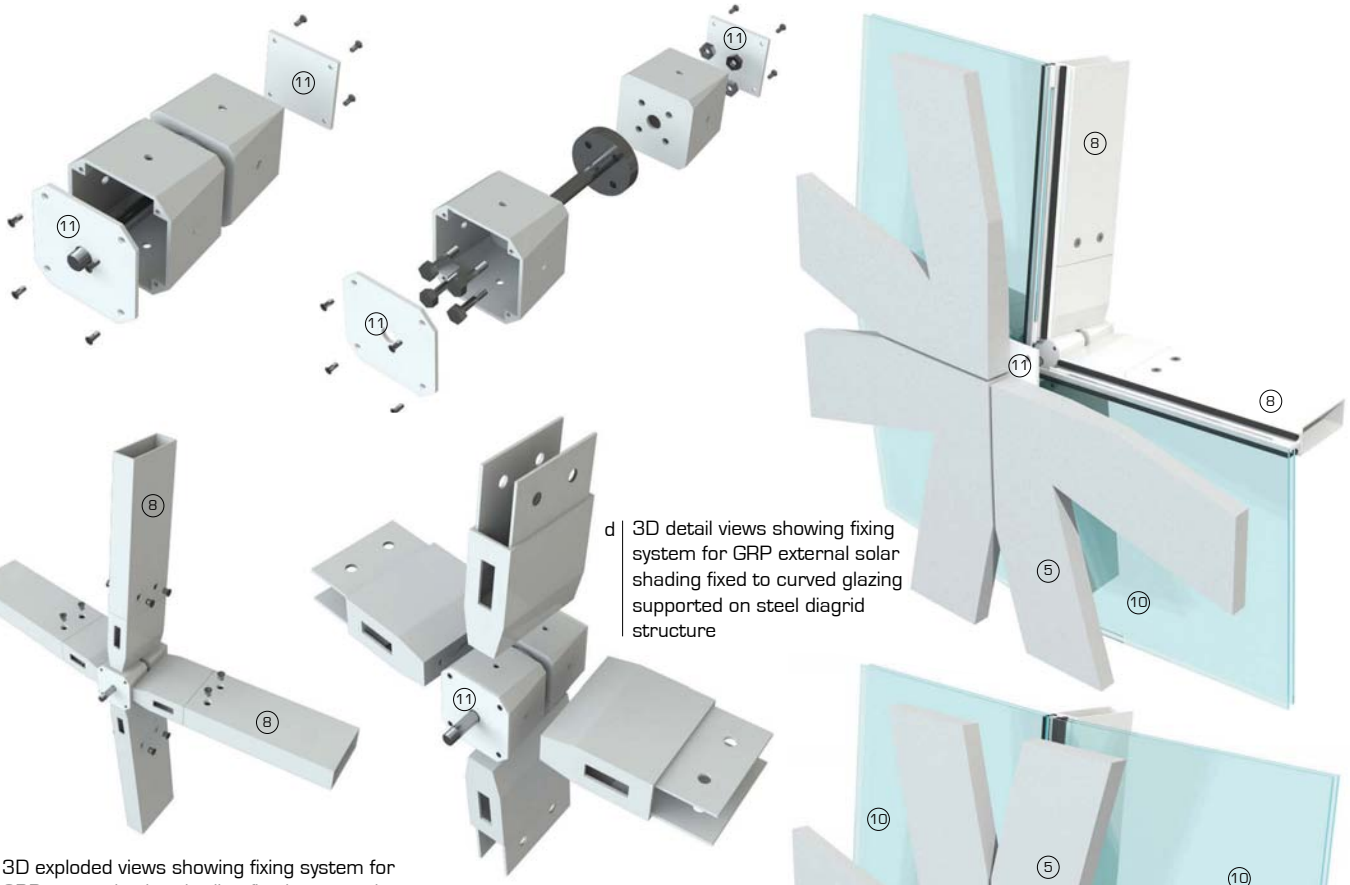
b | 3D detail view showing GRP external solar shading fixed to curved glazing supported on steel diagrid structure

Details

1	GRP rainscreen cladding
2	Thermal insulation
3	Primary steel tube structure
4	Internal finish
5	GRP external solar shading
6	Concrete floor slab
7	Concrete primary structure
8	Steel diagrid facade structure
9	Glazing frame
10	Double glazing
11	Fixing bracket

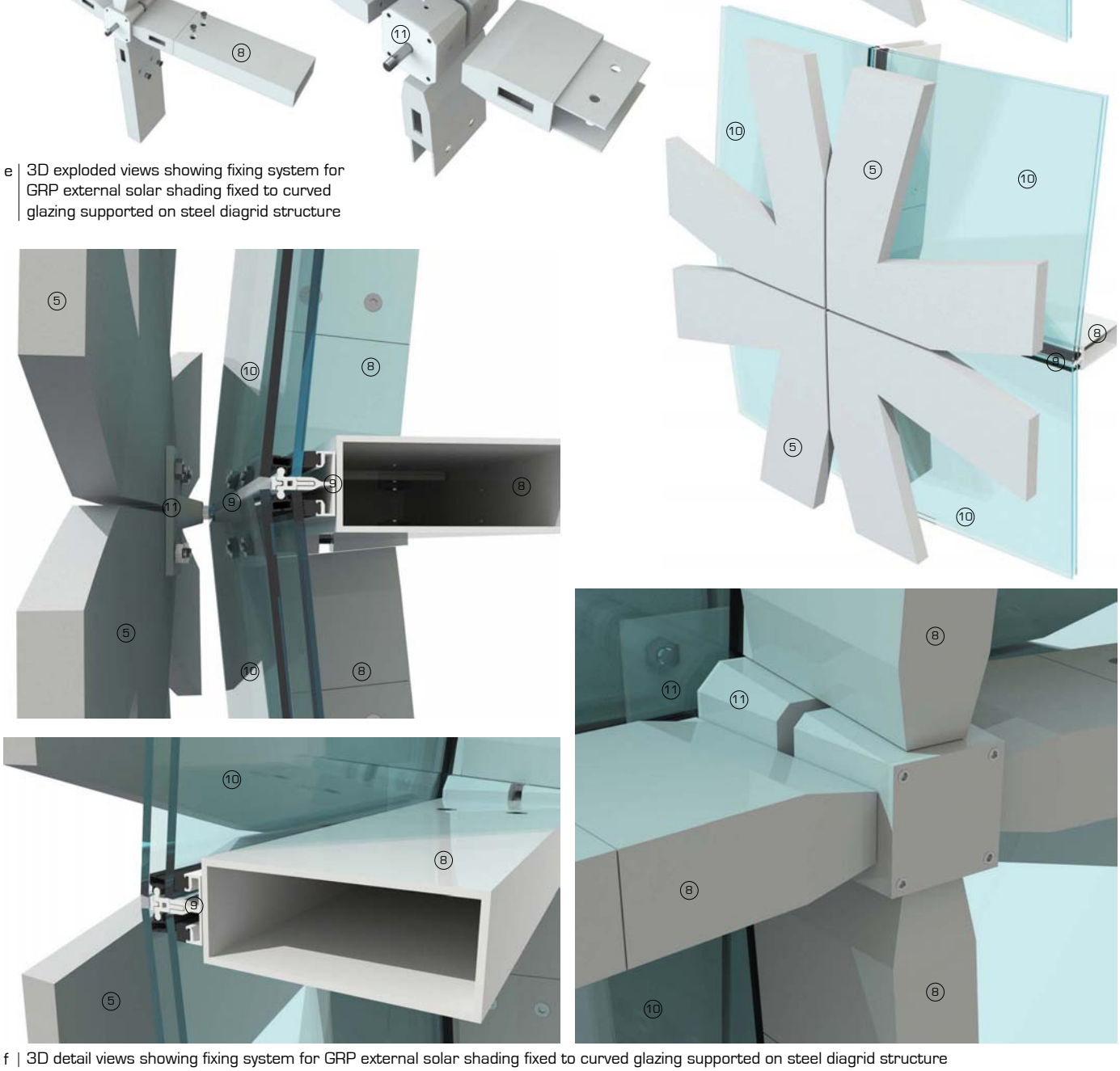


c | 3D exploded views showing GRP external solar shading fixed to curved glazing supported on steel diagrid structure



d | 3D detail views showing fixing system for GRP external solar shading fixed to curved glazing supported on steel diagrid structure

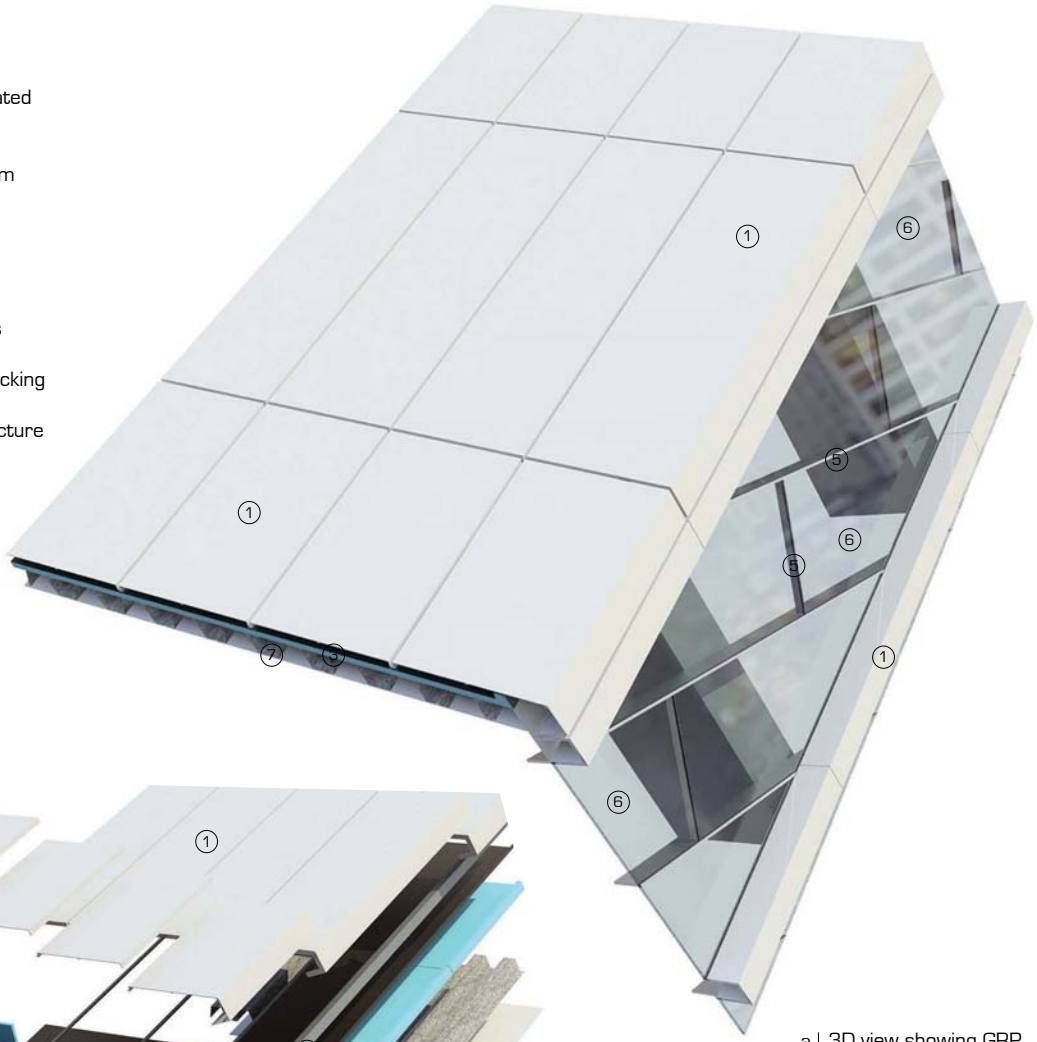
e | 3D exploded views showing fixing system for GRP external solar shading fixed to curved glazing supported on steel diagrid structure



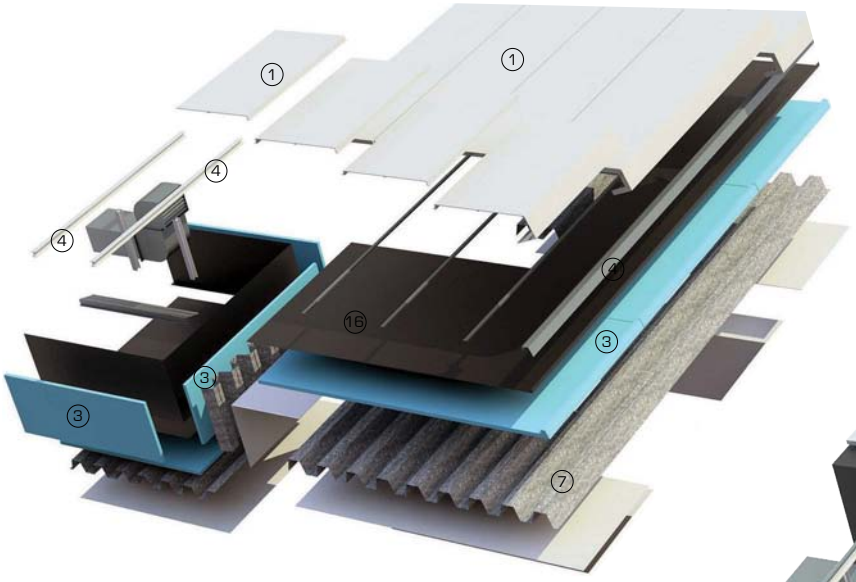
f | 3D detail views showing fixing system for GRP external solar shading fixed to curved glazing supported on steel diagrid structure

Details

1 GRC rainscreen cladding
2 Primary steel columns (insulated and faced)
3 Thermal insulation
4 Rainscreen panel fixing system
5 Glazing frame
6 Double glazing
7 Profiled metal deck
8 Steel tube secondary facade support structure
9 GRC external shading louvres
10 GRC terrace decking panels
11 Plastic spaces for terrace decking
12 Steel roof truss structure
13 Primary in-situ concrete structure
14 Internal finish
15 Gutter
16 Waterproof membrane



a | 3D view showing GRP rainscreen roof on profiled metal deck and interface with unitised glazing system

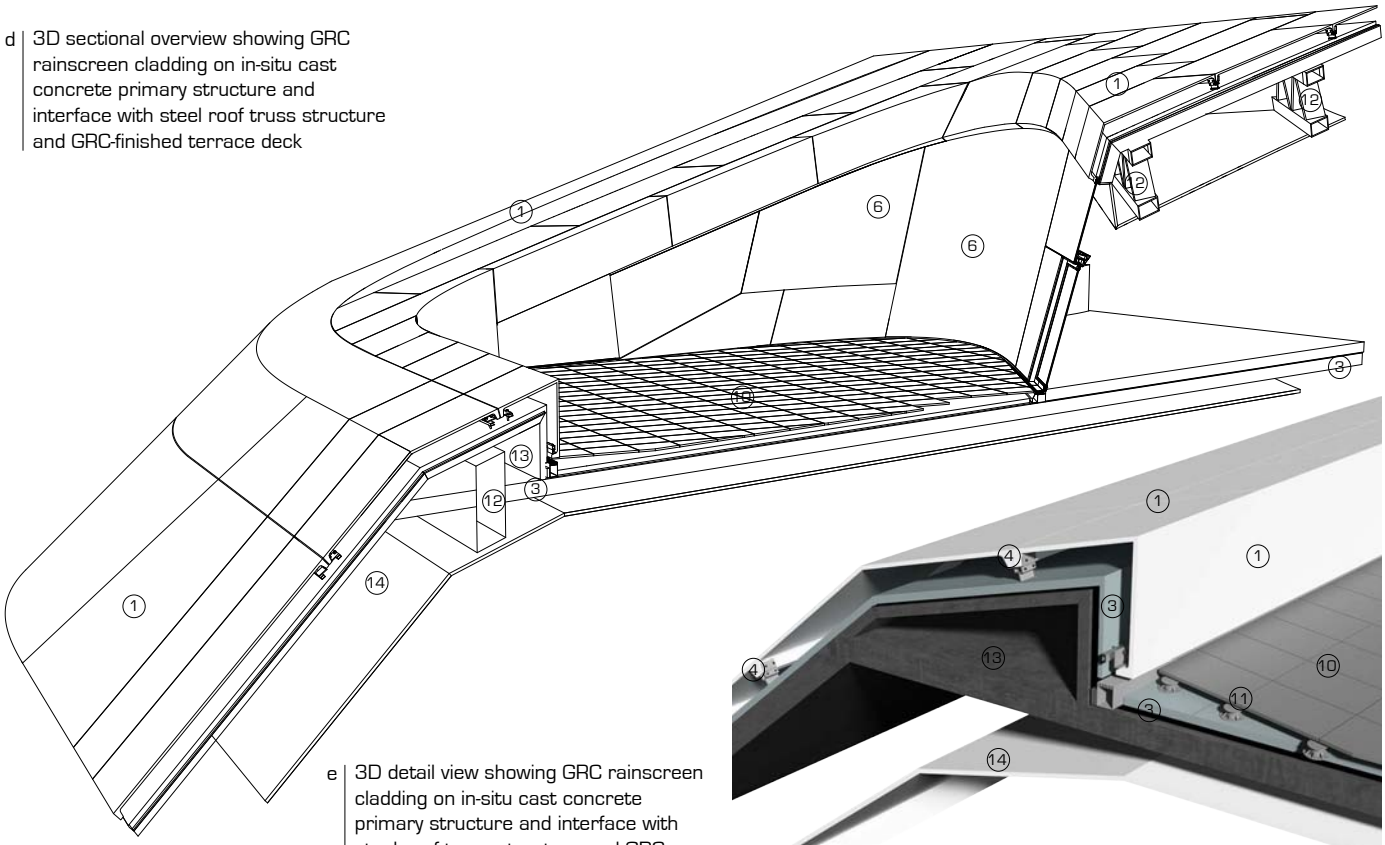


b | 3D exploded fragment view showing GRP rainscreen roof on profiled metal deck

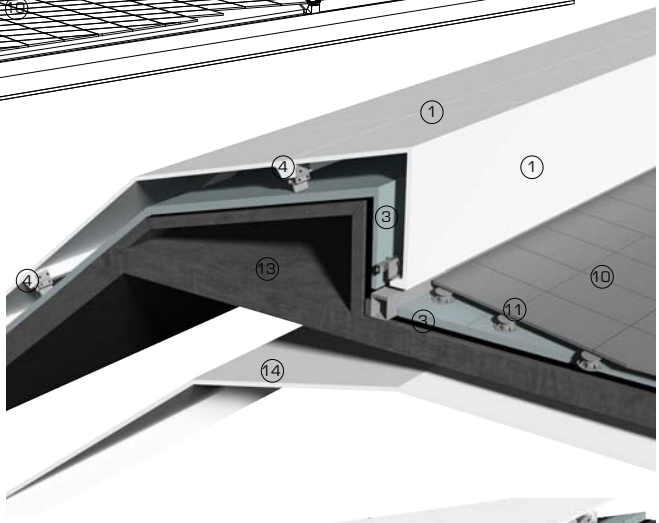


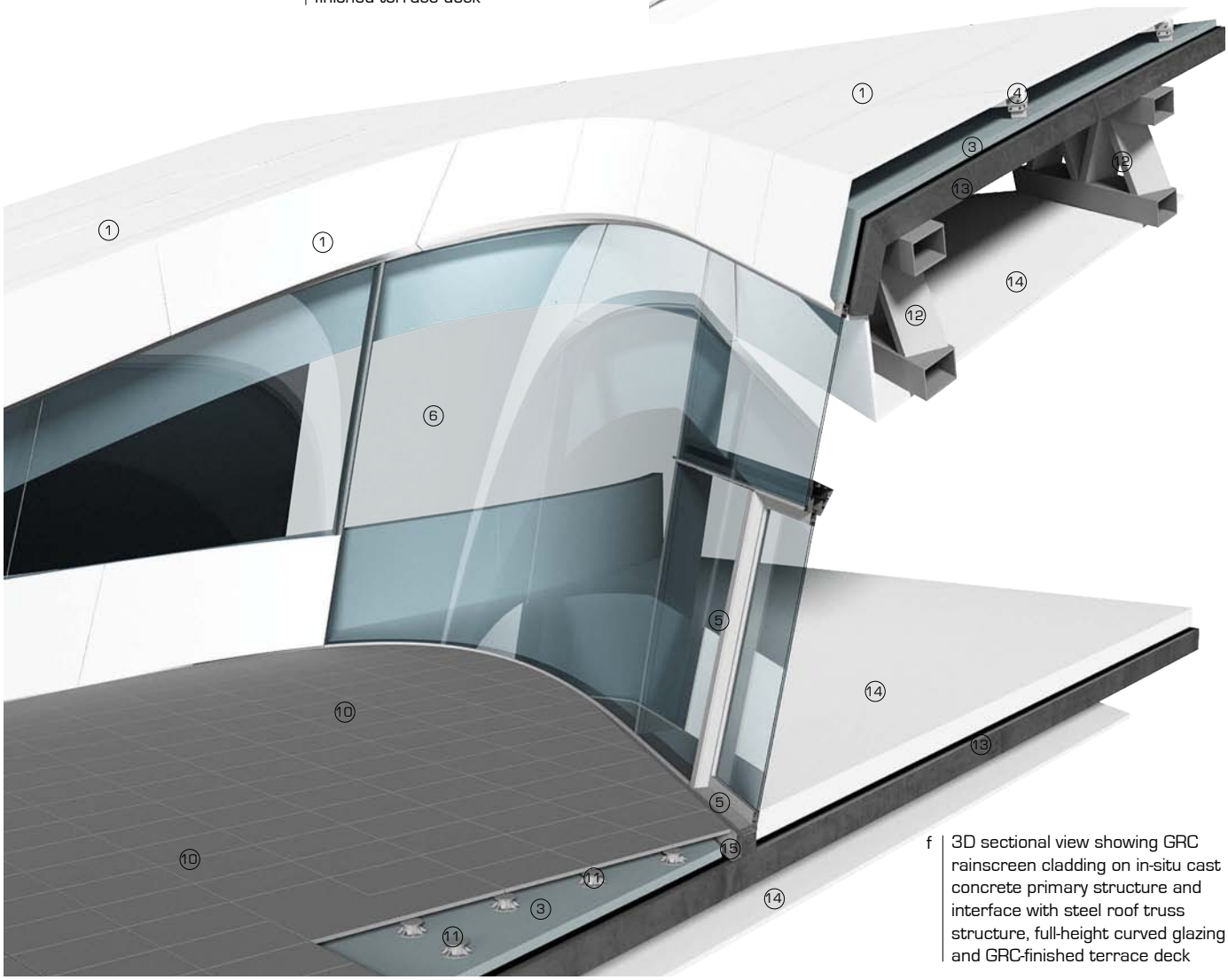
c | 3D cutaway views showing GRP rainscreen roof on profiled metal deck and interface with unitised glazing system

d | 3D sectional overview showing GRC rainscreen cladding on in-situ cast concrete primary structure and interface with steel roof truss structure and GRC-finished terrace deck

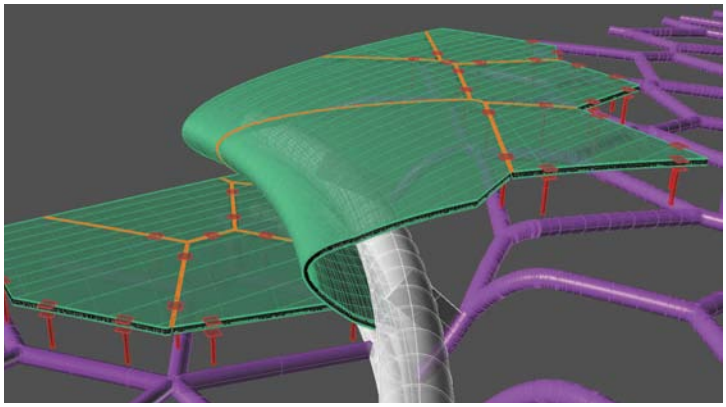


e | 3D detail view showing GRC rainscreen cladding on in-situ cast concrete primary structure and interface with steel roof truss structure and GRC-finished terrace deck

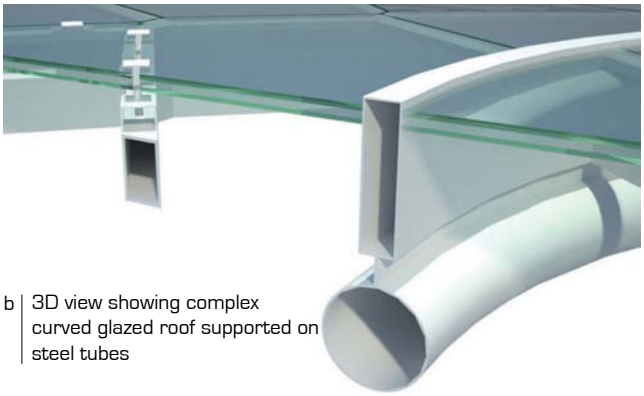




f | 3D sectional view showing GRC rainscreen cladding on in-situ cast concrete primary structure and interface with steel roof truss structure, full-height curved glazing and GRC-finished terrace deck

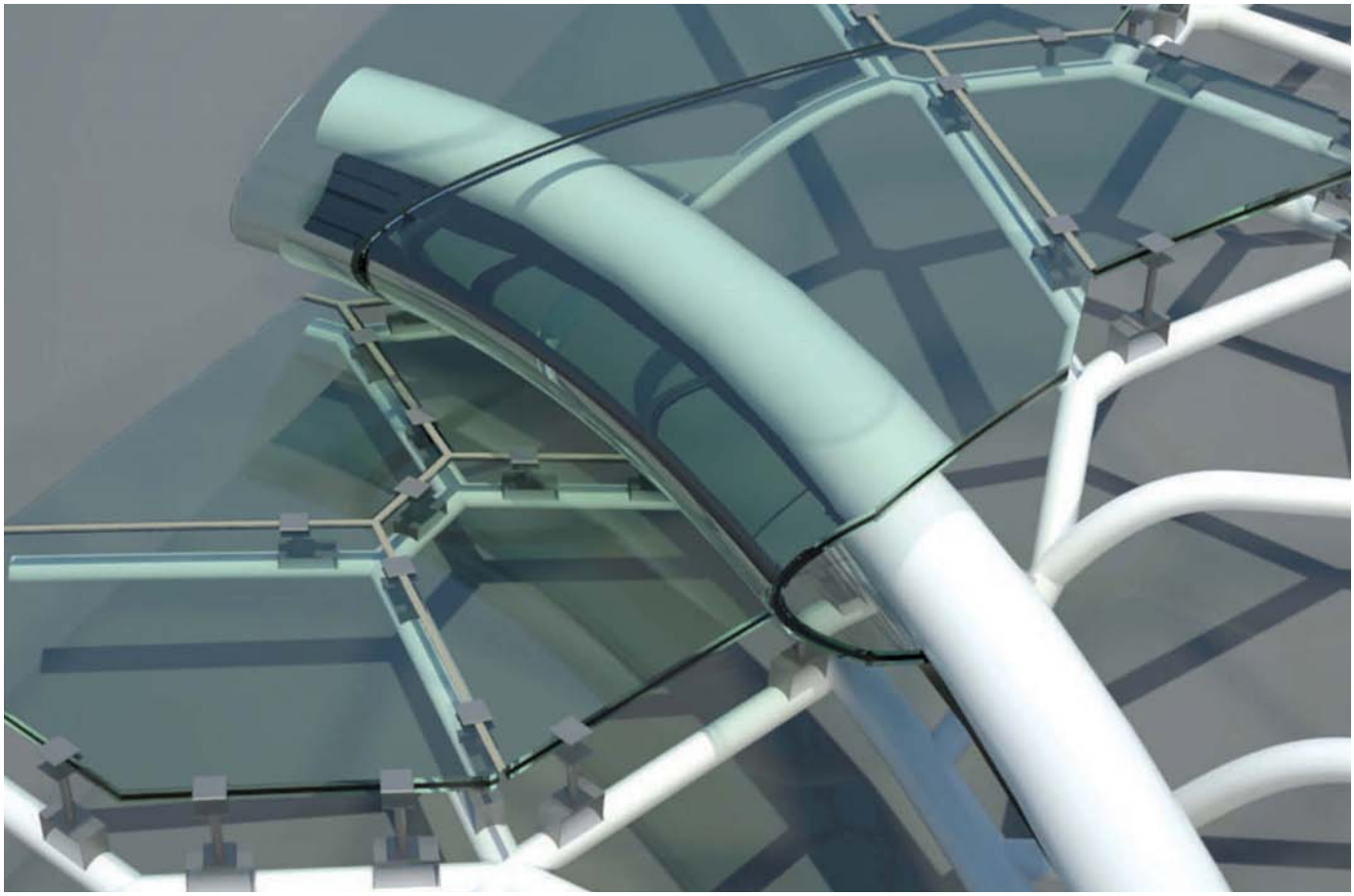


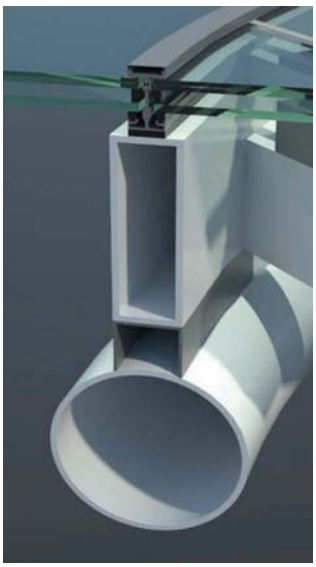
a | Working digital model of complex curved glazed facade and roof supported on steel tubes

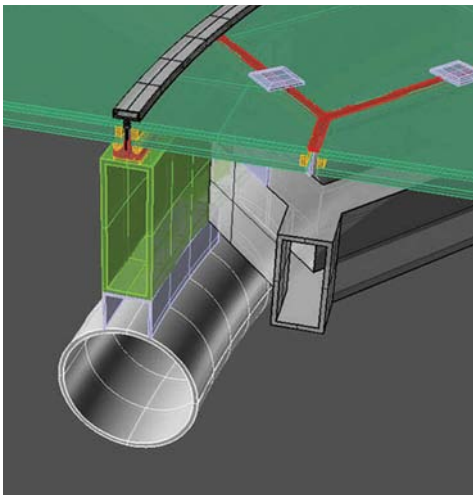


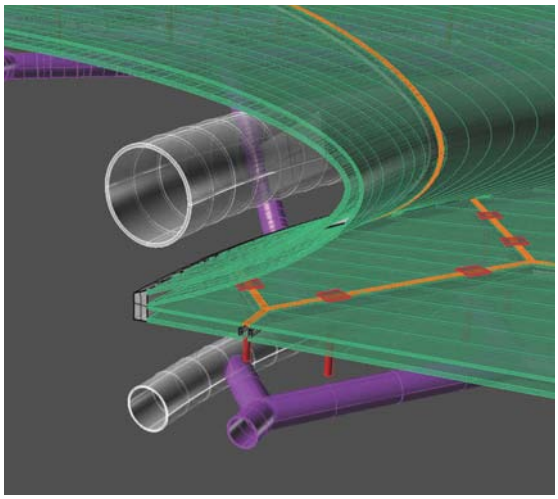
b | 3D view showing complex curved glazed roof supported on steel tubes

c | (Below) 3D view showing complex curved glazed facade and roof supported on steel tubes

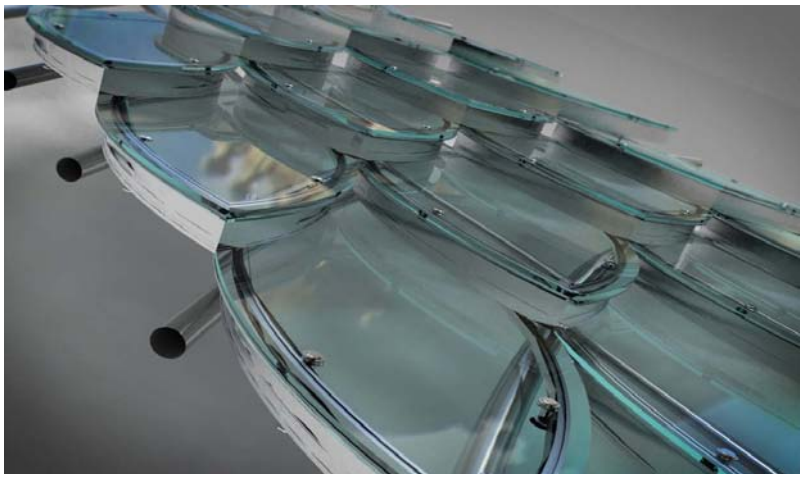


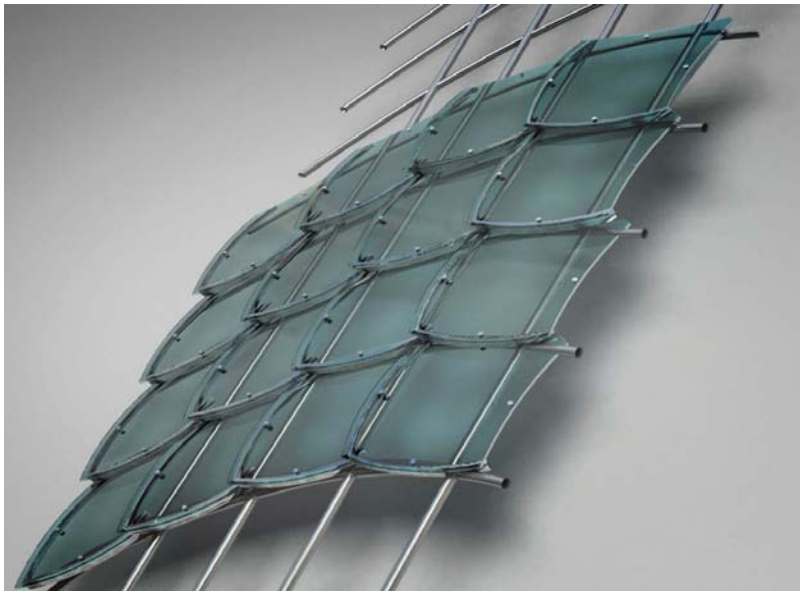




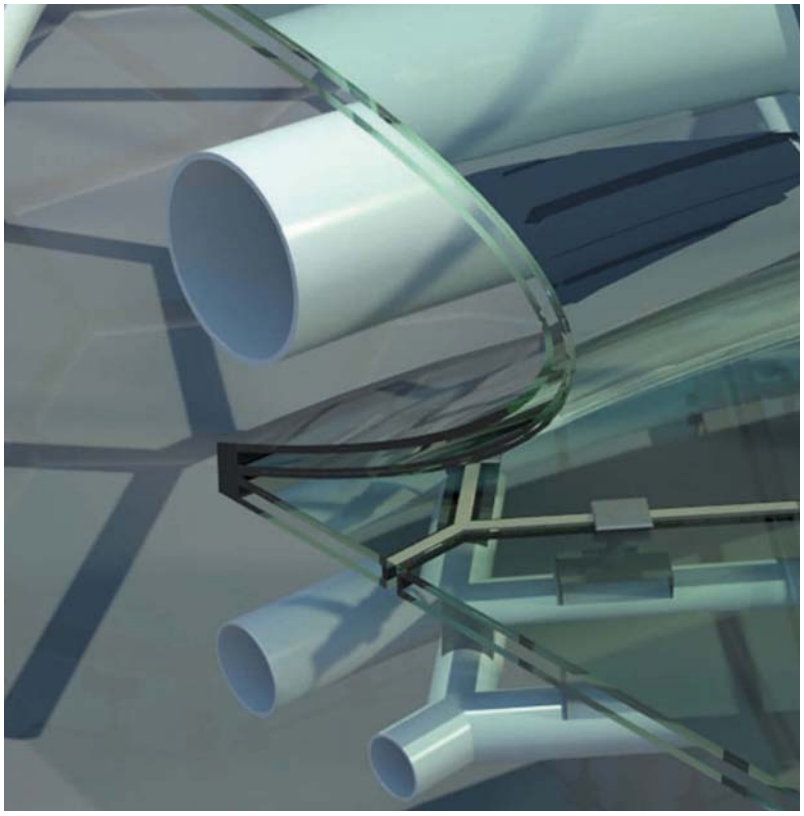


d | (Below right) 3D view showing complex curved glazed roof supported on steel tubes
(Below) Working digital models of complex curved glazed facade and roof supported on steel tubes





f | 3D views showing shingled glazing system supported on steel tubes



h | 3D views showing complex curved glazed roof supported on steel tubes



e | 3D view showing shingled glazing system supported on steel tubes



g | 3D physical scale model of shingled glazing system supported on steel tubes

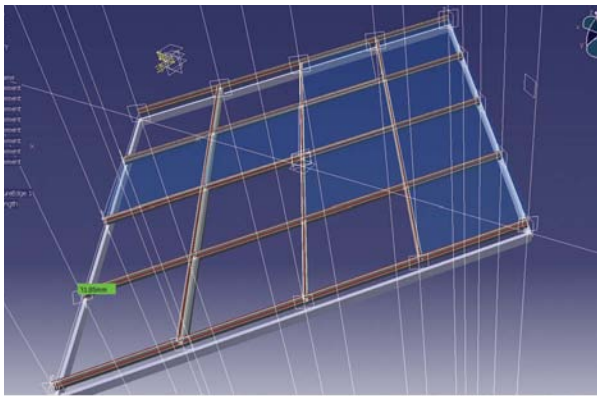




a | (Right) Working digital model of shingled glazing system supported on steel tubes

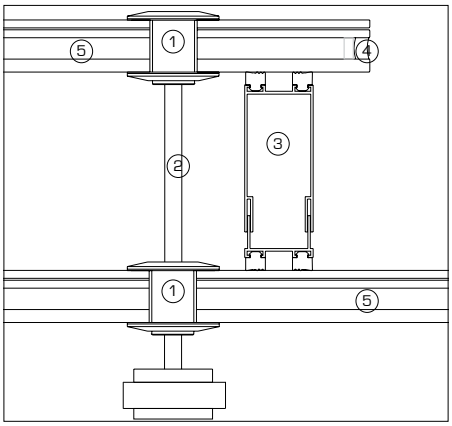


b | 3D views showing shingled glazing system supported on steel tubes

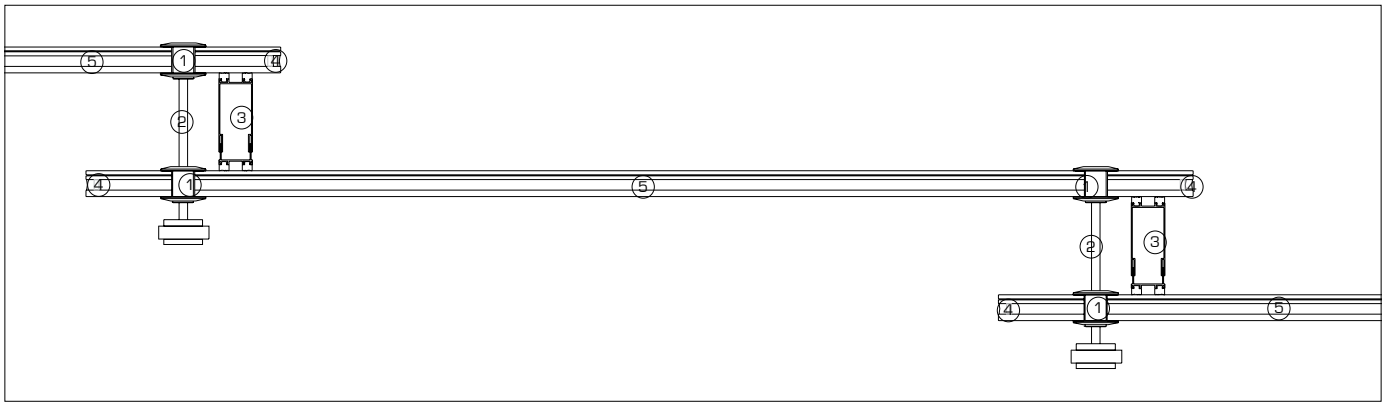


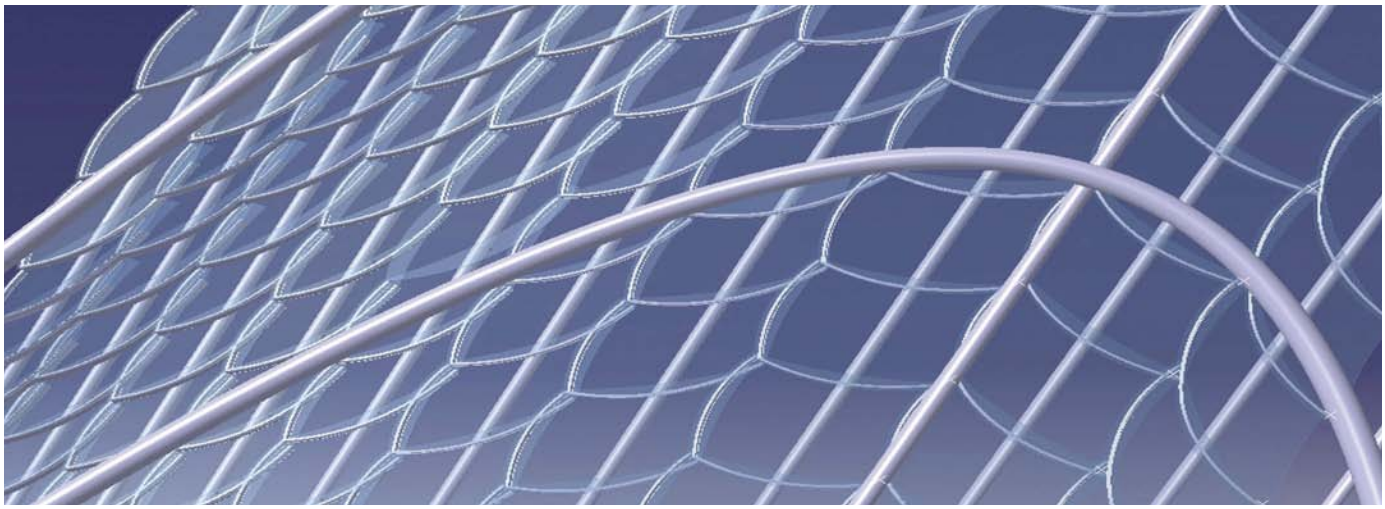
Details

1 | Bolt fixing
2 | Steel rod support system
3 | Steel box
4 | Rubber seal
5 | Double glazing

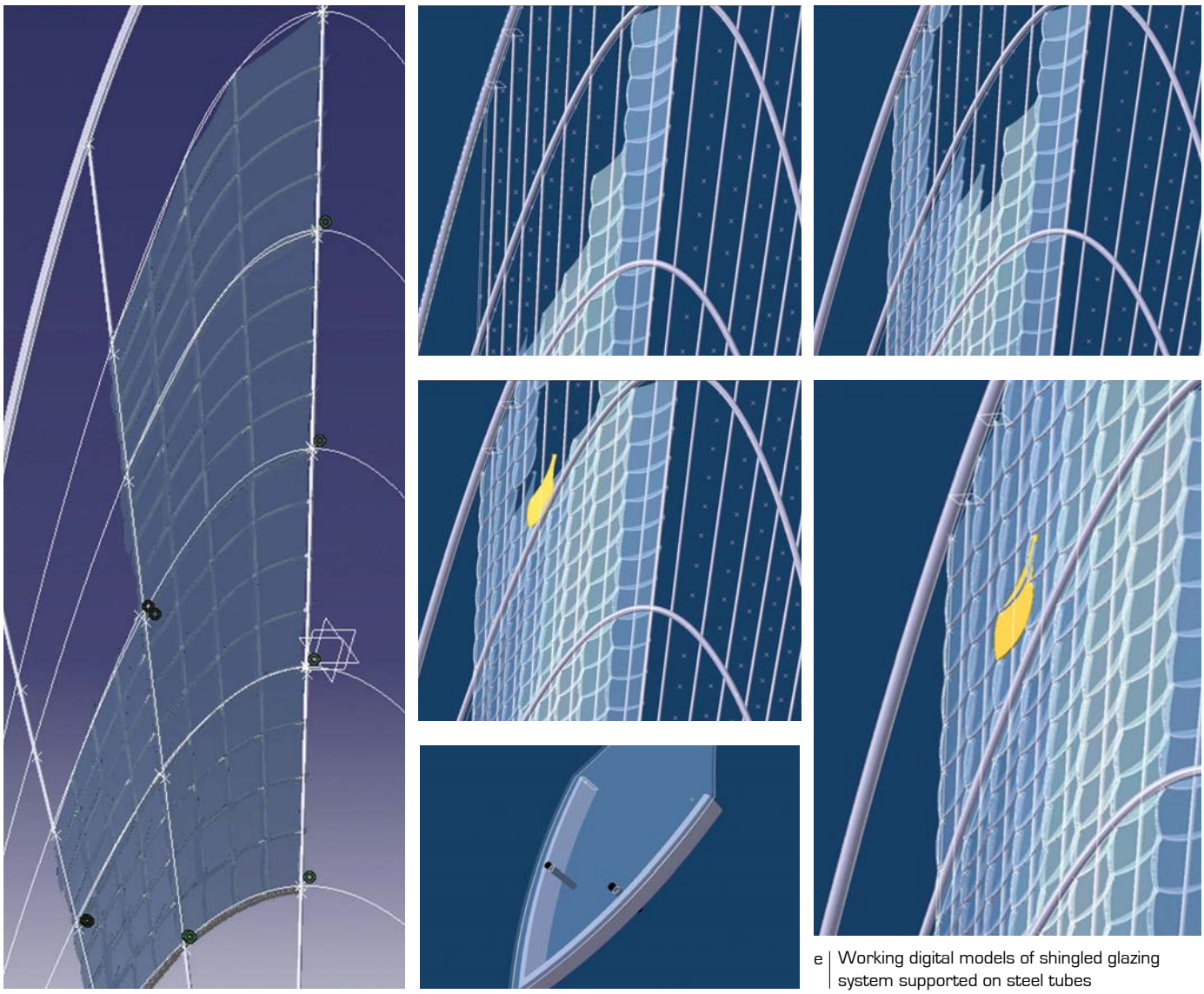


c | Vertical sections. Detail of shingled glazed roof fixing system

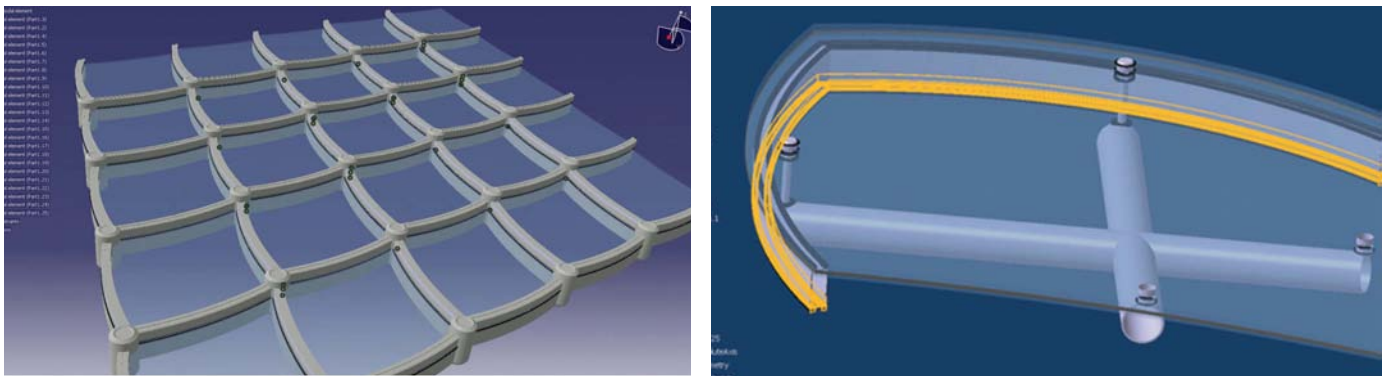


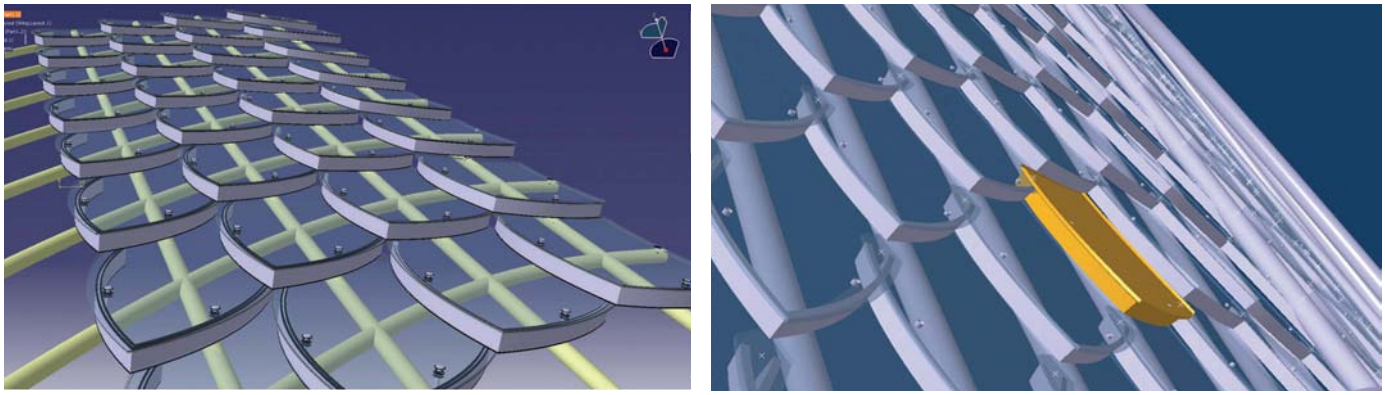


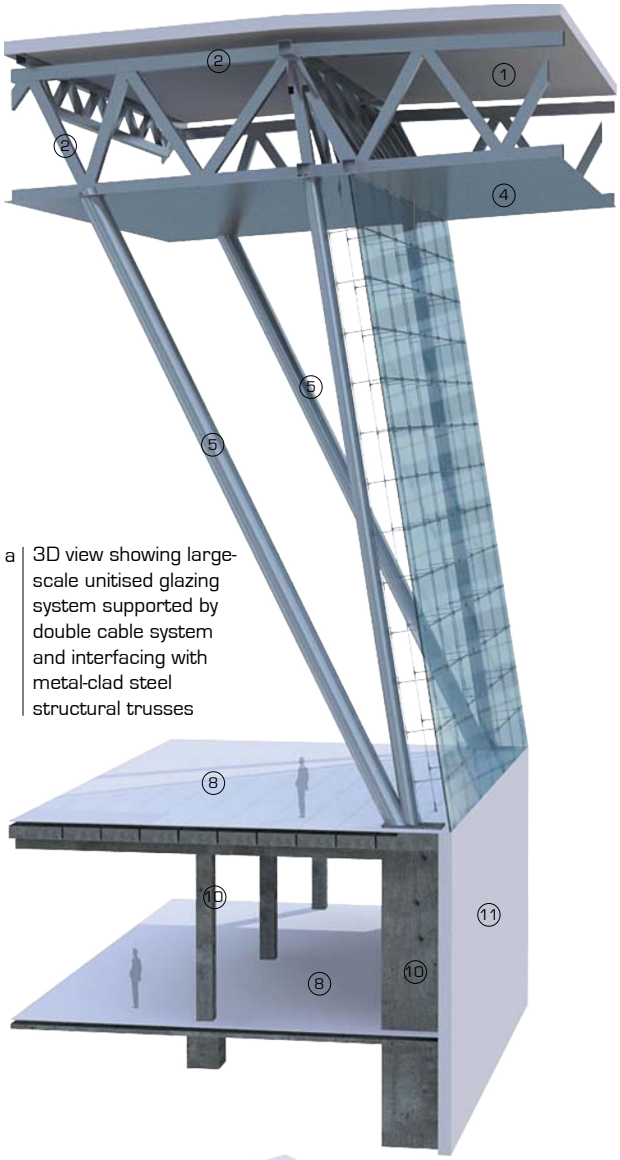
d | Working digital model of shingled glazing system supported on steel tubes



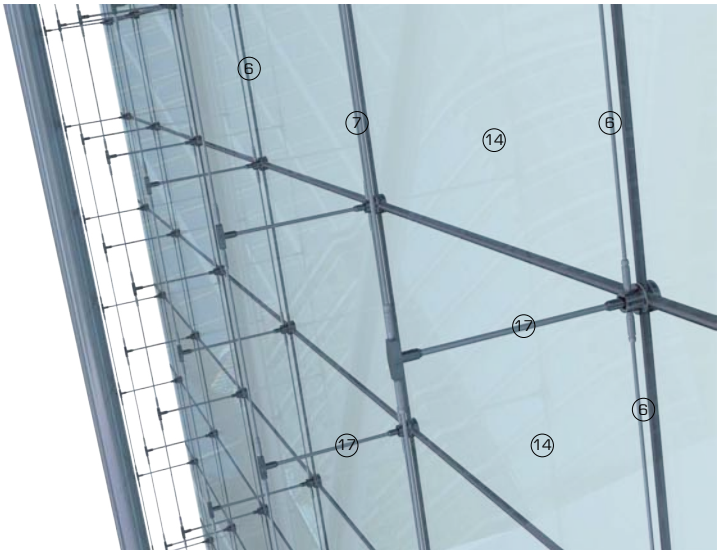
e | Working digital models of shingled glazing system supported on steel tubes





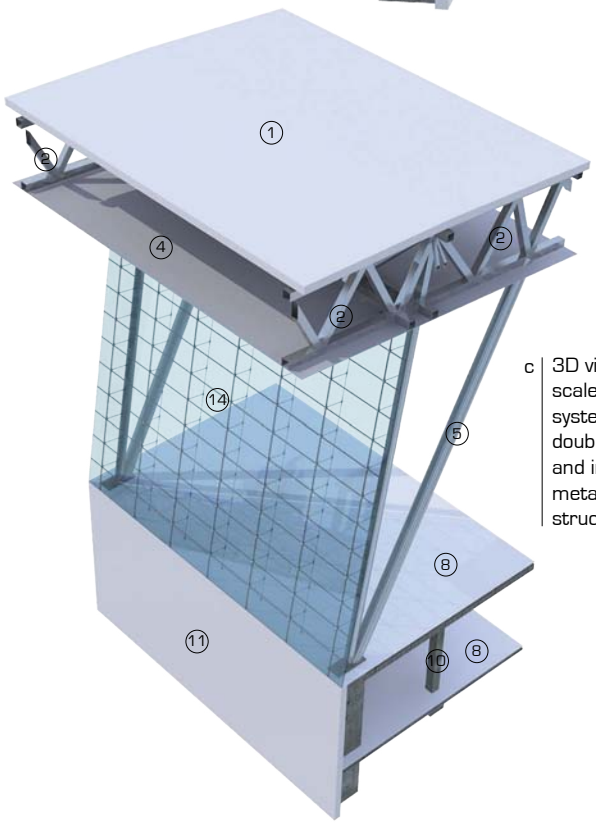


a | 3D view showing large-scale unitised glazing system supported by double cable system and interfacing with metal-clad steel structural trusses

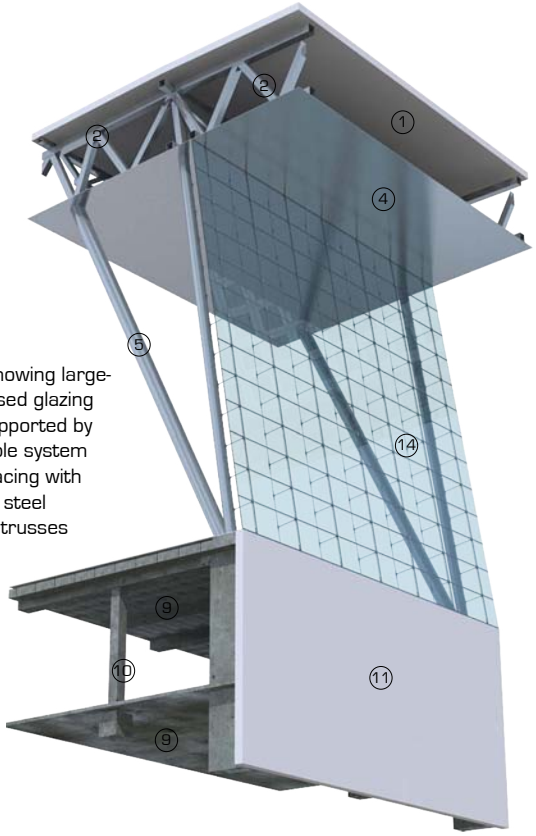




b | 3D detail views showing large-scale unitised glazing system supported by double cable system

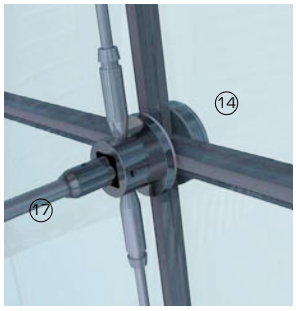


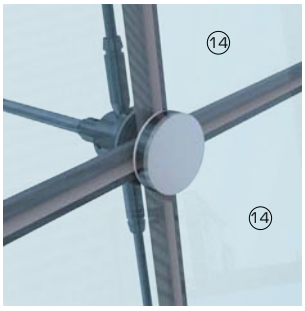
c | 3D view showing large-scale unitised glazing system supported by double cable system and interfacing with metal-clad steel structural trusses



Details

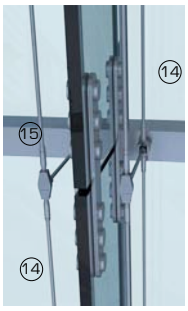
1	External roof cladding
2	Primary roof truss
3	Secondary steel truss
4	Soffit panel
5	Inclined steel column
6	Inner cable
7	Outer cable
8	Internal floor finish
9	Floor slab
10	Concrete primary structure
11	External wall cladding
12	Glass fin
13	Double glass fin
14	Double glazing
15	Horizontal glazing frame
16	Steel clamp
17	Steel support rod





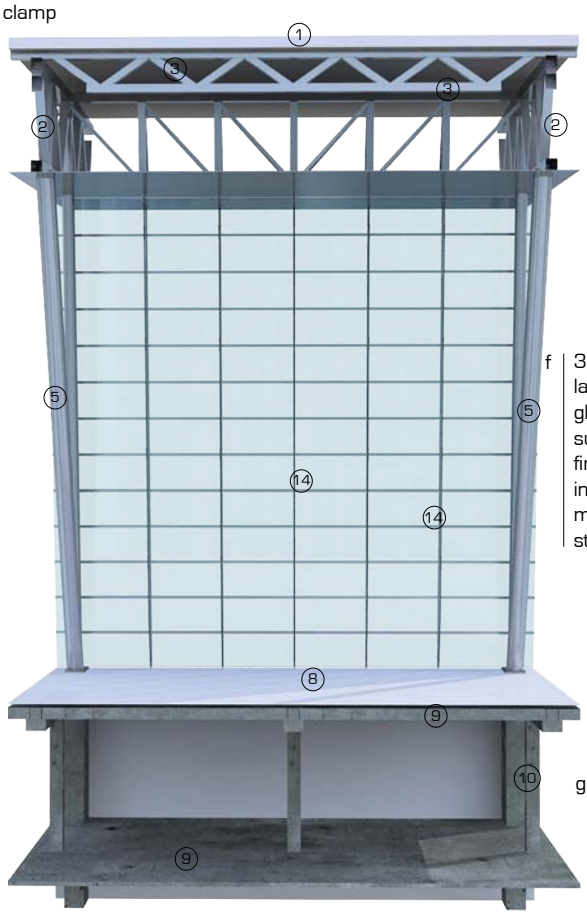




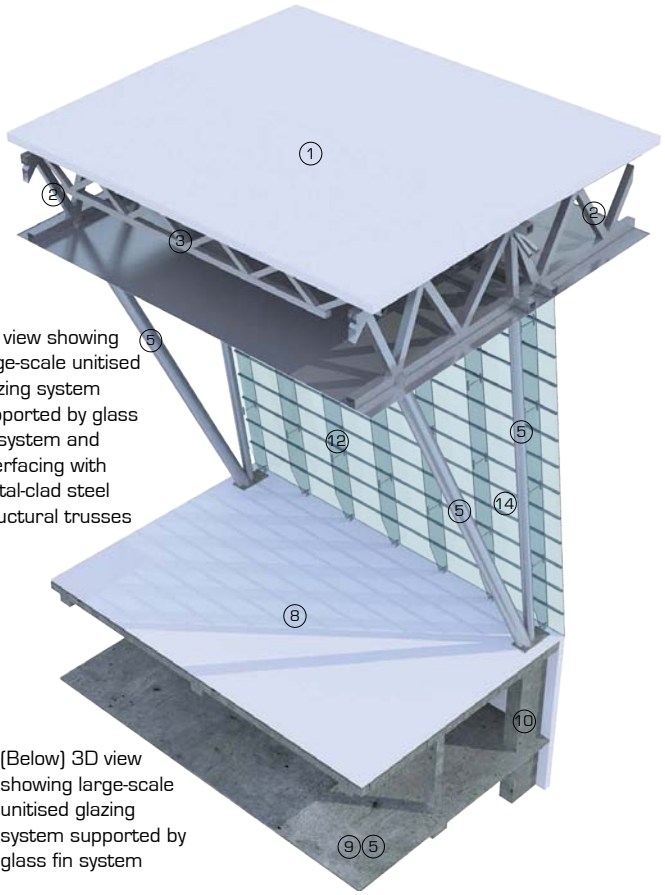


d | 3D detail views showing cable-supported glazing system at glass clamp

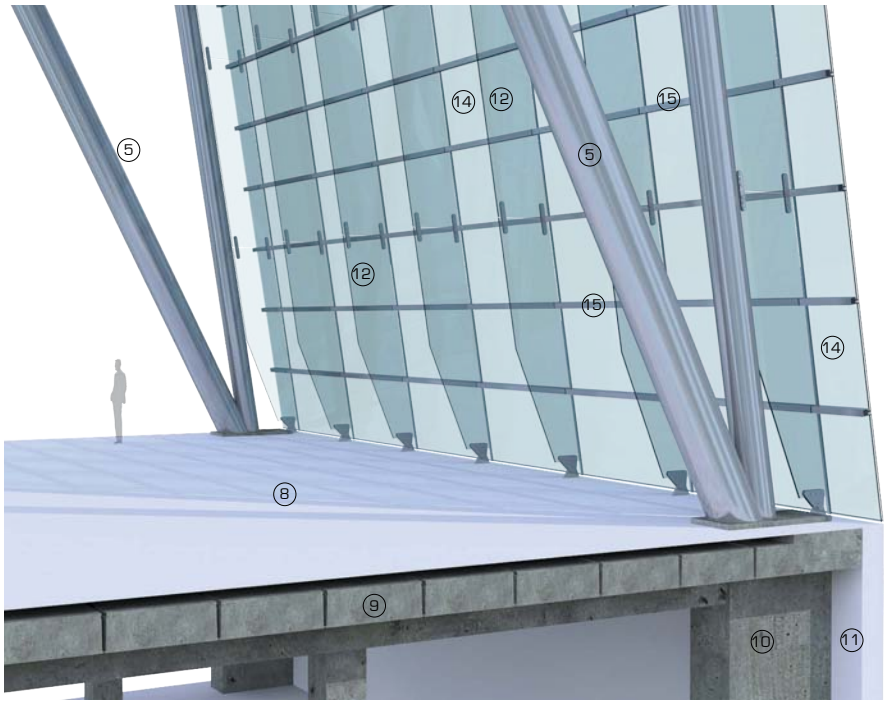
e | 3D detail views showing glass fin-supported glazing system in various configurations



f | 3D view showing large-scale unitised glazing system supported by glass fin system and interfacing with metal-clad steel structural trusses



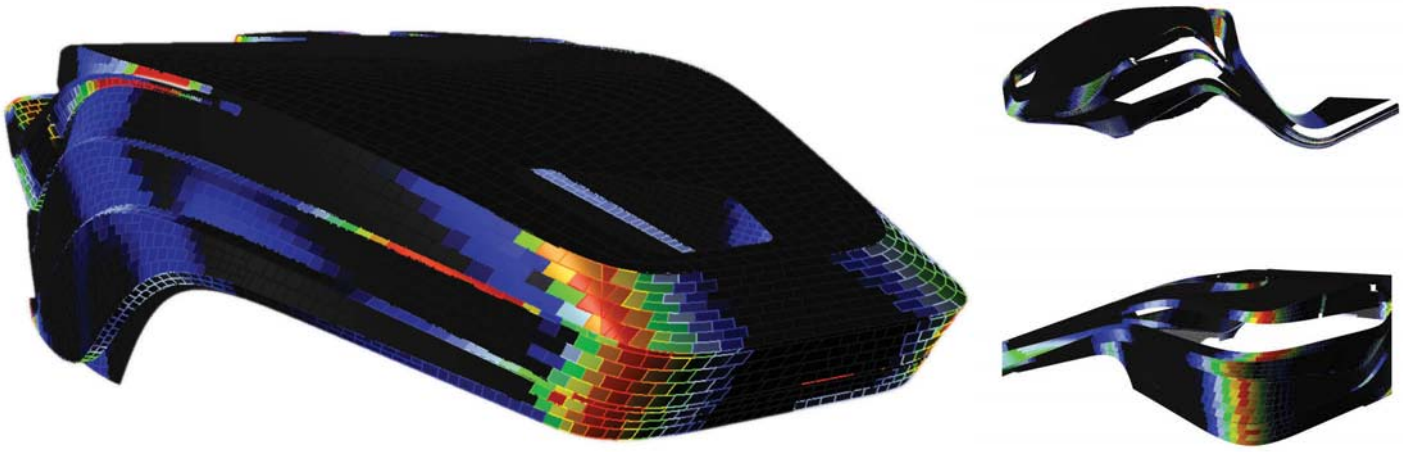
g | (Below) 3D view showing large-scale unitised glazing system supported by glass fin system



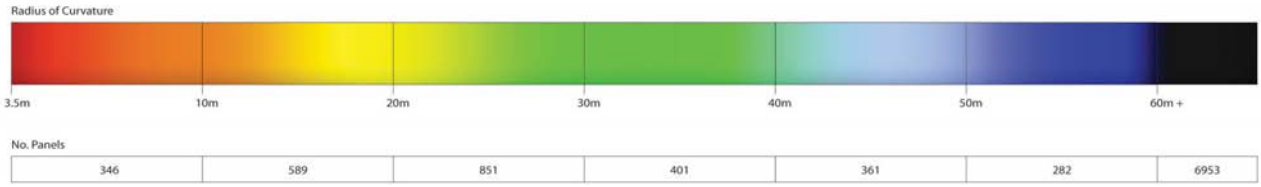


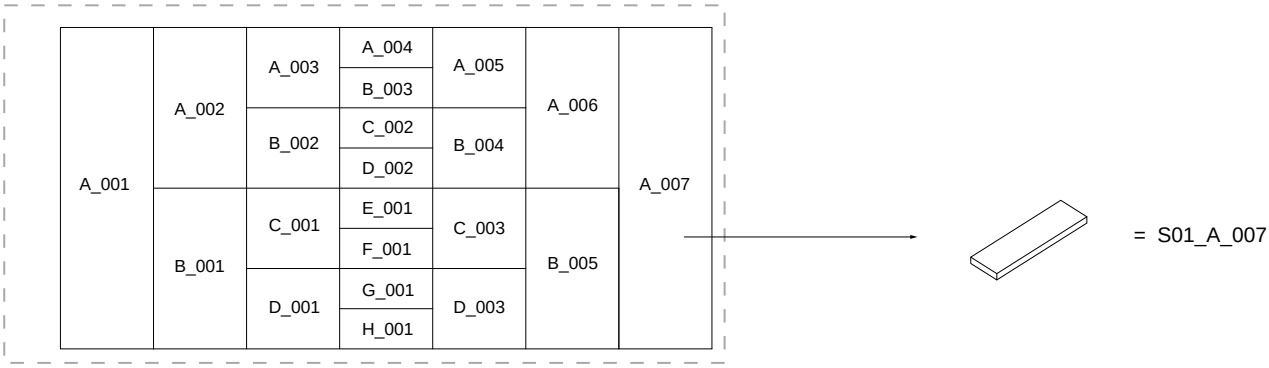


h | 3D view showing large-scale unitised glazing system supported by glass fin and double cable hybrid system

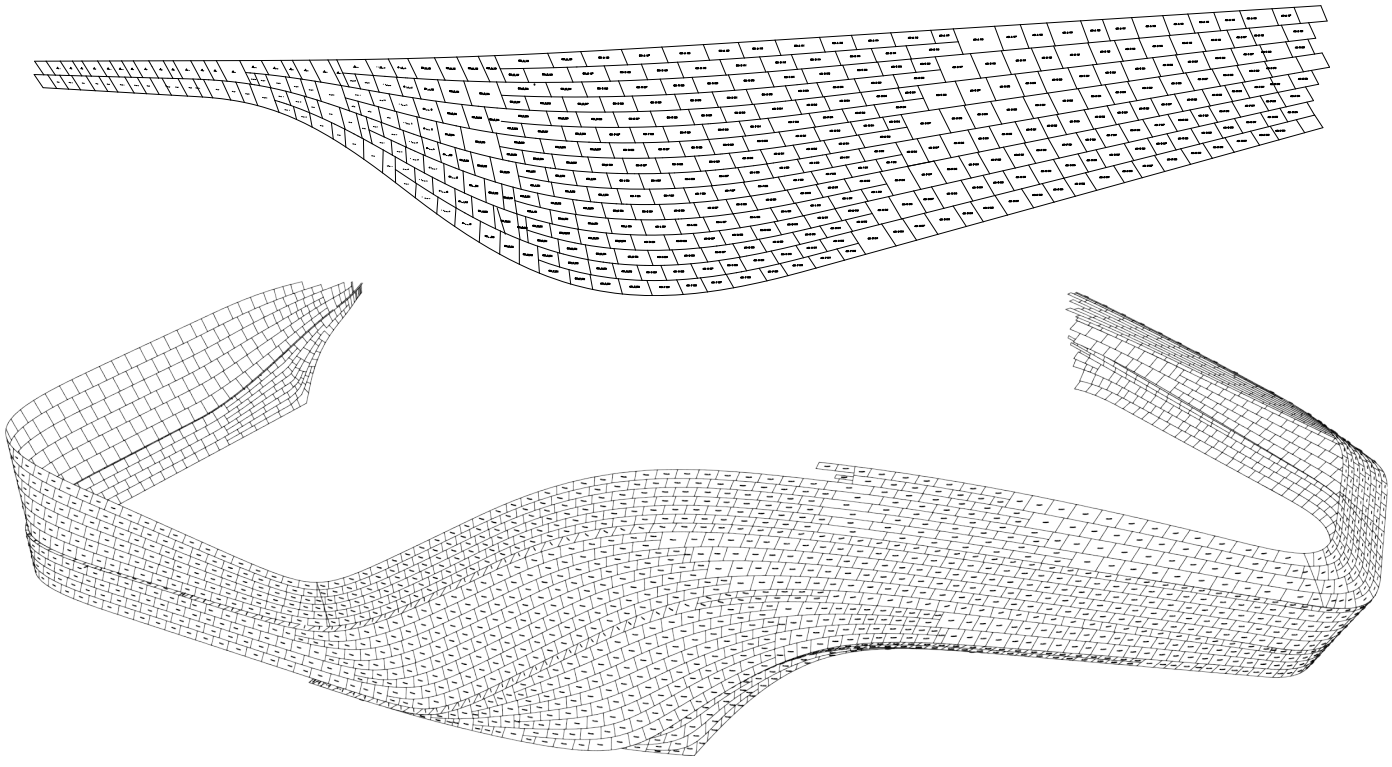


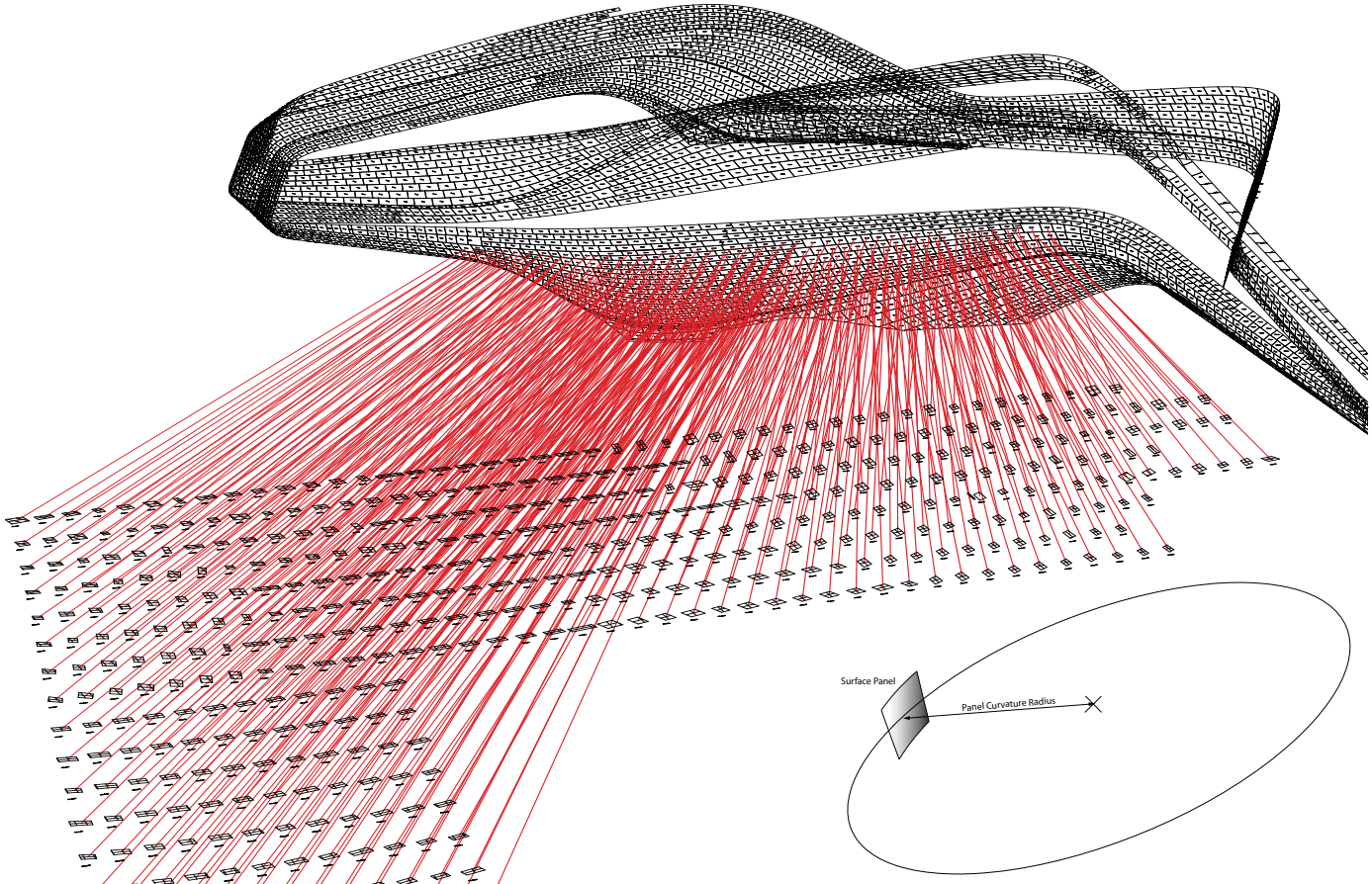
a | 3D views showing curvature analysis of individual panels model for facade of complex geometry



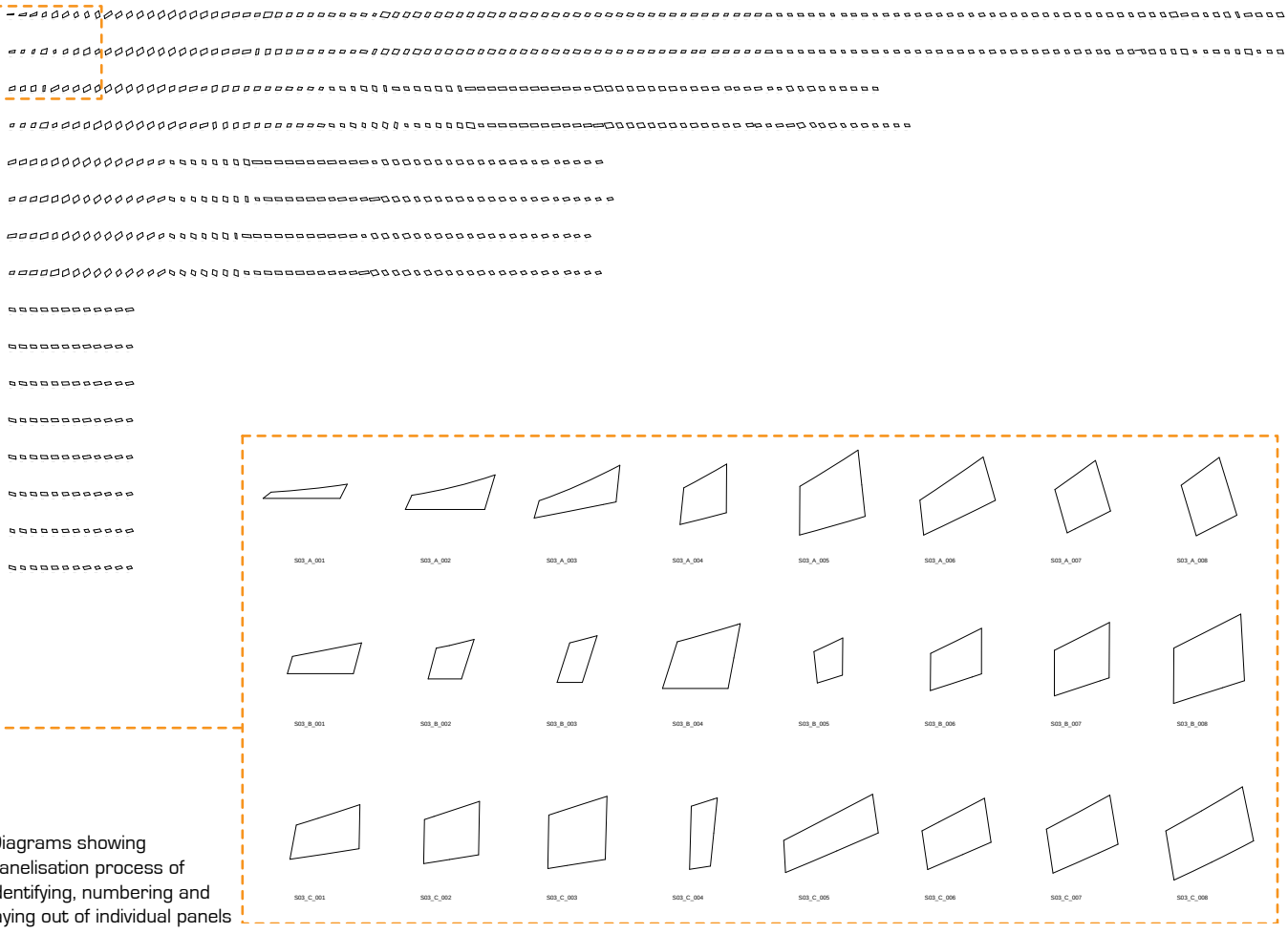


b | Diagrams showing panelisation process of identifying and numbering individual cladding panels

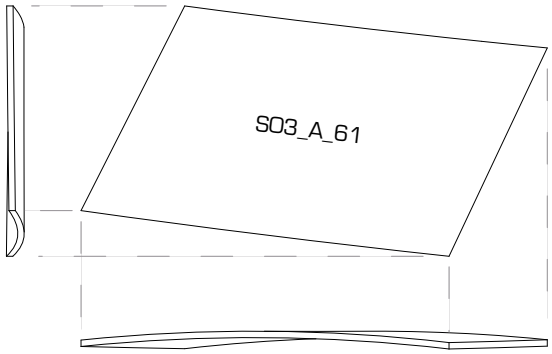


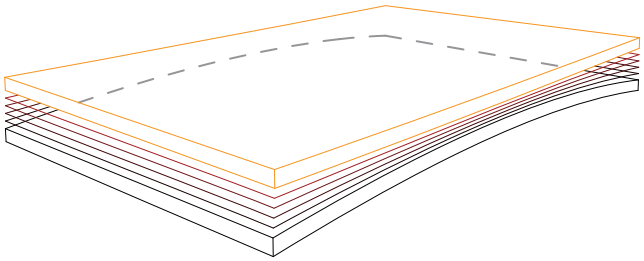


c | Diagrams showing panelisation process of identifying and numbering individual panels

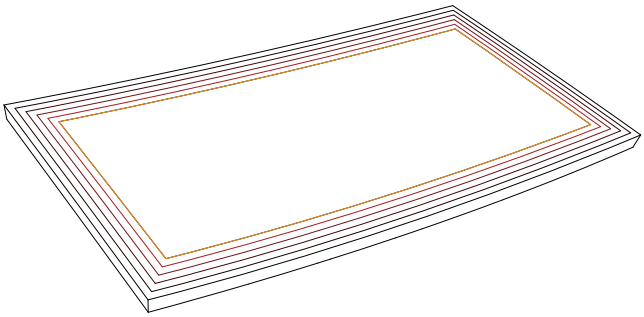


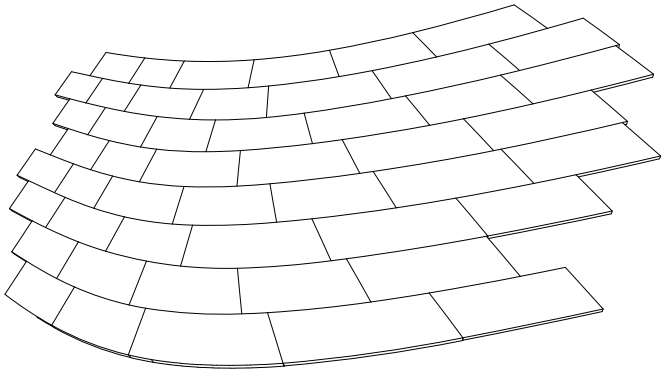
d | Diagrams showing panelisation process of identifying, numbering and laying out of individual panels

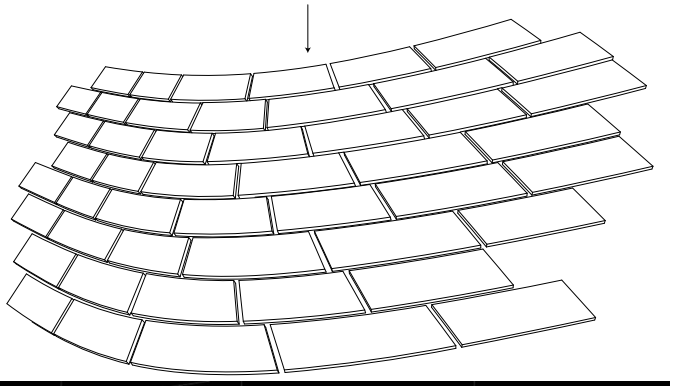




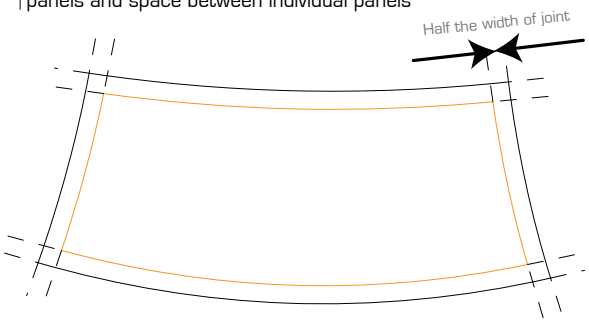
Geometry is unrolled to a flat surface so it can be bent into the mould for fabrication

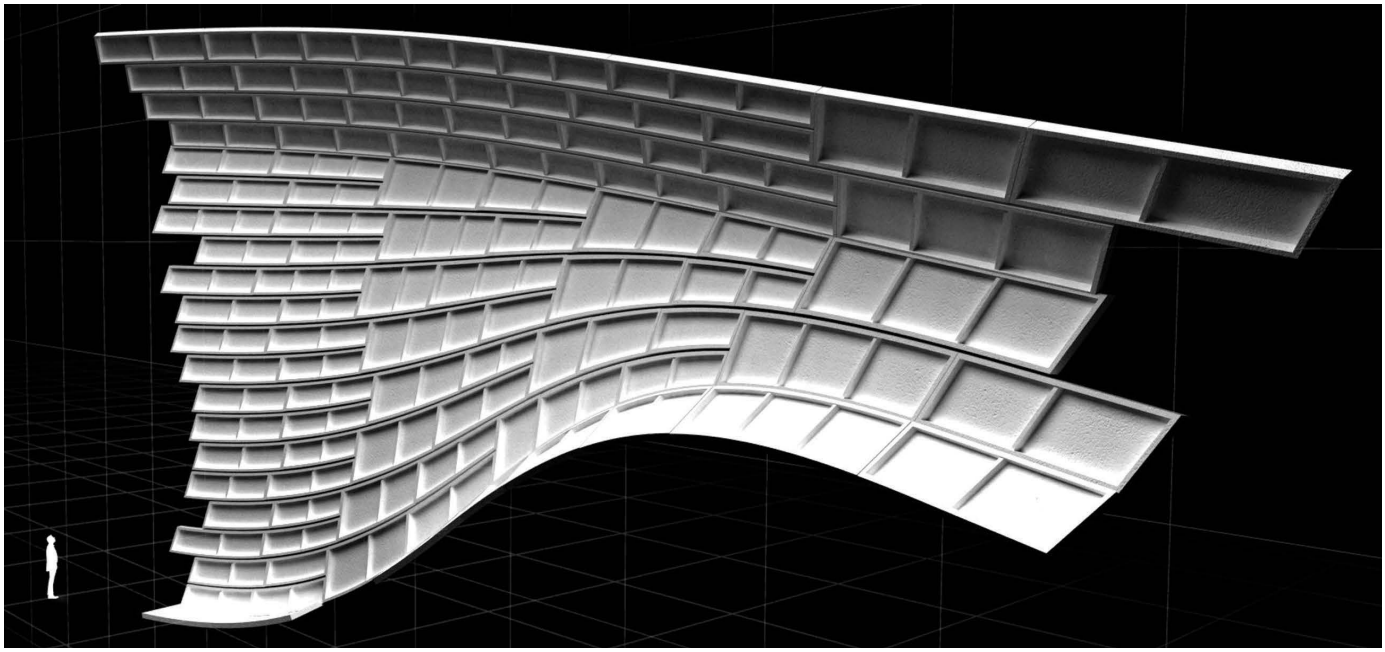




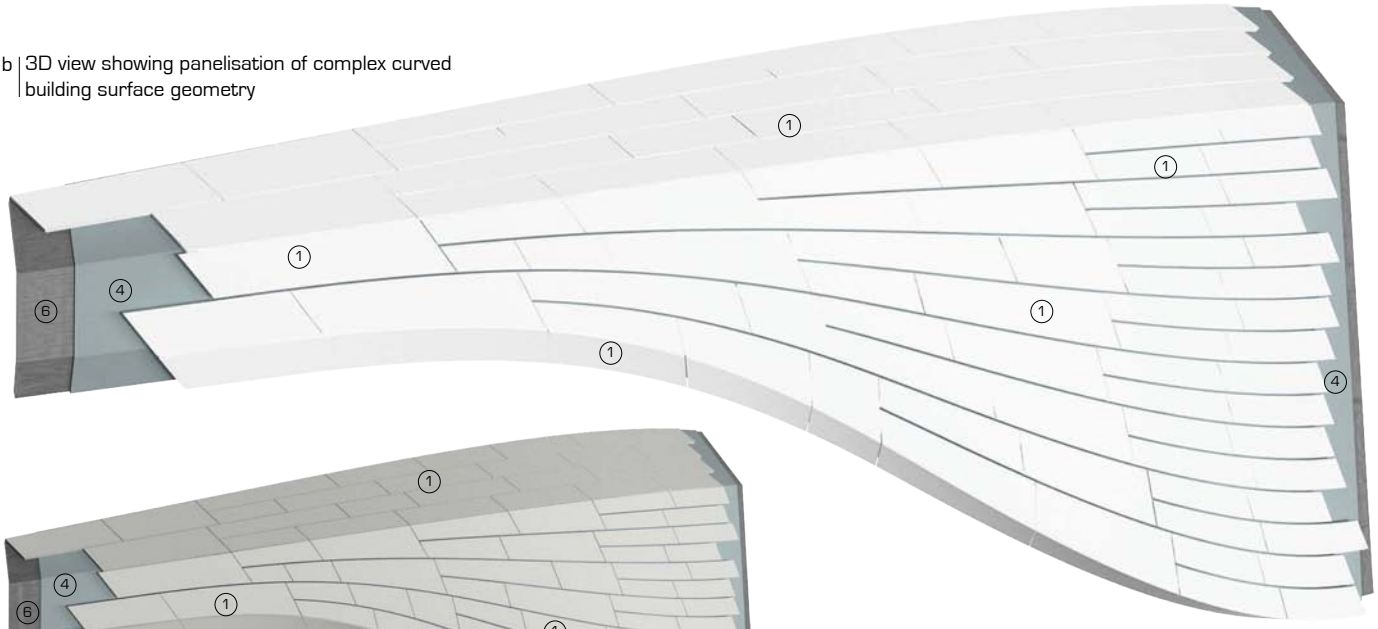


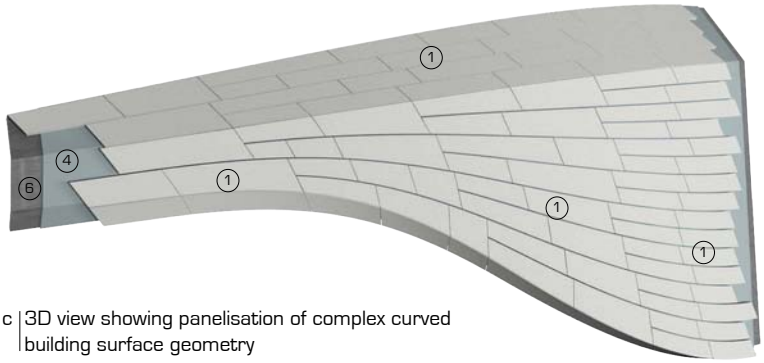
a | Diagrams showing panelisation process of identifying, numbering and laying out individual panels and space between individual panels



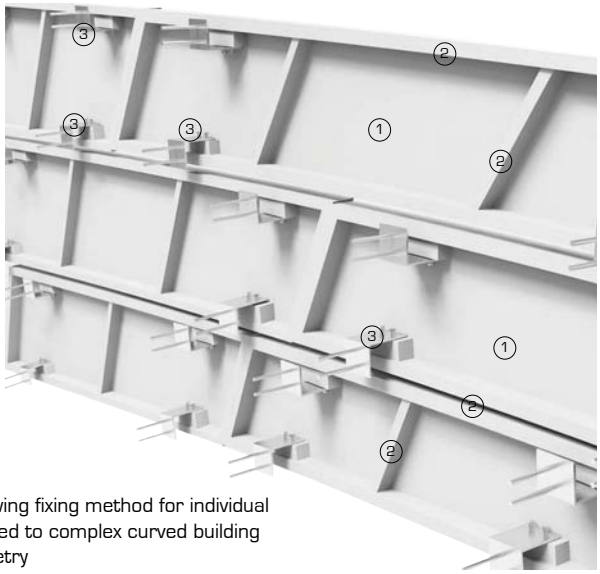


b | 3D view showing panelisation of complex curved building surface geometry

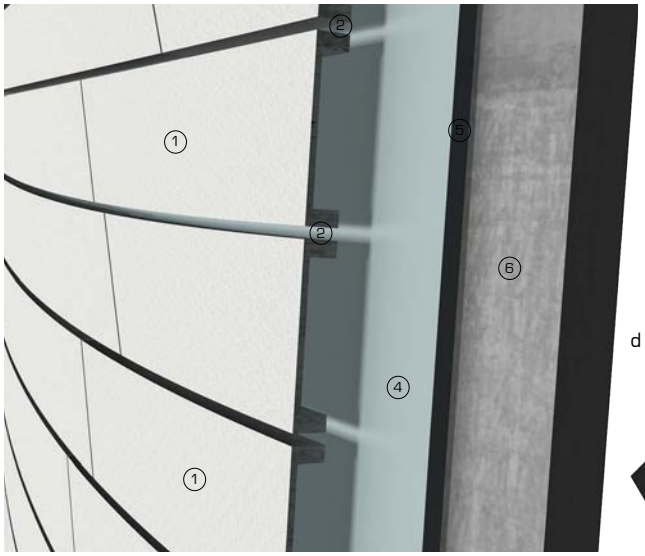


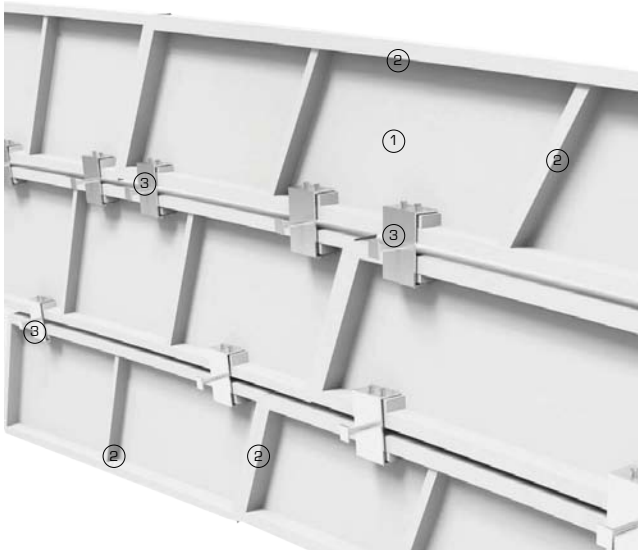


c | 3D view showing panelisation of complex curved building surface geometry

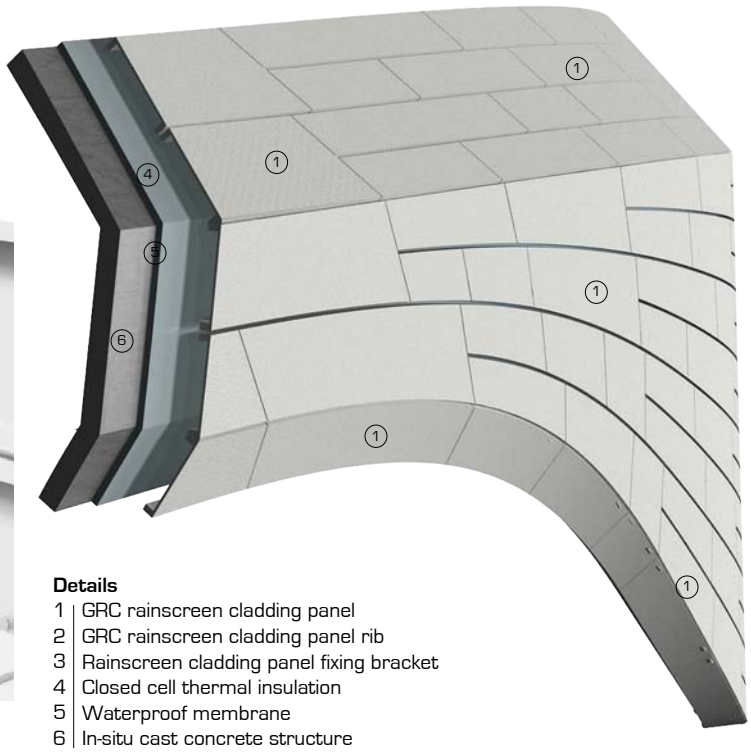


d | 3D views showing fixing method for individual GRC panels fixed to complex curved building surface geometry



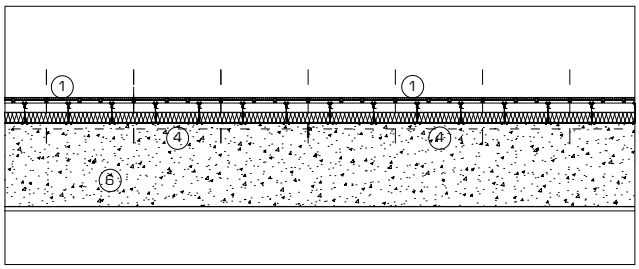


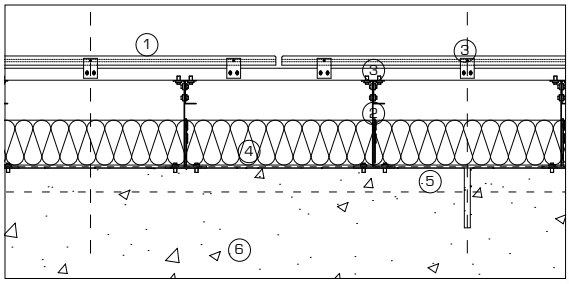
e | 3D view showing panelisation of complex curved building surface geometry



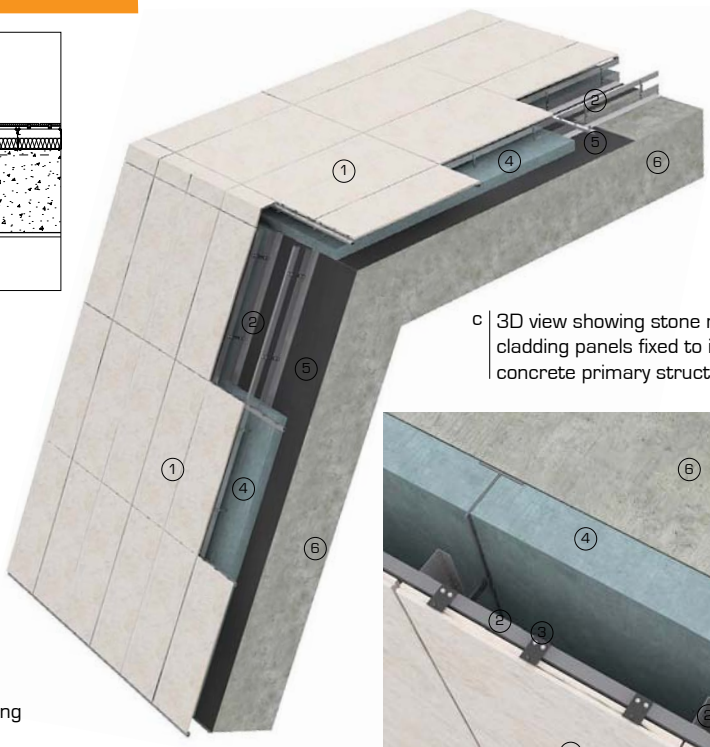
Details

1 | GRC rainscreen cladding panel
2 | GRC rainscreen cladding panel rib
3 | Rainscreen cladding panel fixing bracket
4 | Closed cell thermal insulation
5 | Waterproof membrane
6 | In-situ cast concrete structure





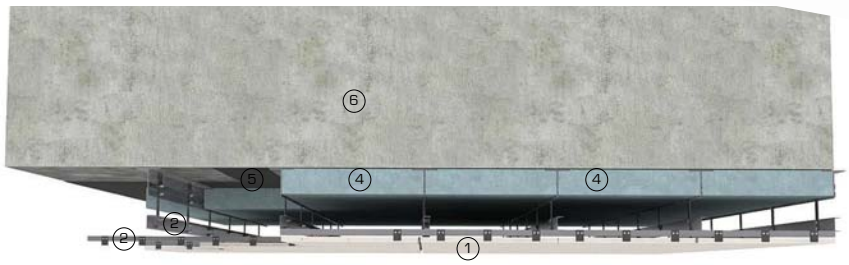
a | Vertical section. Stone rainscreen cladding panels fixed to in-situ cast concrete primary structure



c | 3D view showing stone rainscreen cladding panels fixed to in-situ cast concrete primary structure



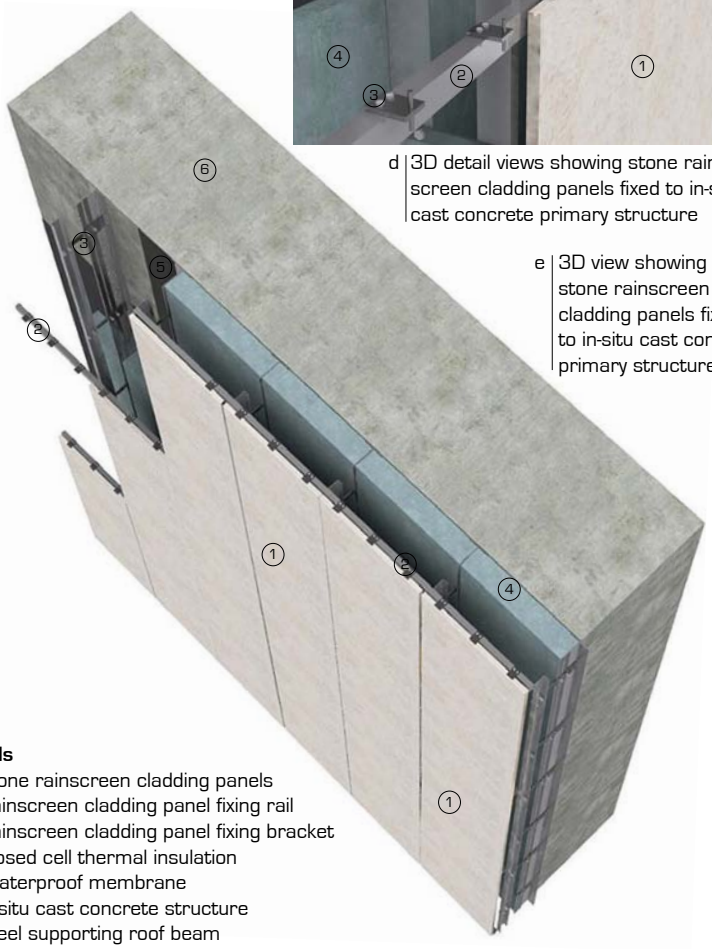
b | (Below) 3D detail views showing stone rainscreen cladding panels fixed to in-situ cast concrete primary structure





d | 3D detail views showing stone rainscreen cladding panels fixed to in-situ cast concrete primary structure



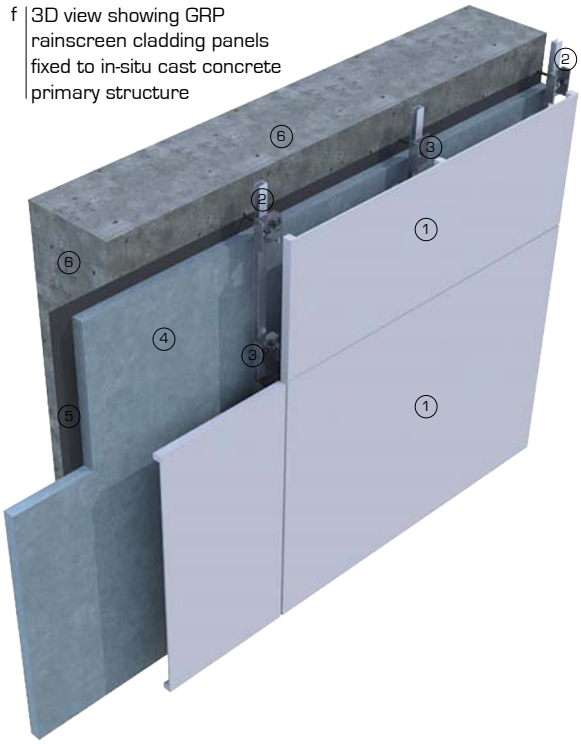


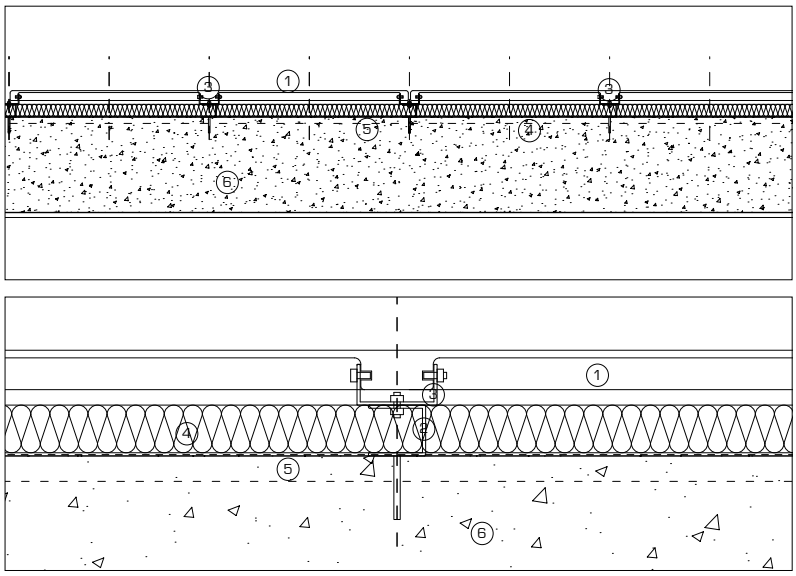
e | 3D view showing stone rainscreen cladding panels fixed to in-situ cast concrete primary structure

Details

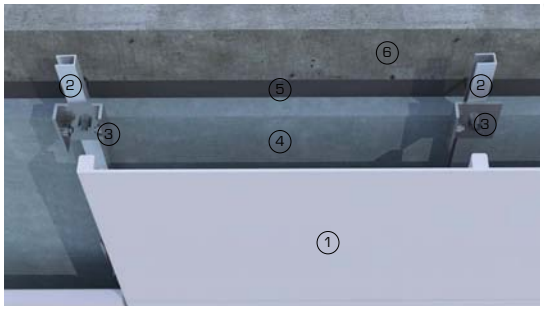
1 | Stone rainscreen cladding panels
2 | Rainscreen cladding panel fixing rail
3 | Rainscreen cladding panel fixing bracket
4 | Closed cell thermal insulation
5 | Waterproof membrane
6 | In-situ cast concrete structure
7 | Steel supporting roof beam

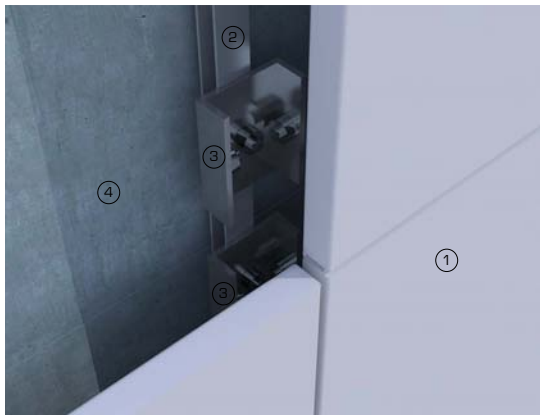
f | 3D view showing GRP rainscreen cladding panels fixed to in-situ cast concrete primary structure



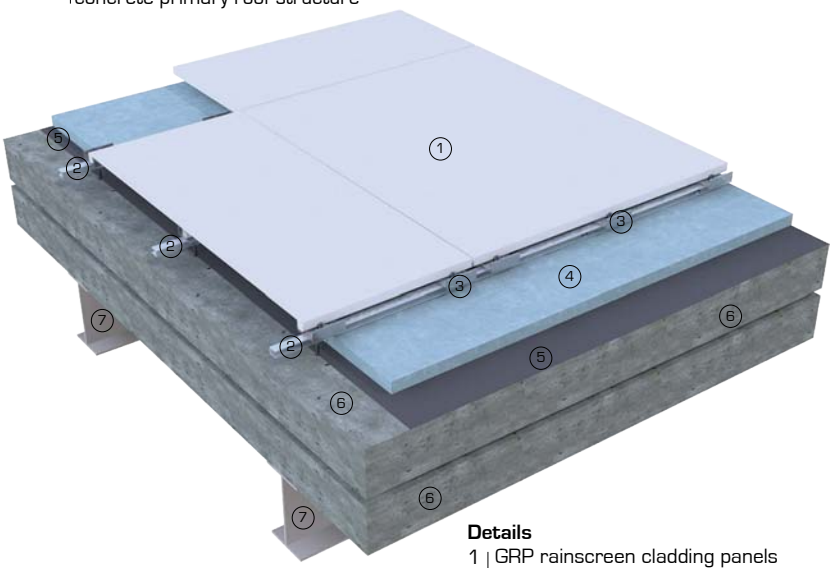


g | Vertical section. GRP rainscreen cladding panels fixed to in-situ cast concrete primary roof structure



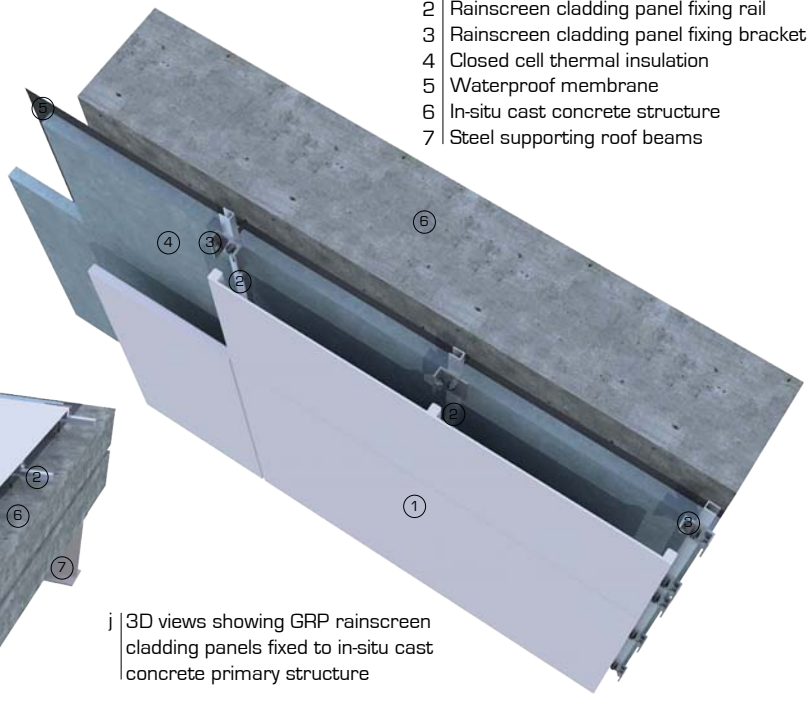


h | 3D detail views showing GRP rainscreen cladding panels fixed to in-situ cast concrete primary structure

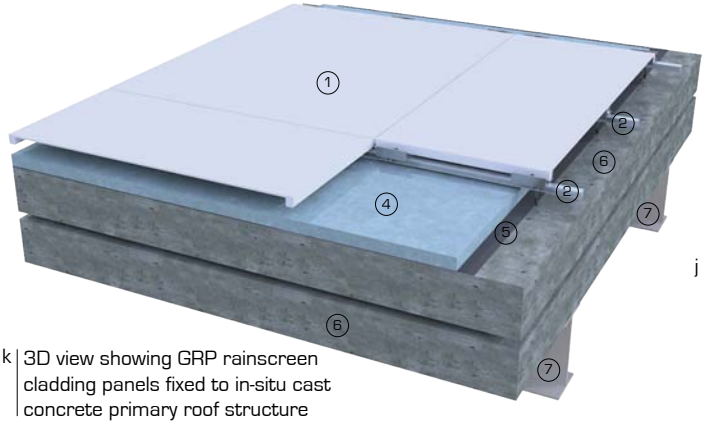


Details

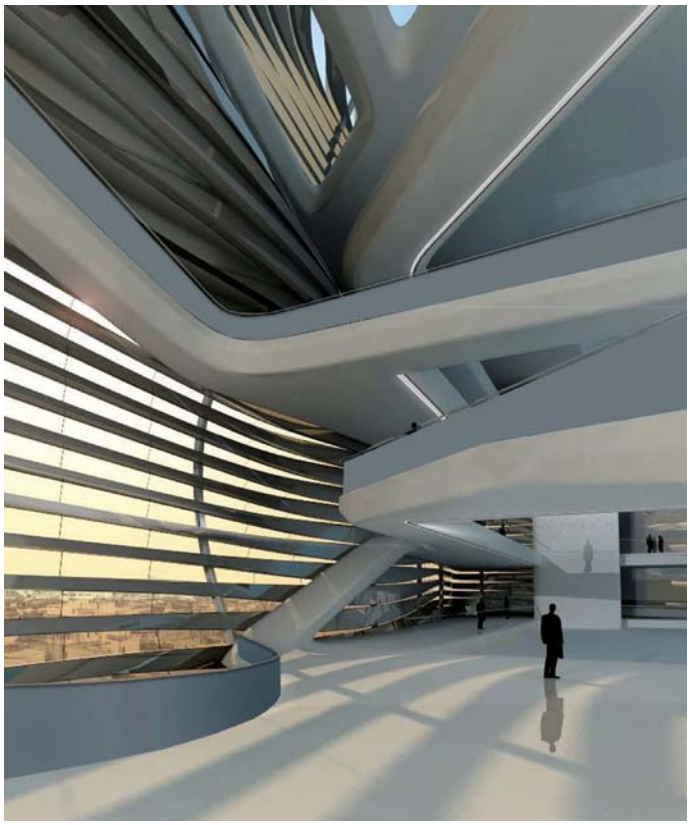
1 | GRP rainscreen cladding panels
2 | Rainscreen cladding panel fixing rail
3 | Rainscreen cladding panel fixing bracket
4 | Closed cell thermal insulation
5 | Waterproof membrane
6 | In-situ cast concrete structure
7 | Steel supporting roof beams



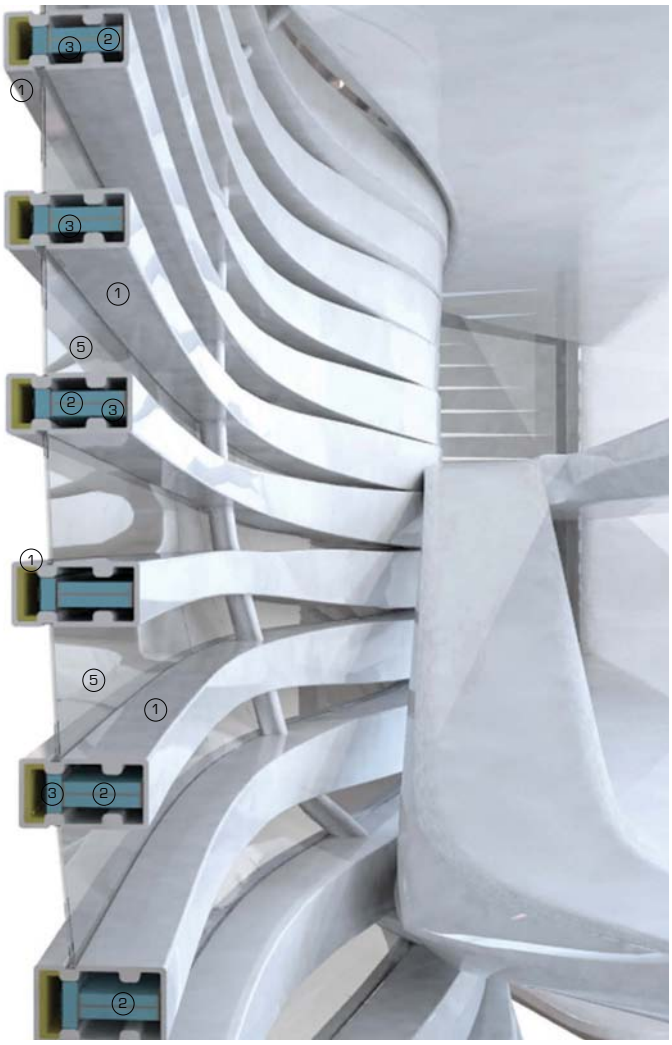
j | 3D views showing GRP rainscreen cladding panels fixed to in-situ cast concrete primary structure



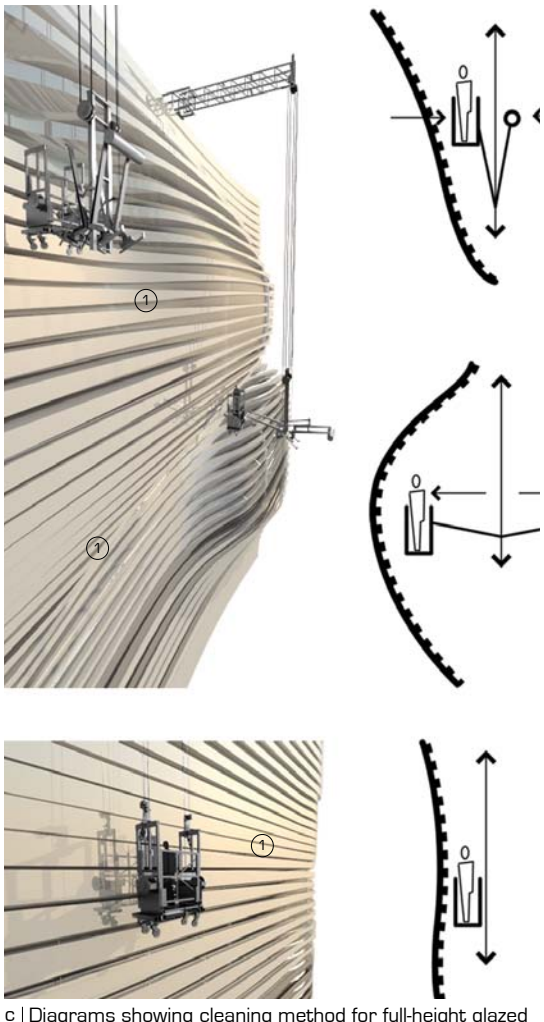
k | 3D view showing GRP rainscreen cladding panels fixed to in-situ cast concrete primary roof structure



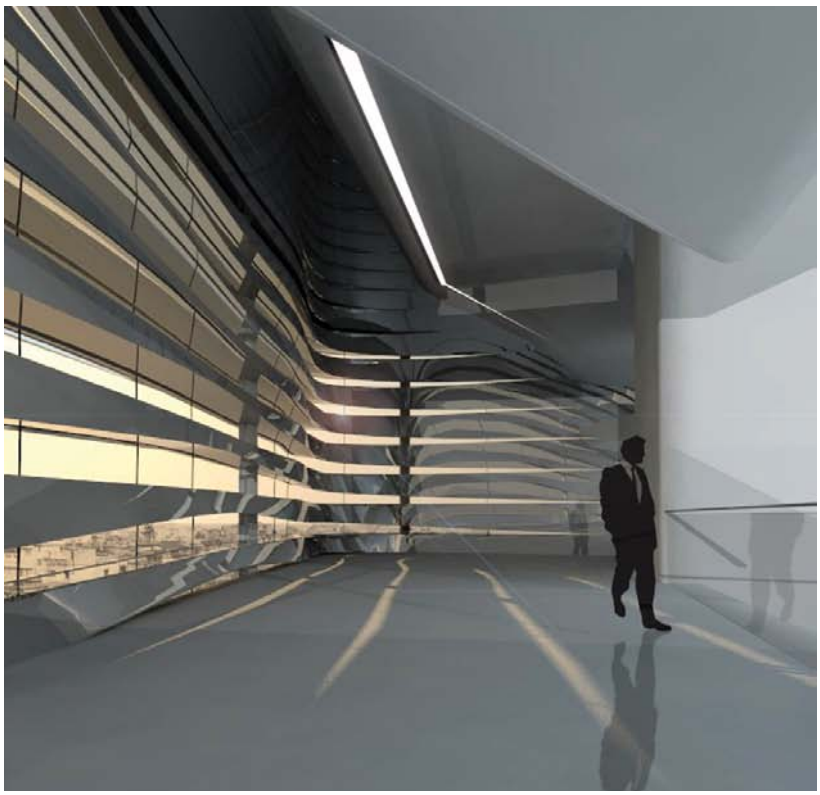
a | 3D internal view showing full-height glazed facade with external GRP cladding over primary steel structure



b | 3D sectional detail view showing full-height glazed facade with external GRP cladding over primary steel structure



c | Diagrams showing cleaning method for full-height glazed facade with external GRP cladding over primary steel structure



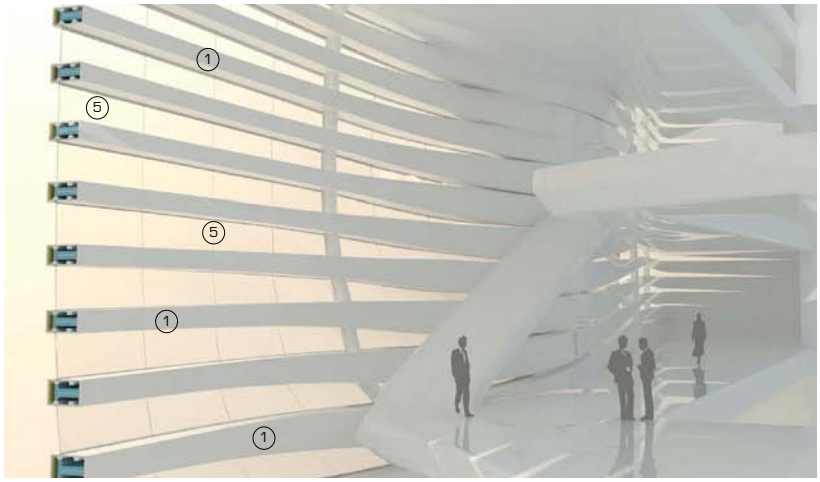
d | 3D internal view showing full-height glazed facade with external GRP cladding over primary steel structure



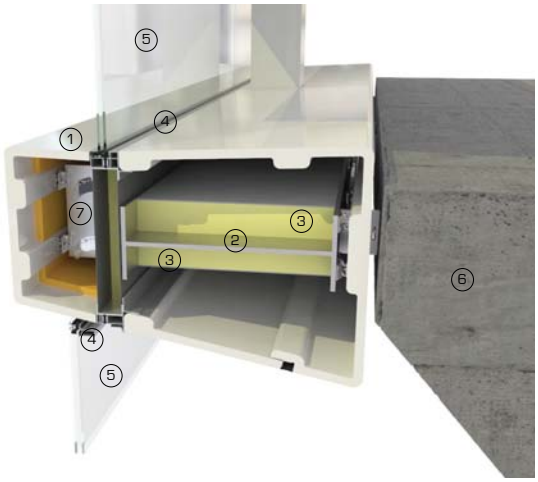
Details

1 | GRP cladding
2 | Primary steel structure
3 | Thermal insulation
4 | Glazing frame
5 | Double glazing
6 | Concrete floor slab
7 | GRP fixing bracket

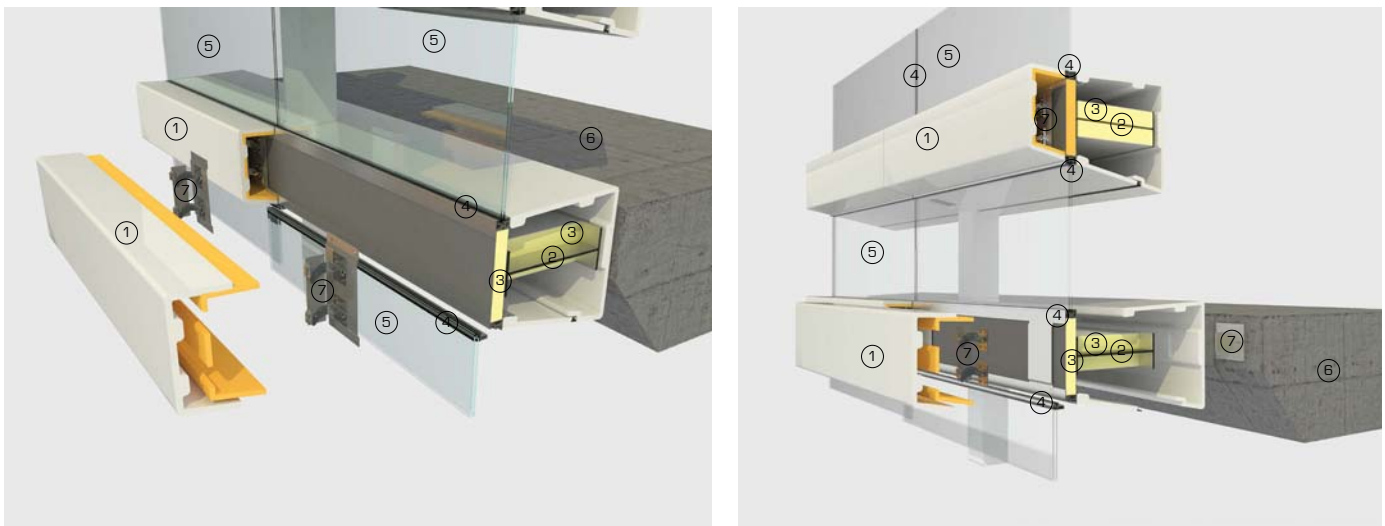
e | 3D sectional detail view showing full-height glazed facade with external GRP cladding over primary steel structure



f | 3D sectional detail view showing full-height glazed facade with external GRP cladding over primary steel structure



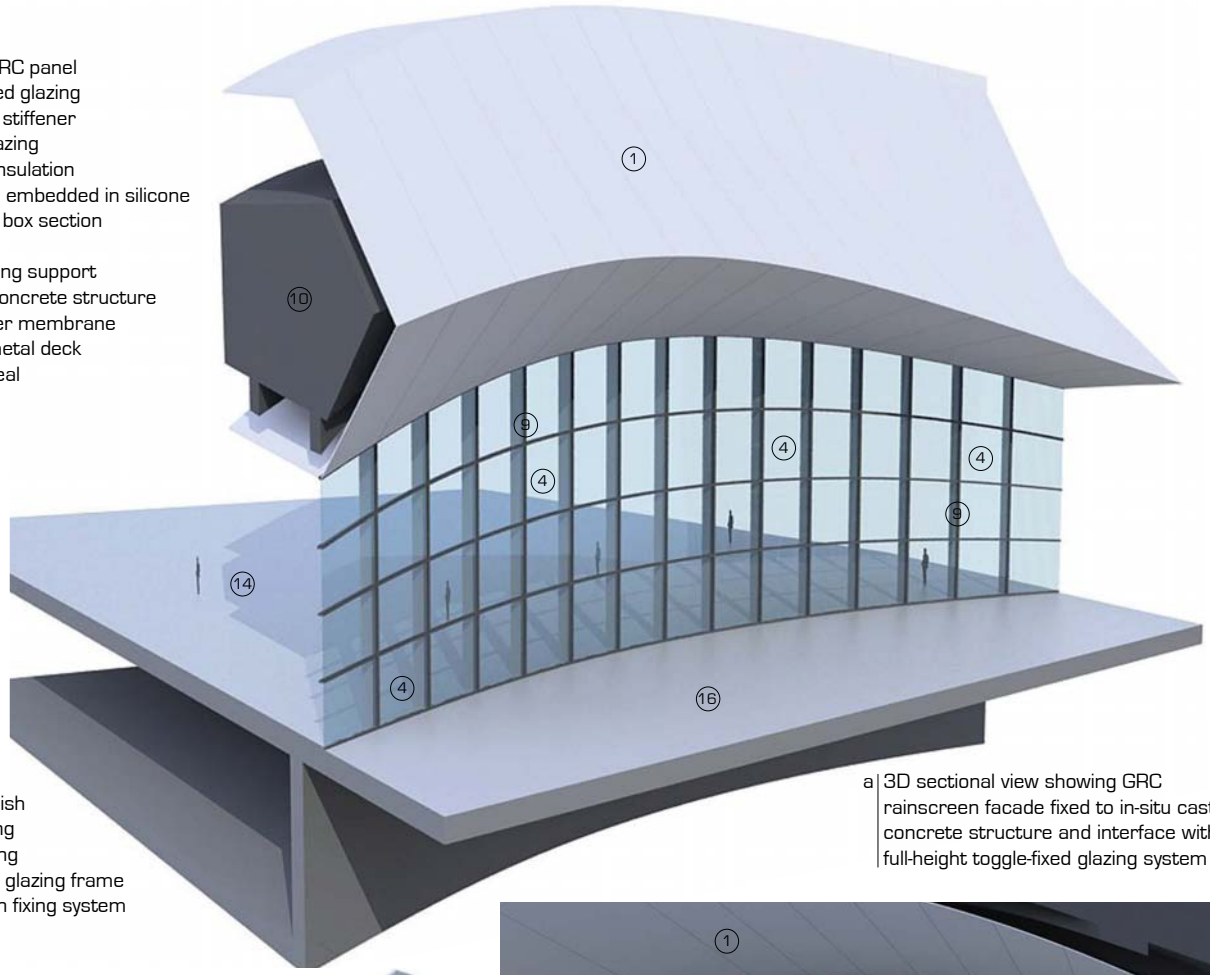
g | 3D detail view showing full-height glazed facade with external GRP cladding over primary steel structure



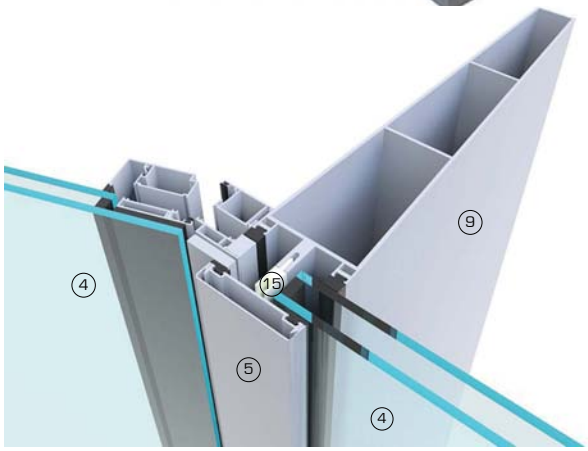
h | 3D exploded detail views showing full-height glazed facade with external GRP cladding over primary steel structure

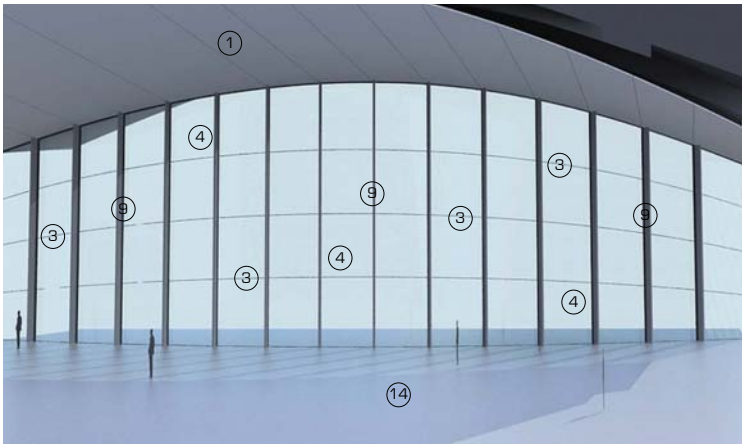
Details

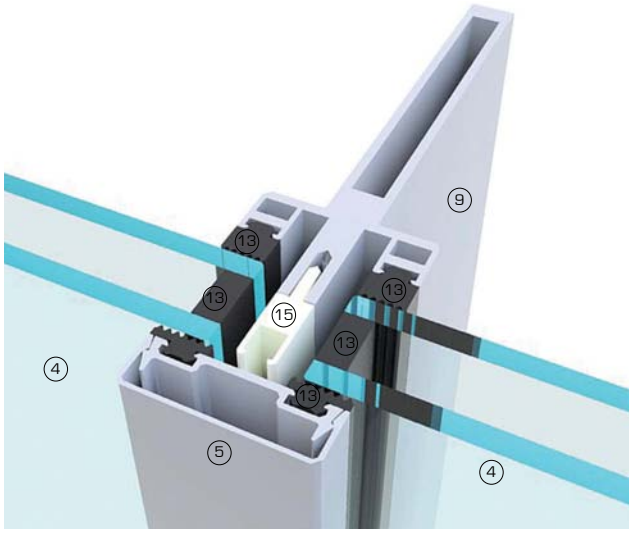
1 Opaque GRC panel
2 Toggle-fixed glazing
3 Mild steel stiffener
4 Double glazing
5 Thermal insulation
6 Metal cap embedded in silicone
7 Mild steel box section
8 Gutter
9 Steel glazing support
10 Primary concrete structure
11 Single layer membrane
12 Profiled metal deck
13 Silicone seal
14 Internal finish
15 Toggle fixing
16 Landscaping
17 Aluminium glazing frame
18 Rainscreen fixing system

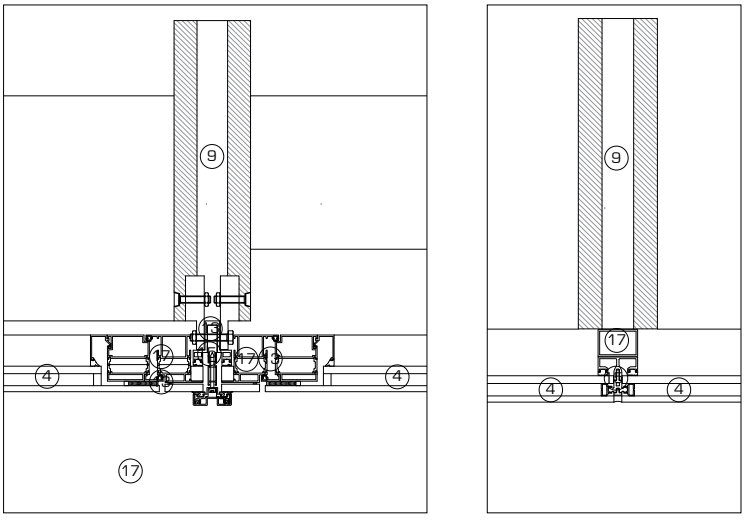


a | 3D sectional view showing GRC rainscreen facade fixed to in-situ cast concrete structure and interface with full-height toggle-fixed glazing system

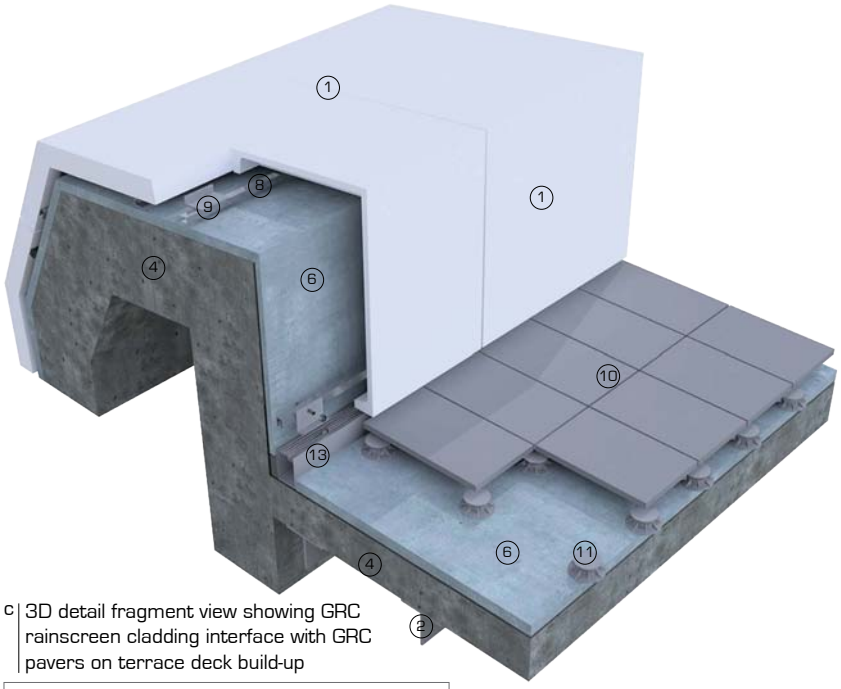




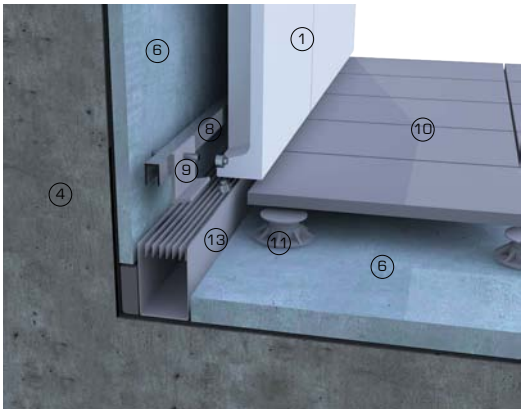




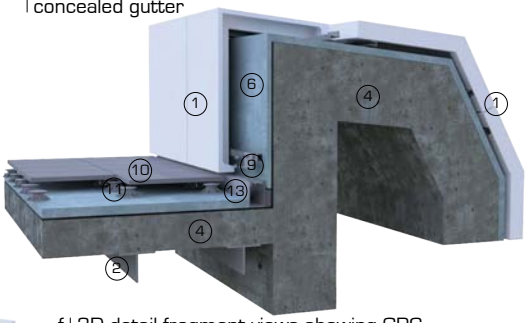
b | (Above) Horizontal sections. Toggle-fixed glazing system (opening light and fixed light configurations)
(Left) 3D detail views showing toggle-fixed glazing system



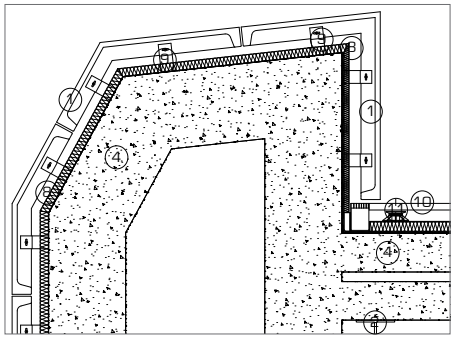
c | 3D detail fragment view showing GRC rainscreen cladding interface with GRC pavers on terrace deck build-up



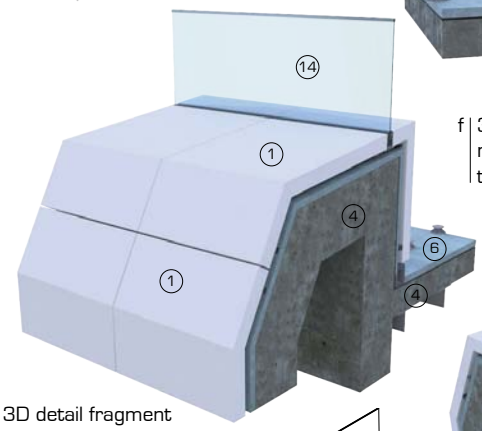
d | 3D detail view showing GRC rainscreen cladding interface with GRC pavers on terrace deck build-up and concealed gutter

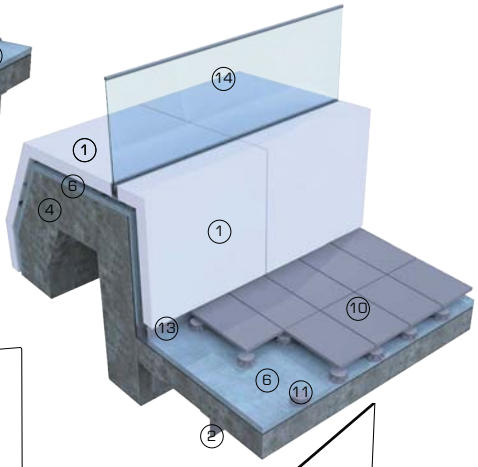


f | 3D detail fragment views showing GRC rainscreen cladding interface with GRC pavers on terrace deck build-up and glazed balustrade

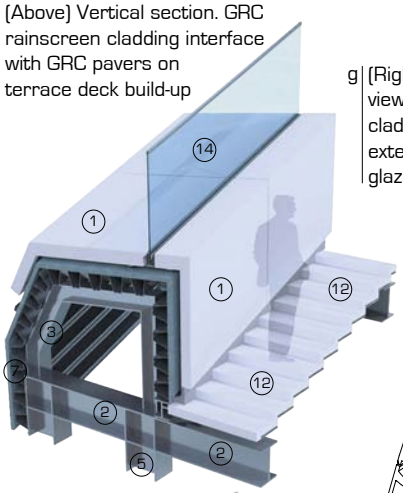


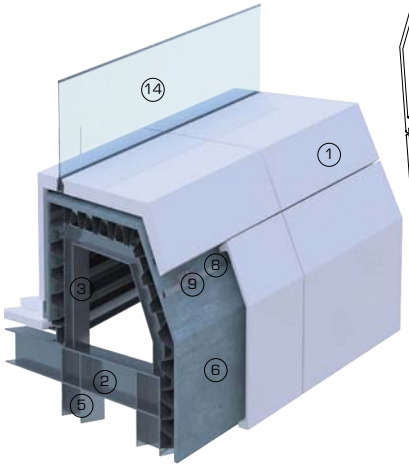
e | (Above) Vertical section. GRC rainscreen cladding interface with GRC pavers on terrace deck build-up

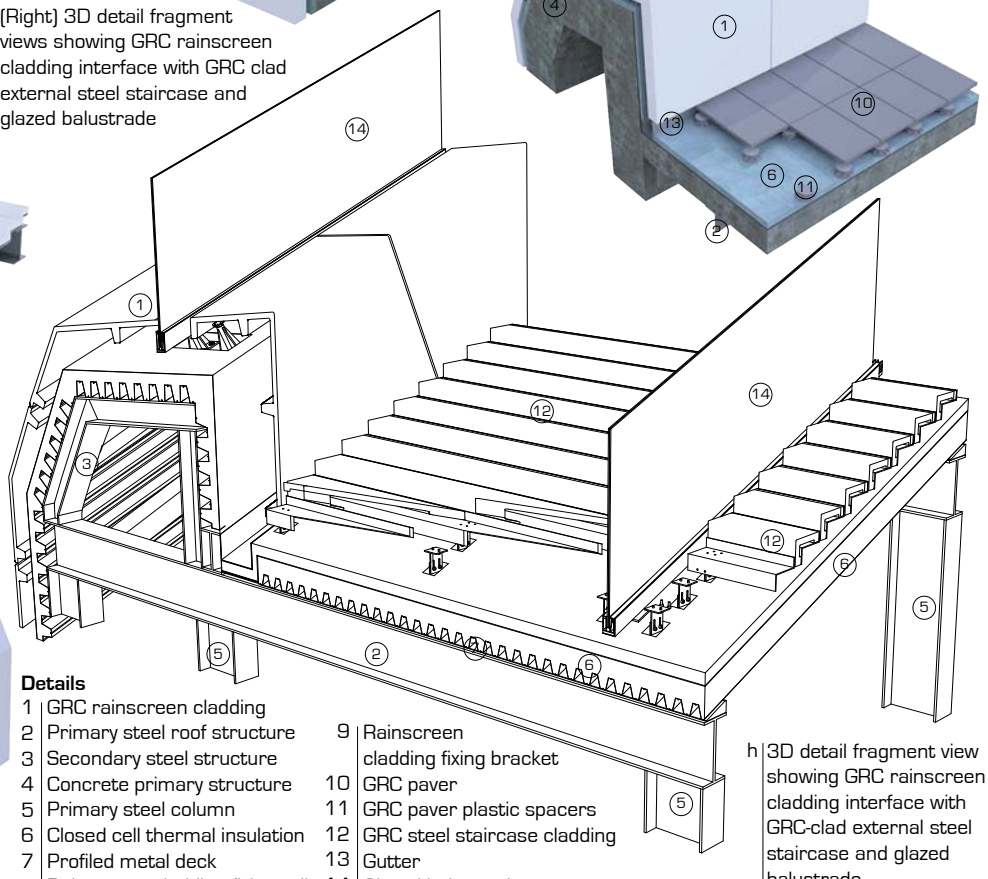




g | (Right) 3D detail fragment views showing GRC rainscreen cladding interface with GRC clad external steel staircase and glazed balustrade







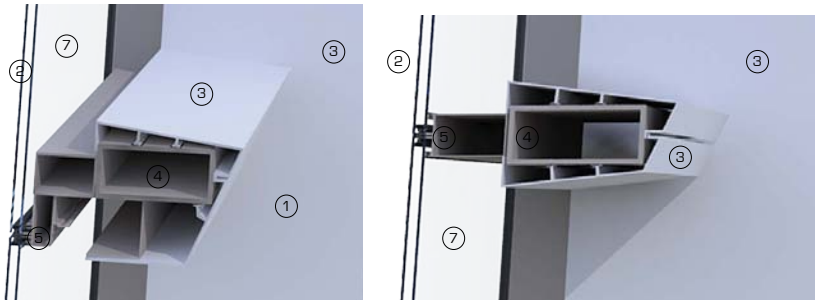
Details

1	GRC rainscreen cladding	9	Rainscreen cladding fixing bracket
2	Primary steel roof structure	10	GRC paver
3	Secondary steel structure	11	GRC paver plastic spacers
4	Concrete primary structure	12	GRC steel staircase cladding
5	Primary steel column	13	Gutter
6	Closed cell thermal insulation	14	Glazed balustrade
7	Profiled metal deck		
8	Rainscreen cladding fixing rail		

h | 3D detail fragment view showing GRC rainscreen cladding interface with GRC-clad external steel staircase and glazed balustrade



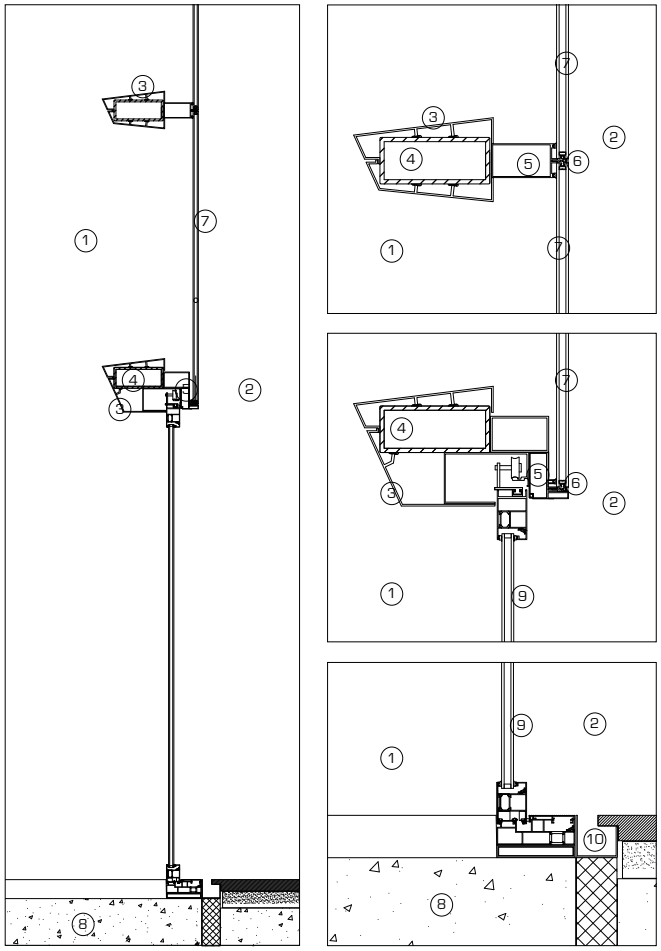
a | 3D sectional view showing GRP-clad steel support structure with full-height toggle-fixed glazing



b | 3D detail views showing GRP-clad steel support structure with full-height toggle-fixed glazing



c | 3D sectional view showing GRP-clad steel support structure with full-height toggle-fixed glazing



e | Vertical sections. GRP-clad steel support structure with full-height toggle-fixed glazing, sliding door and interface with ground



d | (Above) 3D views showing sliding door within GRP-clad steel support structure and toggle-fixed glazing, in closed and open positions

f | (Right) 3D sectional view showing GRP-clad steel support structure with full-height toggle-fixed glazing



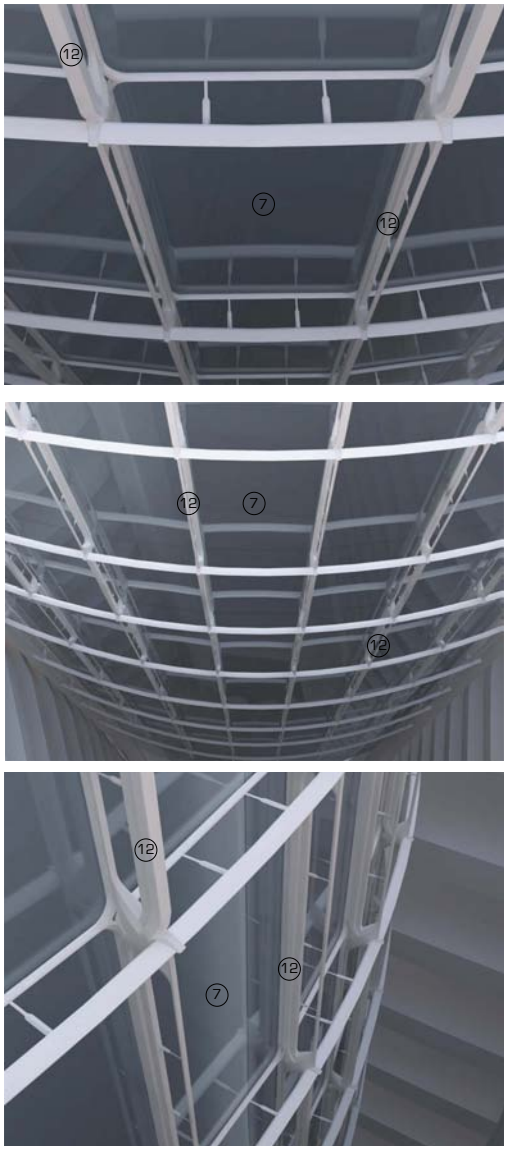
g | 3D views showing cast aluminium glazing frames supporting full-height glazing



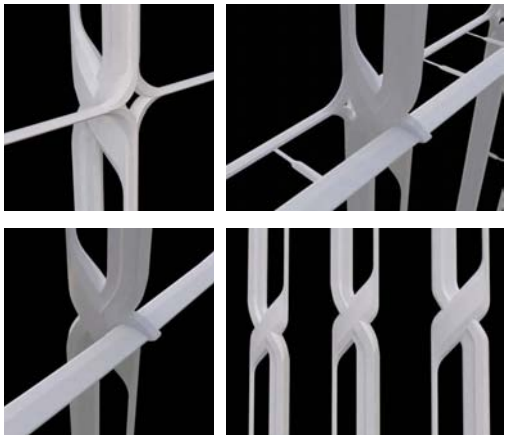
h | 3D views showing cast aluminium glazing frames supporting full-height glazing with cap piece



j | 3D view showing cast aluminium glazing frames supporting full-height clamped glazing



k | 3D internal views showing cast aluminium glazing frames with double-layer rod support



l | 3D views showing cast aluminium glazing frames, in various configurations

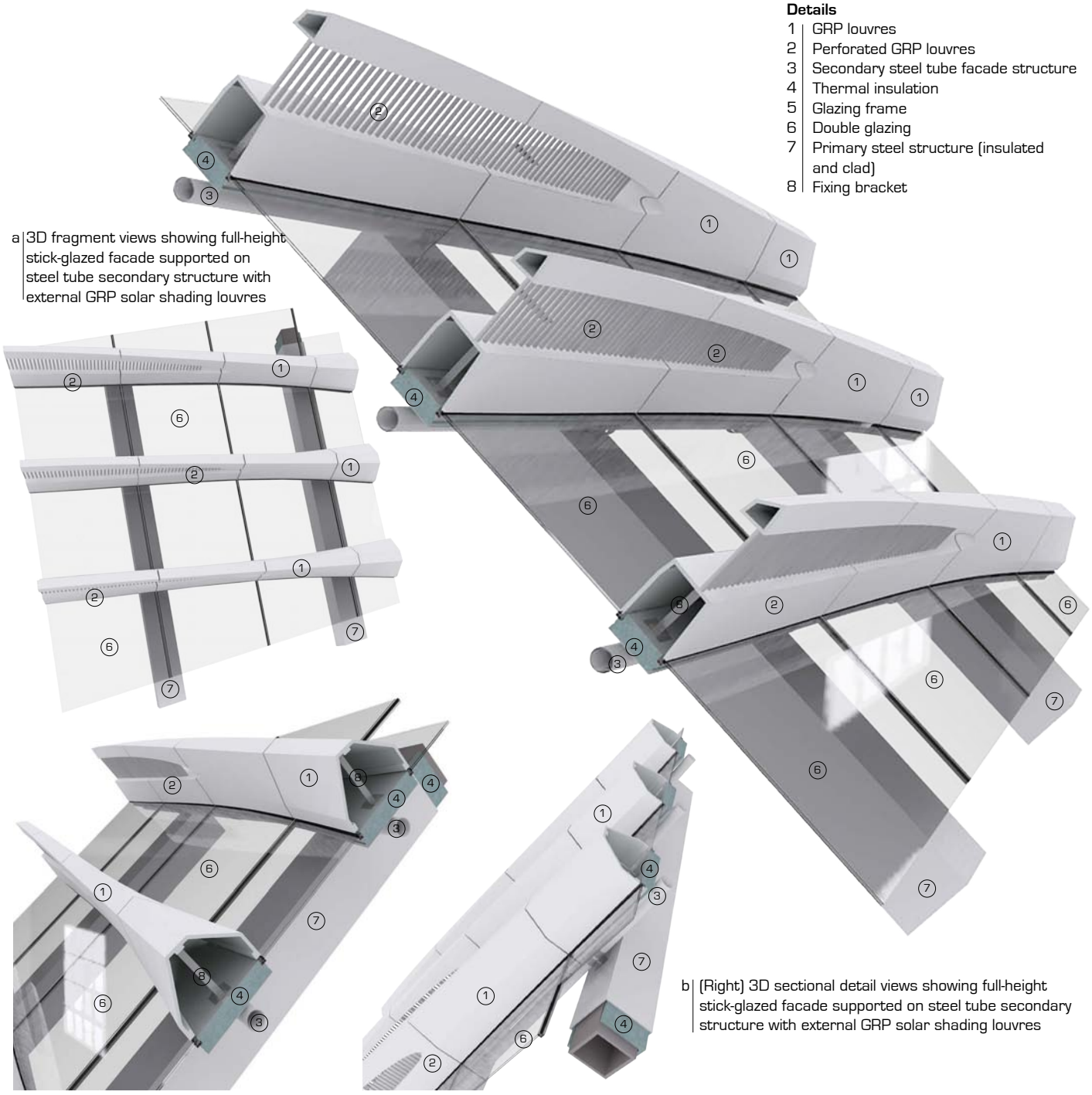
Details

1	Internal
2	External
3	Metal cladding to glazing support structure
4	Steel support structure
5	Glazing frame
6	Toggle-fixing
7	Double glazing
8	Ground
9	Sliding door
10	Gutter
11	Clamped glazing fixing
12	Cast aluminium glazing frame

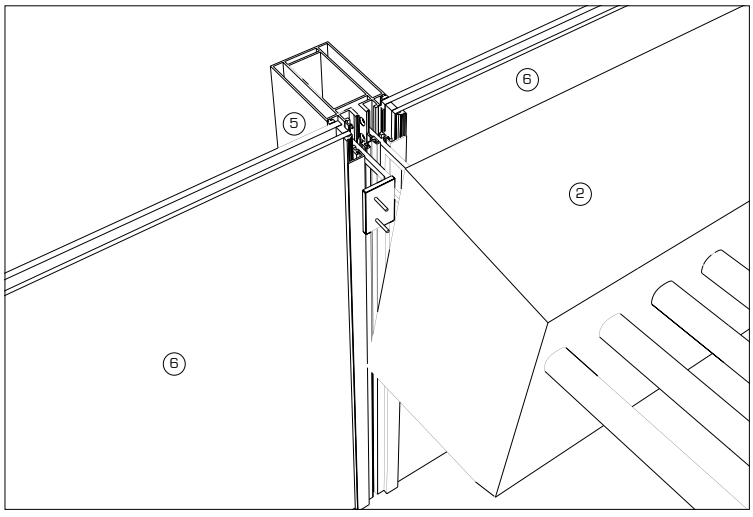
Details

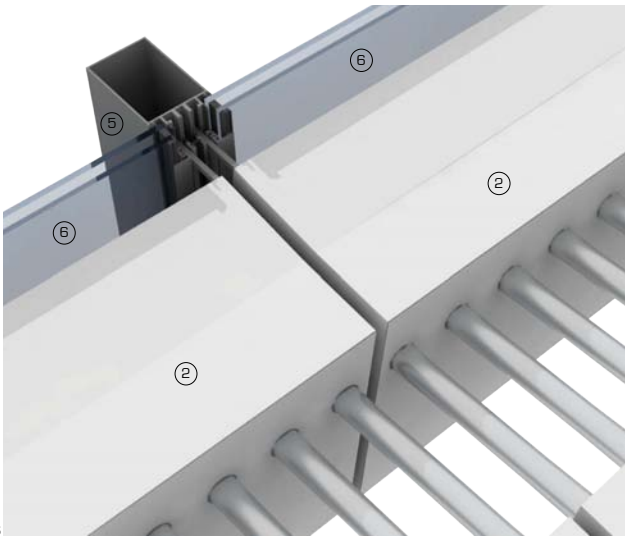
1 GRP louvres
2 Perforated GRP louvres
3 Secondary steel tube facade structure
4 Thermal insulation
5 Glazing frame
6 Double glazing
7 Primary steel structure (insulated and clad)
8 Fixing bracket

a 3D fragment views showing full-height stick-glazed facade supported on steel tube secondary structure with external GRP solar shading louvres

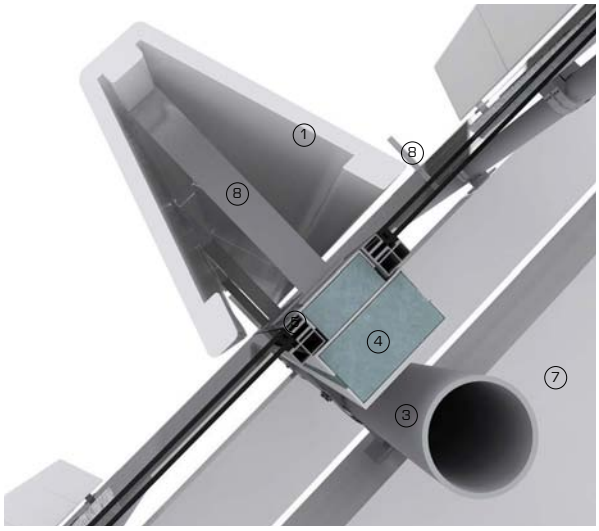


b (Right) 3D sectional detail views showing full-height stick-glazed facade supported on steel tube secondary structure with external GRP solar shading louvres

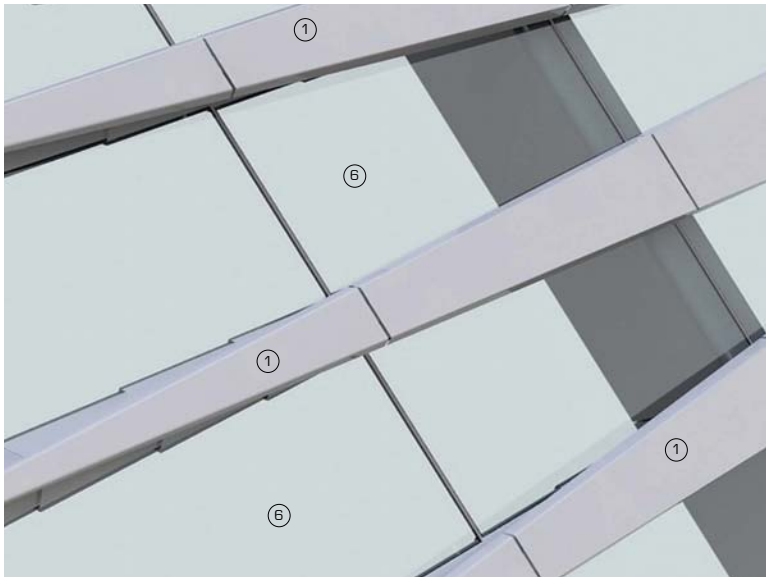




c 3D detail views showing stick-glazed facade with external GRP solar shading louvres

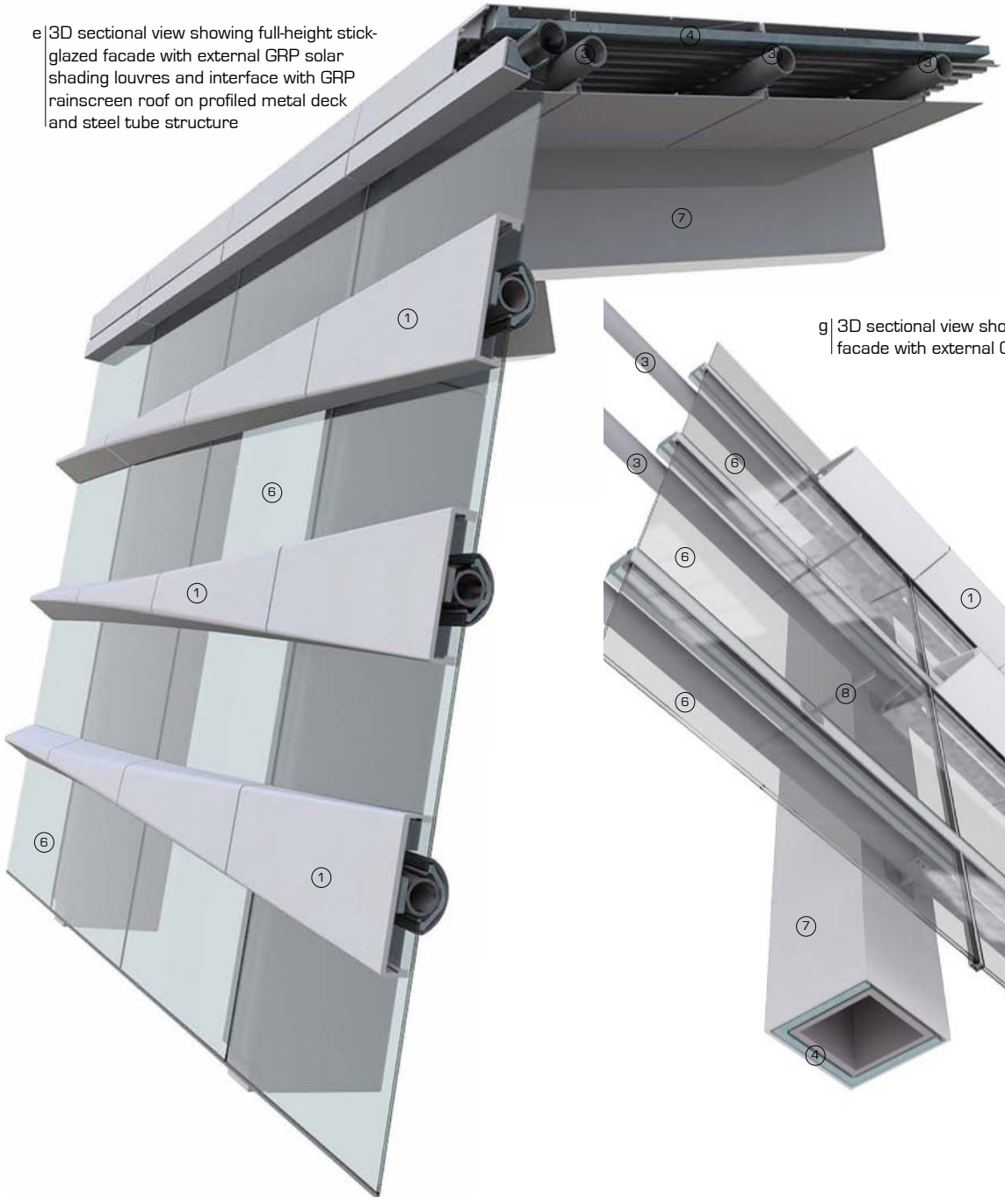


d | 3D detail view showing stick-glazed facade supported on steel tube secondary structure with external GRP solar shading louvres



f | 3D view showing stick-glazed facade with external GRP solar shading louvres

e | 3D sectional view showing full-height stick-glazed facade with external GRP solar shading louvres and interface with GRP rainscreen roof on profiled metal deck and steel tube structure



g | 3D sectional view showing full-height stick-glazed facade with external GRP solar shading louvres





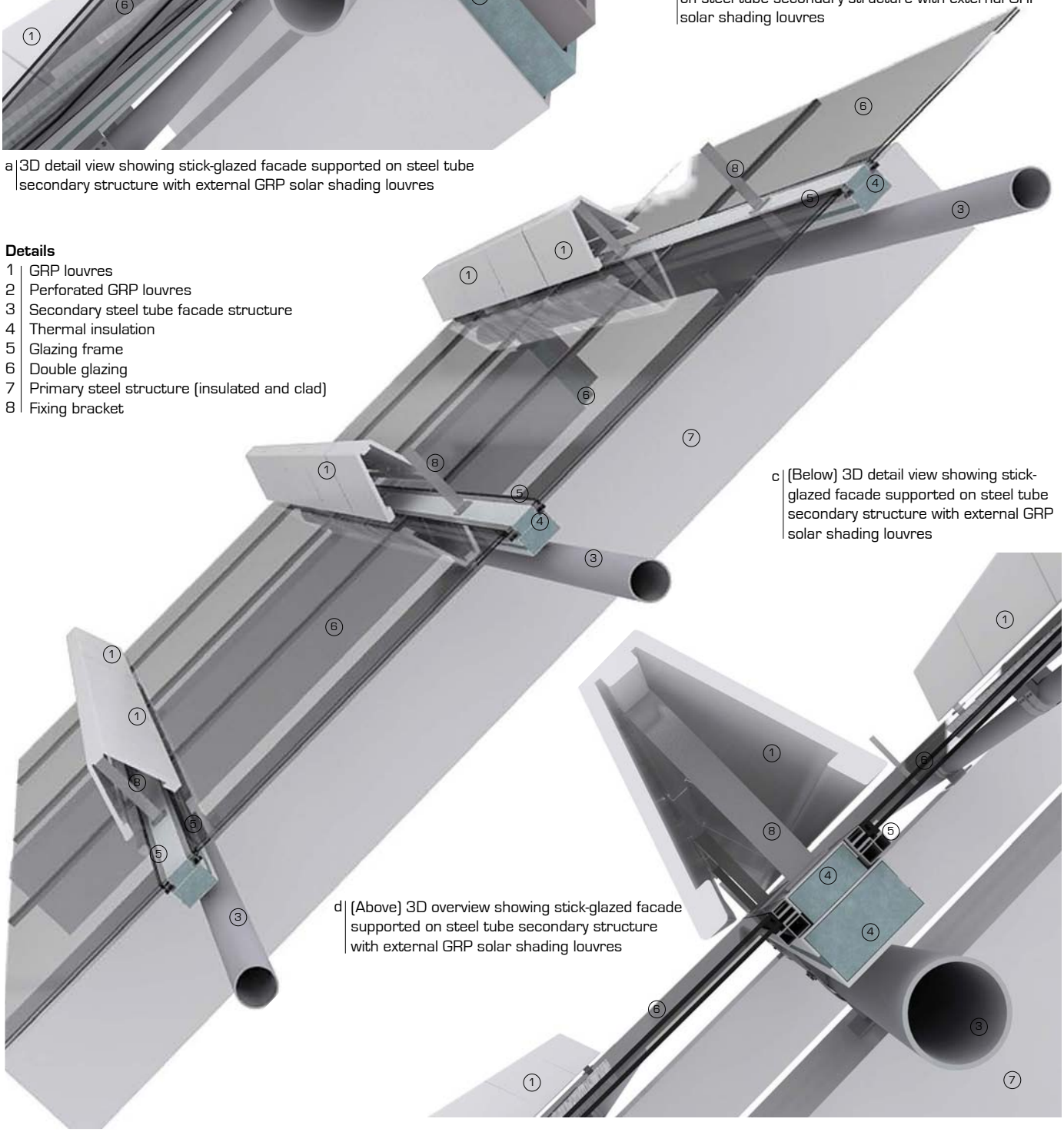
a | 3D detail view showing stick-glazed facade supported on steel tube secondary structure with external GRP solar shading louvres



b | 3D detail view showing stick-glazed facade supported on steel tube secondary structure with external GRP solar shading louvres

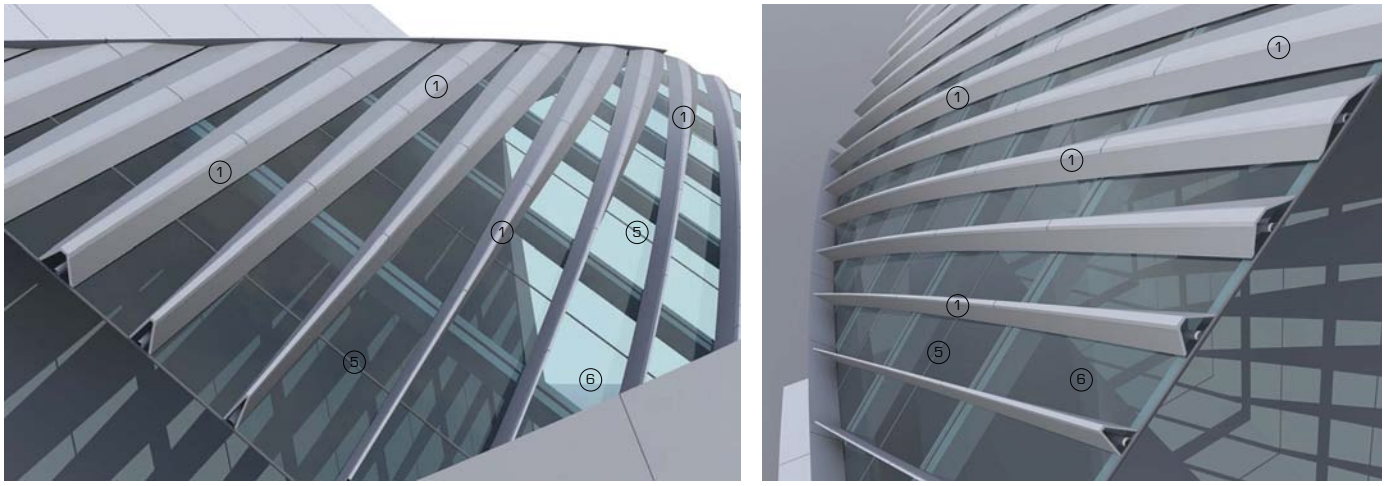
Details

1 | GRP louvres
2 | Perforated GRP louvres
3 | Secondary steel tube facade structure
4 | Thermal insulation
5 | Glazing frame
6 | Double glazing
7 | Primary steel structure (insulated and clad)
8 | Fixing bracket

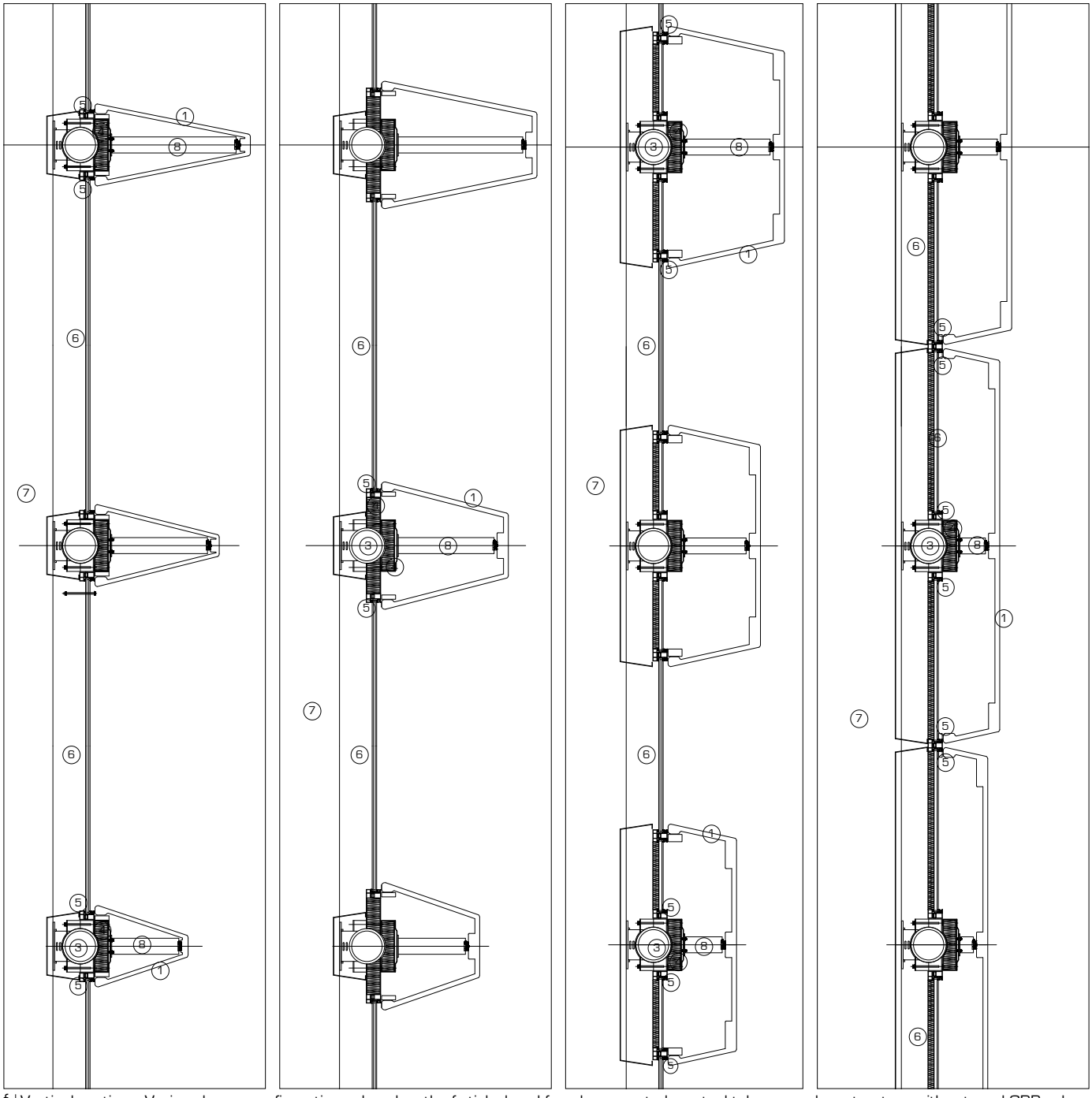


c | (Below) 3D detail view showing stick-glazed facade supported on steel tube secondary structure with external GRP solar shading louvres

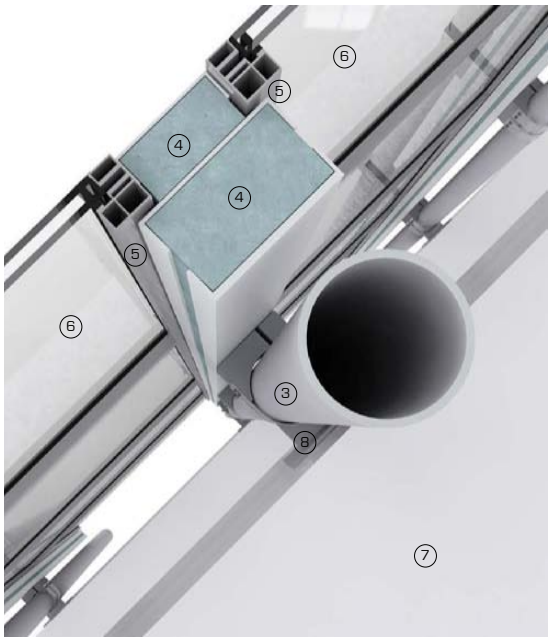
d | (Above) 3D overview showing stick-glazed facade supported on steel tube secondary structure with external GRP solar shading louvres



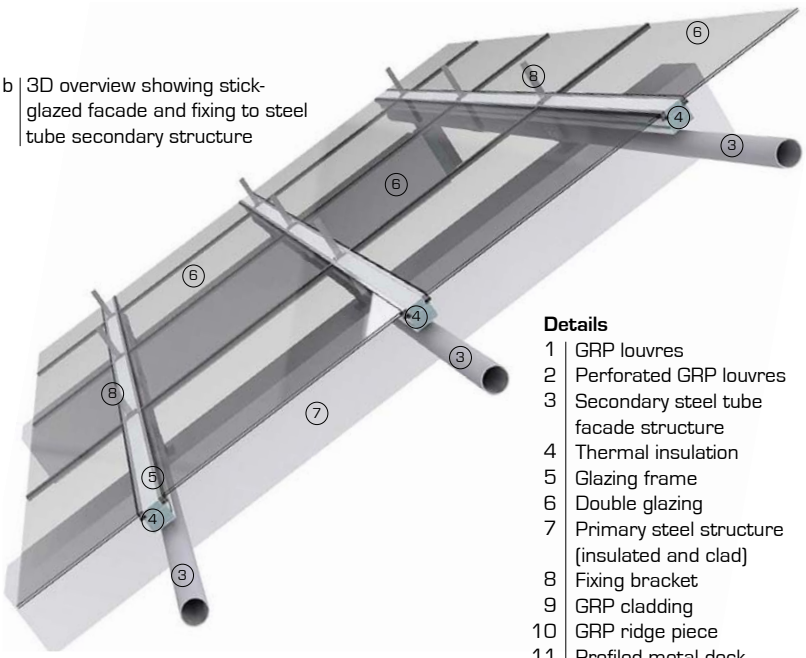
e | 3D overviews showing stick-glazed facade supported on steel tube secondary structure with external GRP solar shading louvres



f | Vertical sections. Various louvre configurations along length of stick-glazed facade supported on steel tube secondary structure with external GRP solar shading louvres



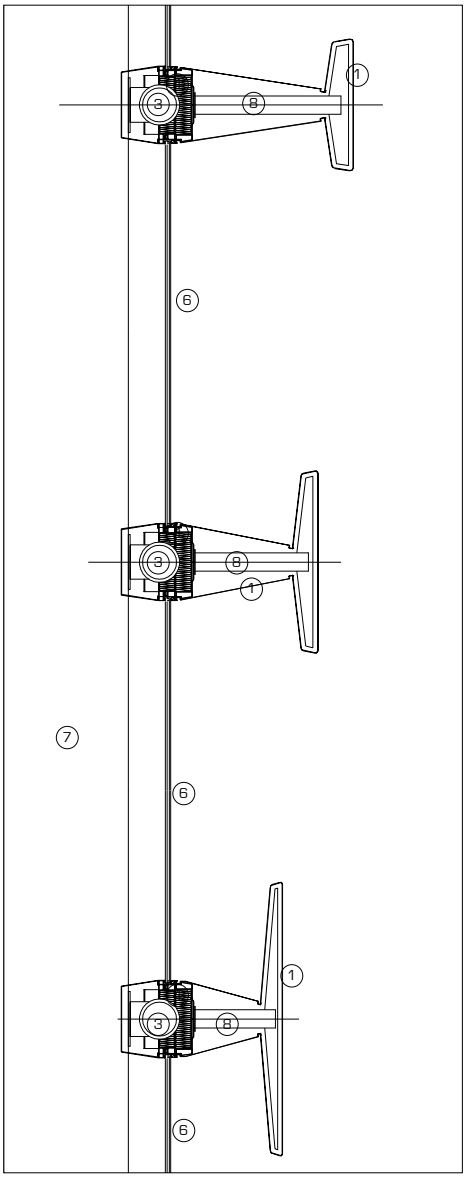
a | 3D detail view showing stick-glazed facade and fixing to steel tube secondary structure

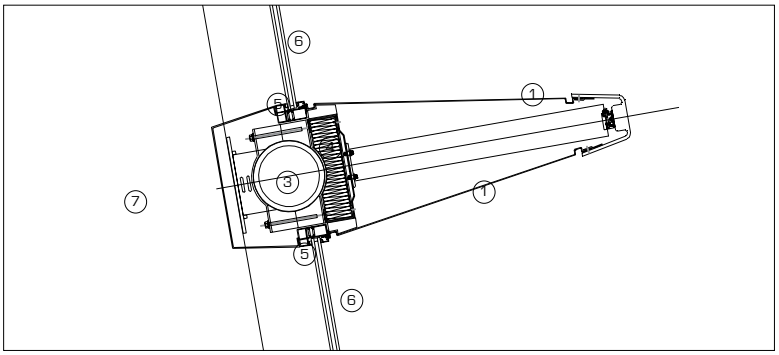


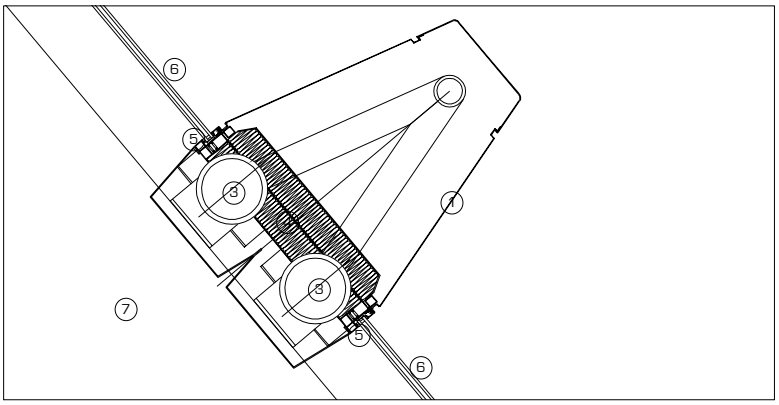
b | 3D overview showing stick-glazed facade and fixing to steel tube secondary structure

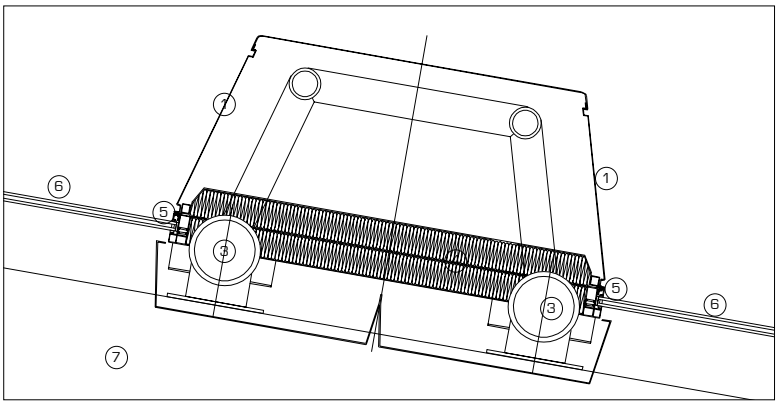
Details

1	GRP louvres
2	Perforated GRP louvres
3	Secondary steel tube facade structure
4	Thermal insulation
5	Glazing frame
6	Double glazing
7	Primary steel structure (insulated and clad)
8	Fixing bracket
9	GRP cladding
10	GRP ridge piece
11	Profiled metal deck
12	Standing seam metal deck

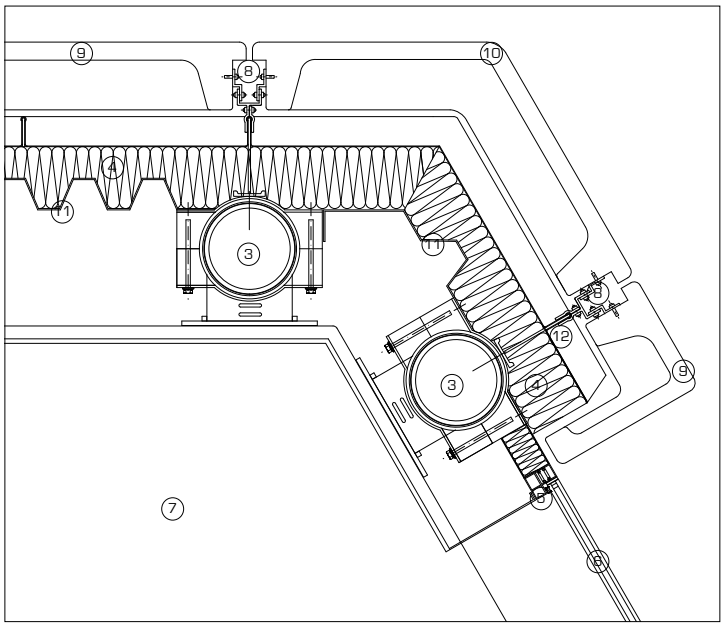




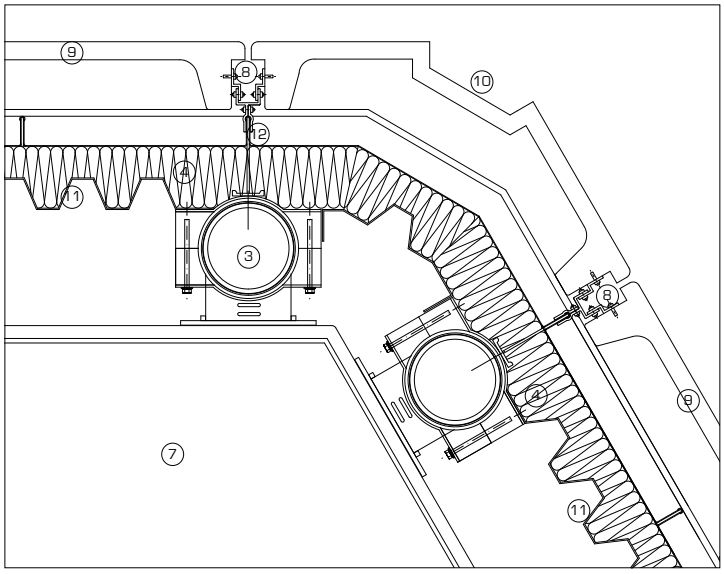




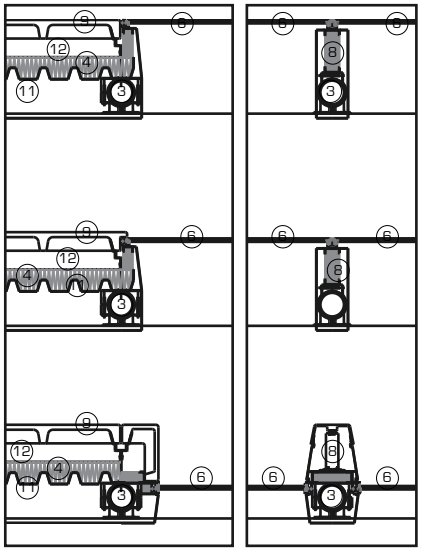
c | Vertical sections. Various louvre configurations along length of stick-glazed facade supported on steel tube secondary structure with external GRP solar shading louvres



d | Vertical section. Interface between stick-glazed facade and GRP rainscreen panels fixed to steel tube secondary structure



f | Vertical section. Edge condition of GRP rainscreen facade panels fixed to steel tube secondary structure

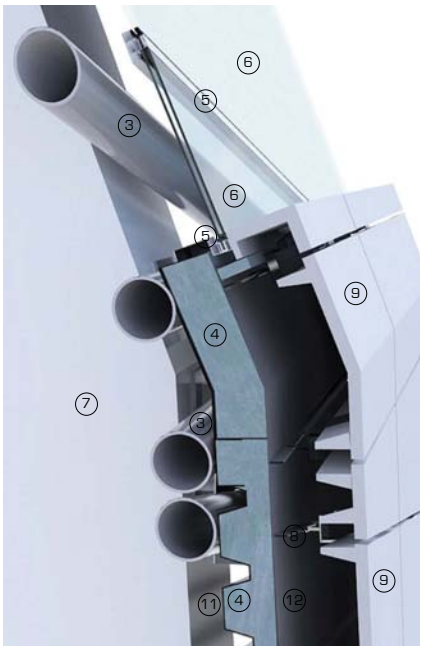


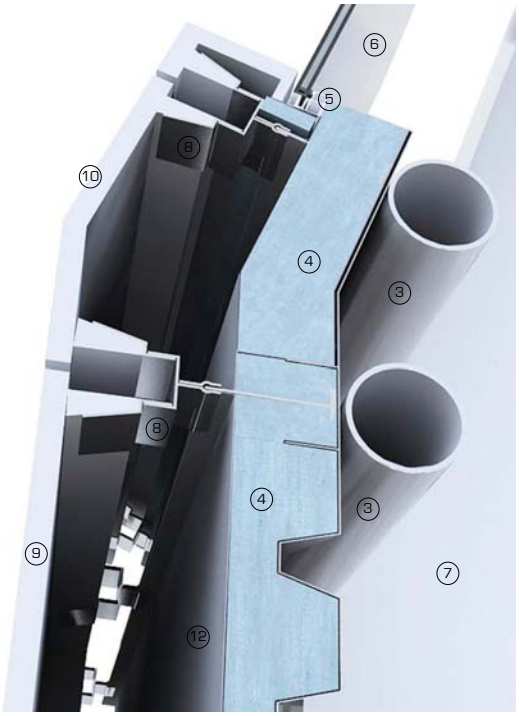
h | Vertical sections. Various configurations of interface between stick-glazed facade and GRP rainscreen panels fixed to steel tube secondary structure



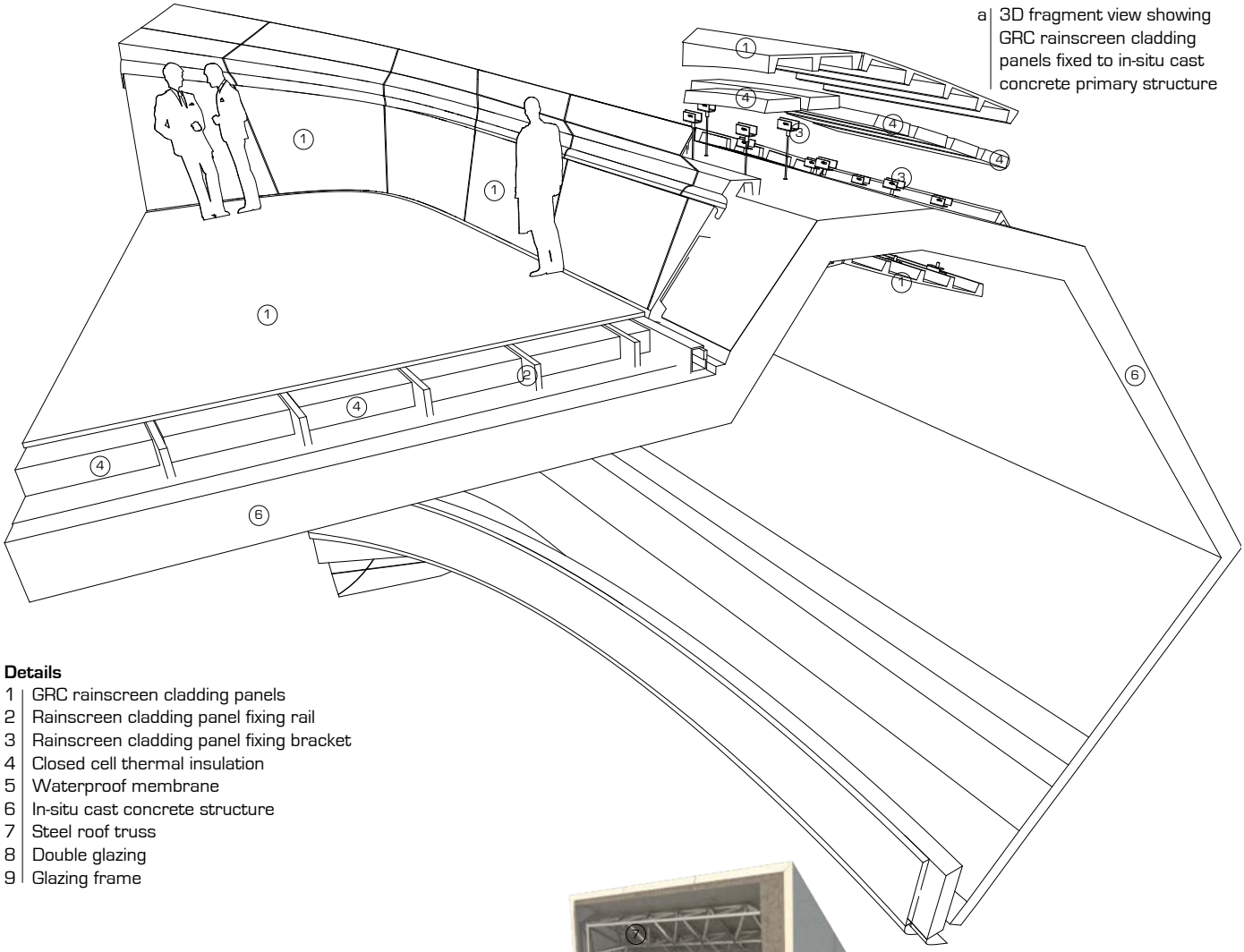
e | 3D sectional view of interface between stick-glazed facade and GRP rainscreen panels fixed to steel tube secondary structure

g | (Below) 3D view showing interface between stick-glazed facade and GRP rainscreen panels fixed to steel tube secondary structure





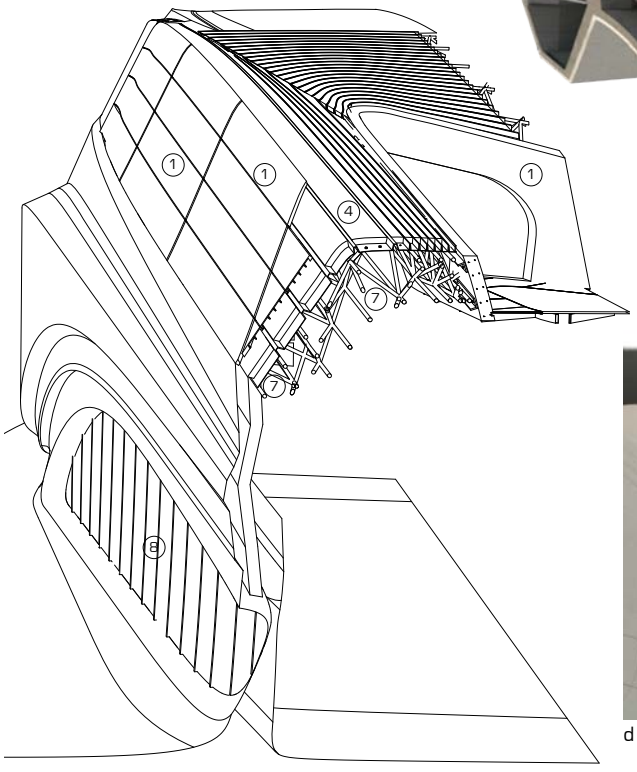
a | 3D fragment view showing GRC rainscreen cladding panels fixed to in-situ cast concrete primary structure



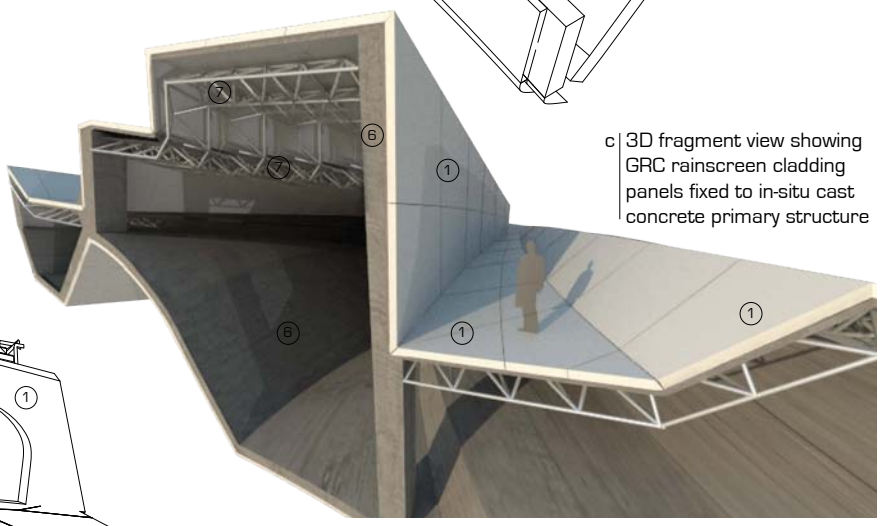
Details

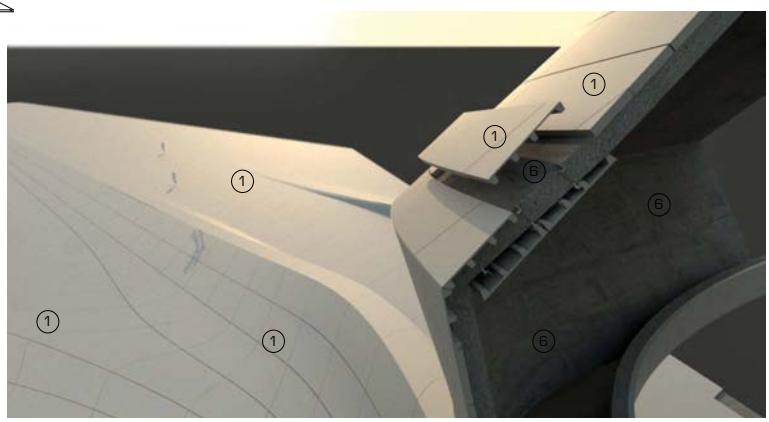
1 | GRC rainscreen cladding panels
2 | Rainscreen cladding panel fixing rail
3 | Rainscreen cladding panel fixing bracket
4 | Closed cell thermal insulation
5 | Waterproof membrane
6 | In-situ cast concrete structure
7 | Steel roof truss
8 | Double glazing
9 | Glazing frame

b | (Below) 3D sectional view showing GRC rainscreen cladding panels fixed to in-situ cast concrete primary structure and interface with full-height glazed facade

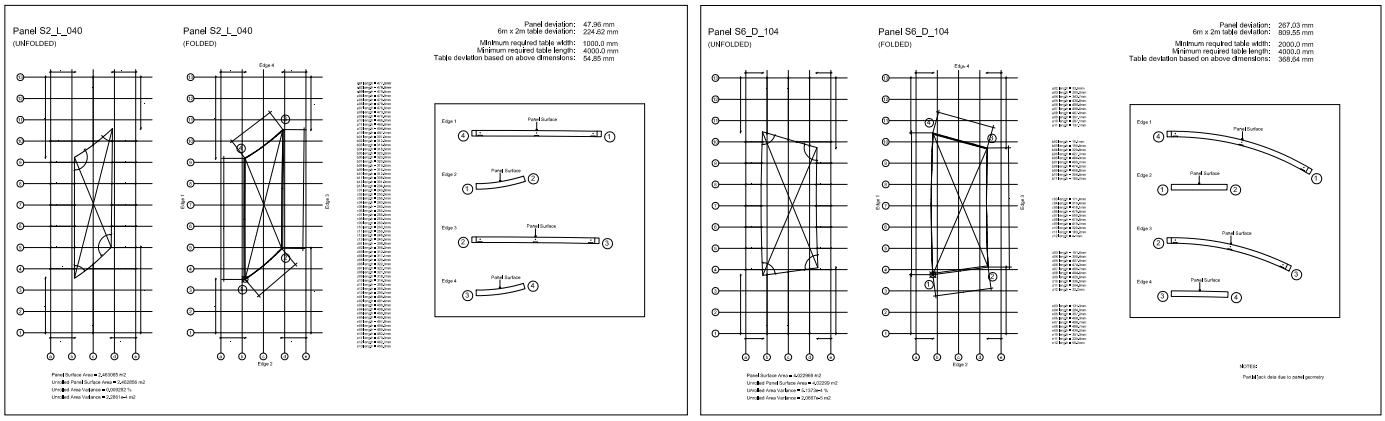


c | 3D fragment view showing GRC rainscreen cladding panels fixed to in-situ cast concrete primary structure

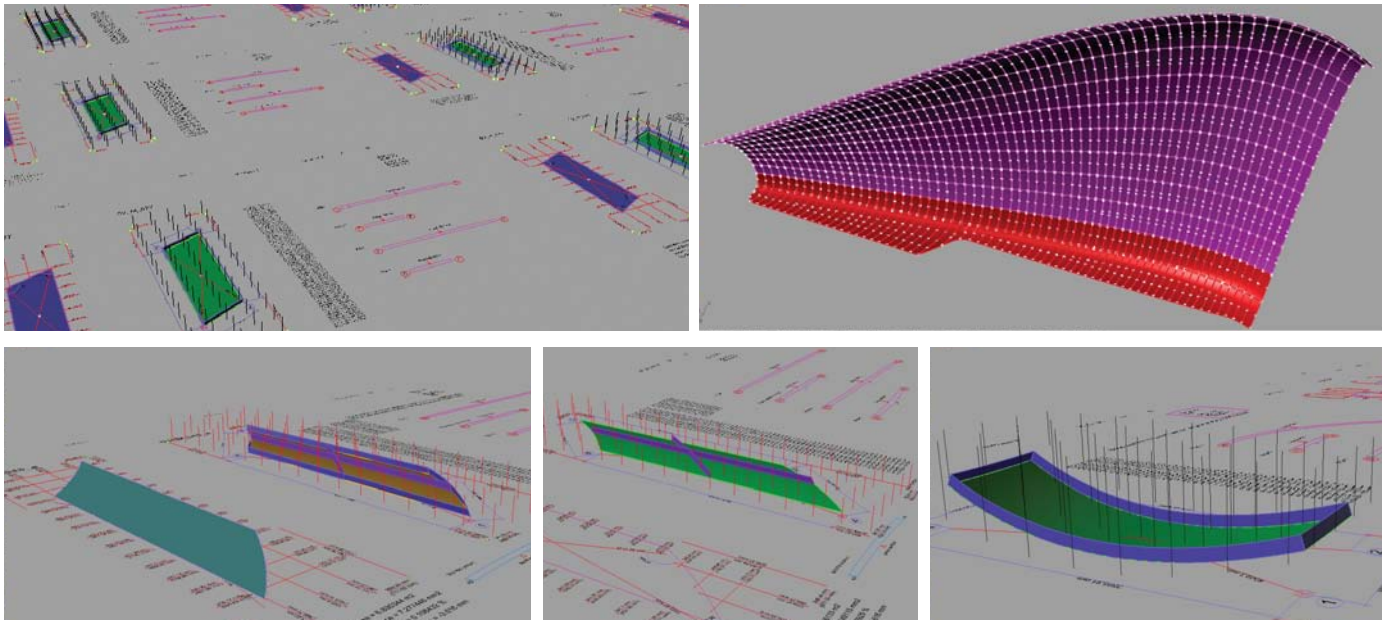


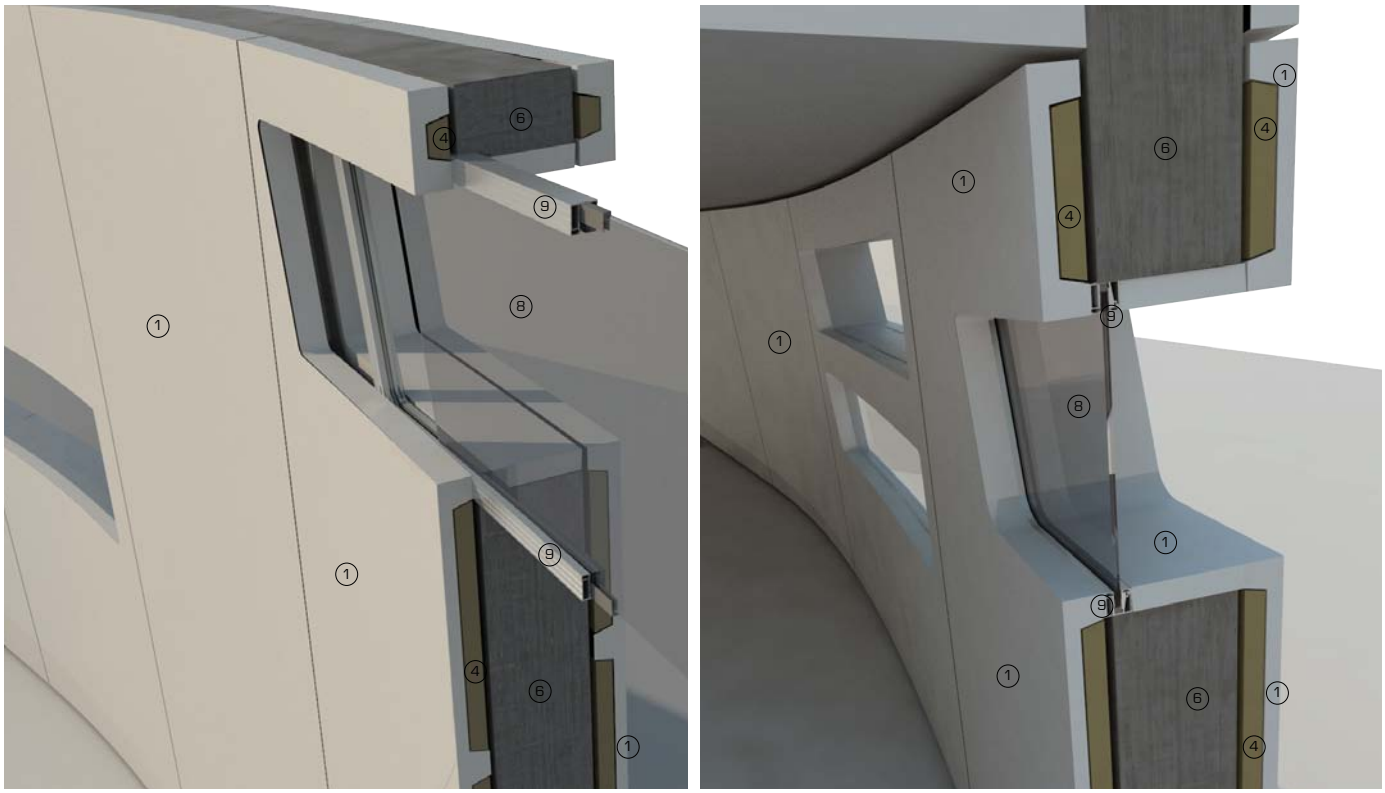


d | 3D sectional view showing GRC rainscreen cladding panels fixed to in-situ cast concrete primary structure

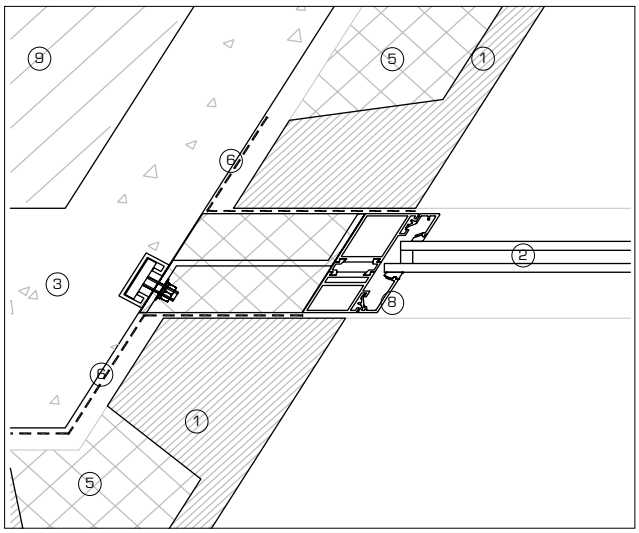


e|(Above and below) Diagrams showing panelisation process of identifying, numbering and laying out individual GRC panels

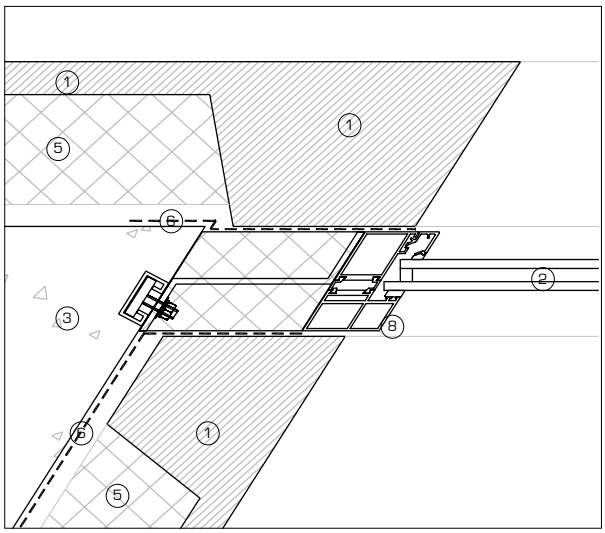




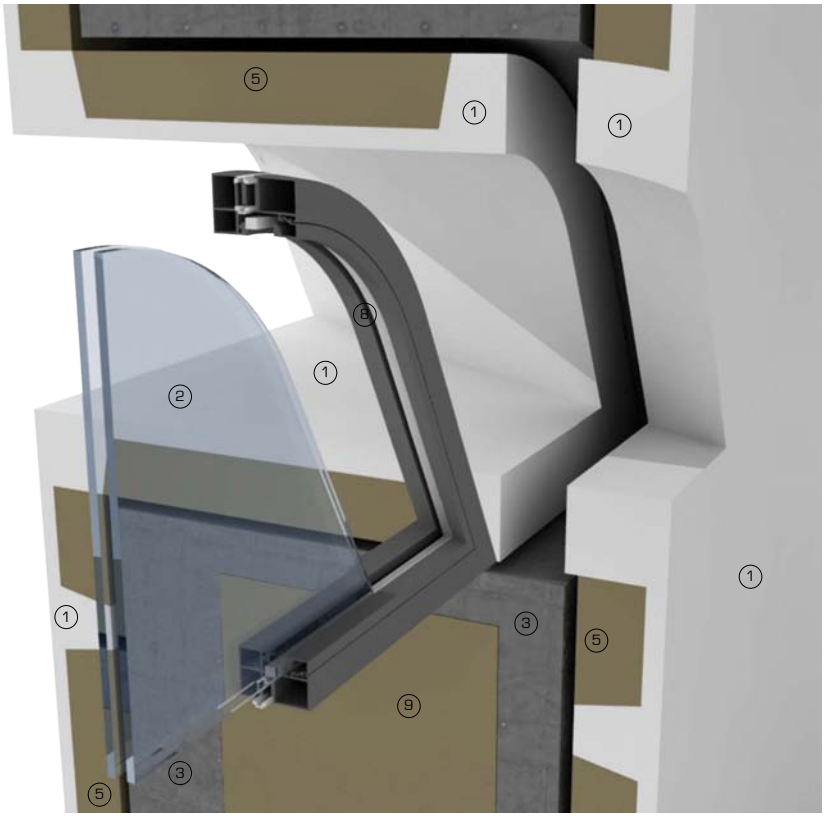
f |3D sectional detail view showing window set within GRC rainscreen cladding panels fixed to in-situ cast concrete primary structure



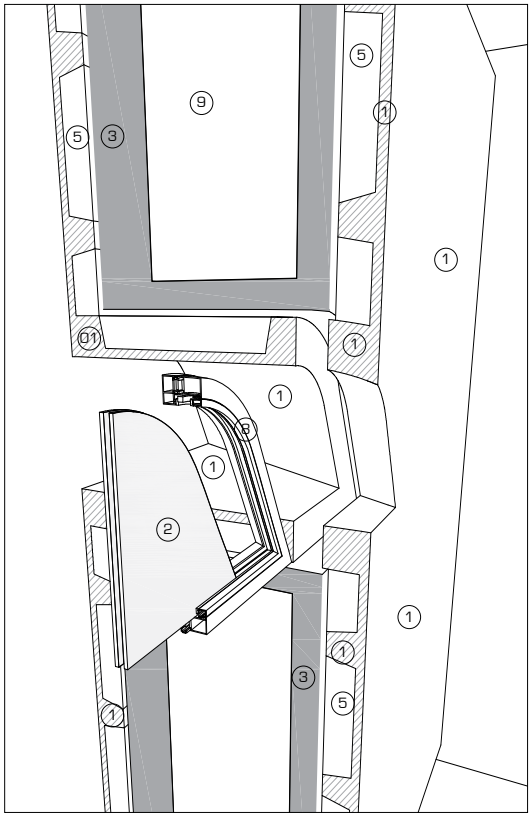
a | Horizontal section. Window in GRC wall



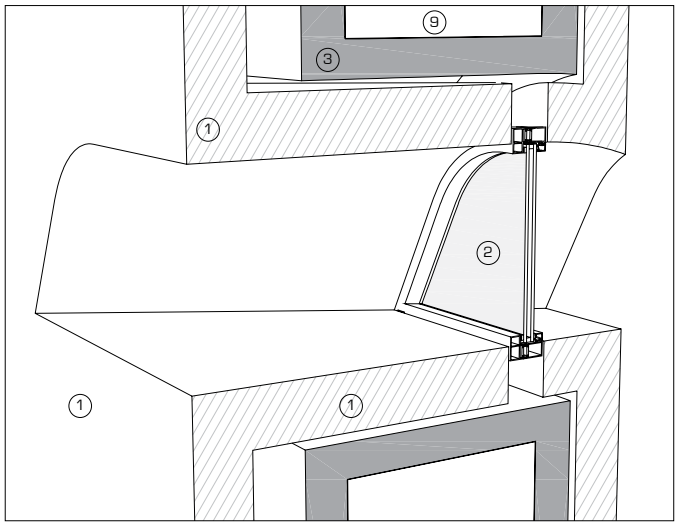
b | Horizontal section. Window in GRC wall

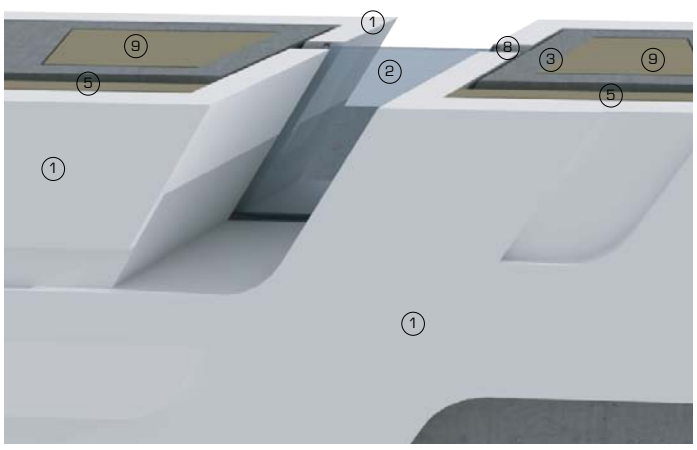


c | 3D exploded view showing window in GRC wall

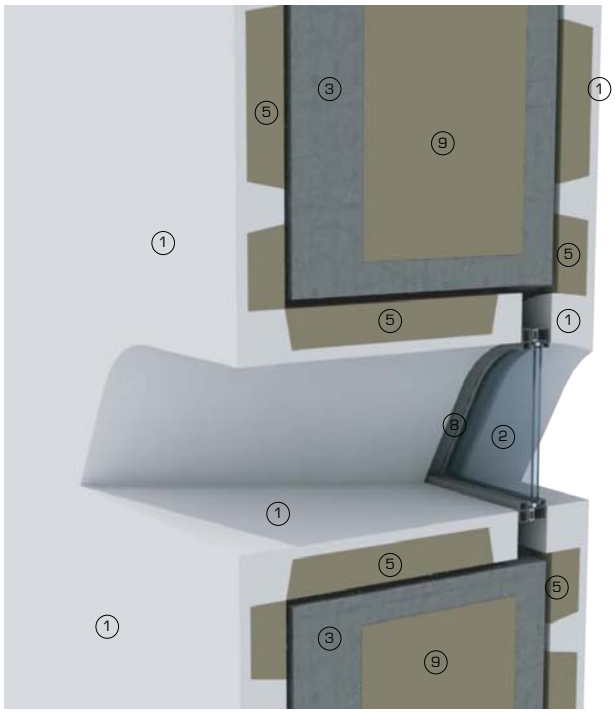


d | 3D exploded view showing window in GRC wall

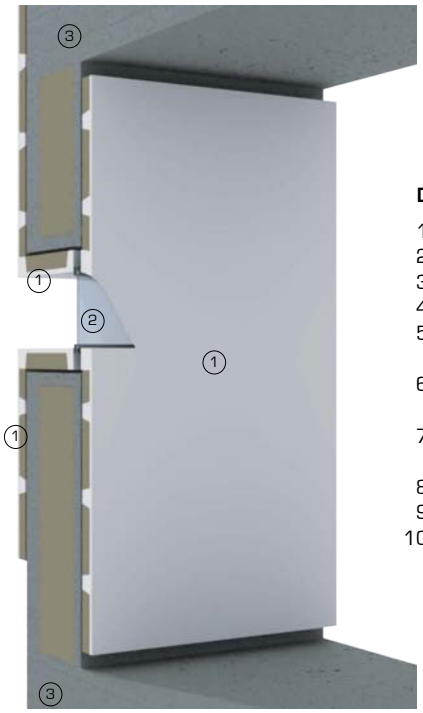




e | (Above) 3D view showing window frame in GRC cladding
f | (Right) 3D detail view showing glazing and GRC-faced wall connection



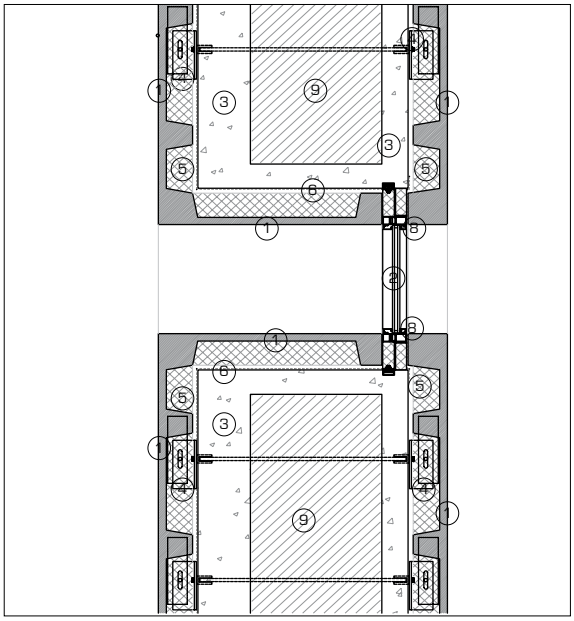
g |3D view showing window frame in GRC cladding



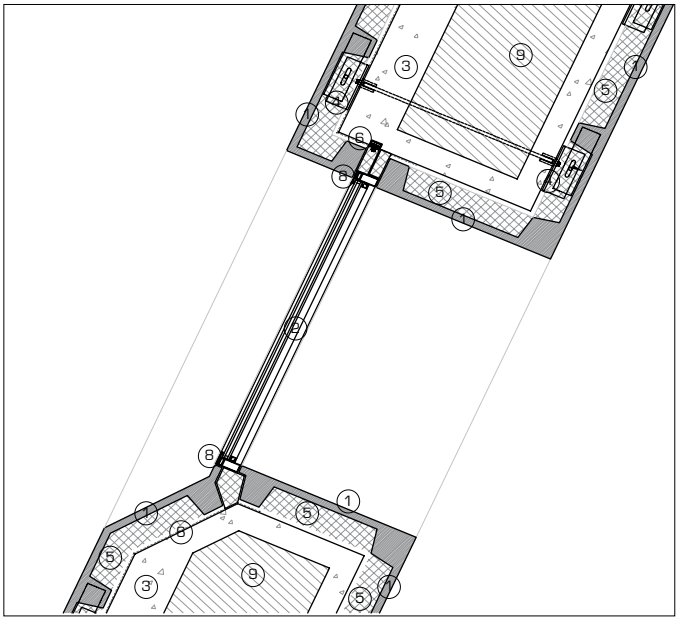
h |3D view showing window frame in GRC cladding

Details

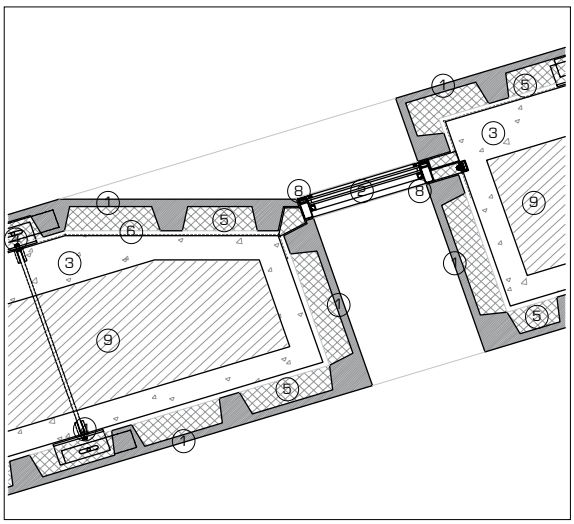
1 | GRC panel
2 | Double-glazed unit
3 | Concrete backing wall
4 | Deadload fixing to GRC panel
5 | Closed cell thermal insulation bonded to GRC panel
6 | Insulated separating layer between GRC & concrete wall
7 | Continuous waterproof membrane
8 | Thermally broken window profile
9 | Thermal insulation
10 | Secondary steelwork to contractor design



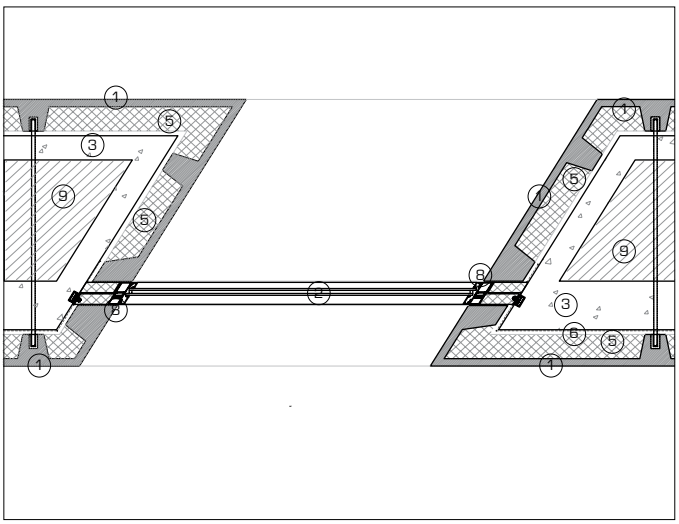
j |Vertical section. GRC cladding and glazing



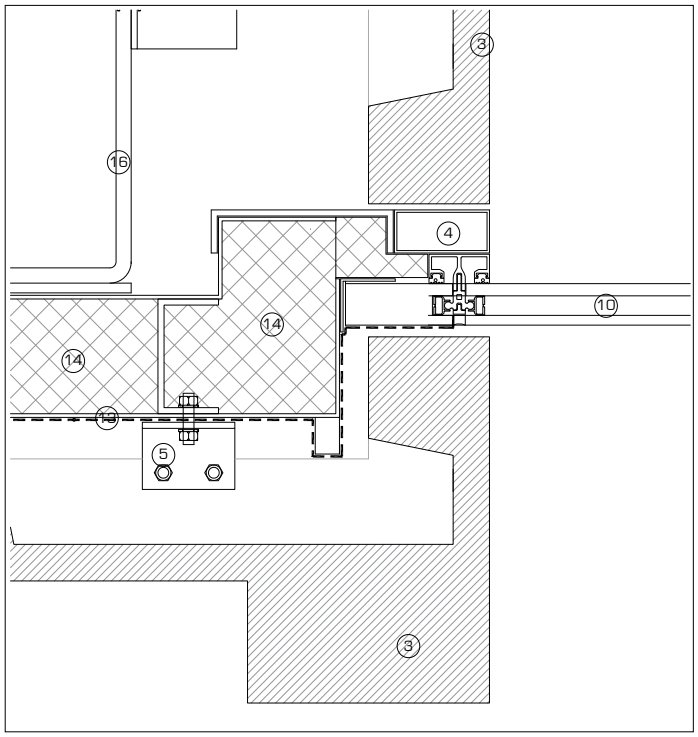
k | Vertical section. GRC cladding and glazing



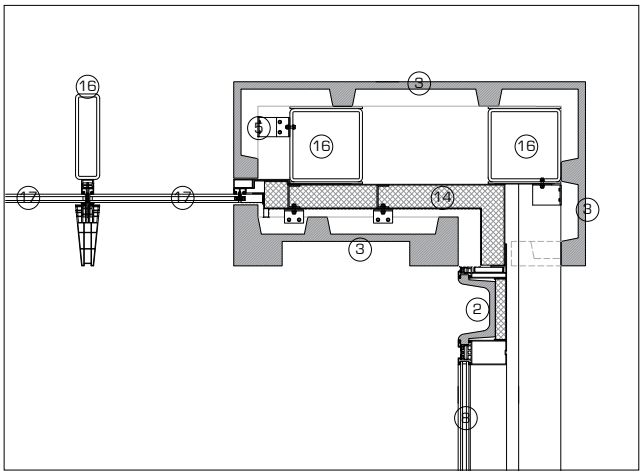
l |Horizontal section. GRC cladding and glazing



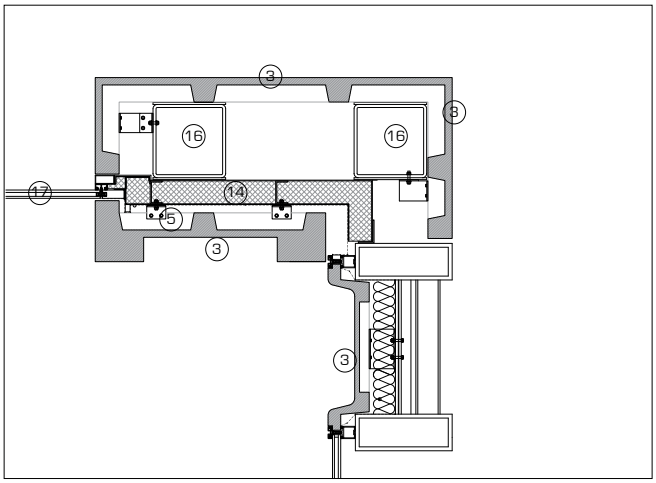
m| Horizontal section. GRC cladding and glazing



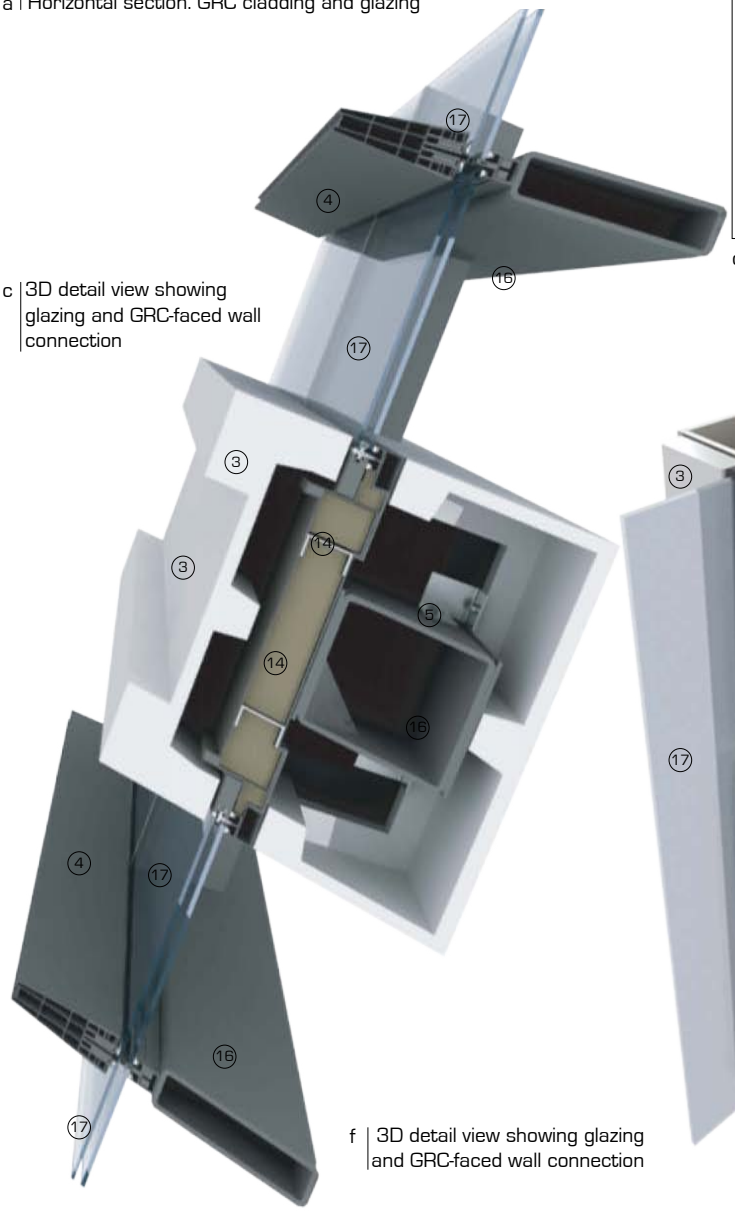
a | Horizontal section. GRC cladding and glazing



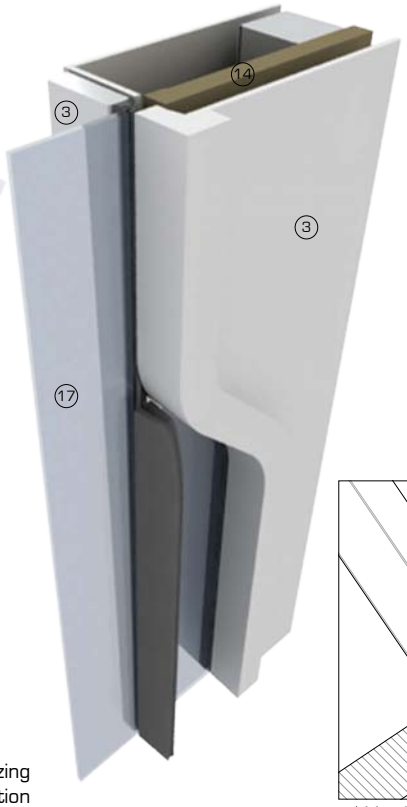
b | Horizontal section. GRC cladding and glazing



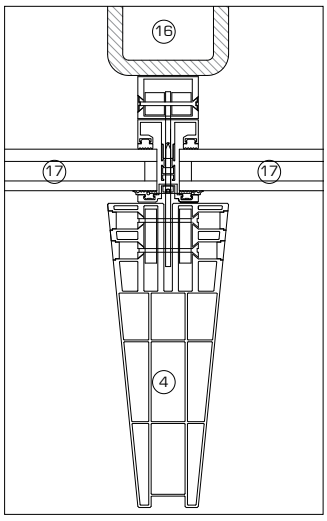
d | Horizontal section. GRC cladding and glazing



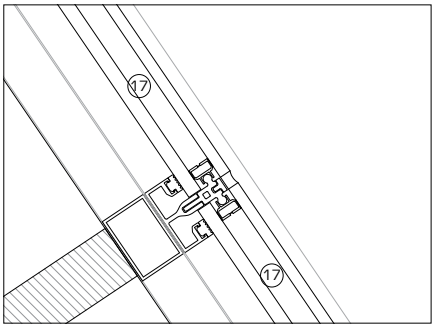
c | 3D detail view showing glazing and GRC-faced wall connection



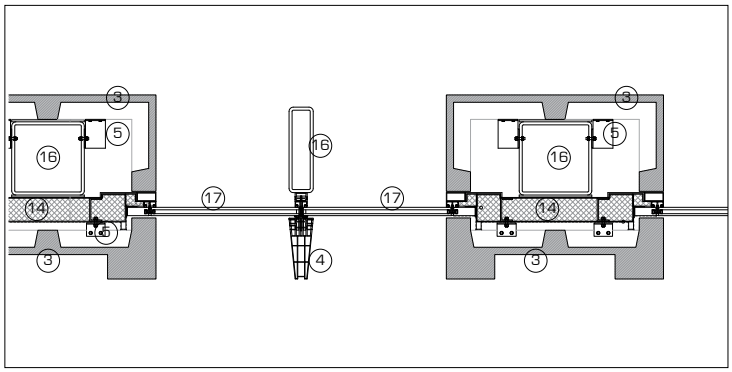
f | 3D detail view showing glazing and GRC-faced wall connection



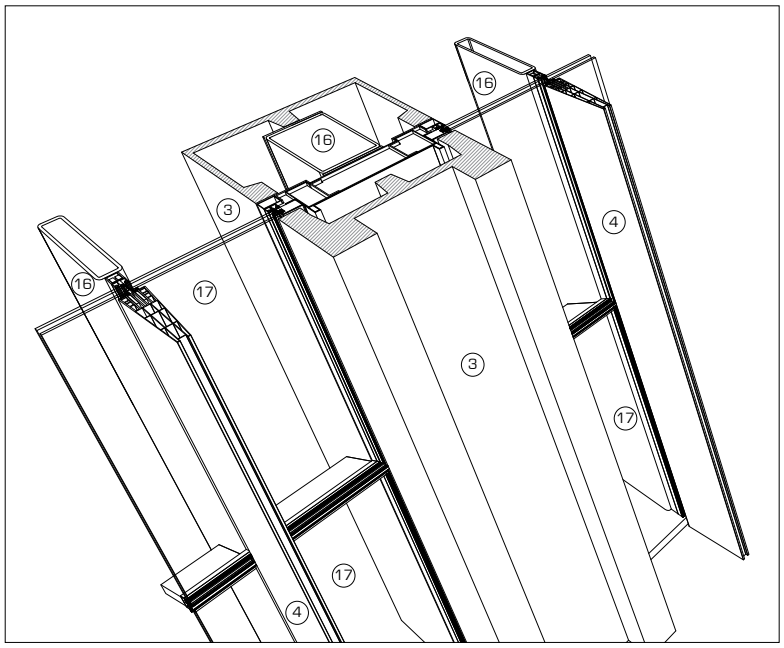
e | Horizontal section. Glazing



g | Vertical section. Glazing



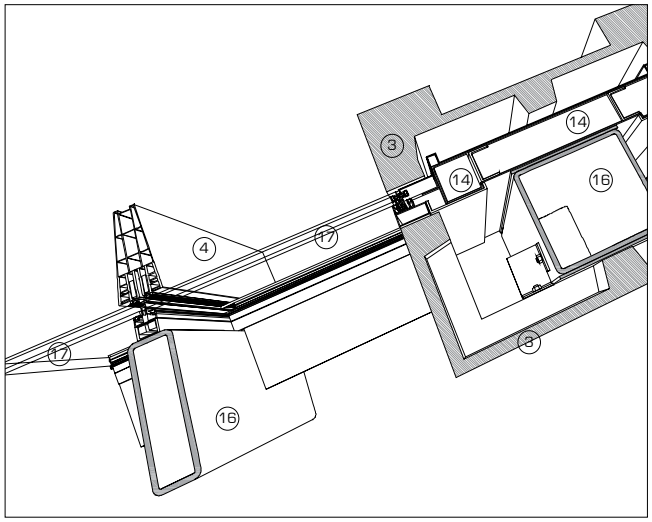
h | Horizontal section. GRC cladding and glazing



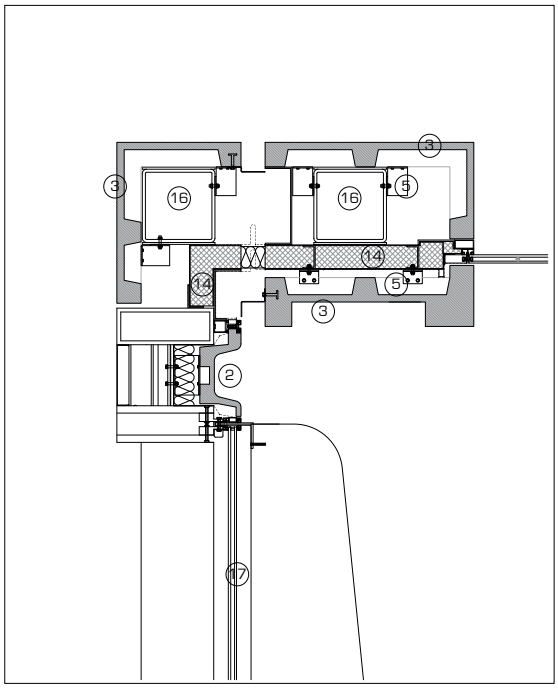
k | 3D detail view showing glazing and GRC-faced wall connection

Details

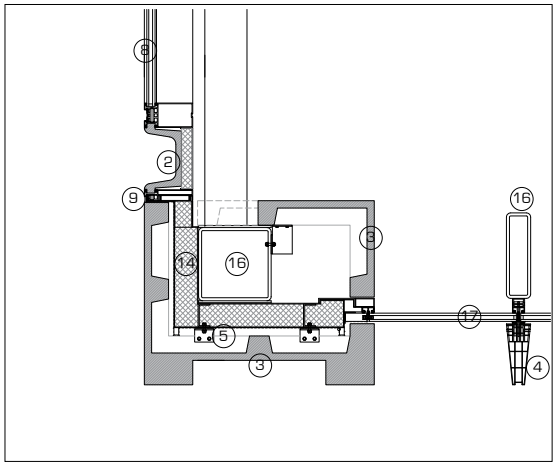
1 | GRC shadow gap panel
2 | Aluminium-faced insulated panel
3 | GRC panel
4 | Extruded aluminium section
5 | Fixing bracket for GRC panel
6 | GRC shading louvre
7 | Extruded aluminium support bracket for GRC shading louvre
8 | Double-glazed unit
9 | Unitised glazing frame
10 | Toggle-fixed glazing system
11 | Metal panel
12 | Rubber-based seal
13 | Continuous waterproof membrane
14 | Thermal insulation
15 | Metal flashing
16 | Secondary steelwork to contractor design
17 | Stick glazing



m | 3D detail of glazing and GRC-faced wall connection



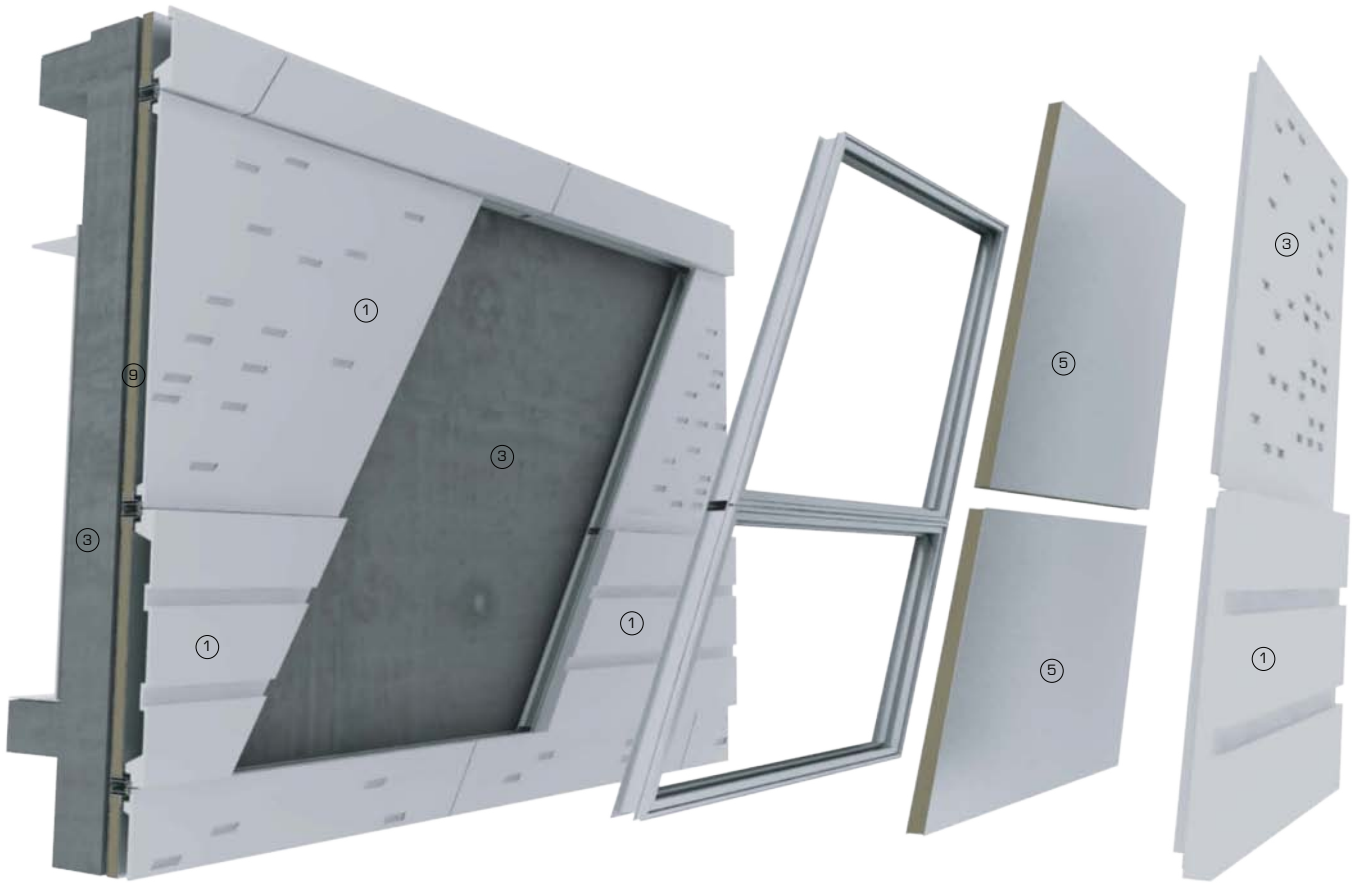
j | Horizontal section. GRC cladding and glazing



l | Horizontal section. GRC cladding and glazing



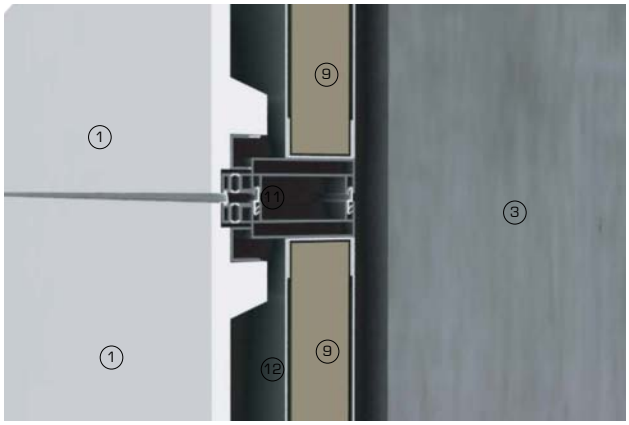
n | 3D detail view showing glazing and GRC-faced wall connection



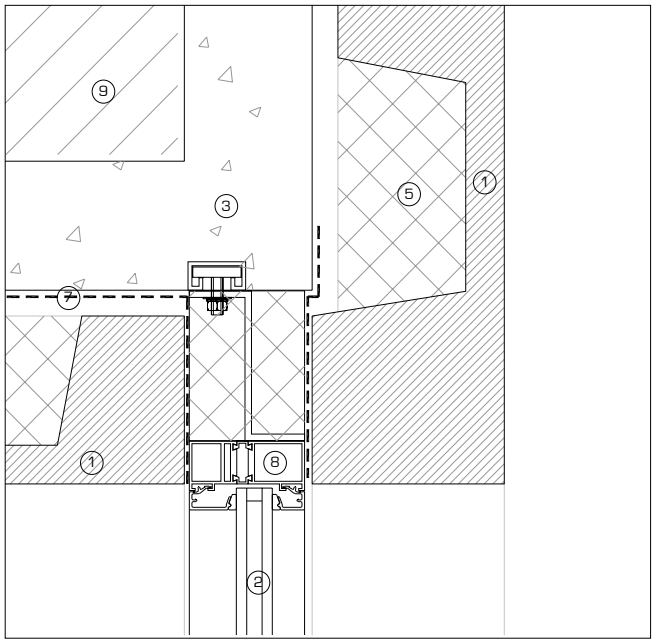
a | 3D exploded view showing external GRC cladding and glazing

Details

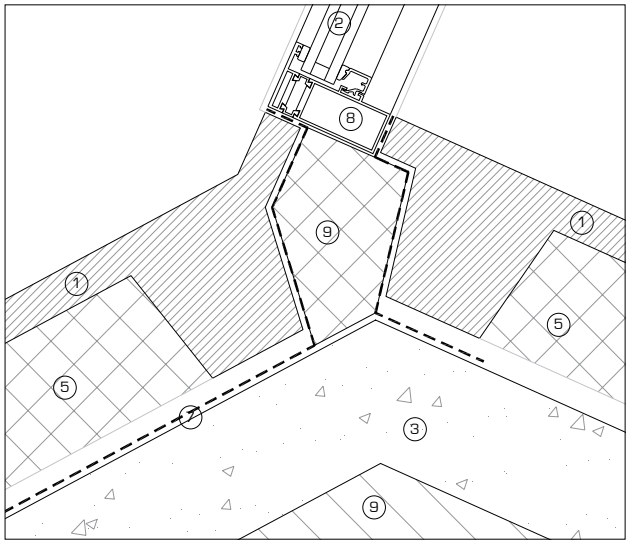
1	GRC panel
2	Double-glazed unit
3	Concrete backing wall
4	Deadload fixing to GRC panel
5	Closed cell thermal insulation bonded to GRC panel
6	Insulated separating layer between GRC & concrete wall
7	Continuous waterproof membrane
8	Thermally broken window profile
9	Thermal insulation
10	Secondary steelwork to contractor design
11	Frame for GRC panel
12	Metal panel



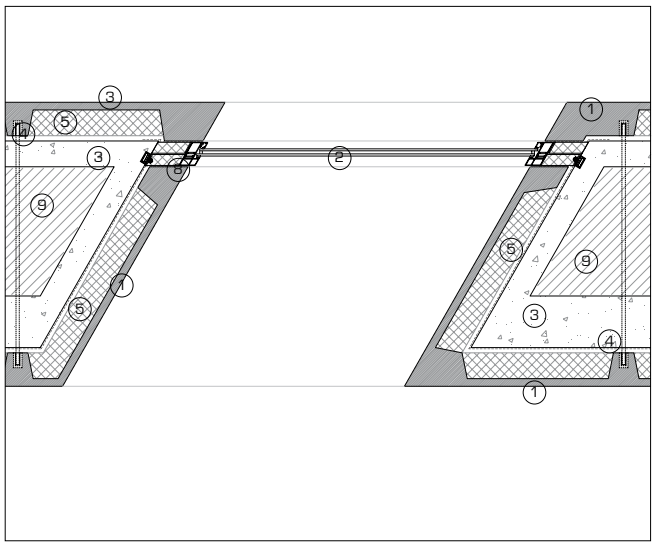
b | 3D detail view showing external GRC cladding



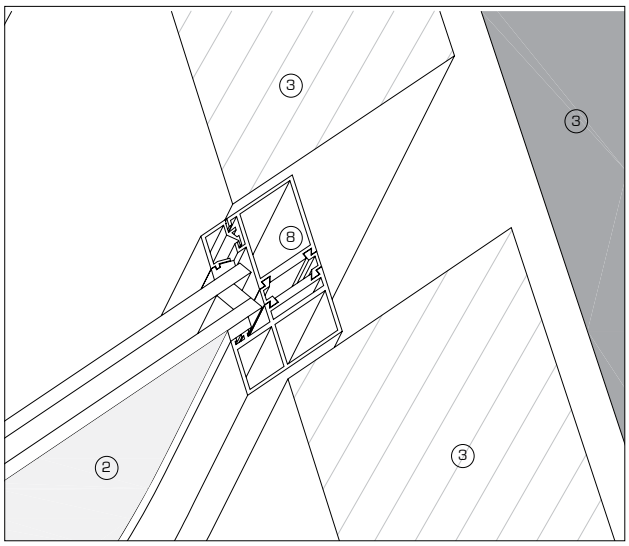
c | Vertical section. GRC cladding and glazing



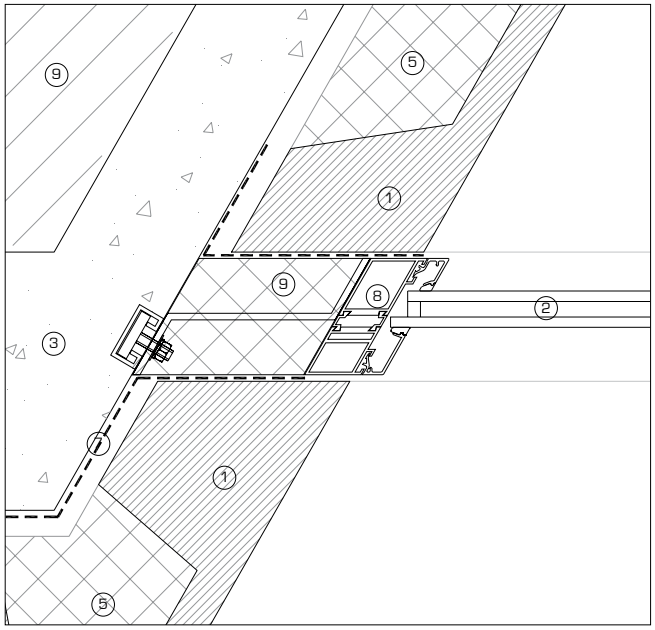
d | Vertical section. GRC cladding and glazing



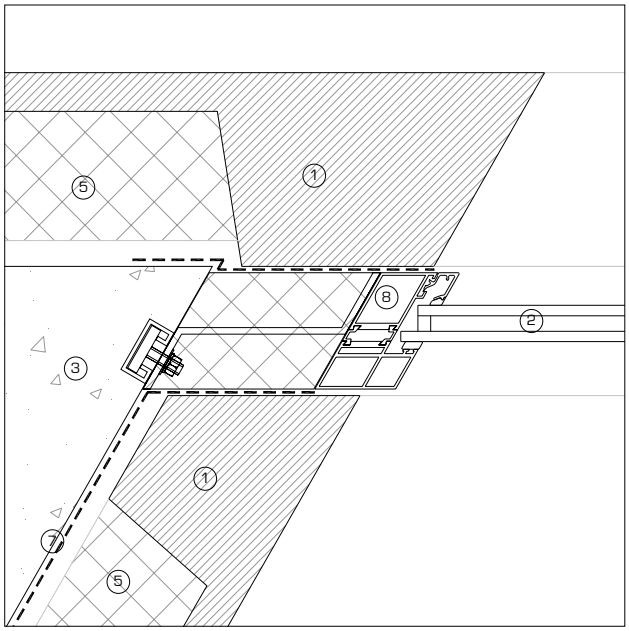
e | Horizontal section. GRC cladding and glazing



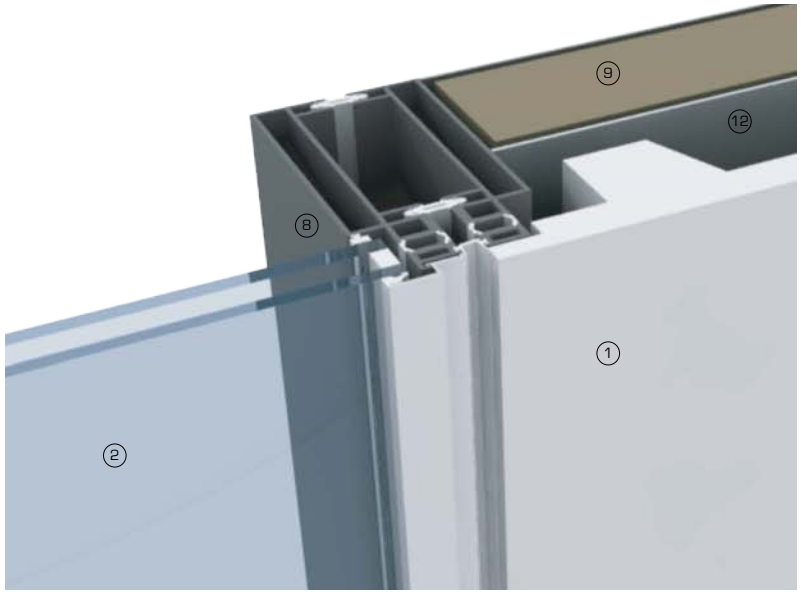
f | 3D view showing window frame in GRC cladding



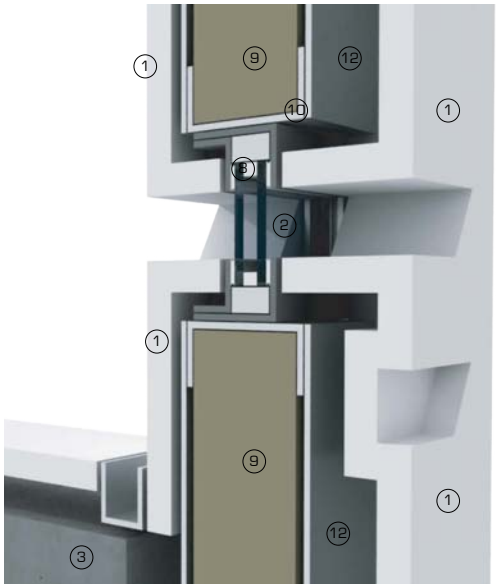
g | Horizontal section. GRC cladding and glazing



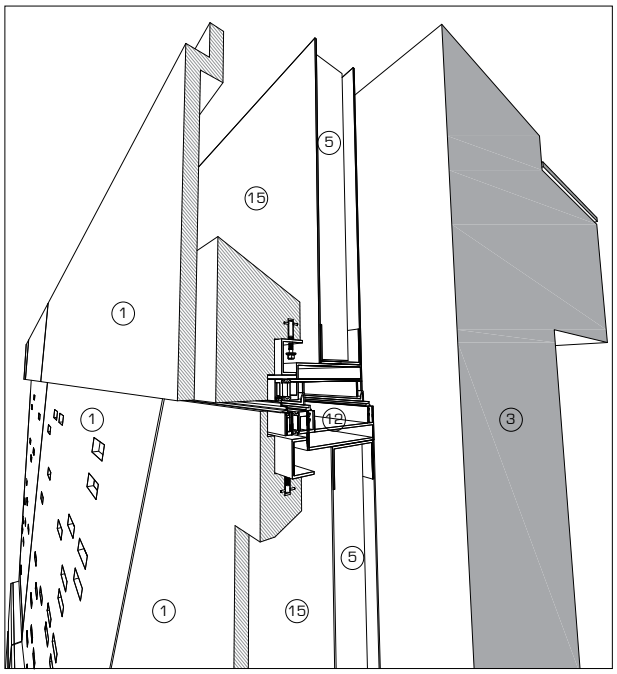
h | Horizontal section. GRC cladding and glazing



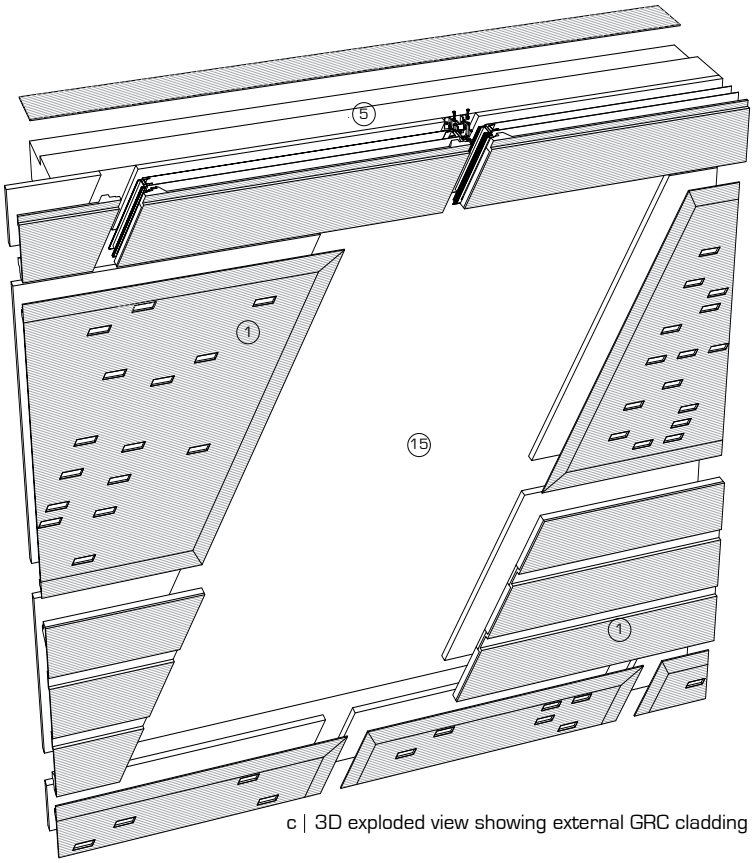
j | 3D detail view showing external GRC cladding and glazing



k | 3D detail view showing external GRC cladding and glazing

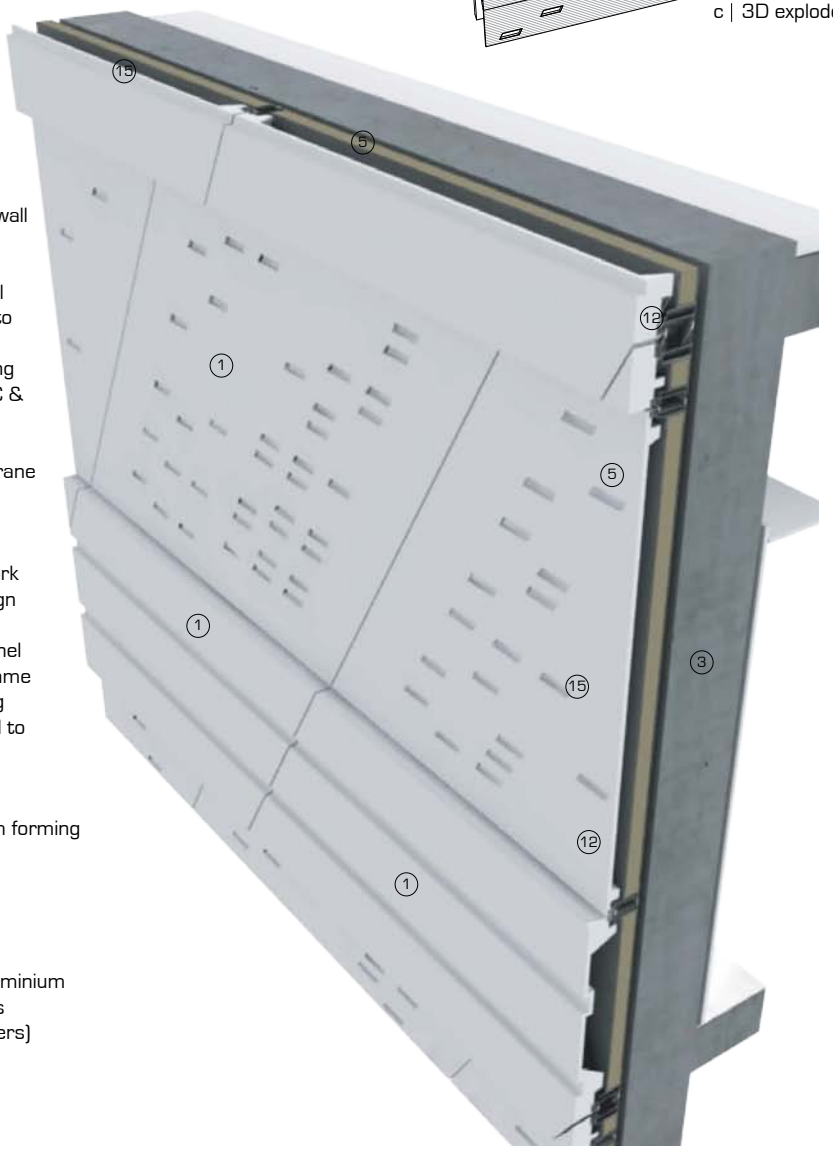


a | 3D detail view showing external GRC cladding



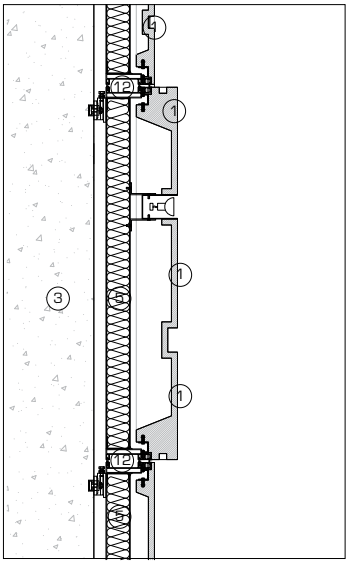
c | 3D exploded view showing external GRC cladding

b | 3D view showing external GRC cladding

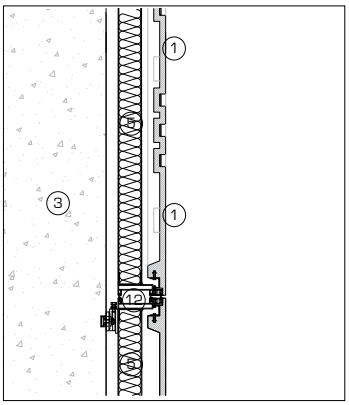


Details

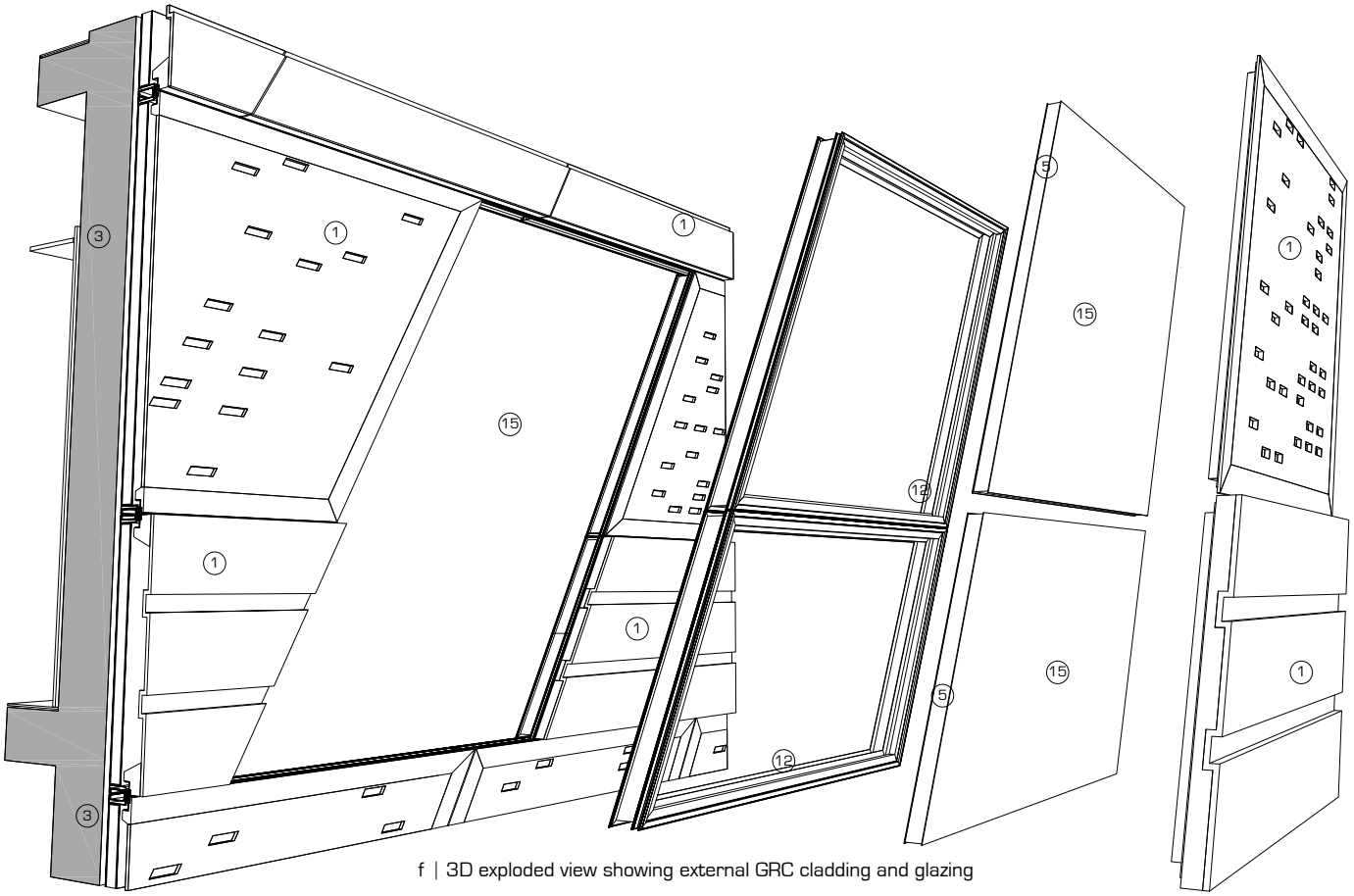
1 | GRC panel
2 | Double-glazed unit
3 | Concrete backing wall
4 | Deadload fixing to GRC panel
5 | Closed cell thermal insulation bonded to GRC panel
6 | Insulated separating layer between GRC & concrete wall
7 | Continuous waterproof membrane
8 | Thermally broken window profile
9 | Thermal insulation
10 | Secondary steelwork to contractor design
11 | Fixing bracket
12 | Frame for GRC panel
13 | Unitised glazing frame
14 | Bracket supporting unitised panel fixed to top of slab
15 | Metal panel
16 | Thermal break
17 | Extruded aluminium forming unitised panel
18 | Rubber based seal
19 | Outer seal
20 | Inner seal
21 | Air seal
22 | Insulated panel, aluminium faced on both sides
23 | Light fitting (by others)



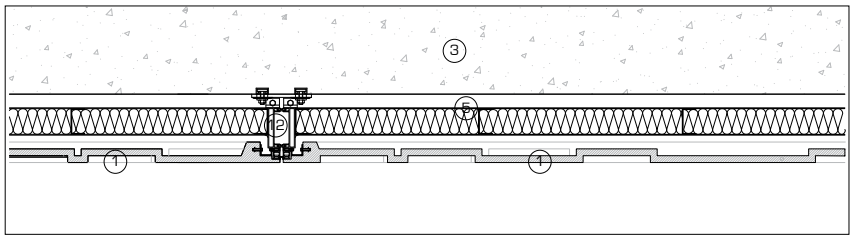
d | Vertical section. GRC cladding



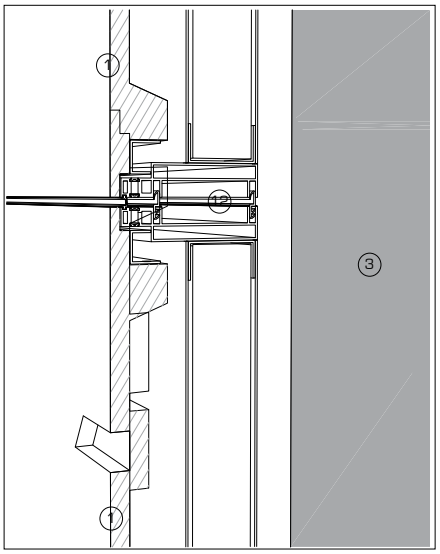
e | Vertical section. GRC cladding



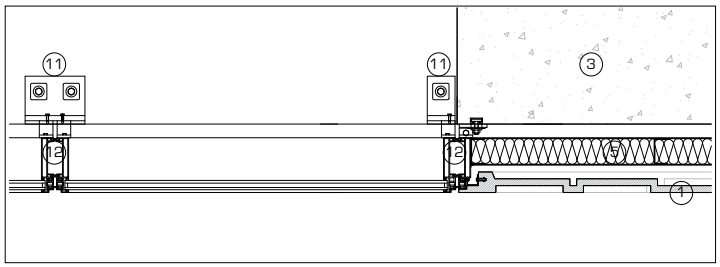
f | 3D exploded view showing external GRC cladding and glazing



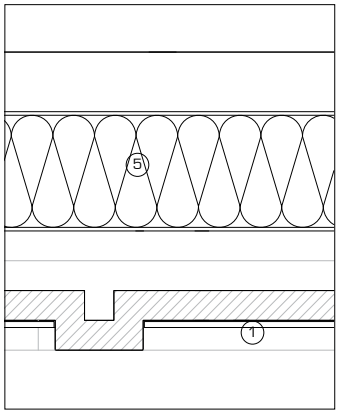
g | Horizontal section. GRC cladding



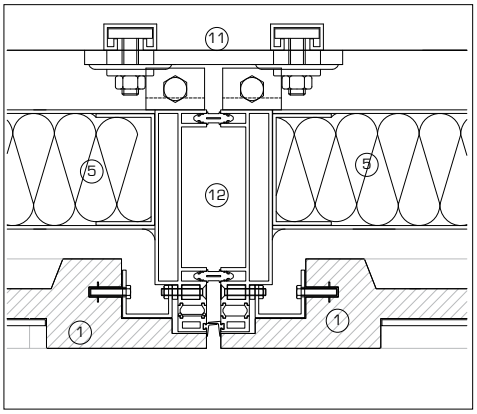
j | Vertical section. GRC cladding



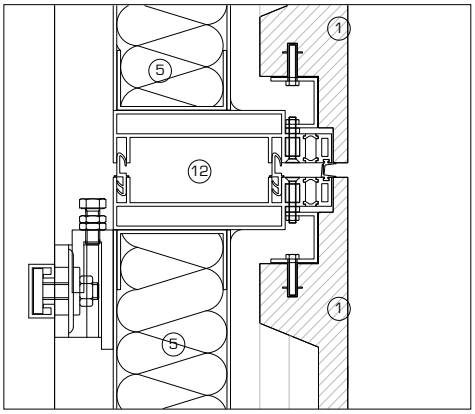
h | Horizontal section. GRC cladding and glazing



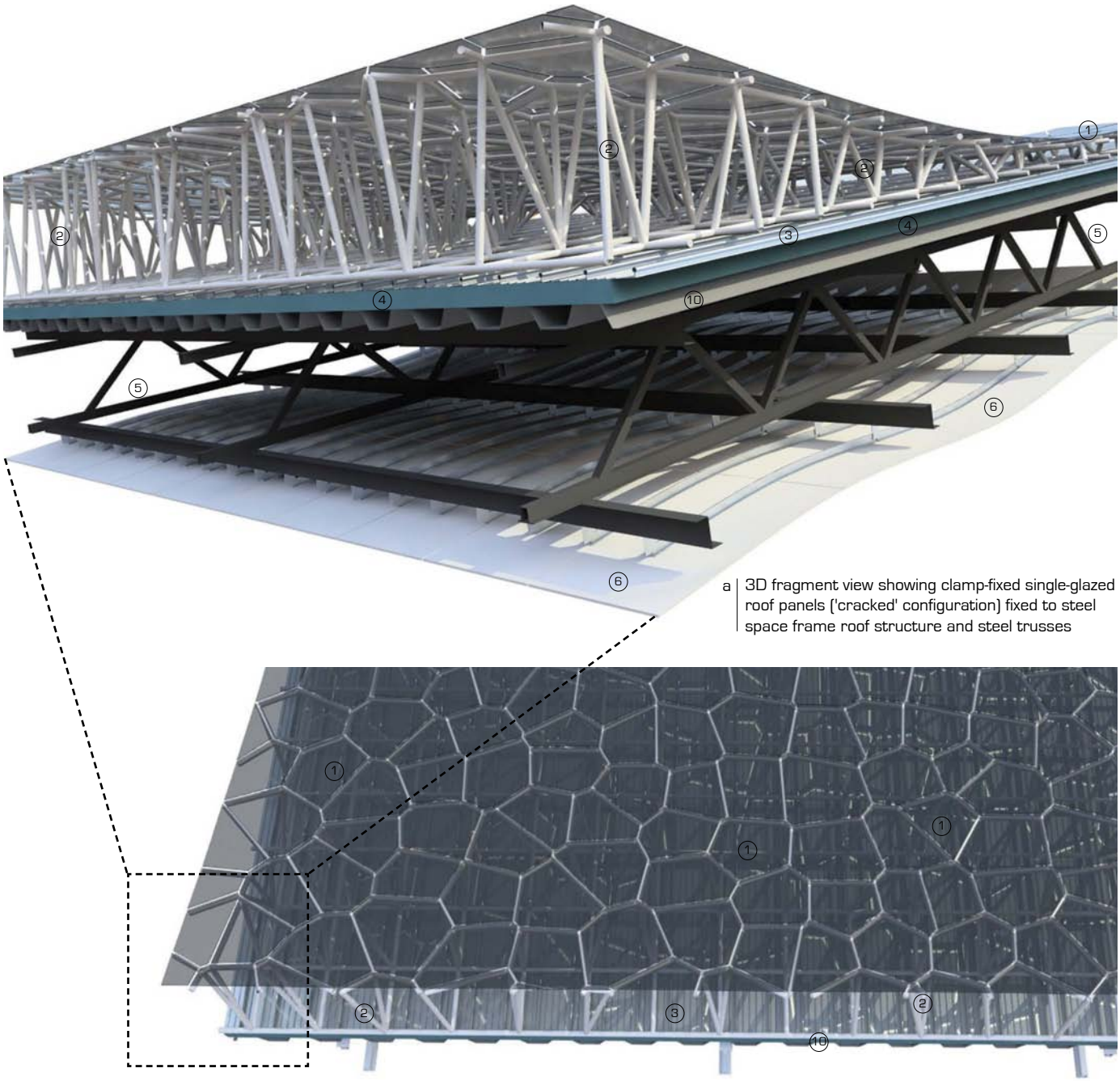
k | Horizontal section. GRC cladding



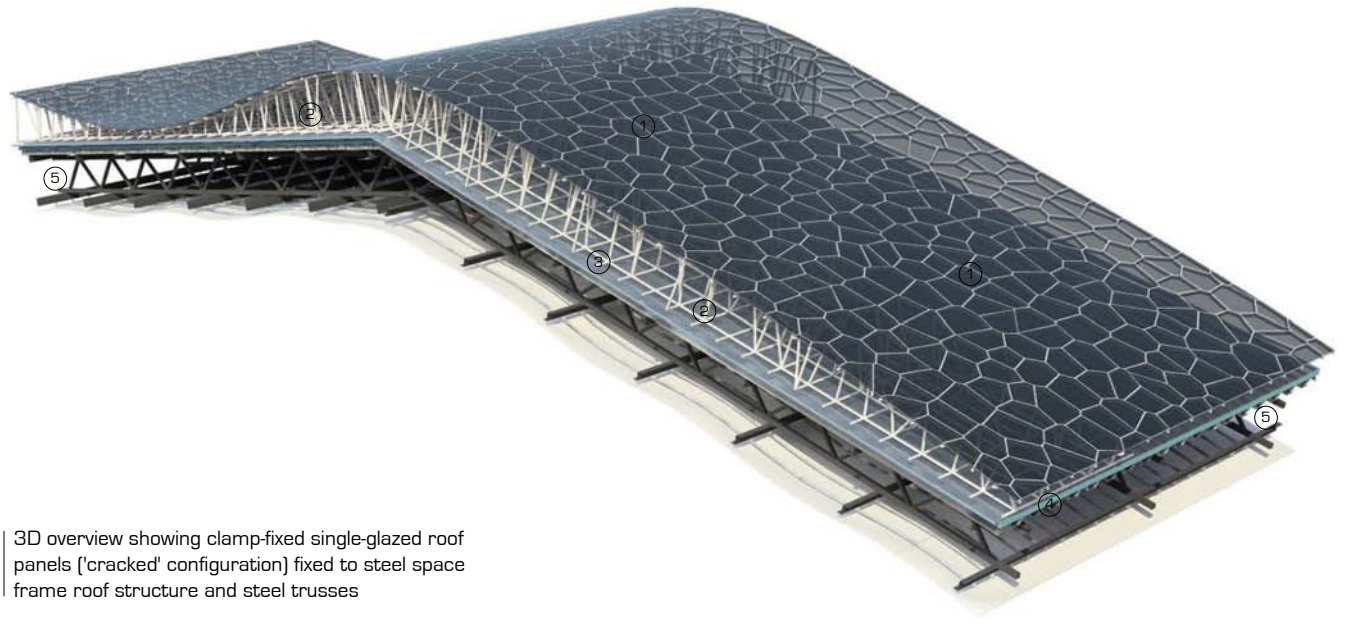
l | Horizontal section. GRC cladding



m | Horizontal section. GRC cladding



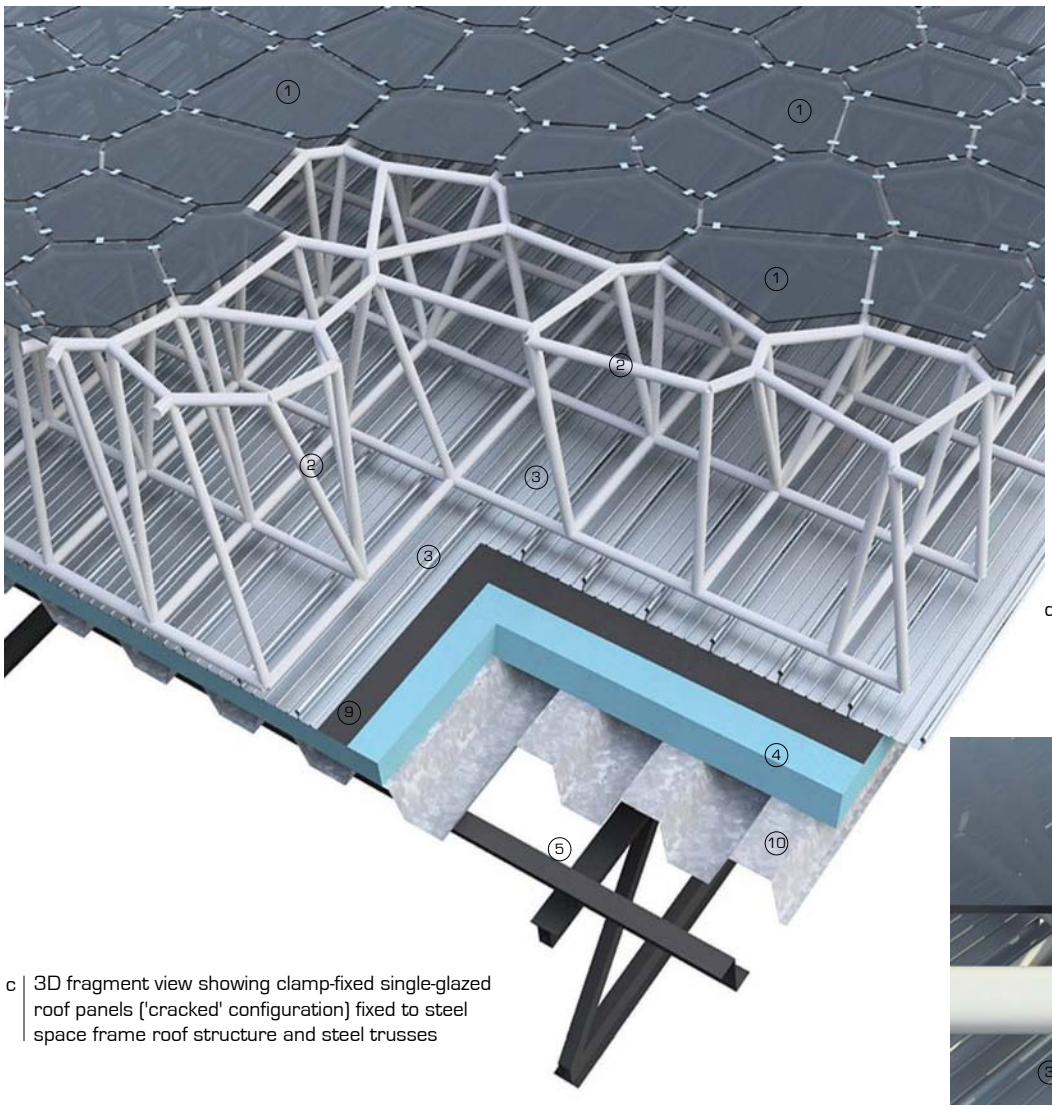
a | 3D fragment view showing clamp-fixed single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure and steel trusses



b | 3D overview showing clamp-fixed single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure and steel trusses

Details

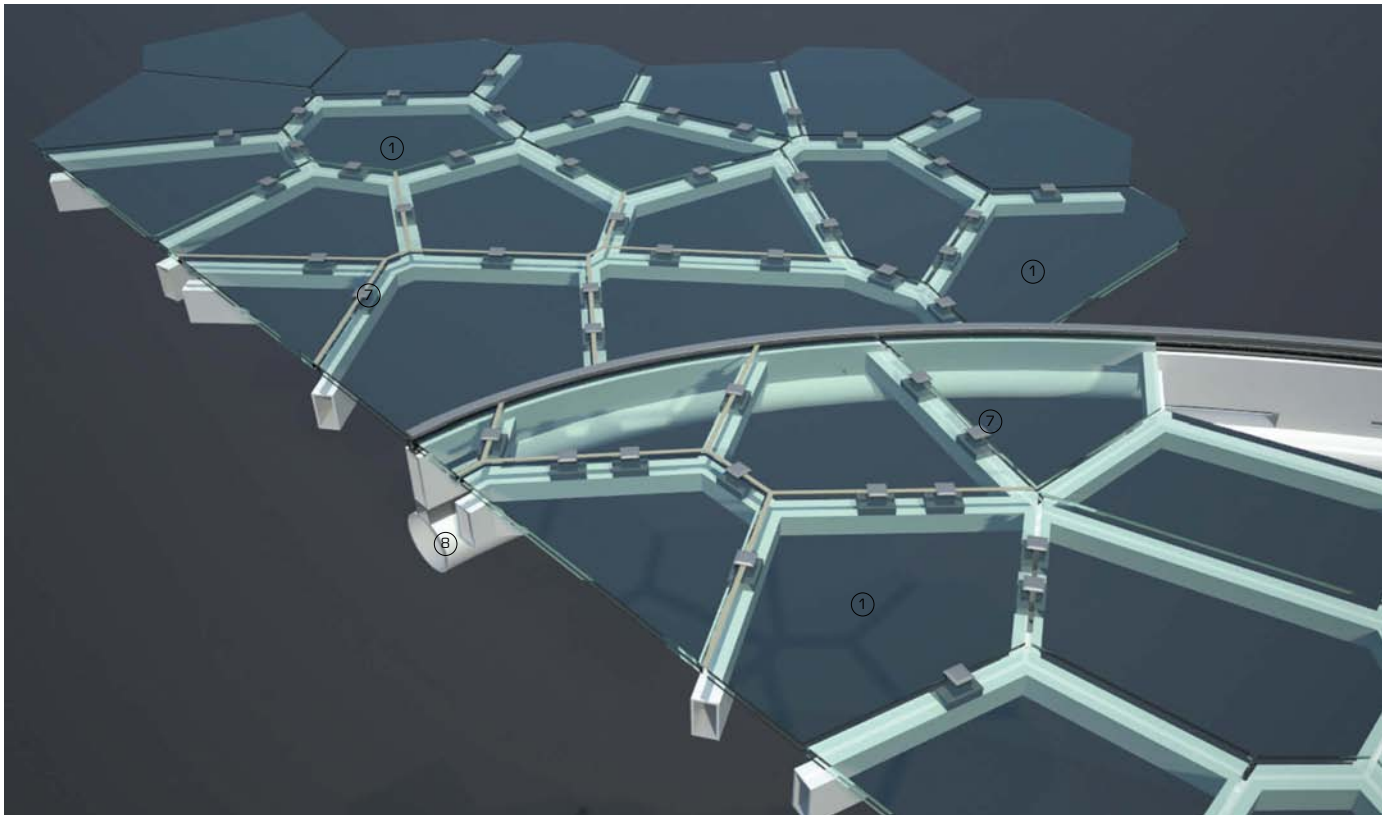
1 | Glazed cladding panels
2 | Steel space frame roof support
3 | Standing seam metal deck
4 | Thermal insulation
5 | Steel roof truss structure
6 | Internal finish
7 | Glazing clamp
8 | Steel tube cladding support
9 | Waterproof membrane
10 | Profiled metal deck



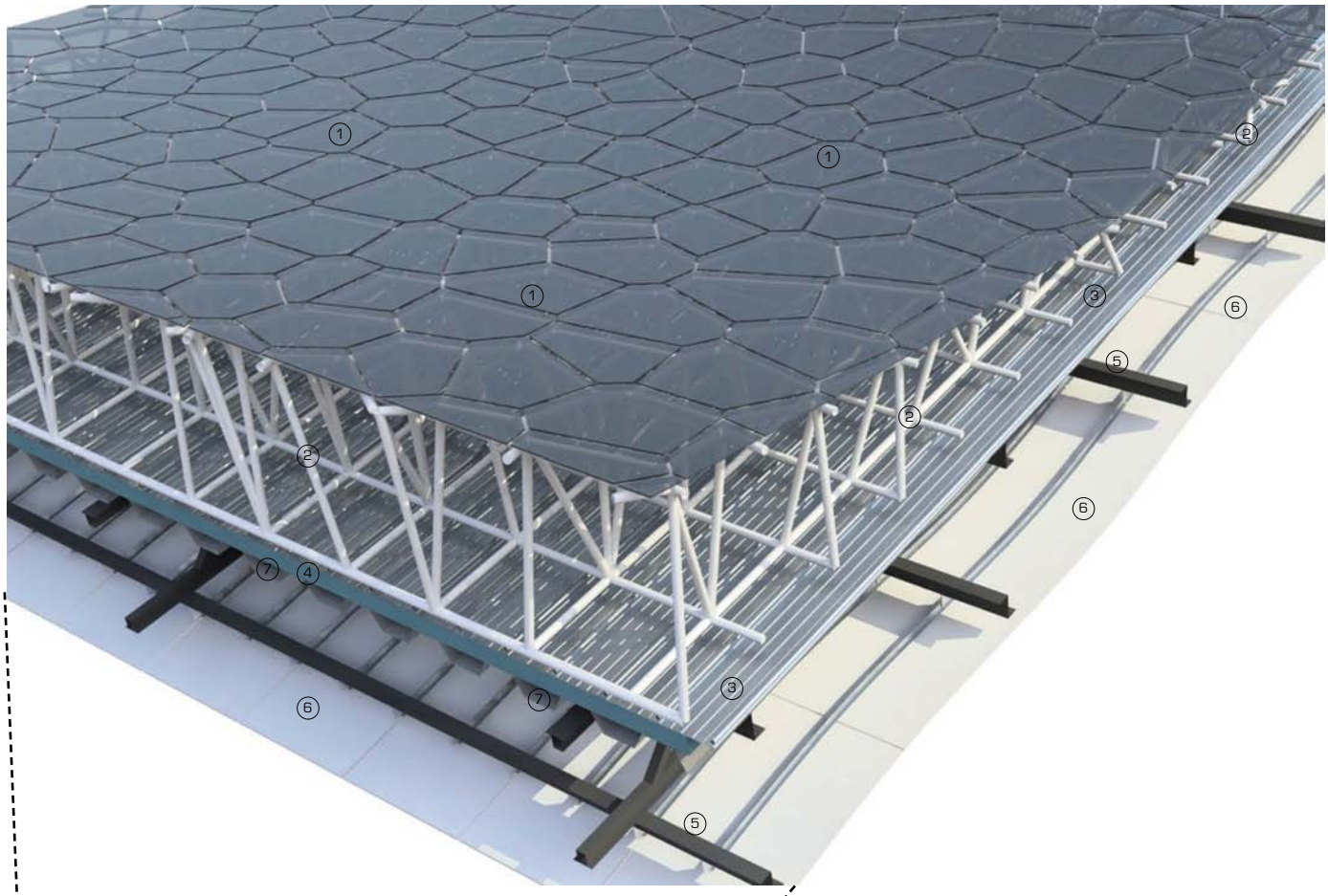
c | 3D fragment view showing clamp-fixed single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure and steel trusses

d | (Below) 3D detail view showing clamp-fixing on single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure

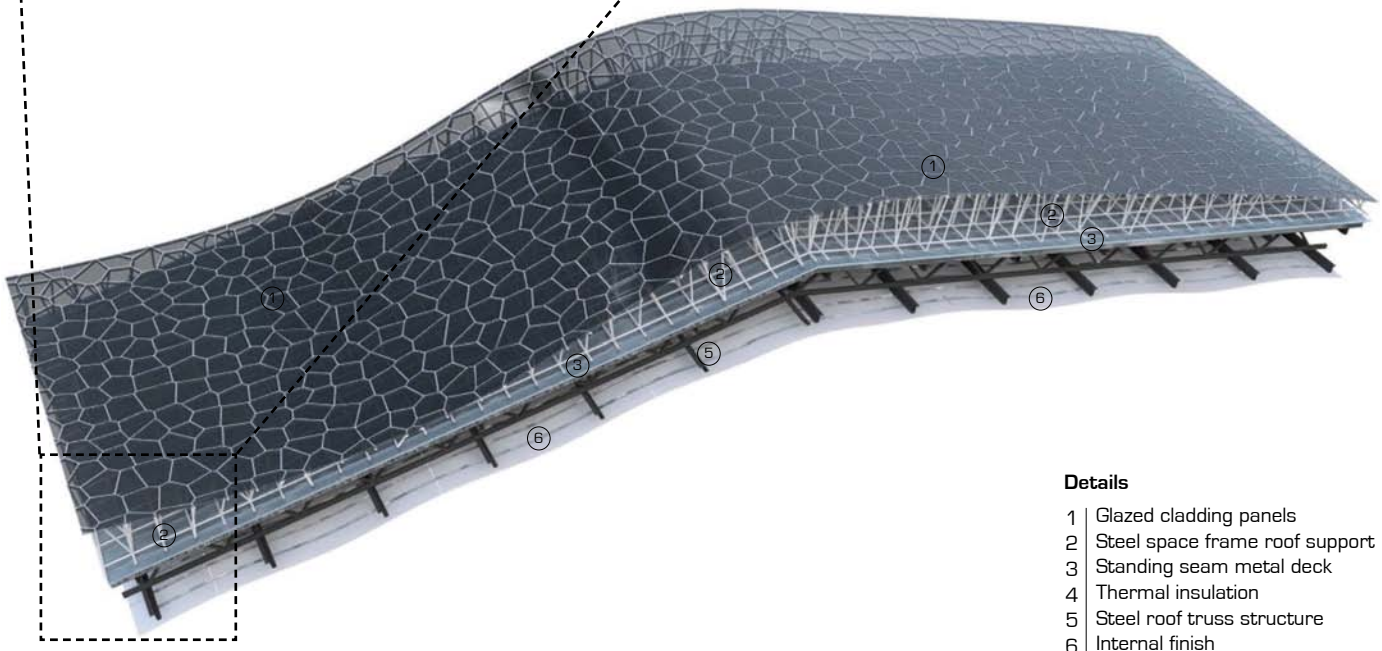




e | Working digital model of clamp-fixed single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure



a | 3D fragment view showing clamp-fixed single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure and steel trusses



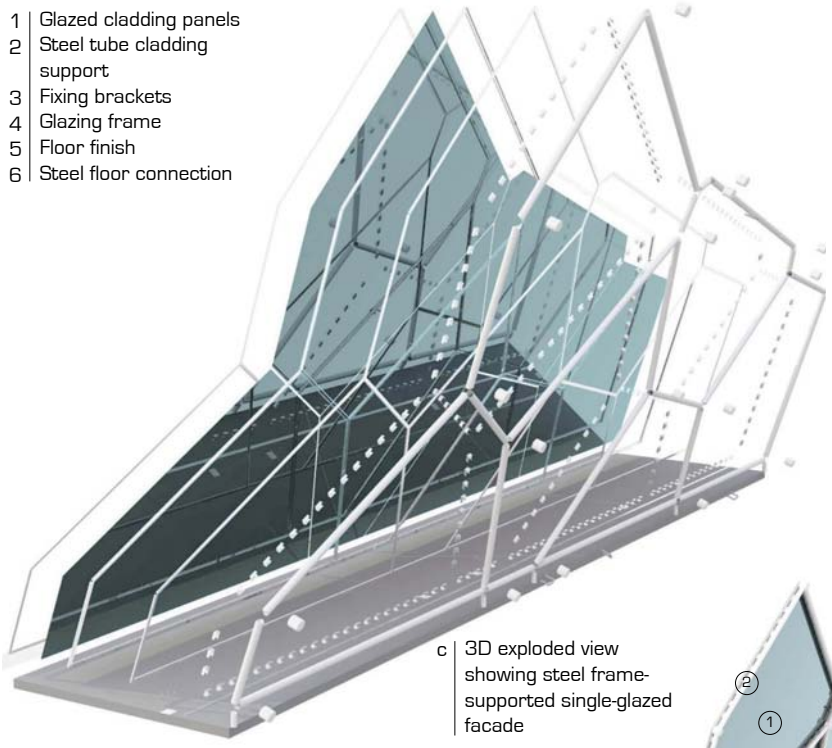
b | 3D overview showing clamp-fixed single-glazed roof panels ('cracked' configuration) fixed to steel space frame roof structure and steel trusses

Details

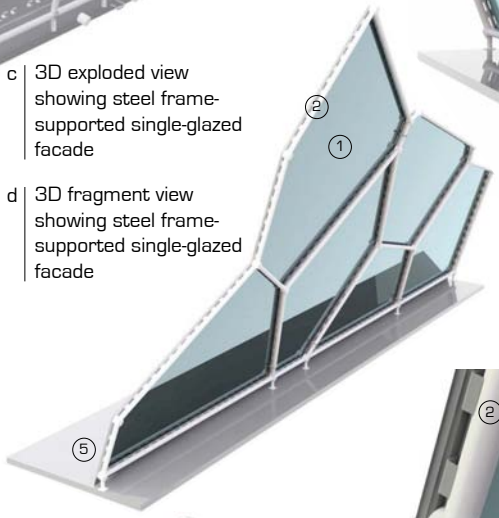
1 | Glazed cladding panels
2 | Steel space frame roof support
3 | Standing seam metal deck
4 | Thermal insulation
5 | Steel roof truss structure
6 | Internal finish
7 | Profiled metal deck

Details

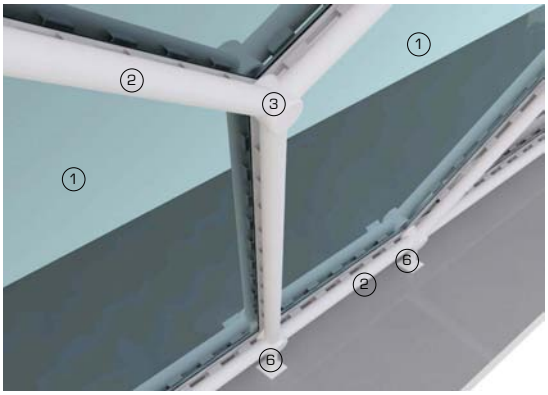
1 | Glazed cladding panels
2 | Steel tube cladding support
3 | Fixing brackets
4 | Glazing frame
5 | Floor finish
6 | Steel floor connection

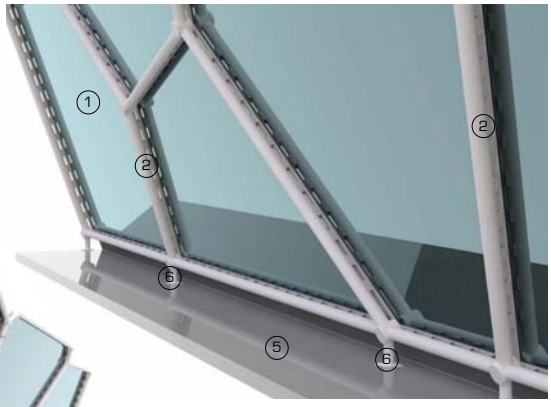


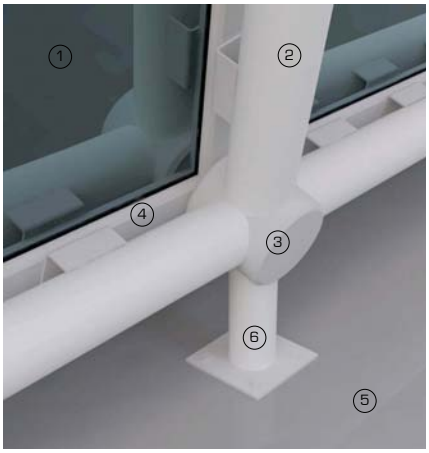
c | 3D exploded view showing steel frame-supported single-glazed facade



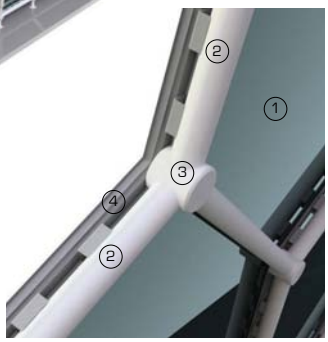
d | 3D fragment view showing steel frame-supported single-glazed facade

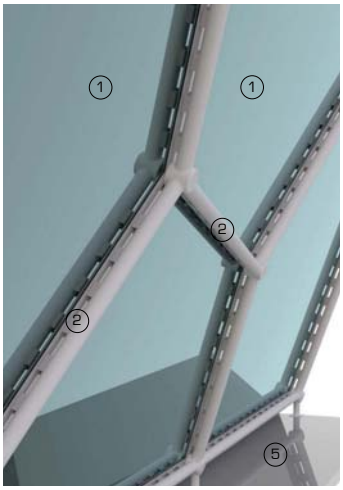


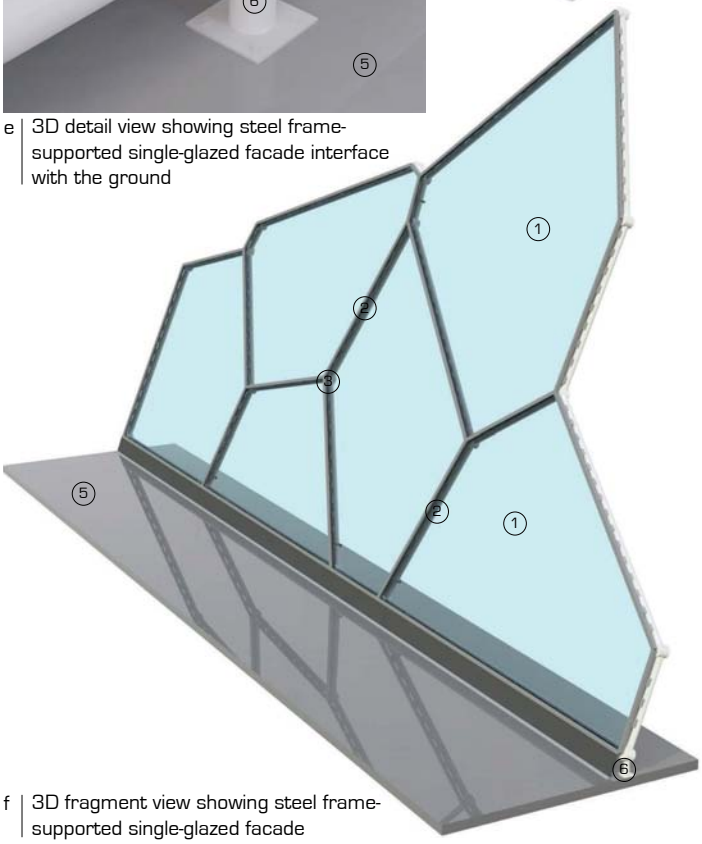




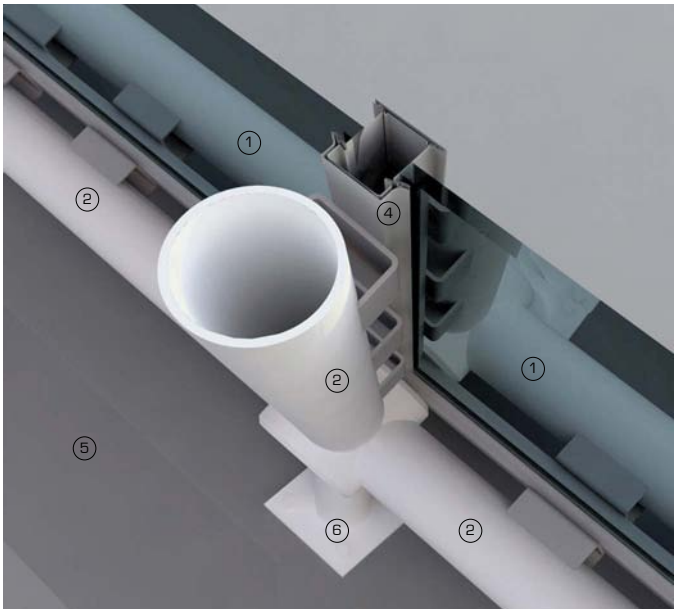
e | 3D detail view showing steel frame-supported single-glazed facade interface with the ground



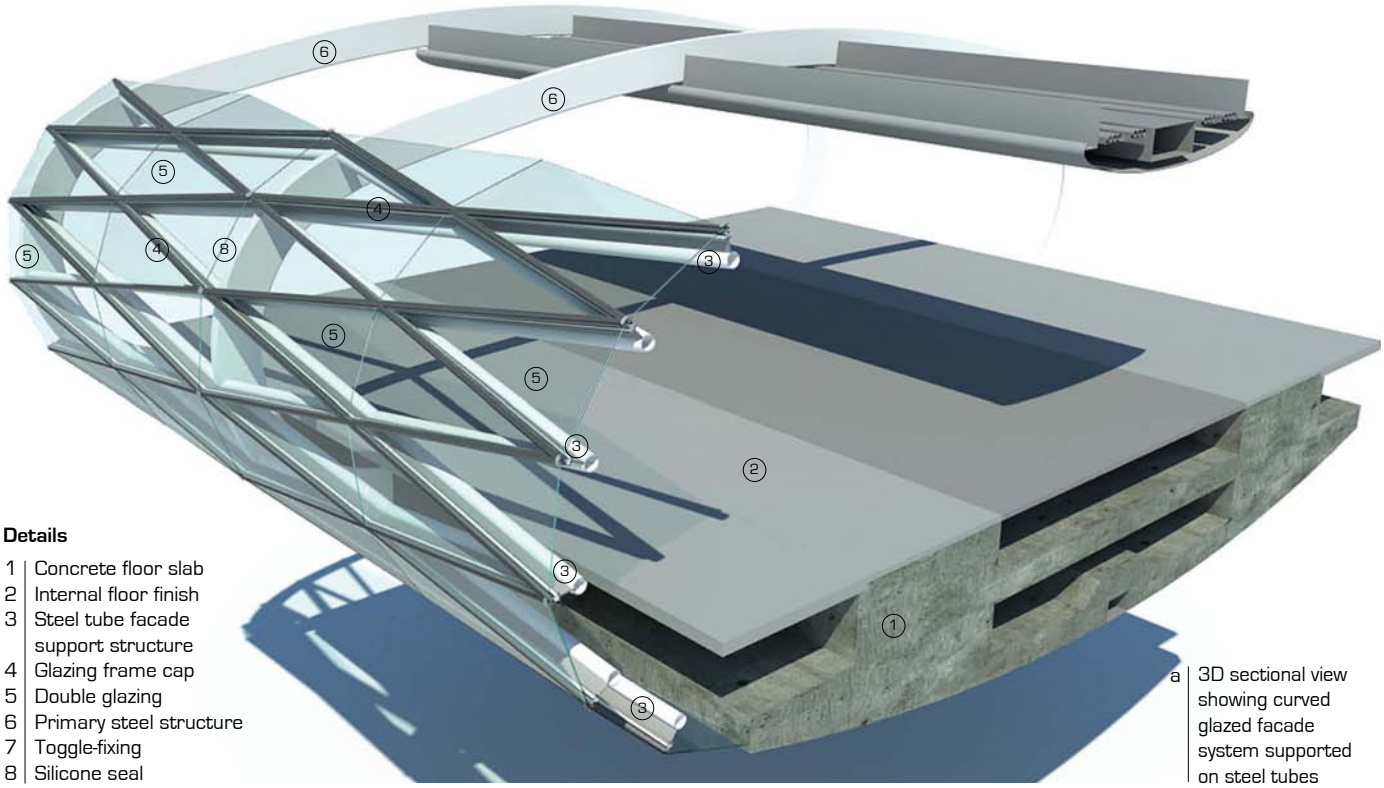




f | 3D fragment view showing steel frame-supported single-glazed facade



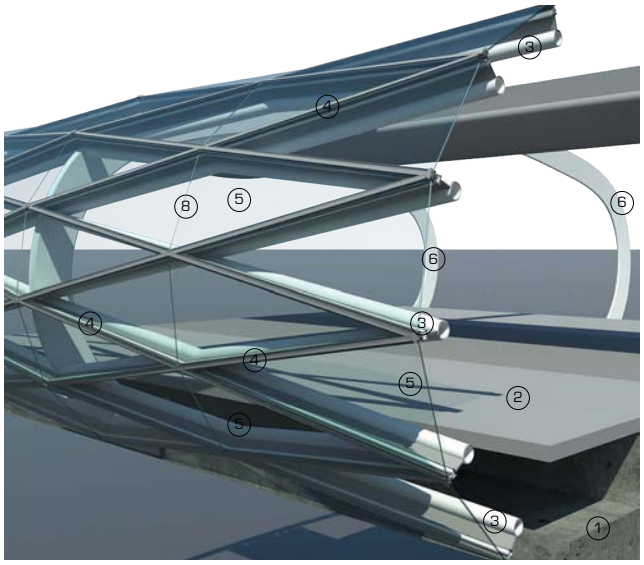
g | 3D detail views showing steel frame-supported single-glazed facade



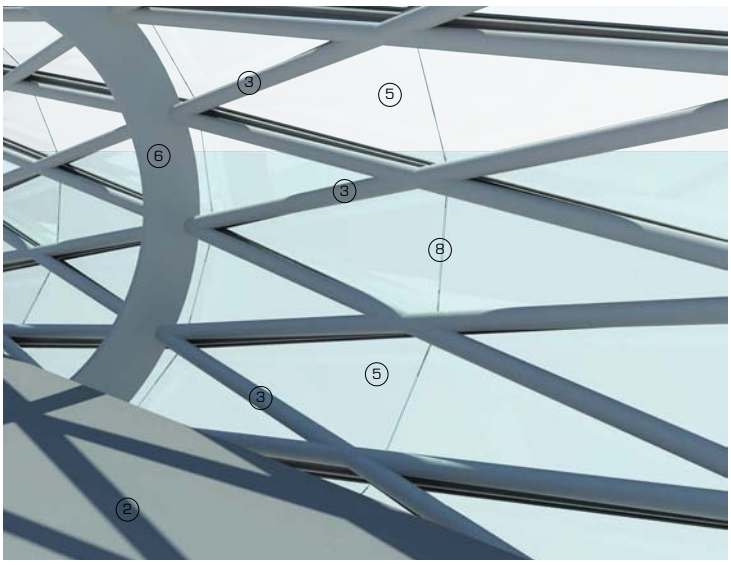
Details

1 | Concrete floor slab
2 | Internal floor finish
3 | Steel tube facade support structure
4 | Glazing frame cap
5 | Double glazing
6 | Primary steel structure
7 | Toggle-fixing
8 | Silicone seal

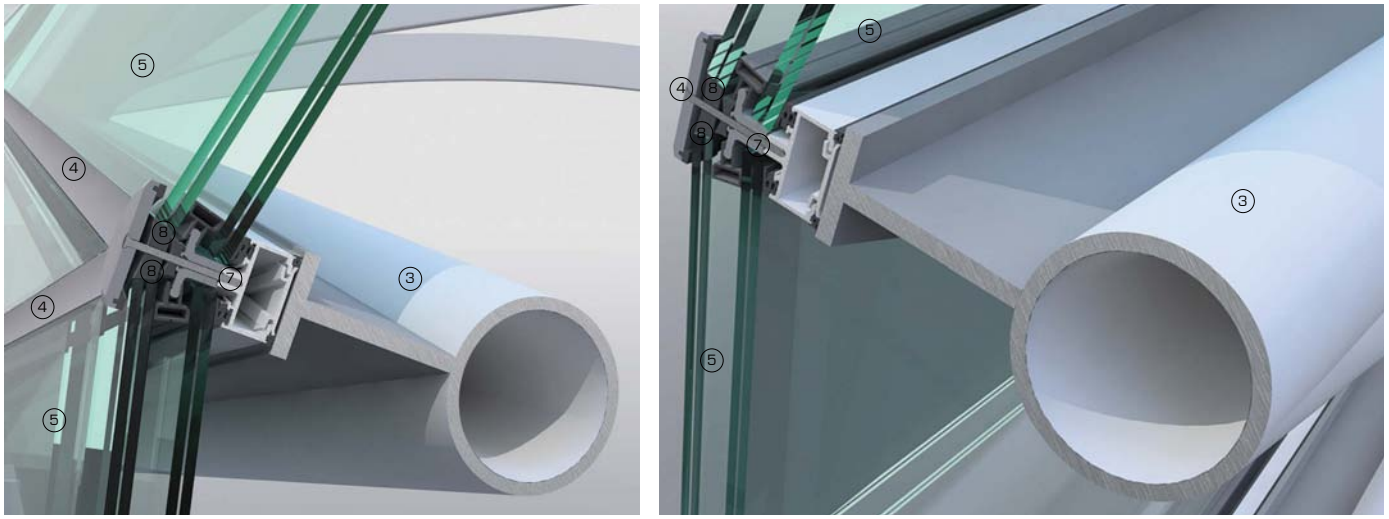
a | 3D sectional view showing curved glazed facade system supported on steel tubes



b | 3D sectional view showing curved glazed facade system supported on steel tubes



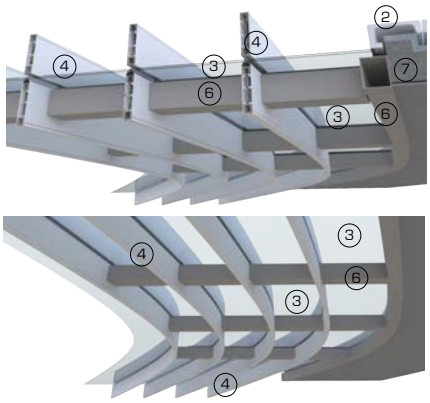
c | 3D internal view showing curved glazed facade system supported on steel tubes



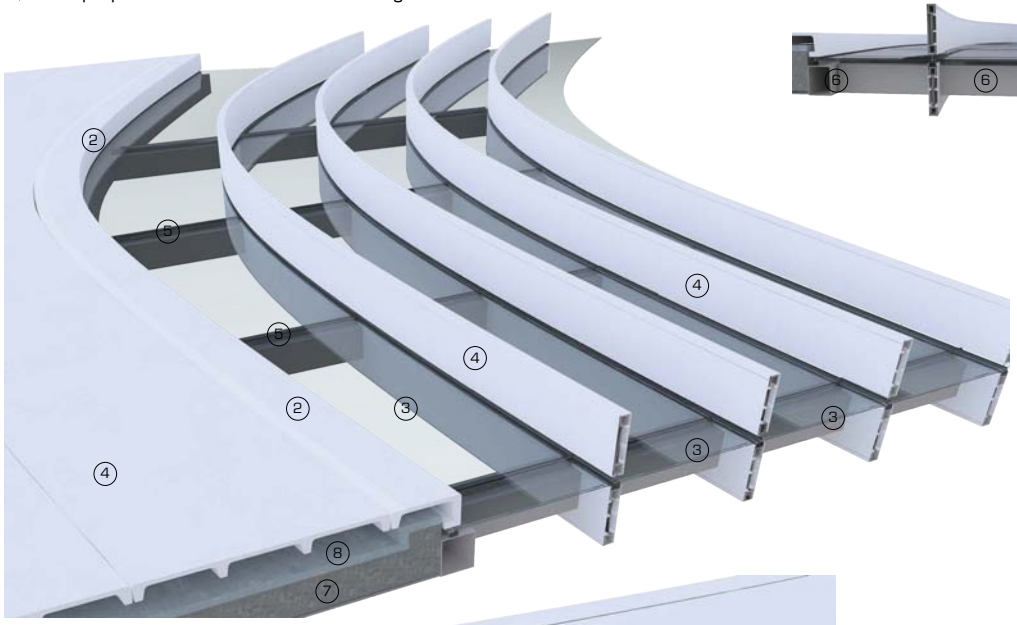
d | 3D detail views showing toggle-fixed curved glazed facade system supported on steel tubes

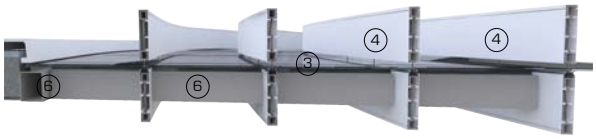


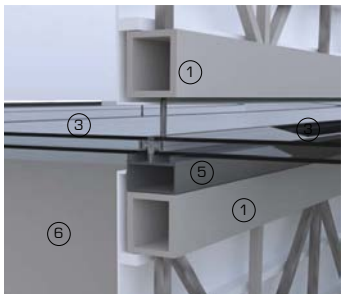
e | 3D sectional view showing toggle-fixed glazed rooflight with GRP-clad structural trusses to form blade-like solar shading louvres and interface with opaque GRP rainscreen roof cladding



f | 3D sectional views showing underside of toggle-fixed glazed rooflight with GRP-clad structural trusses to form blade-like solar shading louvres

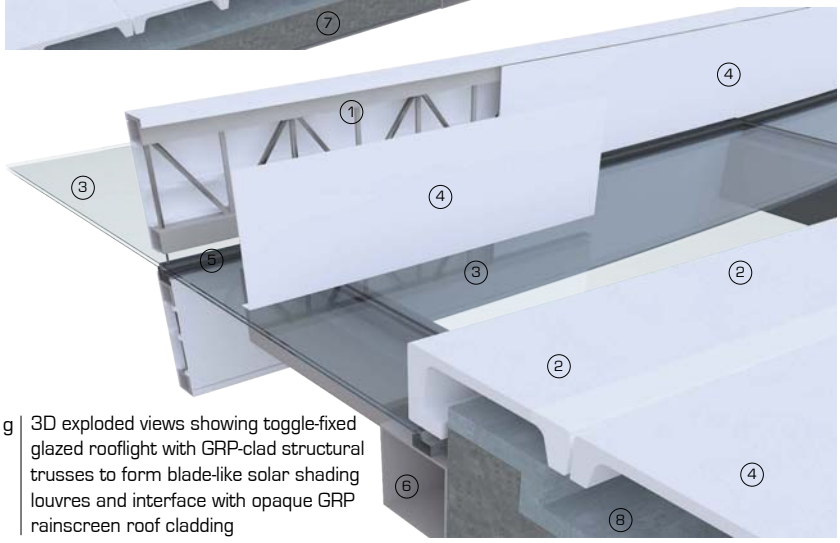




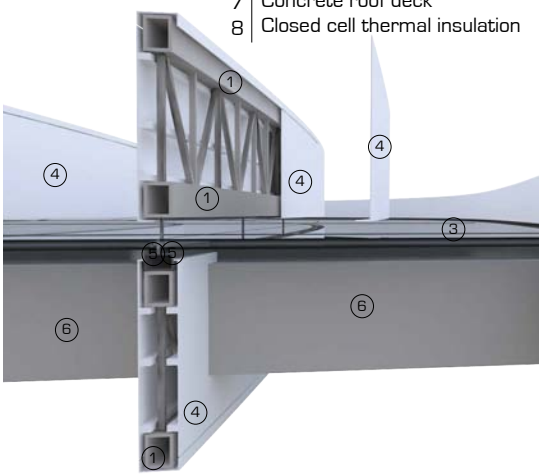


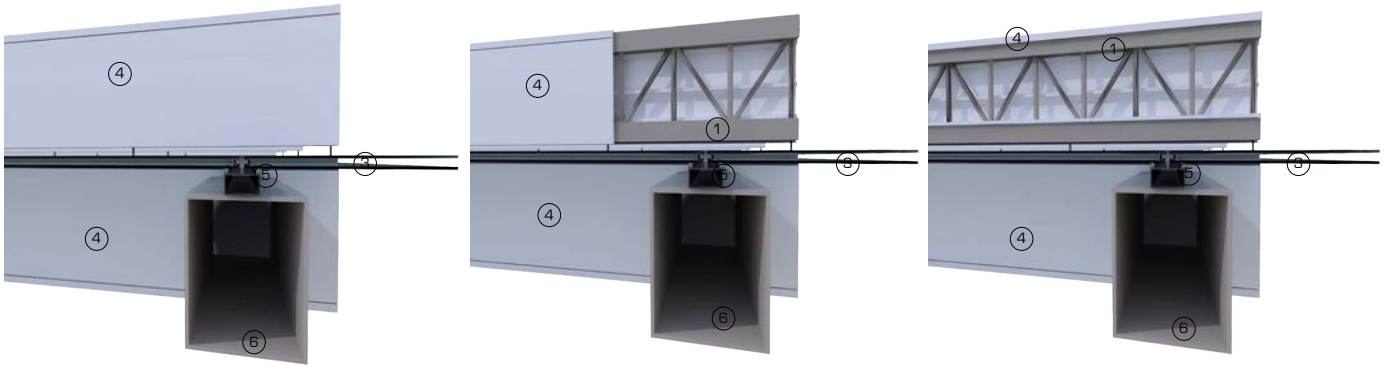
Details

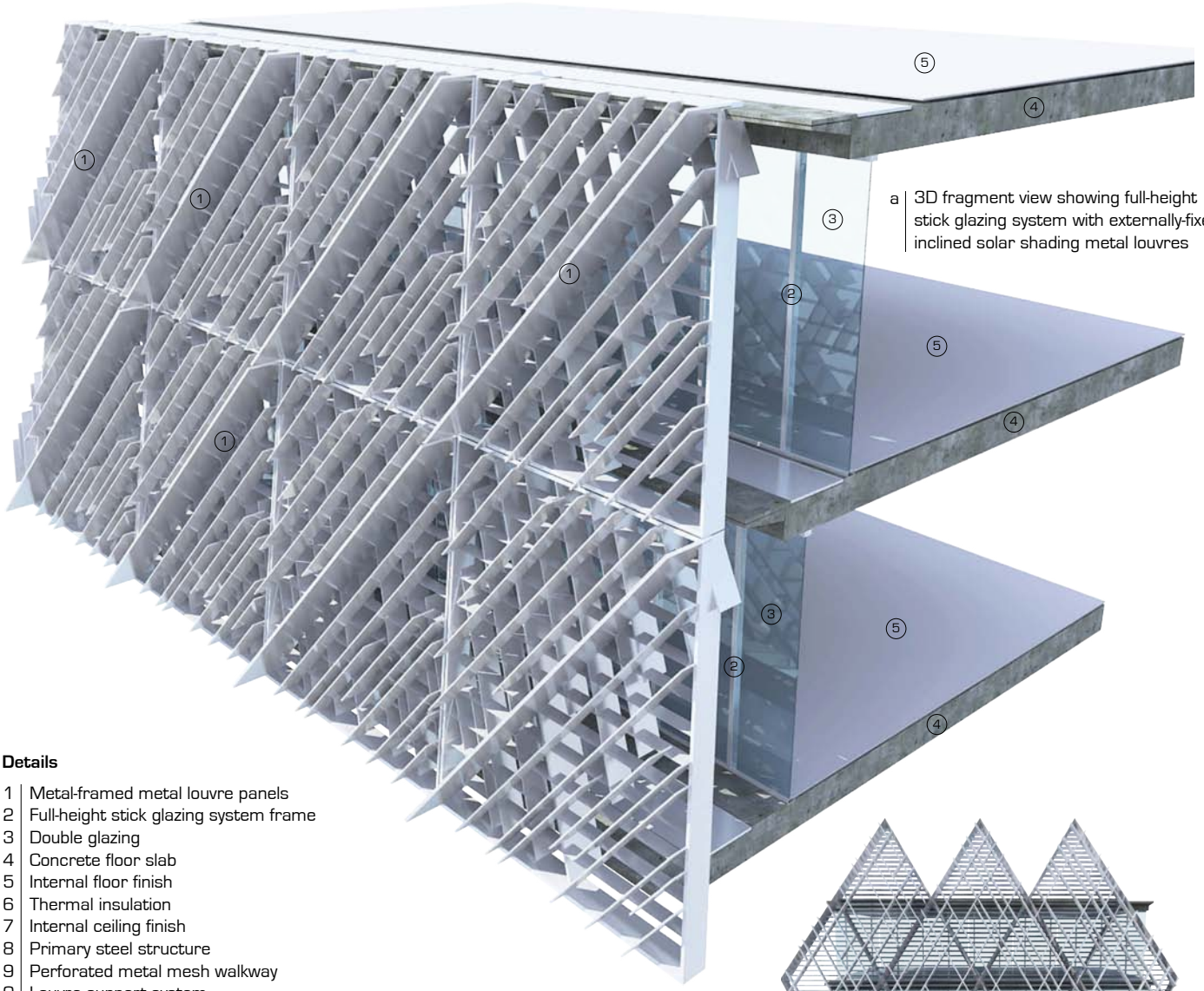
1 | Primary steel truss structure
2 | GRC edge piece
3 | Toggle-fixed glazed rooflight
4 | GRC cladding
5 | Glazing frame
6 | Steel structural member
7 | Concrete roof deck
8 | Closed cell thermal insulation



g | 3D exploded views showing toggle-fixed glazed rooflight with GRP-clad structural trusses to form blade-like solar shading louvres and interface with opaque GRP rainscreen roof cladding



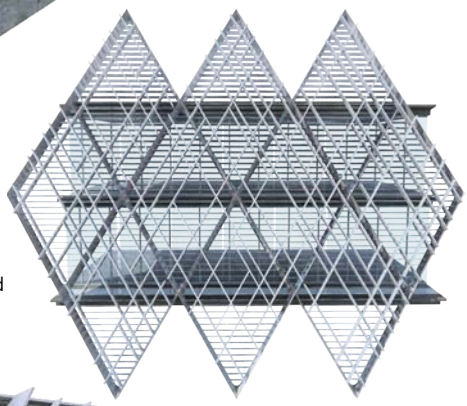




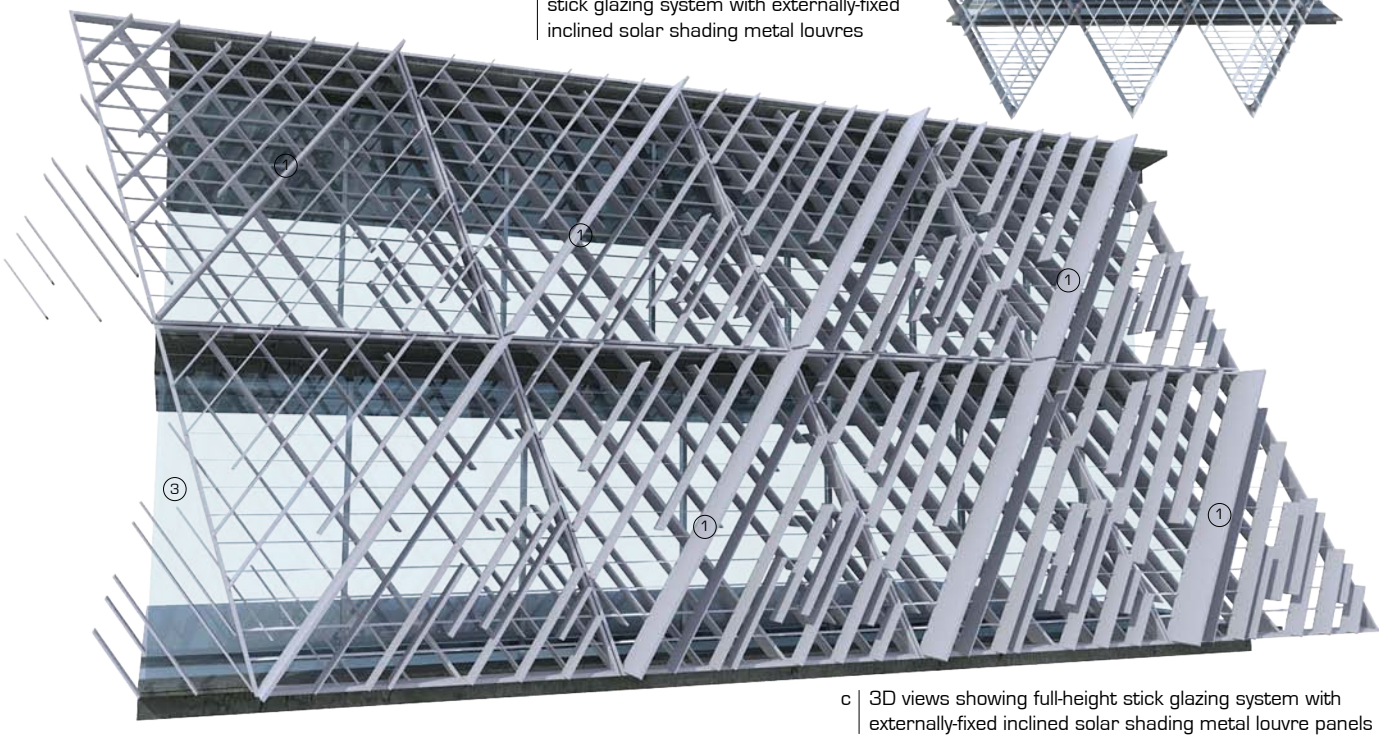
a | 3D fragment view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvres

Details

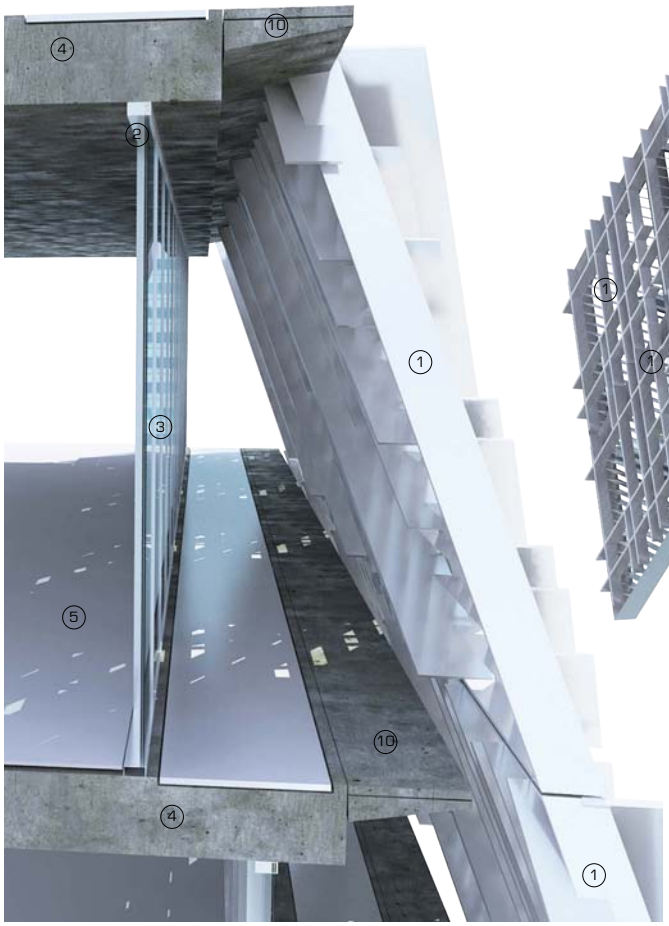
1 | Metal-framed metal louvre panels
2 | Full-height stick glazing system frame
3 | Double glazing
4 | Concrete floor slab
5 | Internal floor finish
6 | Thermal insulation
7 | Internal ceiling finish
8 | Primary steel structure
9 | Perforated metal mesh walkway
10 | Louvre support system
11 | Metal flashing



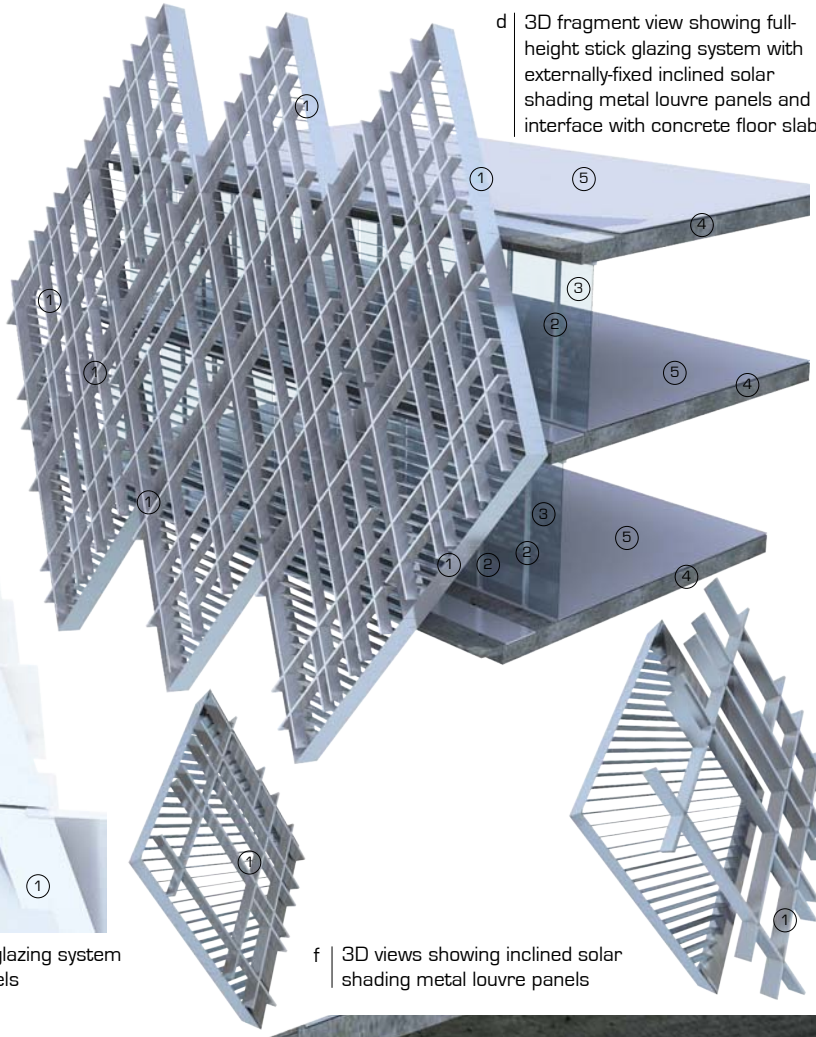
b | 3D fragment view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvres



c | 3D views showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels

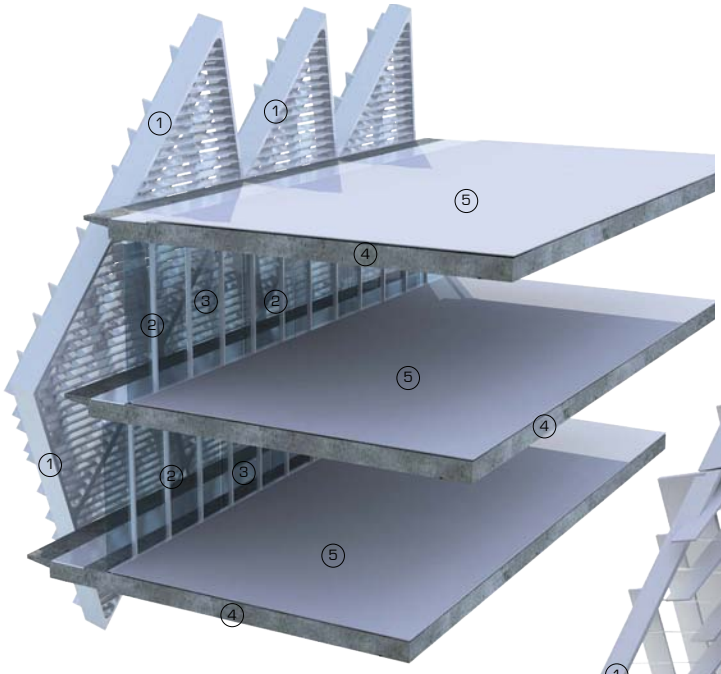


e | 3D sectional view showing space between full-height stick glazing system and externally-fixed inclined solar shading metal louvre panels

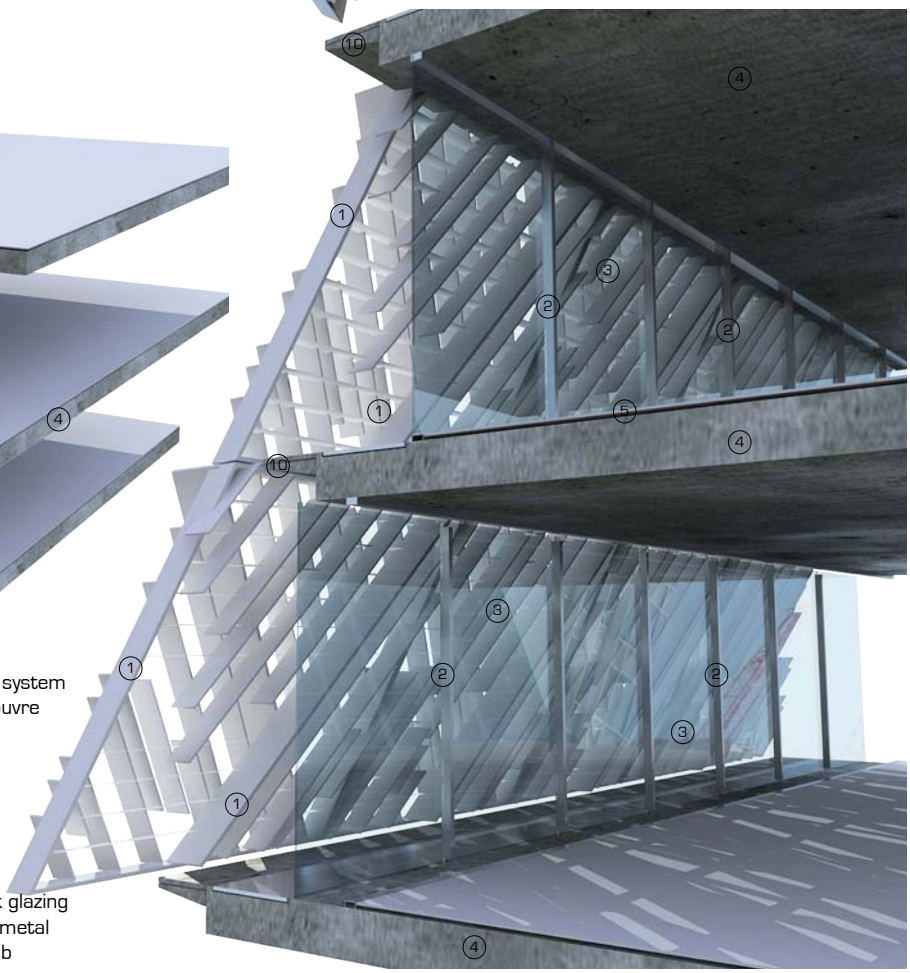


d | 3D fragment view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and interface with concrete floor slab

f | 3D views showing inclined solar shading metal louvre panels



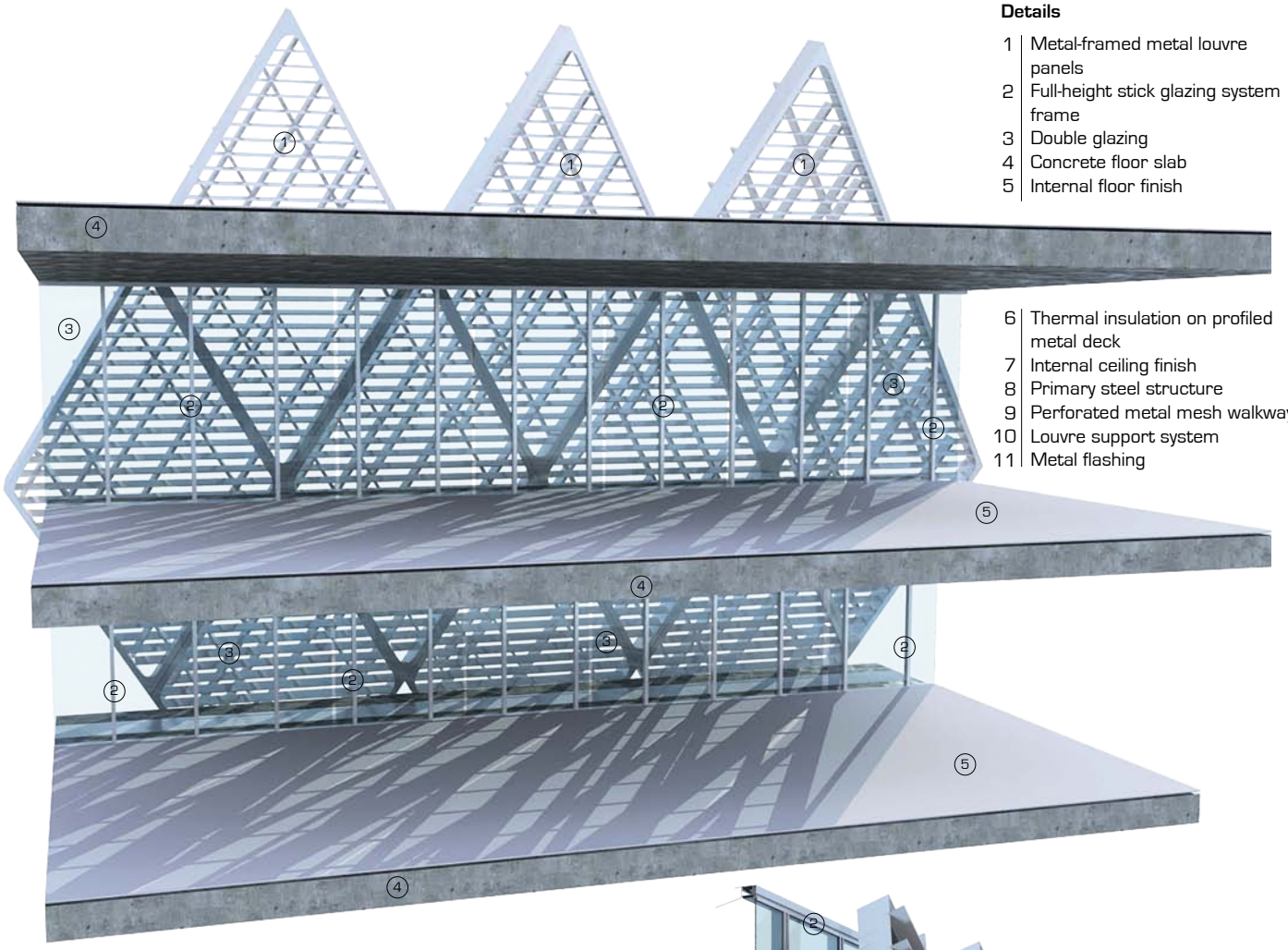
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h | 3D internal fragment view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and interface with concrete floor slab

Details

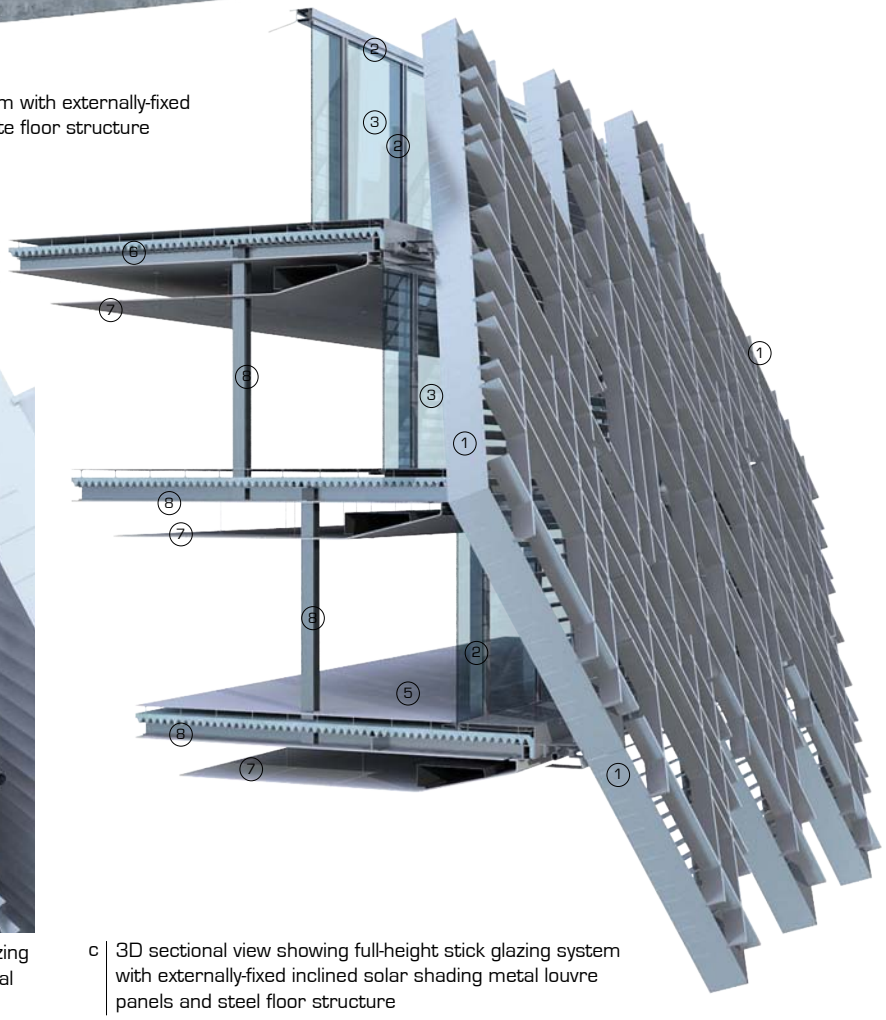
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a | 3D internal view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and concrete floor structure



b | 3D internal sectional view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and steel floor structure



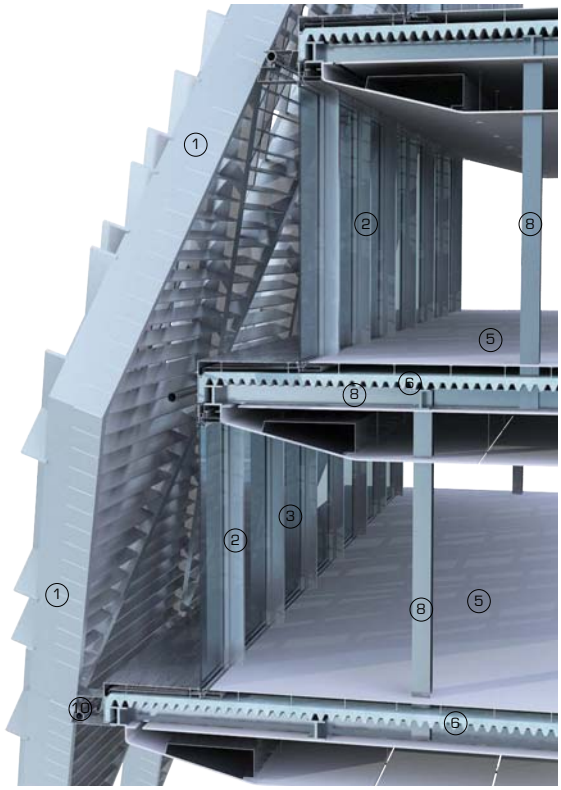
c | 3D sectional view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and steel floor structure



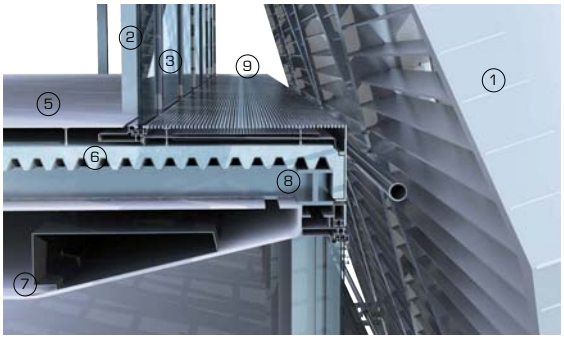
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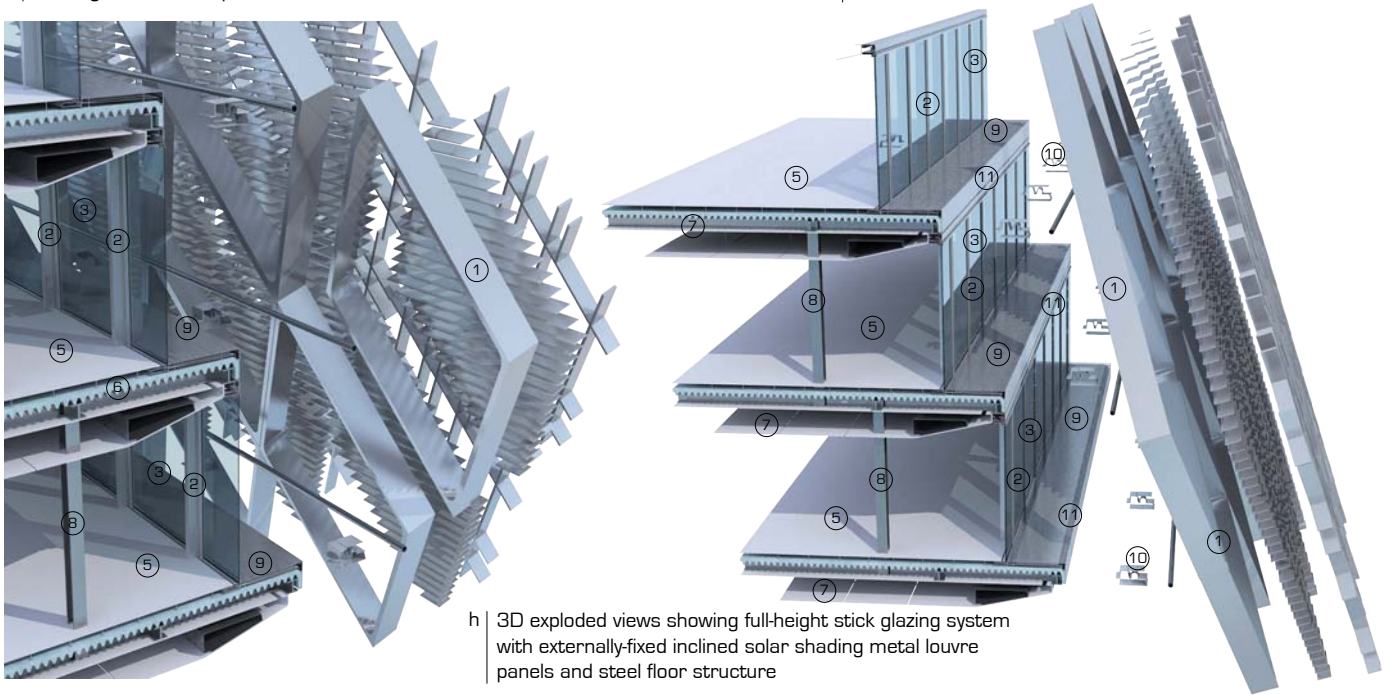
f | 3D view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and steel floor structure



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g | 3D detail view showing full-height stick glazing system with externally-fixed inclined solar shading metal louvre panels and steel floor structure



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07
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The glossary of terms here is aimed to explain words used in the context of this book. These are not intended to be general definitions and should be used accordingly. Topics are arranged in alphabetical order.

Butt joints
These are a contemporary type of joint where two materials are brought together and sealed with a different material such as silicone, as in an external wall. Traditionally, joints in walls have been formed by some form of lapping or interlocking of materials, as in the corners of window frames. Butt joints have the advantage of allowing movement to occur in the joint, as where adjacent panels are supported separately. An example is the use of silicone sealant between bolt fixed glazed units, where double-glazed units move independently and may experience considerable amounts of movement if secured to a structure that allows higher deflections than frames, such as cable net structures. An essential requirement of most butt joints is to ensure that there is sufficient surface on either side of the joint for the sealant to seal against, allowing it to stretch in several directions without losing adhesion.

Capped systems
Glazed walls or roofs which are fixed to a continuous framing system on all sides are referred to as being 'edge restrained'. Since most panels in glass or metal, for example, have four sides, these systems are generally called 'four edge restraint' systems, with the panels being held in place by pressure plates. Since the pressure plates have visible screws which are not always aligned neatly, an additional cover cap is set on top of the pressure plate. The cap is made in extruded aluminium and is coated, typically with a colour to match any adjacent metal panels or doors. Such systems are called 'capped systems' to differentiate them from those which have a silicone seal on the outside, such as 'toggle' glazing and 'silicone bonded' glazing, where only a silicone strip is visible from the outside. Sometimes a capped joint is used in one direction on a glazed wall, while a silicone seal is used in the opposite direction.

Cavity wall
This form of construction was developed from the 1920s onwards in brick construction as an alternative to thicker loadbearing walls, which were both unreliable in their ability to keep out rainwater and vapour as well as being more expensive to construct. The cavity wall divides the wall into two halves, or 'skins'. The outer skin is the weather barrier, and is assumed to become completely soaked during a rainstorm. The inner leaf is not in contact with the outer leaf, so it remains generally dry. The two skins are joined together with cavity wall ties, designed to encourage water in the cavity from dripping off the ties and down the cavity rather than being carried onto the face of the adjoining inner skin. The cavity wall has developed by setting thermal insulation either within the cavity, on the outer face of the inner skin, or within the inner leaf itself.

Cladding
This term refers to non-loadbearing facade systems which are applied to a building envelope in a way which is independent of the building structure. Cladding may even be used to give a completely different expression to the building suggested by either the building structure or the organisation of spaces within the building. This independence of cladding from its supporting structure has been exploited by many contemporary architects to create textures and geometries which accept this independence of the technology of the building envelope, and work with the opportunities provided by the non-loadbearing nature of cladding. Since the primary structure of the building is set behind the cladding, the external envelope can be configured to give precedence to other design considerations as primary forms of architectural expression, such as daylight, solar control and the visual expression of individual spaces within a building without direct reference to the structural frame.

Composite materials
These have been developed to mix two or more different materials together in order to benefit from the strengths of each so as to overcome the weaknesses inherent in one or other of the materials. In wood, for example, where a length of timber can span only as long as it can be cut from a tree, lengths of timber sections can be increased significantly by gluing strips or particles of timber to make board material. This combination uses the benefits offered by timber of lightness in weight and ease of working the material with increased size and greater stability to reduce the effects of moisture movement. Reinforced concrete can be regarded as a composite material, with steel reinforcement providing strength in tension which is lacking in regular concrete. GRP, or glass reinforced plastic, is a mixture of resins providing – conceptually at least – compressive strength, with glass fibre giving tensile strength.

Curtain walling
This refers historically to glazed wall systems which were 'hung' in panels or as a metal framework into which glass panels were set. While the concept is clear, these systems are not always hung in the manner of a curtain, and do not always span from floor to floor. Contemporary curtain walling is described as being either 'stick' systems, 'unitised' systems, or 'panelised' systems (explained under separate headings). Consequently, the term curtain walling is not referred to in this book as it is too generic, with 'glazed walls' used instead to allow the primary material to take precedence. Curtain walling was developed in the years following 1945, primarily in the United States where it was a practical way of enclosing tall buildings without the need for lifting heavy materials such as stone and brick high up, where they were slow and difficult to manage, making them far less economical in industrialised countries.

Double skin facades

These are essentially two skins of external wall which provide a thermal buffer in winter and natural ventilation in summer. The thermal buffer ensures that solar gain in winter months can be used to heat a building, while in summer, windows at high level can be opened into a void between inner and outer skins without experiencing the effects of wind gusts. Double skin facades can vary from 1000mm in width, with two walls separated by a maintenance walkway, to a thickness of 300mm, where the double skin is set within a single wall construction, typically as unitised panels. With the wider version, comprising two walls set apart, the cavity can be ventilated form the outside, either with open joints or with controlled louvres. Thin double skins are ventilated from inside the building, sometimes actually linking the void within the wall to the mechanical ventilation system.

Eaves

These are junctions between the top of an external wall and the underside of a sloping roof, which typically overhangs the wall. Where the external wall is made as a cladding system rather than a traditional loadbearing wall, the relative movements of wall and roof need to be taken into account in the weather tightness of the junction. There is also a need for continuity of thermal insulation from wall to roof, sometimes providing ventilation into the roof space and sometimes providing a complete seal from wall to roof. As an interface between primary elements of a building which are usually performing in quite different ways, using quite different forms of construction, eaves junctions require the lapping of the waterproofing for the roof to form a continuity with that of the wall. As an interface, an eaves detail usually requires one of the systems of wall or roof to take precedence from a visual point of view, so this becomes an additional requirement of their design.

Embodied energy

This is the amount of energy required to construct a building or part of a building. No specific standards can be applied at this stage, as an essential component in the energy required to construct a building is the delivery of materials to site, which can vary enormously, but which favour as local a sourcing of materials as possible. In practice this can be difficult to agree on, as it needs to be established how far up the supply chain to go when calculating the energy required to make primary materials for a building. In the case of polymers, for example, the dependence on oil from different parts of the world being transported can create complicated scenarios for calculation. Timber is considered to have zero embodied energy as a material, but the energy used to fell, cut and transport the material is much higher; though not as high as that for the metals used in fixings which allow the timber to be made useful as a building material.

In-situ cast concrete

This method of working with concrete, also called cast-in-place concrete, is based on forming the material on site using formwork that is set up specifically for the casting process, before being moved to the next stage of casting. The method can be used to create large-scale concrete structures or walls. An important consideration is the formwork, which is used increasingly as a kit of parts that can be moved and reassembled quickly for the next part of the work. If the concrete is to be a visible part of the construction, as in the case of columns or external walls, the provision of joints and junctions with adjacent elements needs to be considered carefully prior to starting on site. Since the casting of concrete reveals very closely the texture of the formwork from which it is cast, the choice of formwork board size, or tube size for columns, is an essential part of the design of the building, and is considered at an early stage of the design.

Lapped joints

This is the traditional method of forming junctions between materials in external walls. In order to ensure that water runs off timber boards, for example, the material is ship lapped, where one board is set over the other. More generally, this principle applies in tiled and slated roofs, and in brick walls where openings are formed so as to lap the external wall around window frames. Where render is used on top of masonry walls, the render forms, effectively, a lap between wall and window. Lapped joints are used in contemporary construction where a butt joint is either not appropriate in terms of its exposure or appearance, or alternatively where ventilation is required, as in rainscreen panel systems and roof coverings. An essential aspect of lapped joints is that they are oriented in a direction that ensures rainwater will run off the joint in a downward direction while allowing ventilation in the upward or lateral direction.

Membranes

These are single-layer materials made in large sizes, typically 1000m to 2000mm in width and in long lengths, supplied in rolls. They are made primarily from polymers, and have the advantage of being possible to bond or weld together, often by heat rather than by naked flame, making them easy to install on site. Their use is mainly as reliable waterproof or vapour-proof layers to large areas of wall or roof which experience relatively little thermal movement. Though reliable, they are relatively fragile unless designed specially for external use, as is the case with thicker, tougher roofing membranes. Mostly, however, membranes are required to be concealed beneath other materials to protect them from the effects of the sun and from suffering accidental damage, such as being walked upon for example. Membranes are usually fixed at points on their underside in order to avoid penetrating the membrane.

Openings
This book shows examples of details around openings as they are often at the interface of different systems, or components from different systems. Windows and doors, for example, do not have obvious ways of being fitted into walls when a very watertight and airtight performance is required. Since facade systems are often developed and tested to quite different standards and with the intention of forming a complete building envelope as a single material system, combinations of two systems are dealt with on a project-by-project basis. As windows and doors are often designed within a single system, it is essential to understand the visual impact that they make on a facade, as well as how they can be accessed for cleaning and maintenance. Openings are required to be assembled in a particular order if made from different materials or systems which can influence their appearance, so the sequence of construction is a consideration.

Parametric design
This is an approach to the design of a building, or part of a building, based on the idea of setting 'parameters' that can be changed dimensionally, while making other parts of the design 'fixed' which cannot be changed. This principle can be applied to the geometry of a set of floor slabs, for example, which may be allowed to change in one direction only, or be used for a set of components which might be changed. This approach suits geometrically complex or large-scale projects where the time required to rebuild the model would be uneconomical. Because parametric design software allows the design to make changes quickly, it allows the designers to try changes to see what happens to an overall building form, for example. This allows the behaviour of the component or building geometry to be understood, sometimes linking floor areas to a building geometry.

Panelised system
This is a general term covering large-scale panels used primarily for external walls. Their use is in prefabricated wall systems where a building is required to be assembled on site quickly, or where the specific site does not make it easy to undertake complicated work; mainly where access is restricted. Where unitised panels in glazed walls are typically around 1500mm wide, panelised systems can be made up to around 7000mm long, depending on their weight, but are typically delivered to site on trailers, so that transportation is an important consideration in their design. These panels may comprise a mixture of systems, such as metal framed backing walls with windows installed, or even precast concrete panels with masonry fixed or forming an integral part of the panel. They are finding use as waterproofed or vapour-proofed backing walls which can be installed quickly on site while the outer skin of the wall is applied later. This allows the building to become watertight at an earlier stage of construction.

Parapets
These are traditional elements of buildings which still form a prominent part of contemporary design. Parapets are formed when an external wall projects up in front of the base of the roof construction, requiring rainwater to be drained into a gutter behind the external wall rather than in front of it. This makes it essential to draw the rainwater down the pipes which are typically set outside the building rather than inside, where they can be difficult to access for maintenance and can be susceptible to damage, causing leaks. Parapets are detailed so as to form a gutter between wall and roof that can fill to capacity without the risk of leaking back into the building. Since parapet gutters can become blocked as a result of the outlet being accidentally covered, the design of these junctions, as well as the provision of overflows to the outside, are essential considerations in their design. The coping, or durable covering set on top of the parapet, has some visual presence on the facade and can be seen as a termination of the top of the building.

Point fixed glazing
This is a recent development that originated with the clamped glazing systems of the 1960s, used mainly as store-front glazing at that time. The technique comprises either bolt-like fixings set near the corners of the glass, or clamps set on both sides of the glass along the edges of the glass, but not necessarily at their corners. An essential part of their design is to ensure that the glass is supported so that it can move in order to avoid putting additional stress into the glass. These systems are typically designed in conjunction with a manufacturer or facade designer who can ensure that the design is suitable both in relation to its supporting structure and for fabrication. Clamped glazing has become more popular in recent years since it is more economical than the bolt fixed method, as clamps can be set between the joints rather than requiring glazed units to be drilled to accommodate the bolt fixing.

Precast concrete
This material is an alternative to in-situ cast (or cast-in-place) concrete. An essential aspect of precast concrete is that it can be used for structures, facades, roofs and interior building components, making the understanding of how the material is used an essential aspect of designing with the material. Because of the weight of concrete and the high amount of material required for its use in construction, its use as prefabricated components requires careful consideration, particularly in expected tolerances in its assembly, which can require wider gaps than those required in other materials. Although precast concrete is used for staircases, for example, these components are often covered up by finished work and so are not revealed. Consequently, the choice of precast concrete over in-situ cast concrete may not be of primary interest to the designer in such applications. Where the use of precast concrete will be of concern is where the material is visible, requiring careful attention to finish; mainly in terms of colour consistency and

texture; as well as how the formwork will leave traces of the pouring method that may or may not be required in the finished work.

Prefabrication and site-based work

The choice between buildings constructed mainly on site or off site in a workshop or factory is based on issues primarily of cost and quality, though it also has to do with increased specialisation in construction. Projects of ambition often require specialist construction skills to undertake the construction. Such specialists are usually set up with their own working environment rather than being based on a succession of building sites. While prefabricated elements and systems are required to be assembled or set into position on site, this environment is too temporary for many specialists, who require a specific planned work environment for them to be effective both as an organisation and in order to produce work of high quality. Quantities of what can be transported to site are usually limited by the capacity and weight allowance of a trailer as well as storage facilities on site. However, some building work is more effectively undertaken on site, using the site as a workshop and storage facility for components. Structural frames and floor slabs in large-scale construction are still mostly site-based, though the amount of prefabrication is increasing.

Rainscreens

These are facade and roof panel systems which allow small amounts of rainwater to enter the joints between panels and be drained down through the framing back to the outside, either at each floor level or at the lowest level of the system. The term was first used for curtain walling, where leaks in earlier forms of curtain walling were overcome not by attempting to exclude any water penetration, but by accepting that it is easier to ensure the water drains away safely when it penetrates joints. The term, in general use, is applied more to open joints in panel systems, typically metal, timber and terracotta than to glazed curtain walls. When used in this context, panels in these materials are generally fixed to a framing system which is secured to the building structure. A separate backing wall is typically used to provide thermal insulation and a waterproof layer. Rainscreen panels have grown in use as a visually refined finish to economical backing walls.

Stick system

This is a method of constructing glazed walls on site from framing and glazed units. Stick glazing is often used in complex arrangements of curtain walling and for smaller projects. Larger projects such as apartment buildings often have many different conditions in their design on the external envelope, which would require many types of unitised panel that are both uneconomical and difficult to install. Smaller projects do not have a sufficiently large envelope to make unitising panels economical and are usually stick built regardless of their level of complexity. The advantages for designers are mainly the flexibility of design, which does not need to be made modular to suit repeated panels, and the narrower size of joint widths, which is usually 50mm to 70mm depending on project requirements. Stick systems can also be combined effectively with supporting steel frames such as those for atrium structures and double skin facades. Where steel frames are used, the aluminium extruded box section on the internal side of the framing can be omitted, allowing the front part of the stick system to be fixed directly to the supporting steelwork, which would typically also be in box sections.

Thermal bridging

This is also called 'cold bridging' but can occur in hot thermal conditions as well as cold conditions. Essentially, the design of different systems of wall and roof construction is gradually being developed to reduce thermal transmission through the build-up. Some parts of the system can perform considerably worse than others, creating a 'bridge' for the passage of heat or cold which is prevented elsewhere in the system. In glazed walling, for example, the thermal performance of the framing is significantly less than that of the glazed panels, and is improved by using a 'thermal break' so that the high thermal transmission of the frame is 'broken' with a polymer-based component set between inside and outside. The thermal break may be a separating strip or may form an integral part of the construction, as is the case with aluminium framing to glazed walls.

U-value and thermal insulation

The U-value of a construction is a measure of the thermal transmission through the material, with systems of lower U-value having higher levels of thermal insulation. The U-value takes into account the thermal transmission of all the layers of construction that make up the wall, so walls of different build-up in section require separate U-value calculations. U-values can be used in calculating the rate of heat flow of spaces in the building, but are separate from the effects of solar gain through glazing, which may also cause thermal transmission. Consequently, double-glazed units have a Low-E coating and vacuum in the cavity to provide thermal insulation, while a separate solar control coating provides protection against the effects of solar gain.

Unitised system

This is a prefabricated method of making facade panels, typically for glazed walls. Its advantage is primarily one of reduced cost for facades with considerable repetition resulting in few panel types; but another advantage is the use of silicone bonding, allowing frames to appear slim on the outside, and for opening lights to have their frames concealed internally. Applying silicone on site in stick systems can be very difficult to achieve due to the time needed, as well as the avoidance of dust around the edges of the bonds.

This book has been a team effort involving members of Newtecnic in London. Drawings were modelled and rendered by the Newtecnic team. The book was designed by Yasmin Watts. The text is by Andrew Watts. The text and overall content of the book was updated with contributions from Howard Tee and Yasmin Watts.

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Yasmin Watts is a sculptor, architect and creative director of Newtecnic, leading the exploration of links between sculpture, architecture and public art. She is a founding director of the company. Yasmin is focused on creating sculptures in public spaces in the built environment; the fusion of architecture and sculpture has been a key driver in the work behind all the projects shown in this book. She is a registered architect in the UK and is a Fellow of the Royal Society of Arts. Yasmin is continuing her research with the Royal College of Art.

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Newtecnic have produced volumes on contemporary building technology which provide reference material for engineering and architecture students and professionals around the world. The Modern Construction Series is published by Birkhäuser Verlag GmbH. In addition, the Facades Technical Review, from RIBA Publications was published in spring 2007.

Newtecnic is an architectural and engineering design company that undertakes the architectural design and engineering design of complex and ambitious construction projects, and associated building envelope systems, for use on its own projects. In partnership with the Engineering Department of Cambridge University, Newtecnic's R&D team has developed, analysed and tested new facade components and assemblies for use on live projects.

The company is led by Andrew Watts, Howard Tee and Yasmin Watts. The Modern Construction series forms an essential part of their research work which informs the design of projects.

The Newtecnic approach, based on research from first principles, allows the company to achieve architectural and engineering design solutions for the complete building, from concept to production information, including engineering and architectural design for structure, facades and the internal environment. The method used is based on technical and visual concepts that are supported by analysis, modelling, geometry and coordination. Newtecnic's work ranges from conception and the development of design concepts to detailed design and engineering analysis for fabrication when working

for contractors. With 3D BIM, Newtecnic designs models that become highly evolved during the design process. Components of these BIM models, with accompanying text and images to illustrate design processes, form the basis of the Modern Construction Series. The engineering and architectural design skills of Newtecnic allow the company to communicate, through the Modern Construction series, the key issues of 21st century building engineering and design. Newtecnic are holders of *The Queen's Award for Enterprise* and are ranked in the top three of *New Civil Engineer 100 Companies of the Year 2019.*

Newtecnic are currently undertaking the architectural design and engineering design of a large-scale technology-oriented and visitor-based project in Nevada, USA.

Further reading

The other books in the Modern Construction Series, which are based on the systems of construction described in this book, are suggested for further reading.

Modern Construction Case Studies, 2nd edition
Birkhäuser, 2019

Modern Construction Envelopes, 3rd edition
Birkhäuser, 2019

Modern Environmental Design, 1st edition
Birkhäuser, 2022

Modern Structural Design, 1st edition
Birkhäuser, 2022

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