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STEEL SUPPORTED GLAZING SYSTEMS

INTERFACES

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FOREWORD

This guide addresses the interfaces between steel frames and various types of modern glazing systems. It was drafted by WS Atkins, as contractors to The Steel Construction Institute, and was part-funded by the Department of Trade and Industry, British Steel (Tubes and Pipes) and The Steel Construction Institute.

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Original artwork line diagrams were prepared by J Wynne and E Balodimou, Oxford Brookes University.

This publication is one of a series on 'Interfaces'. Other publications in the series are:

- Curtain Wall Connections to Steel Frames.
- Electric Lift Installations in Steel Framed Buildings.
- Connections Between Steel and Other Materials.
- Design of Steel Framed Buildings for Service Integration.

CONTENTS

SUMMARY

The use of sophisticated bolted glazing systems, in which glazing panels are supported by steel structures, has increased significantly in recent years. This publication is principally concerned with the design of the interface details between glazing panels and steel support structures. It provides guidance for use by architects, structural engineers and cladding designers, including design issues and general principles of detailing and installation.

Descriptions are included of the various glass types in common usage in bolted glazing systems, of methods of making bolted attachments and of generic types of steel support structures.

A range of case studies illustrates the use of bolted glazing systems in modern steel buildings. Selected structural design information for glass is included in an Appendix.

Interfaces : Supports en acier pour systèmes de parois en verre

Résumé

Les systèmes de parois en verre boulonnés, dans lesquels les panneaux en verre sont supportés par des structures en acier, connaissent depuis plusieurs années un succès grandissant. Cette publication est principalement concernée par le dimensionnement des pièces d'interface entre les panneaux en verre et la structure en acier. Elle est destinée aux architectes, ingénieurs de structures et spécialistes du dimensionnement des enveloppes. Elle couvre le principe de dimensionnement ainsi que les détails structuraux et la mise en place de ces systèmes.

Les différents types de verres utilisés habituellement pour les parois en verre ainsi que les systèmes d'attaches et de supports métalliques sont décrits dans la publication.

Une série d'exemples illustre l'utilisation de ces systèmes dans les immeubles modernes en acier. Une annexe donne des informations concernant les caractéristiques structurales du verre.

Verglasungssysteme mit Stahlunterkonstruktion

Zusammenfassung

Der Einsatz anspruchsvoller geschraubter Verglasungssysteme, bei denen die Glasscheiben von einem Stahltragwerk unterstützt werden, hat in den letzten Jahren erheblich zugenommen. Diese Publikation befaßt sich hauptsächlich mit dem Entwurf der Verbindungsdetails zwischen Glasscheiben und Stahlunterkonstruktion. Sie dient als Anleitung für Architekten, Tragwerksplaner und Fassadendesigner und erfaßt Entwurfs- und Berechnungsprobleme sowie allgemeine Grundsätze der Detaillierung und Montage.

Beschreibungen der verschiedenen gebräuchlichen Glastypen in geschraubten Verglasungssystemen sind enthalten, ferner Möglichkeiten für Schraubenverbindungen und Unterkonstruktionen aus Stahl.

Eine Reihe von Fallstudien verdeutlicht die Anwendung dieser Systeme in modernen Stahlbauten. Ausgewählte Informationen zur Berechnung von Glas befinden sich im Anhang.

Interfases: Sistemas de vidrio soportados por estructuras de acero

Resumen

Recientemente se ha incrementado el uso de refinados sistemas de pernos de sujeción para paneles de vidrio soportados por estructuras de acero.

Esta publicación se refiere al proyecto de los detalles de interfase entre los paneles de vidrio y los soportes de acero. Es una guía para arquitectos, ingenieros de estructuras y proyectistas de revestimientos e identifica los objetivos del proyecto así como los principios generales de elaboración de detalles y proceso constructivo.

Se incluyen descripciones de los diferentes tipos de vidrio de uso habitual en sistemas con pernos de sujeción asi como de los métodos de fabricación de uniones empernadas y de tipos genéricos de estructuras de acero para soporte.

Una serie de casos prácticos sirven para ilustrar el uso de estos sistemas en edificios modernos de acero. También se incluyen en un apéndice detalles de información estructural útil para proyecto.

Interfacce: sistemi di supporto per pannelli di vetrata

Sommario

Recentemente si è diffuso l'uso di raffinati sistemi di collegamento bullonati per il fissaggio di pannelli di vetrata a strutture in acciaio. Questa pubblicazione tratta principalmente la progettazione dei dettagli relativi alle interfacce tra i pannelli di vetrata e gli elementi in acciaio. Viene fornita una guida di pratico utilizzo per architetti, ingegneri strutturisti e progettisti di elementi di tamponamento. Sono in aggiunta identificati le linee progettuali e i principi fondamentali relativi al dettaglio e all'istallazione.

Le più comuni tipologie vengono descritte principalmente con riferimento ai pannelli di vetrata bullonati. Sono in oltre presentate le tecniche di collegamento dei bulloni e vengono illustrati i vari tipi di strutture di supporto in acciaio

La casistica considerata e presentata nella pubblicazione illustra l'utilizzo dei sistemi di supporto in edifici in acciaio di recente costruzione. Nell'appendice sono invece riportate mirate informazioni relative alla progettazione strutturale.

Anslutningar: Glassystem med stålstomme

Sammanfattning

Användandet av avancerade skruvade inglasningssystem där glaspanelema bärs av en stålstomme har ökat kraftigt de senaste åren. Denna publikation ägnas i huvudsak åt utformning av anslutningsdetaljer mellan glaspaneler och den bärande stålstrukturen. Den Innehåller vägledning för arkitekter och konstruktörer, samt identifierar var problemen återfinns och de huvudsakliga principema för utformning och montering.

Publikation omfattar beskrivning av olika glastyper I kombination med skruvade infästningar, vanliga infästningssystem och olika bärande stomsystem.

Ett flertal referensexempel illustrerar användningen av dessa system i moderna stålbyggnader. Ett urval av konstruktionsförutsättningar för glas finns i ett appendix.

1 INTRODUCTION

Modern glazing systems often rely on steel support structures which are visually expressed and important architectural elements. Tubular steel components and trusses combine structural efficiency with aesthetics.

The glazing systems are frequently bolted to steel support structures. The bolts provide point support to the glazing panels instead of the continuous edge support provided by conventional frames. Applications of bolted glazing systems range from simple shop windows to multi-storey glazed walls and large atria.

Bolted fixings are commonly located toward the corners of glazing panels, and sometimes additionally at intermediate points on long edges. They connect glazing panels to glazing support attachments which in turn are connected to support structures. A typical arrangement is illustrated in Figure 1.1.

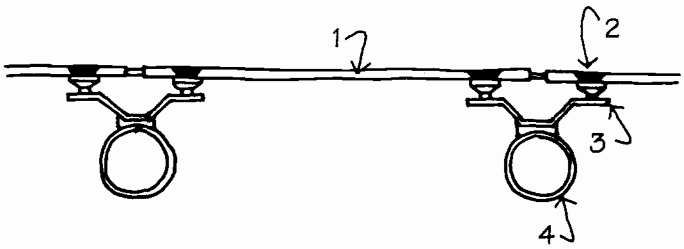


Figure 1.1
Typical bolted glass fixing arrangement

Key:
1. Glazing panel
2. Bolted fixing
3. Glazing support attachment
4. Support structure

1.1 Components of steel supported glazing systems

The main components may be defined as follows:

Glazing panel
A panel of transparent or translucent material used as infill within wall or roofing system. Most commonly the panel will be glass (single or double glazed units) or a glass laminate, but other materials may be used.

Bolted fixing
A connection device that attaches glazing panels to glazing support attachments. The method of load transfer (of forces in the plane of the panel) is usually by bearing. However, bolted fixings may be used to develop clamping forces, in which case, load transfer is by friction.

Glazing support attachment
The element that transfers loads from one or more bolted fixings to the support structure. These range from simple fin plates to more complex 'spider' type machined or cast components.

Support structure
The steel beams, columns, trusses, etc. that transfer self weight, wind and other imposed loads to the building structure, or to foundations.

1.2 The interface

This publication is principally concerned with the design of glazing support attachments, since these form the interface between support steelwork and the bolted fixings which in turn support glazing panels. The attachments however cannot be considered in isolation.

Considerations that should inform their design include:

- Construction and manufacturing tolerances associated with both the glazing panels and the support structure.
- Movement of the glazing panels and support structure as a result of thermal effects and under applied loads (including out-of-plane rotation of glazing relative to glazing attachments).
- Loads that arise as a result of the self weight of the glazing system, including applied loads and load transfer effects that may occur when glazing panels are broken or removed.

Tolerances
Glazing panels can be manufactured to a high degree of accuracy, and are often required to be set out to within ± 2 mm of a theoretical grid (this reflects the accuracy with which it is possible to measure the installed position).

Support structures, (commonly bolted and/or welded steelwork), cannot be manufactured economically to this degree of accuracy. It is common to specify tolerances of ±5 mm for the positions on the support structure at which glazing support attachments are connected. The attachment details should therefore be able to provide an adjustment at least equal to the specified tolerance for these positions, in order that the setting out accuracy (noted above) can be achieved.

Tolerances for the accuracy of the support structure larger than ±5 mm may be adopted, but these need to be reflected in the amount of adjustment that is provided at the connection between attachment and support structure.

Tolerance strategies usually demand that steel support structures are treated differently from conventional steelwork in terms of their design and specification.

Tolerances on the positions of holes in glazing panels, manufacturing tolerances for the support attachments, and tolerances for the installed position of glazing panels relative to the theoretical grid, may be accomodated by providing adjustment at the connection of bolted fixings to glazing support attachments. Provision may also be made at this point for thermal movements.

Movement

Glazing panels expand and contract as a result of thermal effects. If movement is resisted, stresses are developed. Provision is therefore usually made for bolted fixings to move freely relative to the support attachments, to avoid generating any additional stresses. Typically, in vertical and sloping glazing, fixings at either the top or the bottom of glazing panels locate into horizontal slots in the glazing attachment (to allow horizontal movement but still support the glass weight), whilst those at the other end locate into oversized holes. Attachments supporting horizontal glazing may all have oversized holes.

The deflection of glazing panels causes rotation about their attachments which must either be resisted (assuming that the stresses that may be developed will not exceed the capacity of the glazing material), or provision must be made in the bolted fixing, the glazing attachment, or elsewhere to allow rotation.

Out-of-plane movements of the supporting structure can further increase out-of-plane rotation of the glazing panel relative to the glazing attachments, whilst in-plane movements may lead to changes in the load sharing between glazing attachments. Movement of building elements to which glazing support structures are attached (normally the main frame) can compound problems and create particular issues at junctions between glazing and other building elements.

Loading

Loading patterns and load transfer in bolted assemblies can be complex. The glazing attachment must transfer the self weight of the glazing panels to the support structure, together with the applied loads, both during construction and in service.

The loads that are experienced by the glazing attachments depend on the construction condition, the deflection of the supports, and alternative load paths in the event of failure of one element.

1.3 Use of the publication

The details, approaches and quantitative data presented in this publication are based upon the experience of the authors and of the advisory group. It is crucially important however that all of the information is used discerningly, and that designers satisfy themselves as to the applicability of the information in any given situation.

It must be emphasised that much of the technology that this publication addresses is relatively new, and as yet is not comprehensively served by design codes. Since glazing failures may result in serious injury or loss of life, great care should be exercised in the design, installation and use of glazing systems.

2 GLAZING PANELS

2.1 Annealed glass

Annealed glass is glass that has been subjected to controlled cooling (annealing) to reduce residual stresses. The most common form of annealed glass is 'float glass', which is produced when molten glass is cast on a bath of molten tin. Annealed glass is normally available in thicknesses of 3 mm to 25 mm and in pane sizes up to approximately 3.2 m × 6 m. As a result of annealing, glass can be easily cut and worked. Annealed glass tends to break by shattering into large pieces and so cannot be used as safety glass. It also has low fire resistance.

2.2 Wired glass

Wired glass is annealed glass with an encapsulated steel wire mesh. Depending on the weight of the mesh, wired glass can be used as fire resistant or safety glass.

2.3 Toughened glass

Toughened glass, sometimes referred to as 'tempered glass', is produced by heating annealed glass to 650-700°C, and then cooling it rapidly such that the centre is at a higher temperature than the surfaces. The centre subsequently cools and contracts, thereby inducing compressive stresses at the surfaces and tensile stresses in the core of the pane.

Toughened glass can be four to five times stronger than equivalent thickness annealed glass. Furthermore, the strength characteristics are more reliable, as the compressive prestress must be overcome before the more unpredictable tensile strength of the glass is utilized. Toughened glass is also many times more resistant to thermal stresses than annealed glass.

As a consequence of the locked-in tensile stresses, toughened glass fractures by fragmenting into small particles. It can thus be considered as a safety glass. Locked-in stresses prohibit cutting, drilling or working of toughened glass.

Spontaneous fracture is far more prevalent in toughened glass than in annealed glass. The heat treatment used in the toughened process can leave nickel sulphide inclusions within the glass in an unstable state. As the nickel sulphide changes to more stable state over time, the inclusion expands. If the inclusion is located in the central tensile zone of the glass, this expansion may lead to fracture. The problem can be largely overcome by using high quality material.

As a means of quality assurance, toughened glass can be heat soak tested. This process does not change the properties, but causes the majority of panes with significant nickel sulphide inclusions to fracture at this stage rather than later in service.

Toughened glass is normally available in thicknesses of 3 mm to 25 mm and maximum pane sizes up to 2 m × 4.2 m (depending on thickness).

2.4 Heat strengthened glass

Heat strengthened glass, sometimes referred to as semi-tempered glass, is produced by a similar process to toughened glass but the cooling rates are varied so that the locked-in stresses are lower than those in toughened glass. Heat strengthened glass is 1.5 to 2 times as strong as annealed glass. Both fracture in a similar manner. Therefore, heat strengthened glass cannot be used as safety glass.

Since the locked-in stresses are lower in heat strengthened glass than in toughened glass, spontaneous fracture due to nickel sulphide or other inclusions is much less common.

2.5 Laminated glass

Laminated glass is produced by bonding two or more panes of glass to an interlayer. The interlayer is usually PVB (polyvinyl butyral), which is a thin plastic sheet material. Annealed, toughened and heat strengthened glasses can be incorporated into laminates. When laminated glass is broken, the interlayer generally prevents the section from separating and falling away. Laminated glass can therefore be used as a safety glass.

Laminated glass is normally described by the total number of panes plus interlayers, e.g. 3-ply is pane/interlayer/pane. The thickness of the PVB interlayer can be adjusted to give the laminate different properties.

Laminated glass can be fire resistant if an intumescent interlayer is used, or if wired glass panes are incorporated.

Joints between glass beams or columns can be constructed by interleaving laminates to form'finger' or 'tenon' joints.

2.6 Insulating units

Insulating units are produced by combining two or more panes of glass in a hermetically sealed unit. The space between the panes is usually filled with air and is generally between 6 mm and 20 mm wide (Figure 2.1). The air is dehydrated by means of a desiccant, usually contained within the spacer around the edge of the unit. Annealed, toughened, laminated, wired or heat strengthened glasses of a variety of thicknesses can be incorporated into the unit.

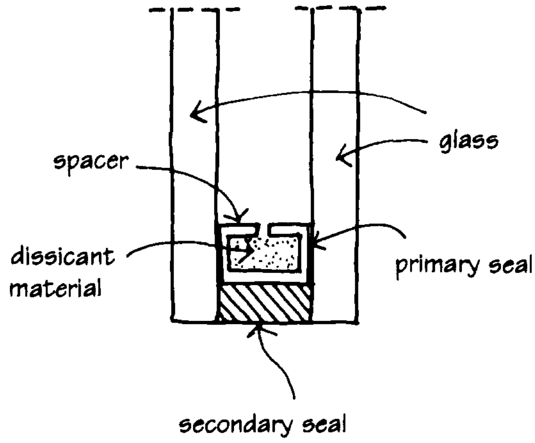


Figure 2.1
Insulated glass unit

The life span of an insulating unit can be over 30 years. One of the main causes of premature failure is breakdown of the edge seal of the units, resulting in internal misting. Edge seals are manufactured from organic materials and so tend naturally to break down over time. However the methods of supporting the panes, transferring wind loads and waterproofing, all effect the service life.

Special details have been developed for bolt holes in insulating units, using internal spacers which prevent leakage and resist the clamping action from the bolted fixing or compression resulting from out-of-plane loads (Figure 2.2).

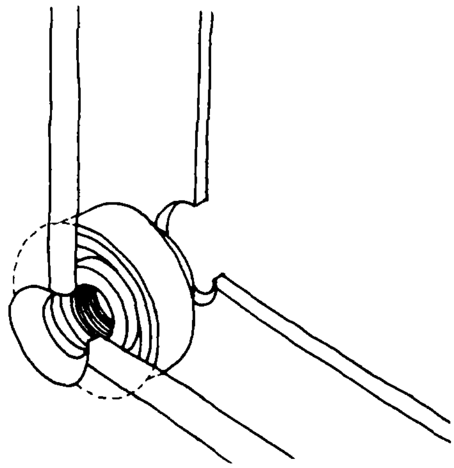


Figure 2.2
Bolt hole in double glazed panel, using spacer

2.7 Weather seals

Joints between glazing panels are generally made watertight by the use of sealants.

Sealants are subjected to tensile and compressive forces, and possibly shear, resulting from relative movement of glazing units. If sealant joints are particularly deep or narrow, greater force is required to deform them than if they are relatively shallow or wide. This may increase the forces on fixings and support structures, and will increase in-plane forces within the glazing panels.

Sealants should be specified accurately. Statements such as 'a silicone sealant shall be used' are insufficient, because of the wide range of sealant types that are available. There are two common one-part silicone sealants used for weatherproofing joints:

- acid cure sealants where acid is present in the wet sealant material.
- neutral cure sealants which are neither acidic or alkaline, and therefore less likely to react with other materials.

Sealants of the acid cure type can have detrimental effects on PVB interlayers in laminated glass and edge seals in double glazed units.

Typical sealant joint widths are in the range of 10-12 mm.

2.8 Panel sizes

Glass is produced in panels up to 3 m × 6 m. These panels are then cut down to more manageable sizes for drilling and toughening. Ultimately the size of the toughening bed limits the size of toughened glass to approximately 2.1 m × 4.2 m. The exact figure varies between manufacturers. More details are given in the Appendix.

Vertical glazing panels up to 2 m × 2 m can generally be supported using four corner fixings (Figure 2.3), whilst panels up to 2 m × 4 m can be supported using 6 fixings (Figure 2.4). Horizontal glazing may require more frequent supports to avoid ponding of water on the surface.

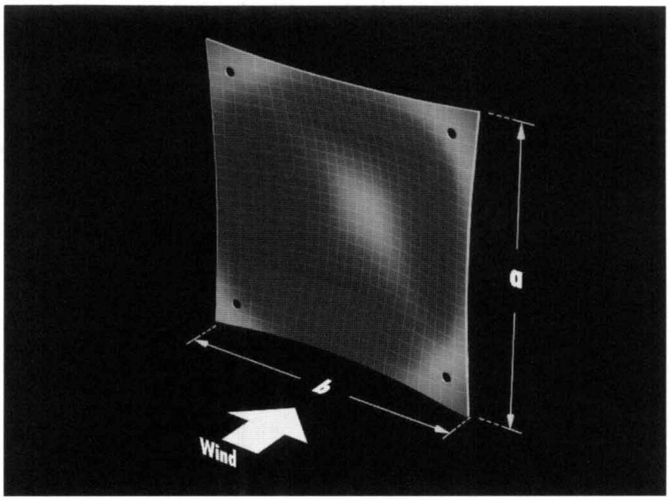


Figure 2.3
Panels with four point corner fixings, illustrating deformation under wind load

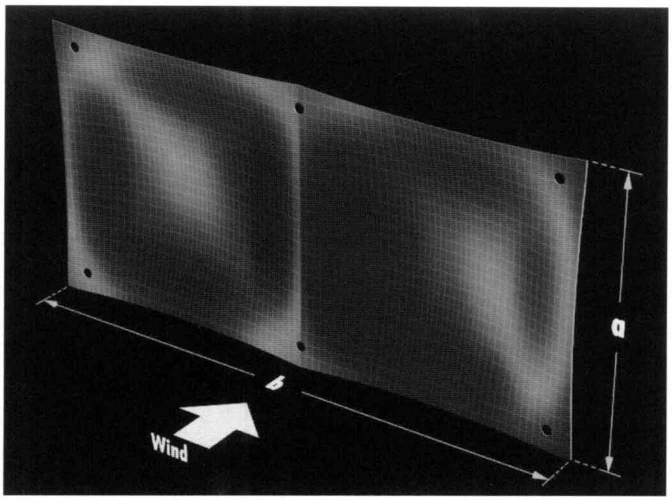


Figure 2.4
Panels with six point corner fixings, illustrating deformation under wind load

Eight fixings are not often required, but are occasionally used to support large glass panels in highly loaded areas, or when used horizontally. Figures 2.3 and 2.4 also illustrate the deformation of the panels under load and show the effects of the local stress concentrations around the point fixings.

When large panels (generally over 1.5 m × 2.5 m) are proposed, issues of lifting and maneuvering them into position should be addressed. Quite often, installation has to be carried out by hand from scaffolding.

Consideration should also be given to the amount of movement at the edge of panels caused either by thermal expansion, or by deflection of the panels or the supporting structure. Generally, edge movement should be limited to 25% of the joint width (i.e. to ±3 mm for a 12 mm joint), although a greater percentage movement value can be achieved with appropriate modulus silicon. Larger panels increase the amount of movement that must be accommodated at each joint.

3 BOLTED FIXINGS

Various types of bolted fixing are available, and can be used in conjunction with a range of glazing support attachments. Generally, the more sophisticated variants have higher capacities than the simple types, but are more costly. Enhanced countersunk fixings and articulated bolts are notable for their ability to accommodate rotation of the fixing relative to glazing support attachments, thereby reducing moments developed in glazing panels.

Some glazing systems use fixings that are countersunk or otherwise set into the plane of the glazing in order to achieve a smooth appearance.

3.1 Standard bolt

Standard bolts (Figure 3.1) are the simplest type of bolted fixing. The bolt head is proud of the plane of the glass.

Load transfer can be by direct bearing of the glass on the shank of the bolt. However, the small contact area limits capacity. It is preferable for a liner to be used between the bolt and the glass to increase the bearing surface and to avoid high point-contact forces. There is little provision for rotation of the glass relative to the fixing under applied out-of-plane loads.

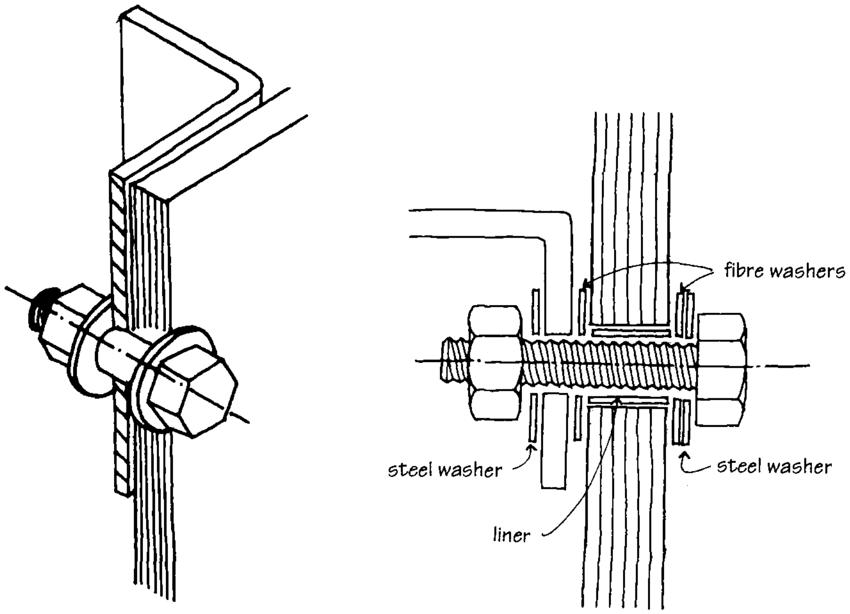


Figure 3.1
Standard bolt

3.2 Simple countersunk bolt

Countersunk bolts (Figure 3.2) allow the bolt head to be flush with the glazing. Use of a liner is again recommended in order to enhance the in-plane load capacity since drilling and other manufacturing inaccuracies can lead to even greater stress concentrations than those associated with standard bolt details. Again, there is little provision for rotation of the glass relative to the fixing under applied out-of-plane loads.

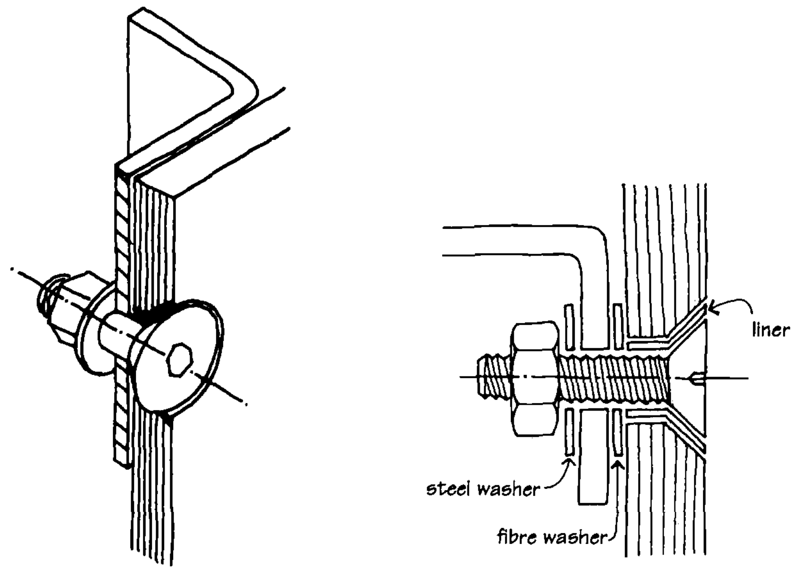


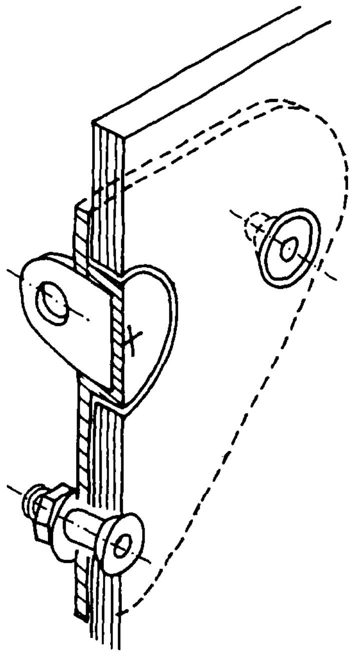
Figure 3.2
Simple countersunk bolt

3.3 Stud assembly

The stud assembly detail (Figure 3.3) provides high levels of in-plane load transfer capacity through a disk connected to a backplate. This disk may be fitted with a liner. Countersunk bolts are used to attach the glass to the backplate. These bolts carry out-of-plane loads but no in-plane loads. The disk and boltheads are flush with the plane of the glazing.

There is no provision for accommodating rotation of the glazing under applied out-of-plane loads. However, provision can be made at the connection of the backplate to the glazing support attachment.

This is a relatively complicated device, since it relies upon three holes being formed in the glass pane.



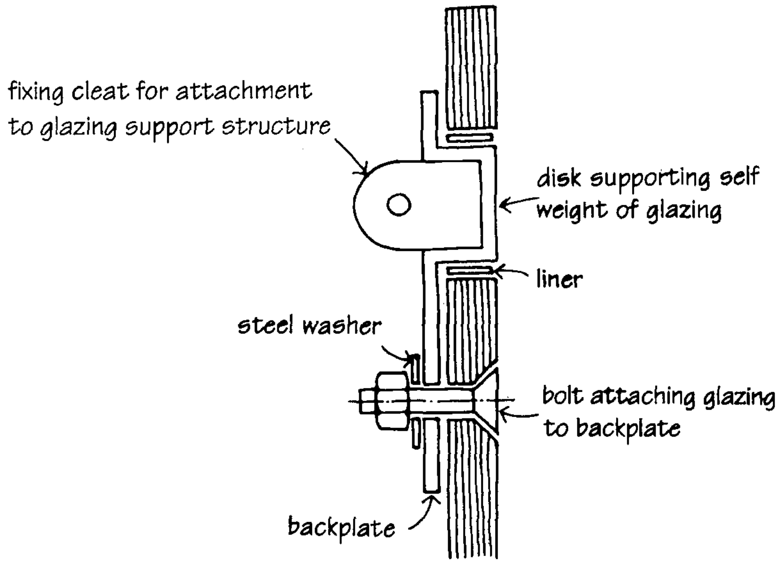


Figure 3.3
Stud assembly

3.4 Patch plate fixing

Patch plates (Figure 3.4) were developed initially for use with glass fins. Plates are fixed to either side of a glass panel on vulcanized fibre, or similar gaskets. These plates are attached by bolts tightened to a specific torque in order to achieve a friction connection.

The bolts are not in bearing with the glass. Increased contact area and wider load spread provide relatively high load carrying capacity for both in-plane and out-of-plane loads.

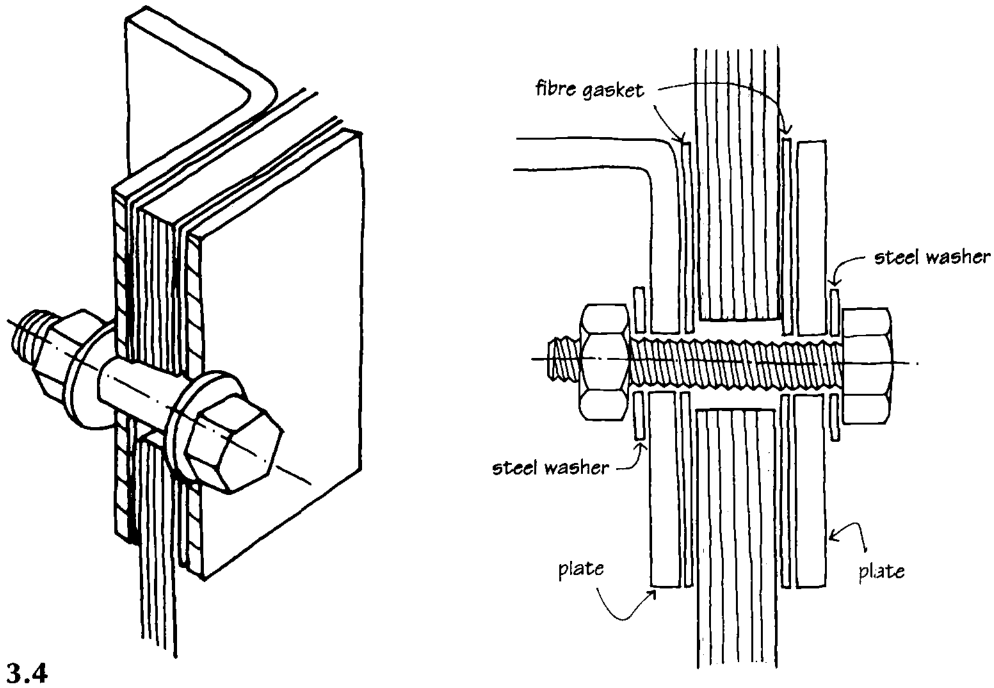


Figure 3.4
Patch plate fixing

3.5 Enhanced countersunk fixing

There are two key differences between this 'enhanced' type of countersunk fixing (Figure 3.5) and the simple countersunk bolt: the use of a threaded backing washer against the inner face of the glazing panel, and the use of flexible washers either side of the support attachment.

The threaded backing washer is included to enable the bolt to be installed conveniently to a predetermined torque. Flexible washers are used at the connection to the glazing support attachment in order to allow the bolt to rotate relative to the brackets.

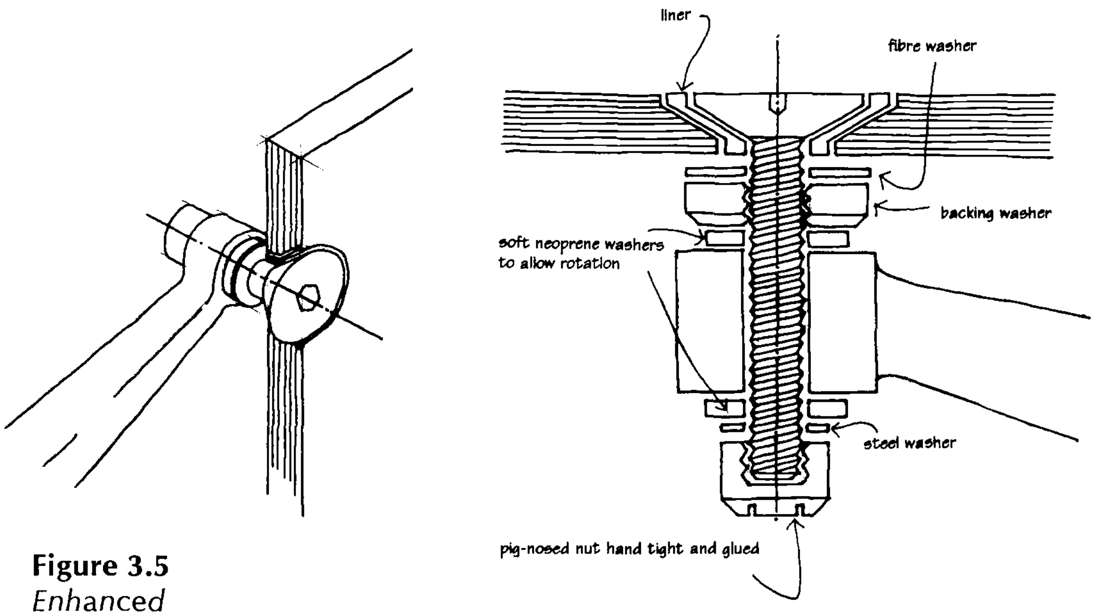


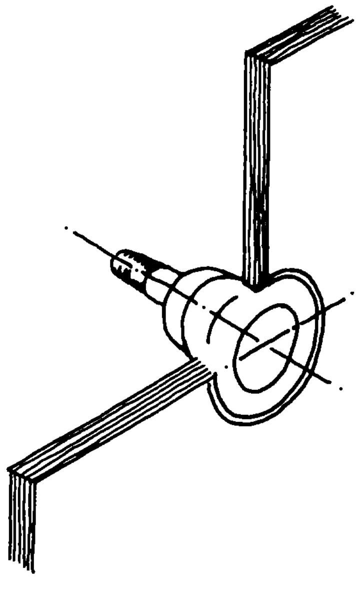
Figure 3.5
Enhanced countersunk fixing

3.6 Articulated bolts

The articulated countersunk bolt detail (Figure 3.6) was developed by Rice Francis Ritchie for the Serres at La Villette in Paris in 1986. It consists of a bolt with a spherical bearing surface, instead of the flat underside of a standard bolthead or the conical underside of a countersunk bolthead. This spherical surface is seated in a bearing cup which is set into the glass panel.

A threaded washer is screwed on the bolt, up to the surface of the glazing panel, to clamp the bolt in place. The washer is tightened to a controlled torque. The main differences between countersunk bolt details and articulated bolt details are that the latter are able to accommodate greater rotational movement of the glass relative to the glazing support attachment.

Articulated bolts allow large panels of glass to be fixed back to flexible support systems such as catenary cables.



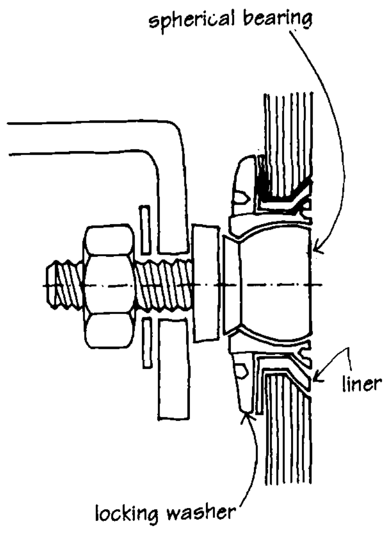


Figure 3.6
Articulated bolt fixing

4 SUPPORT STRUCTURES

For the purpose of this publication, framing systems have been categorised as follows:

a) Point-fixed glass on base supported steelwork
- Simple posts
- Trusses and fins

b) Point-fixed glass top hung with wind trusses.

c) Point-fixed glass on cable systems.

d) Glass fin stiffened systems.

The posts and trusses are commonly fabricated from tubular sections (refer to the Case Studies).

4.1 Point-fixed glass on base supported steelwork

4.1.1 Simple posts 2.5 - 4.2 m high

Vertically spanning posts (typically, circular hollow sections) may be used to provide mid-height restraint to glazing panels that are supported at their base. These posts are often located on the joint line (Figure 4.1), or at the centre of panels (in which case glazing support attachments are fixed to arms connected to the posts (Figure 4.2). The use of arms halves the number of posts that are required.

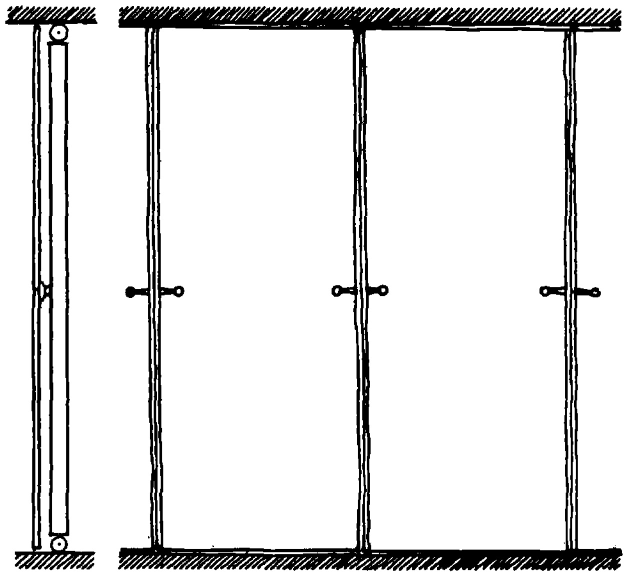


Figure 4.1
Posts located at panel joints

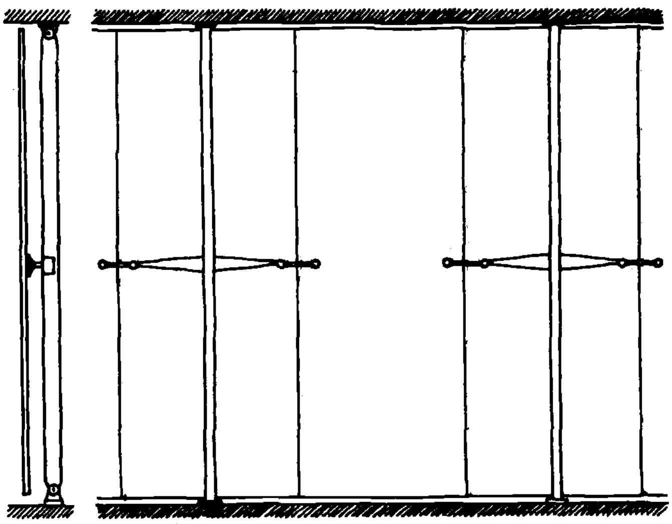


Figure 4.2
Posts with cantilevered arms

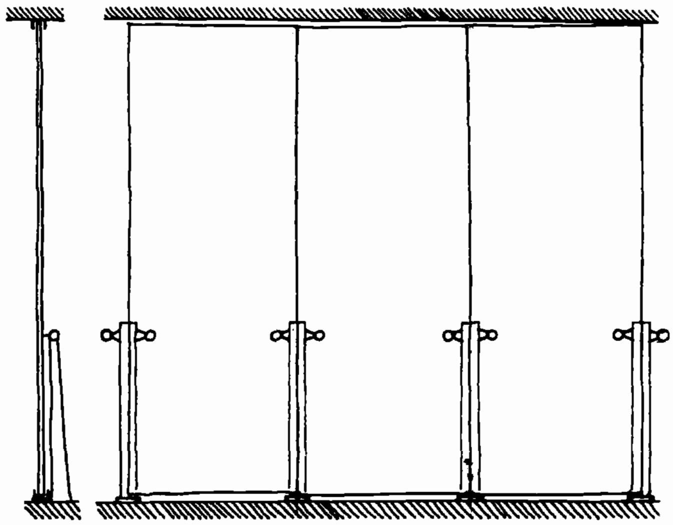


Figure 4.3
Cantilevered posts

An alternative to using posts is to attach glazing panels to freestanding handrails or vertically cantilevered posts (Figure 4.3).

4.1.2 Trusses and fins (4 m height and above)

Base supported lattice trusses, vierendeel trusses, bowstring trusses or fins, may be used to support glazing where the height of glazed walls exceeds that which can practically be achieved using posts (typically 4 m and above).

Lattice trusses comprise two chords with triangulated web members. Circular hollow sections are commonly used for both chord and web members. Their ends may be pin jointed, in which case it is common to taper the truss, or may be designed to resist moments, in which case the full depth of the truss is normally maintained and a moment resisting multiple bolt connection is used.

Vierendeel trusses rely on moment connections between the chords and the perpendicular web members. Consequently, rectangular or square hollow sections are often used, since these have good resistance to local deformation. Again, end connections may be either pinned or moment resisting.

Bowstring trusses comprise a main compression member usually with one, two or sometimes three slender rods or cables spaced from the compression member on struts to provide resistance to bending. Their end connections are generally pinned.

Vertically orientated fins can provide similar stiffnesses to lattice or vierendeel trusses.

Glazing support attachments are normally located at the node points of trusses. Lattice and vierendeel trusses can be glazed on either side (or on occasions on both sides, as for example when used in twin skin facades). Glazing panels supported on bowstring trusses may either be positioned to one side of the truss (in which case they are often attached to extended struts, see Figure 4.4) or be set within the truss (in which case the system needs to be detailed to allow the truss members to pass through the plane of the glazing). An example of the latter approach is given in the Waterloo International Station case study (Section 7.1).

Trusses and fins are generally installed at spacings corresponding to the width of the glazing panels that they support. Spacings of 1.5 to 2.5 m are therefore typical. This may be increased by introducing cantilevered arms with pivot supports (Figure 4.5). A further advantage of cantilevered arms is that their angular rotation about their connection to the trusses/fins can provide high levels of vertical adjustment at the point of attachment of the glazing support.

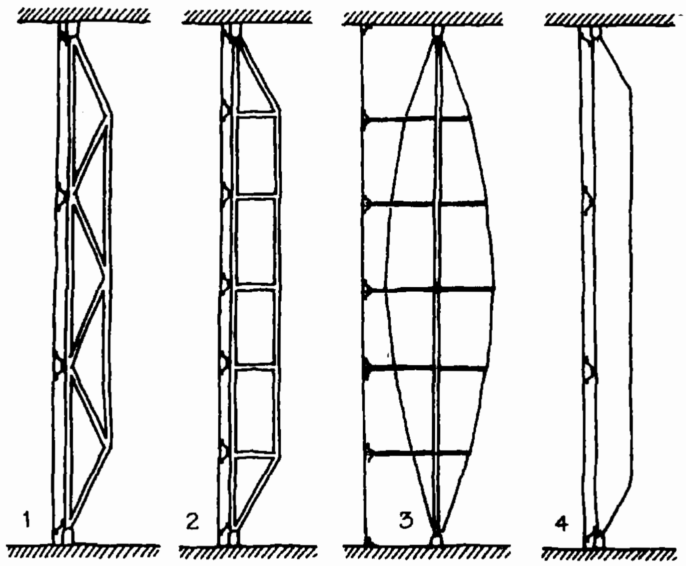


Figure 4.4
Truss types

Key:
1. Lattice truss
2. Vierendeel girder
3. Bowstring truss
4. Fin

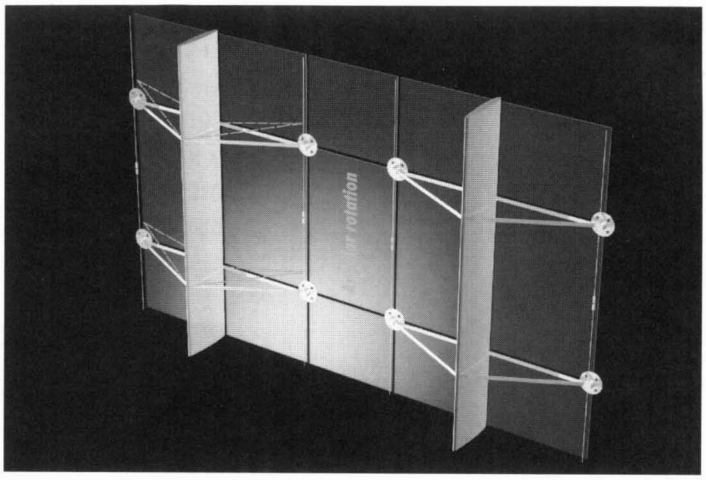


Figure 4.5
Cantilevered arms

Lateral restraint is often provided by tension systems based upon wires or rods. Turnbuckles or similar devices can be incorporated to provide length adjustment, and can be used to pull trusses or fins into correct alignment (Figure 4.6).

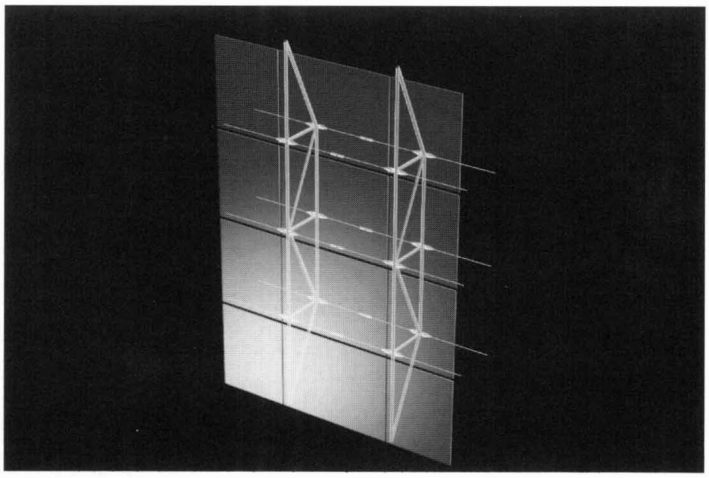


Figure 4.6
Lateral restraint with turn-buckle type adjustment

4.2 Point fixed glass, top hung with wind trusses

It is possible to reduce the size of visible supporting steelwork by hanging glazing panels, either from a series of tension elements, or from panels immediately above.

4.2.1 Support by steel wires or rods

Hanging glazing panels from tension elements is relatively straightforward. The self weight of each panel is transferred, using appropriate attachments to carbon steel or stainless steel rod, or wire hangers.

The tension elements are restrained from moving under wind loads by connecting them to horizontal wind trusses (Figures 4.7 and 4.8). Articulated links can be incorporated at the point of connection (Figure 4.9) in order to accommodate tolerances and movements. The tension elements can also restrain the trusses against deflecting vertically.

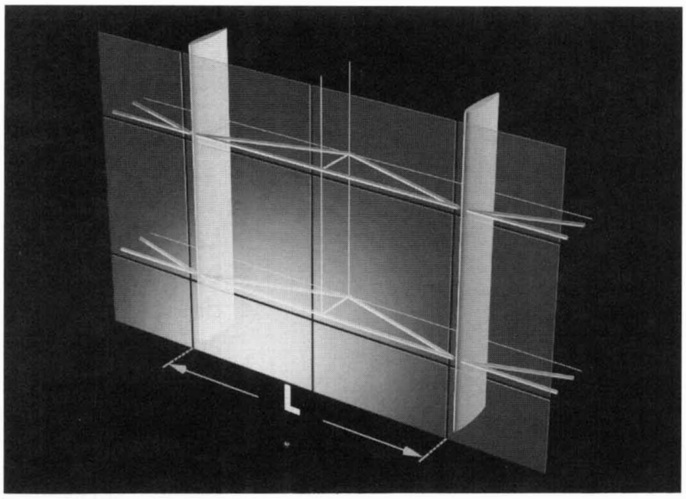


Figure 4.7
Typical wind truss arrangement (A)

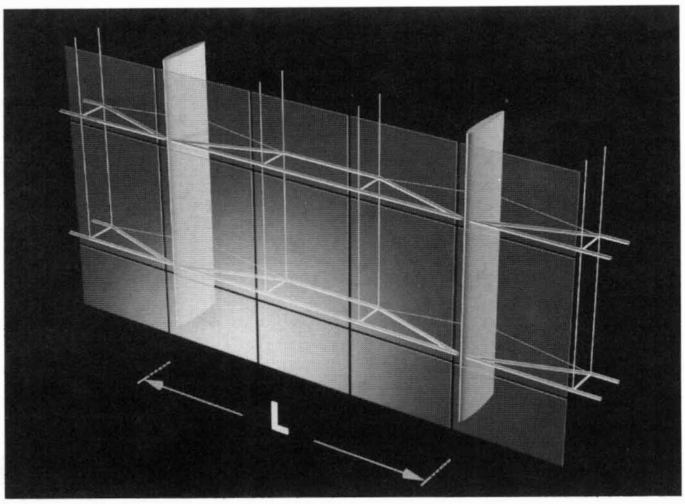


Figure 4.8
Typical wind truss arrangement (B)

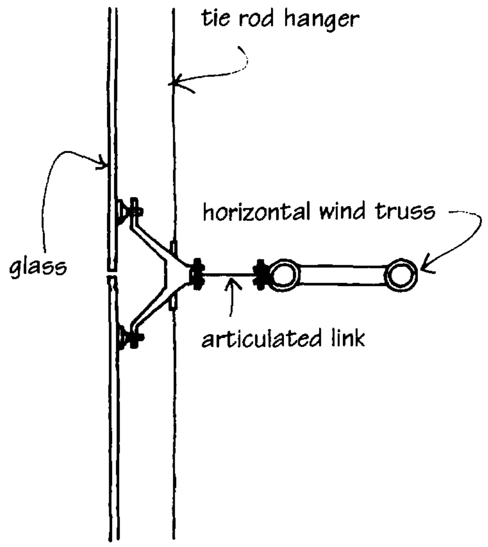


Figure 4.9
Articulated link at connections to wind girder

When glazing panels are hung from tension members, turnbuckles or similar devices can be used to make adjustments to their vertical alignment.

4.2.2 Support by glazing to glazing connection

Special glazing support attachments may be used to hang glazing panels from each other in vertical stacks (Figure 4.10). The approach limits the maximum height that can be achieved, since the fixings in the upper panels can be highly stressed.

Manufacturers quote different fixing capacities and as a consequence the height of glass walls that each is able to achieve varies. Practical aspects such as movement of the supporting structure can also restrict height. Adjustment can be provided at links to achieve correct vertical alignment for glazing panels.

Wind loads may be resisted by either horizontal or vertical wind trusses, similar to those identified in Section 4.2.1. Horizontal trusses are the most common. Normally the brackets that connect glazing panels incorporate connection arrangements to the trusses.

These systems are not recommended over unprotected entrances or where glazing failure could cause injury to people below.

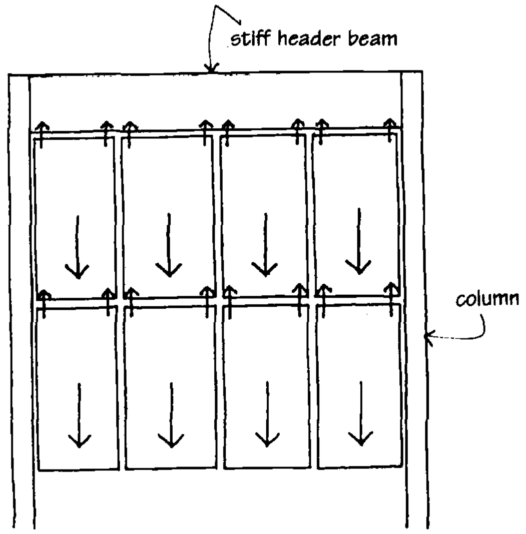


Figure 4.10
Glass panels hung one beneath the other

4.3 Point fixed glass on cable systems

Support structures can be constructed almost entirely from tension elements, such as rods or wires, and are therefore very light both physically and visually.

However, the boundary support structure can be heavier than other systems, since loads cannot be taken directly to ground but have to be transferred at both ends of the cables.

The weight of vertical glazing is either supported by a tie rod hanger system or by each panel being suspended from the panel above (as described in Section 4.2). Opposing catenary cables are often used to provide resistance to reversal loads and bending (Figure 4.11).

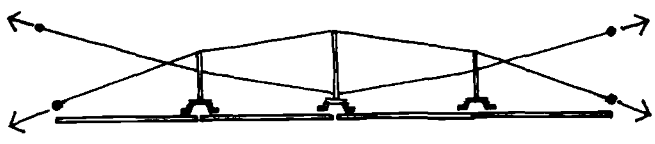


Figure 4.11
Opposing catenary cables

Catenary systems become very flexible if there is a loss of tension in the cables. It is therefore important that the structures they connect to are relatively rigid. Pre-tensioning is generally required to reduce movements and assist initial set-up. This should be calculated carefully and be sufficient to avoid excessive loss of tension due to thermal expansion whilst not liable to overstress the ties at low temperatures.

Under a uniform wind load, cable movements are symmetrical about the mid-span. In uneven loading conditions, movements are more complex.

Construction of catenary support systems requires careful sequencing and control. The support structure must be erected and lined and leveled before the catenary system can be installed. The sequence of erection of the cable system, and number of temporary supports that are needed depend upon the particular design.

When the two opposing catenaries are connected, they can be pre-assembled on a flat surface using a jig. Having accurately set-up the lengths and node point locations they can be lifted into position and connected to the compression frame.

4.4 Glass fin stiffened systems

Glazing panels may be attached to glass fins using a variety of techniques including bolting and silicone bonding. Fins are normally oriented perpendicular to glazing panels and are often made from laminated material.

Two common connection methods for attaching glazing panels to glass fins are illustrated in Figure 4.12.

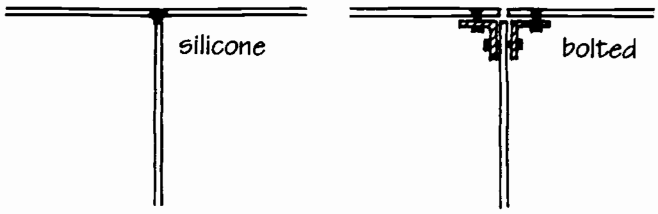


Figure 4.12 *Glass fin connection methods*

The accuracy of holes drilled in fins is the same as for any other piece of glass (± 1 mm is possible refer Section 5.2.2). The end connection detail between glass fins and steelwork should be able to accommodate tolerances in the three orthogonal directions and any differential movement that may occur between the steel and the fin. By clamping a steel (or stainless steel) shoe to the end of glass fins, larger loads and movements can be accommodated than by using simple bolted connections.

Installation of fin stiffened systems is relatively straightforward. Support brackets and fins are erected, lined and leveled. The main glazing panels can then be offered to them, their position checked, and the attachments made. When the glazing is silicon bonded to the fins, it is important to hold it accurately in position in the temporary state so as to achieve good alignment and to avoid secondary stresses that could adversely affect the connection.

The conditions under which sealants are applied are critical; advice should be sought from manufacturers.

5 DESIGN ISSUES

5.1 Tolerances

5.1.1 Glazing panel tolerances

Glass glazing panels are generally very accurate in terms of thickness, edge dimension, squareness, bow and roller wave (small undulations in the glass surface caused by passage over transport rollers during colouring). Drilling accuracy for bolt holes in glass (carried out prior to toughening) has improved considerably as a result of the widespread use of computer controlled machinery. Accuracies of $\pm$ 1 mm from the theoretical position can normally be achieved.

5.1.2 Alignment of glazing panels in walls

Any inaccuracy in the bolt position or size of glass panels is normally accommodated by slight adjustments to the width of the joints between panels and at the connection between the glazing and the glazing support.

It is normally important that the surfaces of glazing panels are well aligned. Toughened glass tends to have greater bow than untoughened glass. It is also important to match bows in adjacent panels to avoid steps. Clamping the panels until the silicone jointing is installed can help this alignment.

Glazing panel grids normally align with the as-built position of support steelwork. Straight joints are maintained both horizontally and vertically. Setting accuracy is limited only by the accuracy of the equipment used for measuring panel positions. It has become customary to set tolerances of ± 2 mm in both directions (Figure 5.1).

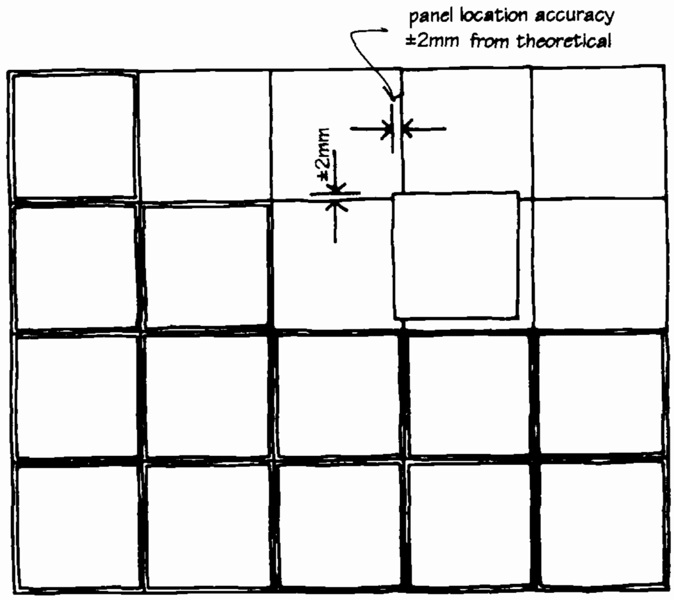


Figure 5.1
Glazing installation tolerances

5.1.3 Support structure tolerances

Generally the National Structural Steelwork Specification is applicable for the steel support structure, but there are particular requirements for accuracy at the positions at the glazing attachment fixing positions.

The support structure will be subject to dimensional variations as a result of both fabrication and erection. Theoretically any reasonable degree of adjustment can be provided at the connection of the glazing attachment to the support structure. However, high levels of adjustment increase both the size and complexity of the glazing attachment, and since designers often strive for particularly elegant solutions, it is usual to restrict the amount of adjustment provided to the minimum that is necessary.

An adjustment of ± 5 mm is common (Figure 5.2), but this necessitates special fabrication skills and facilities. Designers may relax tolerances in order to simplify fabrication and reduce cost, but this must be reflected in the amount of adjustment that is provided at the glazing attachment.

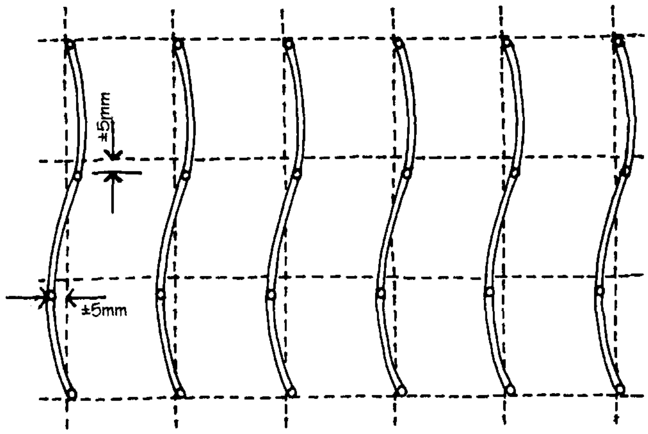


Figure 5.2
Tolerances of attachment points

Large support structures often incorporate devices to pull members into the correct alignment laterally (see Section 4.1.2).

Rotational inaccuracies are particularly difficult to accommodate without recourse to complex and costly adjustment devices. Therefore, a narrow tolerance range is often specified for the position of the glazing support connection points in one direction, for instance along the axis of the structural member to which connection is being made; a wide tolerance range is specified in an opposing direction, for instance perpendicular to the axis of the structural member. Adjustment in the direction with the wide tolerance range can then be carried out using simple tapered shims (Figure 5.3). An alternative approach is to use two tapered shims set one above the other, both of which can be independently rotated to achieve variable angular corrections in any direction within a 360° arc around the axis of the connection point.

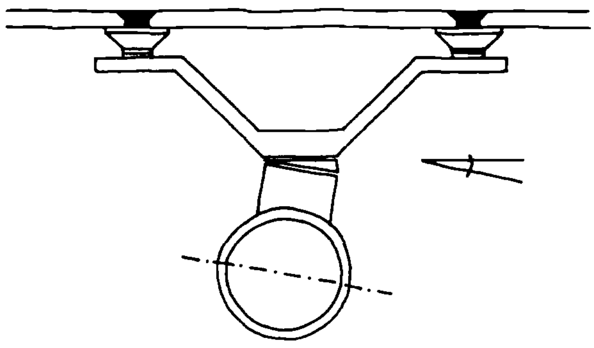


Figure 5.3
Adjustment of rotational inaccuracies using tapered shims

5.2 Movement

5.2.1 Glass movement: out-of-plane

A deflection limit of L/100 for mid span deflection under working loads is reasonable for most applications (Figure 5.4).

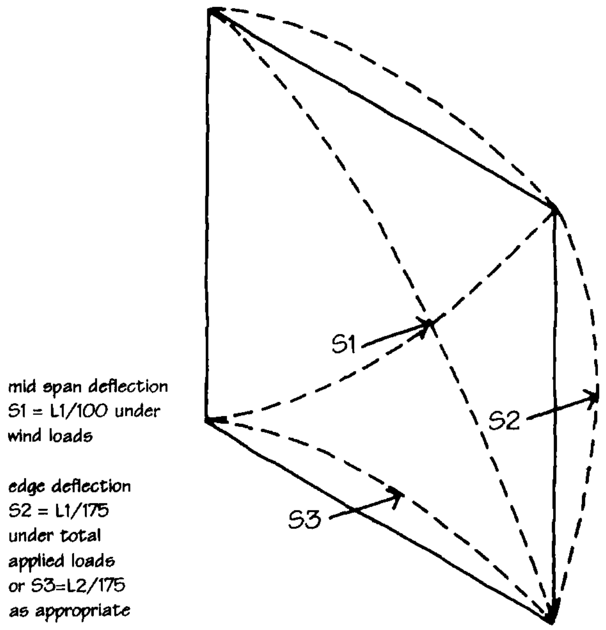


Figure 5.4
Suggested deflection limits for single glazed bolted glass

Permissible edge deflection should not normally exceed L/100 for a single glazed toughened panes and L/175 for double glazed units (in order to avoid damage to edge seals). The flexibility of bolted fixings and support attachments must accommodate the total rotation of glazing under applied loads and should be considered in conjunction with any rotation than may occur as a result of deflections of the support structure.

If glazing supports cannot rotate, the resulting moment will need to be resisted by the glazing, the bolted fixings and the glazing support attachments.

Simple deflection formulae for plates generally give safe (pessimistic) values for glass. If more accurate values are required, then finite element analysis can be used, or individual panes can be tested.

5.2.2 Glass movement: in-plane

Glazing panels can experience surface temperature variations of $-15°C$ to $+45°C$ in severe locations in the UK. Glass has a coefficient of thermal expansion of 7.75×10^{-6} per $\times$ °C, which may be compared to a value of 12×10^{-6} per °C for steel and concrete. Movement relative to the support structure depends on the temperatures of both, but could reasonably be expected to give a worst case movement of only ± 0.25 mm at each corner of a 2 m $\times$ 2 m panel (Figure 5.5).

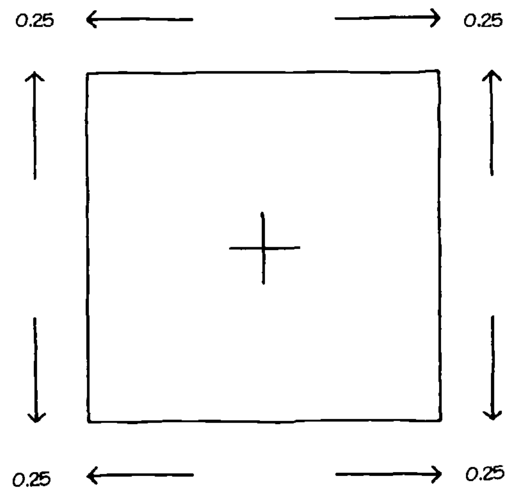


Figure 5.5
Worst case relative movement at the corners of a glass panel 2 m × 2 m

5.2.3 Support structure: out-of-plane movement

One of the most important factors in setting limits for out-of-plane deflection is the amount of rotation that can be accommodated in the glazing supports. This rotation occurs as a result of deflection of the glazing panels under applied loads and the deformation of the support structure. Often a deflection limit of L/360 will produce excessive rotation and more restrictive limits are necessary.

DESIGN

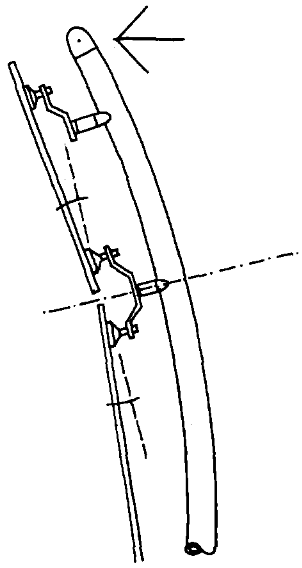


Figure 5.6
Deflection and rotation at fixings

5.2.4 Support structure: in-plane movement

Large areas of glass are often provided over and around open spaces such as entrance halls and atria. These often require large support structures. In-plane movement occurs as a result of lateral wind loads, temperature variations, and deflections under self weight and applied loads.

It is necessary to predict and accommodate support structure movements which occur:

a) During construction.

b) During glazing installation.

c) In service.

Silicone joints can cause glazing panels to behave monolithically rather like a deep beam. This can have two potential implications (Figure 5.7):

- Loads can concentrate at particular panel fixings such as adjacent to columns.
- An additional load can be applied to the glass from the supporting structure.

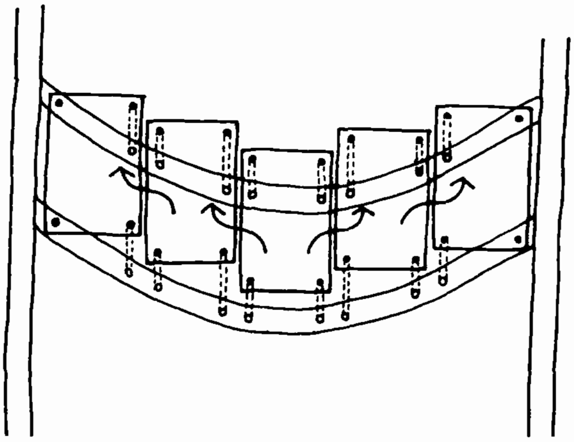


Figure 5.7
Transfer of load via silicon joints

Alternatively, panels may rotate (Figure 5.8) or move independently (Figure 5.9), in both cases causing increased downward loading in certain fixings and possible load reversal in others. The effects must be quantified and the glazing support, glazing panels and bolted fixings designed accordingly.

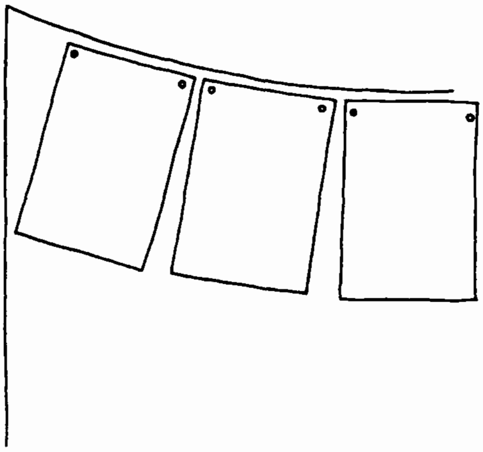


Figure 5.8
Glazing rotates due to beam deflection

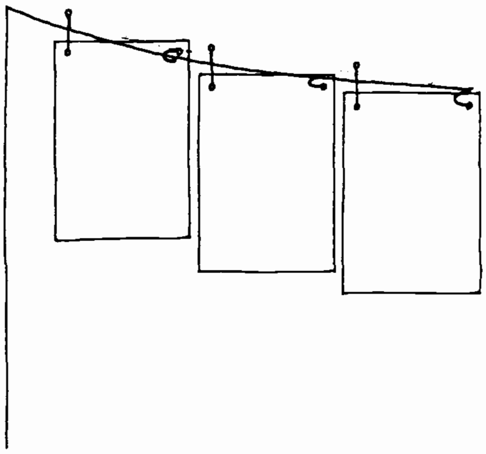


Figure 5.9
Load shifts to one fixing due to beam deflection

5.2.5 Main frame movements

Building frame movements can present various design issues. Whilst these are generally outside the scope of this publication, two common cases are presented below.

Glass wall built into the main frame

There are two different design situations for sway movements of the type indicated in Figure 5.10, depending on how glazing support structures are connected to the building frame. If the support structure does not sway with the building, checks must be made to ensure that differential movements at the perimeter of glazed walls can be accommodated in the local details.

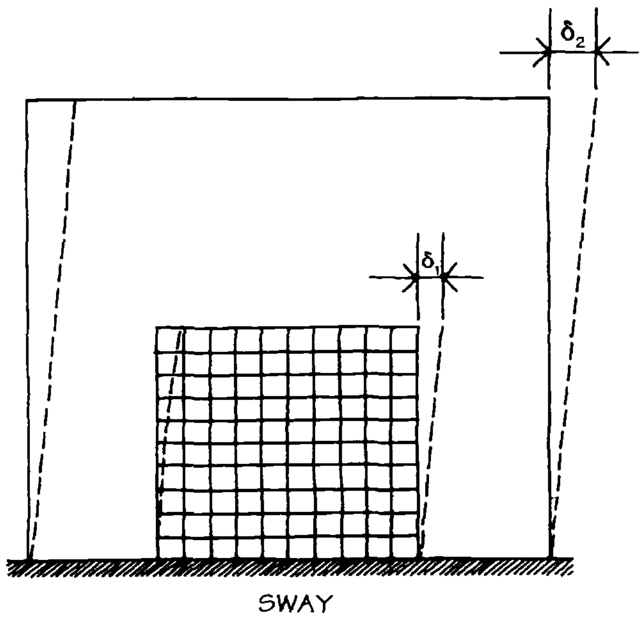


Figure 5.10
Sway movements

Alternatively, if the support structure does sway with the building, either the relative movements must be fully accommodated by flexing or sliding in the glazing support attachments, or the glazing panels must be free to 'shear' or move relative to one another.

Glazed atrium between buildings

It is common for glazed structures to link buildings or parts of buildings to form atria. The distance they are required to span can vary as a result of thermal effects illustrated in Figure 5.11, and as a result of wind sway. The following techniques may be used to overcome differential movements (Figure 5.12):

a) Sliding or articulated joints can be introduced.

b) The glazing support can be designed to be free-standing and structurally independent.

c) The glazing support can be designed to resist the applied forces.

The relative merits of these techniques depend on the effect of stresses on the support structure, and detailing around sliding or articulated joints.

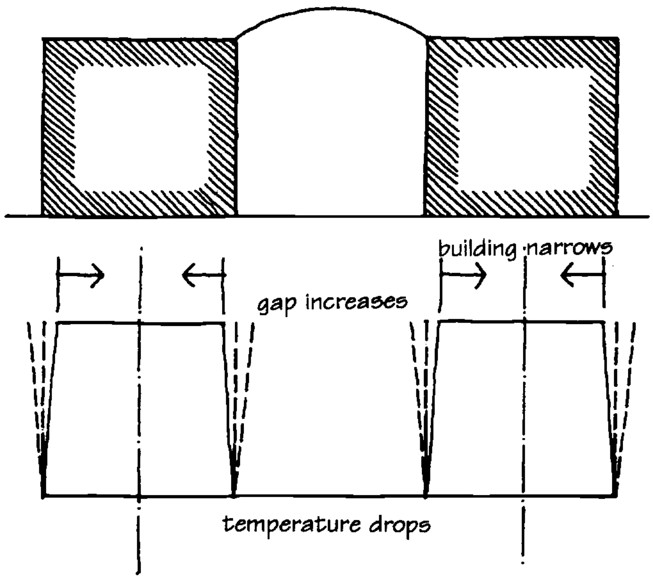


Figure 5.11
Differential movements between adjacent blocks

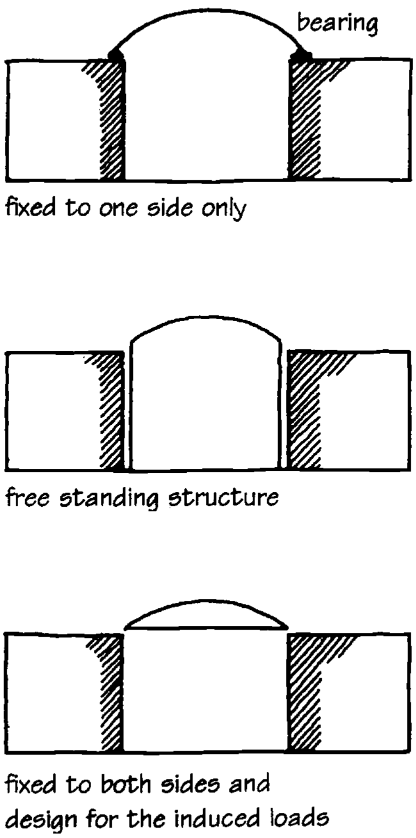


Figure 5.12
Methods of accommodating differential movements

5.3 Loading

5.3.1 General

British Standard BS 6399 *Design Loading for Buildings* should be used to determine the appropriate dead, live, snow and wind loads for glazing. The standard has the following parts:

Part 1 Code of practice for dead and imposed loads

Part 2 Code of practice for wind loads

Part 3 Code of practice for imposed roof loads

BS 6399: Part 2 should be used in conjunction with appropriate local wind coefficients for cladding. This assumes much higher wind loads at the corners and edges of roofs, sometimes more than twice the average value applied to the whole facade (Figure 5.13).

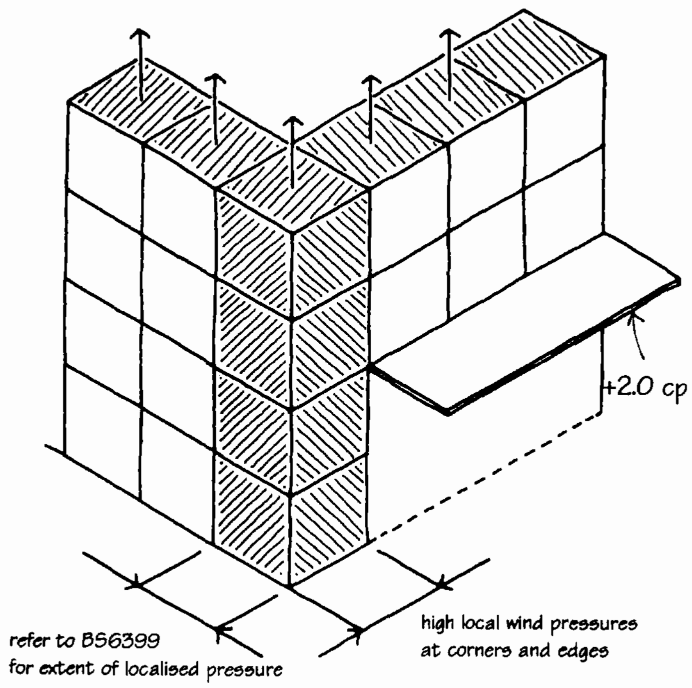


Figure 5.13
High wind load effects at corners and edges of buildings

5.3.2 Unguarded glass walls

Consideration must be given to the use of an equivalent of a handrail load for glass walls without a guard rail. Reference should be made to BS 6180 for further guidance.

The magnitude of forces that glazing is designed to resist should be related to the risk of damage should a panel break. This is particularly important for upper storeys, or buildings where there is public access. Where necessary, fixed rails may be provided for the safety of the building occupants.

5.3.3 Maintenance

Horizontal and sloping glazed assemblies may need to resist loads from cleaning and maintenance equipment. Advice on the magnitude and types of loading that may occur should be taken from specialist suppliers and installers.

5.3.4 Effects of breakages

Where glass panels are hung one beneath another, the effects of panel failures should be considered. It is essential that alternative load paths are provided so that large sections of glazing will not progressively break and collapse as a result of a single panel failing (Figure 5.14). The effects of failures of glass fins should also be considered.

A further accidental load case should also be considered where multiple panels are broken or removed to ensure that a dominant opening is not created that could lead to additional internal wind pressures.

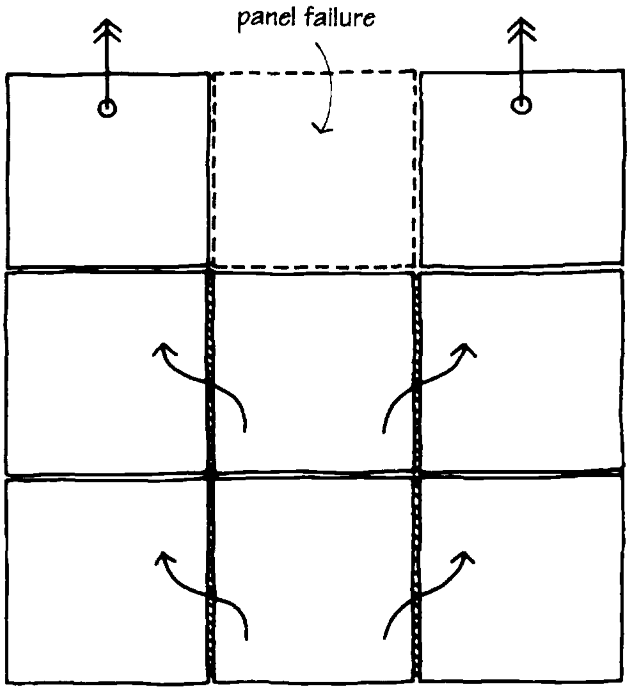


Figure 5.14
Alternative load path

5.3.5 Accidental loads: bombs, blast and other explosions

The advice of a structural engineer conversant with explosion damage should be sought. Consideration should be given to the hazards caused by glazing shattering during an explosion. If glazing is retained in place during an explosion, loads will be transferred to the supporting structure. Alternatively, glazing may be allowed to separate from the supporting structure. In the latter case, risks to building occupants and persons in the surrounding area must be considered.

5.3.6 Seismic loads and vibration

It is unusual to need to design to resist seismic load conditions in the United Kingdom. However, it is common to need design glass walls to withstand some form of vibration or excitation. In such locations, the frequency, amplitude and maximum acceleration should be determined, and the additional lateral or vertical loadings on the panels calculated.

It is sometimes necessary to carry out tests on a mock-up to determine the natural frequency and sensitivity of glazed structures. Provided that natural damping of the cladding is sufficient, damage should not occur. Advice should be sought from a vibration specialist.

5.4 Durability and replacement

5.4.1 Glass

Provided that the surface is not mechanically damaged, glass requires virtually no maintenance apart from cleaning.

Toughened glass should not be scratched as deep scratches form a potential crack source. Exposure to weld spatter and hot grinding debris during construction or maintenance work should also be avoided, since internal stresses in the glass can be disturbed leading to possible failure.

As with the general maintenance and replacement of minor components such as seals, it is essential that any piece of glass can be removed and replaced with relative ease. This is not a problem for simple, single panels fixed directly back to a rigid steel support frame. The silicone seal can be cut away and the point fixings unbolted, allowing the panel to be lifted clear.

Overhead glazing should be regarded as a 'fragile roof' and should not be used for maintenance, unless it has been specifically designed for the appropriate loadings.

5.4.2 *Stainless steel*

Stainless steel has a long design life. Surface contamination (particularly when making attachments in mild steels) should be avoided, and specialist advice should generally be sought concerning the correct grade of stainless steel, particularly in high chlorine and other severe environments. Guidance from the use of stainless steel is given in the SCI publication 'Architects' guide to stainless steel'.

5.4.3 Rubbers and silicones

Many rubber and silicone materials last fewer than 25 years. Only the best have 40 year design lives. Replacement and maintenance should therefore be considered at the design stage.

For instance, it should be possible to remove joint gaskets and replace them without lifting out glazing panels, and ideally without need for extensive temporary access systems.

6 GLAZING SUPPORT ATTACHMENTS

Glazing can be attached directly to the support structure (for example to angles welded to posts), but it is much more common to use separate components, called glazing support attachments, that form an interface between the glazing panels and the support structure. The attachments provide the structural inter-connection and they allow relative adjustment in position. The attachments can take many forms but the most common are:

- *Angle brackets*
- *Spiders*
- *Pin brackets*
- *Clamping devices*

The structural function of the glazing support attachments is primarily to transfer the applied loads acting on the glazing panels (wind, snow, maintenance, etc.) and the self weight of the glazing panels to the support structure. They must also be able to resist any moments that are developed and any internal forces due to thermal or other effects.

Angle bracket, spider and pin type connections share many common design features. Generally, the weight of vertical and sloping glazing is carried by one set of fixings at either the top or the bottom edge of the panel. To allow for movement of the bolted fixings relative to the support attachment in one direction, the attachments have horizontally slotted holes. On the opposite edge, the attachments have oversized holes, allowing movement in two directions (Figure 6.1). Where the glazing is horizontal, the attachments may simply have oversized holes at each connection.

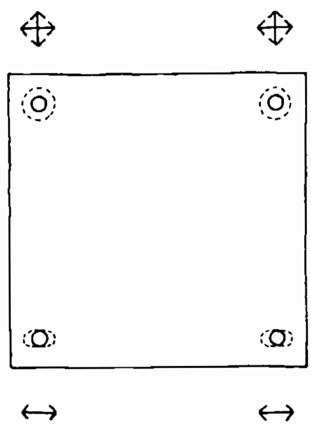


Figure 6.1
Provision for movement in glazing support attachments (bottom hung)

The size of slots and holes in the attachments should reflect the amount of adjustment that is needed to accommodate tolerances, combined with allowances for thermal movements. These are illustrated schematically in Figure 6.2. If required, provision should also be made for in-plane movement of the support structure resulting from wind sway or other effects.

Angle bracket, spider and pin type attachments must also resist any moments arising as a result of deflection of the glazing panels or the support structures. However, as described in Section 3,

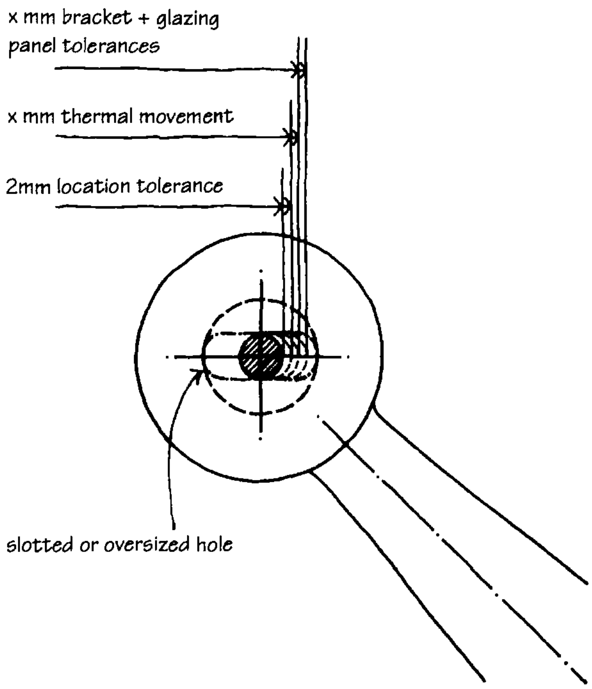


Figure 6.2
Slotted or oversize holes in glazing support attachment

bolted fixings are often designed to rotate relative to support brackets. Flexible washers may be used at the connection to the support bracket or a bearing may be incorporated into the fixing. These techniques minimise or eliminate moment transfer.

Support structure tolerances are generally accommodated by providing adjustment of the fixing position of the glazing support attachment relative to the structure. Provision for $\pm$ 5 mm adjustment is common, refer Section 5.1.2.

Consideration also needs to be given to adjustment to accommodate tolerance on alignment (in all three rotational directions), as described in Section 5.1.3

6.1 Angle brackets

Angle brackets are the simplest form of attachment. They may either be welded directly to the support structure or bolted to a cleat or fin plate.

The advantage of the bolted type of bracket is that adjustment is possible between the angle and the cleat in one, two or three directions by introducing slotted or oversized holes, and by using shims or spacers.

In order to allow the dimension between the cleat and the angle bracket to be fully adjustable, the arrangement at the nominal position should include an amount of packing which can be either increased or decreased. If the arrangement is such that the angle bracket is bolted directly to the cleat in the nominal position, then movement is only possible in one direction, by adding packing.

Where slotted or oversized holes are provided, angle brackets should be bolted to cleats using high strength friction grip bolts (Figure 6.3) to prevent slippage.

Cleats used in this type of glazing support system are sometimes termed 'spring plates', because of their ability to flex about their narrow axis. Care should be taken if this flexibility is relied upon, since the load necessary to achieve suitable levels of elastic movement can easily exceed the moment capacity of glazing panels, or other components in the glazing system.

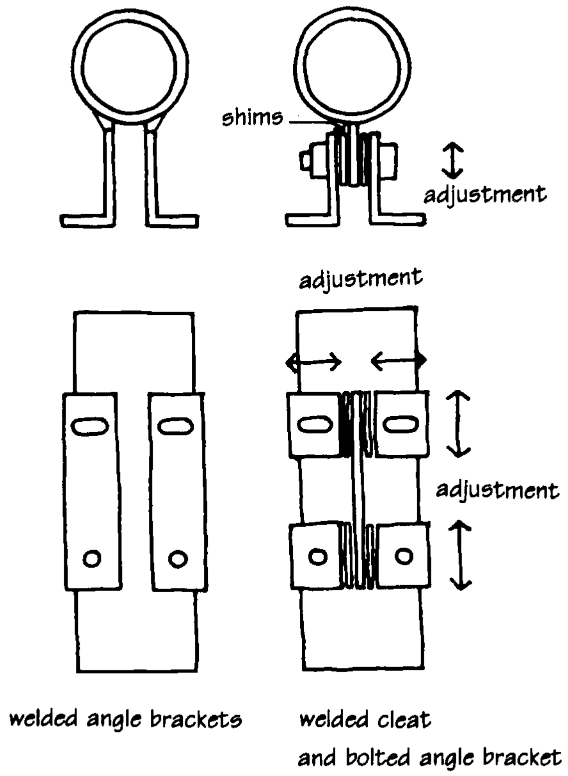


Figure 6.3
Angle brackets

6.2 Spiders

Spiders are brackets with one, two, three or four arms radiating from a central hub. Glazing panels are attached to the ends of the arms, and the brackets in turn are attached to the support structure. Spiders are generally manufactured as profiled, machined or cast components.

Single brackets, with four arms, may be used at each attachment position, or brackets may be used in pairs (each with two arms).

6.2.1 Single brackets

Single brackets (Figure 6.4) commonly locate onto a single threaded stud or bolt. Adjustment of the attachment relative to the support structure, parallel to the plane of the glazing, is usually provided by sliding or serrated details. Shims or spacers can be used to provide out-of-plane adjustment. The arrangement at the nominal position should include an amount of packing which can be either increased or decreased to accommodate the tolerances and adjustments.

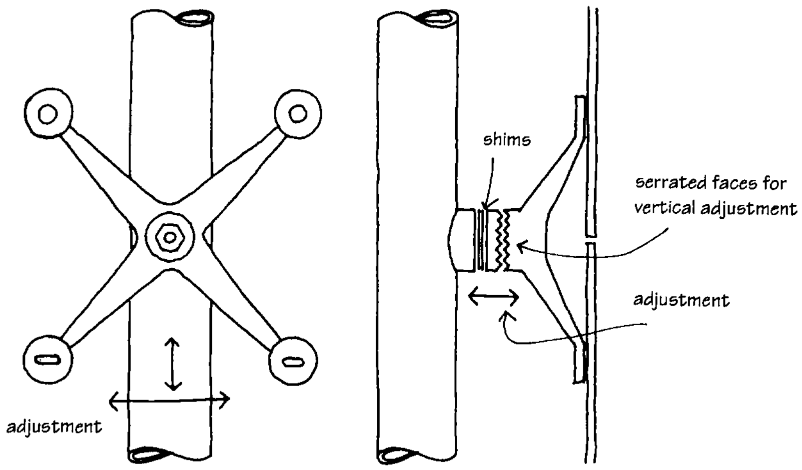


Figure 6.4
Single bracket spider

6.2.2 Paired brackets

Paired brackets (Figure 6.5) commonly attach to a cleat and can, where necessary, provide relatively high levels of adjustment in the plane of the cleat. Shims can be used between the brackets and the fin to allow adjustment perpendicular to the plane of the fin. This adjustment can be used to vary the distance between the brackets and hence the width of the joints between glazing panels running in the direction parallel to the cleat.

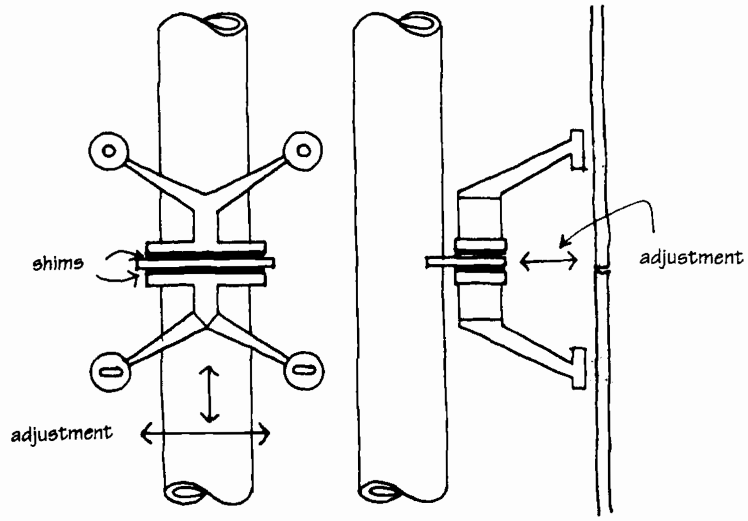


Figure 6.5
Paired bracket spiders

6.3 Pin brackets

Pin brackets (Figure 6.6) are a variant of spider arrangements. They are commonly connected to cleats on support structures. The key difference between pin brackets and paired spider details is that the brackets provide a sliding connection detail to the fixing bolts. This arrangement provides improved tolerance and can accommodate rotation in one direction.

Glazing connection details can be designed to rotate about the pin and can therefore accommodate high levels of deflection of the glazing or support structure in one direction. Flexible washers, bearings or other devices may be required, to accommodate rotation in other directions.

One type of pin bracket detail is illustrated in Figure 6.6. In this arrangement, the pins are clamped to cleats by means of a pair of conical elements that are screwed onto the central portion of the pin, either side of the cleat. A single rod acts as the pin on each side of the cleat, so the two are aligned along this axis. The fixing bolts of the glazing panels can be adjusted along the pins using a sliding end detail, whilst the position of the pin axis can be adjusted vertically and horizontally by using slots or oversized holes in the cleat. The relative position of the two pin axes can also be adjusted, together with the widths of all joints in the glazing system.

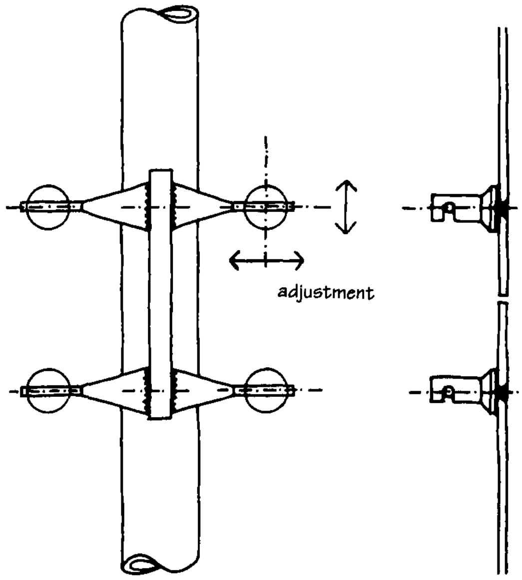


Figure 6.6
Paired pins

6.4 Clamping devices

Clamping devices are often used with glass fins. The fins stiffen the glazing panels against out-of-plane deflections due to wind forces, etc. When glazing is used horizontally or is inclined, the fins can also be used to resist deflection due to self weight.

Fins are commonly attached to glazing using bolted connections. They normally rely on friction between steel plates or angles and gaskets or the glass surface. They can be supported at each end or can be cantilevered.

Forces are transferred via rigid clamping devices (normally angle brackets) into the supporting structure (Figure 6.7).

The brackets are bolted and tightened onto the fin to a specific torque to ensure a friction connection is achieved and to ensure that the load is not transferred via the bolts in bearing (Figure 6.8). Provision for adjustment is normally made at the connection of the angle brackets to the fin. Oversized holes can provide adjustment in the plane of the fin, whilst shims can be used perpendicular to the fin.

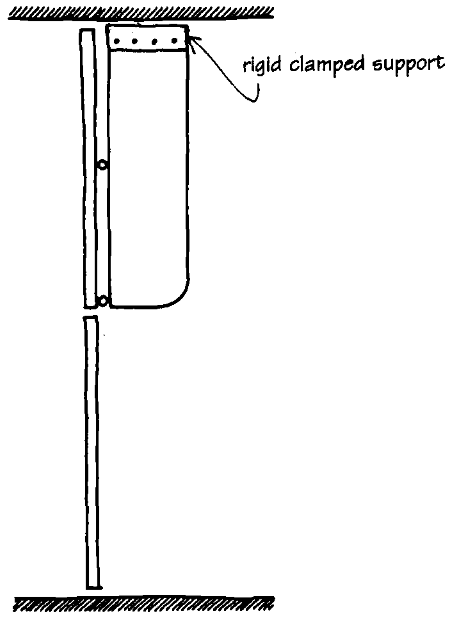


Figure 6.7
Clamped cantilevered glass fin

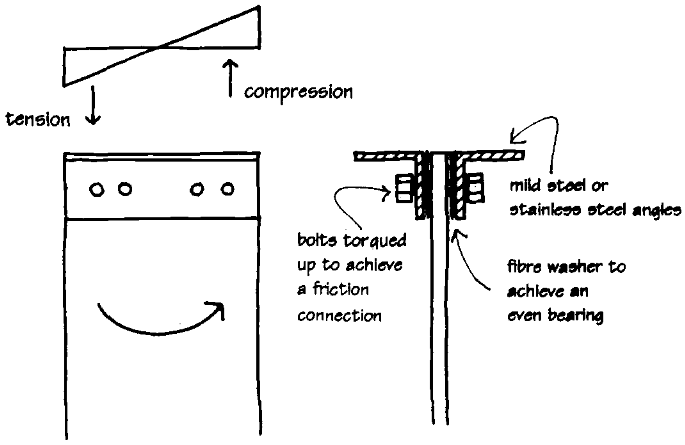


Figure 6.8
Clamped cantilevered glass: clamp detail

7 CASE STUDIES

7.1 Glazing systems at Waterloo International Terminal, London

Structural Engineer: Anthony Hunt Associates
Architect: Nicholas Grimshaw and Partners

The train shed roof at Waterloo International Terminal in London covers the 5 tracks and platforms that serve the 400 m long Eurostar high speed trains (Figure 7.1). It comprises a series of asymmetric three pinned arches with spans between 48.5 m at the widest point and reducing to 32.7 m at the narrowest. Each arch is formed of a shorter west truss and a longer east truss. The trusses are prismatic in cross-section with compression elements made from tube, and tension elements made from rod.

Figure 7.1
General view of Waterloo Terminal

West elevation glazing
On the west elevation the trusses are external (Figure 7.2), with the glazing hung beneath. Glazing panels are rectangular and rely upon adjustable support devices to achieve the snaking conical geometry.

Each glazing panel (up to 1.2 metres wide and 3.6 metres long) is supported by extruded aluminium beams fixed to the long sides. The aluminium beams span 3.6 metres vertically between tubular steel transoms that also stabilise the main arch trusses (Figure 7.3). Special cast stainless steel brackets were developed (Figure 7.4) to connect the beams to the trusses. Each has two radial arms which can be rigidly fixed at any angle relative to the transoms via interlocking serrations. A single centre bolt holds both arms to the boss. Angular adjustment is achieved between the boss and a saddle bolted to the structural steelwork. Polished stainless steel rods pass through the arms and allow differential horizontal movement from thermal effects and live load/wind movements. This detail also gave some tolerance during the initial construction stages. Slotted holes in the beams give tolerance and movement capacity in the vertical direction.

The roof is supported on a reinforced concrete structure which can experience thermal movements of up to 55 mm. In addition, as 800 tonne trains enter they cause a downward deflection of 11 mm which in turn causes adjacent bays to bend upwards by 6 mm. The glazing system was designed to accommodate all of the movements without danger of glass breakage. Each panel in effect 'floats' beneath the structure and is sealed to the adjacent panel with a concertina rubber gasket.

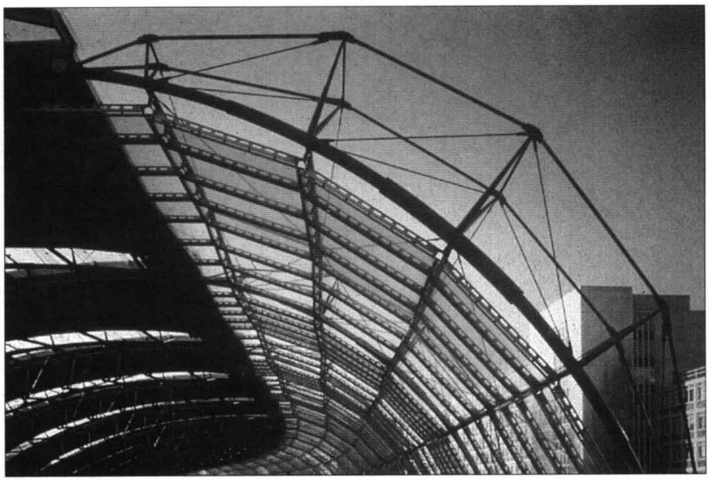


Figure 7.2
Glazed western facade

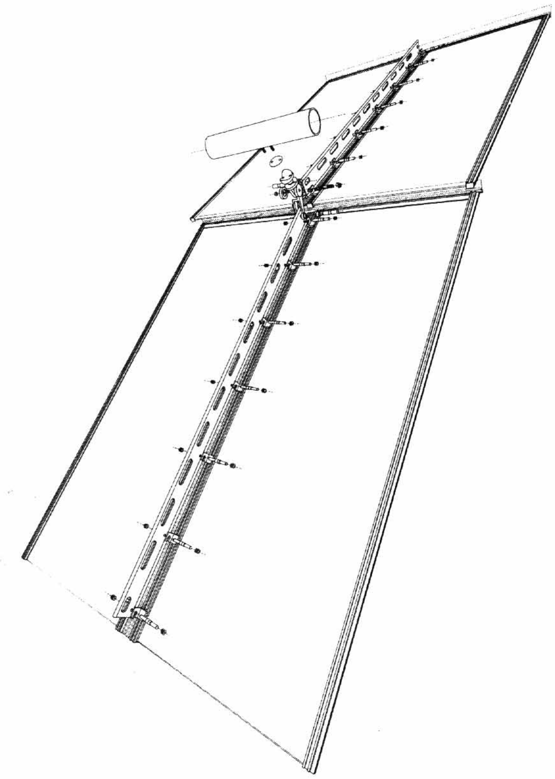


Figure 7.3
Glazing detail, west elevation

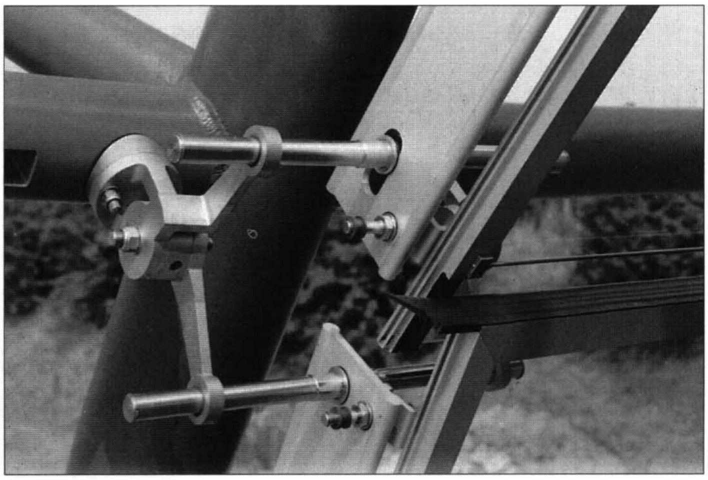


Figure 7.4
Stainless steel bracket detail

East elevation glazing
The long trusses forming the east elevation have glazing directly above them which forms a series of roof lights (Figure 7.5). Panels of glass up to 3.6 m x 1.8 m are bolted to glass fins at 1.8 m centres using stainless steel angle brackets. These fins in turn are attached to the trusses and transfer the self weight of the glazing and the applied loads.

Figure 7.5
Glass fins, east elevation

Concourse Glazing
A glass wall 50 m long and 8 m high was developed for the southern end of the original Waterloo station concourse (Figure 7.6). The elevation faces directly down the arched train shed allowing views of the Eurostar trains arriving and departing.

Panels of glass 2 m x 2 m with holes drilled in each corner are bolted via 4-way stainless steel spider castings to 76 mm diameter, tubular steel posts at 2 m centres. These posts form the compression elements of bowstring trusses. Tension elements of the trusses are 12 mm diameter stainless steel rods connected to the posts using tapered struts.

Struts in the bowstring trusses are effectively continuous through the plane of glass. This was possible as a result of a special multi-part spider bracket (Figure 7.7).

Trial assembly and load tests were carried out prior to starting work on-site to prove the design. The inner bowstring was assembled and lightly tensioned to the correct shape before lifting into the vertical orientation. The glass was then installed before the outer (suction) bowstring was fitted. In this temporary state the post was able to resist wind loads of up to 15 m/sec without any restraints or propping. Above this wind speed, erection work would have had to be stopped and the truss temporarily supported from the adjoining scaffold whilst the outer frame was installed.

In the completed state, positive pressure wind forces are resisted in tension by the inner bowstring system and suction wind forces are resisted by the outer system. The effects of asymmetric or uneven wind loading were considered, and proved a determining criterion in setting the size of the post.

The inner and outer bowstring tie rods have a left and right hand thread in order to adjust the lengths and tension in the systems, in order to align the central post.

Laterally it was necessary to provide restraint to the posts at 4.0 m centres vertically to stop the small diameter section from buckling under the effects of glass weight and wind loading. Diagonal ties (in a plane parallel to the glazing) transfer the restraint forces to the truss ends. The diagonal ties were pre-tensioned using turnbuckles and a temporary Tirfor to ensure that they will not slacken excessively during hot weather conditions, or be overstressed during cold conditions. At the same time, each of the posts was correctly aligned to within 5 mm of its theoretical position.

Spider fixings were installed to an accuracy of ±3 mm vertically. They are attached by a single centre bolt, and slippage is prevented by a small peg installed through an existing hole in the spider into a hole drilled, *in situ,* into the saddle beneath.

Oversized holes in the ends of the spider castings, combined with a 12 mm silicone joints, provided tolerance for the installation of the glazing panels and accommodate thermal and support structure movements.

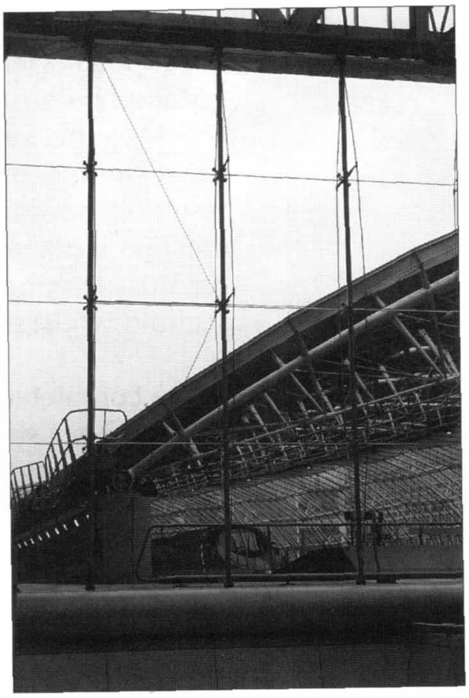


Figure 7.6
Concourse glazing

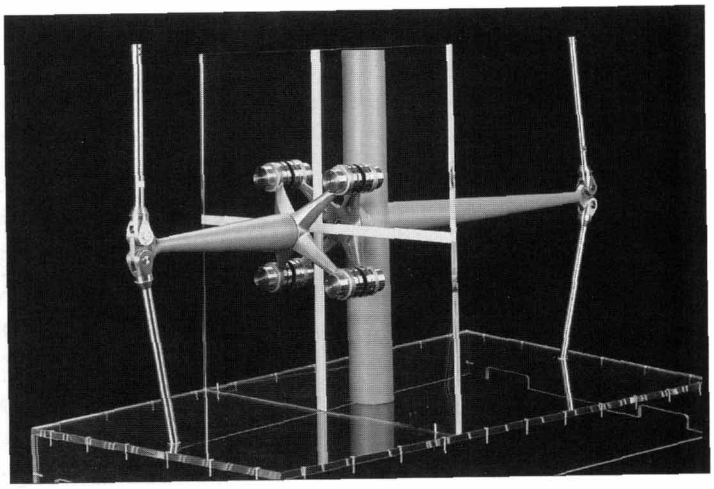


Figure 7.7
Multi-part spider bracket

[Figures 7.1 to 7.7, courtesy of Nicholas Grimshaw and Partners, UK]

(Authors: Mike Otlet and David Kirkland)

7.2 Proctor and Gamble building - Brooklands Surrey

Structural Engineer: Anthony Hunt Associates
Architect: Aukett Associates

This project has two major glazed parts: the Main Atrium and the Street (Figure 7.8 and 7.9)

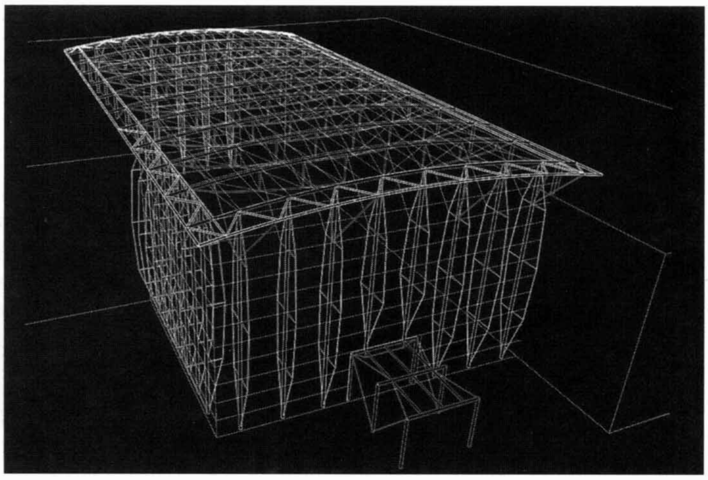


Figure 7.8
Main atrium: computer model

Figure 7.9
Main Atrium: interior

The main atrium is 44 m long, 21.6 m wide and 15.4 m high at the crown of the shallow curved glass vault roof.

Cigar shaped primary trusses span the width of the atrium at 4.05 m centres, in some instances onto the roof of the buildings bounding the atrium, and in others onto vertical tension assisted columns.

Laminated glass purlins at 1.35 m centres span between the trusses carrying the double glazed planar roof (comprising a 12 mm thick, toughened outer layer with a 16 mm air gap and then two 6 mm plate-glass sheets laminated together, forming the inner layer). The planar double glazed atrium roof units are 1.35 m × 2.08 m, with six points of support (Figure 7.10). Laminated glass purlins are bolted to the primary trusses through double plate cleats. The units are mounted 225 mm above the centreline of the steel truss top booms.

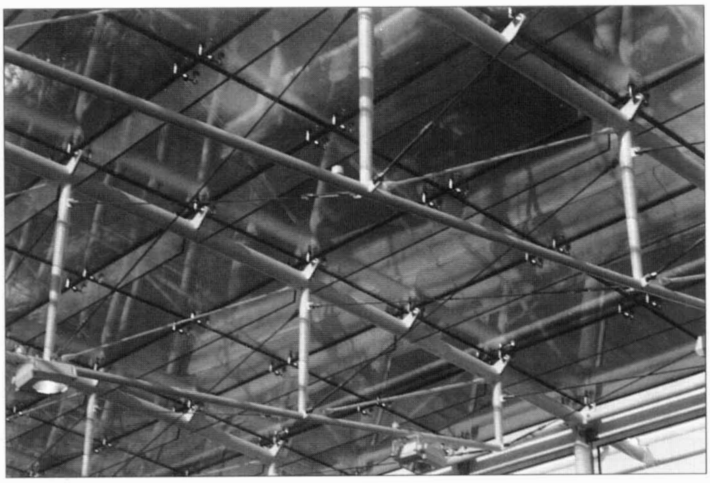


Figure 7.10
Glass roof with glass support fins

Tubular maintenance gantry rails external to the roof transfer their loads to the primary roof structure through an external two leg spider casting. This casting attaches the purlin to the truss connection by way of two stainless steel planar type fittings with universal joints. The approach avoids any penetrations through the silicone joints between the glazed units.

Two tubular trusses, one at each gable (and curved in elevation to follow the roof line), provide bracing to the atrium roof. The trusses are inter-connected via tensioned stainless steel yacht rigging cables.

A 4.05 m × 2.7 m section of the roof glazing, together with the laminated glass fins and steelwork support, was assembled in the works and rigorously tested.

The vertical wall glazing to the atrium is attached to the tension assisted vertical CHS columns by similar modified planar fixings to those used in the roof. The columns vary in height, the tallest being approximately 15 m.

The design team developed an electropolished stainless steel casting with 4 short tapered circular legs which connect modified planar type fittings to the steel structure. Adjustment is provided by slotted holes at the end of the arms.

Double glazed units of similar size to those in the roof, but without the anti-sun coating, are mounted 200 mm forward of the columns. They are attached to the structure using the spider casting. A central bolt fixes them to a tapped metal disc welded to the CHS columns. Adjustment is provided by an oversized hole in the centre of the 'spider' and a locking washer on the bolt.

The stainless steel tension assisted system, in addition to supporting the weight of the glass roof and wall, resists wind loads to the atrium walls. The internal rods are active during positive pressure loading to the atrium and the external rods are active during the negative pressure loading. All rods and end fittings are 316 grade stainless steel.

The external part of the tension structure could not be erected until the vertical glazing was installed and the structure was temporarily restrained (against negative wind pressures) to the internal scaffold. The compression load is transferred from the tapered external strut through the external 'spider' casting, into the planar bolts, into the internal 'spider' casting and then into the 140 mm CHS column.

A 'glass street' will in the future connect a series of three office buildings. A small section currently serves as an entrance area to the atrium of the Phase I building. This comprises four primary steel 8.8 m high columns support a horizontal steel and aluminum brise soleil.

Figure 7.11
Proposed 'street' link between office buildings

[Figures 7.8 & 7.10, courtesy of Anthony Hunt Associates
Figure 7.9, courtesy of PORTAL UK Ltd
Figure 7.11, courtesy of Aukett Associates]

(Author: David Hamilton)

7.3 Glass Hall, Neue Messe Leipzig

Engineer and Architect: Vongerken Marg and Partner in cooporation with Ian Ritchie Architects

The glass hall is the principal space through which all visitors to the Leipzig trade fair enter. The hall covers an area 244.75 m × 70 m, and is 28 m high at its crown (Figures 7.11, 7.12 and 7.13). The glazing surface totals about 2.8 Ha (28,00 sq m or 7 acres). The hall provides a tempered external environment and is linked directly to the exhibition spaces by glass bridges. The architectural objective was to treat the hall as part of a landscaped valley between the two ranks of exhibition spaces and conference buildings, and to maintain maximum transparency within this landscape. To this end, the hall is enclosed in frameless glazing using low iron 'white' glass (which does not have the characteristic green tint inherent in normal float glass).

The structure is kept to a minimum, and covers no more than 15% of the surface. The glass is suspended 500 mm below a tubular grid 3.125 m square. Glass panels are about 3.1 m × 1.55 m, made in two layers of 8 mm, and 8 + 10 mm toughened glass laminated with 1.5 mm PVB interlayer.

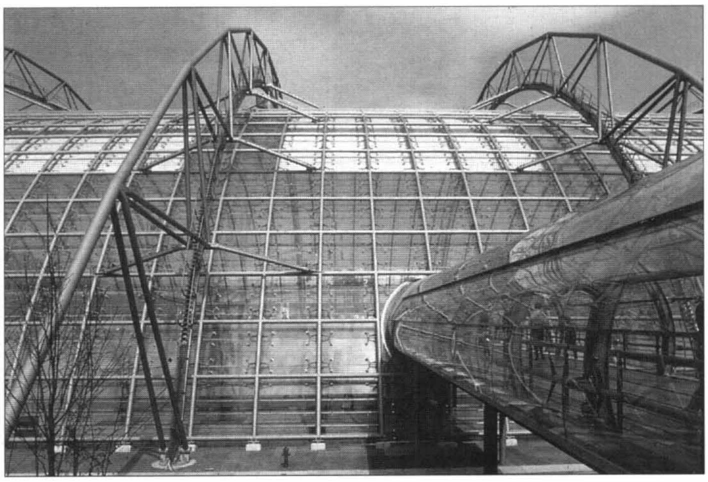


Figure 7.12
Exterior view of glass envelope

Figure 7.13
Interior view of glass envelope

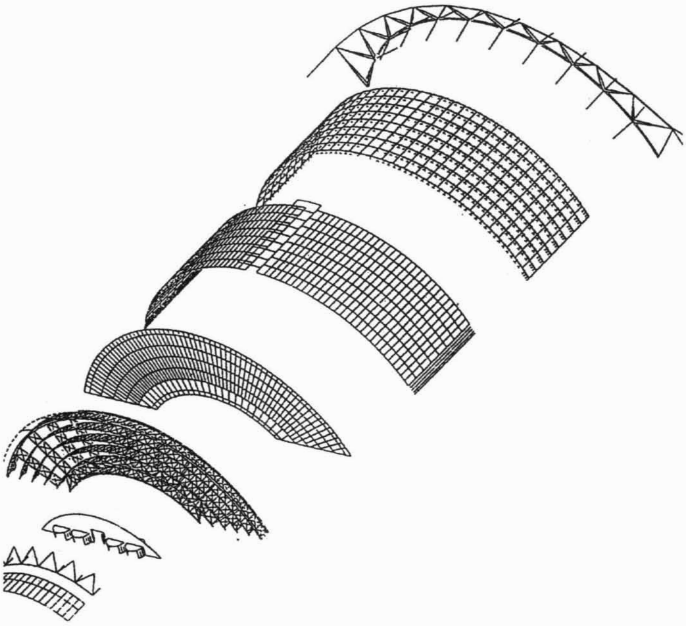


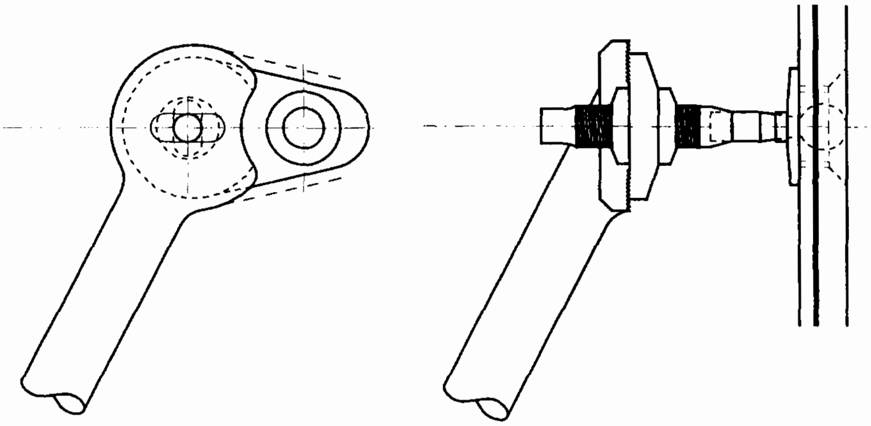
Figure 7.14
Exploded isometric view of roof elements

End walls are structurally independent, and stand as a series of interconnecting arch trusses cantilevered from the ground.

The primary structure can undergo in-plane deformations of up to about 15 mm within a single 3.125 m square module of the grid shell (i.e. deformation from square to rhombus). These in-plane deformations are taken up by the glass fixings, which are articulated with one or two degrees or freedom, according to their position (Figure 7.15). One connection on each panel is fixed.

The length of the building (244 m) would conventionally require one or two movement joints. However, the elasticity and low modulus of all the joints allowed movement to be distributed throughout the entire length of the glazed envelope.

Figure 7.15
Articulated fixings for glass panels



The programme demanded that glazing was prefabricated in parallel with the primary steelwork. The interface between the glass and the structure is designed to absorb 150% of maximum permitted deviations.

The arm fixings can take up small tolerances only in the plane of the grid shell due to slightly oversized holes (a proposal by the architects for slotted connections was not taken up by the contractors). The major tolerances are accommodated by the 'fingertip' connections (Figure 7.13) of the arms where a slot and radial movement (with serrated interlocking) are provided. These fingertips in turn connect to the ball jointed glass fixings that allow the glass to rotate under loadings or due to structural movement rather than induce bending stresses in the glass panel.

Further details on stainless steel components this case are given in the SCI publication, *Architects' Guide to Stainless Steel.*

[Figures 7.12 & 7.13, courtesy of Ian Ritchie Architects
Photos by, Jocelyne Van den Bossche
Figure 7.14, courtesy of W S Atkins]

(Author: Simon Conolly).

7.4 Bridgewater Hall, Manchester

Architect: RHWL

Engineer for glazed wall: W S Atkins

The entrance area to Bridgewater Hall theatre and concert hall is bounded by a large glass wall (Figure 7.16). Panels of glass 1.5 m x 2.5 m are individually hung from 12 mm diameter stainless steel drop rods suspended from the perimeter of the roof (Figure 7.17).

The arrangement allows for simple replacement of panels and avoids the possibility of multiple panel failure leading to progressive collapse.

Wind loads are resisted by horizontally spanning Vierendeel trusses located along each of the glass joints at 2.5 m centres. The delicate Vierendeel trusses which span up to 6 m between reinforced concrete columns are comprised of two 60 mm diameter solid mild steel bars at 200 mm centres, connected by flat plates.

A second set of vertical rods hold the Vierendeel trusses in position and stop buckling and sag under self weight and wind reversal. These rods are also suspended from the roof and are tensioned to the concrete slab at the first floor level with a large spring to ensure a reasonable pretension can be achieved under all load conditions. In particular, this ensures that when the roof has a snow load the rods do not slacken. Conversely, when there is a full front of house, the rods are not overstressed as a result of the cantilever concrete floor deflecting and pulling down the roof.

Although an initial concern, vertical movements of the roof perimeter were established to be quite small (less than 3 mm across any panel width). Given the flexibility of the drop rod support brackets, this was considered acceptable, and no additional provision was made. Furthermore, since the glass panels are supported directly from the drop rods, at worst the weight of the single panel would be on only one fixing and loads would remain well within the capacity. Laterally, the movements are insignificant.

The glass deflection was designed not to exceed a maximum of span/100, which was calculated using simple deflection formulae.

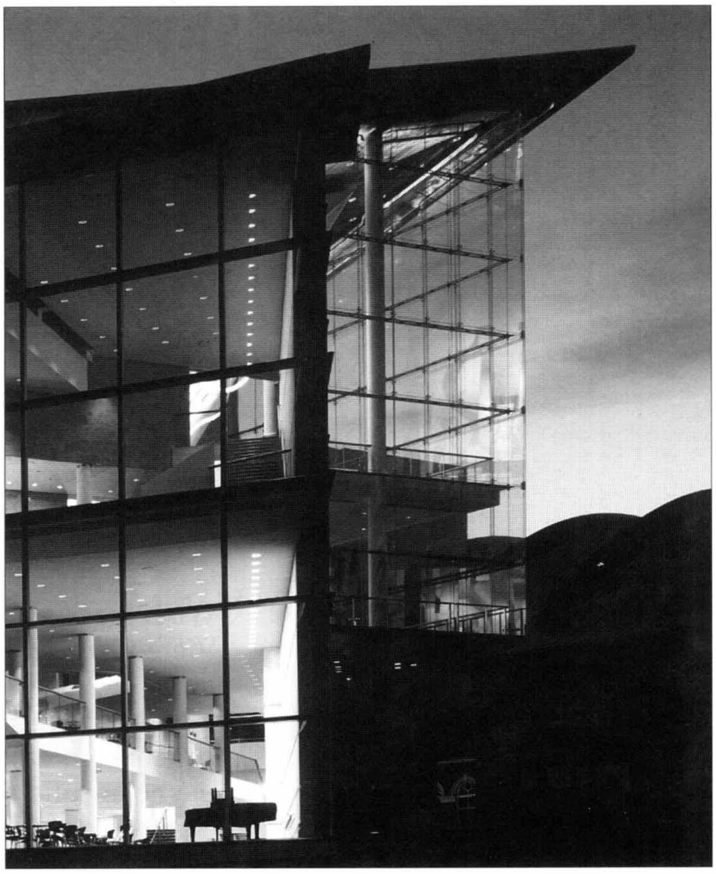


Figure 7.16
Entrance to Bridgewater Hall

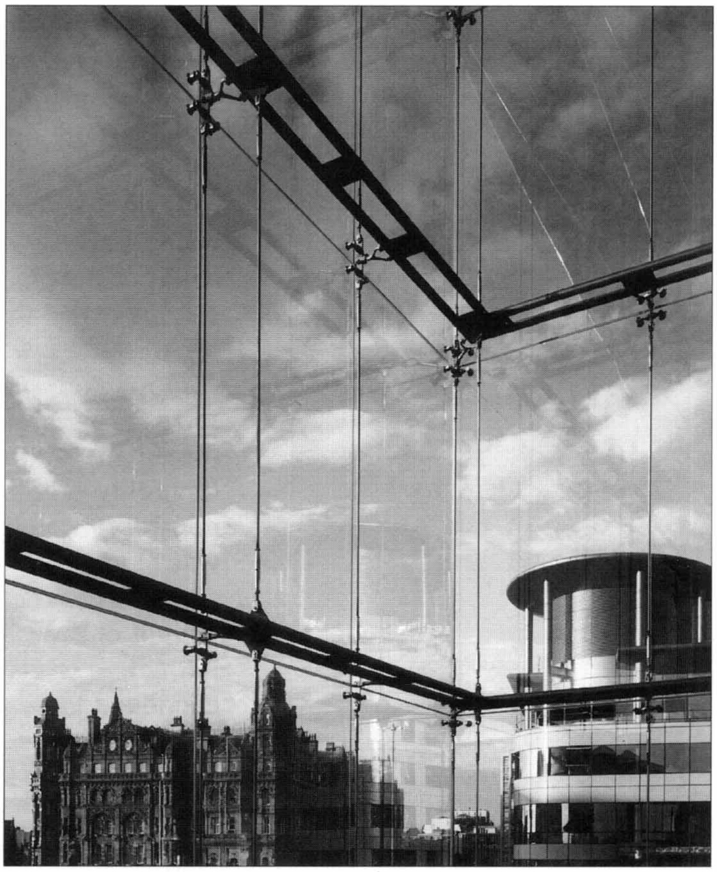


Figure 7.17
Glass panels hung from a stainless steel rod

Vertical tolerances were accommodated by adjustment devices in the drop rods. Adjustment was also provided at the ends of the vierendeel trusses, and at their connection to concrete columns.

The Vierendeel trusses were initially erected, lined and leveled before hanging the drop-rods that support the glazing. At the time of the installation of the drop-rods, the roof & cladding was largely complete.

The hanger fixing position was then lined and leveled prior to the installation of the glass. Where necessary the drop-rods were re-adjusted to achieve a horizontal glass joint before the silicone jointing operation.

[Figures 7.16 & 7.17, courtesy of W S Atkins]

(Author: Mike Otlet)

APPENDIX A: Background information on glass

At the time of publishing, a design guide for glass facade and roof systems is in course of preparation by the Institution of Structural Engineers. That guide will contain authoritative information for design. It is recommended that reference be made to it when it is available.

The following data is presented for the purposes of concept design only and has been prepared in advance of the Institution of Structural Engineer's publication being available. For specific projects, values should be agreed with the appropriate glass manufacturer. Attention is drawn to Section 1.3 regardig use of this publication.

A.1 Structural parameters

Density	2.5 tonnes/m^3
Young's Modulus	70×10^3 N/mm^2
Poisson's Ratio	0.23
Thermal Expansion Coefficient	7.75×10^{-6} /K

A.2 Design thickness

Annealed glass

The design thickness of glass should generally be the minimum thickness according to the tolerances specified in BS 952 for monolithic glasses. Table A1 gives the values for nominal thicknesses that are normally available in the UK.

Toughened glass

The design thicknesses are the same as the annealed glass from which they are manufactured.

Laminated glass

The design thickness depends on the duration of the load and the temperature. No account is taken of the thickness of the interlayer.

Short duration loads (e.g. wind, human action) and snow loads:

Design thickness t_d = sum (t_i)

where t_i are the design thicknesses at the individual glass plies.

Long duration loads (e.g. floors, shelves, aquaria, self weight+):

For deflection: Design thickness $t_d = \sqrt[3]{\Sigma t_i^3}$

For strength: Design thickness $t_d = \sqrt[2]{\frac{\Sigma t_i^3}{t_m}}$

where t_m is the design thickness of the thickest glass ply.

+ For ease of computation, where the self weight of the glass is to be combined with snow loads, the short duration formula for design thickness is normally used.

Table A.1 *Thicknesses of common glass types*

Glass type	Nominal thickness mm	Design thickness mm
Float glass (stock for toughened glass)	3*	2.8*
	4	3.8
	5	4.8
	6	5.8
	8	7.7
	10	9.7
	12	11.7
	15	14.5
	19	18
	25^x	24^x
Patterned	4	3.5
	6	5.5
Wired (all types)	7.7	7.35

* not available as toughened glass
^{x} not widely available

A.3 Design basis

To carry out a provisional or concept design, the following points should be given consideration:

1. A load factor of 2.6 is often applied to any long term load (snow should be treated as a long term load). It is not necessary to combine maintenance loads with snow load.

   It is arguable that these high load factor should not apply to toughened glass in which the time dependency of applied loads does not take effect unless surface tensile stress is induced.

2. The minimum thickness of glass allowing for manufacturing tolerances should be used.

3. Deflections should be checked. Deflections at limiting stress will be larger for toughened glass than for annealed glass. Deflections will also be higher when glass is not supported on all edges.

4. Laminated glass can be considered as a single layer of glass of the same overall thickness for short term loads, but should be considered as separate panes for long term loads (to allow for creep at the interlayer).

5. Panes in an insulating glass unit should share the load in proportion to their stiffnesses. Where panes form part of a double glazing system which is not hermetically sealed, each pane should be designed for the full wind pressure or suction.

Simple bending theory over-estimates the stress in a thin plate supported on four sides when the deflection due to the applied lateral load is large compared to the plate thickness. A more accurate result may be obtained by using formulae which take deflection into account. However, as this is a conservative approximation, it is not considered appropriate to introduce this complication into these provisional design recommendations. The stress figures in Appendix A.4 assume simple bending theory is used. They may increased if more accurate stress analysis is used (in consultation with the manufacturer).

Toughened and heat strengthened glass are substantially stronger than annealed glass but the elastic modulus is the same. Hence, design of toughened and heat strengthened glass panes is often governed by deflection.

The theoretical tensile strength of glass is very high, but, in practice, tensile strength is governed by fracture initiating at surface defects or flaws, and failure will occur at a very much lower level of stress. The random nature of the condition of the glass surface means that the strength of two otherwise identical pieces of glass may vary considerably.

The flexural strength of float glass is appreciably lower when subject to a sustained load compared to its strength under a short term load. The relative strength under a sustained load may be of the order of 3/8 of that for a short term load (as in BS 5516). This lower strength is thought to be due to reduction of the load carrying capacity at stress concentrations due to stress corrosion at a microscopic level.

A.4 Allowable stress (short duration loads)

The allowable stresses currently used in the UK for design of glass for short duration loads (e.g. wind, human action) are given in Table A.2. These values should not be used for designers outside the UK.

Table A.2 *Allowable stresses in glass (generally used in the UK)*

Glass type	Body stress N/mm^2	Edge stress N/mm^2
Float Glass < 6 mm	41	28
Float Glass 8 mm	34.5	22.9
Float Glass < 10 mm	28	17.8
Patterned Glass	27	27
Wired Glass	21	21
Toughened Glass (all types and thicknesses)	59	59

The 'body stress' corresponds to the body of the panel. The 'edge stress' corresponds to the local edge stress.

The allowable stress for laminated glass depends on the weakest glass type incorporated in the composite, and on the thickness. The allowable stresses are also related to the wind code existing in various countries.

The value for toughened glass is lower than could be justified purely by the strength of the material. However, the additional strength can rarely be utilized since deflections tend to be large with toughened glass, particularly when it is not fully framed.

A.5 Allowable stress (long duration loads)

The allowable stresses generally accepted for use in the UK for long duration loads applied to glass are given in Table A.3.

Table A.3 *Allowable stresses for glass (long duration loads)*

Load type	Annealed glass N/mm^2	Toughened glass N/mm^2
Snow	Short duration stress/2.6	Short duration stress/2.6
Water and shelves	7	35
Floors	8.4[(1)]	35
Self weight	As per the load type it is associated with, or 7 if assessed separately	As per the load type it is associated with, or 35 if assessed separately

(1) Working stresses for long duration loads apply to both the body and the edge, except in the case of annealed glass in floors, which is only used with all edges fully supported.

A.6 Deflection limits

There are often no specific structural reasons why the deflection of glass should be restricted, provided the glass is capable of supporting the loads without fracture. However, glass is a material which the general public regards with suspicion. If glass deflects too much, which large panes of a strong thin material can easily do, it may engender alarm amongst people in the immediate vicinity.

In particular situations, a more stringent deflection limit may be appropriate. Alternatively, where glass panel is well away from the immediate vicinity of people, this deflection limit could be relaxed.

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