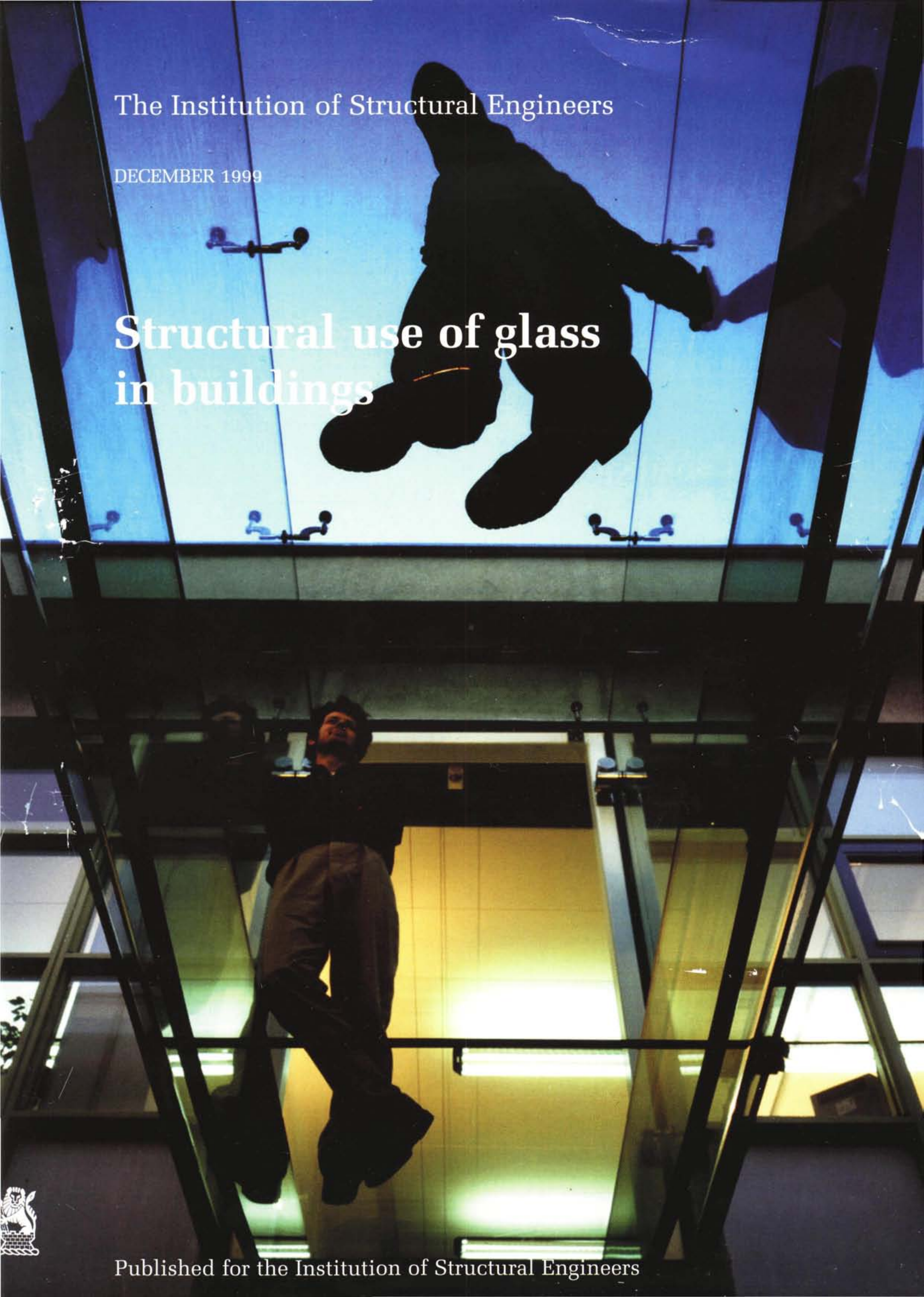


The Institution of Structural Engineers

DECEMBER 1999

Structural use of glass in buildings

Published for the Institution of Structural Engineers

Contents

Foreword

Glass is a man-made material, which has been around since 10,000 BC, and has enjoyed in the past few years an upsurge of interest in its use structurally in buildings. There are very few publications on the design of glass used structurally and it is intended that this publication will bridge this gap.

The *Guide* is not intended to be a code of practice but a basis of information for those interested in the structural use of glass. It is intended for those people who have little or no knowledge of the structural use of glass and the details contained therein will be of interest not only to engineers but also to members of the other professions in the construction industry.

Examples are given for simple design as well as references and guidance for those people wishing to advance their knowledge further in the structural use of glass.

It is a publication that not only contains a wealth of information, but also makes very interesting reading.

I would like to thank all members of the Task Group and our Secretary, Sue Doran, for their help and contributions in producing this document. In addition, I would like to single out our consultant, Chris Jofeh of Ove Arup & Partners, whose enthusiasm and hard work in researching, drafting and preparing the final text of the document ensured keeping to our original programme, and who was magnanimous when receiving and incorporating comments on the drafts from the Task Group members.

R J SAUNDERS
Task Group Chairman

Acknowledgements

The preparation of this report was partly funded by the Department of the Environment, Transport and the Regions under the 'Partners in Technology' programme. This funding was used principally for the appointment of the Consultant to the Task Group, Mr C G H Jofeh, whose role was to research available information, visit manufacturers, suppliers and designers, collate information provided by other members of the Task Group and write the drafts of the report for consideration by the Group and prepare its final text.

1 Introduction

1.1 General

Glass remains an elusive material for engineers, feared because it is brittle, under-used because useful design data is so hard to find. This is especially vexatious because it is a material much sought after by architects. It is hard to think of any modern building in which glass does not play an important part. Transparency and translucency are essential features of much modern architecture.

There are many books and many precedents that inspire designers to use glass but the data designers need is not easy to find. It exists, but it is not available from a single source. This *Guide* attempts to assemble the information that structural engineers will need. In doing so it touches on many issues that influence design but which are not necessarily themselves structural, for example, condensation, colour and acoustical behaviour.

This *Guide* is aimed at two distinct groups of users:

- the first group wants straightforward advice on how to do something in glass with guidance on the applicability of the designs or details that are offered
- the second group wants to design in glass from first principles. This group needs reliable data and advice on the critical factors when designing with glass. The second group is not looking for a prescriptive approach, which is better provided by codes of practice, including the forthcoming European code.

As far as possible, this *Guide* compares and contrasts the structural behaviour of glass with that of other, better-known, structural materials. In particular it uses some excellent charts which are with grateful thanks reproduced from *Materials selection in mechanical design*, by M. F. Ashby of Cambridge University, to set glass in the context of other materials.

There are 17 chapters. Chapters 2 to 5 cover principles, design requirements, design selection and calculations. Chapters 6 to 15 cover different applications of glass as a structural material in roofs, facades and elsewhere, and include worked examples. Chapter 16 covers specification and Chapter 17 contract and procurement, inspection and maintenance. There are also 6 appendices.

1.2 Scope

This *Guide* deals with the design of glass in buildings where the glass plays a structural role. It may resist only wind load or it may do more, carrying its own weight or perhaps supporting live load from people walking on it or leaning against it.

This *Guide* is principally aimed at structural engineers. Its scope is therefore largely but not entirely limited to those issues most of concern to structural engineers:

- strength
- stability
- stiffness
- durability
- robustness
- buildability

Structures do not exist in isolation from the buildings they serve. The *Guide* therefore also addresses some of the other issues that may influence structural behaviour or place constraints on what can be achieved. In doing so it does not seek to provide, for example, up-to-the-minute data on what coatings and heat treatments are available from which manufacturers. However, it does try to list where such advice can be obtained and to advise what influence coatings and heat treatments (and other processes) may have on structural behaviour.

By listing issues that need to be considered when designing structural glass, the *Guide* will be of use in clarifying design responsibilities amongst the design team. It should be noted that this team might well include the glass manufacturer, the glass fabricator and the glass installer.

This *Guide* has limitations. Its purpose is to provide general guidance based on existing good practice as a starting point from which designers can carry out further studies and research according to circumstances. It is not intended to define the responsibilities of any parties, or to relieve them, in a given contract.

In particular, the reader should not assume that it is possible to write a specification using only the headings or numerical values given in this *Guide*. The information presented is typical UK industry information and as such may not be representative of the output of any particular manufacturer or fabricator.

Whether experienced in glass design or not, most users will use this *Guide* in their own way, turning to those points of entry they find most immediately useful. The *Guide* therefore attempts to provide a flexible approach to fit in with the ways that designers work in practice, for example:

- It provides detailed guidance but recognises that the designers must make the final judgment, based on the specific contract they are handling.
- It includes information important to the designer, presented to show what are the critical aspects.
- Information and issues are often presented as checklists, to save the reader from having to scan extensively.
- Information is linked to explanations, to show how it relates to the general principles underlying the structural behaviour of glass.
- The chapters follow a particular sequence but the reader can follow his or her own route through if preferred, using the cross-referencing.
- Advice on critical design issues is highlighted in blue in Chapters 6 to 14.

1.3 Status of this report

The Institution of Structural Engineers has produced this report as a guide and, as such, it is only intended for use as a guide.

It is not intended to provide the definitive approach in any situation, as in all circumstances the party best placed to decide on the appropriate course of action will be the designer undertaking the particular project.

1.4 Relevant Standards

Throughout this *Guide*, reference is made to appropriate British and other Standards. It should be noted that British Standards are in the process of being superseded by European Standards. The reader should always ensure that the most recent relevant Standard is being used.

Those seeking to apply this *Guide* outside the UK should make reference to the appropriate national standards or regulations.

1.5 Other references

Throughout this *Guide*, reference is also made to a wide range of textbooks, which may be revised and reissued from time to time. Care should therefore be taken when referring to, for example, tables in textbooks whose numbers may be different in later editions to those referred to in this *Guide*.

1.6 Sources of information

Laminated Glass Information Centre
299 Oxford Street
London W1R 1LA
Telephone: 020 7499 1720
Fax: 020 7495 1106

Glass and Glazing Federation
44-48 Borough High Street
London SE1 1XB
Telephone: 020 7403 7177
Fax: 020 7357 7458

Centre for Window and Cladding Technology
University of Bath
Claverton Down
Bath BA2 7AY
Telephone: 01225 826541
Fax: 01225 826556

Glass Association of North America
3310 SW Harrison Street
Topeka
Kansas 66611-2279
USA
Telephone: 1 785 266 7013

Glass Research and Testing Laboratory
Texas Tech University
Lubbock
Texas 79409
USA
Telephone: 1 806 742 3476

The UK reader should consult the Glass and Glazing Federation for the names and addresses of suitable manufacturers, fabricators and installers.

2 Principles

2.1 Behaviour of glass as a structural material

Glass behaves in a crucially different way from other, more familiar, structural materials such as steel or aluminium. It does not yield: it fractures and its failure is stochastic (i.e. prediction is risk-based, or statistical).

Structural engineers designing steel structures have typically concentrated their attention on limiting stresses at places of maximum bending and shear. Because steel is plastic and will yield and flow if it is locally overstressed, and lack of fit and its associated stress concentrations are not generally a problem.

Designers cannot ignore stress concentrations and cannot ignore lack of fit when designing glass.

Glass in panes can deflect by more than its own thickness. This takes designers into the realm of large deflection theory, which is unfamiliar territory for most engineers. One consequence is that it has been customary to express stresses in glass as if small deflection theory were valid. This gives rise to the problem that the use of a realistic allowable stress with small deflection theory can lead to the calculation of glass thicker than it really needs to be. Quoted design stresses for use with small deflection theory will be larger than realistic design stresses used with large deflection theory.

Basic properties of glass

This section draws heavily on *Engineering materials — an introduction to their properties and applications*, by M. F. Ashby and D. R. H. Jones and on *Materials selection in mechanical design*, by M. F. Ashby.

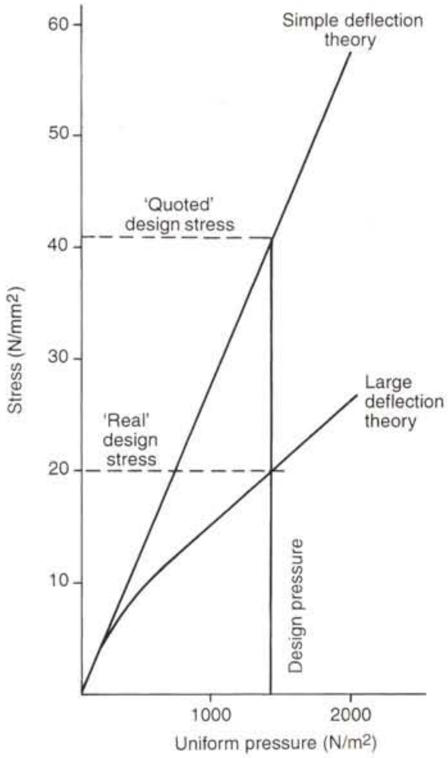


Fig. 2.1. A comparison of small and large deflection theory (reproduced from *Glass in Buildings*, eds. Button & Pye, by permission of Butterworth-Heinemann)

Materials may be classed into five groups:

- Metals and alloys
- Polymers
- Elastomers
- Ceramics and glasses
- Composites

The difference between glasses and ceramics is that ceramics are crystalline, inorganic non-metals; glasses are non-crystalline (or amorphous) solids. Most engineering glasses are non-metals but a range of metallic glasses with useful properties is now available. These are known by a number of names: metallic glasses, glassy metals, metglass, and so on. They are metals or alloys that are produced by cooling from the molten state so rapidly that crystallisation does not have time to occur. Scholze (1991) describes their properties. This *Guide* is only concerned with non-metallic glasses. Clear glass for glazing is typically of the soda-lime silica type and its general physical and mechanical properties are described in BS EN 572. Composition varies between manufacturers but is generally as shown in Table 2.1.

Table 2.1 Typical composition of soda-lime-silica glass

Silica	SiO_2	70-74%
Lime	CaO	5-12%
Soda	Na_2O	12-16%

with small amounts of magnesium, aluminium, iron and other elements

Materials can have properties that are intrinsic or attributive. All these affect the way in which products are designed.

Intrinsic properties

- Bulk mechanical properties
- Density
- Modulus and damping
- Yield strength, tensile strength and hardness
- Fracture toughness
- Fatigue strength, thermal fatigue resistance
- Creep strength
- Bulk non-mechanical properties
- Thermal properties
- Optical properties
- Magnetic properties
- Electrical properties
- Surface properties
- Oxidation and corrosion
- Friction, abrasion and wear

Attributive properties

- Price and availability
- Production properties
- Ease of manufacture
- Fabrication, joining and finishing
- Aesthetic properties
- Appearance, texture and feel

To set glass in the context of other materials, with which designers may be more familiar, the following charts are reproduced from *Materials selection in mechanical design*, by M. F. Ashby with permis-

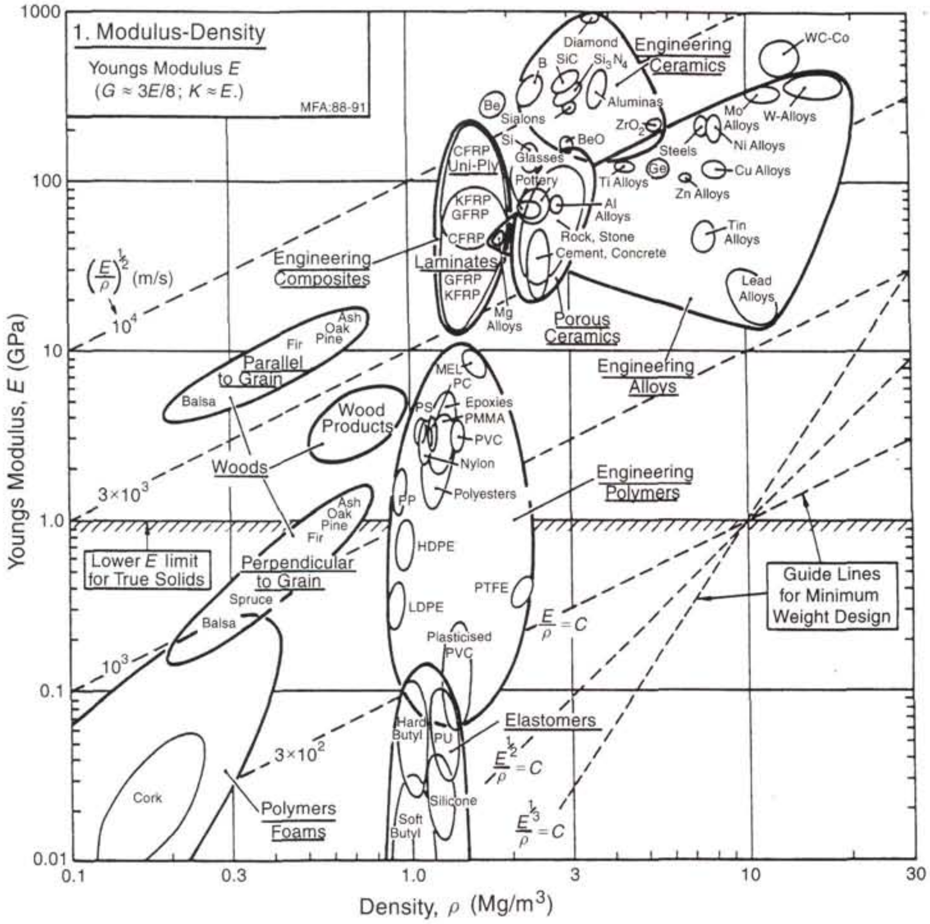


Chart 1: Young's Modulus plotted against density

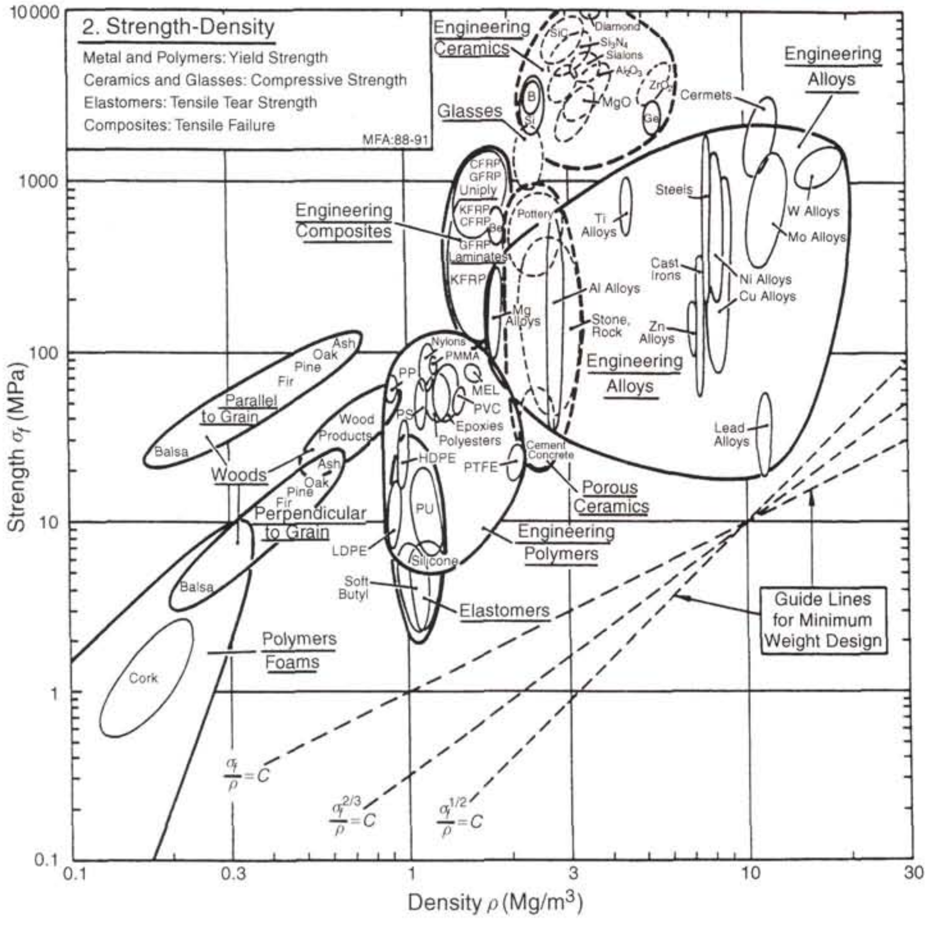


Chart 2: Strength plotted against density

Chart 3: *Fracture toughness plotted against density*

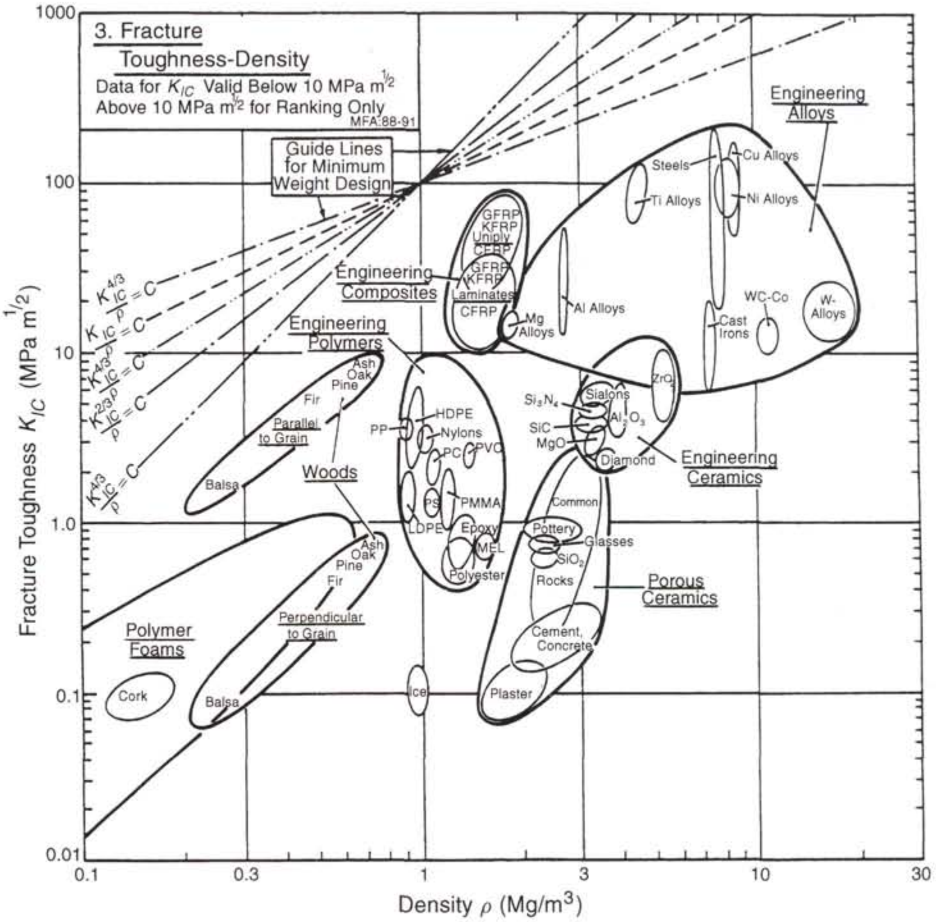


Chart 4: *Young's Modulus plotted against strength*

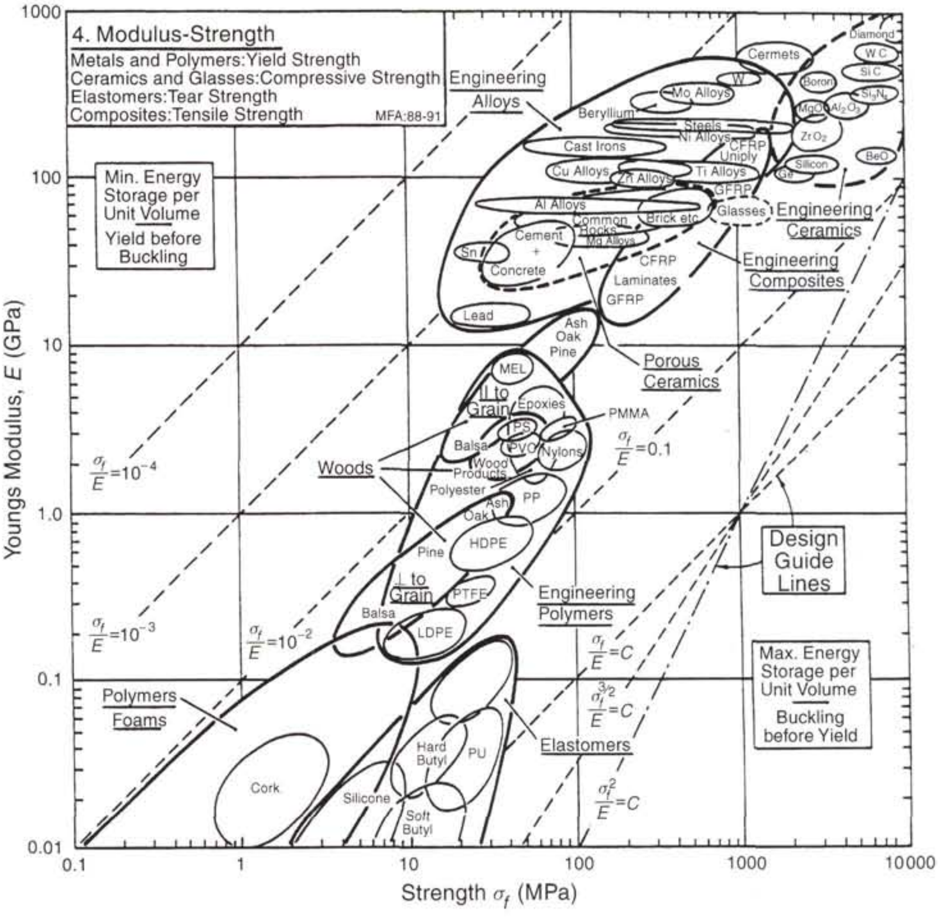


Chart 7: Fracture toughness plotted against strength

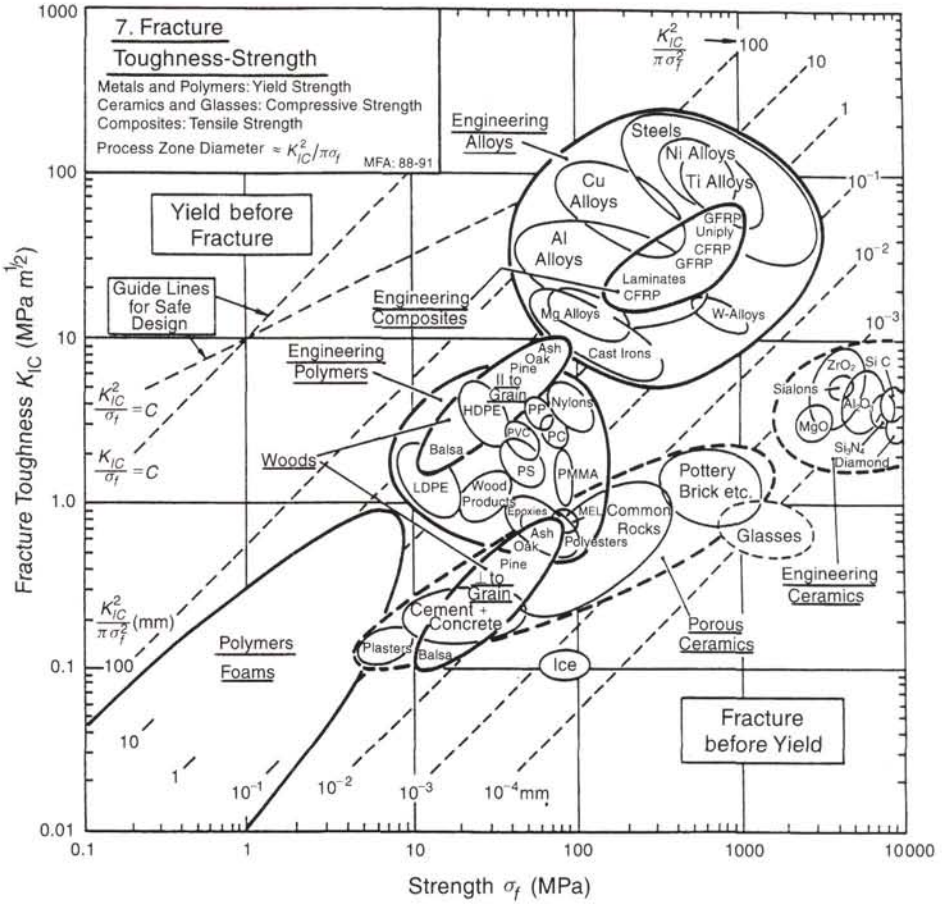
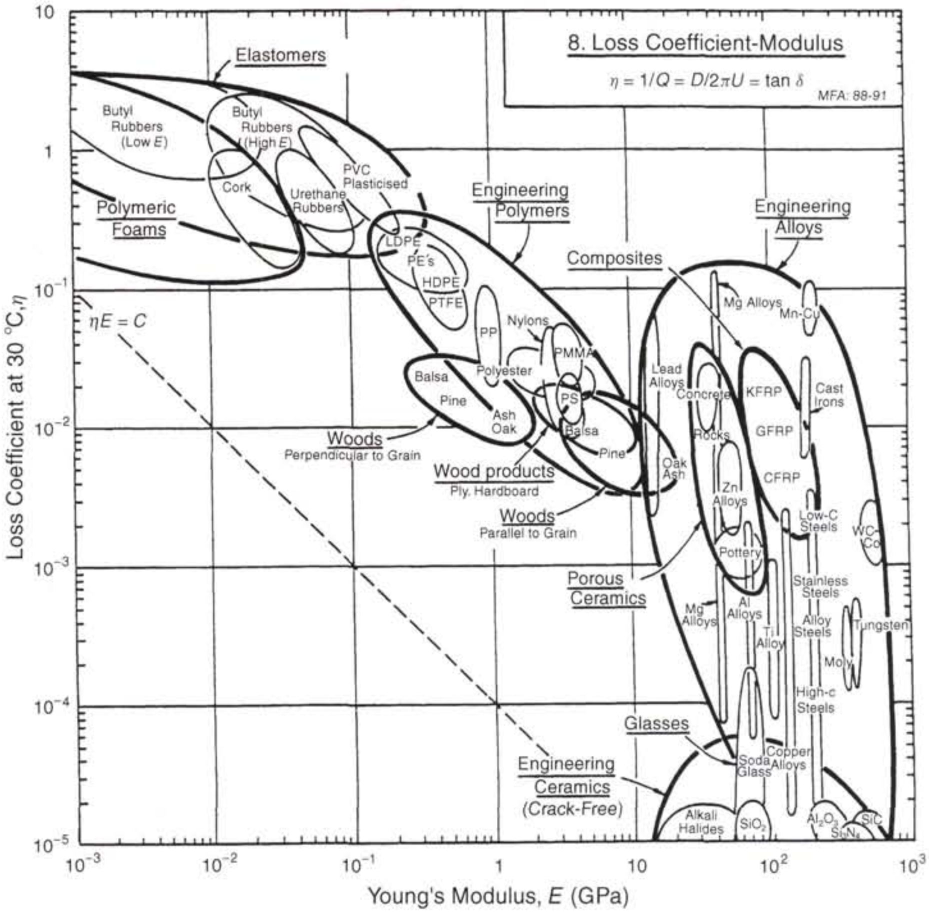


Chart 8: Loss coefficient (damping) plotted against Young's modulus



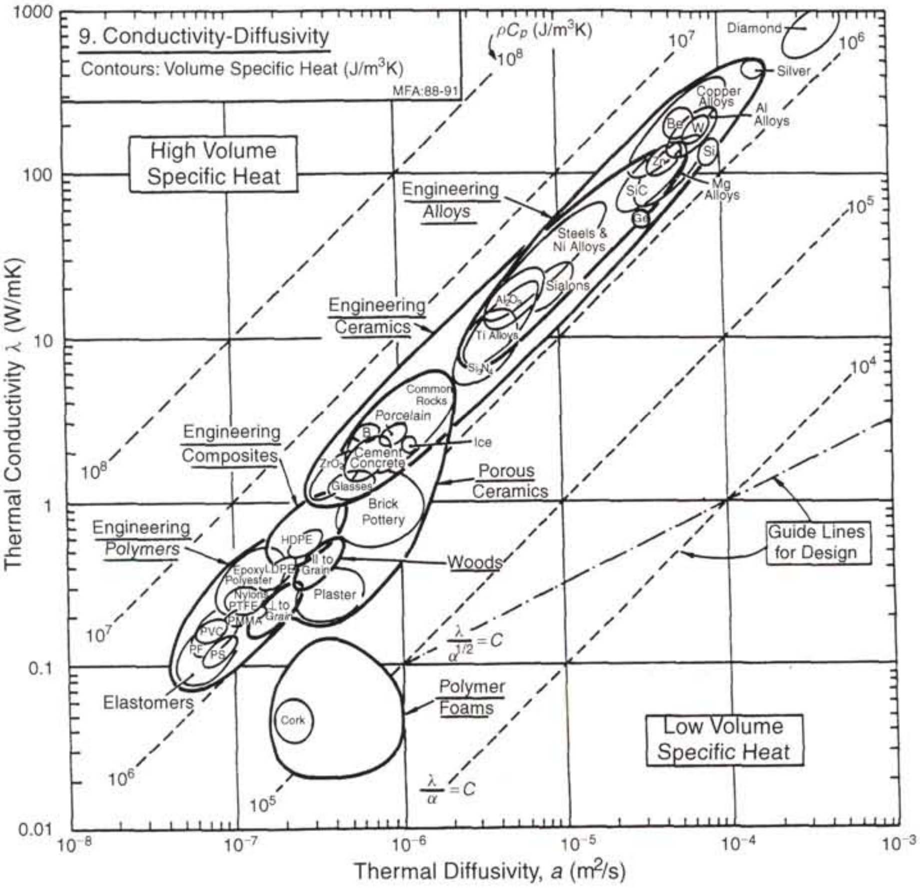


Chart 9: Thermal conductivity plotted against thermal diffusivity

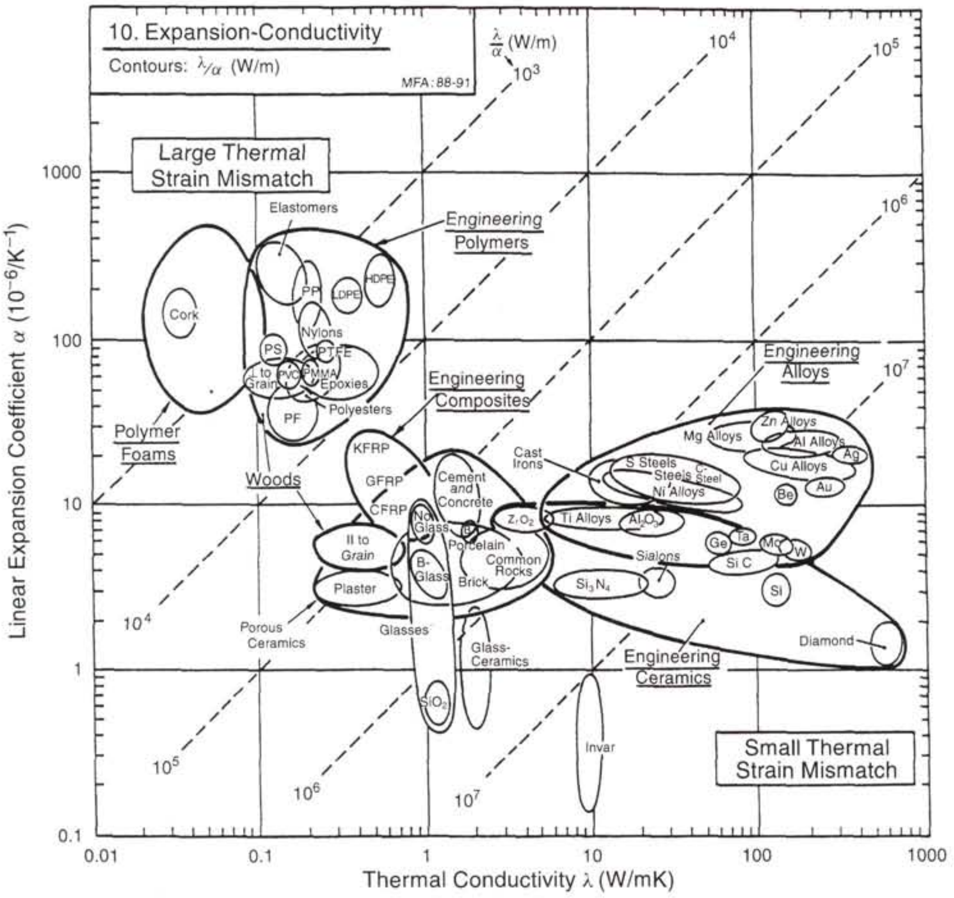


Chart 10: Linear expansion coefficient plotted against thermal conductivity

Chart 11: Linear expansion coefficient plotted against Young's Modulus

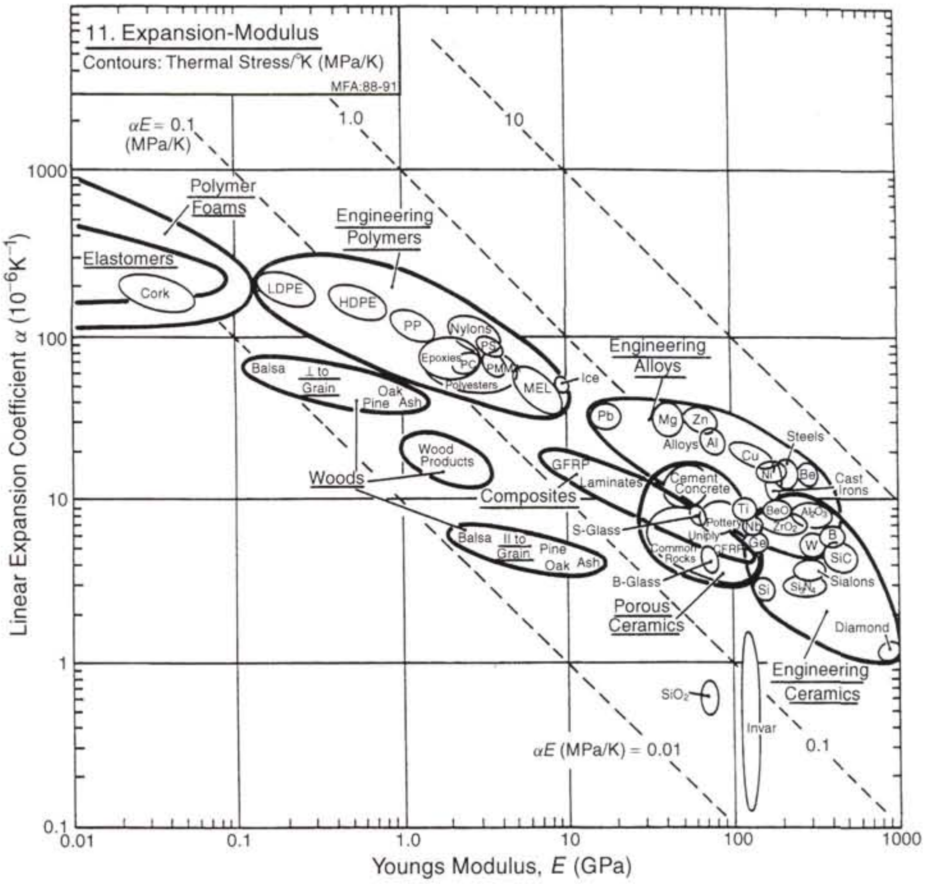
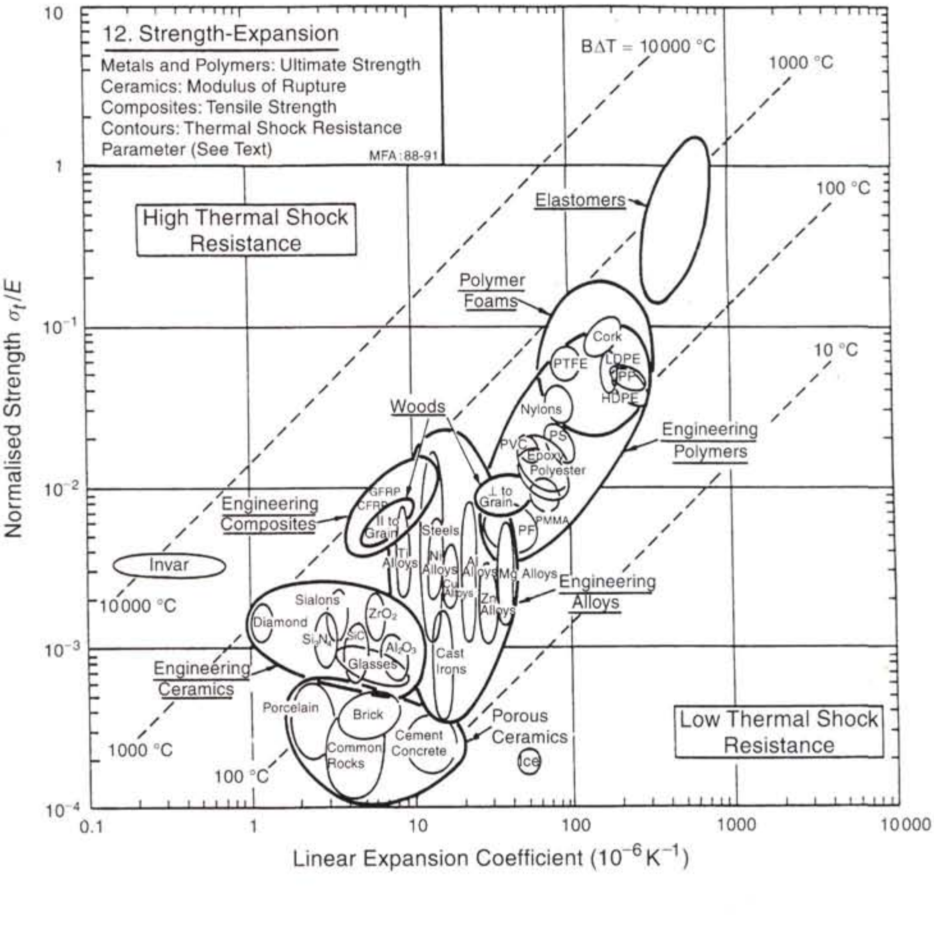


Chart 12: Normalised strength plotted against linear expansion coefficient



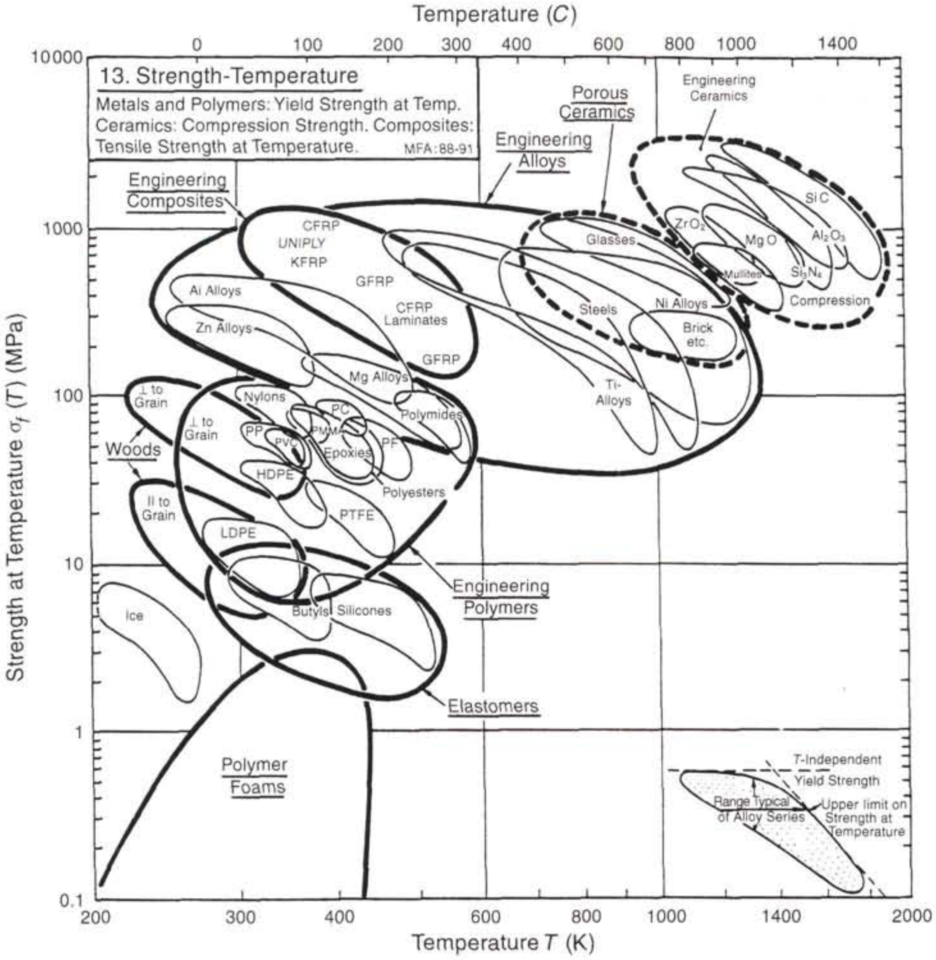


Chart 13: Strength plotted against temperature

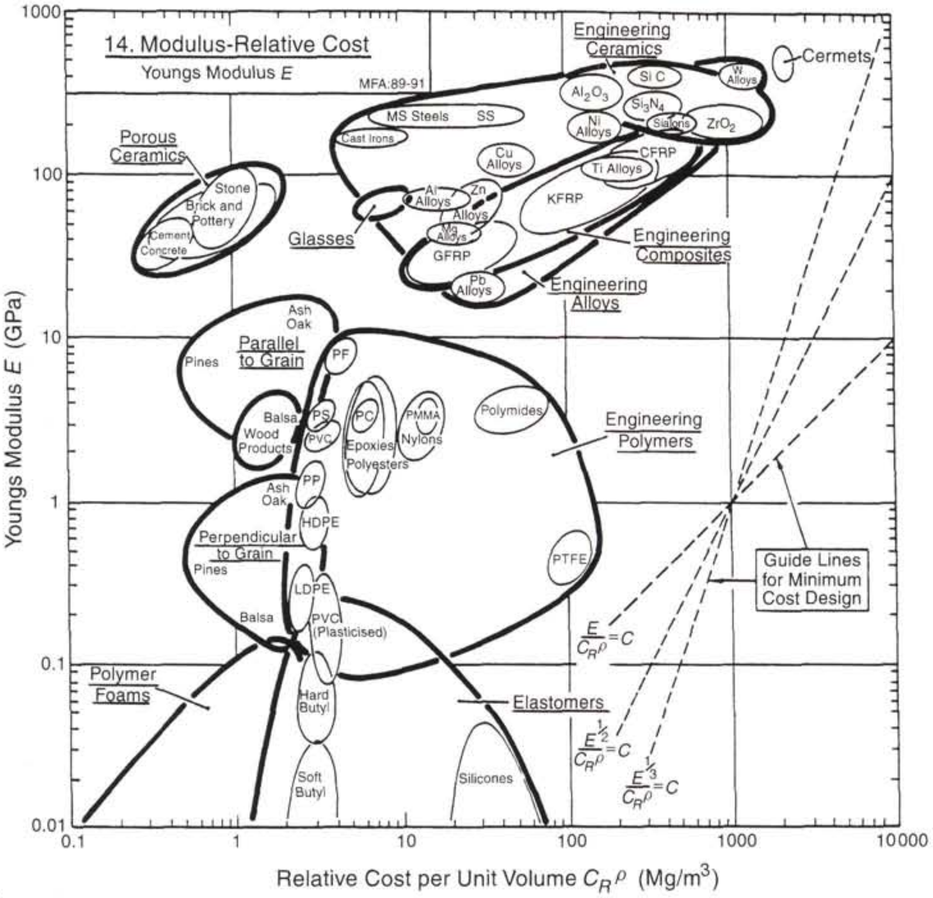


Chart 14: Young's Modulus plotted against relative cost per unit volume

Chart 15: Strength plotted against relative cost.

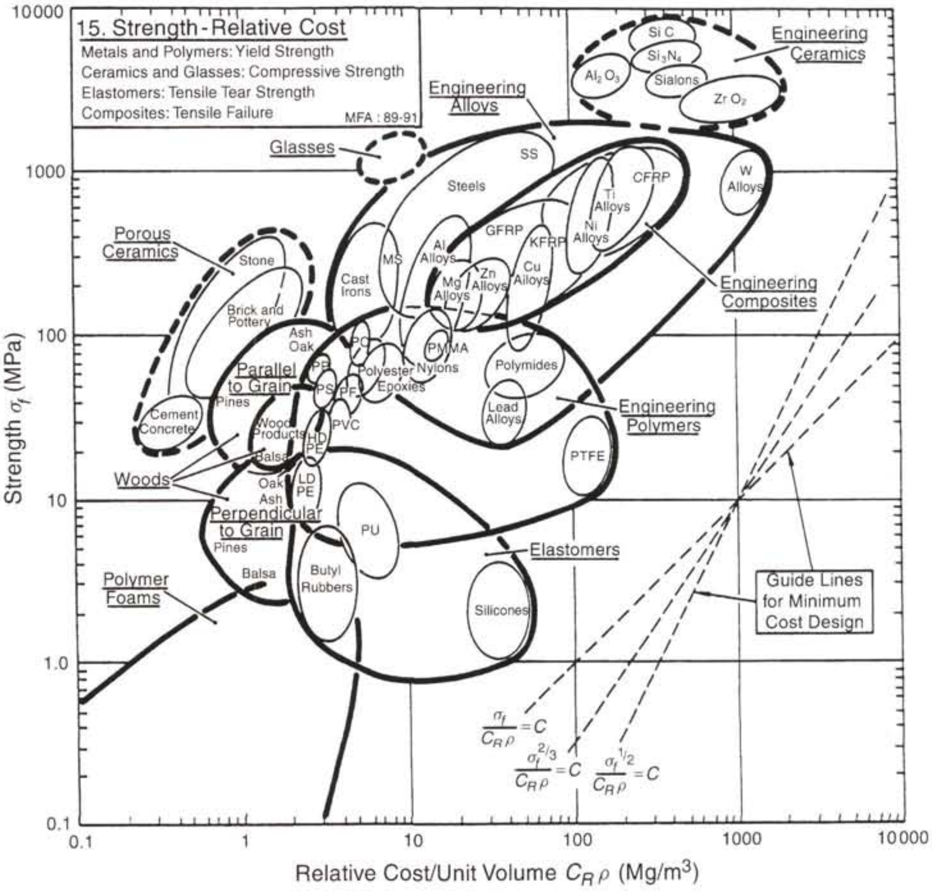
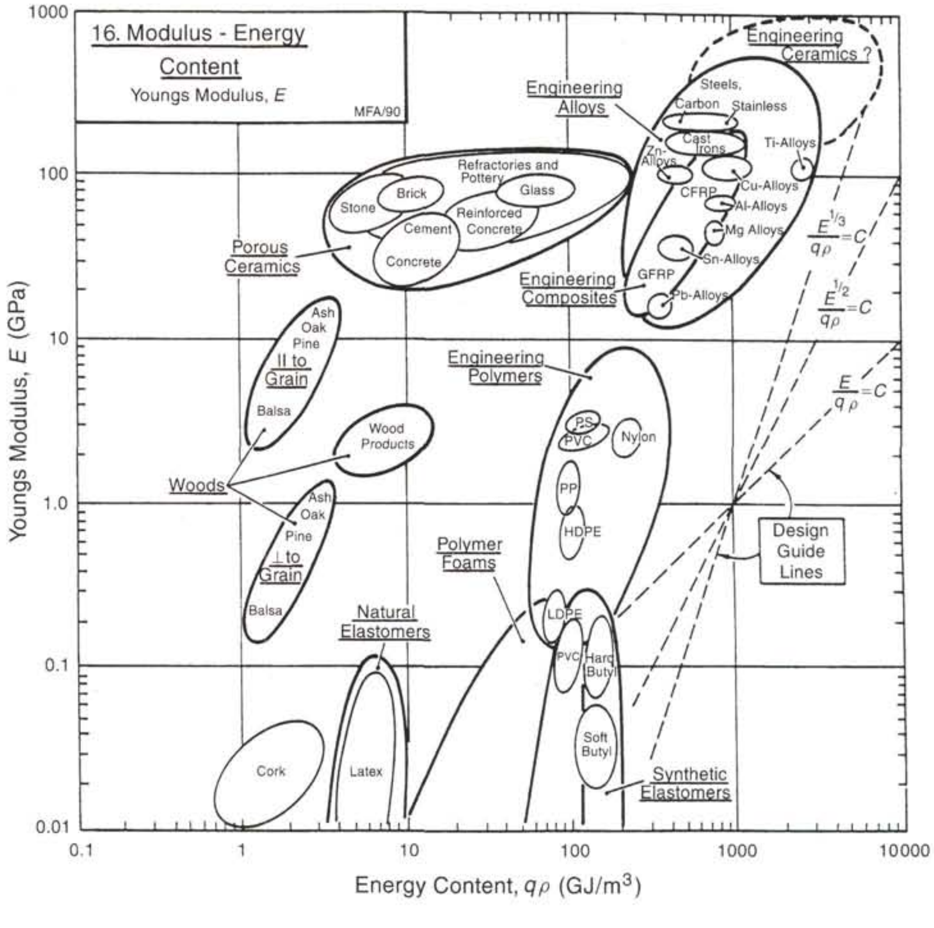


Chart 16: Young's Modulus plotted against energy content



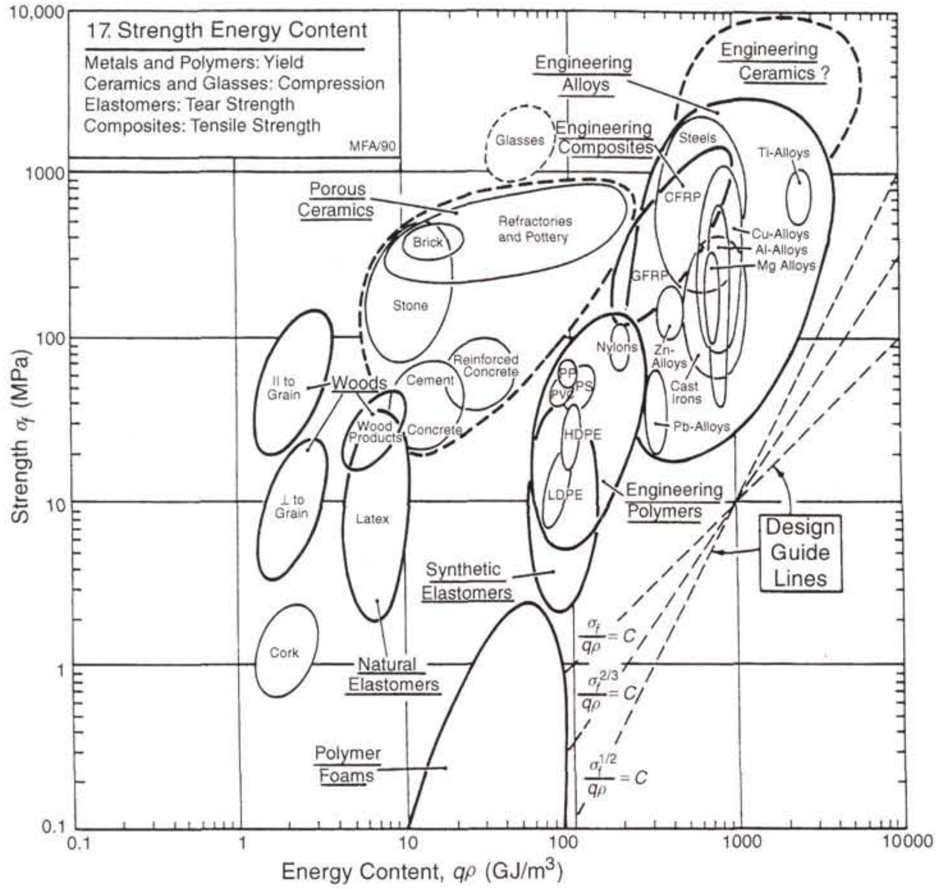


Chart 17: Strength plotted against energy content

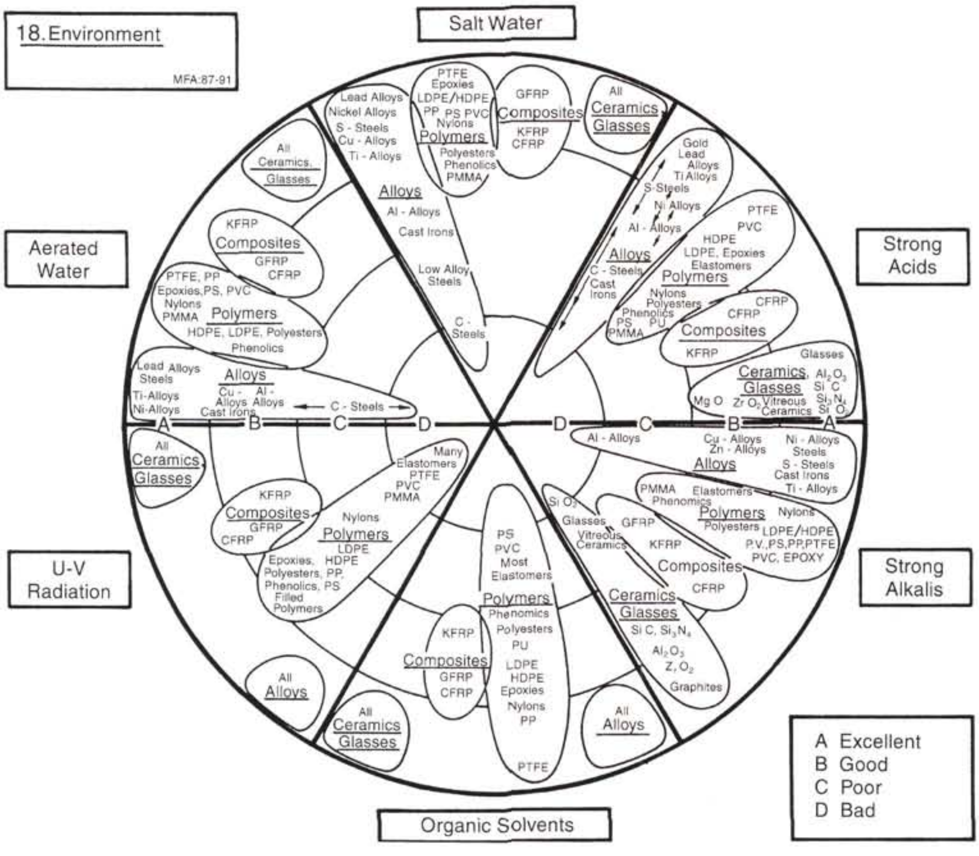


Chart 18: Comparative ranking of resistance to attack by six common environments

Fig. 2.2 Illustration of large telescopic mirror (courtesy of Galaxy Picture Library)

sion from Butterworth-Heinemann and the author and are gratefully acknowledged.

Structural design involves choosing a shape as well as a material. The immensely wide choice of materials is narrowed, first, by applying primary constraints dictated by the design and then by seeking the best subset of materials which maximise the performance of the component.

Primary constraints are imposed by characteristics of the design that are non-negotiable: temperature, chemical environment, that it must be a conductor or an insulator of electricity, and so on. In structural engineering we usually apply our primary constraints unconsciously when we narrow our material choice to steel, timber, concrete or, sometimes, aluminium or plastic.

Further narrowing is achieved by seeking the combination of properties that maximise performance. For most load-bearing components performance is limited by a combination of properties, such as $E^{0.5}/\rho$ for a light stiff beam.

It may surprise some readers to be reminded that glass is the preferred structural material for the world's largest ground-based optical telescopes. Glass provides the right strength, stiffness, dimensional stability and lack of thermal distortion and has the right fabrication properties to support and position a 6m diameter mirror with a precision about equal to the wavelengths of visible light.

Fig. 2.3 The main legs of the Commerzbank, clad in glass (courtesy of Foster & Partners)

Another surprising use of glass is as a cladding material to protect a steel structure. This is what occurs on the main legs of the Commerzbank in Frankfurt (1997; Architect: Sir Norman Foster & Partners. Engineer: Ove Arup & Partners). Instead of the more conventional steel or aluminium, glass panels with insulation behind them provide durable protection to the steelwork. In the past, glass ashlars were used to line coal hoppers to protect the steel from abrasion.

Many processes are possible to produce glass with the right combination of properties to meet a particular need. Float glass (see section 2.1.1) can

Table 2.2 Typical properties of annealed glass

Density	2500kg/m^3
Modulus of elasticity	70-74kN/mm^2
Shear modulus	30kN/mm^2
Poisson's ratio	0.22
Yield strength	Theoretical value is 3600N/mm^2 but behaviour is fracture-governed
Tensile strength	5000N/mm^2 but fracture-governed
Tensile ductility	0
Compressive strength	>1000N/mm^2 but complimentary tensile stresses will govern
Hardness	6 MoH
Loss coefficient at 30°C	10^{-5} to 10^{-4}
Toughness	0.01kJ/m^2
Fracture toughness	0.7MN/m$^{3/2}$
Softening temperature	About 530°C – varies with composition
Glass transition temperature	About 570°C – varies with composition
Maximum service temperature	Approx. 280°C (but beware temperature differences, especially in annealed glass)
Thermal conductivity	1W/m/K
Thermal diffusivity	6 × 10^{-7}m^2/s
Coefficient of thermal expansion	7.7–8.8 × 10^{-6}/K
Variation in rate of crack growth with humidity and stress	See Fig 2.5

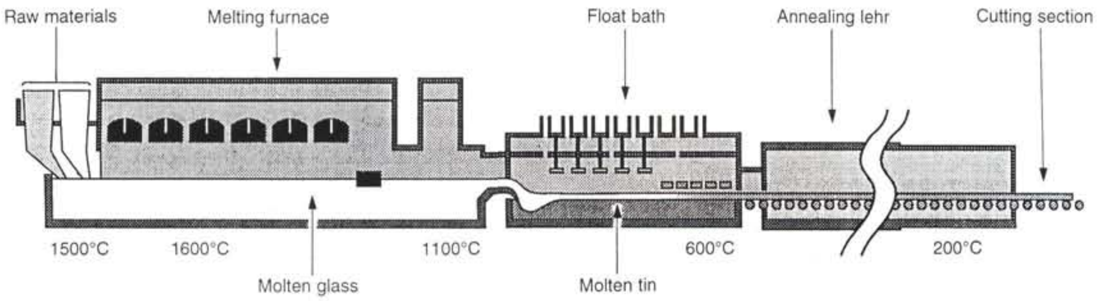


Fig. 2.4 The float glass process (courtesy of Pilkington)

be clear, tinted or coated. It can then be heat-treated or bent. It can then be further printed, laminated and double-glazed. Button and Pye (1993) describe these processes in more detail.

2.1.1. Average mechanical properties of annealed float glass

Annealed glass is today usually made by the float process.

The chemical ingredients, which include silica sand, soda ash, limestone and salt cake, are blended with cullet (recycled broken glass) and heated in a furnace to about 1500°C to form molten glass. The molten glass is fed onto the top of a molten tin bath. While on the tin bath, controlled heating permits the glass to flow, forming a flat ribbon of uniform thickness.

At the end of the tin bath the glass is slowly cooled. Then it is fed off the molten tin into the annealing lehr (or oven) for further controlled gradual cooling. Changing the speed at which the glass ribbon moves into the annealing lehr can vary the thickness of flat glass. The Chambers Dictionary definition of anneal is to heat and cool gradually. The glass edges are trimmed to give a constant width to the emerging sheet, which is then cut to length.

Annealed glass behaves perfectly elastically until the moment it fractures. Shards of annealed glass are dangerous. There is no creep (glass does not 'flow') and there is no fatigue in the metallurgical sense. There is slow growth of cracks under sustained or cyclical loading. Gy (1999) describes a year-long experiment involving 19mm toughened glass which concluded that the deformation of a permanently loaded glass structural element should increase by less than 3% over 50 years.

It is not only impact that causes brittle fracture of annealed glass. Bending stresses, thermal stresses, imposed strains – all of these cause elastic deformation and may cause fracture. No warning is given. Whether or not fracture will occur depends on the flaws in the glass, the stress level, the stressed surface area and the duration of the load. The flaws in the glass may be inherent or may result from the cutting or grinding or drilling of the glass and from the environment to which the glass has been subjected. Humidity encourages crack growth. Cut edges of annealed glass are often weaker than its flat surfaces. This means that annealed glass beams are designed to lower stresses than glass plates, unless limiting deflections is the governing criterion.

The condition for the onset of fast fracture is given by, in general:

$$\sigma\sqrt{(\pi a)} = \sqrt{(EG_c)}$$

where a is the half-length of the crack, E is the Young's Modulus and G_c is the toughness of the glass. G_c has units of kJ/m^2 and is the toughness of the glass, sometimes known as the critical strain energy release rate.

The equation says that fast fracture will occur when, in a material subjected to a stress σ, a crack reaches some critical size a or, alternatively, when material containing cracks of size a is subjected to some critical stress σ.

This equation is the mathematical description of the well-known phenomenon that annealed glass is stronger under short-term loading than it is under long-term loading. Charles (1958) and Inglis (1913) describe early work in this field.

When annealed glass breaks it breaks into large sharp pieces which can be extremely dangerous. On the other hand, an annealed glass pane may not fall out of its frame when broken and may continue to be able to support light loads because alternative load paths exist across the pane. Annealed glass panes do not spontaneously fracture, as do some other types of glass from time to time.

Wired glass (BS EN 572-3 and 572-6) is sometimes thought of as stronger than ordinary annealed

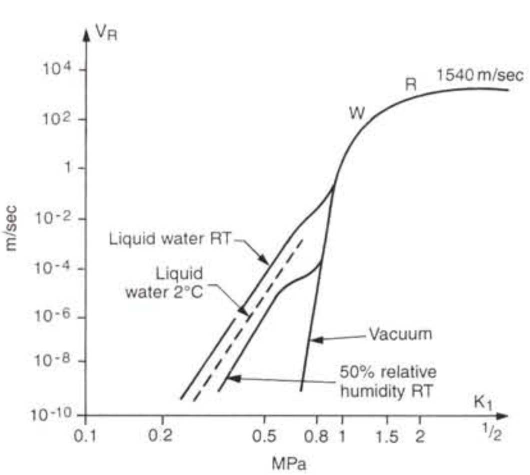


Fig. 2.5 Graph of crack growth speed versus stress intensity for different humidities (after Sedlacek)

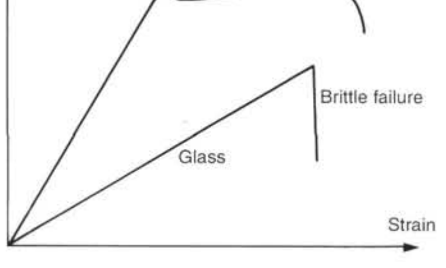


Fig. 2.6 Graph comparing stress/strain curves for steel annealed glass (after Chaunac and Serruys)

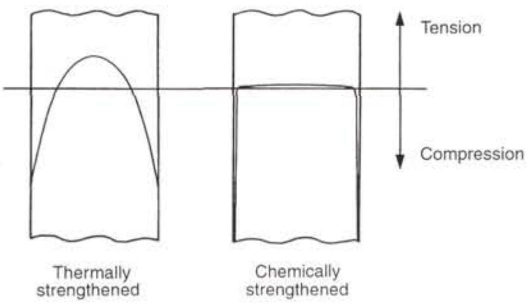


Fig. 2.7 The stresses in toughened glass both thermal and chemical (after Creyke, Sainsbury & Morrell)

glass because the wires are regarded as reinforcement. Unfortunately the opposite is true. The wires act as crack inducers and weaken the glass. The Canadian Code *Structural design of glass for buildings*, CAN/CGSB-12.20-M89, advises designers to assume that wired glass is half as strong as ordinary annealed glass of the same thickness. The advantage of wired glass is that it holds together when broken.

Patterned glass (BS EN 572-5) can be designed to the same stresses as flat glass as long as the minimum thickness at any section is used.

The coefficient of thermal expansion of glass depends on the chemical composition of the glass. In normal float glass additives such as alkalines can vary the coefficient between 8 and 9 × 10^{-6}/K. Borosilicate glass has a coefficient of 3–5 × 10^{-6}/K and purer SiO_2 glass, such as fused silica or quartz glass, has lower values, around 5 × 10^{-7}/K, which makes it useful for use in the construction of cooking surfaces (the so-called 'ceramic hobs').

2.1.2 Toughened glass

Thermally toughened glass (prEN 12150), which the Americans call fully tempered glass, begins with annealed glass. It is then heated to approximately 620°C and quenched (cooled rapidly) by jets of cooled air. This has the effect of cooling and solidifying the surface first. As the interior cools it tries to shrink. The interior goes into tension and the surface of the glass into compression, which in European glass is usually between 90 and 150N/mm^2. The maximum obtainable stress level is discussed by K. Blank in Kurkjian (1985).

The benefit that this confers is that surface cracks do not propagate under compressive stress and so toughened glass can sustain higher stresses than annealed glass. The process is described by Vitkala (1997, a, b & c).

One note of caution: Americans (and others) sometimes use 'tempered' to mean 'fully tempered'.

A different pattern of stresses can be achieved by chemical toughening in which the composition of the surface of the glass is altered. This is done by dipping the panes into electrolysis baths in which the glass's surface sodium ions are exchanged for potassium ions, which are 30% bigger. This creates an external layer under pressure. The advantages of this process over thermal toughening are no thermal deformation of the glass, and thinner sheets of glass can be toughened. The disadvantage is a much thinner surface compressive layer, which is likely to be less robust than the thicker layer produced by thermal toughening.

There are two principal types of thermally toughening furnace: vertical, in which the glass is transported through the system suspended vertically from special tongs; and horizontal, in which it is transported horizontally on special rollers

ASTM standard C1048-85 specifies that the surface compression be a minimum of 10,000 psi (69N/mm^2). European manufacturers (including the UK) can generally be relied upon to produce a surface compressive stress of at least 85N/mm^2. Some manufacturers say they can produce much higher stresses than this in thick sections of glass.

There are tests that can indirectly measure the surface compressive stress. One approach is to use the fragmentation test defined in BS 6206. In this test a pane of glass is struck in a controlled manner. When the glass breaks the number of fragments in a standard area are counted. The surface compression can be deduced from the number of fragments. It is anticipated that the forthcoming European Standard prEN 12150 (Karlsson, 1997) will eventually supersede BS 6206. As the surface stress increases so the number of fragments in a given area increases but fragment count alone cannot be used a measure of surface stress for design purposes. It is suitable for use as a rough and ready quality control measure.

Another approach is to use an optical instrument called a differential surface refractometer (dsr). It measures the twist of polarised light from the tin surface of the glass and this can be converted to a surface stress.

Toughened glass panes exhibit high values of bending strength because of the locked-in compressive surface stresses and the inherent strength of the annealed glass. The obvious analogy is with prestressed concrete. In many cases, deflection may limit the design and the strength of toughened glass may not be fully exploited.

It has been found that bolt holes do not cause large changes in surface stress, as long as their diameter is at least equal to the thickness of the glass. This enables cooling air to pass readily through the holes so that they cool at a similar rate to the rest of the glass. All cutting and drilling and grinding of the glass must be carried out before the glass is toughened, to avoid shattering it.

Float glass may contain impurities. If the glass is simply annealed these do not usually cause any problems but toughened glass is notorious for suddenly shattering for no apparent reason. The reason is the presence of tiny inclusions of nickel sulphide that undergo a phase change in which they expand. This cracks the glass and the locked-in energy of the toughening process does the rest. The glass breaks into a shower of small cubes known as dice. There is a quality control process known as heat-soaking that causes most of the phase changes to occur in the factory.

Toughened glass will also shatter if the surface is deeply enough scratched for the crack to penetrate the tensile zone of the glass.

The size of the manufacturer's furnace will determine the largest pane that can be toughened. Generally, sizes up to 4.2m × 2.4m can be made horizontally and up to 3.5m × 2.5m vertically. Longer and thinner toughened panes may be possible. Colvin (1997) provides further details of the availability of processed glass products.

The Glass and Glazing Federation's *Glazing Manual* contains a Standard for the quality of toughened glass. This will need to be supplemented for specific projects. Chapter 16 provides a specification checklist.

2.1.3 Heat-strengthened glass

Heat strengthening is a similar process to toughening but the levels of prestress that are produced are lower. When the glass breaks it breaks like annealed glass rather than toughened.

ASTM C1048 defines a pattern of breakage for heat-strengthened glass. It is anticipated that the forthcoming European Standard (prEN 1863) will define the range as 25 to 40N/mm^2.

The Glass and Glazing Federation's *Glazing Manual* contains a comparison between heat-strengthened and toughened glass and specifies the surface compressive stress for heat-strengthened glass as between 24 and 69N/mm^2.

2.1.4 Laminated glass

Laminating is a process in which two or more pieces of glass are bonded by means of an interlayer. The two principal materials for the interlayer are Polyvinylbutyral (pvb) and resins such as acrylic. The interlayer can be as little as 0.4mm thick or as much as 6mm. Though two layers of glass is the most common arrangement, over 25 layers have been successfully bonded in an assembly over 100mm thick. The forthcoming European Standard is prEN 12543. For further information about what the industry can produce the reader should consult the Laminated Glass Information Centre, whose address is given in section 1.6

Laminates can incorporate many thicknesses and many combinations of glass types to give a range of products with the required range of mechanical and optical properties. Other materials such as polycarbonates can be included. Annealed, heat-strengthened and toughened glass can all be laminated, as can bent glass. Heat-strengthening and toughening both cause small amplitude waves (caused by the rollers over which the heated glass travels) in the glass. These increase the separation between sheets being laminated and make pvb laminating impractical. The solution is to use resin laminating. Both these processes are described below. Bent glass is widely used in the automotive industry (Lappe, 1997) and generally uses pvb laminating.

Sheet laminating

The sheet interlayers can be pvb or polyurethane or a pvb/polyester/pvb sandwich. pvb is the commonest sheet interlayer material. The sheets of glass are assembled with an extruded sheet of pvb between them. The 'sandwich' is then passed through an oven that heats it to about 70°C, from which it passes between rollers that squeeze out any excess air and form the initial bond. The laminate then moves to an autoclave where it is heated to about 140°C under a pressure of about 120psi (0.8N/mm^2). The largest size that can be made by this process is approximately 6m × 3m. Colvin (1997) provides further details of the availability of processed glass products.

Resin laminating

The two main resins used are acrylic and polyester. The sheets of glass are brought together and held the right distance apart by double-sided tape around their perimeter. Resin is poured between the two sheets and when all the air has been displaced the open edge is sealed and the laminate stored horizontally while the resin cures and solidifies. Curing is by chemical reaction or UV light. Size is limited by the ability of the fabricator or by the size of panes available.

Structural behaviour

This depends on the type(s) of glass used and on the properties of the interlayer. Hooper (1973) showed that, for the interlayer materials he considered, short-term out-of-plane loads were resisted by the laminate acting compositely. Long-term out-of-plane loads were simply shared by the two sheets of glass in proportion to their relative stiffnesses, because of deformation of the interlayer. Later research in the USA has refined these conclusions and is described by Minor and Reznik (1990), by Behr, Minor and Norville (1993) and by Norville (1997). Jacob (1997) describes a new limit state design model for laminated glass. Norville (1999) argues that both test data and theoretical studies indicate that laminated glass displays strength and behaviour under short-term loading equivalent to monolithic window glass of the same type and nominal thickness. Sobek, Kutterer and Messmer (1999) describe research at the University of Stuttgart into the time and temperature dependence of the shear stiffness of the interlayer.

Increasing temperature softens the interlayer and reduces composite behaviour, which can be significant in double-glazed units, which can act as solar collectors.

Laminated glass offers a number of performance benefits.

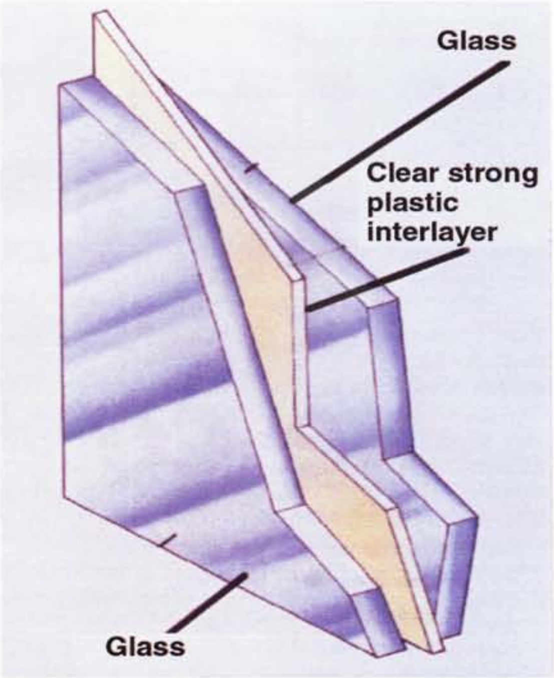


Fig. 2.8 The manufacture of a laminate (courtesy of Laminated Glass Information Centre)

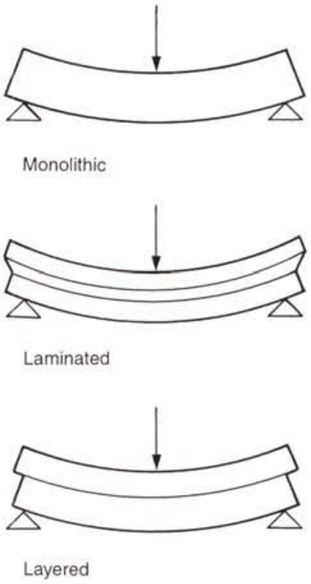


Fig. 2.9 A comparison between composite behaviour and load-sharing (courtesy Andrew Pye)

Fig. 2.10 Laminate damaged by bullet (WB & B Strategic communications)

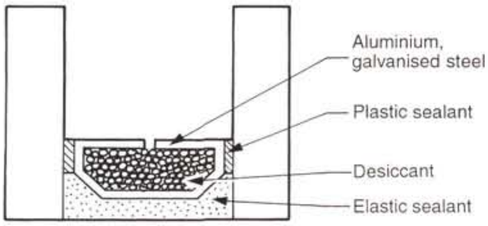


Fig. 2.11 Illustration of a hermetically sealed unit, labelled to show the main components (after Beye & Klein)

Fig. 2.12 Building B8 at Stockley Park, near London. (courtesy of Ian Ritchie Architects)

Safety

If an impact or other cause breaks one layer or both layers of glass, the interlayer can prevent penetration and any broken pieces of glass will remain bonded to the interlayer. This minimises the likelihood of serious cuts or injuries caused by falling glass.

Intumescent resin interlayers are available. In a fire these turn into a foam which not only prevents the passage of fire but also reduces the conduction and the radiation of heat through the glass. This protects people who may need to pass it on their way out of the building.

Security

The use of thicker interlayers increases the penetration resistance of the panel, giving protection from sledgehammer attack. Multilaminates also provide increased resistance. Some bullet-resistant laminates include sheets of polycarbonate to improve their performance.

Laminated panes can, if properly held at their edges, also improve safety from bomb blasts. This is discussed further in chapter 15.

Solar control

Tinted and translucent interlayers are available which modify the passage of solar radiation. There are even laminates which when examined minutely show themselves to have interlayers that are louvered in the manner of Venetian blinds. These can be used to exclude, for example, high altitude summer sun while admitting low altitude winter sun.

Compagno (1996) describes a wide range of modern glass compositions and surface treatments, including body-tinted glass, photosensitive glass, photochromic glass, dichroic coatings and ceramic-enamel coatings. He also describes a range of fillings for insulating glass units. Vitkala (1999) describes the toughening of low emissivity glass.

Sound control

Laminated glasses are better than single sheets at absorbing sound, because of the damping effect of the interlayer. This is more effective at higher frequencies.

Laminating is a versatile process. Manufacturers are often willing to discuss new ideas with designers. In many cases it may be possible to produce special products simply by modifying an existing product.

2.1.5 Multiple glazing

This is a term that covers two main types of glazing: hermetically sealed units and window or walling systems that contain two or more separate panes of glass.

Hermetically-sealed units

These are commonly known as insulating units. Their construction is covered by BS 5713 and the forthcoming European Standard prEN 1279 and their historical and future development is described by Beye and Klein (1997).

Sealed units are constructed in a variety of ways but most have similar basic components.

A hollow spacer tube, normally aluminium, separates the panes of glass. This tube is filled with a desiccant to keep the air in the cavity dry. The panes of glass and the spacer tube are sealed together around their perimeter with either a single seal of epoxy polysulphide or butyl, or a dual system using a primary seal of polyisobutylene and a secondary seal of polysulphide, polyurethane or silicone. These seals must be able to bond the glasses, allow them to move a little and keep water vapour out of the cavity.

Almost all imaginable thicknesses and types of glass, clear, tinted, reflective, low emissivity, laminated, toughened and patterned can be incorporated into units (Davies, 1997). Cavities typically vary between 6mm and 20mm. Cavities can be filled with air or other inert gases.

The main benefits of such units are improved thermal and acoustic insulation. Building B8 at Stockley Park (1990; Architect Ian Ritchie Associates; Engineer Ove Arup & Partners) uses 1.385m × 3m insulating glass units. The inner pane is 6mm toughened glass with a low emissivity coating; the outer pane is 12mm toughened and the 16mm cavity is filled with argon. The larger than

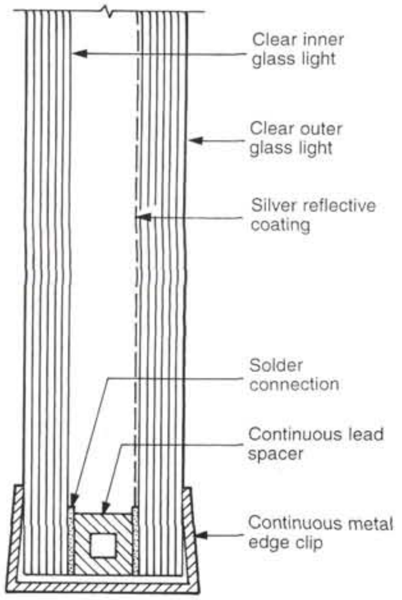


Fig. 2.13(a) Diagram of a double-glazed unit, the John Hancock Building (reproduced from *Why buildings fall down* - Levy & Salvadori – by permission of W. W. Norton & Company)

usual thickness of the outer panes carries the countersunk bolts, helps limit deflections and gives some acoustic protection from a nearby heliport. This thickness also gives rise to the characteristic green tint of the glass facade.

Load sharing in insulating units

Atmospheric pressure is about 100kN/m^2. Wind pressures in the UK rarely exceed 2.5kN/m^2 (but can be higher elsewhere). The question arises: do the panes of an insulated unit share loads? In general the answer is yes, though it is not so for small stiff panes of glass separated by deep cavities. The analysis that leads to this conclusion is contained in Appendix D.

Temperature changes and atmospheric pressure changes

Because they are sealed, insulating units are affected by temperature changes and by atmospheric pressure changes.

Temperature changes

During its life, an insulating unit will be exposed to varying air temperatures on its surfaces and to the effects of solar radiation. Both surfaces also lose heat continuously by radiating long-wave radiation.

When the gas in the unit changes temperature its pressure changes in accordance with Boyle's Law. Low atmospheric pressure combined with high temperatures produces the greatest expansion of the gas. High atmospheric pressure combined with low temperatures produces the greatest contraction of the gas. Watch out for insulating units manufactured somewhere cold at sea level and then installed somewhere sunny in the mountains! For further information see Appendix E.

The inner and outer panes will expand and contract in response to thermal changes. How they are separated and sealed and their shape and size will all effect the stresses that are induced by this.

The John Hancock Building in Boston (Levy and Salvadori, 1994) had a difficult time when it was young, with glass falling from the building during a windstorm that hit during construction. Failure of its 1.35m × 3.45m double-glazed units was finally attributed to the connection between the lead spacer and the outer reflective pane. The connection was found to be too stiff, resulting in unacceptable strains being imposed on the outer pane, which cracked it. All 10 344 double-glazed panels were replaced by single sheets of toughened glass.

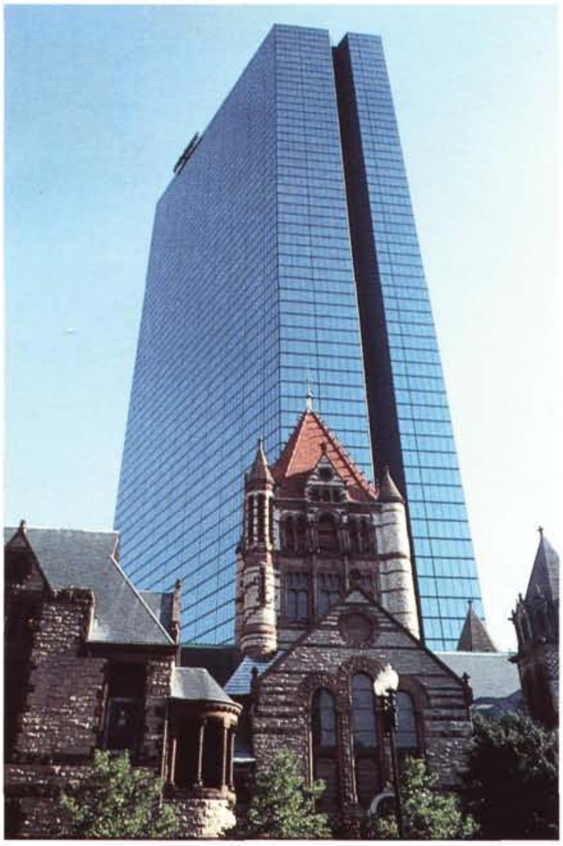


Fig. 2.13(b) The John Hancock Building (courtesy of Architectural Association/Joe Ker)

Atmospheric changes

At sea level, atmospheric pressure is about 14psi or about 100kN/m^2. It commonly varies as high and low pressure systems cross the UK by plus or minus 5%, i.e. plus or minus 5kN/m^2. This may vary in other countries.

If the glass panes are small and thick, i.e. stiff, then atmospheric pressure changes can generate significant stresses in the glass. This phenomenon is reinforced by the use of rigid edge seals. If the panes are relatively flexible then they can bow at relatively low stresses but this can produce visible distortions when viewing reflections in the glass.

An approach to the calculation of the effects of atmospheric pressure and temperature on insulating units is given in Appendix E.

2.1.6 Glass blocks

Hollow glass blocks are available in many sizes from 115mm × 115mm × 80mm thick up to 300mm × 300mm × 95mm thick. Solid blocks are also available, from 120mm × 120mm × 40mm up to 200mm × 200mm × 50mm.

Hollow blocks are manufactured in two halves that are sealed together at high temperature. When the sealed block is annealed to room temperature, the internal pressure drops to about 0.3 of atmospheric pressure. This partial vacuum improves the thermal insulation and the acoustic insulation of the block.

Traditionally, glass blocks have been used for walls and floors. In the former, reinforcement in the horizontal and vertical joints is used to deal with tensile forces, in a way similar to a reinforced concrete wall.

In floors, the blocks are supported, via resilient

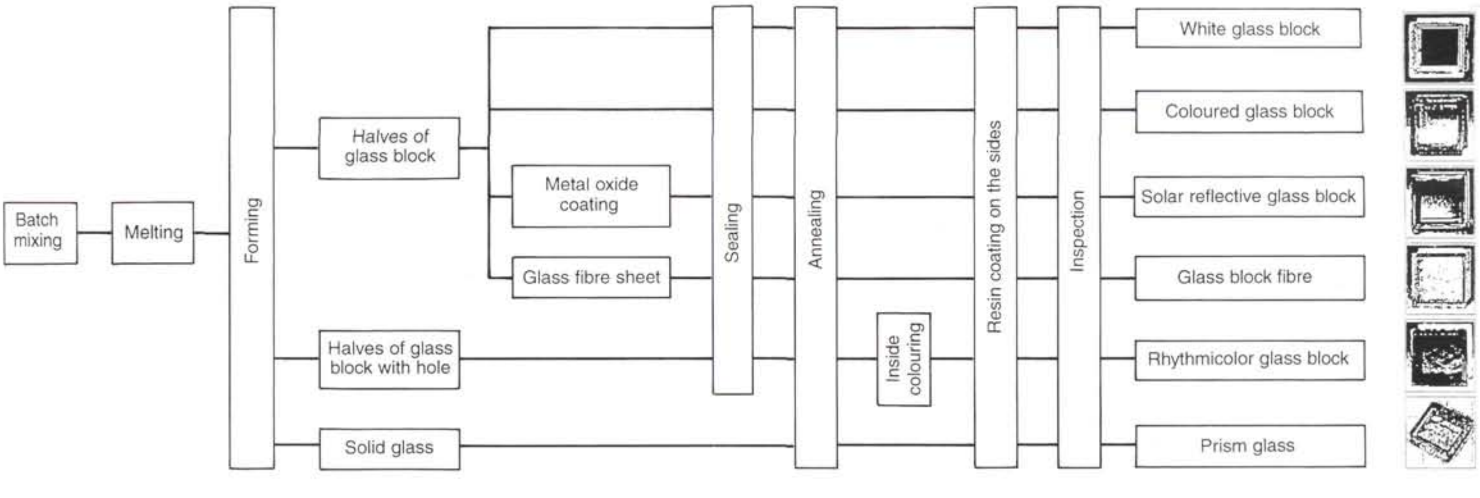


Fig. 2.14 The manufacture of hollow blocks (courtesy of Nippon Electric Glass)

spacers, by steel or cast-iron gratings.

As the glass in glass blocks is annealed, it may be expected to have properties similar to those listed in Table 2.2. Structural design with glass blocks would be very similar to structural design of masonry: the most practical structural uses would be walls and elements in which the dominant stresses are compressive. Short-term tensile loads can be carried with some confidence but long-term tensile loads are either designed out or carried by reinforcement, which supplies all the ductility. Post-tensioning may be of benefit here.

However, history has governed our perceptions and there is reluctance to design glass block walls to resist anything other than self-weight and out-of-plane loads. Cracking is the issue. A glass block wall acting as a loadbearing element in a building will be subjected to forces and movements that may crack the wall. The traditional solution has been to provide soft joints around the wall so as not to subject it to these forces and movements. A structure supporting a glass block wall should not deflect more than span/600 in order to reduce the risk of cracking the wall. The forthcoming European Standard, prEN 12725, actually forbids the use of glass blocks as loadbearing elements

2.2 Non-structural issues that influence design

2.2.1 Thermal transmission

In normal float glass, thermal transmission is a critical factor in heat loss and gain which in turn affects the heating and cooling costs of the building.

The thermal resistance of glass as a result of conduction is only marginally affected by the thickness of the glass. This has led to the widespread use of insulating units with two or more layers of glass separated by air or other inert gases. Load sharing in insulating units is described in section 2.1.5 and Appendix D.

The decision whether to use single glazing or insulating units can depend on the expectations of the users of the space and also on the level of thermal analysis that the designers are willing or able to undertake. In a transiently used space such as a shopping mall it may well be reasonable to use single glazing for the roof because people using the mall will be dressed for the weather and will be satisfied if they are sheltered from the rain and the wind.

For building B6 at PotsdamerPlatz in Berlin (1997; Architect: Renzo Piano Building Workshop;

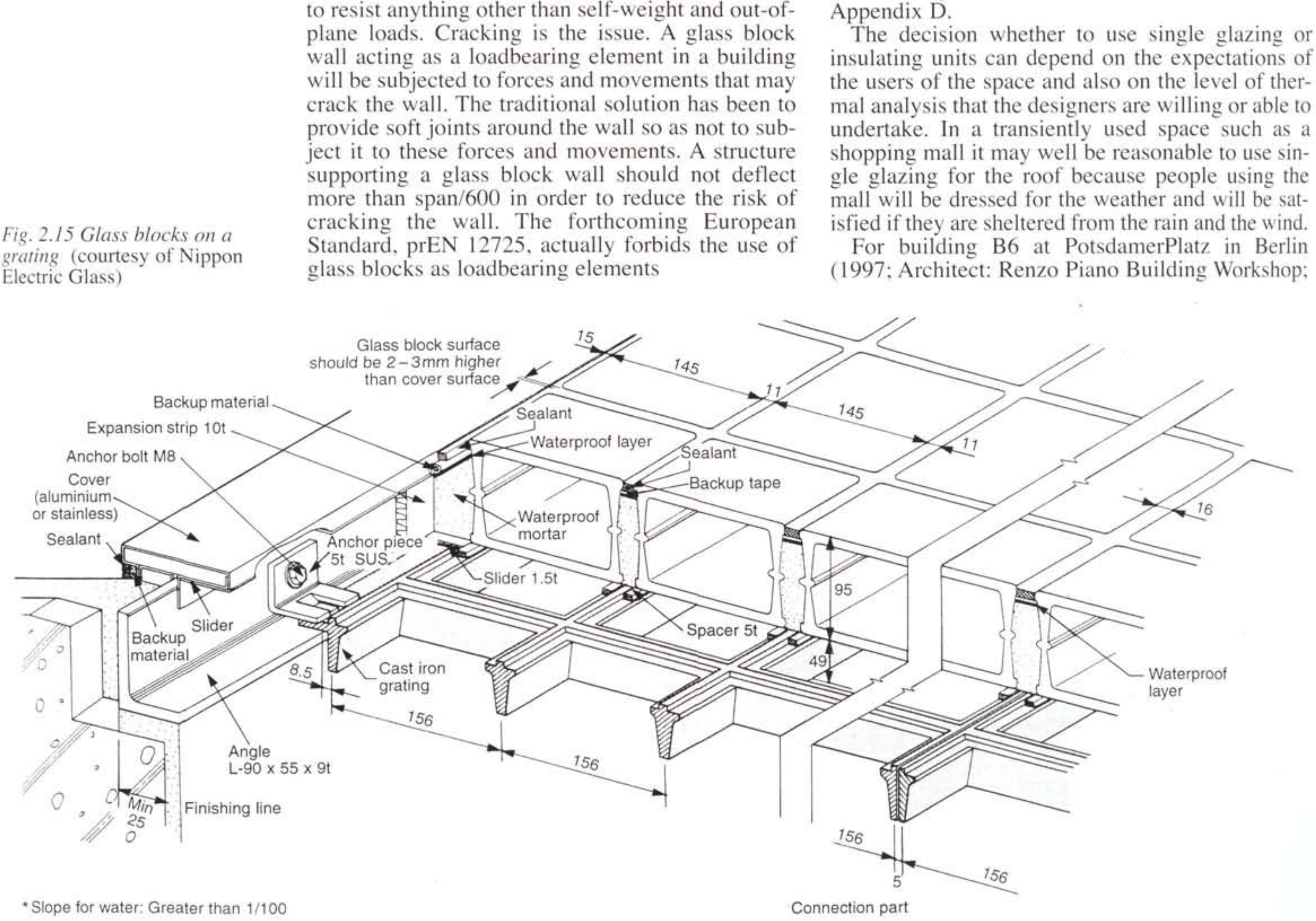
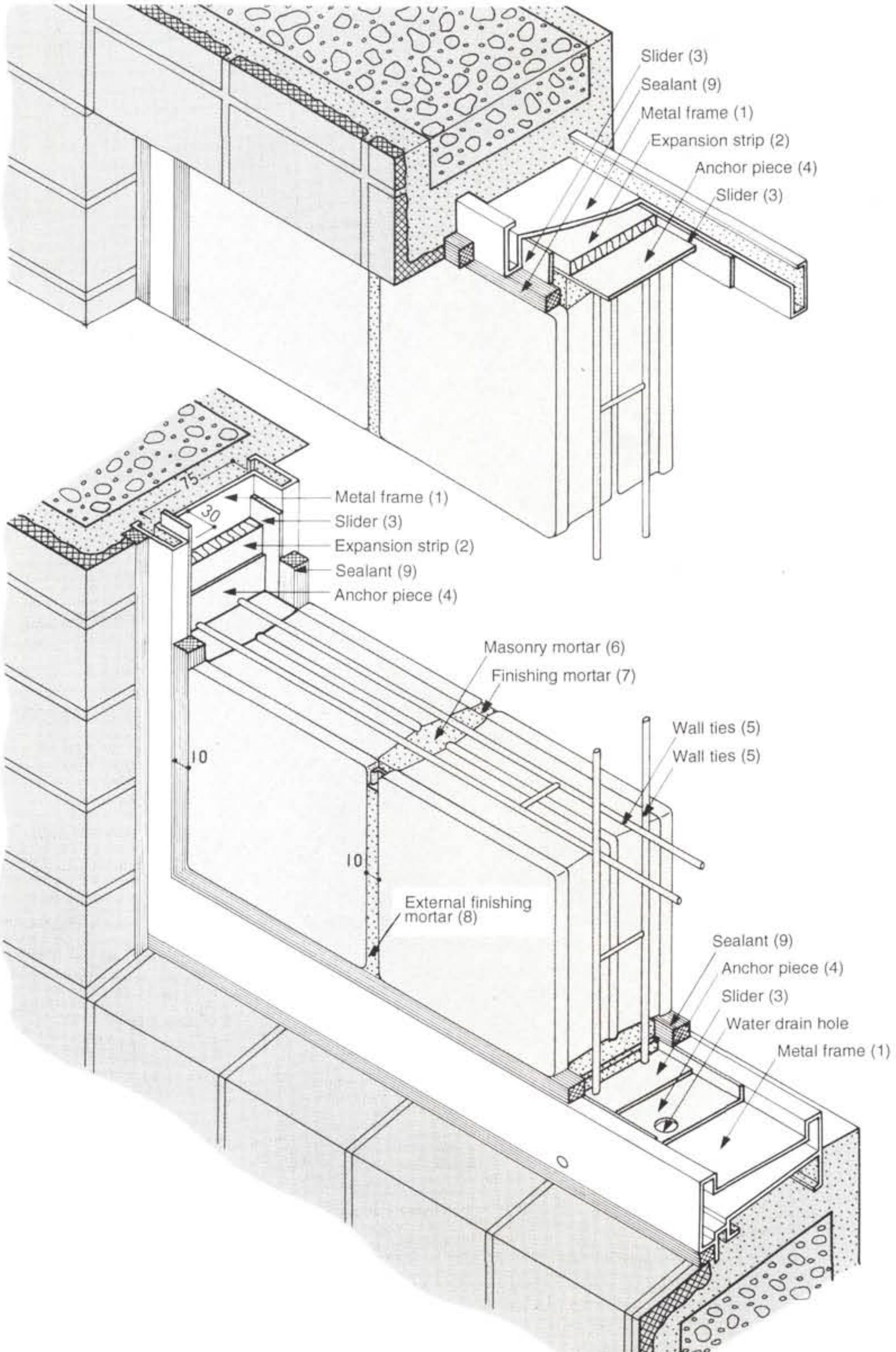


Fig. 2.15 Glass blocks on a grating (courtesy of Nippon Electric Glass)

Fig. 2.16 Reinforcement in glass block wall (courtesy of Nippon Electric Glass)



Engineer: Ove Arup & Partners) extensive thermal modelling was used to persuade the authorities that heat losses from the single-glazed space were low enough to be acceptable and that the users would be comfortable.

Thermal stresses in glass can be significant. It is an internal force created by a temperature difference between the centre and the edge of a piece of glass, a common cause of which is partial shading. A temperature difference of 1°C between the centre and the edge of a glass plate causes a stress of about $0.6N/mm^2$, according to the Canadian Code.

All types of annealed glass are susceptible to thermal breakage and the risk increases when tinted, heat absorbing, reflective or coated glass components are used in double- or triple-glazed units. If the annealed glass edge has been damaged or is poorly cut, breakage is likelier at lower temperature differences than in glass in good condition.

Section 6.3.3 provides a checklist of items to

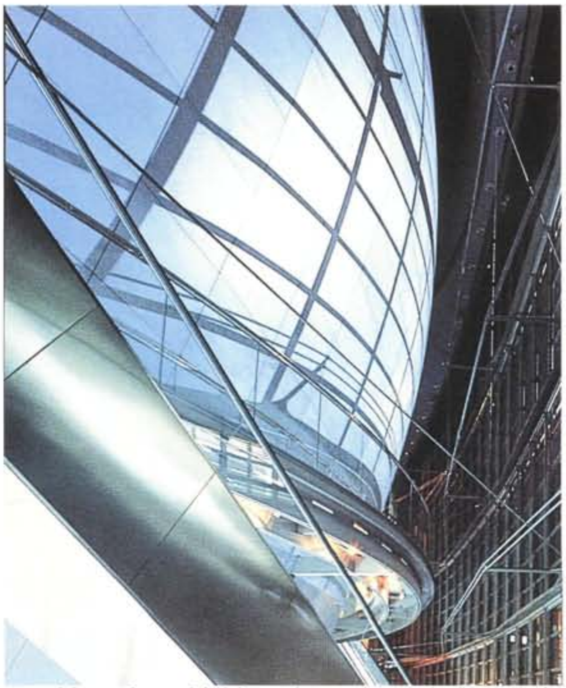


Fig. 2.17 Building B6 at PotzdamerPlatz (courtesy of Gotz Gmbh)

consider when thinking about thermal stresses in glass. Appendix D of the Canadian Code covers this issue in some detail.

2.2.2 Solar radiation

The transparency or translucency of glass are its most important properties for use in buildings. Because glass is not crystalline its properties are isotropic and light passes through transparent glass without being scattered.

Radiation from the sun and sky extends beyond the narrow band that we can see, which has wavelengths between approximately 380 and 780nm. Below 380nm is the ultraviolet region and above 780nm is the infra red (IR) region. Our eyes are, not surprisingly, tuned around the peak spectral density of solar radiation, which occurs at around 480nm. Atmospheric scientists usually refer to radiation between 150nm and 3000nm as short-wave radiation and that beyond 3000nm as long-wave radiation.

Fig. 2.18 Exterior of Waterloo International Station roof (courtesy Nicholas Grimshaw & Partners Ltd/Jo Reid & John Peck)

Table 2.3 The relative energy content of solar radiation

Region	Energy content
UV	3%
Visible	53%
IR	44%

Soda-lime-silica glass transmits radiation with wavelengths between 315nm and 3000nm. Radiation outside these wavelengths is almost completely absorbed. Objects (the soil, buildings, human beings) at 'normal' temperatures radiate most energy at wavelengths of between 8000 and 12000nm and this energy is absorbed by glass. This is the origin of the term 'greenhouse effect'. In general terms a glasshouse provides two forms of control: first, it is a radiative filter; and second, it reduces turbulent heat losses because it gives almost complete wind shelter. The radiative filter was always held to be the dominant heating mechanism but it can been seen that shelter can be equally or more important.

As the glass absorbs this long wave radiation it heats up and in turn begins to lose heat by a combination of radiation, conduction and convection.

2.2.3 Condensation

Condensation occurs when the surface temperature of the glass falls below the dew point of the air in contact with it. An insulating unit will usually have higher temperatures on its inside face than a single sheet of glass. It would therefore appear to be not a safe choice to select single glazing but double-glazing may not be necessary and it may not be affordable.

With very low U-value insulating units (i.e. very good insulators) external condensation is also possible. This occurs because there is insufficient flow of heat from the interior to keep the outside surface of the glass above the dew point.

The designers need to decide how much condensation might occur and how frequently. Then they need to decide what, if anything, should be done about it.

At Waterloo International Station, London (1994; Architect: Nicholas Grimshaw & Partners; Engineer: Anthony Hunt Associates), the upper panes overlap the lower panes, as in a traditional greenhouse, but with a neoprene sealing lip which contains a tiny channel to collect condensation and hold it until it evaporates.

2.2.4 Rainwater runoff

In a facade, whether vertical or sloping, a crucial consideration is that of water dammed by clamps or other projections.

Water that runs down a steep or vertical face needs to go somewhere when it reaches the bottom of the face. The choice facing the designers is whether to intercept some of the water part of the way down or to collect a larger quantity at the bottom.

On a flat roof, the issues are, again, those of damming but also those of providing sufficient falls and sufficient outlets of the right size to allow the water to drain from the roof at an acceptable rate. The design should take account of the possibility of blocked drains and the effect of wind combined with the build-up of water on the roof. Designers should also carefully look at options available for creating falls and at the deflections of the roof under load.

At the Kemper Memorial Arena in Kansas City

(Levy and Salvadori, 1994), one of the causes of its sudden collapse on 4 June 1979 was ponding of water during a severe downpour. The ponding was made worse by strong winds and by the cumulative deflections of the roof deck, the joists supporting the deck, the trusses supporting the joists and the long-span portals supporting the trusses. These circumstances combined to overload a bolt, already weakened by fatigue. When the bolt failed it shed load to its neighbours which failed in turn and the roof began to collapse.

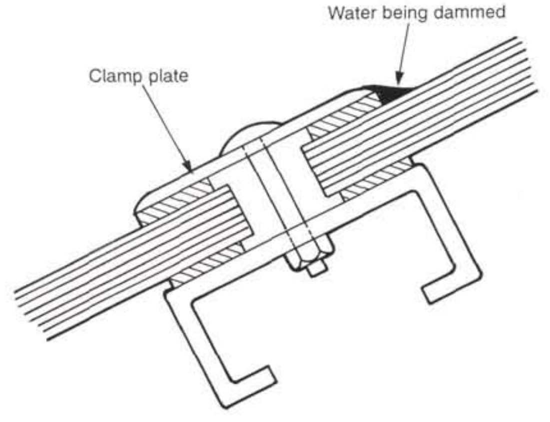


Fig. 2.19 Water being dammed

2.2.5 Fire

When talking of fire resistance it is important to distinguish between integrity (the ability to hold together) and insulation (the ability to resist the passage of heat).

Glass, being incombustible, can be used as a fire protection material. Wired glass was made commercially available at the end of the 19th century as a product that would hold together, thus preventing the spread of smoke and flames. Laminated glasses with intumescent interlayers are now available. With the right framing, both such glasses can provide up to 2hrs fire resistance (i.e. integrity).

The first real alternative to wired glass was borosilicate glass, which has a different chemical composition to ordinary window glass (i.e. soda-lime-silicate glass). Borosilicate glass has been used for many years for ovenware and laboratory glass, thanks to its low coefficient of thermal expansion and its high softening temperature. A modified composition of this glass, heat-strengthened, can provide fire resistance (integrity only) for up to 120 minutes.

An alternative product with very good fire-resistant properties is ceramic glass. Its coefficient of thermal expansion is close to zero and, with the appropriate framing, it can provide up to 240 minutes of integrity-only fire resistance.

It is important to remember that glass on its own is not fire resistant. It needs a frame with the right fire resistance too. Glass products that give full fire resistance (insulation as well as integrity) should be glazed into a frame that also gives insulation, otherwise the whole assembly can be classified for integrity only.

Particular care is required to detail timber frames to support glass when resisting fire. The effect of the charring of the wood must be considered. Steel frames tend to warp when subjected to fire, breaking the glass and causing problems for bead fixing methods. As a result, nearly all steel frames used for fire resistance are proprietary systems, specifically engineered to be more robust than ordinary frames and to have better fixings. Steel is a good conductor of heat, so special designs are required for frames used for full insulation fire resistance. Nolte (1999) reports that harmonising European Standards for fire testing building components has resulted in establishing tougher requirements.

2.2.6 Acoustic behaviour

Glass can be used to reduce outside noise so that the occupants of a building are not unduly disturbed. Achieving this may require thick glass, or laminated glass, or multiple panes. Mass is the most important factor.

To determine what is needed involves defining the external noise level, and the required internal noise level. From these it is possible to calculate the degree of attenuation required. The attenuation provided by glass (or other building materials) is not a constant across all frequencies.

Single panes of glass attenuate noise by using their mass to absorb some of the energy in the sound. Toughened and wired and patterned glass behave the same way. The softer interlayers used in laminated glass give it slightly better acoustic attenuation at some frequencies than the same mass of single glass. Double-glazing generally gives worse attenuation than the same mass of single glass because of resonances in the system. Varying the cavity width between 6mm and 16mm makes little difference but wider cavities can improve performance again.

None of this means anything if air gaps are not sealed effectively.

For more information the reader is referred to

Fig. 2.20 An intumescent interlayer (left) before and (right) after it has done its job (courtesy of Pilkington)

Pilkington (1993) and the draft European Standard prEN 12758-1.

2.2.7 Access

The CDM Regulations (Health and Safety Commission, 1994) require designers and specifiers to have adequate regard to health and safety in their decision-making process.

The structure of this risk management process includes the need for the designer/specifier to adopt a hierarchy of risk control in the following sequence:

- avoid foreseeable risks
- combat risks at source
- give priority to measures that protect all
- provide information about residual risks

Ove Arup & Partners (1997) provides clear guidance for designers on meeting their legal obligations, with sections specifically devoted to glazing.

Access will be needed for installation, cleaning, inspection, maintenance, repair and replacement. Glass will be used in the building envelope, which means that it is very likely that workers will be working at height, and exposed to the wind and the rain.

Significant hazards associated with this are workers falling and workers dropping objects. Glass panes are often surprisingly heavy – a 2m × 3m pane 12mm thick weighs about 1.8kN (approximately 180kgf or 400lbf).

The designer will need to consider the following issues in particular:

- Are there particular access problems for people or materials?
- Will the public need to be protected?
- Will scaffolding be required?

2.2.8 Installation

The designer will need to consider the following issues in particular:

- Has access for installation been considered?
- How much handling of the glass will be required?
    - On/off lorries
    - In/out of storage
    - Up/down the building
- How will the glass be handled?
- Will special handling equipment be needed?
- Will the workers require special protective clothing?
- Will the public need to be protected?
- Will scaffolding be required?
- How are the elements to be lifted?
- How are the elements to be fixed?
- How are the elements to be sealed?
- Can the glazing be prefabricated at ground level and then safely lifted and fixed into place in all locations?
- How is the facade or roof to be tested?

2.2.9 Cleaning

The designer will need to consider the following issues in particular:

- How is safe access for cleaning to be achieved?
- How will windows be opened for cleaning?
- Will size of opening lights limit cleaning options?
- Will permanently installed equipment be provided for the outside of the building and for the underside of atrium roofs?
- How will water be provided for cleaning the glass?
- How will the water be removed from the surface of the glass?

2.2.10 Inspection

The designer will need to consider the following issues in particular:

- What inspection is required?
- What frequency of inspection does the design require or assume?
- How is safe access for inspection to be achieved?

2.2.11 Maintenance

The designer will need to consider the following issues in particular:

- Life to first maintenance
- The use of low maintenance materials
- Will the maintenance/repair company be as knowledgeable as the original designer and installer?
- How is safe access for inspection to be achieved?

2.2.12 Repair and replacement

The designer will need to consider the following issues in particular:

- How is safe access for replacement to be achieved?
- Will the maintenance/repair company be as knowledgeable as the original designer and installer?
- Can elements of the facade or roof be safely dismantled?
- Has access for replacement been considered?
- How much handling of the glass will be required?
    - On/off lorries
    - In/out of storage
    - Up/down the building
- How will the glass be handled?
- Will special handling equipment be needed?
- Will the workers require special protective clothing?
- Will the public or the building's occupiers need to be protected?
- Will scaffolding be required?
- How are the replacement elements to be lifted?
- How are the replacement elements to be fixed?
- How are the replacement elements to be sealed?
- Can the replacement glazing and/or framing be prefabricated at ground level and then safely lifted and fixed into place in all locations?
- How are the replaced areas of facade or roof to be tested?

2.2.13 Availability

Designers are advised to consult one or more reputable manufacturers early in the design process to check on lead times for different types and sizes of glass. Some glass is available ex-stock while other products may be manufactured only once per year.

Special items will almost always have a long lead-time. An example of what can be produced is the 50ft by 8ft pane of 3/8 inch polished plate glass (15.2m × 2.4m × 9.5mm) installed in the Power and Production Pavilion at the Festival of Britain in 1951.

Glass is a sophisticated product that may pass through several hands before it is installed and it is important to be aware of and record the supply chain. When there are problems, traceability is essential. The major glass manufacturers do buy glass from each other, so the company contracted to supply the glass may well not be the company that made it. For example, a piece of glass may be made, cut, drilled, coated, toughened, heat soaked and laminated before being installed.

A reputable toughener will correctly mark the glass to indicate the standard to which it has been toughened, for example to BS 6206, class A, B or C. Glass to be used as safety glass in the UK is required to be permanently marked in a visible location identifying it as safety glass.

Heat soaking is not carried out to the same standard by all manufacturers and is not carried out at all by some. Bordeaux and Kasper (1997) discuss a heat soaking process that is claimed to be a significant improvement on the widely used DIN 18516 Part 4. It is expected that a new European standard will be in place by the year 2000.

2.2.14 Appearance, fit and position

Moor (1997) provides well-illustrated examples of the work of artists making increasingly wide use of new experimental techniques and materials with glass.

Glass is visually important in many modern buildings. The Willis Corroon building (formerly Willis Faber and Dumas) in Ipswich, England (1975; Architect: Foster Associates; Engineer: Anthony Hunt Associates) has walls entirely made of glass, suspended from the roof and stiffened against the wind by glass fins.

The accuracy of fit of the glass and its flatness are crucial to the appearance of the facade.

Glass, like any building component, must fit into the space allocated for it. It must be connected to the surrounding building or to its supporting structural frame in a way that delivers the forces that require resistance while allowing relative movements to occur that the glass cannot tolerate.

Ryan *et al.* (1998) cover this important aspect of glass design in detail.

The 12m high glass walls at the main terminal building at Stansted Airport, England (1991; Architect: Foster Associates; Engineer: Ove Arup & Partners) are supported by structural steel mullions that run from floor to roof and by steel and aluminium transoms that span between mullions. Under extreme environmental conditions, analysis showed that the roof structure might sway by up to 100mm. It was also visually important that the walls not appear to support the edge of the roof, which was then free to move up and down by 100mm. The architect and engineer devised a sliding prop detail that allowed the roof to prop the wall against wind loading but to slide parallel to the wall. It also allowed the roof to rise and fall without bearing on the tops of the mullions.

One surprising consequence of this was that the corner bays of glass warped as the roof swayed.

Aluminium clamps with cover strips and neoprene seals hold the 1.8m tall by 3.6m wide panels of insulating glass. These allow any inaccuracies in manufacturing to be concealed in the overlap, leading to a uniform appearance.

Fig. 2.21 Willis Corroon building (courtesy of Foster & Partners)

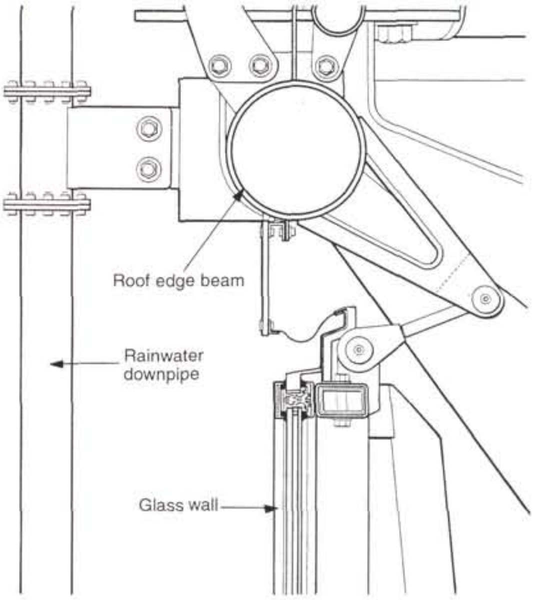


Fig. 2.22 Stansted detail (courtesy Foster & Partners)

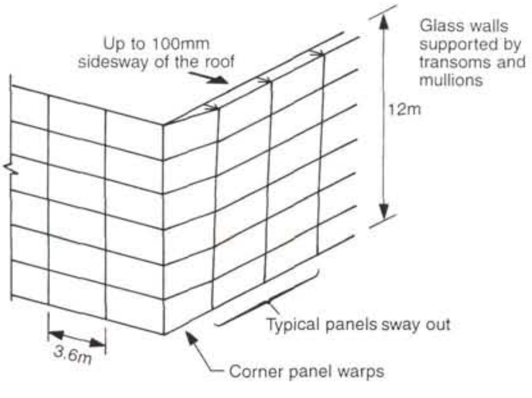


Fig. 2.23 Corner warp at Stansted

In complete contrast to this is the roof of the new Waterloo International Station, London (1994; Architect: Nicholas Grimshaw & Partners; Engineer: Anthony Hunt Associates). The form of the roof was very constrained by the route of the rail tracks and local planning restrictions. This led to a complicated doubly curved area of glass on the northern side of the arched roof.

To avoid the need for thousands of differently sized and shaped pieces of glass, the designers developed a flexible support and jointing system for

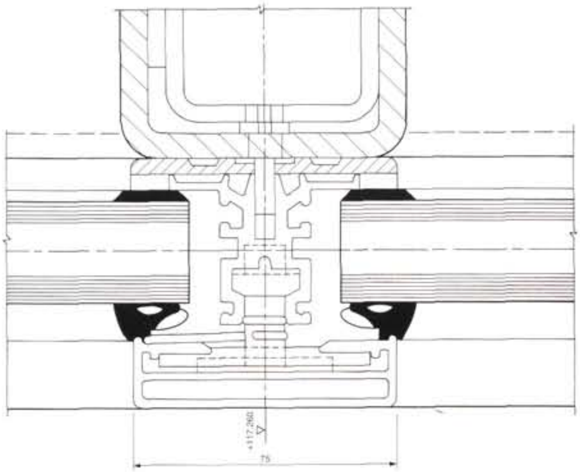


Fig. 2.24 Edge of glass in clamp at Stansted (courtesy Foster & Partners)

Fig. 2.25 Curved roof at Waterloo (courtesy of George Stowell)

Fig. 2.26 Structural attachments at Waterloo (courtesy of Nicholas Grimshaw & Partners Ltd)

the glass. This flexibility also freed the glass from being strained by thermal movements of the main structural frame.

Upper panes overlap lower panes, as in a traditional greenhouse, but with a neoprene sealing lip which contains a tiny channel to collect condensation and hold it until it evaporates and stops wind-blown rain going back up between the panes. The sides of adjacent panes at the same level are connected by a concertina-like neoprene seal, which can accommodate a varying separation between adjacent edges, both in- and out-of-plane. Thus a warping surface was constructed from flat rectangular components.

This flexibility was not achieved without structural penalty. The supporting structure has to provide considerable adjustment in the location and rotation of the points of attachment. The designers developed a very elegant system of articulated connection pieces, some of which were site-welded to the main roof trusses, but the cost was high and the degrees of freedom provided made it possible to install panes of glass out of their desired locations.

In complete contrast again, and a direct design descendant of Willis Corroon, are the many Planar-supported glass facades on buildings all around the world. The Planar system was developed by Pilkington Glass and an early example is the Renault building, Swindon, England (1982; Architect: Foster Associates; Engineer: Ove Arup & Partners). It is shown in Fig. 9.1. The feature of significance to this section of the *Guide* is the silicone seal between adjacent panes of glass. Unless the glass is manufactured accurately and installed accurately, the nominally 10 or 12 or 15mm wide seals will vary in width unacceptably.

In Germany, Schlaich has developed a method of generating doubly curved geometries that can be tiled with parallel-sided panes of glass.

The Glass and Glazing Federation's *Glazing Manual* contains guidance on the manufacture of

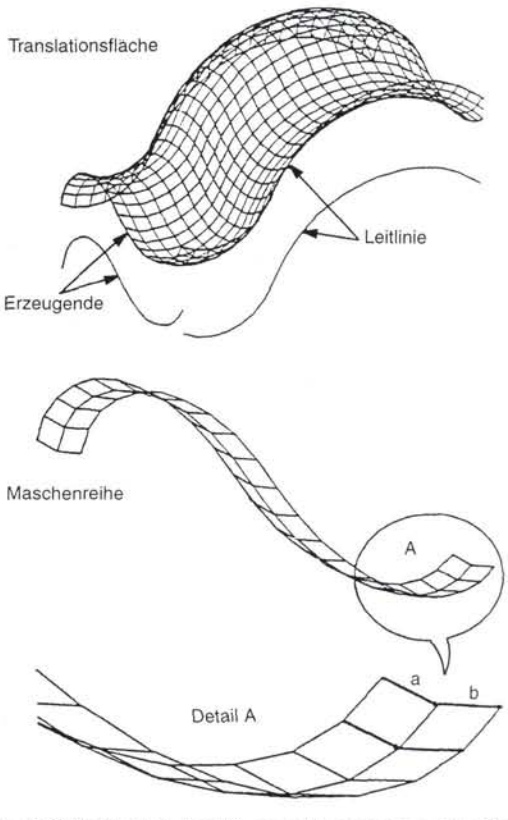


Fig. 2.27 Schlaich's doubly-curved geometry generation

curved glass. Car windscreens are advanced examples of what is possible (Pennells, 1997 and Matsushita, 1997).

2.2.15 Durability

Glass is extremely durable. The oldest finds of glass date from 10,000 BC in Egypt and some are still in good condition. Appendix A provides more information about the history of glass.

As chart 18 shows, glass has excellent resistance to the following:

- salt water
- strong acids
- organic solvents
- ultra-violet radiation
- aerated water

It has poor resistance to strong alkalis.

Borosilicate glass (any silicate glass having at least 5% of boron oxide (B_2O_3)) is widely used for applications in which resistance to heat is important, such as oven dishes and laboratory glassware.

Glass can be abraded and it is common for the surfaces of glass panes to be sand- or grit-blasted before subjecting them to strength tests. This is intended to achieve a controlled surface defect condition.

The glass pyramid at the Louvre Museum in Paris (1988; Architect: I. M. Pei; Engineer: RFR) contains 10mm-thick clear white glass which was poured, then ground and polished to achieve as perfect a plane as possible with the maximum transparency and the minimum reflectivity. The glass was made very accurately and the structural details reflect this.

There are applications, such as glass floors or glass treads for stairs, in which it is desirable to abrade the surface of the glass so that subsequent abrasion by foot traffic will not result in further changes to the appearance of the glass. The right kind of abrasion can also make the glass less slippery and hence safer to tread on, as is shown in Chapter 13. Toughened glass should not be abraded, in case the process causes flaws that penetrate the surface compressive layer of the glass.

2.2.16 Environmental impact

There is growing awareness of the need to reduce and reverse the environmental damage that our species is causing through its use of technology.

This requires processes that are less toxic and products that are easier to recycle, lighter and less energy-intensive. Concern about environmental friendliness must be injected into the design process, taking a lifecycle view of the product that includes manufacture, distribution, use and final disposal.

All materials use energy, which is used to mine, refine, fire and shape. When we use energy we use the outputs of a power generating process which produces pollutants: waste heat, CO_2, oxides of nitrogen, sulphur compounds and dust. One of the environmental advantages of glass is that it can be recycled. As was mentioned earlier, cullet is an essential ingredient in the manufacture of float glass. Witte (1997) describes how architectural and automotive glass is recycled in Europe, with particular reference to Germany. He identifies two plants in the UK which recycle flat glass.

The use of glass in the envelope of a building will also influence its energy consumption. The change can be quite surprising to those who have not been through the argument before.

A glass facade will not be as good an insulator as, for example, a well-insulated cavity wall made of brick and block. On the other hand, a glass wall will allow natural daylight to replace electric light for part of the year. It may also be the case that the internal heat gains (those generated by the occupants of the building and all their plant or equipment such as computers and printers) exceed the heat losses through the comparatively poorly insulated glass facade. In such an instance, to over-insulate the wall would increase the demand for cooling plant to remove unwanted heat from the building, at further energy cost.

If the glass facade is on the southern elevation of

Table 2.4 A comparison of the energy content (also known as embodied energy) of glass with other well-known materials (Source: Ashby (1997))

Material	Energy content	Energy content
	MJ/kg	GJ/m^3
Cast irons	60-260	468-1500
Aluminium and alloys	290-305	754-884
Stainless steels	110-120	825-972
Carbon steels	50-60	390-468
Polypropylene	108-113	95-102
Polystyrene	96-140	96-154
Glass	**13-23**	**32-57**
Bone china	270	540-580
Bricks	3.4-6	6.8-12
Concrete	3-6	7-15
GFRP	90-120	160-220
Wood	1.8-4.0	1.2-3.6
Reinforced concrete	8-20	20-50

the building (in the northern hemisphere) then the designers will also need to prevent unwanted solar gain during the summer. External shading is a commonly used technique, as at Building B6 at Stockley Park, near London (1990; Architect: Ian Ritchie Architects; Engineer: Ove Arup & Partners).

2.2.17 Life cycle costing

Life Cycle Management aims to match the life and performance attributes of the procured item to the requirement defined by the client, or defined by the designers in conjunction with the client as part of the development of the brief.

The item under consideration should be selected on a least cost basis including the costs of any provisions for safe maintenance. Where the life of the item is less than the intended life of the building, the design should make suitable provision for easy and safe removal and replacement.

Design life should be categorised as follows:

- Replaceable: having a shorter life than that intended for the building, with replacement planned at the design stage, with the owner operating the intended maintenance and life-cycle management regime.
- Maintainable: will last as long as the intended life of the building with periodic treatment and minor repairs, provided that a proper inspection and maintenance regime is carried out over the full life of the building.
- Lifelong: will last as long as the building, with minimal or no maintenance.

It is worth remembering that:

- Usage of parts of the building cannot be foreseen, and the designer has no control over this.
- Products at the leading edge of technology are unlikely to have a history on which to found a sound prediction.
- Large assemblies of components may introduce interactions that reduce the life of individual parts.

Cladding items such as sealants and sealed units (i.e. double-glazing) are likely to fall into the replaceable category.

If glass is to be used structurally then access for replacement in case of damage will be needed. This is analogous to the access needed for inspection and replacement of bridge bearings.

2.3 Behaviour of other materials often used with glass

Designers should take care when choosing materials to be used with glass. This is not simply because of possible incompatibilities in intrinsic properties of the base materials such as the coefficient of thermal expansion. It is also because of the coatings used with materials which may be incompatible or which may need maintenance that is difficult to carry out without harming the glass or its coatings in some way. Examples are shown in Table 2.5.

A simple question might be: 'will my chosen adhesive stick to my chosen low emissivity coating?' A material that has some desirable properties may also have some undesirable ones and the reader should investigate carefully.

Table 2.6 gives the properties of some materials used in contact with glass and some materials used instead of glass.

Table 2.5 Coatings used with materials

Material	Coatings
Timber	Preservatives, paints and stains
Steel	Paints, polyester powder coating, galvanising
Aluminium	Anodising, polyester powder coating
Glass	Hard and soft solar control coatings, low emissivity coatings, fritting, acid etching, screen printing, adhesive films, coloured ceramic coatings

2.4 Fabrication

Most manufacturers have said that they can cut annealed glass to the following accuracy:

- Length ± 2 to 4mm
- Squareness (difference in length between diagonals of a rectangle) ±2 to 4mm

Because glass is produced by a process that involves rollers, the surface of a pane of glass is not completely flat. It may have surface waves with and amplitude of 0.7 to 1.0mm.

The thickness of a pane of float glass manufactured to BS EN 572-2 can vary as shown in Table 2.7.

In particular it should be noted that flat glass manufactured to conform with US Standard ASTM C1036-91 may be thinner than flat glass of the same nominal thickness manufactured to conform with UK standards.

Holes can be drilled to the following accuracy:

- Diameter: ± 0.5mm
- Distance between centres of holes: ± 0.5mm to 2mm

Computer-controlled cutters can achieve ± 0.5mm, which is the accuracy needed for the positioning of countersunk holes.

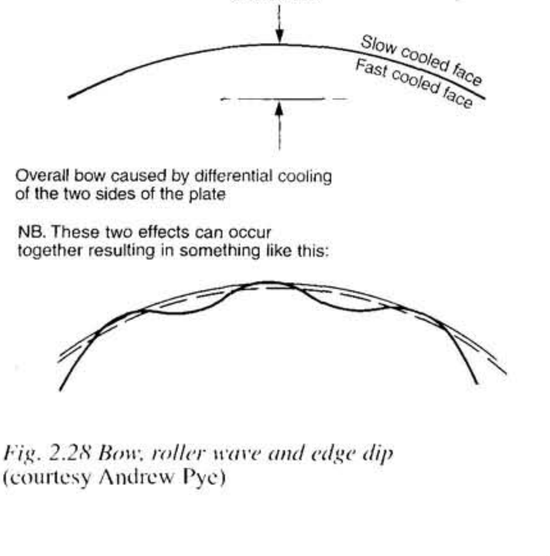


Fig. 2.28 Bow, roller wave and edge dip (courtesy Andrew Pye)

Table 2.6 Some typical material properties

Material	Young's Modulus (kN/mm^2)	Yield strength/ ultimate tensile strength (N/mm^2)	Hardness MoH/Brinell/ Other	Coefficient of thermal expansion ($\times 10^{-6}$/K)	Resistance to attack by six common environments	Remarks
Glass	70	3600/5000	4.5-6.5	7.7-8.8	See chart 18	Fracture governs, not yield or tensile strength
Mild steel (BS 5950) Grades S275 to S355	205	275-355 yield strength	4-5/130 (not relevant to metals)	12	See chart 18	Corrosion protection may be needed. Weld spatter will damage glass. Fire protection may be needed for structural steel
Austenitic stainless steel (BS 5950) Grades 316 and 304	190-200	190/490-690	6.5 as above	16.5 Grade 316 17 Grade 304	See chart 18	Swimming pools require careful selection of the correct grades of stainless steel
Aluminium alloy (BS 8118)	70	Typical extrusion, 5000 series 130/275	2-3/27-80	23	See chart 18	Corrosion protection may be needed
Softwood: Parallel to grain Perpendicular	10-16 0.4-1.3	UTS 100-140 3-4	Janka Hardness - 2000-3000	3.5 24-45	See chart 18	Some timbers fall outside these ranges. Inherently variable material. These results are for small clears with 9-12% moisture content. Properties dependent on: • Defects (knots, grain straightness, etc) • Moisture content • Duration of load • Use BS5268 Part 2 for characteristic stresses which account for natural variations
Hardwood: Parallel to grain Perpendicular	10-16 0.4-1.3	UTS Can't measure 10-12	Janka Hardness - 1910-10450	3.6 32-39	See chart 18	
Plasticised PVC setting blocks	0.01	15	74-80 IHRD, to BS 903, Part A26	150	See chart 18	Sealed hardwood such as teak or mahogany has traditionally been used
Neoprene setting blocks	0.7-20 (at 100% elongation)	3.5-24 for all neoprenes	Shore A hardness 80-90, to BS 2782, Part 3, Method 365B		See chart 18	Geometry can be as important as material properties
Vulcanised fibre gaskets						This is an electrical product, defined by the withdrawn BS2768
Nylon bushes	1.5-3.8	55/70		80-100	See chart 18	
Polycarbonate	2.5	60/70		70	See chart 18	
ETFE film	1.3-1.6	30-35/40-46		110-170	See chart 18	Rapid loss of strength with elevated temperature
Silicone	0.1-1.0 UTS/ strain at failure	0.5-1.3 UTS	17-50 Shore A Durometer	Not measured	Generally inert and resistant to all chemicals likely to be encountered in a construction application. However they may be attacked by concentrated acids, some solvents and some oils, depending on the duration and temperature of the contact	

Table 2.7 Variations in thickness of float glass manufactured to BS EN 572-2

Nominal thickness	Tolerance
2 to 6mm	± 0.2mm
8 to 12mm	± 0.3mm
15mm	± 0.5mm
19mm and 25mm	± 1.0mm

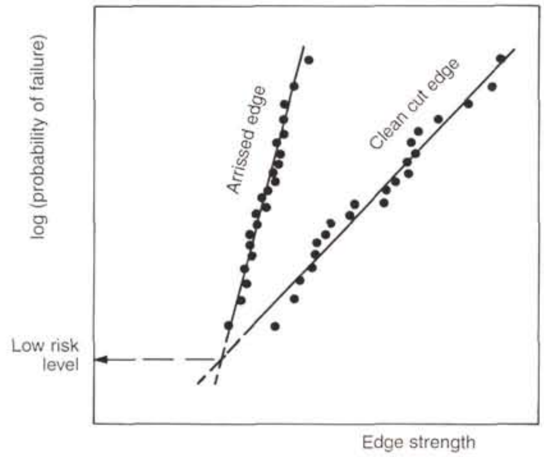


Fig. 2.29 Comparison of the strength of arrissed edges and clean cut edges (reproduced from *Glass in Buildings*, eds. Button & Pye, by permission of Butterworth-Heinemann)

Bow and warp of annealed float glass is rarely, if ever, a problem.

The thermal toughening process introduces bow, roller wave and edge dip, which are shown in Fig 2.28.

Toughened glass can be produced with the following flatness: bow: ± 3mm/m along edges and diagonals.

Vertically toughened or heat-strengthened glass may also have tong marks resembling small dimples close to one edge.

You get what you pay for: accuracy is a function of cost.

Ryan *et al.* (1998) discuss the interfaces between steel and glazing in buildings. Glass may be attached to steel, aluminium, timber, concrete, brick and other materials. The normal accuracy of manufacture of the glass may be significantly better than the installed accuracy of the materials it must interface with, so it may not be worthwhile to demand extraordinary accuracy of manufacture of the glass. On the other hand, fine accuracy may be needed visually for alignment.

A common complaint of contractors is the unnecessarily high accuracy often called for by designers and specifiers. This may well have implications for safety on site if, for example, it increases the time that people must spend high off the ground.

Fig. 2.30 Inverted Louvre pyramid (courtesy RFR)

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Fig. 2.31 Building B8 at Stockley Park, showing its external sunshades (courtesy Ian Ritchie Architects)

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3 Design requirements

3.1 Introduction

This chapter draws heavily on Arup Research and Development (1993)

It is assumed that the designer/specifier (on behalf of the client) must always make the design decisions specific to the contract. This chapter provides notes that the designer may wish to consider.

The development of the client's brief, the design requirements and their detailed description in terms of constraints and requirements rest on judgments by the designer in discussion with the client, users and others. For a particular contract there may be other factors that cannot be foreseen here and the designers will need to incorporate them into this analysis.

Designers will have their own ways of describing and initiating design requirements. In this section two distinct descriptions of requirements arising from the brief — constraints and targets – use the same headings. Some can be expressed numerically either for or by the designer. Some can be expressed only qualitatively but nonetheless should be as explicit as possible. It is against such descriptions that the intermediate and eventual design decisions are best assessed.

Constraints
These are externally imposed limitations or requirements which, at least in the short term, the designer cannot change. The most obvious are those imposed by national building regulations and other legislation.

Targets
These are the requirements set by the designer, either in response to the constraints or even where constraints have not been defined. They may exceed the constraints, for example where better insulation is provided than that required by national building regulations. Targets may change, and certainly more often than constraints.

The requirement headings
The headings used are:

- Client's programme and budget
- Form and function
- Context
- Structure
- Climate control
- Internal environmental control
- Durability and working life (including maintenance and repair)
- Health and safety
- Environmental impact
- Security
- Construction method
- Design process
- Site processes
- Contract administration

3.2 Client's programme and budget

This heading covers those considerations that are entirely a consequence of specific client requirements. These may include items in the following paragraphs.

Type of work
New build, repairs and maintenance, refurbishment or replacement

Contract programme
For a roof or a facade, programme is likely to be a significant constraint on a designer's choices.

Sequencing
Some areas of the building may need to be watertight while still accepting the presence of following trades, which could damage completed work.

Budget
There will be several ways in which budget constraints may be placed on a roof or facade, such as:

- as part of an elemental cost plan
- as a specific budget limit
- constraints on particular parts of the roof and/or facade
- via value engineering trade-offs between roof, facade and other elements
- part of a life-cycle costing exercise
- part of a general policy for maintenance budgeting

Existing design decisions
By the time the design of a roof or facade is approached in detail other design decisions may limit the choices available to the designer.

Preferred systems and materials
Some clients have strong views about particular systems, perhaps influenced by earlier problems or by the views of their maintenance staff. This may raise CDM issues of design responsibility.

Some clients may wish to limit the use of certain materials for ethical reasons or because of consideration of their neighbours.

Building occupation
Where works are to be carried out adjacent to or above an occupied part of a building, the designers have a CDM duty to the occupiers and the public (see sections 2.2.7 and 2.2.8).

Quality management regime
This may significantly affect the provision of information and the checking procedures.

3.3 Form and function

This heading covers issues relating to the shape and appearance of a facade or roof or other glass elements and their relationship to the function/purpose of the building.

Appearance
Clients may not be aware of the eventual visual impact of services penetrations, plant, attachments, communications hardware, access gantries, window-cleaning platforms, rainwater disposal, solar shading and lightning protection which may be visible through a roof or facade.

Geometry/configuration
There may be constraints because of planning requirements:

- depth of plan of the building
- overhead restrictions
- perimeter conditions
- client's corporate image

- location of points of support
- location of service penetrations
- the need to avoid intruding on protected views
- rights of light
- lightning protection
- security

Targets will have to be set for:

- response to local or site features
- consequences of internal or functional requirements (e.g. the need for privacy or for visual/acoustic isolation)
- buildability
- energy consumption
- influence of building on local micro climate
- control of sunlight penetration
- control of rainwater runoff

Roof and facade zones and penetrations
The designers will need to define:

- the depths of the roof and facade zones (which may vary across the building)
- allowable movements of the roof and facade (both in- and out-of-plane)
- location of movement joints
- the number and type of penetrations
- discharges from services

Access/traffic
Considerations will include structural loadings, abrasion, durability, and safety. For example, will the roof ever be used as a terrace for assembly of people or as a means of escape? (See section 2.2.7.)

3.4 Context

This heading covers local factors that are not a consequence of the client's brief.

Local climate
Rainfall, wind, exposure

Nature of the site
Views, local planting (may affect drainage), adjacent buildings

Appearance
Local planning requirements

Local environment
Air pollution, ground pollution, fauna (birds which eat silicone seals!)

Administrative systems
Legal constraints such as planning requirements, easements, party wall arrangements or rights of light, and land ownership issues

3.5 Structure

This heading covers all aspects of structural performance, both by the primary structure and by other components and elements.

Loadings
Dead loads, imposed loads, wind loads, seismic loads (even in the UK in certain circumstances). Annealed glass is weaker for long-term loads than for short-term loads. Whether a pane of glass is horizontal or vertical can make a significant difference.

Deflections
The deflection of the primary structure may be limited by the relevant codes. The deflection of the facade or roof may be limited by other factors, such as watertightness, control of ponding, or the acceptable strain in flexible sealants (see section 2.2.4).

Movements
Glass facades and roofs may bridge between elements of the primary structure that are separated by movement joints or they may abut elements of structure that move significantly. A glass facade or roof may be very stiff in its own plane and intolerant of imposed movements. Early consideration of how movements are to be accommodated may significantly influence decisions about support for glass.

3.6 Climate control

This heading covers the general implications of climate.

Sun
Solar radiation affects a building's heat balance; strong sun and shade can induce high stresses in a single pane.

Wind
Wind uplift can be particularly high at the edges of roofs; outward wind pressures can be high at the corners of walls; movements of glass can be disturbing to the occupants.

Rain, hail and snow
The exclusion and disposal of water is a dominant issue in flat roof design; the build-up of snow loads at changes in geometry can be significant structurally.

3.7 Internal environmental control

This heading covers the principal parameters of a building's internal environment and their relationship to the design of roof and facade.

Humidity & condensation
Unless a building is air-conditioned, its internal relative humidity will be determined by external conditions, internal temperatures and any internal functions which generate water vapour.

Acoustical control
The acoustical environment will be determined mostly by the arrangement of internal volumes, their surface absorptions, and the insulation of internal divisions. Roofs and facades may be required to contribute to preventing noise from outside breaking in or noise from inside breaking out.

Lighting control
Natural daylighting through a roof or facade can be a real benefit to the building's occupants but the designers need to be aware of the risks of too much light, high contrast and glare. Careful co-ordination with artificial lighting is required. External and/or internal shading of some form may also be required.

Special internal environments
In some cases the internal environment required may imply severe constraints, such as:

- unusual levels of relative humidity

- intolerance of noise intrusion
- particular control of air intakes
- natural light required across a deep plan

3.8 Durability and working life (see section 2.2.15)

This heading covers the performance of a roof or facade or other glass elements over the building's life. Particular considerations include:

Maintenance

- Can the roof and facade be accessed easily? (See section 2.2.7)
- Is detailed inspection easy? (See section 2.2.10)
- Is any pattern of staining likely?
- Does the detailing allow easy component replacement? (See section 2.2.12)
- Is the design resistant to vandalism?

Planned maintenance
See section 2.2.11 and Chapter 17.

3.9 Health and safety

CDM
The CDM Regulations (HSC, 1995) require designers to consider the health and safety of the construction workforce and those affected by construction work. The CDM definition of construction is a broad one and it includes maintenance, cleaning, repair, replacement and eventual demolition.

Fire
The principal aspects are:

- fire resistance, including the protection of means of escape
- flame spread
- combustible materials

See also section 2.2.5.

Lightning protection
Needs to be considered early if it not to spoil the appearance of the glass.

3.10 Environmental impact (see section 2.2.16)

Much more attention is being paid these days to the environmental impact of materials used in buildings. Potential constraints or targets include:

Excluded materials
Often clients will want certain materials excluded. Designers may also wish to check if products are harmful to the environment, even if not prohibited by current legislation. This consideration could extend to products needed to clean a glass roof or facade. Advice on good practice in the selection of materials in construction may be found in Sheehan (1997).

Non-renewable materials
Glass is definitely a renewable material but the designer may wish to check the other materials that make up the facade or roof.

Embodied energy and energy consumption
See section 2.2.16.

3.11 Security

This covers the following items:

- control of entry
- resistance to vandalism.

3.12 Construction method

This heading covers how the roof or facade or other glass elements are to be installed, which may have significant implications for how they are designed. Particular issues include:

Reference to suppliers and manufacturers
There are specialists with considerable experience in installing large areas of glass; some offer a design service as well, perhaps linked to the use of proprietary products and systems.

Dimensions
Considerations include:

- dimensional co-ordination
- tolerance and fit
- general movements of the primary frame and of the facade and/or roof system
- designed movement joints

Particular guidance may be found in Ryan *et al.* (1998)

Buildability
This means taking account of site factors and site processes. The designer may be able to take advantage of the special skills of a specialist installer.

3.13 Design process

How the design process is organised can affect the design choices, for three main reasons:

- Division of design responsibilities – how much will be left to the sub-contractor?
- Extent of research – the extent to which designers research roof and facade systems depends on the particular contract and on their familiarity with appropriate systems.
- Contract programme – the allocation of time and resources to the many tasks needed may well be made in the context of early assessments of potential solutions.

3.14 Site processes

Designers should consider, when developing the scheme design, factors such as:

- Access – onto the site, across the site, up the building
- Storage – inadequate storage space may adversely affect the quality of what is built
- Off-site work – prefabrication under controlled conditions is likely to produce better quality more safely than assembling pieces high off the ground in the wind and the rain.
- Availability – the availability of labour and/or

materials may affect design choices.

- Health and safety – designers must always consider the health and safety of the construction workforce and of those affected by the activities of the construction workforce.

3.15 Contract administration (See Chapter 17)

The administration of the contract can affect the balance of decision between design choices, for example:

Procurement
How the work is bought can affect design choices:

- the use of nominated suppliers
- tendering procedures and criteria for acceptance
- warranties and guarantees
- the requirement of site labour of a particular quality
- form of specification (performance or materials and workmanship)

Type of contract
Latham (1994) contains a good summary of the main features of the different forms of contract commonly used in the UK construction industry, providing a starting point for a more detailed review.

3.16 References and other suggested reading

Arup Research and Development: *Flat roofing: Design and good practice*. CIRIA/BFRC, 1993

Construction Industry Advisory Committee (1995): *Designing for health and safety in construction: a guide for designers to the Construction (Design and Management) Regulations*. HSE Books, 1995.

Health and Safety Commission (1995): *Managing construction for health and safety: Construction (Design and Management) Regulations* 1994: approved code of practice. HSE Books.

Latham, Sir Michael (1994): *Constructing the Team*. HMSO, July 1994

Ryan, P., Otlet, M., and Ogden, R. G. (1998): *Steel supported glazing systems*. SCI Publication 193

Sheehan, A. (1997): *Good practice in the selection of construction materials*. British Council for Offices and British Property Federation

See Appendix B for UK national building regulations.

4 Design selection

4.1 General approach

The purpose of design selection is to arrive at a description of the roof or facade or other glass element, either as a performance specification or in terms of materials, workmanship and details.

Roofs and facades are defined in terms of the following principal items:

- Dimensions and geometry
- Structure (including roof falls)
- Drainage system
- Thermal insulation
- Solar control
- Acoustical control
- Health and safety
- Details, joints and junctions

Other glass elements may be defined more simply, because they are not part of the envelope of the building.

For an extensive selection of modern design of glass in buildings the reader is referred to:

- *The Architectural Review*, May 1998
- *Detail Zeitschitt für Architektor and Baudetail*, April/May 1998 (in German, with summaries in English)
- Krewinkel (1998)

4.2 Gravity system

4.2.1 Facade

The designers are immediately faced with a fundamental decision, that of how best to support the glass. It is not a decision that can be taken in isolation of other decisions that must be taken, such as how the facade resists lateral loads, how it copes with damage and how it accommodates movements. For simplicity of description however, this section will concentrate on the different ways that gravity can be resisted.

Many modern glass facades are suspended. Examples include:

- the Serres at La Villette in Paris (1986; Architect/Engineer: RFR)
- the NCM Building in Cardiff (1995; Architect: Holder Mathias Alcock with Nicholas Hare; Engineer: Ove Arup & Partners)
- the Kempinski Hotel at Munich Airport (1993; Architect: Helmut Jahn; Engineer: Schlaich Bergermann & Partner)
- the Centro de Arte Reina Sofia in Madrid (1992; Architect Ian Ritchie Architects; Engineer Ove Arup & Partners)

At La Villette, the glass is suspended in vertical rows of four panes, one above the other, each connected to the other by connection pieces at their corners. The upper pane of each vertical row is hung from the main frame at the centre of its top edge. With this central suspension point, the glass is able to find its own balance and to hang perfectly vertical, irrespective of the straightness or deflection of the support tube. Deflection of the support structure can be the main problem with two point fixings.

Each pane of glass is suspended from the one directly above by two-hole connections which:

- fix the distance between the horizontal edges of the panes so that the joints are of even width
- articulate so that they can rotate sideways to ensure that they cannot attract lateral load.

Fig. 4.1 *The Serres at La Villette* (courtesy of RFR)

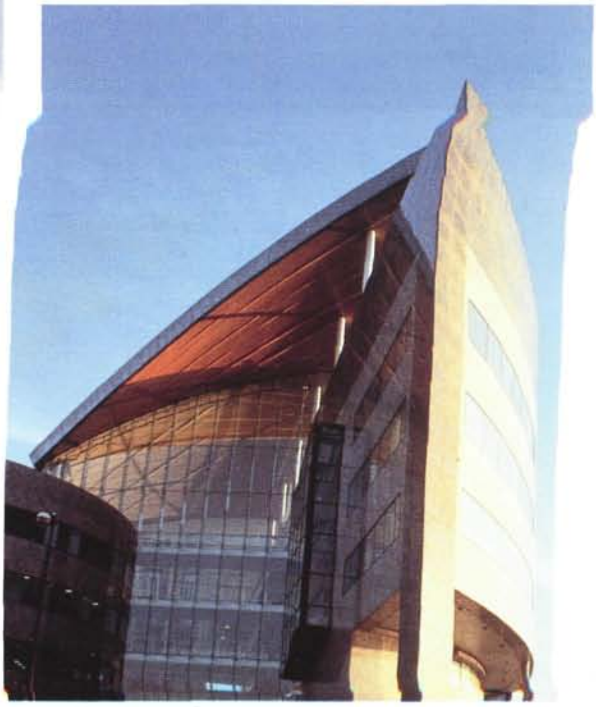


Fig. 4.2 NCM headquarters, Cardiff (courtesy of M. B. P.)

Fig. 4.3 The Kempinski Hotel (courtesy Schlaich Bergermann)

Fig. 4.4 The Centro de Arte Reina Sofia in Madrid (courtesy of Ove Arup & Partners/Peter Mackinven)

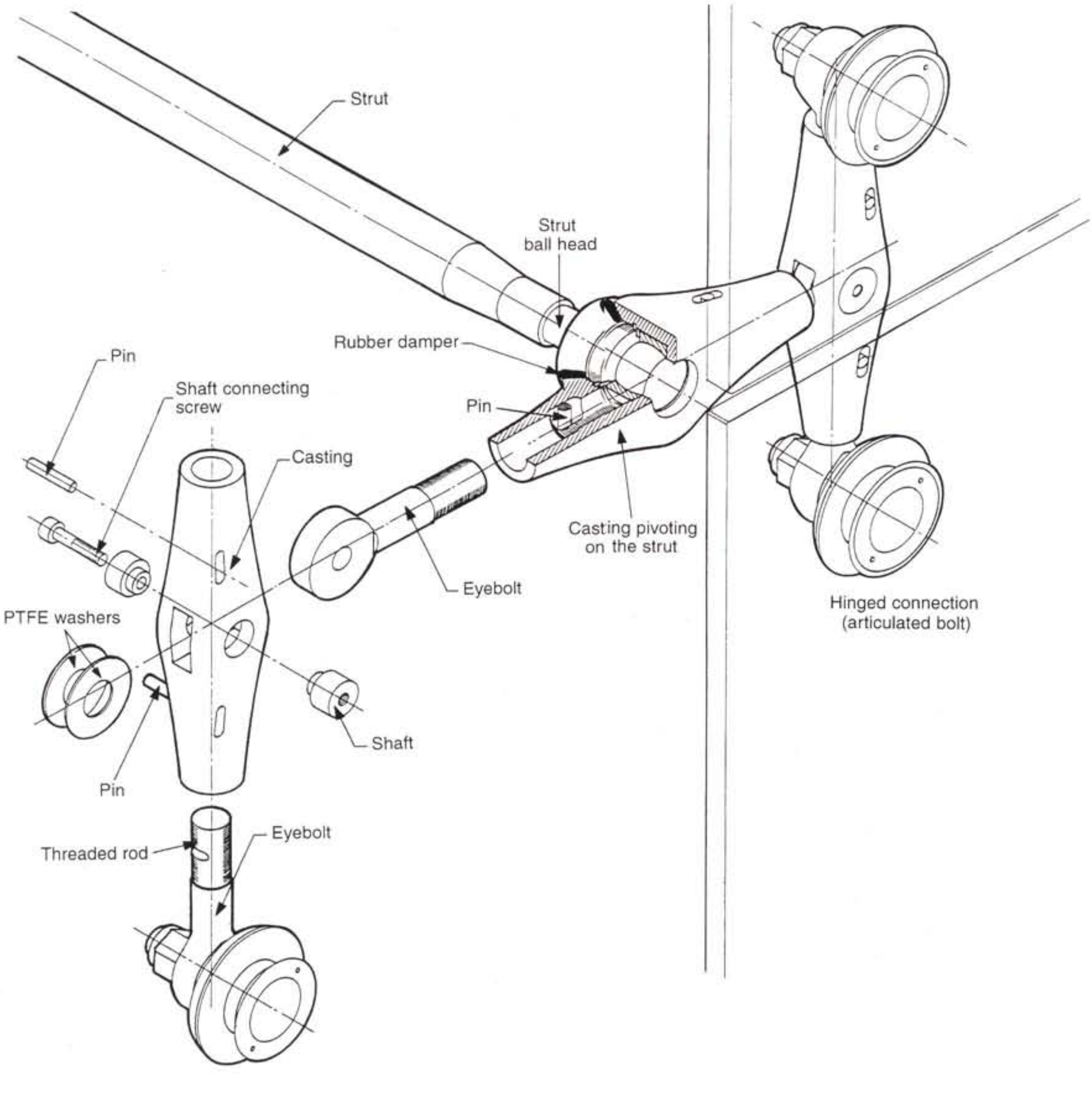


Fig. 4.5 Glass to glass connections at La Villette (reproduced by permission of E & F N Spon from *Structural glass* – Rice & Dutton (eds.))

Fig. 4.6 Movements of main frame of NCM Building relative to the glass wall

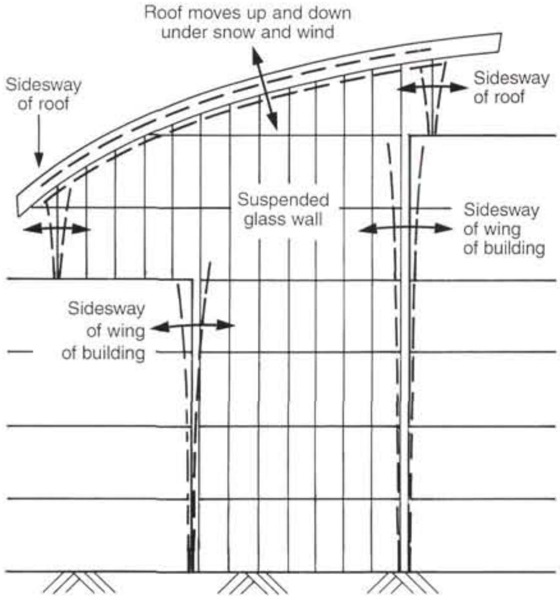
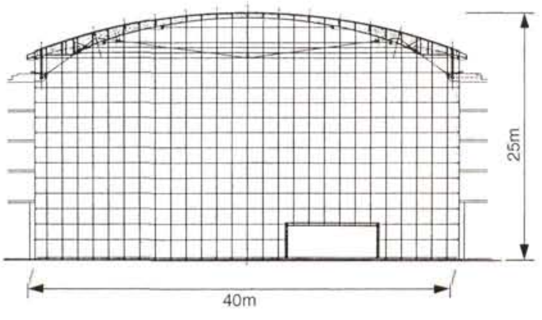


Fig. 4.7 Cable net structure at Kempinski Hotel (courtesy Schlaich Bergermann)



The disadvantages of supporting the upper panes by a single central bolt are that they are more highly loaded than with two bolts and that two bolts provide better redundancy than one. The detailing at La Villette provided a large adjustment capacity for out of tolerance glass. Later projects, such as the Louvre Pyramid, have details that rely on greater accuracy in the manufacture of the glass.

At the NCM Building, each pane of glass is connected to vertical fins of glass which are suspended from the roof structure. The vertical fins are made of sections 4m long that are bolted together via stainless steel plates. Pilkington's patented Planar connections attach the double-glazed panes to the plates. At its tallest point the glass facade is 35m tall.

The decision to suspend such a height of glass was taken after considering how best to ensure that the movements of the main building frame did not affect the glass.

The glass wall at the Kempinski Hotel is supported by a tennis racket structure of horizontal and vertical cables. Panes of glass 1.5m square are attached at their corners to the intersections of the cables. The horizontal cables are prestressed to 85kN each and the vertical cables much less.

It was considered inappropriate to prestress the vertical cables as much as the horizontal because they are suspended from an arched girder that spans 40m between the wings of the hotel. The vertical cables carry the weight of the 10mm-thick glass panels.

At Reina Sofia, glass towers 35m tall enclose lifts and stairs. Each pane of glass is carried on its own central support arm with a balancing downward load carried in the tie-down rod.

The loads from these support arms accumulate along the length of the rods to maxima at the top of the support rod and the bottom of the tie-down rod. In order to minimise the effects of temperature causing differential movements between adjacent vertical chains of glass panels, the designers chose to anchor the tie-down at the top and provide a spring at the bottom

This did not limit movements enough, so two different stainless steels, with different coefficients of thermal expansion, were used for the support rod and the hanger. For more detailed information section 4.8 lists two papers, one by the architect and one by the engineer, which describe the glass towers and the design process.

If a facade is not suspended then it is probably supported from below. Support can come from a steel or aluminium framework, such as at Stansted Airport. In such a case the critical issues for the glass are resistance to lateral load and dealing with movements imposed by the deflections of the frame, rather than gravity. Of more immediate interest are those facades in which the glass itself resists gravity. This would, on the face of it, appear to be a sensible approach because the long-term gravity load is resisted by compression. However, buckling of thin panes or fins can become a design constraint, particularly when gravity and bending combine to produce large compressive stresses.

In the 1980s and 1990s the engineer Roland Hill designed a number of glass squash courts. These

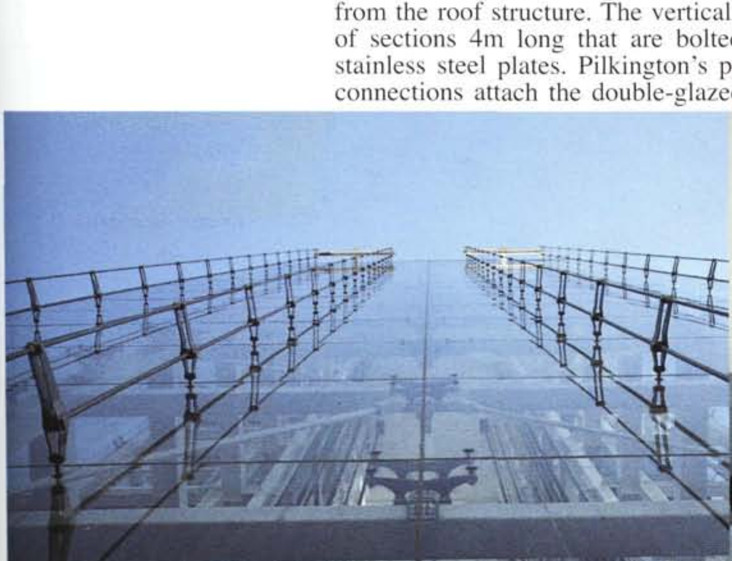


Fig. 4.8 Reina Sofia glass support structure (courtesy of Ove Arup & Partners/Bruce Gibbons)

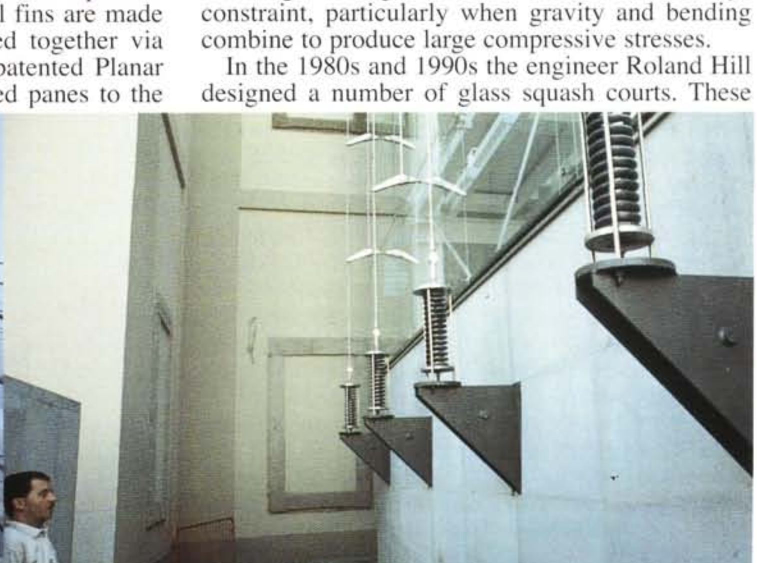


Fig. 4.9 Springs at Reina Sofia (courtesy of Ove Arup & Partners/Bruce Gibbons)

used base-supported glass up to 4.5m tall, with the panes held by base steel supporting angles with fibre gaskets to prevent any glass to metal contact. Glass fins provide out-of-plane stability.

In 1994 the same engineer designed a 6m-tall glass tower sculpture for the opening of the Channel Tunnel. It is 1350mm × 1350mm square on plan and 6m tall, with one lift of glass of 4150mm and another of 1350mm. An internal diagonal glass pane is provided for redundancy, in case of damage.

At St Donat's Arts Centre in South Wales (1997; Architect: Loyn & Co.; Engineer: Ove Arup & Partners) double glazed panels are bolted via Pilkington's Planar fixings to vertical glass fins up to 4.5m tall (Marshall, 1997).

The fins rest in steel channels bolted to the concrete slab. The crucial issues for the fins were lateral load and resistance to buckling. The final fin dimensions were established by considering permissible deviations in the positions of the concrete floor and steel roof, as well as dead load deflections of the floor and roof before the glass was installed and live load deflections afterwards.

At a small elegant conservatory in London (Architect: Bere Associates; Engineer: Campion & Partners) the 2.1m-tall 12mm toughened glass walls are base-supported. Lateral restraint for the walls and gravity support for the glass roof beams comes from ingenious columns made of stacked glass castings. Threaded through the castings, which are usually used as isolators for high voltage cables on electricity pylons, is a 20mm diameter stainless steel tie rod.

The entrance canopy to KP Foods at Billingham, Teeside (Dawson, 1995), is a shallow 'V' shape, made of stainless steel and glass, supported at each end on three free-standing glass panes arranged in a 'T' (1995; Architect: Studio BAAD; Engineer: Techniker). These panes provide both gravity support and lateral stability. Each pane is 2.1m high by 1.425m wide and is a laminate of 2 sheets of 10mm toughened glass with a 3mm cold-poured resin interlayer. The connection between canopy and glass involved thin stainless steel fins that were UV bonded into the 3mm gap between the laminated glass panes.

4.2.2 Roof

As with the facade, the designers are immediately faced with a fundamental decision, that of how best to support the glass. Again, it is not a decision that can be taken in isolation of other decisions that must be taken, such as how the roof copes with damage and how it accommodates movements. For simplicity of description however, this section will concentrate on the different ways that gravity can be resisted.

One fundamental difference between horizontal (or sloping) and vertical glazing is that horizontal glazing is subjected to permanent gravity loads from its self-weight and, possibly, to long-term gravity loads from snow. Codes of practice in the UK and elsewhere have addressed this either by factoring up the long-term or permanent loads or by factoring down the glass strength. This makes sense when considering annealed glass but is questionable when it comes to toughened glass. The properties of toughened glass are not time-dependent, as long as the precompression is not overcome.

Glass roofs are more susceptible to impact from falling objects than glass facades. Broken glass in a roof is more likely to fall on people than broken glass in a facade. Because the glass may be more nearly perpendicular to the sun's rays than facade

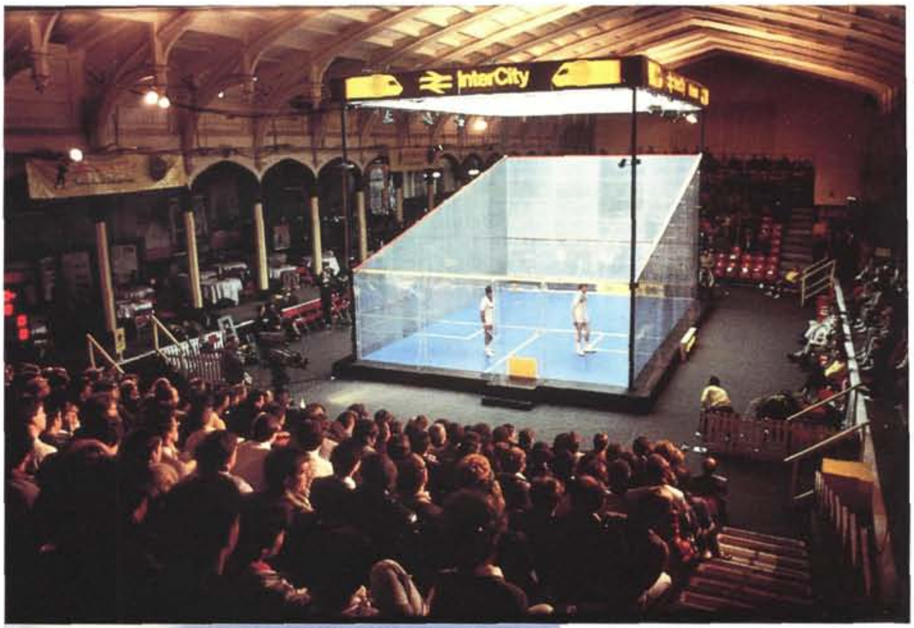


Fig. 4.10 Squash court in Bristol designed by Roland Hill (courtesy of Roland Hill/Stephen Line)

Fig. 4.11 Glass tower sculpture at the Channel Tunnel entrance (courtesy of Roland Hill Consulting Engineers)

Fig. 4.12 Glass walls at St. Donat's Arts Centre (courtesy of Martin McCabe)

Fig. 4.13 Conservatory at a house in Clapham, South London (courtesy Bere Associates/Michael Heyward)

Fig. 4.14 Entrance canopy to KP Foods at Billingham (courtesy of Jeremy Cockayne/Studio BAAD)

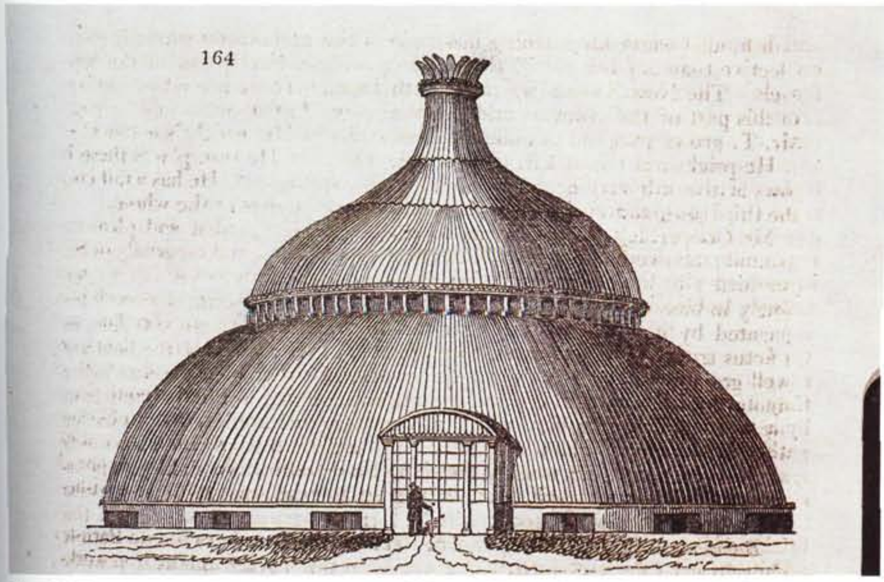


Fig. 4.15 Mrs Beaumont's Dome (courtesy of Royal Horticultural Society, Lindley Library)

glass and because it is at the top of the enclosed space, roof glass may reach higher temperatures than facade glass. The thermal stresses may well constrain the designer to choose toughened glass.

We are all familiar with images of the Palm House at Kew (1848; Architect Decimus Burton; Engineer: Richard Turner), the Crystal Palace in London (1851; Architect and Engineer Joseph Paxton) and with the great Victorian Railway stations. All used or use glass extensively in their roofs, supported by frames of steel or iron. These were preceded by some bulging curved glass houses designed by J. C. Loudon and built by W. & D. Bailey in the second quarter of the 19th century. The delicate wrought iron frames were braced in-plane by the glass. It is reported that the frame of Mrs Beaumont's dome, built in 1827 at Bretton in Yorkshire, swayed alarmingly in the wind during construction but once glazed was steady as a rock.

In all of these wonderful buildings, small panes of glass are supported on two or four edges by frames to which they are attached by putty. This is still a valid way to support glass roofs (but not double-glazed units), even if nowadays we use more elaborate arrangements of structure, glass and sealant.

An obvious successor to the great 19th century glass roofs is the Waterloo International Terminal, with its sinuous roof glazed like the scales on a lizard's back.

Grid shells have long held a fascination for engineers, probably because of their economical use of material but they can be susceptible to unbalanced loads, such as wind-driven snow. The History of Hamburg Museum (1989; Architect: von Gerkan, Marg + Partner; Engineer: Schlaich, Bergermann and Partner) has a modern glass roof that covers a large L-shaped courtyard of a 1923 building. The form of the structure is a pair of intersecting barrel vaults, one about 14m wide and one about 18m wide.

The structure consists of a grillage of 60mm-wide by 40mm-deep solid galvanised steel glazing bars bolted together to form a loadbearing grid of quadrilaterals approximately 1.7m on each side. In-plane stiffness is provided by pairs of 6mm diameter diagonal steel cables. The glass could have provided this itself but Schlaich preferred to make evident the elements that provide the in-plane stiffness and hence chose to use steel cables rather than the glass. Engineers may be confident that the glass can provide all the in-plane stiffness needed but if they want to do so they will need to persuade the checking authorities and the insurers. At three locations fan bracing provides additional out-of-plane stiffness to the vaults.

The size of each glass pane was calculated and cut by computer. The panes are laminated using 6mm sheets of annealed glass. Each pane sits on a strip of neoprene silicone rubber on top of the frame and is restrained at the corners by a wide circular plate at the intersection of the glazing bars. The plate is large enough to restrain the corners of four adjoining panels of glass, using a simple bolt fixing.

The relatively small panel size and the bedding of the neoprene gave a tolerance to accommodate the double curvature of the roof. In places where the curvature was most marked, some glass panels were folded across a diagonal by cutting the upper and lower glass sheets on site and allowing the interlayer to support the fold, protected by site-applied silicone.

Heating cables are provided, not to prevent condensation, but to prevent excessive snow build-up.

The design is well described by Holgate (1997).

The development of point-supported glass, as exemplified by Pilkington's Planar system or St Gobain's Spider system, can be used with great elegance to produce simple roofs that come close to floating. In Terrasson, south-west France, Ian Ritchie Associates and Ove Arup & Partners designed a greenhouse which provides shelter, information, exhibitions and coffee to visitors in a new park (Conolly, 1995). A horizontal transparent glass roof hovers above a space enclosed by massive gabion walls.

The extension to a private house in Hampstead, London was one of the first buildings to use glass beams to support a nearly horizontal glass roof (1992; Architect: Rick Mather; Engineer: Dewhurst McFarlane & Partners). The beams are fabricated from 12mm-thick annealed glass sheets cut to a curved profile 200mm deep at the supports and 275mm deep at mid-span. Each beam consists of 3 sheets of glass laminated by 2mm-thick resin, providing redundancy should one or even two sheets crack. The roof panels are double glazed (toughened outer and laminated inner) and are connected to the beams by structural silicone.

The beams are bolted at one end to metal brackets attached to the wall of the original house. At the other end they are supported, via a mortice and tenon connection, by laminated glass fin columns. Walker (1996) describes the extension.

Glass beams are constrained by considerations of permanent tension in cut edges. This starts engineers thinking about structural arrangements in which glass is kept in compression and other materials, better suited, deal with tension. At Schloss Juval in the South Tyrol (Anonymous, 1997), steel trusses spanning up to 13.4m support a glass roof over a courtyard of an ancient building. What is special about this is that the glass spans the 4m between the steel trusses by acting as the compression boom of a simple truss, with a steel cable taking the tension.

The glass panes are made of two 8mm toughened heat-soaked sheets with a 1.52mm pvb interlayer. (1997; Architect and Engineer: Danz)

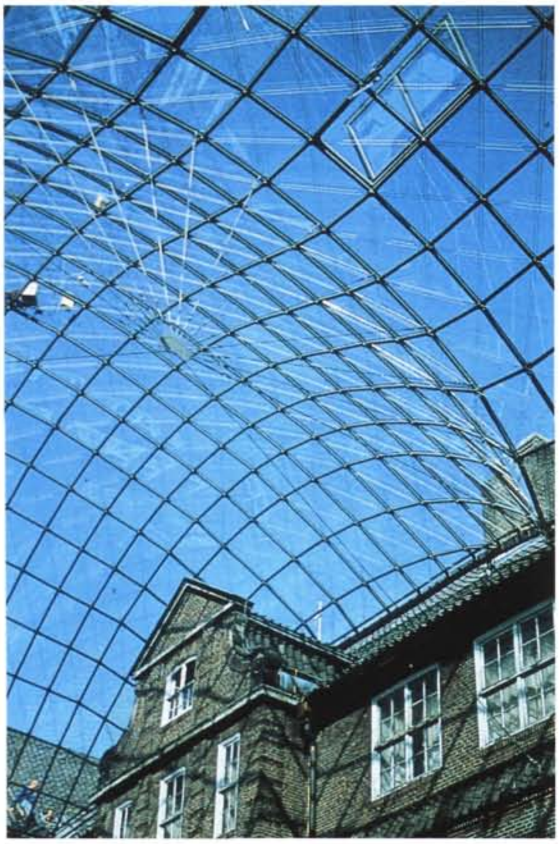


Fig. 4.18 History of Hamburg Museum courtyard roof (courtesy Schlaich Bergermann)

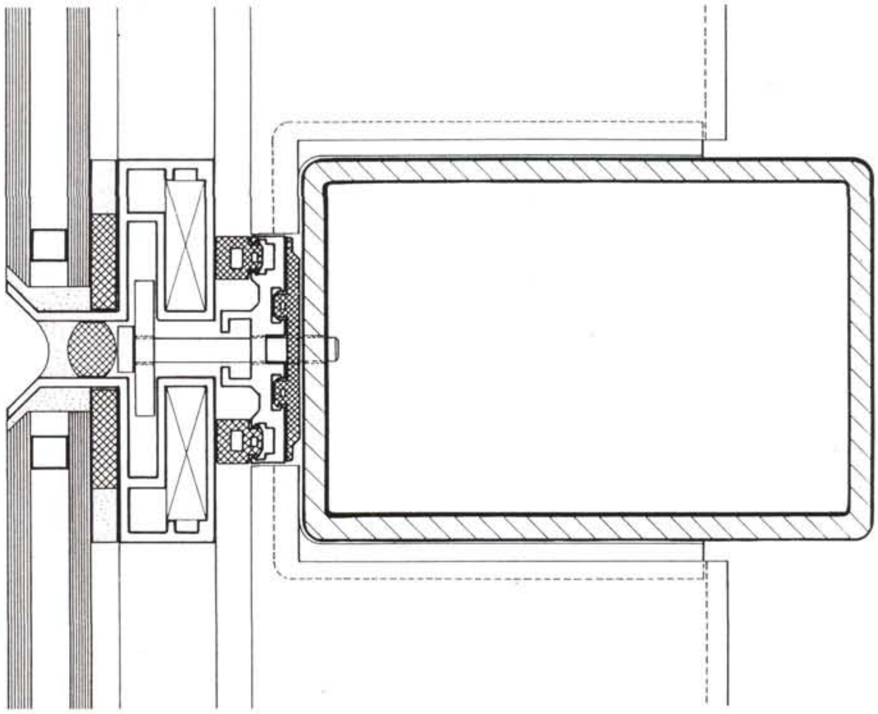


Fig. 4.16 Diagram of structure, glazing and seals (courtesy Foster & Partners)

4.3 Lateral load system

Glass roofs and facades may be subjected to lateral loads both in-plane and out-of-plane from explosion, wind and seismic activity. In this they are no different from roofs and facades made of other materials.

The difference comes from the unforgiving nature of glass. The designer needs to consider very carefully what forces or deformations may be applied, how they will be applied, if they are to be resisted and how they will be resisted.

At Parc de La Villette, the glass facades of the

Fig. 4.17 Waterloo International Terminal (courtesy of Nicholas Grimshaw & Partners Ltd/ITW-Reid & Peck)

Fig. 4.19 Cutting and folding of panes (courtesy of Schlaich Bergermann)

Fig. 4.22 Glass roof at Schloss Juval in the South Tyrol (courtesy of Ines Schöttle)

Fig. 4.20 Roof at Terrasson, France (courtesy of C. J. Van Den Bossche)

Fig. 4.21 Glass beams supporting glass roof in Hampstead (courtesy of Dewhurst Macfarlane & Partners/Rick Mather/Chris Gascoigne)

Serres were articulated so that the glass could not even try to resist any in-plane forces. If blockwork had been used instead of glass the designers would have had the option of jamming in the blockwork so that it resisted any in-plane forces or of providing soft joints all around the blockwork so that it did not try to. Even if the workmanship had not been very good and a soft joint became a hard joint, the worst that would have happened would have been some cracking of the blockwork. With glass subjected to stresses it was not designed to carry, or compelled to deflect in an unacceptable way, sudden failure may be expected.

4.4 Alternative load paths

The key question for a designer to ask when designing a glass roof or facade is, 'What happens if a pane is broken?' In order for a small breakage not to have a disproportionate consequence, the structure must be able to carry its loads by more than one path.

Damage may be caused by accident or it may be deliberate.

Once more La Villette provides a model of clear thinking about a significant aspect of glass design. If an upper sheet in a vertical row of four sheets breaks, then it can no longer support the three remaining sheets below it. They will then transfer their loads to the adjacent sheets of glass through the horizontal castings of the four-hole connections and via shear stresses in the silicone joints. The possibility of sudden changes in load paths causing violent shocks at the suspension points was addressed by the use of shock absorbers and springs.

The springs provide another service at La Villette and in other glass walls that followed. They enable the engineer to ensure that the supporting beam from which the glass is suspended is uniformly loaded by the weight of the glass. Without the springs a deep glass wall would try to act as a deep beam, transferring all its weight to its end supports, as shown in Fig. 4.23.

At the small private house extension in Hampstead mentioned previously, even if an entire laminated glass beam fails, the glass panes of the roof will still stay up by adjusting from 4-edge support to 3-edge support.

At a domestic scale annealed window glass will often stay in place even when severely cracked. Alternative load paths exist within the sheet of glass.

4.5 Serviceability

Facades and roofs exist to keep the rain out of buildings. It is therefore important that designers understand the deflections that a roof or a facade may be subjected to during its life, so that they can design the appropriate seals. The strain to which a seal may be subjected will crucially influence the choice of material for the seal.

Flat roofs may be susceptible to ponding. This can occur on a large scale as a result of the sums of all the deflections of all the components in the roof. It can also occur on a smaller scale when a salient capping profile or other projection dams the flow of water.

The 40m wide by 25m tall facade of the Kempinski Hotel at Munich Airport bows in up to 90cm under full design wind pressure. This sounds a lot but a closer look at the deflected shape shows very little strain imposed on the seals between adjacent panes.

The designer should not assume uniform wind pressures across, for example, a glass facade. Partial load cases will often dominate the design because of the need to control movements, as shown in Fig. 4.24.

A deflection of this magnitude suggests that the wall has a low first natural frequency, low enough to be susceptible to wind-excited vibration. However the volume of air in the atrium behind the glass wall acts as a damper and controls vibrations to an acceptable degree.

It is not only large-scale facades that can deflect noticeably. Glass panes spanning of the order of a metre are large deflection structures. Under strong winds they will deflect in a way that can cause serious concern to people who have not seen this before.

The deflections of the supporting or adjacent structure should also be taken into account. For example, a glass facade suspended from a steel structure that spans, say, 20m or 30m, can expect noticeable deflections at mid span which must be taken into account when detailing the connections at the bottom of the facade and when installing the facade.

4.6 Accommodation of movement

The movements of supporting structure, both in and out of the plane of the glazing, need to be accommodated in a way that does not lead to unacceptable stresses in the glass. There may well be serviceability criteria associated with weathertightness or appearance that govern acceptable movements. The Kempinski Hotel (Holgate, 1997) (Fig. 4.3) is a good example of a fresh approach to the sometimes unthinking compliance *L*/175 or other arbitrary rule (see Table 6.4).

Fig. 4.23 Shock absorbers at La Villette (courtesy of RFR)

Ryan *et al.* (1998) list all the possible movements of the glass and its primary and secondary support structures and point out the special care needed to limit imposed rotations on the glass at bolted connections.

Dawson (1996) describes the articulation designed into the glass-clad vault of the 244m-long, 79m-wide and 28m-tall Leipzig Neue Messe (1996; Architect: von Gerkan, Marg + Partner with Ian Ritchie Architects; Engineer: IPP with Ove Arup & Partners).

4.7 Safety — accidental or deliberate damage

The design and selection of glass for overhead and sloped glazing requires special attention for a number of reasons:

- Sloped glass is more susceptible to impact from falling objects, wind-borne debris and thrown objects than vertical glass.
- Sloped glazing in most cases is more likely to fall from the opening when it breaks than vertical glass. Good design indicates that the choice of glass must be based on eliminating or minimising hazards so far as is reasonably practicable.
- Snow loads may be imposed on the glazing for long periods. The strength of annealed glass and the contribution of the plastic interlayer in laminated glass are both time dependent.

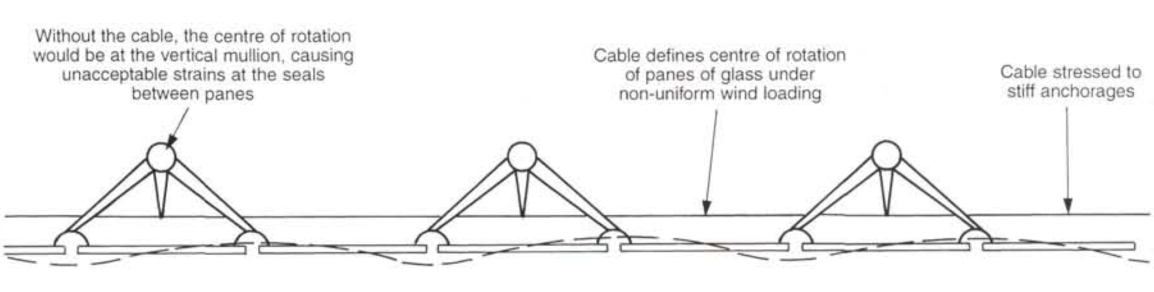


Fig. 4.24 Diagrams based on Roissy, showing how large movements could occur and how to prevent them

- For most orientations, sloped glass and overhead glass may reach a higher temperature than vertical glazing because the sun's radiation is more nearly normal to the glass surface and because of stratification of warm air in the building. The converse is also true, and the orientation of the sloped or overhead glass may allow its temperature to fall further than that of vertical glass on clear nights.

Further guidance on the selection of non-vertical overhead glazing from the point of view of safety may be found in section 7.1 of The Glass and Glazing Federation's *Glazing Manual*.

Guidance on the selection of glass for impact resistance in buildings in the UK may be found in BS 6206, BS 6180, BS 6262 and The Building Regulations *Approved Document N*.

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5 Calculations

5.1 Introduction

Before carrying out any calculations, it is most important that the designer has a clear idea of how the structure will behave. There is nothing unusual about this notion and it applies as much to steel or concrete as it does to glass. The reason for its emphasis here is that an engineer inexperienced in glass design may feel tempted to take refuge in the calculations. Because of the brittle nature of glass it is also important that the designer has a clear idea of how the structure is to behave after one or more glass elements have failed. It is also important to assess the safety implications of failure of a piece of glass: what is the likelihood of people being injured by falling glass, for example?

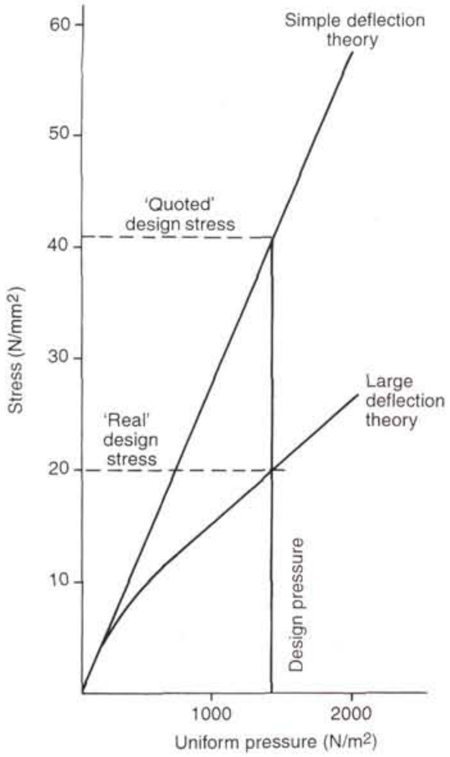


Fig. 5.1 A comparison of small and large deflection theory (reproduced from *Glass in Buildings*, eds. Button & Pye, by permission of Butterworth-Heinemann)

It is only when the structural behaviour is understood that decisions can be made about what calculations are appropriate. As a simple example, consider a pane of glass supported along all four edges. Under wind load it may behave like a plate, in which case Kirchoff's linear theory, which can be found in Timoshenko's (1959) *Theory of plates and shells*, is applicable. However, if the plate defects laterally by more than half its thickness, then large deflection non-linear theory comes into play, to take account of the membrane stresses that are set up.

As most modern design seems to involve large thin panes of glass, it might be assumed that for even the simplest design it would be necessary for the designer to solve some complex differential equations. Fortunately this is not so, which is just as well because obtaining appropriate material data (for example the characteristic strength of weathered annealed glass) can be a challenging business.

For rectangular panes of glass, with continuous lateral support along all four edges, the international standards listed in Table 5.1 provide simple ways of determining the appropriate glass thickness to resist specified design loads.

Care should be taken when using design standards from one country with materials from another. For example, variations in allowable glass thickness may differ. Design calculations should be based on the thinnest glass that could be produced, for a given nominal thickness, with appropriate allowances for weathering of the surface of the glass. Weathering normally affects strength rather than thickness.

Most manufacturers will provide guidance on what thickness glass should be used, based on their experience. Engineers should satisfy themselves that the guidance is appropriate.

Table 5.1 International Standards

UK	BS 6262	Glazing for buildings	Under revision
The Netherlands		Concept Richtlijn: Constructief Glas	Gives design stresses and material factors
The Netherlands	NEN 2608 and NEN 2608A	Vlakglas voor Gebouwen	Gives load factors
Australia	AS1288-1994	Glass in buildings – Selection and installation	
USA	ASTM E1300-94	Standard practice for determining the minimum thickness and type of glass required to resist a specified load	
Canada	CAN/CGSB-12.20-M89	Structural design of glass for buildings	
EC	CEN/TC129/WG8	Draft for 'Design of glass panes Part 2: Design for uniformly distributed load'	In draft

5.2 Limit state approach

The draft European standard adopts a limit state approach to the structural design of glass. This is rational and familiar to most engineers.

5.2.1 Strength

The US and Canadian standards are based upon a failure prediction model developed at Texas Tech University (Beason and Morgan, 1984). The American Code charts are said to be based on a probability of failure under design load of 8/1000 for annealed glass but in practice they achieve better than this. In the USA the applied loads and the allowable loads are expressed in working, i.e. unfactored terms. In Canada and The Netherlands and the forthcoming European Standard the factored load is compared with the factored resistance.

5.2.2 Serviceability

Deflections of the glass and its supporting structure should be considered carefully. How people perceive the deflections is a function of their expectations. Apparently large movements in a glass assembly that is detailed to look rigid would be more alarming than in one which is detailed differently. Generally, toughened glass panes will deflect much more than annealed glass panes of the same strength, because they will be much thinner.

5.3 Loads

Because the strength of annealed glass in tension is time-dependent, it is appropriate to consider the duration of loading and to apply appropriate factors. The Canadian Code makes the distinctions shown in Table 5.2. This is consistent with practice in The Netherlands which considers dead load, static live load and dynamic live load (i.e. wind gusts). It is also consistent with the recommendations of Sedlacek *et al.* (1995).

The American Code involves the calculation of an 'equivalent design load', which it defines as 'the magnitude of a 60s duration constant load provided by the specifying authority to represent the cumulative effects of the components of all loads acting on the glass'. Unfortunately it goes on to say, 'The transformation of loads to account for variations in magnitude, direction and duration is beyond the scope of this document'. Fortunately, guidance is available from a number of other sources, including Figure 3 of Sedlacek *et al.* (1995), which shows how the relative strength of annealed glass varies with load duration.

Table 5.2 Canadian Code load durations

Load type	Approximate equivalent load duration
Wind and earthquake	1 minute
Sustained (snow, ponding)	1 week to 1 month
Continuous (dead load, hydrostatic pressure)	1 year to 10 years

Table 5.3 Typical properties of annealed float glass

Characteristic compressive strength	over 1000N/mm^2
Characteristic tensile strength	10 to 100N/mm^2

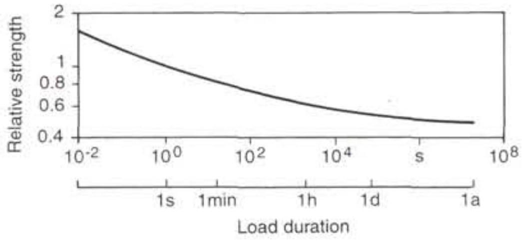


Fig. 5.2 Diagram illustrating the relationship between time to failure and applied stress (after Sedlacek)

Table 5.4 Variation of exponent *n* with environment

Environment	*n*
Water at 25°C	16.0
Air with 50% RH at 25°C	18.1
Air with 10% RH at 25°C	27.0
Vacuum at 25°C	70.0
Melting snow at 2°C	16.0

5.4 Strength

There is a phenomenon known as the static fatigue of glass, which some consider a misnomer. A more accurate title would be sub-critical crack growth. Cracks or flaws grow slowly with time under sub-critical stress until a length is reached at which the stress intensity at the crack tip reaches a critical value, the highly strained atomic bonds at the crack tip break very quickly and rapid fracture occurs. This is described further in section 5.5. The expression 'stress corrosion' is sometimes used, with the slope of the graph of crack growth velocity versus stress intensity factor on log-log paper being referred to as the stress corrosion constant. Alkaline solutions make most glasses more prone to slow crack growth, as does increasing temperature. For further data the reader is referred to Creyke, Sainsbury and Morrell (1982).

The relationship between time to failure and applied stress has been extensively researched and can be summarised by the equation:

$$\sigma^n T = \text{constant}$$

where: σ is stress
T is duration of stress and
n is a constant.

Sedlacek (1995) presented values of n as shown in Table 5.4. Sedlacek recommends using n = 16 for design purposes and this value is also recommended by Pilkington Glass Consultants.

The equation implies that for extremely long duration loads allowable stresses must decrease to negligible values but in practice it has been found that this does not occur. There is a lower limit below which glass strength does not fall. Figure 3 of Sedlacek *et al.* (1995) shows a reduction in rela-

Table 5.5 Time-dependent strengths of annealed glass in the Netherlands

Dead load	1
Static live load	2.4
Dynamic live load (i.e. wind gusts)	4

tive strength from 1 for a one-second duration load to around 0.5 for a one-year duration load. Conversely, for a load of duration of 0.01 second glass has a relative strength of about 1.6. These figures are roughly consistent with BS 5516, in which short duration wind loads are resisted by 2.6 times the strength available to resist long duration snow loads.

Table 5.5 shows the relative strengths for ordinary, i.e. annealed, float glass used in The Netherlands.

In summary, the strength of a piece of annealed glass depends on the following main factors:

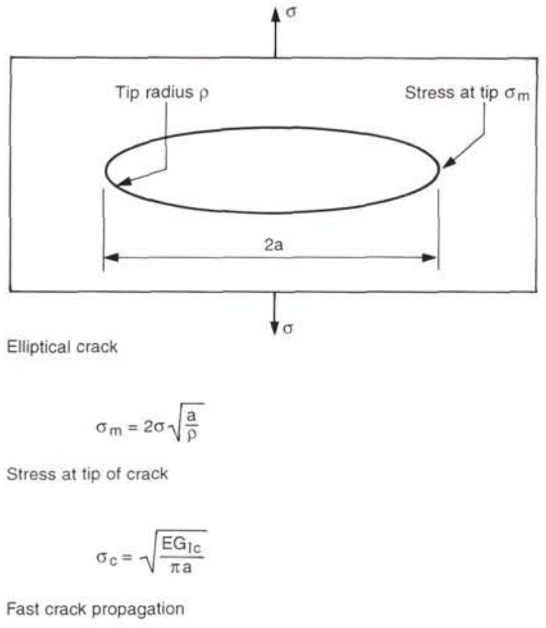
- the duration of application of the load
- the environmental conditions, especially the humidity
- the size of the stressed area
- the distribution of stresses across the stressed area
- the condition of the surfaces and edges of the glass

5.5 Fracture mechanics

If, by heat-strengthening or toughening, the surface of the glass is prevented from experiencing any tension in service, then cracks cannot grow and it is not appropriate to carry out any fracture mechanics calculations. Similarly, if annealed glass is to be used in circumstances in which the engineer is confident that it will not experience tensile stresses in service, then cracks cannot grow and it is not appropriate to carry out any fracture mechanics calculations.

The foundations of fracture mechanics were laid by a British naval architect, Professor Inglis, in 1913. He recognised that a slot, hole or notch in a metal plate tended to reduce its tensile strength by more than would be predicted from considering only the reduction in tensile area. He showed that the stress field near the discontinuity is magnified by an amount that depends on the radius of curvature of the discontinuity compared to its length perpendicular to the stress field.

Fig. 5.3 Stresses at the tip of an elliptical crack



Following Inglis, A. A. Griffith carried out pioneering work in fracture mechanics at the beginning of the 20th century and the randomly distributed flaws or discontinuities across the surface of a piece of glass are referred to as Griffith flaws.

While Griffith flaws are present on the surface of any glass, the strength of glass is also modified by the presence of major (visible) defects, which can be the origin of cracks under applied tensile stresses. The edges of a plate of glass are more prone to damage from accidental contact than the surface. The energy of an impact on the face of a piece of glass can usually be absorbed by deflection (bending) of the glass but edge impact is resisted by the full in-plane stiffness of the glass plate or beam and delivers a higher and more damaging impulse.

Under load, stresses concentrate at the tips of these flaws or cracks, which may well be invisible to the naked eye. Griffith stated that crack propagation will occur if the energy released upon crack growth is sufficient to provide all the energy that is required for crack growth. This can be expressed mathematically as:

$$\sigma_c = \sqrt{\frac{EG_c}{\pi a}} \quad \text{(see Fig. 5.3)}$$

where σ_c is the stress required to fracture a plate with a crack of length $2a$, E is Young's Modulus and G_c is the critical elastic energy release rate or toughness of the glass, with units of energy per unit plate thickness and per unit crack extension. This equation indicates that fast fracture will occur when, in a material subjected to a stress σ, a crack reaches some critical size a, or, alternatively, when material containing cracks of size a is subjected to some critical stress σ. The equation shows that the critical combination of stress and crack length for fast fracture is a material constant.

Fracture mechanics can provide a rational basis for the design stresses given in national codes and standards (Sedlacek *et al.* 1995). For everyday engineering calculations it is not an appropriate approach, because of its length and complexity.

For an application where the engineer decides that fracture mechanics calculations are necessary, then Sedlacek *et al.* show how it is possible to calculate the integrated life experience of the glass, i.e. the damage accumulated by loads of varying intensity and duration under different environmental conditions. Chapter 18 of Ashby and Jones (1998) describes very clearly the statistics and the time dependence of brittle fracture. Creyke, Sainsbury and Morrell (1982) provide a clear guide to design with non-ductile materials; chapter 3 covers brittle fracture and strength and chapter 4 the effects of time under load. Porter and Houlsby (2000) propose a new design method for crack-abraded glass members, based upon a 'design crack'.

Some observers have noted that glass has the ability to reverse damage (i.e. heal the microcracks) if it is returned to an unstressed state and some therefore question whether wind damage is accumulative. Conversely, the surface condition of a sheet of glass is changed every time the glass is cleaned (i.e. new microcracks are generated). The engineer must decide whether damage reversal is something that can be relied upon in design.

5.6 Stress concentrations

Because steel is plastic, it yields and flows if it is locally overstressed. Glass does not do this. When it is overstressed it breaks without warning. It is therefore very important that the designer tries hard to eliminate any design features that may cause stress concentrations. Section 9.5 illustrates some bolted glass details in which the reader can see the efforts made to avoid stress concentrations.

Bolted glass is widely used because of its transparency. What may also be invisible to the casual observer is the extraordinary effort by bolted glass designers to avoid stress concentrations around the bolts. Bolted design does need very careful attention.

Whenever glass is used, there will be forces that have to be transmitted from the glass to another material, often a structural frame. Traditionally soft setting blocks, fibre gaskets, protective bushes and rules such as 'avoid glass to metal contact' have been used to limit stress concentrations to acceptable levels.

Research work is underway at Oxford University into the behaviour of different materials and different shapes of setting blocks. Pilkington recommend the long-term average bearing stresses for setting blocks in Table 5.6, based on BS 6262.

Chapter 9 illustrates some of the different ways in which designers have dealt with stress concentrations at bolted connections.

Pilkey (1997) and Roark & Young (1977) can be of help in assessing stress concentrations.

5.7 Fatigue

Glass is not subject to fatigue. The perfect linearity of the stress–strain curve means that reversals of stress perform no net work on the material and so no damage or work hardening can occur.

Glass always fails by brittle fracture, never by ductile fracture. Cyclic loading can cause cracks to grow (in ductile materials as well as in glass). For many materials there exists a fatigue limit: a stress amplitude below which fracture does not occur, or occurs after a very large ($> 10^8$) number of cycles. The fatigue ratio is the ratio of the fatigue limit to the yield strength. As glass does not have a yield strength, other than in theory, this ratio is not much use for glass designers. It is mentioned to help compare and contrast glass with other, more familiar, materials.

Table 5.6 BS 6262 allowable bearing stresses

Material	Allowable bearing stress
Hardwood	2.5N/mm^2
Plastics and hard rubbers	1.5N/mm^2

In metals such as steel, the stress amplitude below which fracture does not occur is referred to as the endurance limit. Following the work of August Wöhler, the graph that plots stress amplitude against number of stress reversals to fracture is referred to as a Wöhler line. An example is given in Alexander and Street (1982). Sedlacek *et al.* (1995) show how the behaviour of glass can be described by equations analogous to the equation for the fatigue strength of steel members and may be interpreted as a kind of Wöhler line.

Fatigue strength of steel

$$\Delta\sigma^{m}N = \Delta\sigma_{R}^{\ m}N_{R} = \text{constant}$$

where:	$\Delta\sigma$	is the stress amplitude
	N	is the number of cycles
	m	is an exponent.

This is shown in Fig. 5.5.

Survival probability of scratched glass loaded at a constant rate

$$\sigma^{\beta}_{S1}S_{1} = \sigma^{\beta}_{S0}S_{0} = \text{constant}$$

where:	σ	is the tensile stress in an area S
	β	is an exponent of value 25
	S_0	is 2400cm^2, which is the reference surface area used in DIN 52 292 Part 2 R 400.

This is shown in Fig. 5.6.

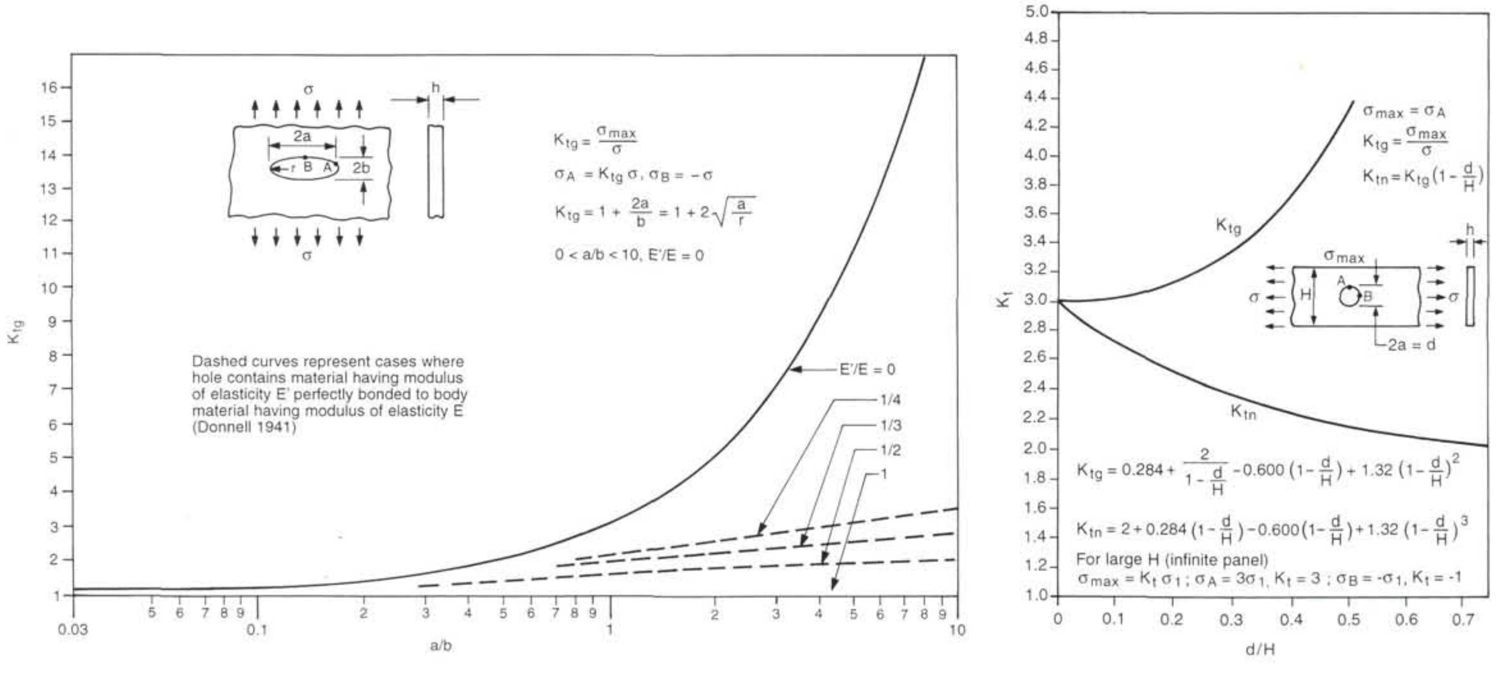


Fig. 5.4 Diagrams of some typical stress concentrations: elliptical crack (Griffith theory) and circular hole in tension field (from *Peterson's Stress concentration factors*, Walter D Pilkey, © 1997 John Wiley & Sons. Inc.)

Fig. 5.5 Wöhler line for a steel (Reproduced from *Metals in the service of Man* – Street & Alexander, by permission of Penguin Books)

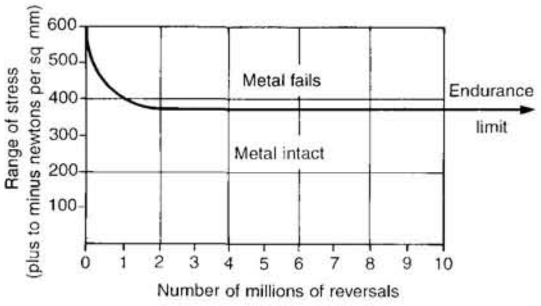
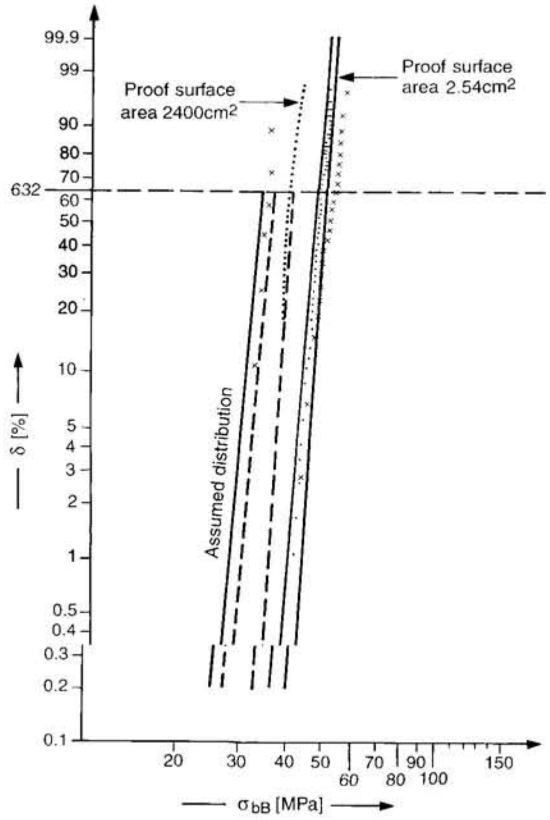


Fig. 5.6 Survival probability graph



Time dependence of glass strength

$A_v t\sigma^n = A_0 T_0 \sigma^n_0$ = constant,

where: σ is stress
t and T are time
A and n are constants for undercritical crack growth, which varies with temperature and humidity.

Sedlacek *et al* (1995) give a range of values of A and n. The subscript '0' refers to the conditions in the DIN 52 292 test. This is shown in Fig. 5.2.

For a clear explanation of static fatigue and life under load, the reader is referred to section 4.4 of Creyke, Sainsbury and Morrell (1982).

In the Netherlands, float glass is allowed to sustain stresses four times higher under wind gusts than under dead load.

By prestressing the glass it is possible to ensure that its surfaces always remain in compression. There is then no question of cracks propagating or of time-dependent strength. The two basic types of prestressed glass are known as heat-strengthened glass and toughened glass (known as fully tempered glass in the USA and elsewhere). These are described in sections 2.1.2 and 2.1.3.

There is no British Standard for heat-strengthened or toughened glass, so the designer is advised to consult one or more reputable manufacturers to learn what levels of prestress are available and what variability exists in the prestress achieved. European Standards are in draft (prEN 1863 and prEN 12150). Figures around 90 to 120N/mm^2 or sometimes even higher are commonly quoted for toughened glass in the UK, although the American standard defines a minimum level of only 69N/mm^2. These are actual, unfactored stresses, determined by optical measurement techniques. 69N/mm^2 is insufficient to ensure that the glass behaves as safety glass, because it will not always break into dice.

Table 5.7 Load duration factors

Duration of load	Example	Modification factor on strength
Short	Wind	0.72
Medium	Snow	0.36
Medium	Climate (for insulating glass units)	0.36
Permanent	Self-weight	0.27
Permanent	Altitude (for insulating glass units)	0.27

Heat-strengthened glass is limited in its upper value of surface compression by the requirement that it breaks like annealed glass. In the UK, actual surface compressions of between 25 and 70N/mm^2 are quoted for heat-strengthened glass, though 70N/mm^2 may behave more like badly toughened' than heat strengthened. Again, the designer should consult one or more reputable manufacturers and should refer to prEN 1863.

The American Standard for both heat-strengthened and toughened glass is ASTM C1048-92 and the equivalent German standard is DIN 18516: Part 4: February 1990. Draft European Standards prEN 1863 and prEN 12150 are recommended over both of these.

In The Netherlands, designers use 'allowable' stresses in toughened glass that are about seven times those in annealed glass for dead load, three times for long-term live load such as snow and twice for short-term live load such as wind gusts. Their ratios for heat-strengthened to annealed are approximately 3, 1.5 and 1.3.

The draft European Standard for glass panes gives the following modification factors to take into account the effect of load duration on strength.

Sedlacek *et al.* (1995) present a range of German allowable stresses for annealed and toughened glass.

5.8 Stiffness

The Young's Modulus of glass is around 70-74kN/mm^2. Linear elastic theory can be relied upon when deflections are small but when, for example, deflections of a plate approach one half of the plate thickness, then non-linear membrane theory is needed to predict stresses and deflections accurately. If the glass has a free (unsupported) edge, then simple deflection formulae are often accurate enough for engineering design purposes. Modelling of the boundary constraints with non-linear analysis is particularly important if accurate answers are required.

Vallabhan (1983) and So and Chan (1996) describe finite element models which can be used to model non-linear plate behaviour.

Vallabhan *et al.* (1994) present a parametric study of the stresses and deflections of axisymmetric circular glass plates, which may be used, of course, for circular plates but also for approximating to other shapes, subject to the judgment of the engineer.

Vallabhan (1999) describes the evolution of non-linear stress analysis of different types of window glass. Analysis of the glass is extended to consider dynamic pressures using a step-by-step integration procedure.

5.9 Movement

Glass facades and roofs may bridge between elements of the primary structure that are separated by movement joints. Even if that is not the case, they will be attached to elements of structure that will move. The glass itself will also move. Movements may be both in and out of the plane of the glass and they may also involve rotation. Early consideration of how movements are to be accommodated may significantly influence decisions about support for glass. Particular attention should be given to the strains that may be applied to weather seals.

Ryan *et al.* (1998) provides comprehensive guidance on movement as a design issue for the interfaces between steel and glazing in buildings. BS 6180: 1995 gives deflection limits for balustrades, including those made of glass.

5.10 Stability

When preparing structural designs engineers' aims include the following:

- to provide adequate reserves of strength in the framework and structural elements to carry the applied loads, and
- to confirm that the stiffness of the framework and elements is such that reserves of elastic stability are high so that load factors computed on the basis of strength alone will not be materially reduced, or
- in the event that stability is a critical factor, to increase the amount or change the distribution of material in the framework and structural elements, to sustain minimum load factors against collapse.

A structure that relies on glass elements should therefore be configured in a way that recognises the glass's contribution in terms of strength and stiffness but is not compromised by the failure of a single glass element. Because glass is brittle it is unlikely that a single glass element can be treated as a key structural element.

5.11 Robustness

Robustness and stability are closely allied when glass is involved. Robustness is a structural quality to be sought at all times and therefore a structure that uses glass elements should be configured in a way that recognises the glass's contribution in terms of strength and stiffness but whose robustness is not compromised by the failure of a single glass element.

In the discussion that followed his paper at the Institution of Structural Engineers, Professor Sedlacek said that the inclusion of a system that gave warning that glass was in distress was essential for the acceptance of the design of loadbearing glass structures. He felt that, in general, a multilayer system used for plates or beams was such a system, with the outer plates considered as damage indicators.

5.12 Stress analysis

5.12.1 Analytical

Glass fails in tension or by buckling. Analytical techniques should therefore be directed towards determining the highest tensile stresses under load and in determining the elastic stability of the element or framework. Tensile strains may be directly applied or may occur as the result of the Poisson's effect when compressive stresses are applied.

It should be noted that the presence of holes leads inevitably to stress concentrations and that it is important not to ignore this. Even the simplest case, that of an infinite thin element with a hole under tensile load, has peak stresses near the hole three times as large as those away from the hole. When the plate under tension is of finite width the stress concentration factor is always more than 3.

Manufacturers have traditionally been reluctant to quote allowable tensile stresses for use in the design of their own glass but some figures have found their way into designers' files. These have almost always been developed based upon simple linear models of behaviour. They should under no circumstances be used when the analytical method takes account of non-linear behaviour. To do so is definitely non-conservative.

A glass plate that has sufficient thickness to resist its design lateral pressures may still be too thin and flexible to be serviceable. Maximum out-of-plane deflection under lateral load may be limited by considerations such as:

- appearance and occupant acceptance
- durability of sealants and plate retention in gaskets
- safety of installation or replacement.

It will then be necessary to calculate deflections as well as stresses.

Haworth & Hooper (1981), Vallabhan (1983), Beason & Morgan (1984) and So & Chan (1996) all show how non-linear plate analysis may be used to calculate stresses and deflections. Fig. 5.7 shows a finite element idealisation used by Pilkington in developing their Planar system of bolted glass support. It shows the level of detail required to model local stresses around a bolt hole.

Consideration of elastic stability of structures is familiar to engineers in applications such as column design or the design of deep thin cantilevering beams. Roark & Young (1977), Timoshenko & Gere (1970) and Horne & Merchant (1965) provide guidance on establishing elastic critical load factors for a wide range of structural elements and loadings. It is up to the engineer to decide on the appropriate value of the elastic critical load factor.

5.12.2 Experimental

Calculations are useful but in some circumstances it is appropriate to carry out physical tests as well.

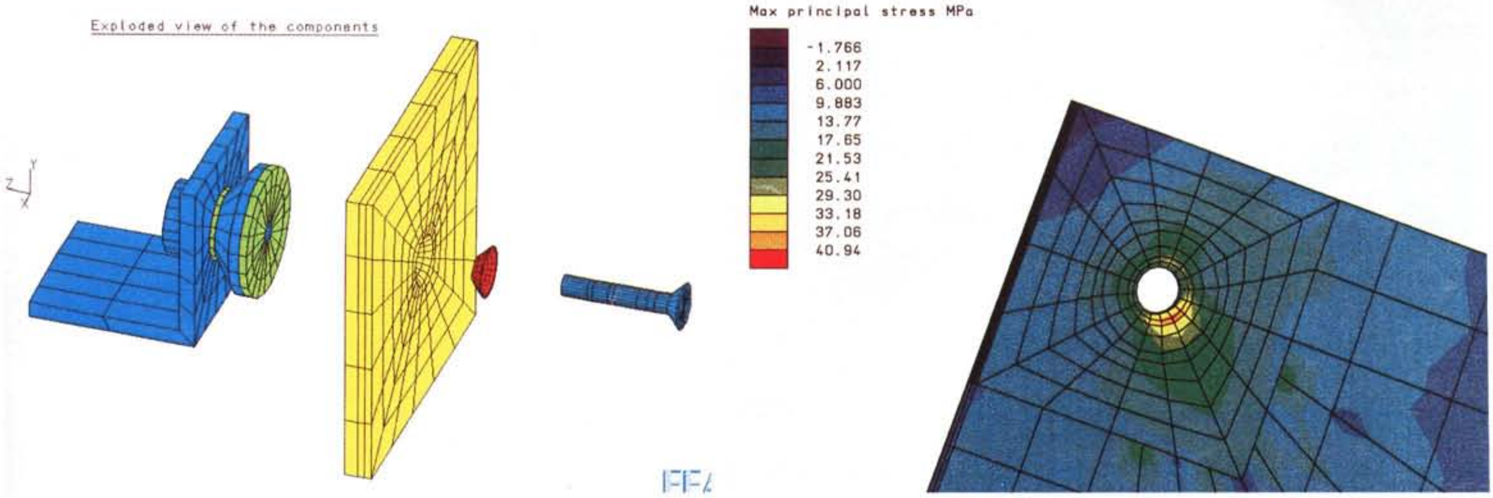


Fig. 5.7 A finite element model of a planar bolted connection and some stress contours (courtesy of Pilkington)

Pilkington used finite element analytical techniques when developing their Planar system of bolted glass. They also carried out physical tests and these showed:

- good correlation with predicted displacements
- poor correlation with predicted stresses, especially around holes.

Sometimes the engineer may be confident that calculations alone will suffice but the checking authority or the insurer may require tests. For example, tests on glazing systems are commonly required in China and in France.

In general the engineer must decide what combination of calculation and load test is appropriate for the structure he or she is designing. He or she must also decide whether or not the test is to be destructive and how many specimens to test.

The decision will be influenced by consideration of a number of factors including:

- cost
- whether there are precedents for the intended application of structural glass
- the consequences of failure of one or more glass elements
- the degree of redundancy in the structure
- the extent and nature of the warning system that indicates glass in distress
- the anticipated stress levels in the glass
- the relevant experience of the intended manufacturer and installer
- the quality assurance systems of the intended manufacturer and installer.

In Germany, if an application of a material or product is not covered by a national standard, it is still possible for it to be used under closely controlled circumstances. For example, high strength steels in Germany are not currently covered by DIN standards. A procedure known as 'Zulassungen' allows a group of experts to define acceptable combinations of production, calculation, testing and use of high strength steels in buildings.

If there is no Zulassungen in place, then a proof engineer, in collaboration with the appropriate local authority, will define the tests necessary for the derivation of acceptable loads for the particular application in question.

There is a philosophical difficulty with tests, described by Popper (1972). He points out that the best that can be hoped from a test is the survival of the conjecture being tested. It cannot be established as certainly true nor even as probable. However, a test can disprove a conjecture. By bringing out mistakes it makes engineers understand the difficulties of the problem they are trying to understand. Popper quotes John Archibald Wheeler as saying, 'Our whole problem is to make the mistakes as fast as possible'.

In comparison with steel or concrete, structural glass has not been tested very much. It is therefore prudent to assume that it is yet very well understood. As a consequence of this, the engineer may well wish to carry out more tests than perhaps would be done with a more familiar material.

5.12.3 Statistical

The analysis of test data requires careful consideration. Engineers are familiar with the Normal Distribution model but the Weibull Distribution model is often used in experiments involving tests-to-failure because it takes into account the random nature of the causes of failure. This is particularly relevant for a brittle material like glass in which the failure-causing flaw may not be located at the point of maximum tensile stress. The Weibull Distribution is described in Weibull (1939 and 1951), in Crowder *et al.* (1991) and in Ashby & Jones (1998).

Section 4.7 of Creyke, Sainsbury and Morrell (1982) shows how to set proof test conditions so that those components that would fail in less than the desired lifetime do so in the proof test.

It is sometimes tempting to remove outlying data to improve the fit of data to distribution models but before doing so it is prudent to check that this is valid. Chauvenet (Fair, 1996) proposed a widely accepted method of deciding whether to accept data.

Proof testing can be used to cheat the statistics by selecting and rejecting the low-strength tail of the distribution. Unfortunately slow crack growth will occur during the process, which hastens the demise of the surviving samples.

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6 Panes supported on 2, 3, 4 or more edges

6.1 General description

Edge support is the traditional way of supporting glass. The USA, Canada, Australia and the UK all have Codes of Practice or National Standards for the design of 4 edge-supported glass. There is a European Code under development for the design of edge-supported glass. The glass can be held in place on its supporting frame by a wide range of products and materials beginning with putty and only limited by budget and human imagination.

With annealed, heat-strengthened and laminated panes, three, four and more edge support provides a degree of redundancy. Even if the glass cracks it can still continue to span across the supporting frame and stay in place long enough to be noticed and repaired. Toughened glass may stay in place if it is well held around its edges but its ability to carry any load will be eliminated by the cracking.

6.2 Rules of thumb

6.2.1 Strength

Traditional variations in national design stresses can be traced to differences in loading. For example, Belgium uses a 1 in 20 year 10 minute wind pressure, compared with the UK's and Holland's 1 in 50 year 3 second gust pressure.

The Dutch design stresses in Table 6.1 are slightly more conservative than those in Table 6.2.

6.2.2 Deflection

Section 4.6 addresses the accommodation of movement.

If the anticipated deflection of a glass pane with all edges supported and held is more than one half of the pane's thickness then its behaviour cannot be modelled accurately by linear theory. Membrane stresses can occur in plates whose edges are supported but not clamped, for example a circular plate supported by a ring. Even if the plate is free to slide over its supports, in-plane circumferential compressive stresses can balance in-plane radial tensile stresses in resisting out-of-plane loads.

Excessive deflection of glass spandrel panels may cause contact between the glass and the material behind (concrete or blockwork, for example) and this may lead to breakage. In cities such as Hong Kong, where land is very expensive, the architect will be under pressure to save every millimetre and may wish to detail very small gaps behind the glass.

Table 6.1 Design stresses (source: Concept Richtlijn: Constructief Glas (Holland), October 1996)

Table of **design stresses** for use with **factored loads** and, where appropriate, **non-linear analysis**. The first figure is for single panes, whether monolithic or laminated. The second figure is for each pane of a double glazed unit. **The reader should not use these or any other stresses without careful thought and further enquiry where necessary**

Type of glass	Permanent loads	Medium-term loads	Short-term (gust) loads
Float glass	7N/mm^2-single 6N/mm^2-double	17N/mm^2-single 14N/mm^2-double	28N/mm^2-single 24N/mm^2-double
Heat-strengthened glass	22N/mm^2-single 19N/mm^2-double	24N/mm^2-single 21N/mm^2-double	37N/mm2-single 32N/mm2-double
Toughened glass	50N/mm^2-single 43N/mm^2-double	53N/mm^2-single 46N/mm^2-double	56N/mm2-single 48N/mm2-double

Table 6.2 Short-term allowable tensile stress for use with unfactored loads
(source: Pilkington Glass Consultants)

Glass type	Short-term allowable tensile stress for use with unfactored loads
Float glass up to t = 6mm	41N/mm^2
Float glass with t = 8mm	34.5N/mm^2
Float glass up to t = 10mm	28N/mm^2
Patterned glass	27N/mm^2
Wired glass	21N/mm^2
Toughened glass	59N/mm^2

Table 6.3 Allowable tensile stresses under medium- and long-term loads for use with unfactored loads (source: Pilkington Glass Consultants)

Load type	Annealed glass	Toughened glass
Snow	Short-term value/2.6	Short-term value/2.6
Water and shelves	7N/mm^2	35N/mm^2
Floors	8.4N/mm^2	35N/mm^2
Self-weight	As the load type it is associated with or 7N/mm^2 if assessed separately	As the load type it is associated with or 35N/mm^2 if assessed separately

NOTE: Some engineers use 30N/mm^2 (i.e. one half of the short-term figure) instead of 35N/mm^2. In the case of annealed glass in floors, long duration working stresses are used only when all the edges of the glass are fully supported perpendicular to the plane of the glass by adquately stiff members

Table 6.4 summarises the limits on deflections set by various international codes and trade organisations.

2 edge support

The deflection of one-way spanning plates in bending is covered by simple linear theory, to be found in any structural handbook.

Non-linear theory deflection will be somewhere between the deflection calculated using linear bending theory and the deflection calculated assuming the pane acts as a catenary. The engineer must decide what support stiffness and degree of attachment are available to permit catenary action.

Triangular pane with 3 edge support

Linear theory deflections may be calculated using formulae given by Roark and Young (1977), table 26, cases 17 (equilateral triangle) and 18 (right angled triangle).

Non-linear theory deflection may be calculated accurately by finite element analysis. An approximate answer can be found by estimating the size of an 'equivalent' circular pane and using the parametric study by Vallabhan *et al.* (1994) or by estimating the size of an equivalent rectangle and using the Canadian formulae given on this page.

Rectangular pane with 2, 3 or 4 edge support

Linear theory deflections may be calculated using formulae given by Roark and Young (1977), table 26, cases 1 to 13.

Non-linear theory deflection with 4-edge support is covered in section 5.12.

Quadrilateral pane with 4 edge support.

Linear theory deflections may be calculated for parallelograms using formulae given by Roark and Young (1977), table 26, cases 14, 15 and 16.

Non-linear theory deflection may be calculated accurately by finite element analysis. An approximate answer can be found by estimating the size of an 'equivalent' circular pane and using the parametric study by Vallabhan *et al.* (1994). The Canadian Code presents a formula for 4 edge-supported glass which it believes will give answers within 10% of measured deflections. The formula is as follows:

$$w = h \exp(r_0 + r_1 x + r_2 x^2)$$

where: w = centre deflection (mm)
$x = \ln[\ln\{p(ab)^2/(Eh^4)\}]$
a = short dimension (mm)
b = long dimension (mm)
h = actual glass thickness (mm)
p = uniform lateral pressure (kPa)
E = Young's Modulus (kPa) (70,000,000kPa)
r_0, r_1 and r_2 are coefficients dependent on the ratio b/a:

$$r_0 = 0.553 - 3.83(b/a) + 1.11(b/a)^2 - 0.0969(b/a)^3$$
$$r_1 = -2.29 + 5.83(b/a) - 2.17(b/a)^2 + 0.2067(b/a)^3$$
$$r_2 = 1.485 - 1.908(b/a) + 0.815(b/a)^2 - 0.0822(b/a)^3$$

Because of the double natural logarithm, the formula is clearly only valid when the expression inside { } is greater than 2.718. It does not work with thick panes spanning short distances under low loads, such as the worked example in chapter 13.

The Canadian Code gives the following example:

a = 1000mm
b = 2000mm
h = 5.6mm (minimum thickness of 6mm glass to Canadian standards)

From these figures it calculates:

$r_0 = -3.4422$
$r_1 = 2.3436$
$r_2 = 0.2714$

From these it calculates:

Pressure	*Centre deflection*
1kPa	8mm
2kPa	13mm
4kPa	21mm

To these figures should be added the deflection of the supports. Rotational and in-plane restraints will reduce the calculated deflections but may rapidly increase stresses around the edges of the plate.

The Canadian Code's calculated deflections agree closely with those derived from the use of Moore's charts in United States Departments of the Army, the Navy and the Air Force (1990). Moore's charts

Table 6.4 Deflection limits

Document	Deflection limit	Notes
BS 6262	$L/125$ (single glazing) or $L/175$ (insulating glass units)	Allowable deflections of the edges of four-edge fully-supported glass
BS 5516	Single glazing: $(S^2 \times 1000)/180$ or 50mm, whichever is the less	Allowable deflection of the edges of 2-edge-supported glass where S = span (m) of supporting edge
BS 5516	Hermetically sealed double glazing: $(S^2 \times 1000)/540$ or 20mm, whichever is the less	Allowable deflection of the edges of 2-edge-supported glass where S = span (m) of supporting edge
BS 5516	Single glazing: $8S$	Allowable deflection of the edges of 4-edge-supported glass where S = span (m) of supporting edge ($S \leq 3$m)
BS 5516	Single glazing: $12 + (4S)$	Allowable deflection of the edges of 4-edge-supported glass where S = span (m) of supporting edge ($S > 3$m)
BS 5516	Hermetically sealed double glazing: $(S \times 1000)/175$ or 40mm, whichever is the less	Allowable deflection of the edges of 4-edge-supported glass where S = span (m) of supporting edge
CAN/CGSB-12.20-M89	$L/175$	Deflection of mullions simply supported at the corners of a glass plate
AS 1288-1994	$L/150$ (buildings < 10m high) or $L/240$ (buildings > 10m high)	Deflection of mullions simply supported at the corners of a glass plate
AS 1288-1994	$L/60$	Deflection of unframed toughened glass under design wind loading
ASTM E1300-94	$L/175$	Deflection of supports of edges of glass under design load
ASTM E1300-94	19mm	Deflection of glass (not mandatory)
AAMA *Skylight and sloped glazing*, 1987	$D_g = 0.4\ (L_g/100)^2$ (insulating glass units)	D_g = max allowable deflection in inches and L_g = span of glass edge in inches
AAMA *Skylight and sloped glazing*, 1987	$D_g = 0.6\ (L_g/100)2$ (other types of glass)	D_g = max allowable deflection in inches and L_g = span of glass edge in inches
GANA *Glazing Manual*, 1997	As ASTM E1300	Warns that 'excessive deflection can cause poor performance of glazing gaskets or tapes and glass-to-metal contact, causing glass breakage'.

AAMA: American Architectural Manufacturers' Association
GANA: Glass Association of North America

Table 6.5 Checklist of items to consider when considering thermal stress

Contributing factor	Description
Heat sinks	Glazing into masonry rebates
Shadows	Vertical, horizontal or diagonal
Shaped panes	Triangles, rounded shapes
Interior temperature	Non-vented heat traps
Applied labels	More than 1% of glass area
Reflective glass	Coated no. 2 or no. 3 surface
Sealed units	Double or triple glazed
Frame mass	Heavy exterior mullions
Glass edges	Impact damage
Orientation	East, South or West elevations
Large sizes	Edge area over 100 000mm^2
Frame type	Non-thermally broken
Interior shading	Heavy curtains, venetian blinds
Adjacent reflecting surfaces	Water, snow, reflective glass
Tinted glass	Bronze, grey, green
Aspect ratio	Length:width ratio > 5
Frame colour	Light or dark
Exterior shading	Returns, projections, overhangs
Glass edges	Serration hackle, spalling, chipping
Outdoor temperature	Below -12°C
Sealed units	Offset spacer corner joints
Altitude	Above 1500m
Solar intensity	Above 800W/m^2
Annealed glass	Clear, $t > 6$mm

Table 6.6 Resistance to thermal stresses

Best	Toughened glass
Medium	Heat-strengthened glass
Worst	Annealed glass

NOTE: Heat-strengthened glass is adequate to resist thermal stresses in most normal UK building environments also predict stresses in the non-linear response of thin plates. For the example just given, the associated peak stresses in the glass are as follows:

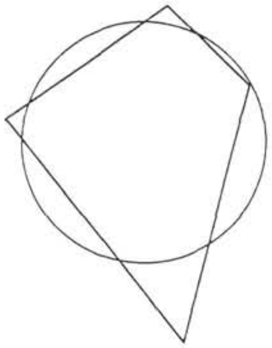
Pressure	Centre deflection	Peak unfactored stress
1kPa	8mm	17N/mm^2
2kPa	13mm	27N/mm^2
4kPa	21mm	40N/mm^2

As the loads increase the peak stresses migrate from the centre of the glass towards the corners.

Regular polygonal panes
Linear theory deflections may be calculated using formulae given by Roark and Young (1977), table 26, cases 19 and 20.

Non-linear theory deflection may be calculated accurately by finite element analysis. An approximate answer can be found by estimating the size of an 'equivalent' circular pane and using the parametric study by Vallabhan *et al.* (1994) or by estimating the size of an equivalent rectangle and using the Canadian formulae given earlier.

Irregular polygonal panes
Engineering judgment may be used to apply the established behaviour of a circular plate or membrane to an irregular shape.



Linear theory deflections may be calculated using formulae given by Roark and Young (1977), table 24.

Non-linear theory deflection may be calculated accurately by finite element analysis. An approximate answer can be found by estimating the size of an 'equivalent' circular pane and using the parametric study by Vallabhan *et al.* (1994) or by estimating the size of an equivalent rectangle and using the Canadian formulae given in earlier.

Circular pane with circular support
Linear theory deflections may be calculated using formulae given by Roark and Young (1977), table 24.

Non-linear theory deflection may be calculated accurately by using the parametric study by Vallabhan *et al.* (1994).

6.2.3 Resistance to thermal stresses

Checklist of items to consider
Thermal stress and breakage cannot always be precisely predicted as many of the contributing factors are difficult to quantify. During the design process the designer should consult one or more reputable manufacturers to evaluate the risk of thermal breakage. The Table 6.5 checklist is taken from the Canadian Code.

Further guidance may be found in Pilkington's *Glass and Thermal Safety*.

6.3 Performance in use

A plate resists wind pressure or other uniformly distributed surface loads by deforming and developing internal and surface stresses. A glass plate under increasing pressure deforms elastically until sudden failure is initiated at a surface flaw that magnifies the effect of the tensile stress. Resistance of glass to pressure is limited, not only by tensile stress, but also by the severity of stress concentrations caused by flaws.

This interaction of stress and flaws means that glass plate resistance is influenced by area, loading history, aspect ratio, surface compressive stress from heat treatment and flaws from manufacturing, handling, installation and cleaning processes. A rational calculation of resistance must account for the pattern of stresses set up by the loading and support conditions, statistical variation associated with the distribution of surface flaws and the accumulated experience of past and current practice. Chapter 5 provides guidance on calculations.

6.4 Selection, design and application

Section 2.2 discusses the many non-structural issues that influence design: thermal transmission, solar radiation, condensation, rainwater runoff, fire, acoustic behaviour, access, installation, cleaning, inspection, maintenance, repair, replacement, availability, appearance, fit, position, durability, environmental impact and lifecycle costing.

Before carrying out any calculations, it is most important that the designer has a clear idea of how the structure will behave. Because of the brittle nature of glass it is also important that the designer has a clear idea of how the structure is to behave after one or more glass elements have failed. It is also important to assess the safety implications of failure of a piece of glass: what is the likelihood of people being injured by falling glass, for example? It is only when the structural behaviour is understood that decisions can be made about what calculations are appropriate.

Increasing areas of glass in buildings have increased the likelihood of damage by flying debris in high winds. The South Florida Building Code contains a test in which a 4" × 2" piece of timber is fired at a piece of glass, which is then cyclically loaded 1000 times. In Australia there has been a trend towards laminated glass in curtain walls and a consequent rash of visual and structural defects. In Hong Kong, the committee that is preparing their new glass code is studying the problem of flying debris and is debating whether it is right to give advice which might lead to higher building costs.

Wills, Wyatt and Lee (1998) presents the work of a research group concerned with assessing the vulnerability of densely populated urban areas subject to tropical cyclone activity. It contains a model for the determination of the damage potential posed by flying debris.

The design and selection of glass for overhead and sloped glazing requires special attention for a number of reasons including the following:

- Sloped glass is more susceptible to impact from falling objects, wind-borne debris and missiles than vertical glass.
- Sloped glazing in most cases is more likely to fall from the opening when it breaks than vertical glass. Good design indicates that the choice of glass must be based on eliminating or minimising hazards so far as is reasonably practicable.
- Snow loads may be imposed on the glazing for long periods. The strength of glass and the contribution of the plastic interlayer in laminated glass are both time-dependent.
- For most orientations, sloped glass and overhead glass may reach a higher temperature than vertical glazing because the sun's radiation is more nearly normal to the glass surface and because of stratification of warm air in the building. The converse is also true, and the orientation of the sloped or overhead glass may allow its temperature to fall further than that of vertical glass on clear nights.

Most manufacturers will provide guidance on what thickness and type of glass should be used, based on their experience. The Glass and Glazing Federation also provides guidance in its *Glazing Manual*, item 7.1.

6.5 Design details

Design details are shown in Figs. 6.1-6.4.

6.6 Worked example

A worked example comparing UK, Australian, Canadian and USA codes appears on pages 70-74.

6.7 References

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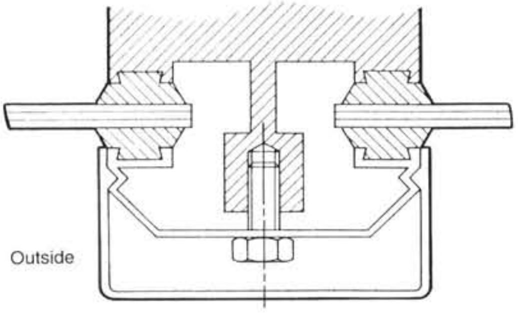
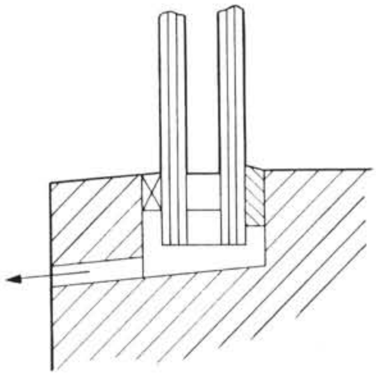



Drained system

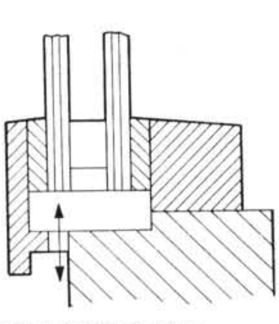
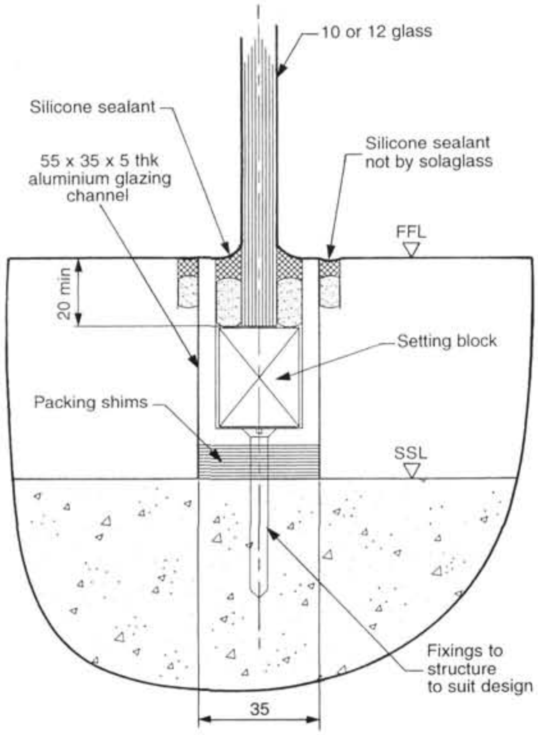

Ventilated and drained system

Fig. 6.1 Some of the many edge details shown in BS 6262 (Extracts from British Standards are reproduced with the permission of BSI under licence number PD/1999 0619. Complete copies of the standard can be obtained by post from BSI Customer Services, 389 Chiswell High Road, London W4 4AL)

Fig. 6.2 Typical edge clamp detail (courtesy of Solaglas)



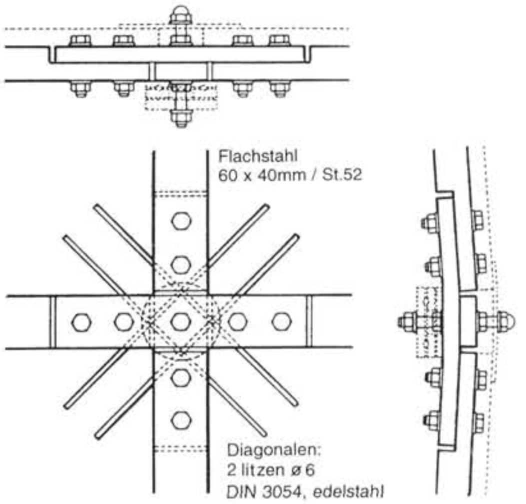


Fig. 6.4 Jorg Schlaich's Hamburg edge detail

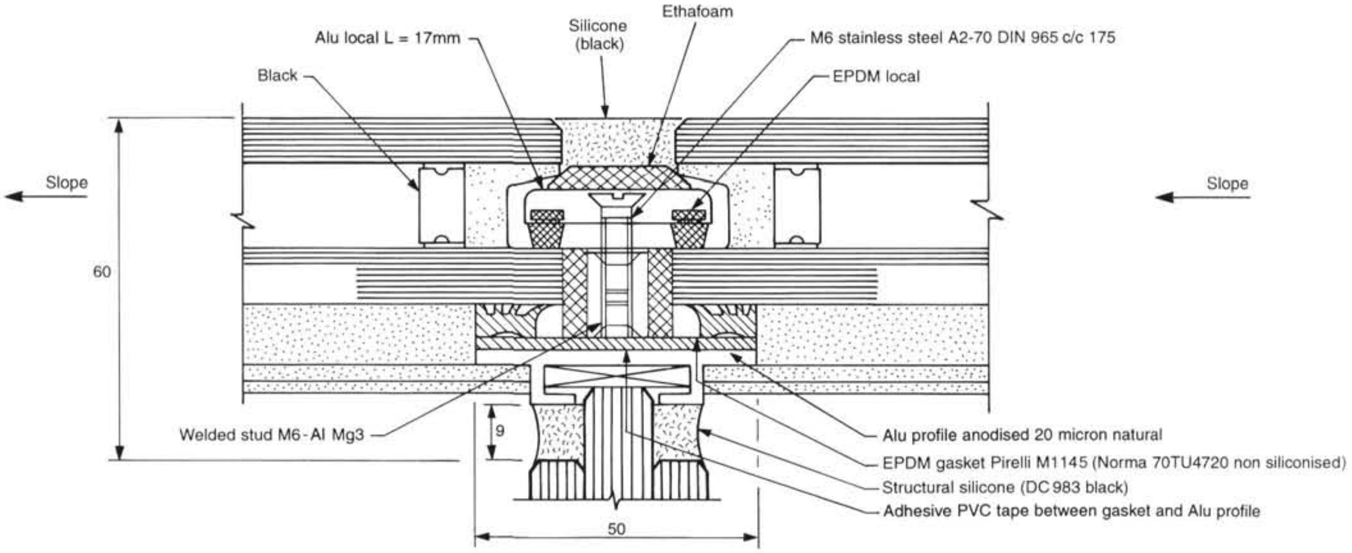


Fig. 6.3 Robert Nijsse's Budapest edge detail

Worked example

This is sloping glazing 1600mm wide by 2800mm tall, leaning outwards at 45° to the horizontal. In addition to its permanent dead load stresses, it is subjected to inward and outward wind pressures of 1.2kPa (3-second gust).

For thermal reasons the unit is to be double-glazed. For visual reasons, a deflection limit of L/100 under full wind load is required.

This worked example will calculate glass behaviour using the British, Australian, American and Canadian Codes. It is not intended to be a model of how to assess an appropriate glass thickness using these different Codes. Rather, by applying the same approach to each Code, it tries to identify some of their differences and some of their similarities.

This worked example ignores the effects of atmospheric temperature and pressure changes on double-glazed (insulating glass) units, which is non-conservative. Appendix E deals with this.

This worked example does not address the different minimum glass thicknesses allowed by different national Codes.

For each non-UK Code it will be necessary to calculate an appropriate wind loading. For a fairer comparison it would be necessary to apply the relevant national wind Code to the same circumstances as the British example. For this exercise the wind load will be assumed to be based only on the current relevant national wind Code's averaging interval, using the table below. This is a crude simplification.

Comparison of codes

Country	Averaging interval for wind speed used in glass code	Ratio of national design wind speed to UK design wind speed	Ratio of design wind pressure to UK design wind pressure
UK	3 seconds	1	100%
Australia	3 seconds	1	100%
Canada	1 minute	0.8	64%
USA	1 minute	0.8	64%

For this worked example, assume a 10mm toughened inner pane and a 10.8mm laminated heat-strengthened outer pane.

Glass area = 1.6 × 2.8 = 4.48m^2.

Aspect ratio = 2.8/1.6 = 1.75

Self-weight of each pane ≈ 0.01 × 25 = 0.25 kPa, acting at 45° to the normal to the surface.

Self weight pressure normal to each pane = 0.25 cos 45 = 0.18kPa

Load-sharing

Appendix D shows that load-sharing of wind loads can occur, with the sharing determined by the relative stiffnesses of the panes. Note that different national codes may take different approaches to load sharing. For example, AS1288 requires each pane of a sealed insulating glass unit to be designed for 0.67 of the total design pressure on the unit, when the panes are of the same thickness. It refers designers to the manufacturer of the sealed unit when the panes are of different thickness.

For the sake of simplicity, this worked example assumes the same approach to be used with each Code, which is described in the following paragraphs.

The stiffness of each pane is proportional to the cube of its thickness, assuming that loads are carried by bending. The relative stiffnesses are shown in the table right.

10mm Toughened inner		$10^3 = 1000$
10.8mm laminated	Fully composite	$10.8^3 = 1260$
10.8mm laminated	Layered (non-composite)	$2 \quad 5^3 = 250$

Whether or not the laminated pane acts compositely depends, among other things, on its temperature. The load-sharing proportions can range between 1000:1260 and 1000:250, i.e. between 44%/56% and 80%/20%.

For simplicity, these worked examples also assume that each pane carries its own self-weight, which is a questionable assumption given the coupling of the panes by the airspace.

The inner and outer panes will be checked for their largest respective loads calculated using these proportions.

Deflections
First check the deflection of the 10mm toughened pane under 80% of the wind load using the Canadian Code method.

80% of 1.2kPa is 0.96kPa. Using the Canadian formulae and a glass thickness of 9.7mm (minimum thickness to BS EN 572-2) gives a mid span deflection under this load of 9mm, which is less than L/100 = 16mm, therefore OK.

Then check the deflection of the 10.8mm laminate, assuming layered behaviour, under 20% of 1.2kPa, i.e. 0.12kPa per 5mm layer (4.8mm minimum thickness to BS EN 572-2).

The Canadian formulae give a mid-span deflection of 8mm, which is also OK.

Thinner glass might, just, satisfy the deflection limit.

Worked example to British Code – BS 6262

Dead load.
BS 6262 does not explicitly deal with long-term stresses in glass because it deals only with vertical glazing, so some means is needed to do this.

BS 5516 converts long-term loads to equivalent short-term figures by multiplying by 2.6. Table 5.7 of this guide gives modification factors for load duration taken from the draft European Code. The ratio of permanent to short term factors is 0.72/0.27 = 2.67.

Therefore, for this worked example, multiply dead load by 2.67 to convert to an 'equivalent' short-term load:

$$0.18 \times 2.67 = 0.48\text{kPa} - \text{say } 0.5\text{kPa}.$$

Toughened glass
The highest share of load of the toughened inner glass is 80% of the wind, i.e.

$$0.8 \times 1.2 = 0.96\text{kPa}.$$

Add to this the short-term 'equivalent' dead load of 0.5kPa, giving a total load of 1.46kPa.

Figure 12 of BS 6262 gives, for a glass area of 4.48m^2 and a 3-second mean loading of 1.46kPa, a glass thickness of 6mm.

Laminated glass
The highest share of load of the laminated glass occurs when full composite action is present and is 56% of the wind pressure, i.e.

$$0.56 \times 1.2 = 0.67\text{kPa}$$

Add to this the short-term 'equivalent' dead load of 0.5kPa, giving a total load of 1.17kPa.

Figure 13 of BS 6262 gives, for a glass area of 4.48m^2 and a 3-second mean loading of 1.17kPa, an annealed glass thickness of 6mm (i.e. 3mm + 3mm). BS 6262 does not contain charts for heat-strengthened laminated glass and neither does BS 5516.

The lowest share of load of the laminated glass occurs when no composite action is present and is 20% of the wind load, i.e.

$0.2 \times 1.2 = 0.24\text{kPa}$

Add to this the short-term 'equivalent' dead load of 0.5kPa, giving a total load of 0.74kPa, to be shared equally between the two layers of glass in the laminate.

Figure 7 of BS 6262 gives, for a glass area of 4.48m^2 and a 3-second mean loading of 0.74/2 = 0.37kPa, an annealed glass thickness of 4mm for each sheet in the laminate.

Conclusion
The proposed build-up satisfies the requirements of BS 6262 for the strength of the glass. Thinner glass might be strong enough and stiff enough.

Worked example to Australian Standard – AS 1288-1994

Dead load.
AS1288, table 3.2, specifies design stresses for ordinary annealed glass and allows wind load to be resisted by stresses double those that resist sustained load.

Therefore, for this worked example, multiply dead load by 2 to convert to an 'equivalent' short-term load:

$0.18 \times 2 = 0.36\text{kPa}$ – say 0.4kPa

Toughened glass
The highest share of load of the toughened inner glass is 80% of the wind, i.e.

$0.8 \times 1.2 = 0.96\text{kPa}$

Add to this the short-term 'equivalent' dead load of 0.4kPa, giving a total load of 1.36kPa.

Figure E3 of AS1288 gives, for a glass area of 4.48m^2 and a 3-second mean loading of 1.36kPa, a glass thickness of 5mm.

Laminated glass
The highest share of load of the laminated glass occurs when full composite action is present and is 56% of the wind, i.e.

$0.56 \times 1.2 = 0.67\text{kPa}$

Add to this the short-term 'equivalent' dead load of 0.4kPa, giving a total load of 1.07kPa.

Figure E8 of AS1288 gives, for a glass area of 4.48m^2 and a 3-second mean loading of 1.07kPa, a laminate thickness of 8.38mm (assuming annealed float glass).

The lowest share of load of the laminated glass occurs when no composite action is present and is 20% of the wind load, i.e.

$0.2 \times 1.2 = 0.24\text{kPa}$

Add to this the short-term 'equivalent' dead load of 0.4kPa, giving a total load of 0.64kPa, to be shared equally between the two layers of glass in the laminate.

Figure E5 of AS1288 gives, for a glass area of 4.48m^2 and a 3-second mean loading of 0.64/2 = 0.32kPa, a heat-strengthened glass thickness of 3mm for each sheet in the laminate.

Conclusion
The proposed build-up satisfies the requirements of AS1288 for the strength of the glass. Thinner glass might be strong enough and stiff enough.

Worked example to Canadian Standard – CAN/CGSB-12.20-M89

The Canadian Code requires that factored resistance is greater than factored loads. For a combination of dead plus wind load it applies factors of 1.25 and 1.5 respectively. The factored loads are combined using a load combination factor and an importance factor. For this example, these are both equal to 1, so the factored load equals 1.25 times dead load plus 1.5 times wind load.

The factored resistance of a plate of glass is expressed as

$R = cR_{\text{ref}}$

where c is a strength coefficient, calculated as the product of 4 components and R_{ref} is the factored resistance of 'reference glass', which is annealed glass loaded to failure in 60 seconds.

Dead load

The Canadian Code deals with load duration via a coefficient c_3, which is used in calculating the load resistance of a glass plate. For annealed glass, c_3 is 1.0 for 1-minute wind gusts and 0.4 for dead load, a ratio of 2.5.

As the Canadian Code does not advise how to combine dead and wind load resistance, this example will multiply dead load by 2.5 and treat it as a short-term load.

$0.18 \times 2.5 = 0.45$kPa – say 0.5kPa.

Wind load

Assumed wind pressure = 0.64×1.2kPa = 0.77kPa, say 0.8kPa.

Toughened glass

The highest share of load of the toughened inner glass is 80% of the wind, i.e.

$0.8 \times 0.8 = 0.64$kPa.

Combine this with the short-term 'equivalent' dead load of 0.5kPa, giving a total factored load of:

$1.25 \times 0.5 + 1.5 \times 0.64 = 1.59$kPa

Toughened glass has a strength coefficient under wind load of 4.0, according to Table 1 of the Canadian Code. It therefore requires that R_{ref} equals $1.59/4 = 0.4$kPa.

Table 2 of the Canadian Code tabulates R_{ref} for different aspect ratios, glass thicknesses and glass areas. For an aspect ratio of 2 (1.75 is not tabulated), 4mm glass is the required glass thickness for strength.

Laminated glass

The highest share of load of the laminated glass occurs when full composite action is present and is 56% of the wind pressure, i.e.

$0.56 \times 0.8 = 0.45$kPa

Combine this with the short-term 'equivalent' dead load of 0.5kPa, giving a total factored load of:

$1.25 \times 0.5 + 1.5 \times 0.45 = 1.3$kPa

Laminated heat-strengthened glass has a strength coefficient under wind load of 2.0, according to Table 1 of the Canadian Code. It therefore requires that R_{ref} equals $1.3/2 = 0.65$kPa.

Table 2 of the Canadian Code tabulates R_{ref} for different aspect ratios, glass thicknesses and glass areas.

For an aspect ratio of 2 (1.75 is not tabulated), 5mm glass is the required glass thickness for strength.

The lowest share of load of the laminated glass occurs when no composite action is present and is 20% of the wind load, i.e. $0.2 \times 0.8 = 0.16$kPa. Combine this with the short-term 'equivalent' dead load of 0.5kPa, giving a total factored load of:

$1.25 \times 0.5 + 1.5 \times 0.16 = 0.87$kPa, i.e. 0.44kPa per layer

Heat-strengthened glass has a strength coefficient under wind load of 2.0, according to Table 1 of the Canadian Code. It therefore requires that R_{ref} equals $0.44/2 = 0.22$kPa.

Table 2 of the Canadian Code tabulates R_{ref} for different aspect ratios, glass thicknesses and glass areas. For an aspect ratio of 2 (1.75 is not tabulated), 4mm glass is the required glass thickness for strength.

Conclusion

The proposed build-up satisfies the requirements of CAN/CGSB-12.20-M89 for the strength of the glass. Thinner glass might be strong enough and stiff enough.

Worked example to US Standard – ASTM E 1300–94

ASTM E 1300 requires the calculation of an 'equivalent design load', which it defines as 'the magnitude of a 60 second duration constant provided by the specifying authority to represent the cumulative effects of the components of all loads acting on the glass'. It goes on to say that 'The transformation of loads to an equivalent design load to account for variations in magnitude, direction and duration is beyond the scope of this document'.

In the absence of alternative advice, this worked example will multiply dead load by 2.5 and treat it as a short-term load:

0.18 × 2.5 = 0.45kPa – say 0.5kPa

Wind load
Assumed wind pressure = 0.64 × 1.2kPa = 0.77kPa, say 0.8kPa

Toughened glass
The highest share of load of the toughened inner glass is 80% of the wind, i.e. 0.8 × 0.8 = 0.64kPa. Add this to the short-term 'equivalent' dead load of 0.5kPa, giving a total load of:

0.5 + 0.64 = 1.14kPa

From the charts in figure A4.1, 10mm annealed glass 1600mm × 2800mm has a 60s duration equivalent design load of about 1.4kPa. Toughened glass has a strength coefficient under wind load of 4.0, according to table A1.1 of the US Code. 10mm toughened glass therefore can sustain a 60s duration equivalent design load of 4 × 1.4 = 5.6kPa.

The charts in figure A4.1 suggest that 4mm toughened glass would be strong enough but that deflection would be a problem

Laminated glass
The highest share of load of the laminated glass occurs when full composite action is present and is 56% of the wind pressure, i.e.

0.56 × 0.8 = 0.45kPa.

Add this to the short-term 'equivalent' dead load of 0.5kPa, giving a total of:

0.5 + 0.45 = 0.95kPa

From the charts in figure A4.1, 10mm annealed glass 1600mm × 2800mm has a 60s duration equivalent design load of about 1.4kPa. Laminated heat strengthened glass has a strength coefficient under wind load of 1.8, according to table A2.2 of the US Code. 10mm laminated heat strengthened glass therefore can sustain a 60s duration equivalent design load of 1.8 × 1.4 = 2.5kPa.

The lowest share of load of the laminated glass occurs when no composite action is present and is 20% of the wind load, i.e. 0.2 × 0.8 = 0.16kPa. Add this to the short-term 'equivalent' dead load of 0.5kPa, giving a total of:

0.5 + 0.16 = 0.66kPa, i.e. 0.33kPa per layer.

From the charts in figure A4.1, 5mm annealed glass 1600mm × 2800mm has a 60s duration equivalent design load of about 0.7kPa. Heat strengthened glass has a strength coefficient under wind load of 2.0, according to table A1.1 of the US Code. 10mm laminated heat strengthened glass, acting as layers, therefore can sustain a 60s duration equivalent design load of:

0.7 × 2 = 1.4kPa.

Conclusion
The proposed build-up satisfies the requirements of ASTM E 1300–94 for the strength of the glass. Thinner glass might be strong enough and stiff enough.

7 Glass beams and fins

7.1 General description

7.1.1 Glass beams

Glass beams are exactly what the name implies – beams made of glass. Early examples can be found in the work of engineers Dewhurst McFarlane (Dawson, 1995) in England and Robert Nijsse (Nijsse, 1993) in Holland.

Glass beams are generally simply supported or cantilevering and are generally limited to the length of a single piece of glass that can be manufactured, i.e. about 6m for annealed glass, 4.5m for laminated annealed glass and 3.9m for toughened glass. A notable exception to this is the entrance canopy to the Yuraku-cho underground station in Tokyo (Dawson, 1997) designed by Dewhurst McFarlane, in which the cantilevering glass beams are made by bolting together 4 lengths of glass.

7.1.2 Glass fins

Like glass beams, glass fins are exactly what the name implies – fins made of glass. They are vertical or sloping beams used to support facades and to help resist wind and other lateral loads. The fins are attached to the panes of glass by silicone adhesive/sealants or by bolting. This Guide uses the term fin for vertical or near vertical elements loaded in bending and beam for horizontal or near horizontal elements loaded in bending.

Glass fins are generally simply supported or propped cantilevers or fully cantilevering. Fins longer than about 8m are usually top-hung and shorter fins are usually bottom-supported. An exception to this is the 13.5m tall ground-based glass wall at The Royal Opera House, Covent Garden, London (Dodd, 1999). Fins are not generally limited in height to the length of glass that can be manufactured in a single piece. The main difference between fins and beams is caused by the difficulty of forming joints that can carry sustained bending moments, particularly in laminated glass.

A notable early example of the use of glass fins is the Willis Corroon building in Ipswich, England (1975; Architect: Foster Associates; Engineer: Anthony Hunt Associates). The structural details of its glass walls are well described by Rice and Dutton (1995).

Fig. 7.1 The entrance canopy to the Yuraku-cho underground station in Tokyo (courtesy of Dewhurst Macfarlane & Partners with Structural Design Group/Kenji Kobayashi)

At the NCM Building in Cardiff (1993; Architect: Holder Mathias Alcock; Engineer: Ove Arup & Partners), the 30m-tall glass wall is suspended via glass fins from the curved roof. Bolted splices connect the 4m long pieces from which the fins are made. Such splices are usually friction-grip connections.

Great care is needed in the design and manufacture of friction grip splices. The material in direct contact with the glass must be soft enough not to cause stress concentrations on the glass and must be elastic enough to accommodate possible differential thermal behaviour between the glass and the splice plates. Some connections use a soft aluminium as the interlayer. If this is done, then particular care is needed to ensure that the correct grade is specified and used and that site processes do not change its hardness (for example grit blasting to roughen its surfaces and improve its coefficient of friction may harden its surfaces). The clamp plates must be sufficiently parallel to the glass surfaces not to cause excessive local bending when the bolts are tightened.

Glass fins and beams can be expensive.

7.2 Rules of thumb

7.2.1 Strength

Tensile strength

The slow growth of invisible flaws under sustained tensile loading has led engineers to design beams (in annealed glass) to very low tensile stresses, to protect the tensile edges, to provide considerable redundancy and even to provide steel cables to carry the tensile loads, relying on the glass to carry compression only.

Glass fins are often made out of lengths of glass that are bolted together. Bolt holes require toughened glass to be used. If bolting is not used, then annealed glass may be used if the circumstances of use and demands on the glass allow it, such as at the restored Covent Garden Opera House, London (Dodd, 1999).

Table 7.1 lists allowable (i.e. unfactored) tensile stresses commonly used in the UK in glass beams and fins for short-term loads such as wind gusts. Stresses should always be calculated assuming the least manufacturing tolerance thickness for a given nominal thickness. Deflection (rarely) or vibration or beam instability may well govern the design. Damage (including flaws not visible to the naked eye) will drastically reduce the ability of a glass edge to carry tensile loads.

Sedlacek (1995) lists some short-term tensile design stresses allowed by different German authorities for annealed glass. These range between 20 and 38N/mm^2 for use with linear plate analysis, and between 15 and 25N/mm^2 for use with non-linear plate analysis.

Table 7.2 lists allowable (i.e. unfactored) tensile stresses commonly used in the UK in glass beams and fins for medium- and long-term loads. Stresses should always be calculated assuming the thinnest allowable beam for a given nominal thickness. Deflection or vibration or beam instability may well govern the design.

Sedlacek (1995) lists some tensile design stresses allowed by different German authorities for toughened glass. These generally range between 35 and 60N/mm², with 105N/mm² allowed under exceptional circumstances.

In the absence of code-based allowable tensile stresses it is left to the judgment of the engineer what figures to adopt. Depending on the level of risk and the degree to which the structural system will give some warning before it fails, it may be appropriate to undertake some testing to establish design values. Chapter 5 provides some guidance for engineers who feel that testing is needed.

As long as the surface of the glass remains in compression under the applied loads, then the question of crack propagation does not arise and so-called 'static fatigue' is not an issue. Fig 7.3 shows how the stresses are distributed in the edge and body of a piece of toughened glass.

Shear strength

Shear stress may be thought to be a problem, because nobody quotes allowable shear stresses in glass.

One technique available to most engineers is finite element analysis. Such an approach will predict the location, magnitude and direction of the principal tensile and compressive stresses in the glass beam. It will quickly become apparent from such an analysis how important it is to take care over how a beam is supported, whether by bearing onto a setting block, or by gluing or by bolting.

Not everyone has access to software capable of performing finite element analysis and not everyone would want to use it if they had it. Much beam behaviour can be well modelled by 'strut and tie' models. Such a model can provide a good assessment of peak tensile stresses at midspan (peak bending) and at the supports (peak shear). This removes the need for allowable shear stresses.

As an alternative, engineers may prefer to use Mohr's stress circles to determine principal tensile stresses in regions of high shear. Examples of this can be found in Roark & Young (1977).

7.2.2 Deflection

At the low stress levels commonly used in designing glass beams and fins, deflection is rarely a problem.

Composite beams that use the glass in compres-

Table 7.1 Short-term allowable tensile stresses (source: Pilkington Glass Consultants/BS 5516)

Glass type	Short-term allowable tensile stress for use with unfactored loads
Float glass up to t = 6mm	28N/mm²
Float glass with t = 8mm	22.9N/mm²
Float glass up to t = 10mm	17.8N/mm²
Patterned glass	27N/mm²
Wired glass	21N/mm²
Toughened glass	59N/mm²

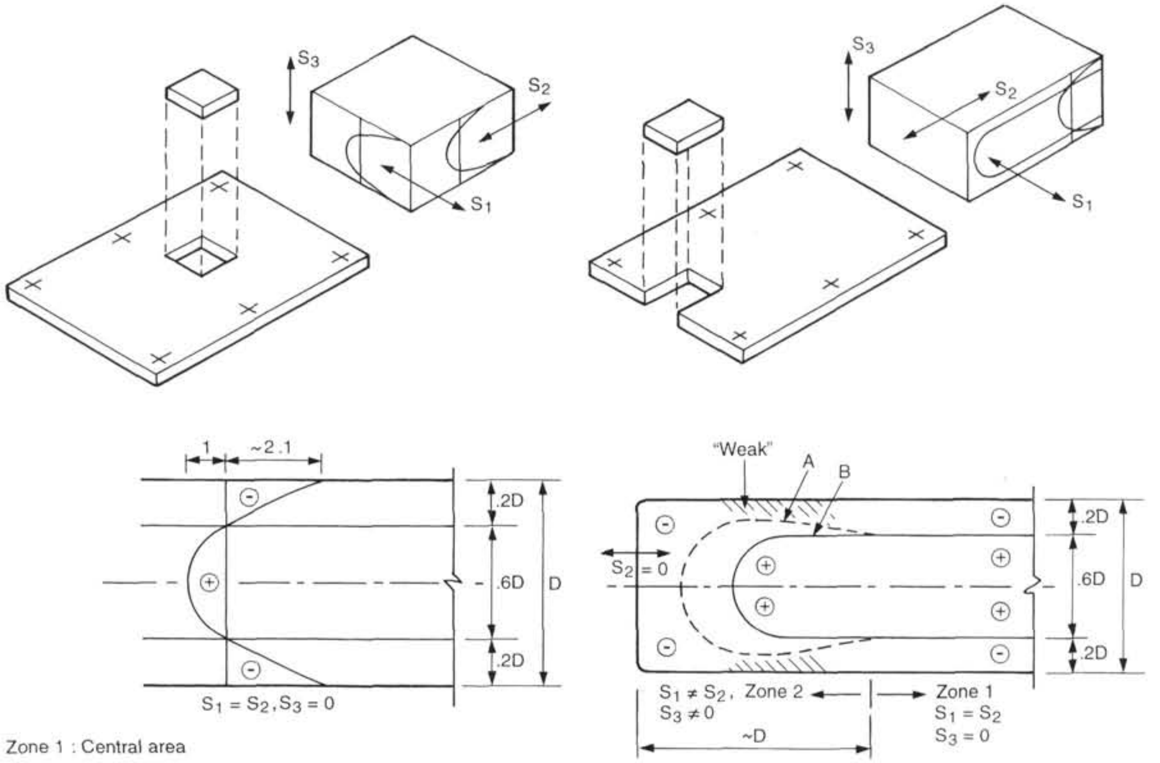
Fig. 7.2 Bolted splice in a glass fin (courtesy of Chris Jofeh)

Table 7.2 Allowable tensile stresses under medium- and long-term loads, for use with unfactored loads (source: Pilkington Glass Consultants)

Load type	Annealed glass	Toughened glass
Snow (2)	Short-term value/2.6	Short-term value/2.6
Water and shelves (3)	7N/mm²	35N/mm²
Floors (4)	8.4N/mm²	35N/m²
Self-weight	As the load type it is associated with or 7N/mm² if assessed separately	As the load type it is associated with or 35N/mm² if assessed separately

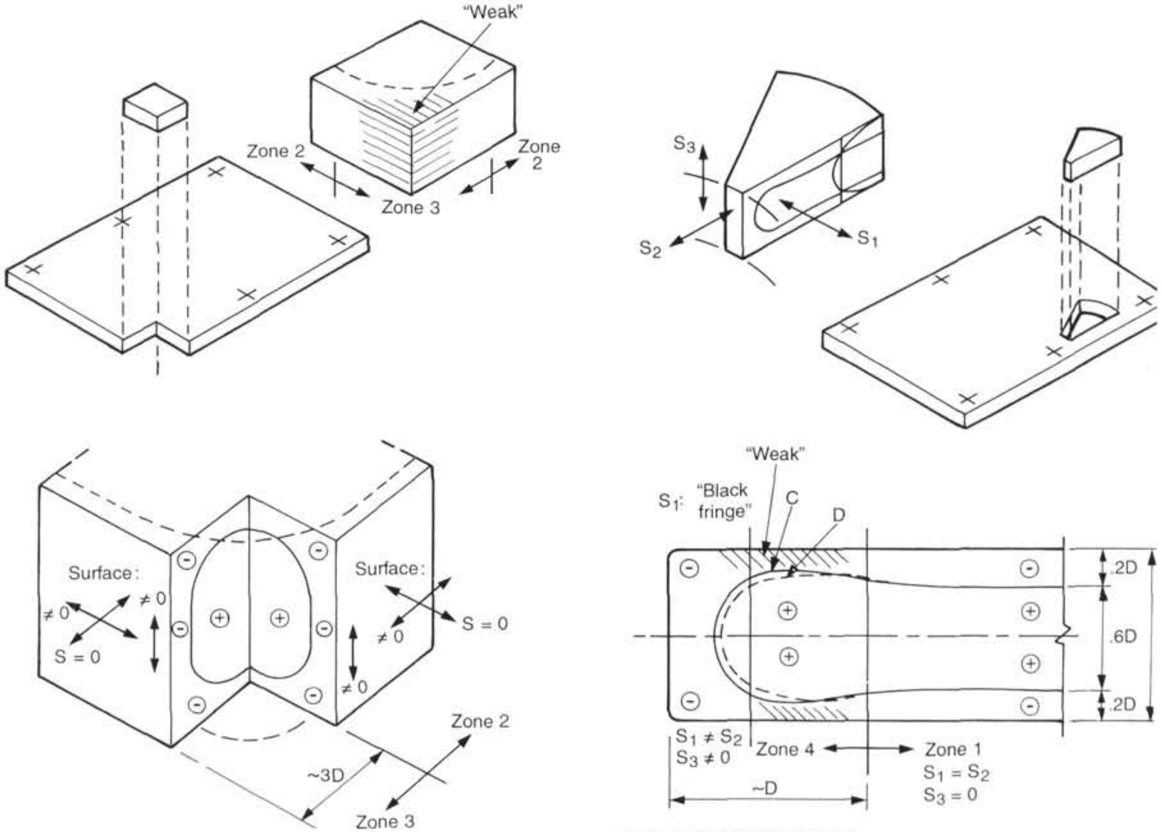
Notes: (1) Some engineers use 30N/mm² (i.e. one half of the short-term figure) instead of 35N/mm²
(2) BS 5516 (Patent glazing)
(3) BS on sight glasses for pressure vessels
(4) As (3) but upgraded when BS floor loads were increased

Fig. 7.3 Edge stresses and body stresses in toughened glass (courtesy RWTH)



Zone 1 : Central area

Zone 2 : Edge



Zone 3 : Corner

Zone 4 : Hole (without cone)

sion and, for example, steel in tension are more likely to be designed at higher stress levels and it is more important that deflections are checked.

Table 7.3 provides a simple way of assessing the minimum I required to satisfy a deflection limit.

Vibration should also be checked. A simple rule of thumb is:

$$F = \frac{16}{\sqrt{d}}\, Hz$$

where F is the first natural frequency in Hz and d is the midspan deflection of beam or tip deflection of cantilever under permanent (inertial) loads in mm.

Many engineers design so that $F > 5$Hz to avoid dynamic excitation by foot traffic or by wind.

7.2.3 Elastic stability

Thin beams, columns and cantilevers can easily become unstable if not adequately restrained. When a glass facade holds the fin in position and provides some restraint against rotation then instability of the fin is unlikely. Without rotational restraint, instability becomes more likely and further analysis should be carried out. Guidance can be found in Roark & Young (1977) and in Appendix E, which reproduces part of the Australian Code relating to fin buckling. Dodd (1999) warns of using the buckling section of the Australian Code for beams or fins with intermediate restraints. So and Chan (1996) describe the use of a finite element approach to both the strength and the stability analysis of a glass wall stiffened by glass fins.

When checking the buckling of the free edge of a glass fin, the first check should be a local buckling check using Bleich (1952), which is described by Yoxon (1987). A simplified check based on this method is:

$$M_{max} < \frac{Et^3}{6(1+\nu)}$$

where M_{max} is the maximum unfactored destabilising bending moment in the fin. Experience with full-size tests shows that $Et^3/6(1 + \nu)$ often determines the buckling limit and this has been confirmed by non-linear finite element analysis.

When using the Australian approach, the engineer should design and detail the restraints to the strength required by the Australian approach.

7.2.4 Resistance to thermal stresses

Thermal stress and breakage cannot always be precisely predicted as many of the contributing factors are difficult to quantify. During the design process the designer should consult one or more reputable manufacturers to evaluate the risk of thermal breakage. Chapter 6 provides a checklist of the various factors that contribute to thermal stress.

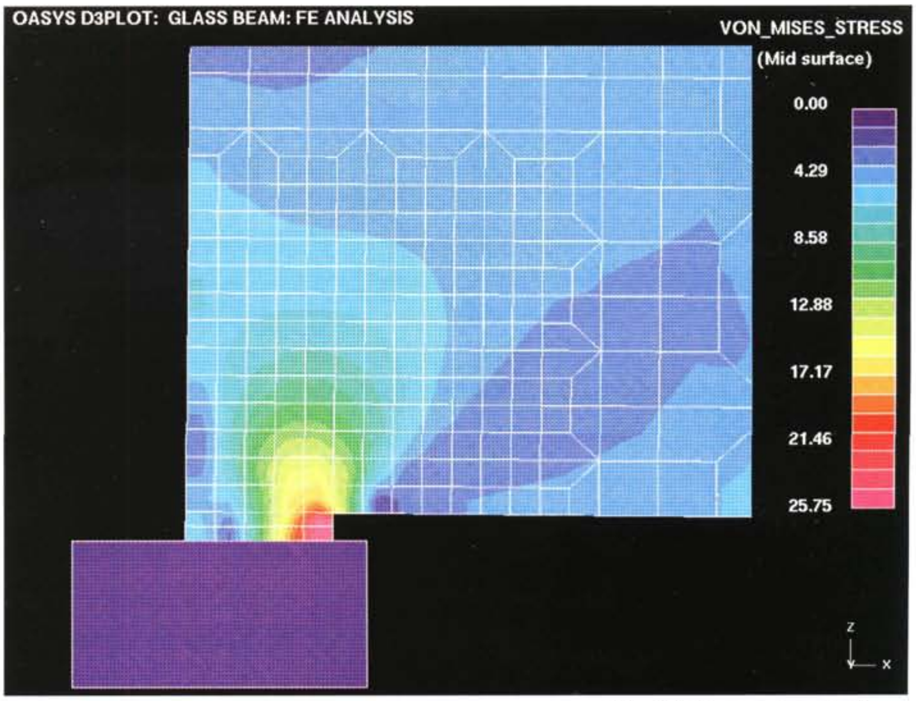


Fig. 7.4 Stresses in a simply supported beam on end bearings (courtesy Ove Arup & Partners)

7.3 Performance in use

A glass beam or fin resists loads by deforming and developing internal and edge stresses. Under increasing load the beam or fin deforms elastically until sudden failure is initiated at a surface flaw that magnifies the effect of the tensile stress. Resistance of glass to pressure is limited, not only by tensile stress, but also by the severity of stress concentrations caused by flaws. Glass beams are very susceptible to flaws or scratches on their tensile edges.

This interaction of stress and flaws means that glass beam resistance is influenced by area, loading history, aspect ratio, edge compressive stress from heat treatment and flaws from manufacturing, handling, installation and cleaning processes. A rational calculation of resistance must account for the pattern of stresses set up by the loading and support conditions, statistical variation associated with the distribution of surface flaws and the accumulated

Table 7.3 Minimum *I* to satisfy deflection limit
Units: L is span in m; E is assumed to be 70kN/mm^2

Load case	Minimum I to satisfy deflection limit (cm^4)		
Deflection limit	$L/200$	$L/360$	$L/500$
UDL of total load W (kN)	$3.72WL^2$	$6.70WL^2$	$9.30WL^2$
Central point load P (kN)	$5.95PL^2$	$10.71PL^2$	$14.88PL^2$
Two point loads, each $P/2$ kN, at the third points of the beam	$10.14PL^2$	$18.25PL^2$	$25.35PL^2$

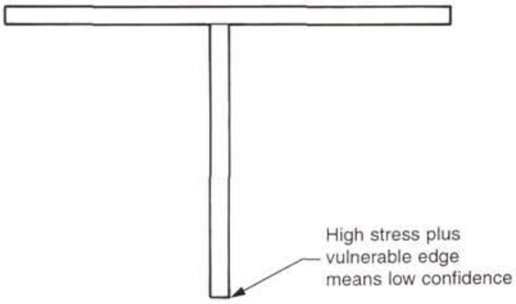
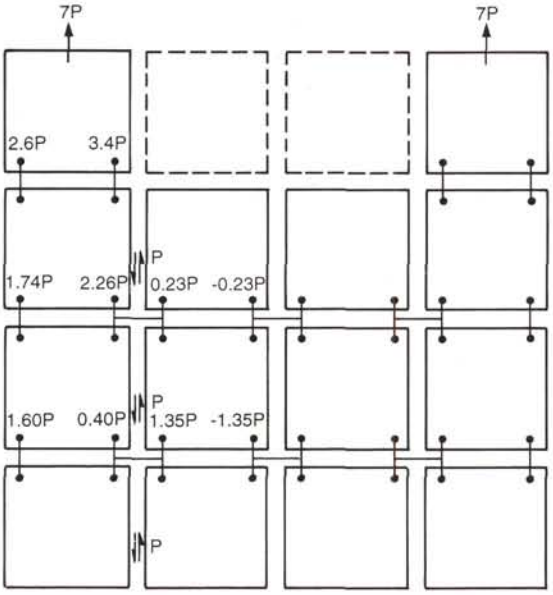


Fig. 7.5 Vulnerable edges of beams and fins



Notes
1. P = weight of a single pane
2. Tension is positive

Fig. 7.6 Analysis of vertical load paths after double breakage in The Serres at Parc de la Villette

experience of past and current practice. Chapter 5 provides guidance on calculations.

If the decision is made to use toughened or heat-strengthened glass and calculations indicate that the surface precompression will not be overcome by imposed tensile stresses, then fracture-mechanics-based calculations will not be needed.

Fig. 7.7 The glass beams that support the glass footbridge between 2 offices of Kraaijvanger•Urbis in Rotterdam (courtesy abt)

7.4 Selection, design and application

Critical issues may include some or all of the following non-structural items:

- thermal transmission and solar radiation
- condensation
- rainwater runoff
- fire
- acoustic behaviour
- access for installation, cleaning, inspection, maintenance, repair, replacement
- availability
- appearance and fit
- durability
- environmental impact and life cycle costing.

Critical structural issues include:

- how the overall structure will behave
- how the structure will behave after one or more glass elements have failed
- the safety implications of failure of a piece of glass, including the likelihood of people being injured by falling glass

When a glass beam supports, for example, a glass roof, the designer should consider what would happen to the glass in the roof if a beam breaks. There should be alternate load paths available to the roof glass so that it does not fail as a result of breakage of a single beam. Even if the roof glass deflects a large amount, this is clearly preferable to its collapse. The same thinking should be applied to the consequences of adhesive failure.

The choice of annealed, heat strengthened or toughened glass will rarely be determined by considerations of strength alone.

7.5 Design details

Figs. 7.7–7.11 show design details for various structures.

Fig. 7.8 The glass cantilevers in the staircase at the Pilkington Exhibition Centre, Lathom (courtesy of Pilkington/Chris Gascoigne)

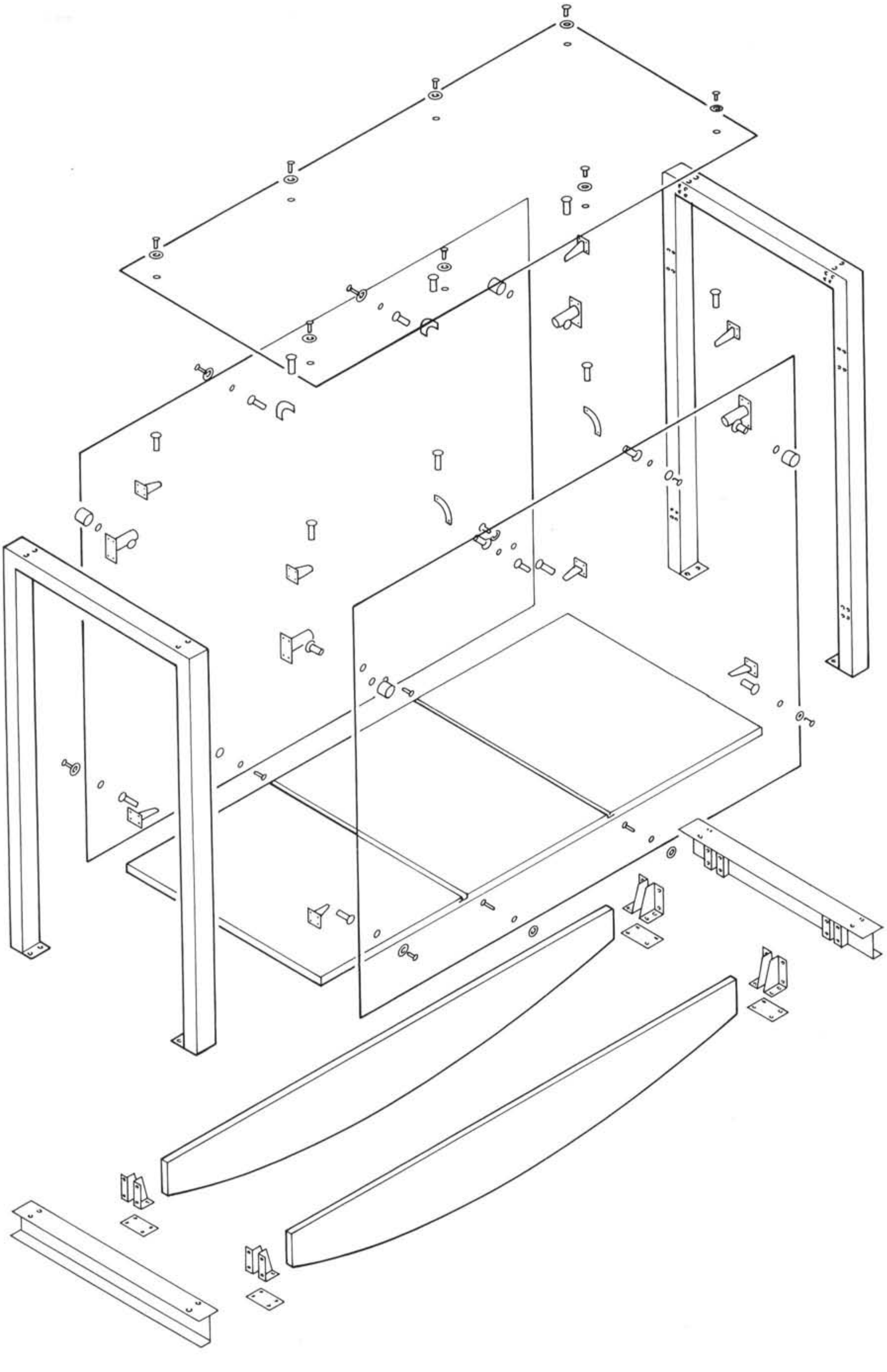


Fig. 7.9 Details of the glass beams that support the glass footbridge between 2 offices of Kraaijvanger•Urbis in Rotterdam (courtesy abt)

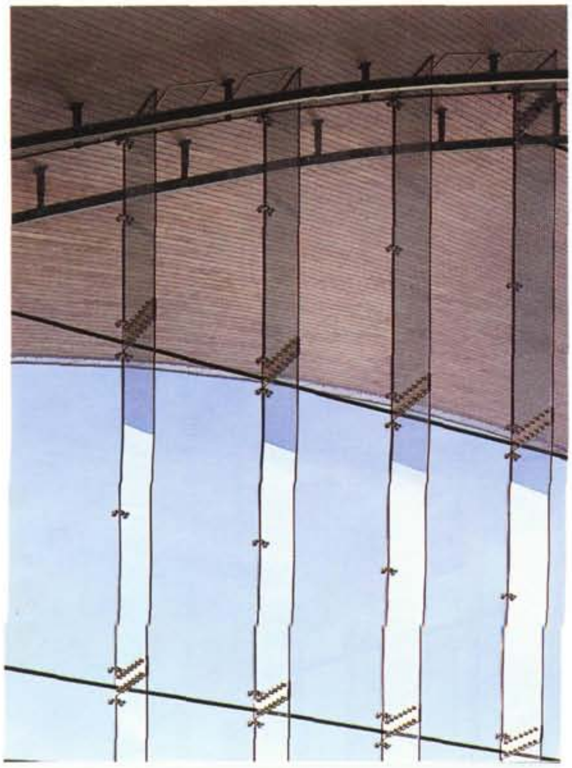


Fig. 7.10 NCM building glass fins (courtesy of Phil Boorman)

Fig. 7.11 Sainsbury Centre for the Visual Arts glass fins (courtesy of Foster and Partners)

7.6 Worked example

A worked example is shown on pages 82 and 83.

7.7 References and suggested reading

Bleich, F. (1952): *Buckling strength of metal structures*. McGraw-Hill, 1952

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So, A. K. W. and Chan, S. L. (1996): 'Stability and strength analysis of glass wall systems stiffened by glass fins'. *Finite Elements in Analysis and Design,* No. 23, p57

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Example of glass fin design

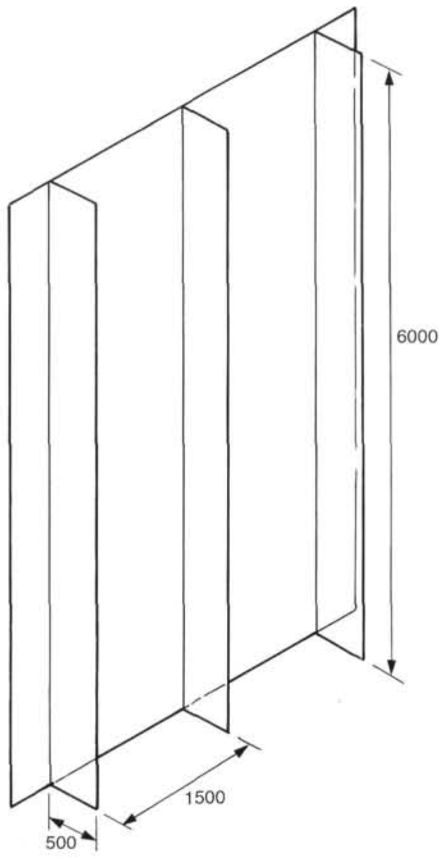
Shown right is a glass fin 6m long by 500mm deep by 10mm thick. It is simply supported and suspended from its top support. It is bolted to the inside face of a glass facade and silicone seals provide continuous attachment between the edge of the fin and the facade. It is assumed that for short-term gust loads the silicone seals are capable of providing lateral restraint to the edge of the fin. It is also assumed that the low modulus of the silicone does not permit any T-beam action between the fin and the facade.

Assume the wind load on the facade may be represented by a short-term gust of 1.5kPa and that the facade (including fins) weighs 0.5kN/m^2 of elevation and that the fins are at 1.5m centres.

Bending moment in the fin = $1.5 \times 1.5 \times 6^2/8$ = 10.13kNm (unfactored)

Axial load in the fin = $1.5 \times 0.5 \times 6$ = 4.5kN tension (unfactored)

Local Buckling check
$M_{\mathrm{max}} < 70 \times 10^3 \times 10^3/\{6(1 + 0.22)\}$Nmm,
i.e. $M_{\mathrm{max}} < 9.56$kNm



Glass fin

Buckling
To check the buckling of the fin we use appendix H of Australian Standard AS 1288–1994, which is reproduced in Appendix C of this Guide. So and Chan (1996) describe a finite element approach to buckling which appears to give less conservative results than AS 1288.

Equation H4 of AS 1288:

$$M_{\mathrm{CR}} = \frac{\left(\pi/L_{\mathrm{a}\phi}\right)^2 \left(EIy\left[\frac{d^2}{4} + y_0^2\right] + (GJ)\right)}{2_{\mathrm{y}0} + yh}$$

$L_{\mathrm{a}\phi}$ = 6m; E = say 70kN/mm^2; G = say 28.7kN/mm^2; d = 0.6m

$I_{\mathrm{y}} = (0.5 \times 0.013)/12 = 4.17 \times 10^{-8}\mathrm{m}^4$

$J = 0.333 \times 0.5 \times 0.01^3 = 1.67 \times 10^{-7}\mathrm{m}^4$

$y_0 = y_{\mathrm{h}}$ = 0.3m (same sign for outward loading; opposite sign for inward loading)

From which M_{CR} = 6.3kNm for outward loading and 18.8kNm for inward loading.

Appendix H of AS 1288 does not consider the beneficial effects of the tension in the fins increasing their buckling resistance. The engineer therefore must decide whether to modify the design to provide increased buckling resistance for outward loading or to do further calculations to justify the adequacy of the current design.

The engineer should remember that once the Australian buckling check has been satisfied, the maximum acceptable bending moment under outward loading will be limited by local buckling capacity, i.e. 9.56kNm, against an unfactored imposed bending moment of 10.13kNm.

Strength
Assumed partial factors on loading are both 1.5

M = Factored bending moment = 1.5×10.13 = 15.2kNm

P = Factored axial load = $1.5 \times 4.5 = 6.75$kN

$Z_{\text{fin}} = 10 \times 500^2/6 = 416\,667\text{mm}^3$

$M/Z_{\text{fin}} = 36.5\text{N/mm}^2$

$A_{\text{fin}} = 10 \times 500 = 5000\text{mm}^2$

$P/A_{\text{fin}} = 1.35\text{N/mm}^2$

The long-term axial stress in the fin is well below the allowable tensile stress for long-term loads in annealed glass suggested by Table 7.2.

By inspection of Table 7.1, toughened glass is required to withstand the short-term bending stress in the fin, even allowing for the fact that Table 7.1 is for use with unfactored loads.

Even if the stresses were acceptable in annealed glass, the suspension assembly at the top of the fin would probably be bolted as would any midspan splice. Such bolted connections tend to require the use of toughened glass. As more research and experience provide greater confidence in the use of adhesives, bolting may be replaced by adhesives in some applications.

Stiffness
Midspan deflection of a fin under unfactored wind load

$= 5 \times 1.5 \times 1.5 \times 6^4/(384 \times 70 \times 10^6 \times (0.01 \times 0.5^3/12)) = 0.005\text{m}$,

i.e. 5mm which equals $L/1200$.

The engineer should also check if wind-excited vibrations could be a problem. By comparison with the wind loading, mid-span deflection under inertial loads is given by:

$d = (0.5\text{kPa}/1.5\text{kPa}) \times 0.005\text{m} = 1.7\text{mm}$,

from which the first natural frequency is approximately:

$$F = \frac{16}{\sqrt{d}}\text{Hz} = 16/(1.7)^{0.5} = 12\text{Hz}$$

Robustness
The edges of glass fins can be damaged by impact from, for example, trolleys or window-cleaning cradles. Consideration should be given to whether the robustness of toughened glass would be preferred to that of annealed and whether the fins require any protection.

Failure of a piece of glass
The designer should consider both the structural and the health and safety consequences of a failure of a fin or a facade panel, both in service and during installation.

8 Glass columns and walls

8.1 General description

Glass columns and loadbearing walls are quite rare. Engineers have generally been reluctant to design compression members in a material that works best in compression!

The reluctance has been based on the brittleness of glass, the fact that it can fail suddenly and without warning. This means that a structure needs to be able to cope with the loss of a column or wall without disproportionate collapse (just like any other structure) and/or the column/wall needs to be well protected against accidental damage.

Recent examples of glass columns and walls include:

- the glass fins supporting the roof of Broadfield House Glass Museum (1994; Architect: Design Antenna; Engineer: Dewhurst McFarlane)
- the stacked glass insulators supporting the roof of a south London conservatory (1995; Architect: Bere Associates; Engineer: Campion & Partners)
- the competition-winning entry for the Construction Tower at the National Exhibition Centre (1998; Architect: Sutherland Hussey Architects with Blyth & Blyth; Engineer: Dewhurst McFarlane)
- the loadbearing glass walls of the Rodin Pavilion at the Samsung Centre, Seoul, South Korea (1998; Architect: Kohn Pedersen Fox Associates; Engineer: Ove Arup & Partners)
- glass rods as the web compression members in trusses by Dutch engineer abt
- glass tubes as compression elements in a tensegrity structure at the University of Stuttgart (1996; Architect: Stefan Gose; Engineer: Patrick Teuffel)
- The 13.5m high, ground-based glass wall at the Royal Opera House, Covent Garden, London (Dodd, 1999)

One design idea for Coventry Cathedral (Architect: Basil Spence; Engineer: Ove Arup & Partners) was to support the main columns on solid glass spheres. This idea was not carried through into construction. Another unexecuted idea, this time for the New Parliamentary Building in London (Architect: Michael Hopkins; Engineer: Ove Arup & Partners), was to support a staircase on a slender steel rod located within, and braced by, a glass tube.

Fig. 8.1 Broadfield House Glass Museum (courtesy of Dewhurst McFarlane & Partners/Design Antenna Ltd

Fig. 8.2 Conservatory at a house in Clapham, South London (courtesy Bere Associates/Michael Heyward)

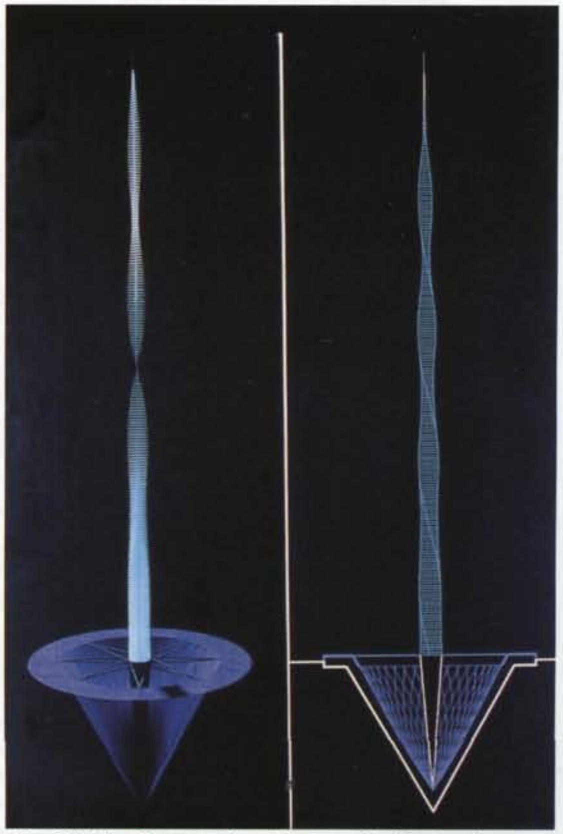


Fig. 8.3 The Construction Tower at the National Exhibition Centre (courtesy of Dewhurst MacFarlane & Partners/Sutherland Hussey)

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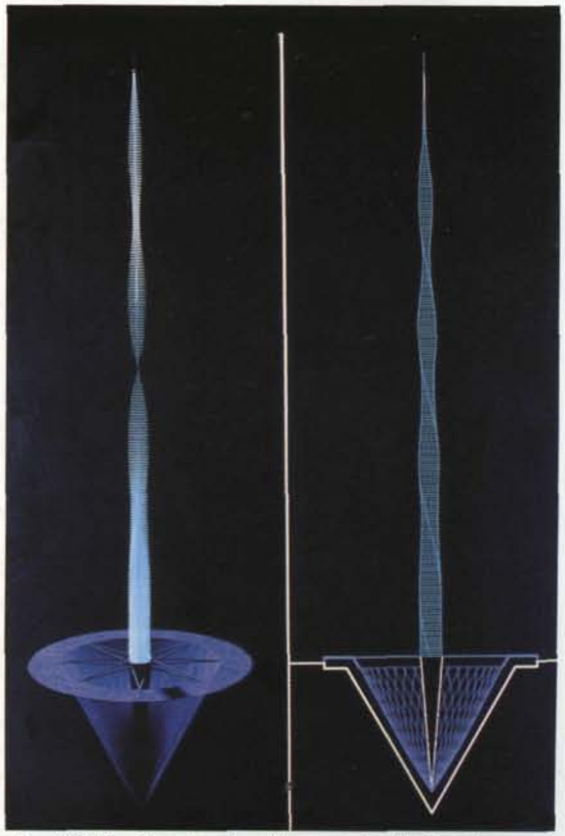

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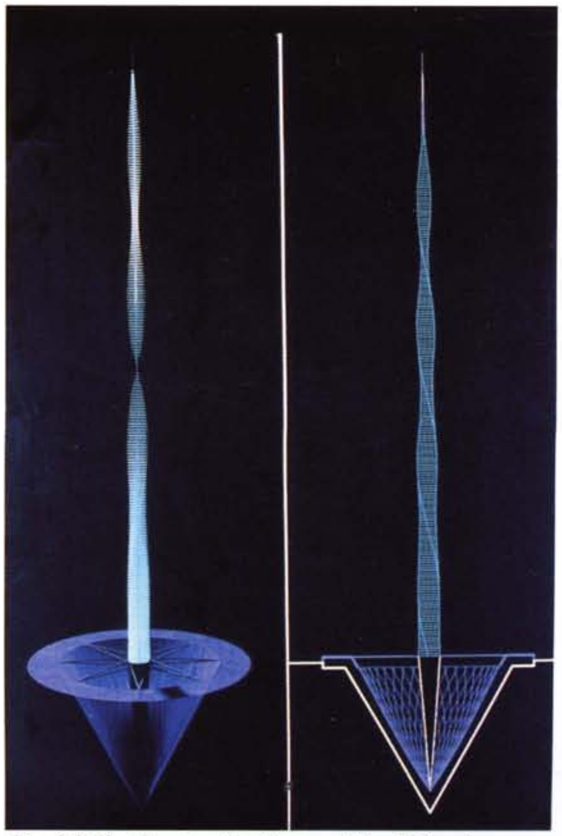
Fig. 8.3 The Construction Tower at the National Exhibition Centre (courtesy of Dewhurst MacFarlane & Partners/Sutherland Hussey)

8.2 Rules of thumb

8.2.1 Load transfer into the column or wall

It is most important to highlight the need for very careful design and execution of the method of transferring load into and out of the glass. Any localised hard or high spots can cause very high local stresses. Because the glass cannot yield, fracture may occur.

8.2.2 Elastic stability

Three of the basic stability conditions are:

- pin-ended column with end point loads
- cantilever with concentrated end axial point load
- cantilever with uniformly distributed axial load

Fig. 8.7 gives the elastic critical load factor, λ_c, for each of these conditions. Each column is H tall and has Young's Modulus E and second moment of area I. P is in kN or other force units and p is in kN/m or other force per unit length units. The presence of applied bending moments can significantly reduce the elastic critical load factor. Guidance on elastic stability can be found in Timoshenko and Gere (1970), Roark & Young (1977) and in Appendix A5 of Ashby (1997).

8.2.3 Strength

Glass columns and walls need to be adequately strong, stiff, stable and robust. The principles governing their design are no different from those governing the design of, say, unreinforced brick piers or walls.

Fig. 8.4 The Rodin Pavilion at the Samsung Centre Seoul, South Korea (courtesy of Kohn Pedersen Fox, Tim Hursley)

For a pin-ended member loaded in axial compression, a factor of safety against Euler buckling is needed. Consideration of buckling will usually limit compressive stresses to values that will cause no problems for the glass. The magnitude of the factor of safety is for the engineer to decide, taking account of the circumstances of the column.

For example, set:

$$P = \pi 2EI/2.5L^2$$

where: $I = bd^3/12$
$E = 70\text{kN/mm}^2$

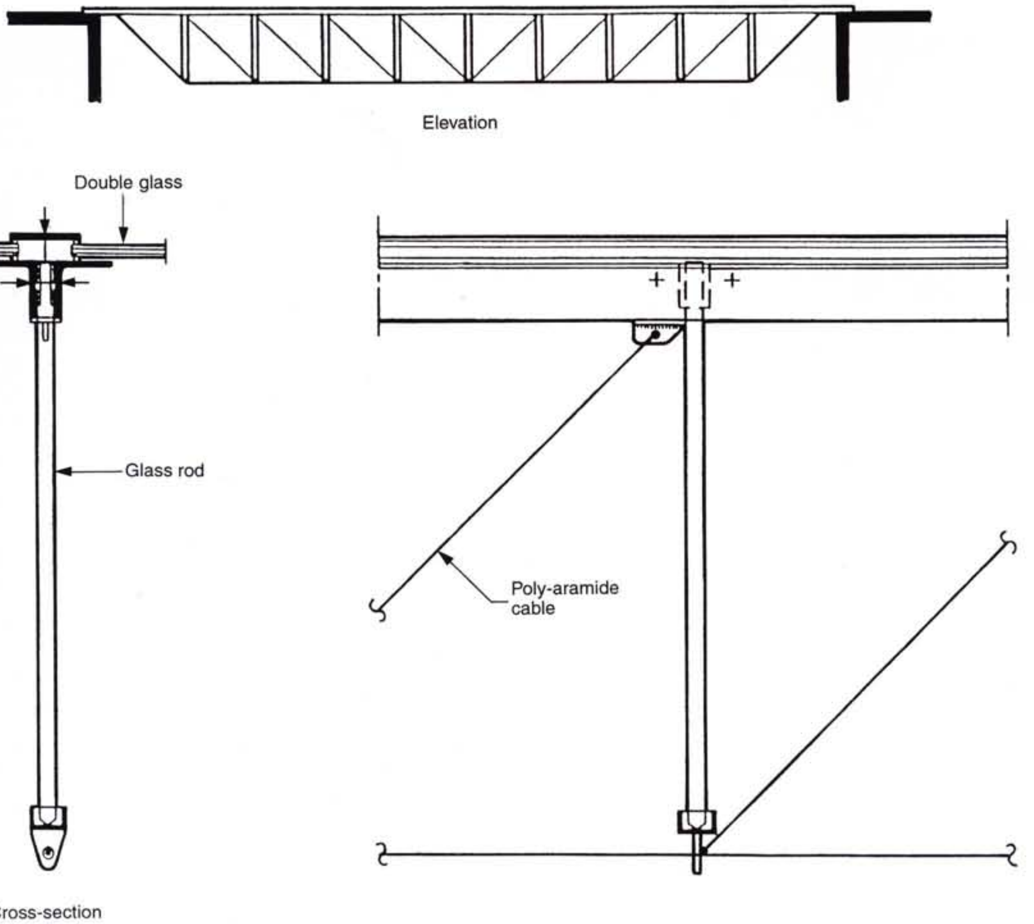

Fig. 8.5 Glass rods as the web compression members in a truss (courtesy of Robert Nijsse, abt)

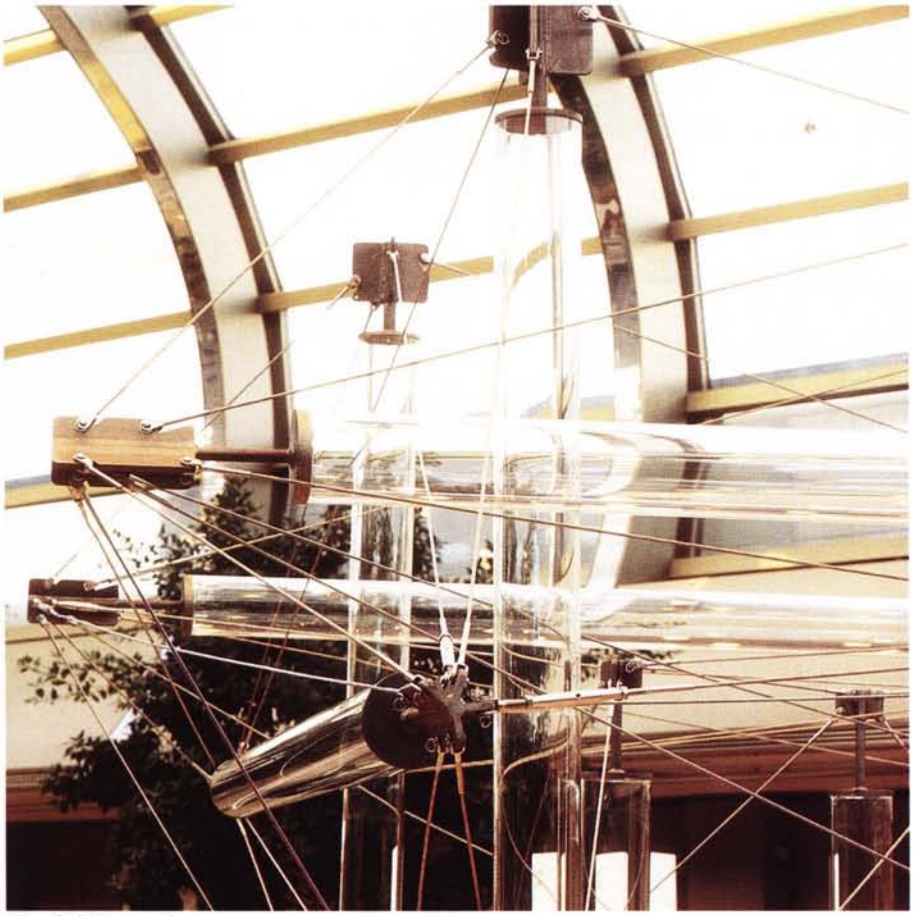

Fig. 8.6 Glass tubes as compression elements in a tensegrity structure (courtesy of Horst Schmecle)

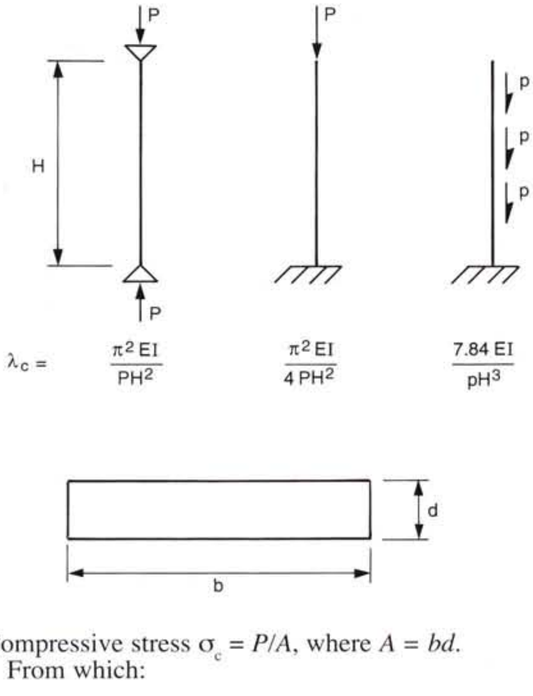

Fig. 8.7 Elastic stability of columns

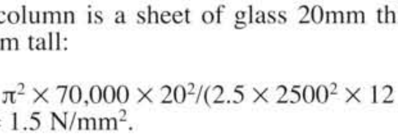

Fig. 8.8 Glass column (or short length of wall)

Compressive stress $\sigma_c = P/A$, where $A = bd$.
From which:

$$\sigma_c = \pi^2 Ed^2/(2.5 \times L^2 \times 12)$$

If the column is a sheet of glass 20mm thick and 2500mm tall:

$$\sigma_c = \pi^2 \times 70{,}000 \times 20^2/(2.5 \times 2500^2 \times 12) = 1.5 \text{ N/mm}^2.$$

Even if the glass is 200mm thick, the above expression yields a working compressive stress of only 150N/mm². Sedlacek (1995) gives the compressive strength of glass as between 400 and 900N/mm².

Columns may of course be subjected to shear and bending, as well as axial load. If tensile or shear stresses are generated, the guidance in Chapter 7 is applicable.

It is possible, with short squat glass columns, to persuade oneself incorrectly that they can withstand enormous compressive forces. The analogy is with concrete cubes, which fail not by an excess of compressive stress but by failure along a shear plane.

8.2.4 Deflection

Lateral deflection of columns is not usually a design criterion, unless it is associated with side sway of a building or of a storey within a building. Under those circumstances the engineer will want to design the lateral system to have the appropriate stiffness to satisfy the serviceability criteria.

Axial shortening of glass columns is unlikely to be a problem, because of the relatively high Young's Modulus of glass (which is greater than those of timber or concrete, about equal to that of aluminium and less than that of steel), the relatively low working stresses and the absence of creep or shrinkage.

8.2.5 Resistance to thermal stresses

Thermal stress and breakage cannot always be precisely predicted as many of the contributing factors are difficult to quantify. During the design process the designer should consult one or more reputable manufacturers to evaluate the risk of thermal breakage. Chapter 6 provides a checklist of the various factors that contribute to thermal stress.

8.3 Performance in use

A column resists loads by deforming and developing internal and edge stresses. A glass column under increasing axial load deforms elastically until sudden failure is initiated either by elastic instability or by a lateral load which causes bending at a surface flaw that magnifies the effect of the tensile bending stress. Glass columns need protection from significant lateral impacts.

A toughened glass column will be less susceptible to damage than an annealed one, but it might seem odd to make a column out of material that is axially precompressed. However, consideration of the effects of out-of-straightness or accidental lateral load show the benefits that precompression can confer in keeping the glass surface in compression. Sometimes the glass column is made of annealed glass and, as with glass beams, the loadbearing element is sandwiched between (and laminated to) outer leaves that protect it from damage, increase its bending stiffness and provide a degree of redundancy.

8.4 Selection, design and application

Critical issues may include some or all of the following non-structural items:

- thermal transmission and solar radiation
- condensation
- rainwater runoff
- fire
- acoustic behaviour
- access for installation, cleaning, inspection, maintenance, repair, replacement

- availability
- appearance and fit
- durability
- environmental impact and lifecycle costing.

Critical structural issues include:

- how the overall structure will behave
- how the structure will behave after one or more glass elements have failed
- the safety implications of failure of a piece of glass, including the likelihood of people being injured by falling glass

When a glass column supports, for example, a glass roof, the designer should consider what would happen to the glass in the roof if a column fails. There should be alternative load paths available to the panes in the roof so that the entire roof does not fail as a result of a single column failure. Even if the roof glass deflects a large amount, this is clearly preferable to its collapse. Avoidance of disproportionate collapse is not, of course, limited to glass structures (see Fig. 8.9).

The choice of annealed, heat strengthened or toughened glass will rarely be determined by considerations of strength alone.

Robert Nijsse of abt has proposed two ways to use glass in columns. The first is to use glass for just the uppermost part of the column. This keeps it protected from likely impacts and means that if the glass does fail the elements supported by the glass fall only a short distance. The second uses a sacrificial glass cylinder to protect an inner, loadbearing, glass column.

8.5 Design details

Examples are illustrated in Figs. 8.10 and 8.11.

8.6 Worked example

A worked example is shown on pages 89 and 90.

8.7 References

Anonymous: 'Rodin Pavilion'. *Architecture,* January 1997, 82

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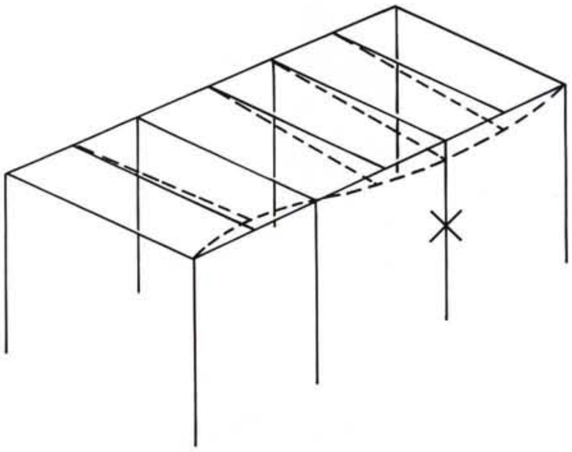


Fig. 8.9 Load paths in a roof following a column failure

Fig. 8.10 Broadfield House Glass Museum (courtesy of Dewhurst Macfarlane & Partners/Design Antenna/ Photo: Katsuhisa Kida)

Fig. 8.11 The Rodin Pavilion (courtesy of Kohn Pedersen Fox, Tim Hursley)

Worked example

A glass column made of bundled rods, supporting a roof (see diagrams below).

Calculate properties of composite section.

This assumes that the tubes are attached in some way, perhaps by the use of adhesive, which enables them to work as a single composite section.

$$A_{\text{tube}} = \frac{\pi}{4}\left(135^2 - 123^2\right) = 2431.6\text{mm}^2$$

$$I_{\text{tube}} = \frac{\pi}{64}\left(135^4 - 123^4\right) = 5068\,959\text{mm}^4$$

$$Z_{\text{tube}} = I_{\text{tube}}/67.5 = 75\,096\text{mm}^3$$

Calculate location of centroid of 5 tubes		
A	$\bar{y}$	$A\bar{y}$
3 2431.6	184.41	1 345 234
2 2431.6	67.5	328 266
5 2431.6	$\bar{y}$	1 673 500

From which $\bar{y} = 137.65$mm

Calculate I_{yy} and Z_{yy}

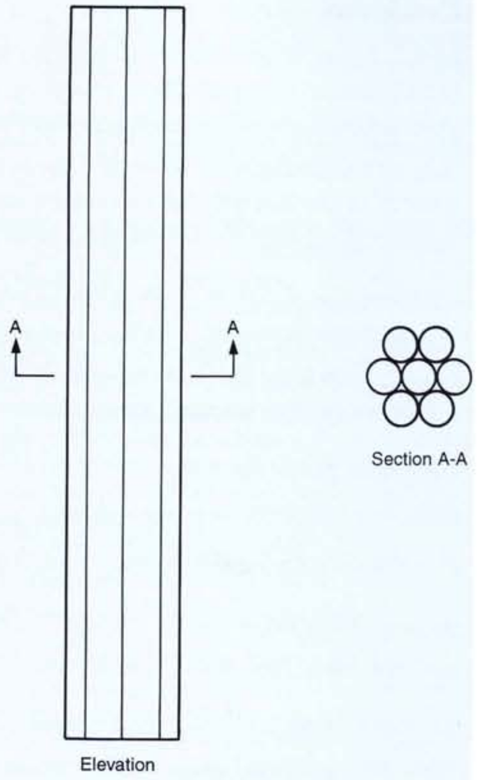
$3 \times 2431.6 \times (184.41 - 137.65)^2 = 15\,952\,791.65$

$2 \times 2431.6 \times (67.5 - 137.65)^2 = 23\,932\,916.62$

$5 \times 5\,068\,959 = \underline{25\,344\,795.00}$

$I_{yy} = 65\,229\,503\text{mm}^4$

$Z_{yy} = I_{yy}/137.65 = 473\,879\text{mm}^3$



Glass column

Calculate Euler buckling

Effective height of column = 4m

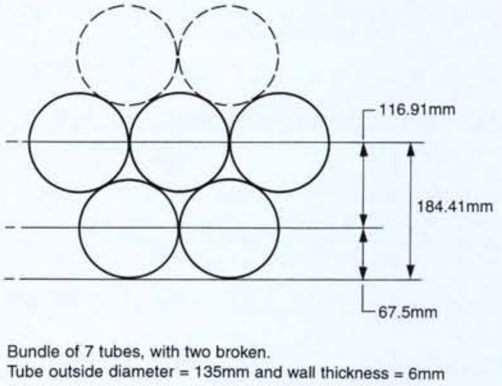
$P_e = \pi^2 \times 70 \times 65\,229\,503/4000^2 = 2817\text{kN}$

Calculate eccentricity of load

$e = 184.41 - 137.65 = 46.76\text{mm}$

Set extreme fibre stresses and calculate associated axial loads

Assume toughened glass and set maximum imposed tensile stress under factored loads = say 50N/mm². Note that toughened tubes are not yet manufactured.



Bundle of 7 tubes with two broken

$$\sigma_t = \frac{P}{A} - \frac{Pe}{Z}$$

$$-50 = P\left(\frac{1}{5 \times 2431.6} - \frac{46.76}{473\,879}\right)$$

From which $P = 3\,044\,213$N, i.e. 3044kN.

(If the glass was annealed and the limit was 7N/mm², then $P = 426$kN)

Now set maximum imposed compressive stress under factored loads = say 300N/mm².

$$\sigma_c = \frac{P}{A} + \frac{Pe}{Z}$$

$$300 = P\left(\frac{1}{5 \times 2431.6} + \frac{46.76}{473\,879}\right)$$

From which $P = 1\ 658\ 142$N, i.e. 1658kN.

Conclusion

In this example, Euler buckling limits the design load that can be sustained by the damaged column because, if we assume a factor of safety against Euler buckling of say 4, then the column should not carry, in its damaged state, more than 2817/4 = 704kN.

It is up to the engineer to decide the appropriate factor of safety taking into account the circumstances of the design and the consequences of failure, and what combination of dead and imposed loads should be checked against the capacity of the damaged column.

Reassess the capacity of the tubes, assuming that they do not work compositely.

Assume the same geometry and load eccentricity as before. Assume that the end connections enable each tube to share the axial load and bending moment equally. A reader with time to spare might care to devise such a connection.

Calculate Euler buckling

Effective height of column = 4m

$$P_e = \pi^2 \times 70 \times 5 \times 5\,068\,959 / 4000^2 = 1094\text{kN}$$

Assume same eccentricity of load as before

e = 184.41-137.65 = 46.76mm

Set extreme fibre stresses and calculate associated axial loads

Assume toughened glass and set maximum imposed tensile stress under factored loads = say 50N/mm^2.

$$\sigma_t = \frac{P}{A} - \frac{Pe}{Z}$$

$$-50 = P\left(\frac{1}{5 \times 2431.6} - \frac{46.76}{5 \times 75\,096}\right)$$

From which P = 1 182 493N, i.e. 1183kN.

Now set maximum imposed compressive stress under factored loads =say 300N/mm^2.

$$\sigma_c = \frac{P}{A} + \frac{Pe}{Z}$$

$$300 = P\left(\frac{1}{5 \times 2431.6} + \frac{46.76}{5 \times 75\,096}\right)$$

From which P = 1 450 787N, i.e. 1451kN

Conclusion

In this non-composite example, Euler buckling divided by a factor of safety again limits the design load that can be sustained by the damaged column. If we assume a factor of safety against Euler buckling of say 4, then the column should not carry, in its damaged state, more than 1094/4=273kN. As might be expected, composite action of the bundled tubes provides a significant increase in column capacity.

It is up to the engineer to decide the appropriate factor safety taking into account the circumstances of the design and the consequences of failure, and what combination of dead and imposed loads should be checked against the capacity of the damaged column.

Both these examples have concentrated on the ability of the column to carry axial and bending loads. Equally important is the design of the end connections to transfer load into and out of the column.

9 Point-supported glass

9.1 General description

Edge support is the traditional way of supporting glass. This was followed by 'patch plates', which are bolted friction grip connections. In recent years, beginning with the Renault Distribution Warehouse, Swindon, England (1982; Architect: Foster Associates; Engineer: Ove Arup & Partners) it has been increasingly popular to support glass using bolted fixings directly connected to the glass. Standard fixings are available from the major manufacturers.

These fixings allow improved transparency and offer architectural opportunities in the detailing of the bolted connections. This chapter concentrates on directly bolted support of glass. Guidance on friction grip connections may be found in Ryan *et al.* (1998). Fig 7.2 shows a bolted friction grip splice in a glass fin.

Toughened glass is almost always used, in order to deal with the concentrated stresses around the bolts. The bolt holes are formed using a diamond drill in annealed glass, which is then toughened. It should also be heat-soaked as a quality check, to reduce the incidence of nickel sulphide inclusions in panels leaving the factory that would otherwise cause spontaneous fracture of the glass. The holes should be at least the glass thickness in diameter, in order to allow free circulation of quenching air through the holes during the toughening process.

Fig. 9.1 Renault glass wall.
(courtesy of Foster & Partners)

Table 9.1 Maximum spans for toughened glass panels using bolted clamp plates
(source: Pilkington Glass Consultants)

Loading		Maximum span (mm) for UK toughened glass			
UDL in kN/m^2	Point load in kN	6	8	10	12
0.5	0.25	1400	1800	2150	2450
1.0	0.5	900	1500	1800	2050
1.5	1.5	-	-	1200	1650

9.2 Rules of thumb

9.2.1 Strength

Maximum spans for bolted toughened glass panels are given in Table 9.1. Note that these figures are for glass held by bolted clamp plates. Smaller spans may be expected with Planar- and Spider-type bolted fixings.

The designer should check these figures with one or more reputable manufacturers, remembering that fully tempered glass to ASTM C1048-92 can have a surface compressive stress as low as 69N/mm^2. The designer should also be aware that 6mm and 8mm toughened glass will not be suitable for use as a glass infill panel to a balustrade if the free path perpendicular to the balustrade is greater than 1.5m (see Chapter 12 for more about balustrades).

Reputable manufacturers will provide guidance on maximum spans between fixings. These will vary between manufacturers because of different levels of prestress in the glass and different bolt details. Fig. 9.2 shows an example of a manufacturer's design chart for bolted glass, such as the Planar or Spider systems.

9.2.2 Deflection

If the anticipated deflection is more than one half of the pane's thickness then its behaviour cannot always be modelled accurately by linear theory.

Predicting the deflections of point-supported glass is just like predicting the deflections of thin post-tensioned concrete slabs. There are rules of thumb that can tell you whether the deflections are likely to be acceptable and there is finite element analysis, which can predict the deflections. Reputable manufacturers will provide guidance for their products.

Smith (1999) and So & Chan (1996) describe how they dealt with non-linear finite element analysis of glass. Smith's work is the basis of the worked example in this chapter.

There are two fundamental approaches to the detailing of bolted glass connections and what differentiates them is their approach to dealing with

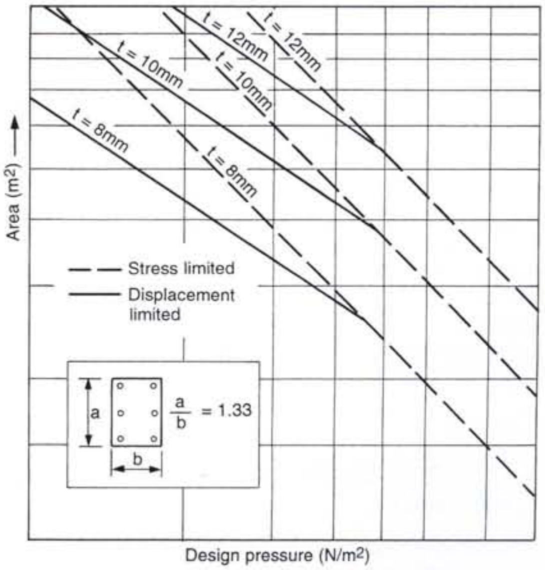


Fig. 9.2 Example of manufacturer's design chart

out-of-plane rotations of the glass surface. In Pilkington's Planar system, the connection between the bolt and the glass is capable of carrying a small bending moment. In contrast, the detail developed by RFR for Parc de La Villette allows rotation of the glass relative to the bolt. Both of these are shown in section 9.5. Fig. 5.7 shows a finite element model used by Pilkington in developing the Planar system.

Whichever approach is adopted, the design, manufacture and installation of the bolted connection (and the weather seals) must also cope with permissible deviations in manufacturing, permissible deviations in installation and the subsequent movements of the supporting structure, both in and out of plane, transitional and rotational. This implies some ability to adjust the geometry during installation and some ability to accommodate movement afterwards. This is covered in more detail by Rice and Dutton (1995) and by Ryan *et al.* (1998).

A pane of glass supported by 4 bolts could have in-plane restraints at the bolts shown in Fig. 9.3.

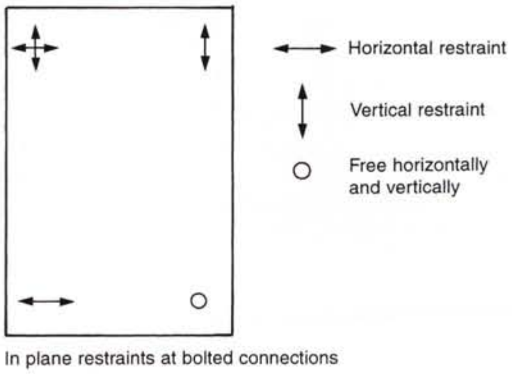


Fig. 9.3 In-plane restraints at bolted connections

9.2.3 Resistance to thermal stresses

Chapter 6 provides a checklist of items to consider. Bolted connections may constrain the glass and its supporting structure to deform together in the plane of the glass. This makes it important that the designer carefully considers thermal effects when detailing the connections.

9.3 Performance in use

A plate resists wind pressure or other uniformly distributed surface loads by deforming and developing internal and surface stresses. A glass plate under increasing pressure deforms elastically until sudden failure is initiated at a surface flaw that magnifies the effect of the tensile stress. Resistance of glass to pressure is limited, not only by tensile stress, but also by the severity of stress concentrations caused by flaws. If a flaw occurs near a bolt, where stresses are already concentrated, then failure may well be initiated even earlier. This emphasises the importance of detailing bolted connections to minimise stress concentrations caused by, for example, steel bearing directly onto glass.

This interaction of stress and flaws means that glass plate resistance is influenced by area, loading history, aspect ratio, surface compressive stress from heat treatment and flaws from manufacturing, handling and installation processes. A rational calculation of resistance must account for the pattern of stresses set up by the loading and support conditions, statistical variation associated with the distribution of surface flaws and the accumulated experience of past and current practice. Chapter 5 provides guidance on calculations.

If the decision is made to use toughened or heat-strengthened glass and calculations indicate that the surface precompression will not be overcome by imposed tensile stresses, then fracture-mechanics-based calculations will not be needed. Bolted glass almost always involves toughened glass.

9.4 Selection, design and application

Critical issues may include some or all of the following non-structural items:

- thermal transmission and solar radiation
- condensation
- rainwater runoff
- fire
- acoustic behaviour
- access for installation, cleaning, inspection, maintenance, repair, replacement
- availability
- appearance and fit
- durability
- environmental impact and lifecycle costing.

Critical structural issues include:

- how the overall structure will behave
- how the structure will behave after one or more glass elements have failed
- the safety implications of failure of a piece of glass, including the likelihood of people being injured by falling glass

The choice of annealed, heat strengthened or toughened glass will rarely be determined by considerations of strength alone.

Most manufacturers will provide guidance on what thickness and type of glass should be used, based on their experience. The Glass and Glazing Federation also provides guidance in its *Glazing Manual*, item 7.1.

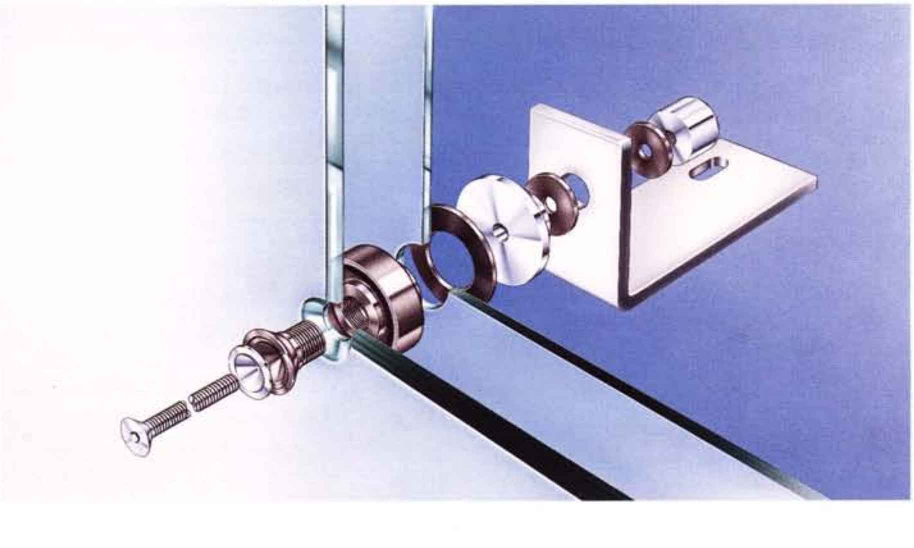
9.5 Design details

Details are shown in Figs 9.4–9.10.

9.6 Worked example

The design of an asymmetric bolted glass panel for part of the roof of the Beyeler Art Gallery in Switzerland is shown on pages 95 and 96.

Fig. 9.4 A typical Pilkington Planar fixing (courtesy Pilkington)



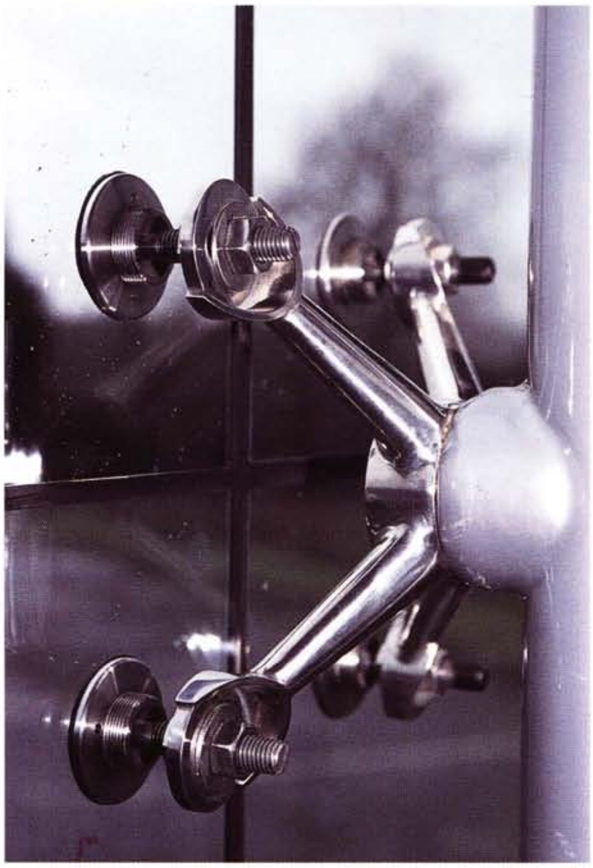


Fig. 9.5 A typical Saint Gobain Spider fixing (courtesy of Saint-Gobain Solaglas/ Spiderglass)

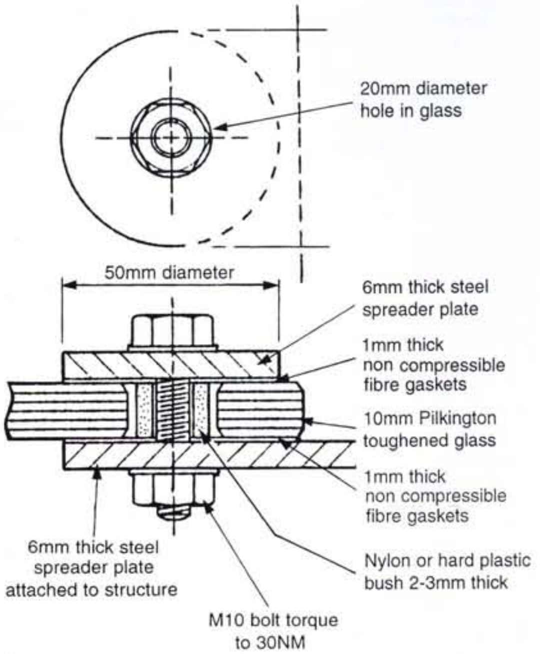


Fig. 9.7 A typical patch plate (i.e. friction grip) fixing (courtesy of Pilkington)

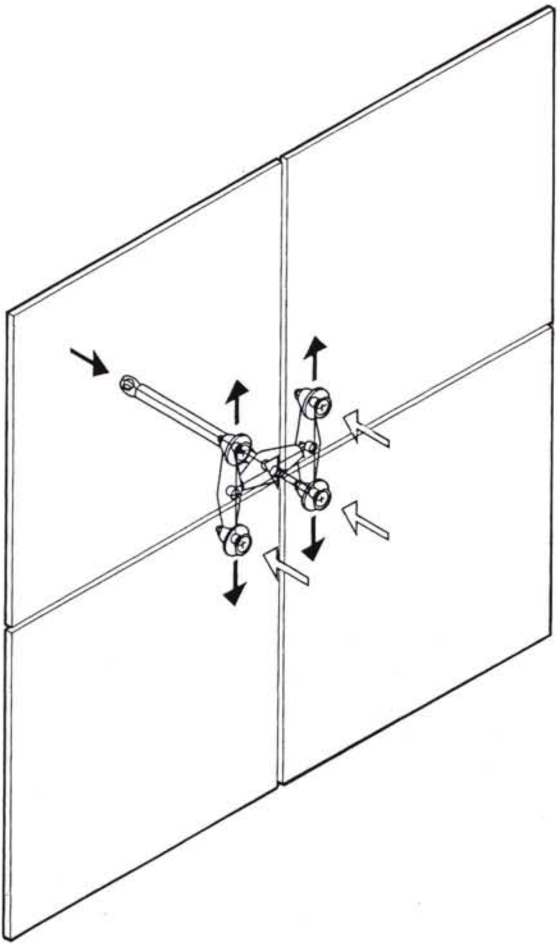


Fig. 9.6 A typical La Villette fixing (reproduced by permission of E & FN Spon from *Structural Glass* – Rice & Dutton)

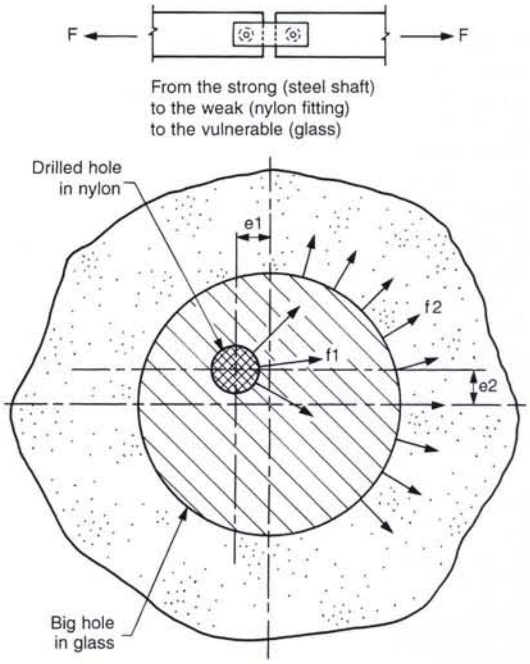


Fig. 9.8 A bolted connection developed by Robert Nijsse (courtesy Robert Nijsse, abt)

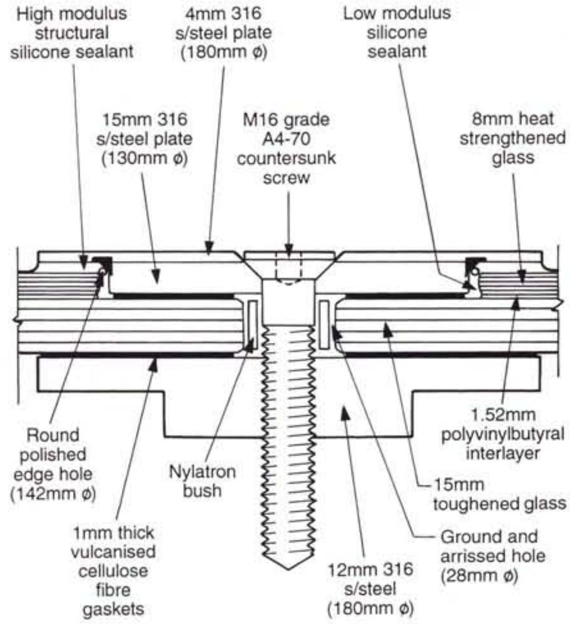


Fig. 9.9 A Beyeler Art Gallery bolted connection
(courtesy Ove Arup & Partners)

Fig. 9.10 A bolted connection developed by Atelier One
(courtesy Atelier One)

9.7 References and other suggested reading

ASTM (1997): *Standard specifications for heat-treated flat glass* — kind HS, kind FT coated and uncoated glass. C1048-97b

Glass and Glazing Federation: *Glazing manual*. 1991

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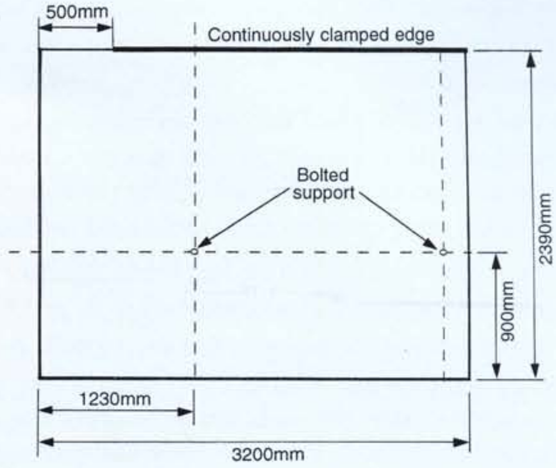
Timoshenko, S. P. and Woinowski-Krieger, S. (1959): *Theory of plates and shells,* McGraw-Hill

Worked example

The design of an asymmetric bolted glass panel for part of the roof of the Beyeler Art Gallery in Switzerland (taken from Smith (1999))



Loading

Unfactored design loads, based on the Swiss code SIA 160-1989:

• Wind uplift	1.9kPa
• Snow load	0.9kPa
• Maintenance load	0.75kPa

Design

A laminated glass was chosen, so that in the event of failure of a layer of glass the interlayer would prevent the broken glass from falling to the ground, with the entire load being carried by the intact layer.

A first estimate was made of a 15mm toughened glass laminated to 6mm heat strengthened glass.

Combined with the code loadings the estimated glass thicknesses gave the following two load-cases:

- 1375N/m^2 short-term wind uplift
- 1425N/m^2 long-term downwards load

Analysis

First stage analysis considered 2 cantilevers, of length 900mm and 1230mm. Hand calculations, using simple bending theory and assuming the glass layers shared the loads in proportion to their stiffnesses, gave principal surface bending stresses of 31N/mm^2 in the toughened glass and 20N/mm^2 in the heat-strengthened glass.

Second stage analysis used a finite element model of the panel. The panel was modelled as a pin-supported single monolithic element, but with the thickness modified to produce a bending stiffness similar to layered glass of equivalent thickness. The analysis assumed elastic linear small deflection theory and therefore could be expected to give unrealistic answers for stresses and deflections but accurate answers for reactions. The reaction at the 'central' support point accounted for 64% of the total load on the panel.

Third stage analysis used software capable of handling large deflections and membrane stresses and non-linear behaviour. The glass layers were modelled using two separate layers of shell elements and the intermediate bonding layer was represented by springs that had the shear stiffness properties of the interlayer material. It was intended to develop a clamped bolted detail that would eliminate bending stresses across the bolt hole and this was reflected in the analytical model.

The results of this model showed the following maximum applied stresses under characteristic loads:

• Toughened glass	50N/mm^2
• Heat-strengthened glass	23N/mm^2

The stresses in the heat-strengthened glass were felt to be too high and the decision was made to increase the diameter of the clamping plates in the bolted supports from about 50mm to 120mm.

A conventional approach to bolting would have had the thicker toughened layer above the thinner heat-strengthened layer, with the upper layer rigidly clamped and the lower layer simply supported, thus avoiding compressing the interlayer. If the lower layer broke, the upper layer could carry the loads, but the lower layer was not strong enough to carry the loads if the upper layer broke.

It was decided to place the heat-strengthened layer on top, so that if the lower toughened layer broke, it would still be able to resist compression, and work compositely with the upper layer in resisting hogging moments at the bolted supports. The interlayer would provide the necessary shear coupling and would hold the broken glass 'dice' in place.

As an additional safety measure, it was checked that the 1.52mm interlayer had sufficient strength to support a glass cantilever even if it was hanging vertically downwards.

The last stage of the analysis and design was the selection of the final panel composition for testing and then installation. Hand calculations were used, based on the reactions and bending stresses from the non-linear analysis. These showed that the tensile stresses in the upper layer, after failure of the lower layer, were still too high. It was decided to increase the diameter of the bolted fixing from 120mm to 180mm, which led to the following panel composition for testing:

- Upper layer: 8mm heat-strengthened glass
- Interlayer: 4 sheets of 0.38mm polyvinylbutyral
- Lower layer: 12mm toughened glass

Testing

Four triaxial strain gauges were bonded to the underside of the panel around a bolted support and four to the topside. More strain gauges were attached in the central area between supports. Dial gauges were used to measure cantilever deflections.

The following loads were applied:

- 1kN concentrated load at three locations, including the cantilevering corner.
- 75% of the snow load
- 100% of the snow load
- 150% of the snow load (measurements taken after 10 minutes)
- 150% of the wind load

Following removal of the loads, the damaged behaviour was observed:

- The toughened glass was broken, using a centre punch to one corner
- 100% snow load was applied to the broken panel
- With snow load removed, the heat-strengthened layer was broken and the behaviour observed.

Under 1kN the free corner deflected 22mm.

Under 150% snow load the peak deflection increased from 19.4mm to 20.4mm over 10 minutes, as the panel behaviour changed from more like monolithic to more like layered. Peak applied tensile stresses under factored snow load were 26N/mm^2.

Peak applied stress in the toughened glass under factored wind load was 71N/mm^2.

When the toughened layer was deliberately broken the release of stored energy and the increase in in-plane dimensions of the layer caused a sudden violent flexing of the panel with dynamic deflections of more than 100mm. When equilibrium was reached the panel was visibly dished upwards away from the support points. The panel was able to support the full snow load.

Finally the top layer was broken, by being struck with a claw hammer in several locations. The upper layer broke into a collection of rigid plates connected by hinges along their edges. The irregular nature of the broken fragments provided some interlock, which prevented sudden collapse. Slow progressive failure was observed.

10 Externally-prestressed glass

10.1 General description

Externally prestressed glass is glass that is compressed by an external arrangement of stressing rods or cables, rather than by toughening or heat strengthening. 'External' means a material other than glass, because the compression could be applied by a steel rod inside, for example, a glass cylinder.

Externally prestressed glass is extremely rare. As with glass columns, engineers have generally been reluctant to design compression members in a material that works best in compression! The reluctance has been based on the brittleness of glass, the fact that it can fail suddenly and without warning.

Externally applied precompression is also comparatively rare in engineering structures, though an example of externally precompressed steel may be found in the roof structure of the passenger terminal at Stansted Airport (1991; Architect: Foster Associates; Engineer: Ove Arup & Partners).

A notable recent example of externally prestressed glass is the competition-winning entry for the Construction Tower at the National Exhibition Centre (1998; Architect: Sutherland Hussey Architects with Blyth & Blyth; Engineer: Dewhurst McFarlane). To be literal about it, even this glass is internally prestressed in that the Kevlar cable that applies the precompression runs through the centre of the glass (Whitelaw and Parker, 1997). However it counts as externally prestressed because it is the Kevlar cable that compresses the stacked glass disks and not heat treatment.

A similar example is the glass column consisting of stacked glass insulators, designed by Bere Associates for a south London conservatory (Welsh, 1995). Threaded through the units to tie them together is a high tensile steel rod.

At Schloss Juval in the South Tyrol (Anonymous, 1997), steel trusses spanning up to 13.4m support a glass roof over a courtyard of an ancient building. The glass spans the 4m between the steel trusses by acting as the compression boom of a simple truss, with a steel cable taking the tension. It is thus, effectively, prestressed by its self-weight (see Figs. 4.22 and 10.2).

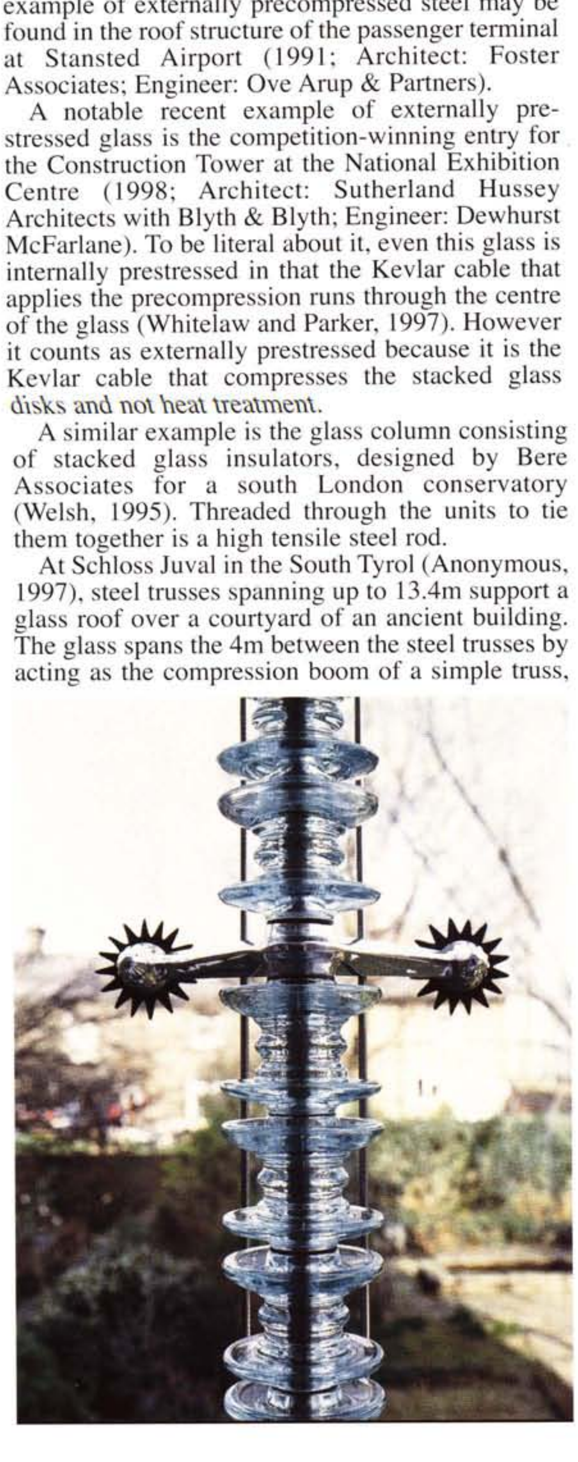


Fig. 10.1 Glass column at South London conservatory (courtesy of Bere Associates/Photo: Michael Heyward)

10.2 Rules of thumb

10.2.1 Elastic stability

Chapter 8 on glass columns and walls described three basic stability conditions for compression members and gave the elastic critical load factor, λ_c, for each of these conditions. Guidance on elastic stability can be found in Timoshenko and Gere (1970), Roark & Young (1977) and in appendix A5 of Ashby (1997).

The way that the precompression is applied can significantly affect the buckling length of the member concerned. The external precompression may not be applied symmetrically, for example in the case of a glass beam. Here the analogy is with a prestressed concrete beam. As with prestressed concrete, it is important to remember that precompression is always accompanied by axial shortening. Appendix E addresses the stability of narrow beams.

A non-linear analysis may be necessary for some types of prestressed structure. Although the structure itself does not deform grossly, any small deflection may have an important impact on the overall behaviour.

For example, a small change in geometry may reduce the tensile force in a cable. Unlike prestressed concrete, cables used to prestress glass are usually attached to slender structures so that the change of main structure geometry may affect the cable force significantly. The worked example in section 10.6 is just such a structure.

When the external prestress is applied internally, as may be the case with a cantilevering column, the prestress has no destabilising effect on the cantilever (and may indeed provide a second-order stabilising effect) but it can cause buckling problems with the column considered as either pin-ended or pinned-fixed, depending on the precise detail at the support. If the void between the cable and the surrounding glass is filled with an appropriate material, forming a bonded tendon, then, as with toughened glass, the compressive forces induced in the glass are not destabilising.

10.2.2 Strength

Externally prestressed glass needs to be adequately strong, stiff, stable and robust. The principles governing its design are no different from those governing the design of glass columns, fins or beams, with attention paid to the effects of the precompression, particularly the accuracy with which it can be applied. Accuracy encompasses the precision of the applied force, its bearing onto the glass and the precision of its line of action.

Chapter 8 provides examples of the design of glass columns.

10.2.3 Deflection

Lateral deflection of columns is not usually a design criterion, unless it is associated with side sway of a building or of a storey within a building. Under those circumstances the engineer will want

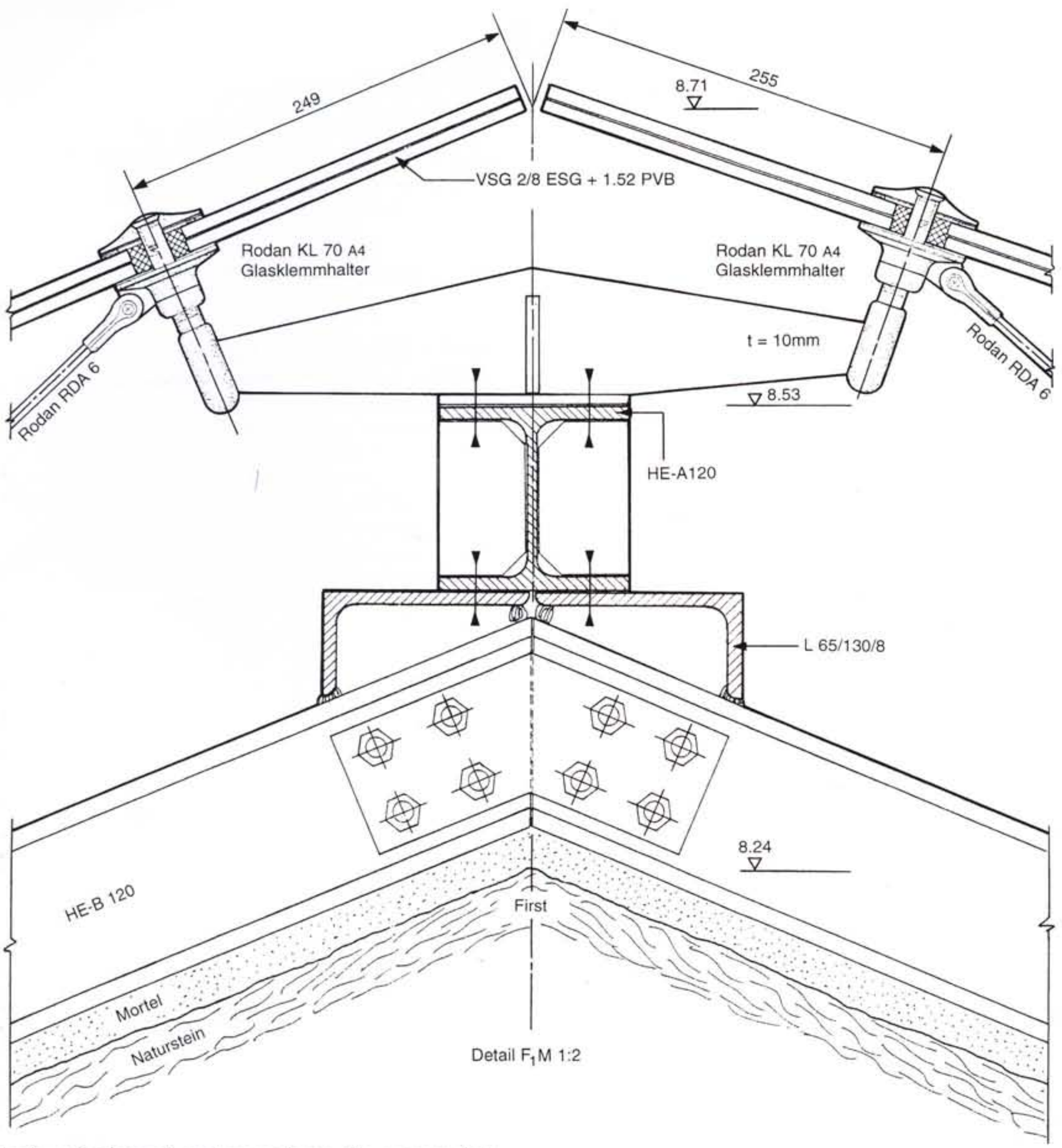


Fig. 10.2 Schloss Juval detail (courtesy Dipl.-Ing. Robert Danz, Schönaich)

to design the lateral system to have the appropriate stiffness to satisfy the serviceability criteria.

Axial shortening and the losses in prestressing force in concrete are well documented. Axial shortening of glass columns is unlikely to be a problem, because of the relatively high Young's Modulus of glass (which is greater than those of timber or concrete, about equal to that of aluminium and less than that of steel), the relatively low working stresses and the absence of creep or shrinkage. However a glass column will shorten three times as much as a similarly stressed steel column and it is possible to imagine a situation in which this could cause problems. In normal practice it seems likelier that usually the glass will be stressed less than the steel, thus lessening the potential for differential shortening.

Axial shortening of prestressed glass beams may cause problems for the supporting structure and should be checked. Asymmetric precompression will camber a glass beam.

10.2.4 Resistance to thermal stresses

Thermal stress and breakage cannot always be precisely predicted as many of the contributing factors are difficult to quantify. During the design process the designer should consult one or more reputable manufacturers to evaluate the risk of thermal breakage. Chapter 6 provides a checklist of the various factors that contribute to thermal stress.

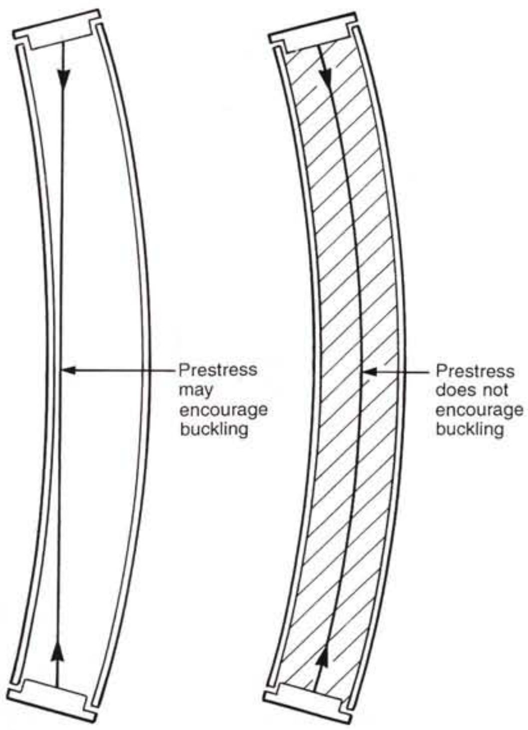


Fig. 10.3 The effect of external prestressing

10.3 Performance in use

Earlier chapters have discussed the performance in use of glass beams, fins, columns and walls. Externally stressed glass is no different, and the same considerations apply. Guidance may be found elsewhere on the performance in use of whatever materials are chosen for the application of the external stressing.

10.4 Selection, design and application

Critical issues may include some or all of the following non-structural items:

- thermal transmission and solar radiation
- condensation
- rainwater runoff
- fire
- acoustic behaviour
- access for installation, cleaning, inspection, maintenance, repair, replacement
- availability
- appearance and fit
- durability
- environmental impact and life cycle costing.

Critical structural issues include:

- how the overall structure will behave
- how the structure will behave after one or more glass elements have failed
- the safety implications of failure of a piece of glass, including the likelihood of people being injured by falling glass

The choice of annealed, heat-strengthened or toughened glass will rarely be determined by considerations of strength alone.

Fig. 10.4 Tensegrity structure at the Design Centre in Stuttgart (courtesy of Horst Schmeck)

10.5 Design details

An example is shown in Fig 10.4, which shows how it may not be buckling but how the load is transferred that limits what a glass column can carry.

10.6 Worked example

A worked example appears on pages 100 and 101.

10.7 References

Anonymous (1997): 'Glasdach auf Schloss Juval in Südtirol'. *Glas* 1/97

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Timoshenko, S. P. and Gere (1963): *Theory of elastic stability,* 2nd edition. McGraw-Hill

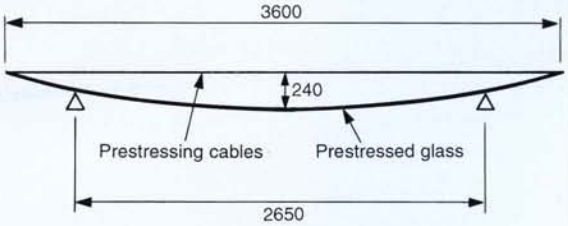
Welsh, J. (1995): 'Cast of thousands'. *RIBA Journal,* October 1995, 34

Whitelaw, J. and Parker, D. (1997): 'Clear winner'. *New Civil Engineer,* 4 September, p16

Worked example

This example considers the laminated glass canopy shown below. The glass is cold-bent and held in its curved shape by the pre-stressing cables.

These calculations assume that both panes are thermally toughened heat-soaked glass with surface compressive stresses of at least 120N/mm^2. They also assume two 6mm sheets of glass with a 1.5mm PVB interlayer, giving an overall thickness of 13.5mm.



Consider the short- and long-term stresses induced by cold-bending the glass

The midspan sag is 240mm and the span is 3600mm. By Pythagoras:

$$R^2 = (R\text{-}240)^2 + 1800^2$$

From which $R = 6870$mm.

Using the familiar equation

$$M/I = \sigma/y = E/R$$

we can say that

$$M = EI/R \text{ and } \sigma = Ey/R$$

When the laminate is initially cold bent (unless the interlayer is softened by warming), the behaviour will at first be composite and I will be:

$$1000 \times 13.5^3/12 = 205\ 031 \text{ mm}^4\text{/m}$$

Assuming $E_{\text{glass}} = 74$kN/mm^2, This gives a bending moment of:

$$74\ 000 \times 205\ 031/6\ 870 = 2\ 208\ 488\text{Nmm/m}$$

and a glass stress of:

$$74\ 000 \times (13.5/2)/6\ 870 = \pm 73\text{N/mm}^2$$

which is tolerable in the short term. Note that BS EN 572 recommends a slightly lower E of 70kN/mm^2, which would lead to a slightly lower figure for the stress in the glass.

After the interlayer has relaxed, the laminate will be acting as a pair of 6mm-thick sheets of glass that share the cold bending. The combined I will then be

$$2 \times 1000 \times 6^3/12 = 36\ 000\text{mm}^4\text{/m}$$

which gives a bending moment of:

$$74\ 000 \times 36\ 000/6\ 870 = 387\ 773\text{Nmm/m}$$

and a glass stress of:

$$74\ 000 \times (6/2)/6\ 870 = \pm 32\text{N/mm}^2$$

which is tolerable in the long term.

Consider local effects where the tendons connect to the glass

The cold bending moment is maintained by tension in the tendons, which in turn cause local bending moments in the glass where they connect. The tendon tension is given by M/240mm, with the following values:

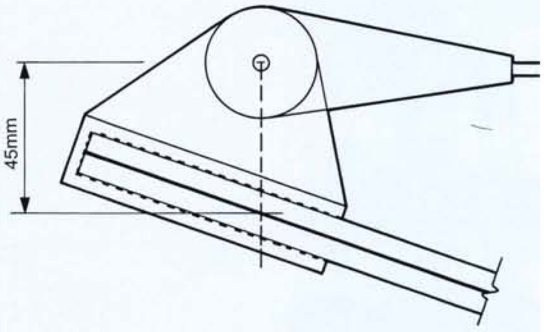
Short term: 2 208 488/240 = 9.2kN/m

Long term : 387 773/240 = 1.6kN/m

With a tendon/glass eccentricity at the connection of around 45mm, the local bending induced at the tendon/glass connections is:

Short term: $M = 9200 \times 45 = 414\ 000$Nmm/m

Long term: $M = 1600 \times 45 = 72\ 000$Nmm/m



The associated local bending stresses are:

Short term: $\sigma = 414{,}000/(1000 \times 13.5^2/6) = \pm 13.6\text{N/mm}^2$ – looks OK

Long term: $\sigma = 72{,}000/(2 \times 1000 \times 6^2/6) = \pm 6\text{N/mm}^2$ – also looks OK

But the tendon/glass connections are local affairs, not uniformly distributed along the glass edges, so the local stresses will be magnified significantly. It will be important to detail carefully so as to distribute the local bending moments into as wide a length of glass edge as possible.

Consider thermal behaviour.

For durability, stainless steel tendons may appear the logical solution. Some stainless steels have a much higher coefficient of expansion α than ordinary mild steel. This means that it will relax more in the summer and shrink more in the winter.

Assume that the unit is manufactured at 15°C and that in service its temperature varies between -15°C and 45°C. Assume that its tendons are mild steel rods of $E = 205\text{kN/mm}^2$ and $\alpha = 12 \times 10^{-6}/°\text{C}$.

The unrestrained tendon thermal strains are given by:

$$30 \times 12 \times 10^{-6} = 3.6 \times 10^{-4}.$$

The unrestrained tendon change in length is given by:

$$3500 \times 3.6 \times 10^{-4} = 1.26\text{mm}.$$

The fully restrained tendon stress is given by:

$$205 \times 10^3 \times 3.6 \times 10^{-4} = \pm 74\text{N/mm}^2.$$

A proper analysis that takes account of both steel and glass behaviour will be needed to determine what stresses and strains will actually occur under these temperature changes. The engineer must decide whether to use the short-term (composite) glass I or its long-term value.

Consider bending in the central 2.65m span under self-weight and applied loads

Factored self-weight bending moment per pane is $1.5 \times 0.006 \times 25 \times 2.65^2/8 = 0.2\text{kNm/m}$ with a bending stress of:

$$0.2 \times 10^6/(1000 \times 6^2/6) = \pm 33.3\text{N/mm}^2 \text{ – looks OK.}$$

Assume a snow load of 0.7kN/m^2 and that, at low temperatures, the interlayer does not creep. Under a factored snow load of $1.5 \times 0.7\text{kN/m}^2$ we get a midspan bending moment of:

$$1.5 \times 0.7 \times 2.65^2/8 = 0.92\text{kNm/m}$$

and a bending stress of:

$$0.92 \times 10^6/(1000 \times 13.5^2/6) = \pm 30.3\text{N/mm}^2 \text{ – looks OK.}$$

Under a midspan summertime point load of 0.9kN we get a midspan bending moment of:

$$1.5 \times 0.9 \times 2.65/4 = 0.89\text{kNm}.$$

Assume that at elevated temperatures the interlayer creeps and the two sheets of glass share the load. If we assume that midspan bending is resisted by at least a metre width of glass, this generates a bending stress of:

$$0.89 \times 10^6/(2 \times 1000 \times 6^2/6) = \pm 75\text{N/mm}^2$$

This looks just about OK but warrants a closer look at the assumption about how much glass carries the load. This could be tested by an analysis that models the behaviour of the glass as a grillage. Strip assumptions are not appropriate for non-ductile materials because local overstressing will not lead to redistribution but to failure.

These simple calculations have begun to address only some of the issues that the design engineer will need to consider in more detail. Other issues include how to cold bend the glass, the detail of the tendon-glass connections and the consequences of glass breakage. As vertical loads are applied to the glass it will sag which will bring its ends closer together, which will reduce the tension in the cables.

11 The structural use of adhesives

11.1 General description

Structural silicone adhesives have been used for the last 25 years to carry short-term tension between panes of glass and their supporting structures. (Wagner, 1999)

The self-weight of the glass has usually been carried by other means for a number of reasons, including uncertainty about the long-term behaviour of the adhesives and the low modulus of elasticity of the adhesives.

Research is now under way at the Centre for Window and Cladding Technology (CWCT), and elsewhere, into the behaviour of a range of adhesives which may enable engineers to design with more confidence for longer-term behaviour. One potential benefit of the use of adhesives is the distribution of loads into and out of the glass over a large area.

Double-sided structural bonding tape and modified epoxy adhesives appear to be the best candidates for structural use with glass.

It should be noted that chemicals can enter the human body orally, by respiration and via skin contact. Proper handling is always required and users should always read the manufacturer's material safety data sheet before handling or use of adhesives.

For a full list of health and safety regulations that should be taken into consideration when using adhesives the reader should consult the Institution of Structural Engineers' report *Guide to the structural use of adhesives* (1999). Of particular relevance are the *Control of Substances Hazardous to Health Regulations (COSHH) 1994*.

Although the process does not use adhesives, it is interesting to recall that the hinges of the inner toughened glass doors of cookers are sometimes soldered to the glass by a vibration heating process.

11.2 Rules of thumb

11.2.1 Strength

The strength of adhesives is dependent upon a number of factors:

- environment (chemical, UV, moisture)
- temperature and thermal behaviour of elements being connected
- rate of application of load
- duration of load
- surface preparation
- surface roughness
- joint dimensions and geometry, including shape of glue edges
- workmanship
- curing

Reputable adhesive manufacturers will quote test data and it is essential that designers understand the nature of the tests and their relationship to the intended application of the adhesive. Table 11.1 lists some of the test standards for cured adhesives.

Published data is often based upon very short-term tests and may not be directly applicable to the

Table 11.1 Test standards for adhesives

Test	Standard
Static shear strength	DIN 53481 and ISO 10123
Modulus of elasticity	DIN 53457 and ASTM D638
Linear coefficient of thermal expansion	ASTM D696
Break loose torque	DIN 54454
Coefficient of thermal conductivity	ASTM C177
Tear strength	ASTM D624
Bond strength	BS 5350
Failure patterns	BS EN 10365
Durometer (Shore A)	ASTM D2440
Peel resistance	DIN 53282
Tensile strength	DIN 53288, ASTM D2095 and ISO 8339
Elongation at break	ISO 8339
5000 load cycles at 11.5% extension/compression amplitude	EN 29046
Overlapping shear strength	DIN 53283 and ASTM D1002
Compatibility of liquid-applied sealants with accessories used in structural glazing systems	ASTM C1087

design in question. Designers should also note that the behaviour of adhesives and sealants are not independent of joint geometry. Gutowski *et al.* (1994) show that strength and strain at failure are significantly reduced with increasing sealant bead dimensions.

In the absence of code-based allowable stresses it is left to the judgment of the engineer what figures to adopt. Depending on the level of risk and the degree to which the structural system will give some warning before it fails, it may be appropriate to undertake some testing to establish design values. Chapter 5 provides some guidance for engineers who feel that testing is needed. Cyclical loading can reduce the strength of adhesive joints. Guidance on the choice of appropriate factors of safety may be found in Institution of Structural Engineers *Guide to the structural use of adhesives* (1999).

For applications in which the adhesive is under long-term load then load testing with the loads applied over, say, a month or more should be considered in order to determine if there is a lower bound figure of adhesive strength.

Research at CWCT has identified a number of significant issues for designers who wish to use adhesives. These may influence the choice of testing regime. They are listed below:

- Time dependency: adhesives tend to flow and may be sensitive to the rate of application of the load
- Adhesives have a wide range of moduli. Adhesives with low moduli are suitable for holding glass in place, whereas higher modulus adhesives are more suitable for carrying shear forces.
- Some adhesives are stronger than the glass to which they are attached and failure can then occur within the glass. This is more likely to lead to complete structural failure than failure within the adhesive or at the interface.
- The behaviour of a glued joint is very dependent on the preparation (degreasing and then priming) of the contact surfaces.
- Etching the glass surface to improve adhesion will reduce the strength of the glass
- In long overlapping joints in shear it is the adhesive at the ends of the joint that transfer most of the load. This supports the findings of Gutowski *et al.* (1994).
- Adhesive properties are temperature-dependent. A drop in temperature will simultaneously shrink glass and metal and increase the stiffness of the adhesive joining them.
- Capillary action by water can debond glued joints. Use of a suitable primer is crucial to minimise the chances of this. Silane is a commonly used primer for glass with modified epoxy adhesives.
- The flatness of the glass or glass and metal surfaces to be joined may mean that the joints need filling, which will restrict the choice of adhesives. The cyanoacrylates are not suitable for this application. Roller wave and end dip are the names given to the lack of flatness of glass as a result of support by rollers during heat treatment.
- Steel generally has a much rougher surface than glass and is much harder to apply adhesive primer to.
- The surface treatment of glass, for example a low emissivity coating, is likely to affect the behaviour of an adhesive joint.

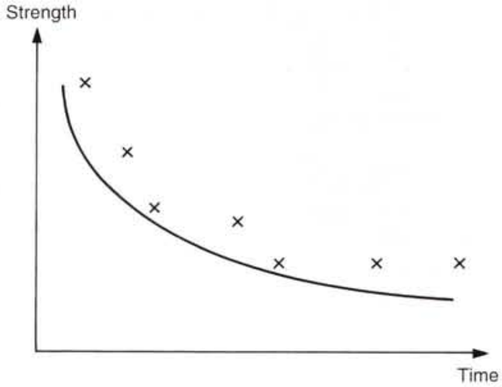


Fig. 11.1 Reduction in strength over time

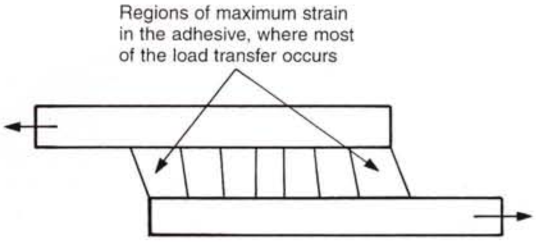


Fig. 11.2 Differential strain in a long lap joint

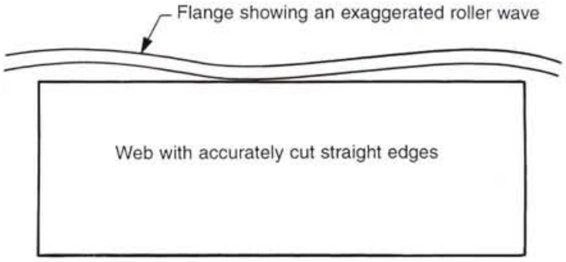


Fig. 11.3 Lack of flatness can cause problems with adhesives

- The behaviour of two-part adhesives is very dependent on how accurately and well the parts are mixed.
- Heat curing can be difficult.
- It is very important to control the joint thickness.
- Finite element modelling of glued joints can indicate where stress concentrations may occur. This is a fraught business because there is general agreement that stress concentration alone is not a reliable indicator of a problem with a joint. Energy absorption may be a better indicator.
- What is needed is a model that produces reliable results, rather than a model that minutely details a stress distribution. The analogy is with structural analysis in building structures: used within recognised limits, the linear models that engineers use give results which engineers use to design structures whose behaviour is acceptable to society. Few engineers believe that they accurately describe structural behaviour. Similarly, FE analysis is probably best used with glued joints as a basis for comparison between, for example, joints of different thicknesses rather than as a predictor of actual behaviour. Block and Travis (1997) illustrate some of the challenges of FE modelling of adhesives.

This last point brings us back to testing. Todd (1995) says that we may test glued joints for a number of reasons:

- to check the quality of an adhesive

- to determine the effectiveness of surface preparation
- to gather data for the prediction of joint behaviour
- to select an adhesive from a group of candidates
- to evaluate the effect of ageing

Complex testing may be required before the decision is made to use a particular joint design in service. Once this initial testing is complete simple tests may be used to check the quality of production, reflecting the critical areas identified during the design stage testing.

Bailey and Minor (1989) describe part of the testing carried out at Texas Tech University into the behaviour of double-glazed units bonded into a supporting frame by structural silicone. Part of the research program involved full-scale tests of these units under simulated wind pressures, with the goal of measuring changes in the shapes of the structural seal (between unit and support frame) and the seal within the units. This provided an understanding of sealant behaviour that enables designers to prescribe appropriate sealant testing.

11.2.2 Deflection

The stiffness and strain of adhesives are dependent upon a number of factors:

- environment (chemical, UV, moisture)
- temperature and thermal behaviour of elements being connected
- rate of application of load
- duration of load
- surface preparation
- surface roughness
- joint dimensions and geometry, including shape of glue edges
- workmanship
- curing

Reputable manufacturers will quote test data and it is essential that designers understand the nature of the tests and their relationship to the intended application of the adhesive.

Table 11.2 compares the shear modulus of different adhesives commonly used with glass.

The Institution of Structural Engineers' *Guide to the structural use of adhesives* (1999) provides the typical properties of a range of structural adhesives. Epoxies generally have the best creep resistance and moisture resistance.

11.2.3 Resistance to thermal stresses

In general, adhesives become less stiff and weaker as temperature increases but not noticeably so under short-term loadings (creep may be a problem under sustained loading). It is possible to glue, for example, metal cover plates or handrails to glass. Aluminium tends to debond because of its high coefficient of thermal expansion compared with glass (nearly three times higher). To quote from Loctite (1995): 'Achieving success in bonding dissimilar materials requires careful engineering considerations'.

Most engineers will be familiar with the behaviour of bimetallic strips, where the different coefficients of thermal expansion of the two metals are exploited to bend the strip when the temperature changes. In a glued joint such behaviour may not be desirable. Investigations of the failure of an epoxy adhesive joint between glass fins and bronze splice plates at an airport showed the sensitivity of the design to the thickness and hardness of the adhesive. The correct level of elasticity of the adhesive was essential for the joint to work. Unfortunately poor control of adhesive thickness and unanticipated hardening of the adhesive combined to cause failure of the joint by breakage of the glass as the fins experienced their first summer temperatures, having been built the previous winter.

Table 11.2 Shear modulus of different adhesives

Adhesive	Shear modulus
Cyanoacrylates*	Highest
Modified epoxies	Higher
Polyurethane resins	Lower
Structural silicones	Lowest

* Cyanoacrylates are probably too strong to use in structural joints in glass. Also they are not suitable as gap fillers.

Some adhesives require heat for curing and some produce heat while curing. The engineer should take careful note of the thermal effects during curing, particularly if the volume of adhesive is not small compared with the adjacent volumes of materials being joined.

11.3 Performance in use

Adhesive bonding may offer some or all of the following benefits, compared with mechanical fastening:

- reduction in weight
- ability to join thinner materials
- better stress distributions at joints
- improved joint strength
- ability to join dissimilar materials
- scope for sealing as well as joining
- increased flexibility in the choice of component materials
- reduction in machining operations
- aesthetic improvement
- easier composite action of built-up sections

Failure of a glass-adhesive-glass joint (for example, at the intersection of the web and flange of a T-section) will be by one of 3 mechanisms:

- tensile failure of the glass
- shear failure of the adhesive (i.e. cohesive failure within the adhesive)
- adhesive slip or plucking failure (i.e. failure at the adhesive/glass interface)

The behaviour in service of the joint will be determined by how well it was made and how cyclical loading, temperature, humidity, chemical environment and age have affected its properties.

An adhesive joint may act to stop the propagation of cracks in glass, though cracks have been known to 'jump' over small structural silicone butt joints between toughened glass plates. The likely mechanism is that the force generated by the approaching crack is transmitted through a thin joint and sets off a sympathetic fracture.

11.4 Selection, design and application

Section 2.2 discusses the many non-structural issues that influence design: thermal transmission, solar radiation, condensation, rainwater runoff, fire, acoustic behaviour, access, installation, cleaning, inspection, maintenance, repair, replacement, availability, appearance, fit, position, durability, environmental impact and life-cycle costing.

Before carrying out any calculations, it is most important that the designer has a clear idea of how the structure will behave. Because of the brittle nature of glass it is also important that the designer has a clear idea of how the structure is to behave after one or more glass elements have failed. It is also important to assess the safety implications of failure of a piece of glass or adhesive: what is the likelihood of people being injured by falling glass, for example? It is only when the structural behaviour is understood that decisions can be made about what calculations and testing are appropriate.

11.5 Worked example

A worked example is shown on pages 107-109.

11.6 References and suggested further reading

ASTM (1995): *Standard test method for determining compatibility of liquid-applied sealants with accessories used in structural glazing systems.* C1087-95

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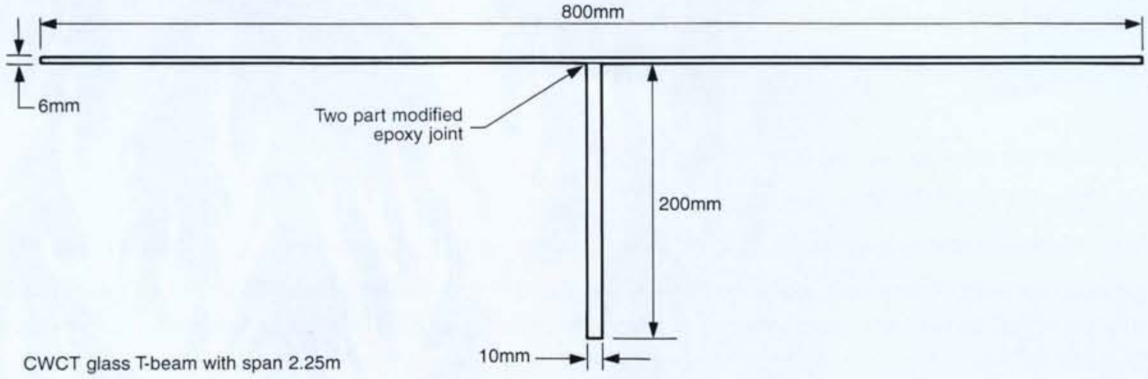
Wagner, W. (1999).: 'The use of silicone sealants for structural sealant glazing'. *Proceedings of The Sixth International Conference on Architectural and Automotive Glass,* Tampere, Finland, 13-16 June 1999

3M *Electrical products:* Scotchcast™ Electrical Liquid Resins 1997

3M: VHB™ *Tapes selection guide*

Worked example

This example is based on the CWCT glass T-beam illustrated below.



CWCT glass T-beam with span 2.25m

Calculate the centre of gravity of the T-section

Area	X	Area x X
800 6 = 4 800mm^2	203mm	974 400mm^3
200 10 = 2 000mm^2	100mm	200 000mm^3
Σ = 6 800mm^2		Σ = 1 174 400mm^3

From which X = 1 174 400/6 800 = 172.7mm

Calculate I of the T-section assuming fully composite section

$800 \times 6^3/12$ = 14 400mm^4

$800 \times 6 \times (203\text{-}172.7)^2$ = 4 406 832mm^4

$10 \times 200^3/12$ = 6 666 666.7mm^4

$10 \times 200 \times (172.7\text{-}100)^2$ = 10 570 580mm^4

Σ = 21 658 478.7mm^4

Calculate Z of the top and bottom of the section

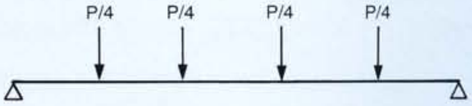
Z_{flange} = 21 658 478.7/(206-172.7) = 650 405mm^3

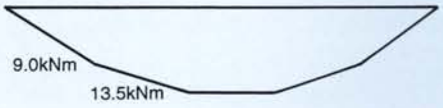
Z_{web} = 21 658 478.7/172.7 = 125 411mm^3

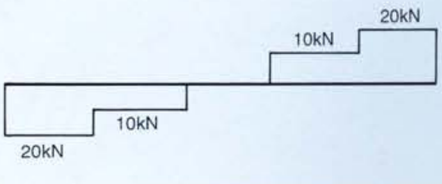
This beam has been tested at CWCT under a 6 point bending test (right, top).

Consider the strength limit state condition when P = 40kN, i.e. each point load is 1 tonne.

The bending moment diagram is shown right, middle and the shear force diagram is shown right bottom.







Calculate extreme fibre stresses in the glass (ignoring shear lag)

$M/Z_{flange} = 13.5 \times 10^6/650\,405 = 20.8\text{N/mm}^2$ (compression)

$M/Z_{web} = 13.5 \times 10^6/125\,411 = 107.7\text{N/mm}^2$ (tension)

This is a very high tensile stress, even for toughened glass.

Calculate shear stress in the web

$\tau = V/A = 20 \times 10^3/2\,000 = 10\text{N/mm}^2$

From Mohr's stress circle, in the case of pure shear, σ_x and σ_y, the two principal stresses, are of opposite sign and magnitude equal to that of the shear stress τ. Therefore, at the supports, there exist principal tensile and compressive stresses of 10N/mm². This is a gross simplification of the actual distribution of stresses at the support, which will depend on the as-built geometry and materials used. (See Fig. 7.4)

Calculate shear stresses in the adhesive

Using the expression

$$q = VAy/I$$

where: q is the shear per unit length
A is the area of the flange
y is the distance from the centre of the flange to the centre of gravity of the T-section,
I is the second moment of area of the T-section
V is the shear force

we calculate:

$$q = 20 \times 10^3 \times 4\,800 \times (203-172.7)/21\,658\,478.7 = 134\text{N/mm}$$

Determine the size of epoxy adhesive joint required to carry this ultimate stress

According to Institution of Structural Engineers *Guide to the structural use of adhesives* (1999), epoxy adhesives typically have shear strengths in the range 15-35N/mm². It goes on to recommend that the material strength should be divided by a partial factor of safety built up as follows:

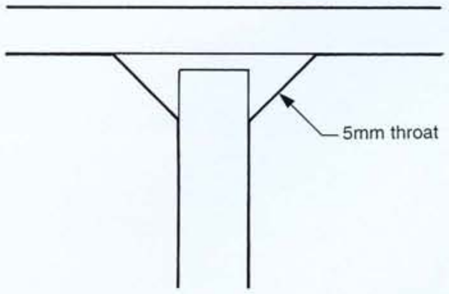
$$\gamma_m = \gamma_{m1} \times \gamma_{m2} \times \gamma_{m3} \times \gamma_{m4} \times \gamma_{m5}$$

where: γ_{m1} is related to the source of the adhesive properties
γ_{m2} to the method of adhesive application
γ_{m3} to the duration of loading
γ_{m4} to the environmental conditions, and
γ_{m5} to fatigue loading.

It recommends the following values:

γ_{m1}	Textbook values	1.5
γ_{m2}	Manual application, with adhesive thickness controlled	1.25
γ_{m3}	Short-term loading	1.0
γ_{m4}	Service conditions outside test conditions	2.0
γ_{m5}	Loading basically static	1.0
γ_m		3.75

Assume a mid-range epoxy strength of 25N/mm^2. The design strength of the epoxy is therefore 25/3.75 = 6.7N/mm^2. The width of epoxy required is therefore 134/6.7 = 20mm. The joint therefore needs to be, in welding terms, a butt joint plus two fillets, as shown below.



This very crude calculation, ignores shear lag and it ignores the flexibility of the adhesive and its influence on the section properties. It has not determined the best separation between web and flange. It does not pretend to have designed an adhesive joint. Finite element analysis, perhaps combined with model testing, may well be required to determine the best shape and size of the adhesive joint. The aim of this simple example is to give some feel for what is possible with adhesives.

12 Glass balustrades

12.1 General description

Glass balustrades are barriers designed to stop people from falling off the edges of floors and stairs. They may be framed in wood or metal, with glass infill panels, or they may consist entirely of glass.

They may be storey-height or they may be around 1.1m tall. This section concentrates on the latter, but the principles involved do not change with the height of the balustrade. The taller the balustrade, the more significant wind loads become.

12.2 Rules of thumb

The regulatory framework in the UK is covered by:

- Approved Document K of the Building Regulations (England and Wales) or similar appropriate national documents
- BS 6180: 1995 *Code of practice for Barriers in and about buildings*
- BS 6206: 1981 *Specification for impact performance requirements for flat safety glass and safety plastics for use in buildings*
- BS 6262: 1982 *British Standard Code of practice for glazing for buildings*

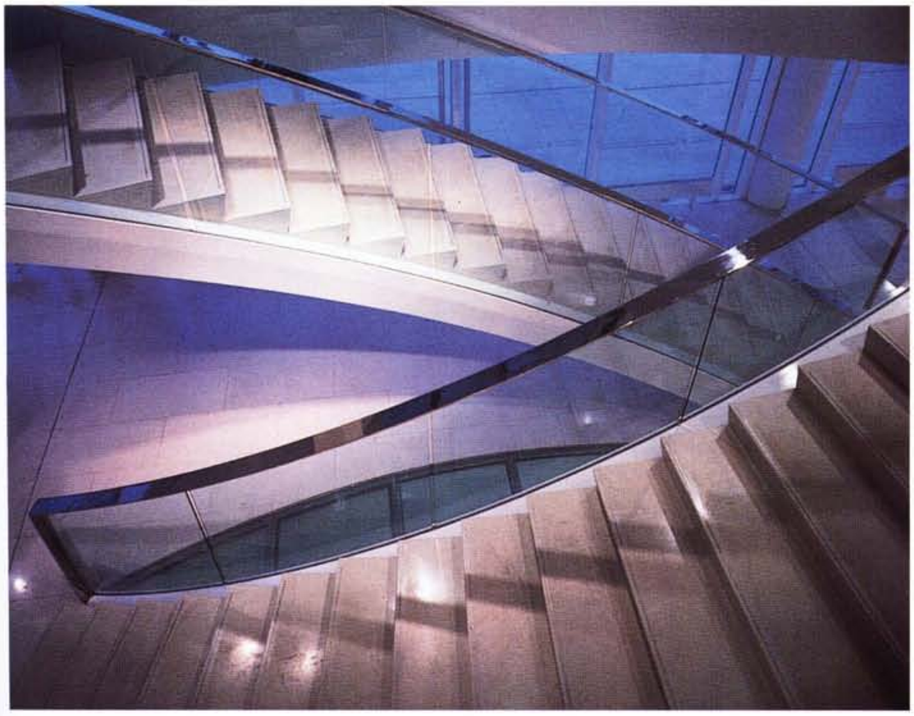


Fig. 12.1 A glass balustrade (courtesy of Ove Arup & Partners/Dennis Gilbert)

Strength

Infill panels supported along all edges
Table 2 of BS 6180 indicates sizes of glass panes for different types and thicknesses of glass which, when used with a glazing method which fully supports the glass along all edges, will withstand the design criteria given in clause 6 of BS 6180.

Bolt-fixed infill panels
Clause 8.4.5 of BS 6180 gives the design criteria and annex C of BS 6180 gives advice on the details of the bolted connections. Table 12.1 indicates maximum spans for bolted toughened glass infill panels using clamp plates.

6mm and 8mm toughened glass will not be suitable if the free path perpendicular to the balustrade is larger than 1.5m, since it will not provide containment, i.e. remain intact, at Class A of BS 6206.

Since toughening varies from manufacturer to manufacturer, it is advisable to seek confirmation of these numbers from one or more reputable manufacturers early in the design process. US toughening levels may be generally lower than UK levels (see section 2.1.2)

Edge clamped or bolted free-standing glass panels
These should always be made of toughened heat-soaked glass. BS 6180 requires that they are configured so that adjacent panels can sustain the loss of a panel, with load sharing via the handrail.

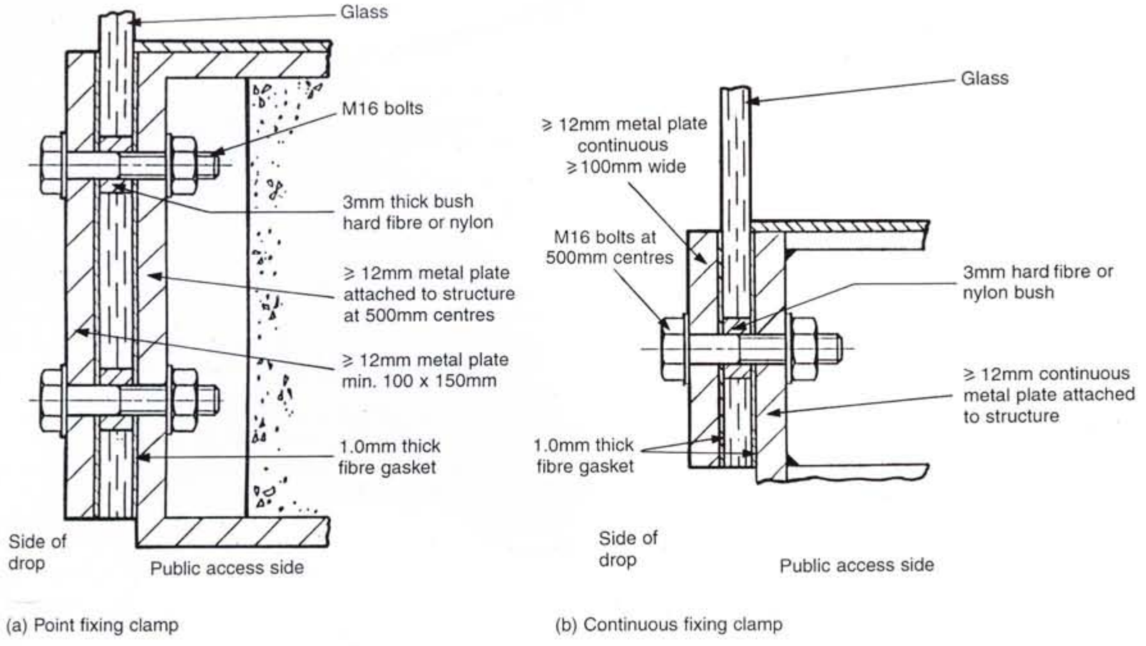
The thicknesses in Table 12.2 may alter if the top

Table 12.2 Usual thickness of UK toughened glass for free-standing glass balustrades

Design line load (kN/m)	Thickness of toughened glass (mm)
0.36	12
0.74	15
1.5	19
3.0	25

Table 12.1 Maximum spans for toughened glass panels using bolted clamp plates
(Source: Pilkington Glass Consultants)

Infill loading from BS 6180		Maximum span in mm for bolted UK toughened glass			
UDL in kN/m^2	Point load in kN	6mm	8mm	10mm	12mm
0.5	0.25	1400	1800	2150	2450
1.0	0.5	900	1500	1800	2050
1.5	1.5	–	–	1200	1650



(a) Point fixing clamp

(b) Continuous fixing clamp

Fig. 12.2 Fig C.2 of BS 6180, showing 2 typical clamping details (courtesy BSI)

edge of the support is significantly above or below finished floor level.

12.3 Performance in use

Annex A of BS 6180 and BS 6399: Part 1 define the imposed loads for which barriers in buildings should be designed. When the glass components of barriers are subjected to half the imposed loads from annex A, the horizontal displacement of any point of the glass, relative to its fixings, should not exceed the smaller of 12.5mm or $L/125$. L is the longest dimension of the glass or, in the case of free-standing glass protective barriers, L is taken as 1250mm. This deflection criterion is an onerous one. At the time of writing (1998) this was being changed.

12.4 Selection, design and application

Critical issues may include some or all of the following non-structural items:

- thermal transmission and solar radiation
- condensation
- rainwater runoff
- fire
- acoustic behaviour
- access for installation, cleaning, inspection, maintenance, repair, replacement
- availability
- appearance and fit
- durability
- environmental impact and life cycle costing.

Critical structural issues include:

- how the overall structure will behave
- how the structure will behave after one or more glass elements have failed
- the safety implications of failure of a piece of glass, including the likelihood of people being injured by falling glass

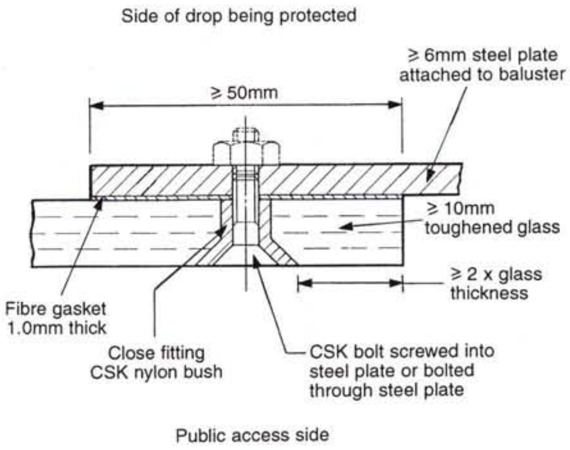


Fig. 12.3 Fig C.1 of BS 6180, showing a typical bolting detail (courtesy BSI)

BS 6180 requires that free-standing glass panels are configured so that adjacent panels can sustain the loss of a panel, with load sharing via the handrail.

The choice of annealed, heat-strengthened or toughened glass will rarely be determined by considerations of strength alone.

Most manufacturers will provide guidance on what thickness and type of glass should be used, based on their experience. The Glass and Glazing Federation also provides guidance in its *Glazing Manual*, item 5.9.

12.5 Design details

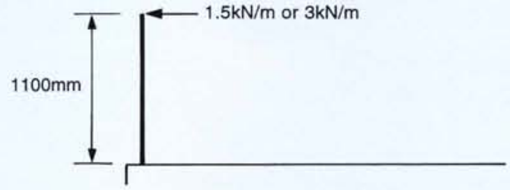
Typical details from BS 6180 are shown in Figs 12.2 and 12.3. (Note: Extracts from British Standards are reproduced with the permission of BSI under licence number PD/1999 0619. Complete copies of the standard can be obtained by post from BSI Customer Services, 389 Chiswick High Road, London W4 4AL).

12.6 Worked example

A worked example is shown on pages 113 and 114.

Worked example

The balustrade to be designed is a free-standing barrier 1100mm tall in a shopping mall or department store, with a free path perpendicular to the balustrade of more than 1.5m.



The design line loads are 1.5kN/m (department store) and 3kN/m (shopping mall), according to BS6180: 1995.

Two possible means of support are:

- point fixing clamps similar to Figure C.2 a) of BS 6180
- continuously clamped glass similar to Figure C.2 b) of BS 6180

The free path perpendicular to the balustrade is more than 1.5m, which means that, according to BS 6180 clause 8.6.4, the glass must satisfy class A of BS 6206, which in turn means a minimum specification of 10mm toughened glass. Heat-soaked toughened glass should be specified to reduce the likelihood of glass fracture caused by nickel sulphide inclusions.

To satisfy BS 6180, the glass must be strong enough to carry the design load and must be stiff enough to limit deflection under one half design load to 10mm (*L*/125, with *L* taken as 1250mm for a free-standing glass balustrade).

Consider deflection

The deflection of the tip of a cantilever under point load is given by:

$$\Delta = PL^3/3EI$$

from which:

$$I_{\text{reqd}} = PL^3/3E\Delta$$

where: $\Delta \leq 10\text{mm}$

$L = 1100\text{mm}$

$E = 70\text{kN/mm}^2$.

The following table calculates the required *I* for the two line loads.

Line load	One half line load	I_{reqd}	Thickness
3kN/m	1.5kN/m	950 714mm^4/m	22.5mm
1.5kN/m	0.75kN/m	475 357mm^4/m	17.9mm

The standard glass thicknesses that satisfy these figures are 25mm and 19mm. This table also shows the importance of supporting the glass in a way that minimises the free height of the cantilever, because deflections are proportional to the cube of the cantilever height. Barriers whose support is below floor level often require additional framing in order to control deflections.

Consider bending stresses in the continuously clamped glass

From Table 2.7 of chapter 2, 19mm and 25mm float glass to BS EN 572-2 can be as much as 1mm thinner than its nominal thickness, so stresses will be calculated using 18mm and 24mm.

The behaviour of glass which is not continuously clamped will be harder to calculate. Reputable manufacturers will provide guidance, which may be based on tests using British Standard clamps, such as that shown in Figure C.2 a) of BS 6180. For this example, the manufacturer consulted confirmed that the same glass worked for both support conditions.

BS 6180 requires, in most circumstances, that a handrail is used, continuously attached to the

Line load	Bending moment	Z of glass	*M/Z*	OK/Not OK (Table 6.2 & Table 6.3)
3kN/m	3.3kNm/m	1000 $24^2/6$ = 96 000mm^3/m	34N/mm^2	OK
1.5kN/m	1.65kNm/m	100 $18^2/6$ = 54 000mm^3/m	30.6N/mm^2	OK

glass, capable of spanning under full design load across the gap caused by fracture of a glass panel.

The designer should also consider the risk to people below of glass breakage.

12.7 References

BSI (1995c): *Glass in building – Basic soda lime silicate glass products*. Part 3. *Polished wired glass*. BS EN 572-3: 1995

BSI (1995): *Code of practice for barriers in and about buildings*. BS 6180: 1995

BSI (1981): *Specification for impact performance requirements for flat safety glass and safety plastics for use in buildings*. BS 6206: 1981

BSI (1982): *British Standard Code of practice for glazing for buildings*. BS 6262: 1982

BSI (1984): *Code of Practice for dead and imposed loads* BS 6399: Part 1: 1984

Department of the Environment, Transport and the Regions and Welsh Office: *The Building Regulations 1997: Approved Document K: stairs, ramps and guards*

Glass and Glazing Federation (GGF) (1991): *Glazing Manual*. The Federation

13 Glass stairs, floors & bridges

13.1 General description

Glass stairs, floors and bridges use glass as the walking surface and sometimes as the supporting structure as well.

At the Stansted Airport Passenger Terminal (1991: Architect Foster Associates; Engineer Ove Arup & Partners) small areas of glass floor abut the steel 'trees' which support the main roof. At the London restaurant Now & Zen (Architect: Rick Mather; Engineer: Dewhurst McFarlane) pavement lights 4m long by 1m wide are made of two sheets of 19mm glass laminated together. Visitors can walk on the 1235mm square glass panels of the National Glass Centre in Sunderland (1998; Architect: Gollifer Associates; Facade Engineer: Arup Facade Engineering) (Allen, 1998)

Modern examples of glass stairs include a two storey staircase for the Joseph shop (Anonymous, 1993) at 26 Sloane Street, London (1990; Architect: Eva Jiricna; Engineer: Dewhurst McFarlane) and the Pilkington Exhibition Centre (Dawson, 1996) in Lathom, Lancashire (1996; Architect: RMJM; Engineer: RMJM). Robert Nijsse of abt is the engineer for a very bold design at the Stedelijk Museum in Zwolle.

Glass floors and glass bridges seem to go together and examples include:

- Whitby Bird & Partners' glass bridge at the Science Museum in London (Fig. 13.6)
- Professor Schlaich's glass bridge at the Deutsches Museum in Munich (Fig. 13.7)
- Robert Nijsse's glass bridge at the offices of architect Kraaijvanger•Urbis in Rotterdam (Fig. 13.8)
- Ian Ritchie's glass bridge – engineer Arup – in the London Geological Museum (Fig. 13.9)
- Atelier One's glass bridge over a Soho courtyard (Fig. 13.10)

13.2 Rules of thumb

13.2.1 Strength

For glass beams, Chapter 7 provides rules of thumb.

Fig. 13.1 Glass floors at Stansted (courtesy of Foster & Partners)

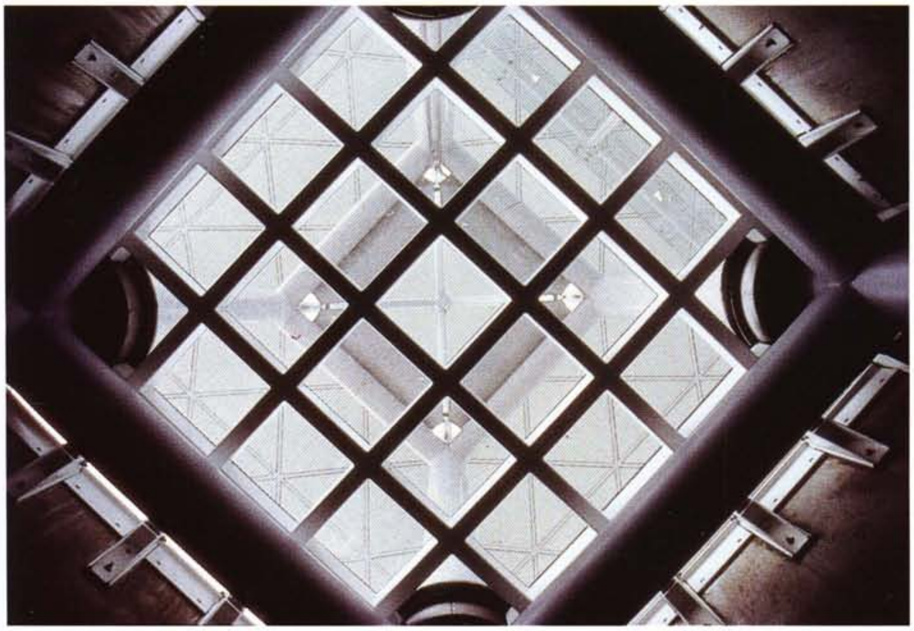


Fig. 13.2 Floor panels at Now & Zen (courtesy of Dewhurst McFarlane & Partners/Rick Mather)

For glass panes supported on 2 or more edges the reader should refer to Chapter 6 and for glass columns and walls Chapter 8. In the UK, imposed loadings are defined in BS 6399: Part 1.

13.2.2 Deflection

Serviceability issues are also covered in the relevant chapters. Walking on glass is likely to be sufficiently unnerving for some people that it is important not to add to their concern by designing a structure that is too bouncy.

13.2.3 Elastic stability

This is also covered in the relevant chapters listed previously.

13.2.4 Resistance to thermal stresses

Thermal stress and breakage cannot always be precisely predicted as many of the contributing factors are difficult to quantify. During the design process the designer should consult one or more reputable manufacturers to evaluate the risk of thermal breakage. Chapter 6 provides a checklist that attempts to quantify the various factors that contribute to thermal stress.

13.3 Performance in use

A beam or plate resists loads by deforming and developing internal and edge stresses. A glass beam or plate under increasing load deforms elastically until sudden failure is initiated at a surface flaw that magnifies the effect of the tensile stress. Resistance of glass to pressure is limited, not only by tensile stress, but also by the severity of stress concentrations caused by flaws. Glass beams and plates are very susceptible to flaws or scratches on their tensile surfaces or edges.

Fig. 13.3 Staircase at the Joseph Shop in Sloane Street, London (courtesy of Dewhurst McFarlane & Partners/Eva Jiricna/Richard Bryant)

Fig. 13.5 Staircase at the Stedelijk Museum in Zwolle (courtesy of abt)

This interaction of stress and flaws means that glass beam resistance is influenced by area, loading history, aspect ratio, edge compressive stress from heat treatment and flaws from manufacturing, handling and installation processes. A rational calculation of resistance must account for the pattern of stresses set up by the loading and support conditions, statistical variation associated with the distribution of surface flaws and the accumulated experience of past and current practice. Chapter 5 provides guidance on calculations.

If the decision is made to use toughened or heat-strengthened glass and calculations indicate that the surface precompression will not be overcome by imposed tensile stresses, then fracture-mechanics-based calculations will not be needed.

13.4 Selection, design and application

Critical issues may include some or all of the following non-structural items:

- thermal transmission and solar radiation
- condensation
- rainwater runoff
- fire
- acoustic behaviour
- access for installation, cleaning, inspection, maintenance, repair, replacement
- availability
- appearance and fit
- durability
- environmental impact and life cycle costing.

Critical structural issues include:

- how the overall structure will behave
- how the structure will behave after one or more glass elements have failed
- the safety implications of failure of a piece of glass, including the likelihood of people being injured by falling glass

Fig. 13.4 Staircase at the Pilkington Exhibition Centre, Lathom (courtesy of Pilkington/Chris Gascoigne)

Fig. 13.6 The glass bridge at the Science Museum, London (courtesy of Whitby Bird & Partners)

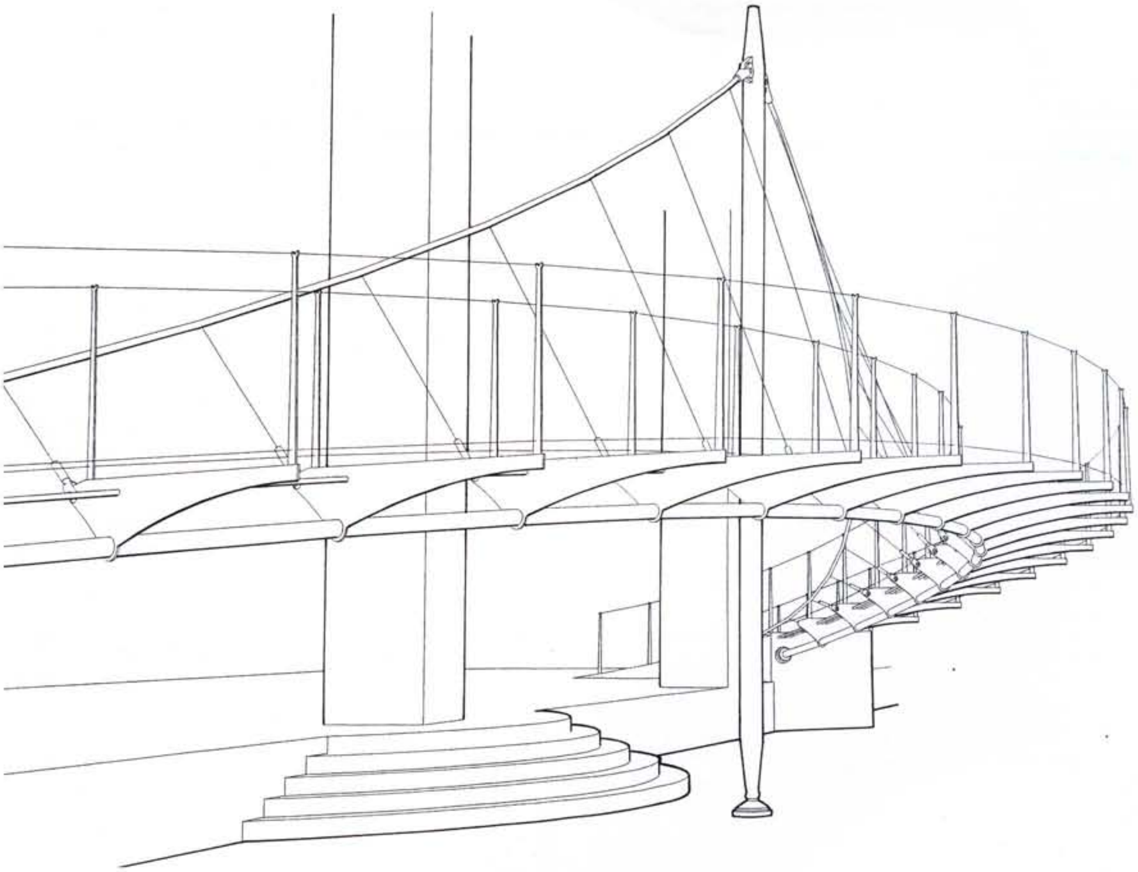


Fig. 13.7 Professor Schlaich's glass bridge at the Deutsches Museum in Munich (courtesy of Schlaich Bergermann und Partner)

It has been customary for designers of floor panels to use 4 edge supported laminated glass. Annealed glass can span (albeit at reduced load) even when broken and the lamination provides additional safety. Acrylic can be used as the back-up layer. Annealed and toughened glass are equally scratchable. Recent stair tread details include those described in Table 13.1.

The choice of annealed, heat strengthened or toughened glass will rarely be determined by considerations of strength alone.

13.5 Design details

Design details are shown in Figs 13.11, 13.12 and 13.13

13.6 Additional information

It is desirable to abrade the surface of the glass so that subsequent abrasion by foot traffic will not produce further changes in the appearance of the glass. The right kind of abrasion can also make the glass

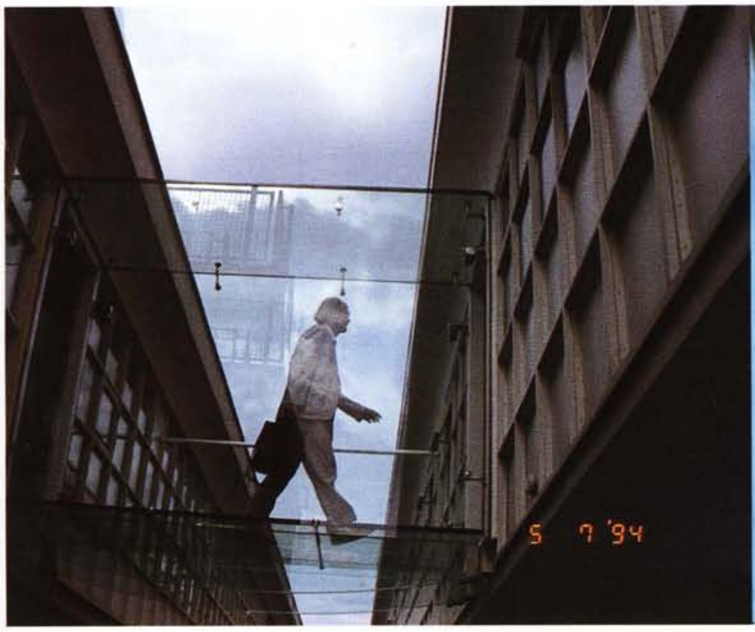


Fig. 13.8 Glass bridge at the offices of architect Kraaijvanger•Urbis in Rotterdam (courtesy of abt)

Fig. 13.9 Glass bridge in The Geological Museum, London (courtesy of Ian Ritchie Architects)

Table 13.1 Details of some recent stairs

Location	Tread construction	Tread support
Joseph shop	19mm annealed glass on 15mm acrylic	Point support
Chicago apartment	3 ply laminated 10mm annealed glass	One way spanning onto edge support
Pilkington Exhibition Centre	2 ply laminated toughened glass	Point support

Table 13.2 Coefficient of friction between glass and shoe heels (source: British Shoe Manufacturers' Association)

Surface finish	Coefficient of friction
Untreated	Lowest
Gloss acid etch	
Dull acid etch	
Light sand blast	
Coarse sand blast	Highest

less slippery and hence safer to tread on, as is shown in Table 13.2. Even with the best roughening, glass may still be very slippery when wet. Care should be taken when considering glass for use in outdoor or wet environments.

Other surface treatments to reduce the risk of slippage include raised studs and grooves filled with neoprene strips. Toughened glass should not be abraded.

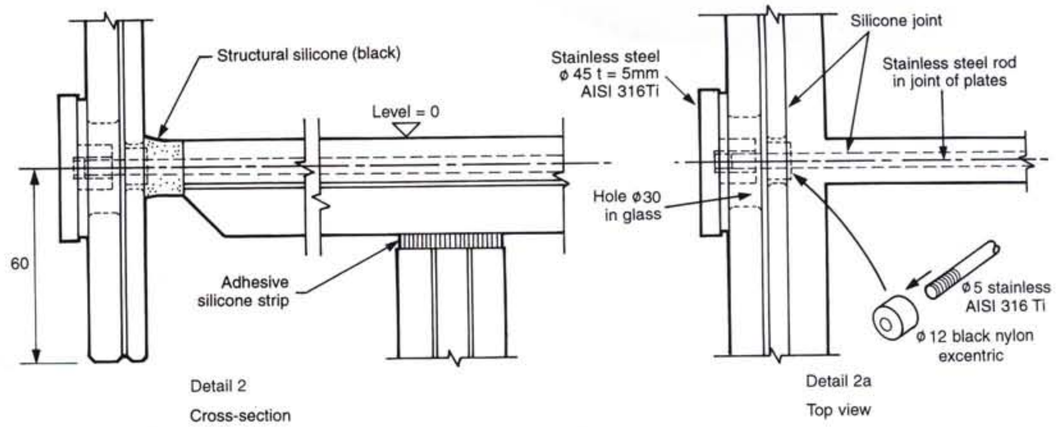
Further guidance may be found in Templer (1992) and GLC (1984 and 1985). Annex C of BS 8204 gives a method for determining slip resistance.

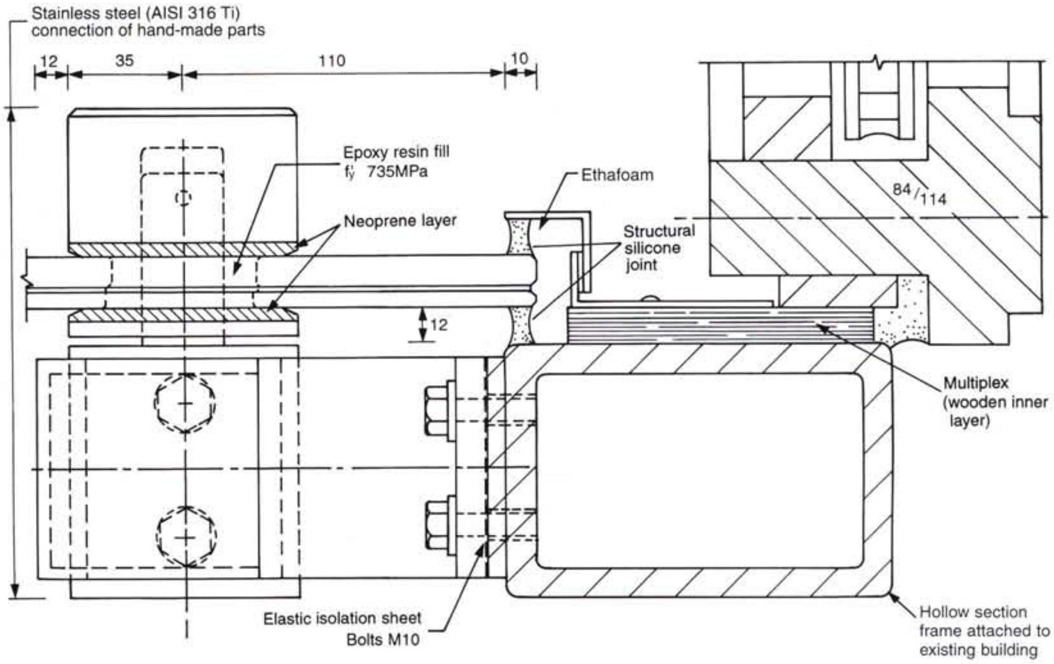
Fig. 13.10 Atelier One's glass bridge over a Soho courtyard (courtesy Atelier One)

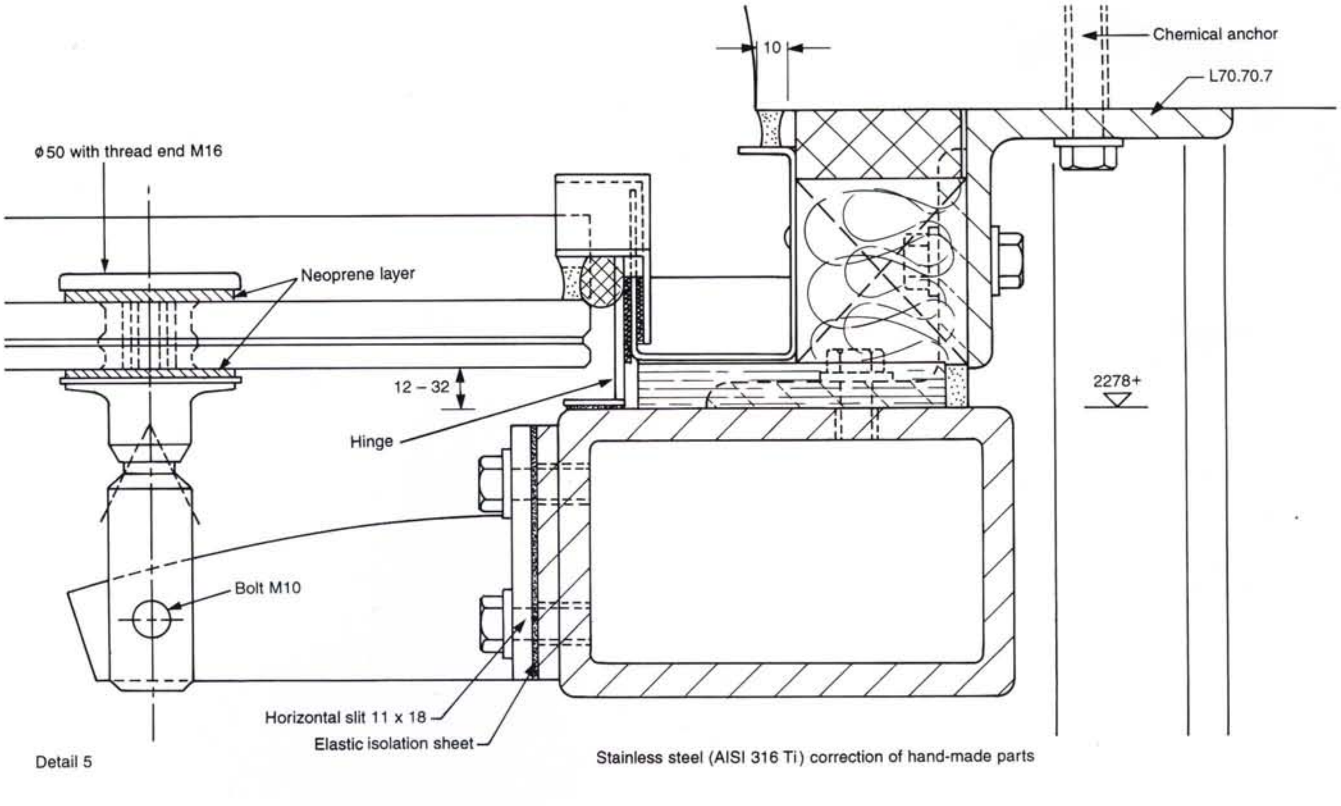
Fig. 13.11 A floor panel at the Law Faculty in Cambridge (courtesy of Foster & Partners)

Fig. 13.12 The glass cantilevers on Pilkington's staircase (courtesy of Pilkington/Chris Gascoigne)

Fig. 13.13 Details of Robert Nijsse's glass footbridge in Rotterdam







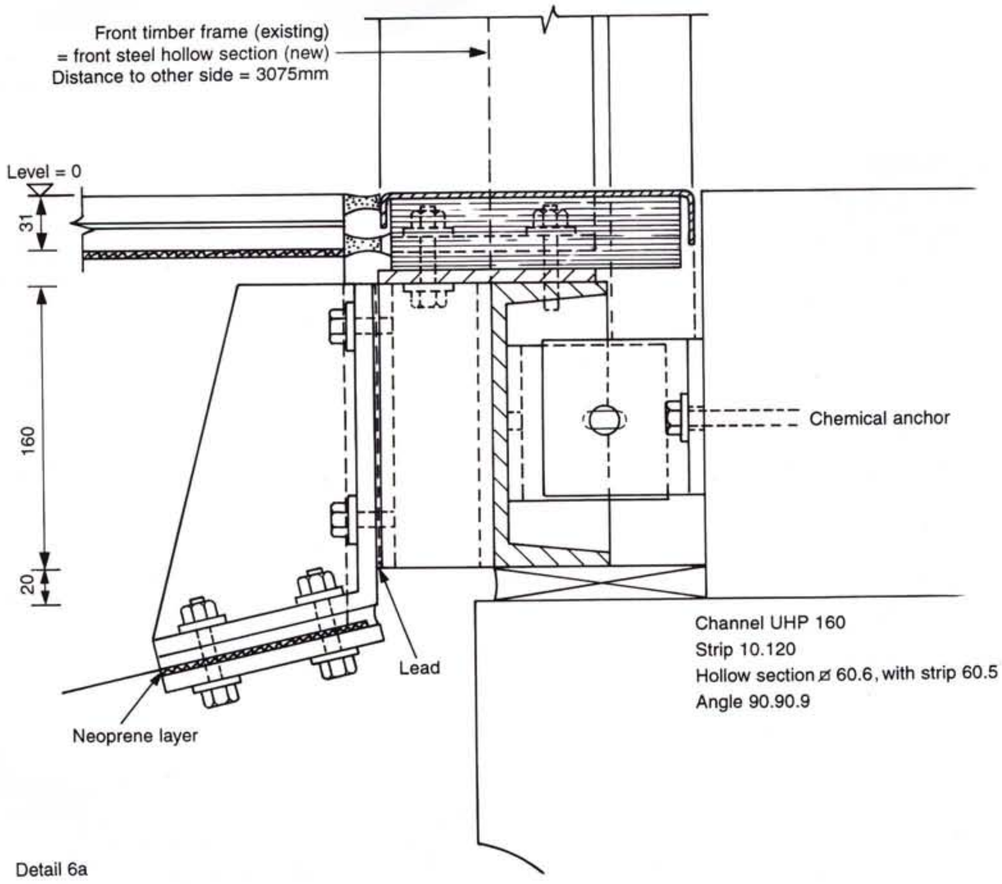


Fig 13.13 (cont'd) Details of Robert Nijsse's glass footbridge in Rotterdam

13.7 Worked example

A worked example appears on pages 121 and 122.

13.8 References

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Davey, P.(1991): 'Airports come of age'. *The Architectural Review,* May, p34

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GLC: *A slip resistant coating for asphalt, steel and concrete surfaces.* GLC Bulletin 143 (7/84)

GLC: *Sheet safety surfaces for floors, methods for evaluation.* GLC Bulletin 145 (2/85)

Roark, R. J. and Young, W. C. (1989): *Formulas for stress and strain,* 6th edition. McGraw-Hill.

Templer, J. A. (1992): *The staircase: studies of hazards, falls and safer design.* MIT, 1992

Worked example

A rectangular glass panel for the floor of an atrium bridge in a new building in central London. The panel is 1.98m × 0.75m. and is simply supported along all four edges by a neoprene bedding strip on a steel angle.

The design UDL is 4kN/m^2. The design point load is 4.5kN applied over an area 100mm × 100mm, with a duration of 30 minutes.

The design adopted uses a 25mm sheet of annealed glass on top of a 19mm sheet of annealed glass, laminated using a PMMA resin interlayer. Two layers of glass provide significant redundancy. Physical tests were also carried out to verify the performance of the panel. The test panels passed the tests.

The 4.5kN load was applied on both an undamaged panel and a panel with the top sheet of glass broken. Three panels were tested in accordance with BS 6206: 1981, section 5 for semi-hard body impact. Three panels were tested by dropping 4.5kg steel ball through a height of 1.2m. For all the impact tests the acceptance criteria were:

- the impactor should not pass through the glass
- in the case of breakage, no pieces of glass large enough to cause injury are released

Calculation of behaviour of the glass under design loads
For simplicity and conservatism, assume that the top sheet is broken and that the bottom sheet carries all the loads. Assume that deflections are small enough for linear bending theory to be appropriate. Assume a factor of 1.4 on dead load and 1.6 on live load.

Self-weight of 19mm + 25mm of glass = $0.044 \times 25 = 1.1$kN/m^2.

Live load = 4kN/m^2 or 4.5kN.

Roark (1975) Table 26 deals with flat rectangular plates. It is important not to use equivalent strip methods (e.g. 'assume the point load is carried by a strip Xmm wide') with materials that cannot yield and redistribute load away from overstressed regions; the analytical models must predict *peak* stresses.

Calculate bending moments and bending stresses

For UDLs we use case 1a of Table 26.

Ratio of sides = $1.98/0.75 = 2.64$, from which $\beta = 0.68$

UDL – DL

Max $\sigma_{DL} = 0.68 \times (1.4 \times 1.1) \times 0.75^2/0.019^2 = 1622.7$kN/m^2 = 1.6N/mm^2

UDL - LL

Max $\sigma_{LL} = 0.68 \times (1.6 \times 4) \times 0.75^2/0.019^2 = 6781.2$kN/m^2 = 6.8N/mm^2

Pt Load – LL

For point loads we use case 1b of Table 26

Ratio of sides = 2.64, from which $\beta = 0.97$

Calculate radius of equivalent loading circle r_0 from

$\pi \times r_0^2 = 100 \times 100$, from which $r_0 = 56.4$mm

Max $\sigma = (3 \times 4500/(2 \times \pi \times 19^2))((1 + \nu)\ln(2 \times 750/(\pi \times r_0)) + \beta)$

$\nu = 0.22$ and $\beta = 0.97$, from which

Max $\sigma = 21.3$N/mm^2

If we test these figures against the Dutch design stresses given in Table 6.1, we find the following:

Load type	Factored stress	Design stress	Conclusion
Dead load	1.6N/mm^2	7N/mm^2	OK
Live load (UDL)	6.8N/mm^2	17N/mm^2	OK
Live load (point load)	21.3N/mm^2	17N/mm^2 and 28N/mm^2	NOT OK and ALMOST OK

This simple analysis suggests that the 19mm glass alone will be strong enough for the uniformly distributed loads but possibly not strong enough for a central point load. It is for the engineer to decide the appropriate load factors and the appropriate design stresses and the appropriate analytical model for the circumstances of the design.

For UDLs, another approach is to treat the floor panel as the base of a swimming pool and to use the design chart in Fig. 15.9 with a water depth of 400mm. This approach gives a recommended minimum thickness of annealed glass of 19mm.

Check UDL deflections using simple bending theory for 2-edge support.

$\Delta = 5wL^4/(384EI)$ where $I = 1000h^3/12$ mm^4

From which

$\Delta = 5wL^4/(32Eh^3)$ where w is in kPa, E is in kPa and L and h are in mm.

For a live load of 4kPa, with L = 750mm, E = 70 000 000kPa and h = 18mm (19mm nominal thickness less maximum deviation permitted for glass manufactured to BS EN 572-2 – see section 2.2.14)

$$\Delta = 5 \times 4 \times 750^4/(32 \times 70\,000\,000 \times 18^3) = 0.5\text{mm}.$$

0.5mm is significantly less than half the plate thickness, so simple bending theory is appropriate.

Hard body impact test

Calculations of whether a pane of glass (or any brittle material) will break under hard body impact are extremely difficult. For a discussion of this the reader is referred to Creyke, Sainsbury and Morrell (1982).

14 Glass in large deflection structures

14.1 General description

For many designers, there is a contradiction inherent in the idea of glass in large deflection structures: glass is part of the external skin of buildings and control of deflections has been assumed to be an essential aspect of maintaining a watertight envelope; glass is notoriously intolerant of imposed deflections and so great effort has been expended in devising stiff frameworks to support the glass and to isolate the glass from movements of the primary structural frame.

The 1990s have shown that these assumptions are not always correct. At Munich Airport's Kempinski Hotel, described in some detail in Chapter 4, engineer Jörg Schlaich's facade deflects 90cm under its design wind pressure. At the terminal building of Stansted Airport, also described in Chapter 4, the 12m-tall glass walls are designed to withstand a nearby explosion and to retain their glass, while undergoing significant deflections, both of the yielding steel supporting structure and of the glass itself.

Ordinary 4-edge-supported panes of glass are usually large deflection structures in their own right, so perhaps the use of glass in large deflection structures is not such a perverse idea after all.

Glass may be used to provide in-plane shear stiffness to a cable net.

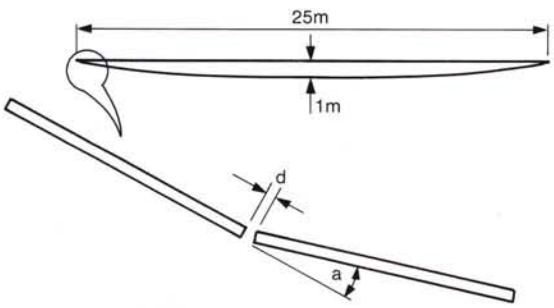
Chapter 15 deals with special applications including blast loading.

Tightrope (large deflection structure)
under self weight

Tightrope under point load

If tightrope is stretched (i.e. prestressed), deflection
is reduced but foundation forces are increased

Fig. 14.1 A tightrope changing its geometry to accommodate the weight of a person walking across. When the tightrope is prestressed it becomes straighter and deflects less under load.



Adjacent panes in large deflection structure

If an initially straight cable spans 25m and deflects 1m under load
the maximum value of "a" between adjacent 1m panes is only
0.6 degrees and the gap "d" increases by 4mm.

Fig. 14.2 Strain on the seals between adjacent panes of glass

14.2 Rules of thumb

14.2.1 Strength

The simplest large deflection structure is a straight cable. Large deflection structures are usually prestressed so as to prevent load reversal, increase their stiffness and to control their vibrations. This can impose significant forces on foundations and supporting structures. A powerful example is the new Millennium Footbridge in London (2000, Architect: Sir Norman Foster & Partners, Engineer: Ove Arup & Partners).

14.2.2 Deflection

Large deflection structures accommodate changes in loading by changing their geometry. The assumptions that underpin conventional structural design are no longer valid, because deflections are no longer small.

However the deformations of the glass elements themselves and of the materials between adjacent glass elements may still be small.

The designer should carefully check that the edges of the large deflection structure are able to move without unwanted resistance from adjacent elements of the building. In the example of Fig 14.2, the cable wants to rotate by 9° at its supports under full design load. The support details need to be configured to accommodate this large rotation. A large flat glass wall with a tennis-racket cable net will require careful detailing around its edges and especially at its corners.

14.2.3 Resistance to thermal stresses

Chapter 6 provides a checklist of items to consider. Bolted connections may constrain the glass and its supporting structure to deform together in the plane of the glass. This makes it important that the designer carefully considers thermal effects when detailing the connections.

14.3 Performance in use

A large deflection structure resists wind pressure or other surface loads by deforming significantly. A glass plate under increasing pressure and under imposed strains deforms elastically until sudden failure is initiated at a surface flaw that magnifies the effect of the tensile stress. Resistance of glass to pressure is limited, not only by tensile stress, but also by the severity of stress concentrations caused by flaws.

This interaction of stress and flaws means that glass plate resistance is influenced by area, loading history, aspect ratio, surface compressive stress from heat treatment and flaws from manufacturing, handling, installation and cleaning processes. A rational calculation of resistance must account for the pattern of stresses set up by the loading and support conditions, statistical variation associated with the distribution of surface flaws and the accumulated experience of past and current practice. Chapter 5 provides guidance on calculations.

If the decision is made to use toughened or heat-strengthened glass and calculations indicate that the surface precompression will not be overcome by imposed tensile stresses, then fracture-mechanics-based calculations will not be needed.

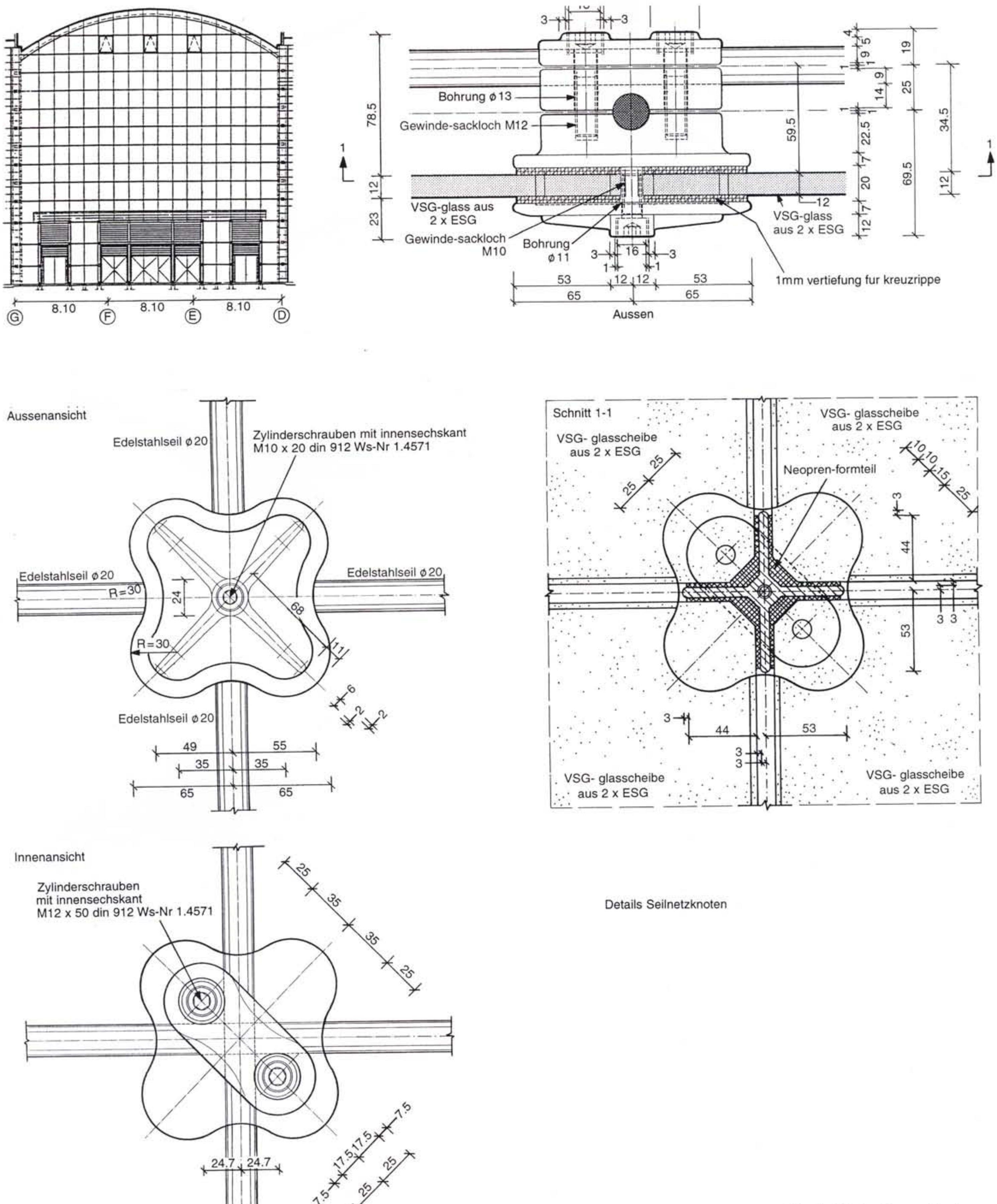


Fig. 14.3 Details used in the World Trade Centre in Dresden (courtesy of Schlaich Bergermann)

14.4 Selection, design and application

Critical issues may include some or all of the following non-structural items:

- thermal transmission and solar radiation
- condensation
- rainwater runoff
- fire
- acoustic behaviour
- access for installation, cleaning, inspection, maintenance, repair, replacement
- availability
- appearance and fit
- durability
- environmental impact and life cycle costing.

Critical structural issues include:

- how the overall structure will behave
- how the structure will behave after one or more glass elements have failed
- the safety implications of failure of a piece of glass, including the likelihood of people being injured by falling glass

The choice of annealed, heat strengthened or toughened glass will rarely be determined by considerations of strength alone.

14.5 Design details

Fig 14.3 shows examples of design details used in the World Trade Centre, Dresden.

14.6 Worked example

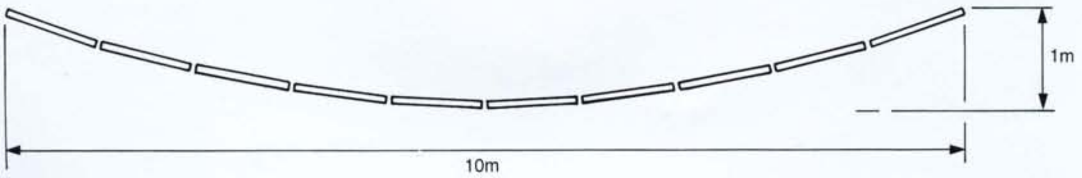
This example considers a glass catenary ceiling above an atrium in an office building and is shown on pages 128–130.

14.7 Suggested reading

Holgate, A. (1997): *Structural Engineering — The work of Jörg Schlaich and his team.* Edition Axel Menges, Stuttgart/London,

Worked example

This example considers a glass catenary ceiling above an atrium in an office building, as shown below. It is a one-way spanning structure, with a span of 10m and a sag, under self-weight, of 1m. A typical spanning unit consists of 10 glass panes, each approximately 1m square, each connected to its neighbours at its corners.



Its design loads are as follows:

Point load anywhere:	0.9kN on a 150mm × 150mm square
UDL downwards:	0.6kPa
UDL upwards:	0.25kPa (internal wind pressure)
Self-weight:	assume 2 × 12mm toughened glass laminated – 0.6kPa

Design load cases

1. Full DL + LL (UDL)

Factored UDL = (1.4 × 0.6) + (1.6 × 0.6) = 1.8kPa

Catenary behaviour

Consider a 1m width of catenary

Horizontal component of catenary tension = $1.8 \times 10^2/(8 \times 1) = 22.5$kN

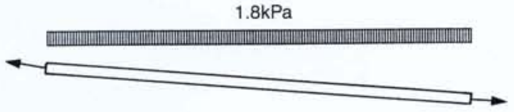
Support vertical reaction = $1.8 \times 5 = 9$kN

Maximum catenary tension = $\sqrt{(22.5^2 + 9^2)} = 24.2$kN

Average applied tensile stress = $24.2 \times 10^3/(2 \times 1000 \times 12) = 1$N/mm^2 - OK. Note that one sheet of the laminate can comfortably carry the tension, which provides welcome redundancy.

Local bending behaviour

Consider a mid-span panel of glass.



Midspan bending moment = $1.8 \times 1^2/8 = 0.23$kNm

To be conservative, assume layered, not composite, behaviour of the glass laminate.

Z of two 12mm sheets of glass = $2 \times 1000 \times 12^2/6 = 48\,000$mm^3.

$M/Z = 0.23 \times 10^6/48 \times 10^3 = 4.8$N/mm^2 - OK.

Note that one sheet of the laminate can comfortably carry the full bending, which provides useful redundancy.

2. DL + LL (Point load)

Catenary behaviour

When the point load is at mid-span, an upper bound on the horizontal component of catenary tension can be calculated by assuming the mid-span sag remains at 1m. Under factored glass self-weight ($1.4 \times 0.6\text{kN/m}^2$) and factored central point load ($1.6 \times 0.9\text{kN}$), the horizontal component of catenary tension is given by:

$H \times 1 = (1.4 \times 0.6 \times 10^2/8) + (1.6 \times 0.9 \times 10/4)$ from which

$H = 14.1\text{kN}$

The vertical reaction at each support is given by:

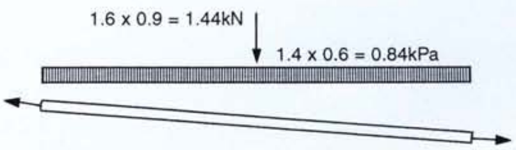
$V = (1.4 \times 0.6 \times 5) + (0.5 \times 1.6 \times 0.9) = 4.92\text{kN}$

Combining H and V gives a catenary tension of 14.9kN per metre width

(Other positions for the load should also be checked.)

By inspection this is less severe than the full DL + LL case – OK

Local bending behaviour



Mid-span bending moment = $0.84 \times 1^2/8 + 1.44 \times 1/4 = 0.47\text{kNm}$

Assume layered, not composite, behaviour of the glass laminate and assume that the central point load bending is carried by the full width of the glass (1m). As the glass is supported at its corners this seems a reasonable assumption. A simple grillage analysis would show whether this is correct.

Z of two 12mm sheets of glass = $2 \times 1000 \times 12^2/6 = 48\ 000\text{mm}^3$.

$M/Z = 0.47 \times 10^6/48 \times 10^3 = 9.7\text{N/mm}^2$ – OK. Note that one sheet can comfortably carry the full bending, which provides useful redundancy.

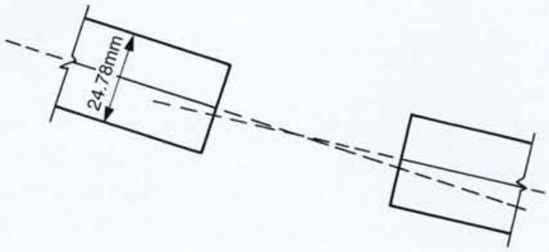
3. DL + WL

$0.9 \times$ dead load comfortably exceeds $1.4 \times$ wind load, so no load reversal will occur and no strength checks are needed for this combination. The designer should be satisfied that impulsive wind loads (a door suddenly opening during a storm) will not cause unacceptable movements of the structure.

Design of connections

Each of the pair of glass-to-glass connections between panels in the same spanning unit needs to be able to carry 24.2/2 = 12.1kN as a design load. The diagram below shows a typical relationship between two adjacent panels.

Such connections might be bolted or glued. In either case, they need to be capable of dealing with the change of slope between adjacent panels and the changes of angle between adjacent panels as the catenary adjusts its geometry to different loads (as a person walks across, for example).



1. Bolted connections

At Parc de la Villette, tests reported by Rice and Dutton (1995) gave 'mean capacities' of 2 tonnes and 4.5 tonnes in 12mm toughened glass for Planar connections and specially-designed articulated bolts respectively. Each articulated bolt (whose outer aluminium spacer had a diameter of 36mm) carried 6kN under typical loads, rising to 7.4kN under exceptional circumstances.

Tests reported by Dawson (1997), carried out during the design of the Yuraku-cho underground station canopy, gave breaking loads of 7 tonnes, 10 tonnes and 11 tonnes for 40mm diameter stainless steel pins in 68mm diameter bezels in 19mm toughened glass.

For this worked example it will be assumed that a bolt can be relied upon to carry a design load of 6kN with an adequate factor of safety in 12mm toughened glass. In a real design, tests would normally be required to demonstrate the satisfactory behaviour of any bolted connection.

On the assumption that one sheet of a laminate is broken and the other takes the entire load, two bolts will be needed to carry the design load of 12kN.

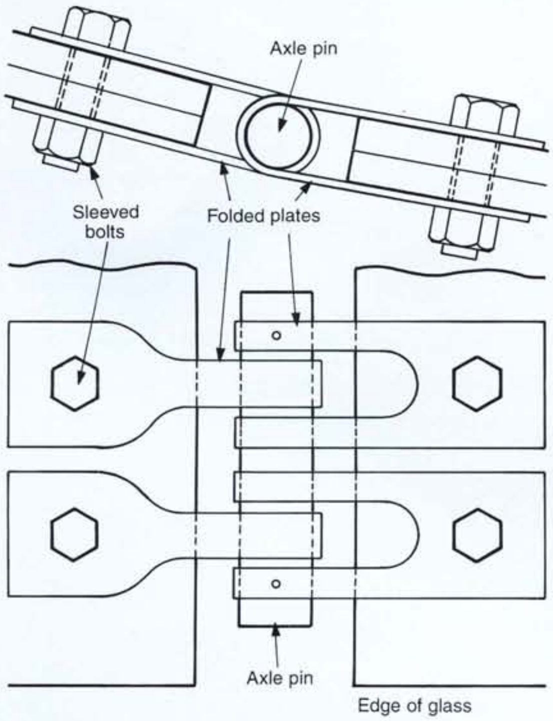
Diagram (a) below indicates one possible way of connecting adjacent panes using bolts.

2. Adhesive connections

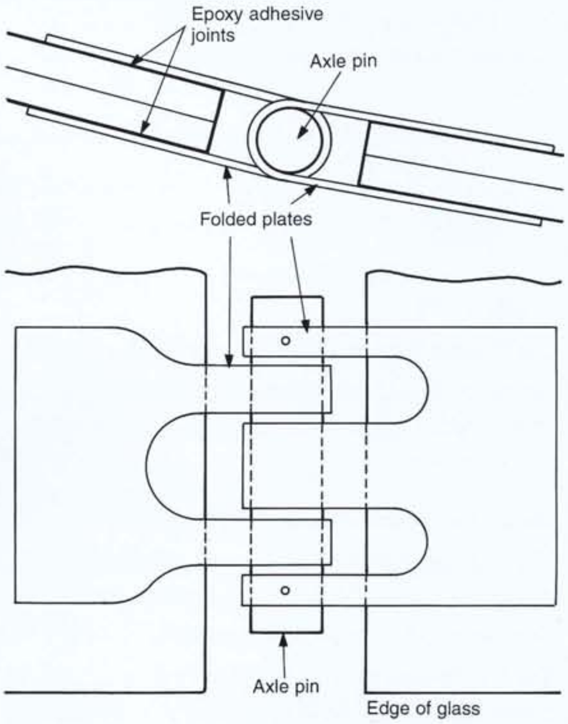
Under full factored DL + LL, a catenary tension of 24kN needs to be transmitted between adjacent panels. If this is shared between two corner connections, then each must be able to carry at least 12kN.

If we assume a connection in which an epoxy adhesive is used in shear, then following the worked example in Chapter 11 the adhesive might be relied upon for 6.7N/mm^2. The area required to transmit 12kN at this stress is 12,000/6.7 = 1791mm^2, say 900mm^2 on each face of the glass.

Diagram (b) below shows one possible way of connecting adjacent panes using an epoxy adhesive joint. It is left to the reader to consider the behaviour of the joint if one pane of the laminate is broken.



(a) Example of bolted connection



(b) Example of epoxy connection

Adjacent 1m wide spanning units will try to deflect differently when they are loaded differently. The designer has a choice: allow such relative movements and design any seals between panels to cope with the possible movements; or connect adjacent spanning units so that they deflect together. This is left as an exercise for assiduous readers.

15 Special applications

15.1 General description

Glass, often thought to be an unpredictable material, is used to resist bomb attack, to withstand hydrostatic pressure in aquaria, to prevent the passage of sledgehammers and bullets and meteorites and to allow astronauts and cosmonauts to look out from their spacecraft without losing air.

15.2 Blast-resistant glazing

15.2.1 Rules of thumb

A blast wave is caused by the almost instantaneous transfer of a suddenly released amount of energy into the surrounding air. This causes a thin front of highly compressed air to be pushed outwards from the explosive source in all directions. The leading face of the front is at extremely high pressure, which reduces across the thickness of the front to zero pressure, followed by a longer zone of suction (i.e. sub-atmospheric pressure). The speed of the blast wave is supersonic and its time to pass a fixed point or to load a surface is therefore very short, measured in milliseconds.

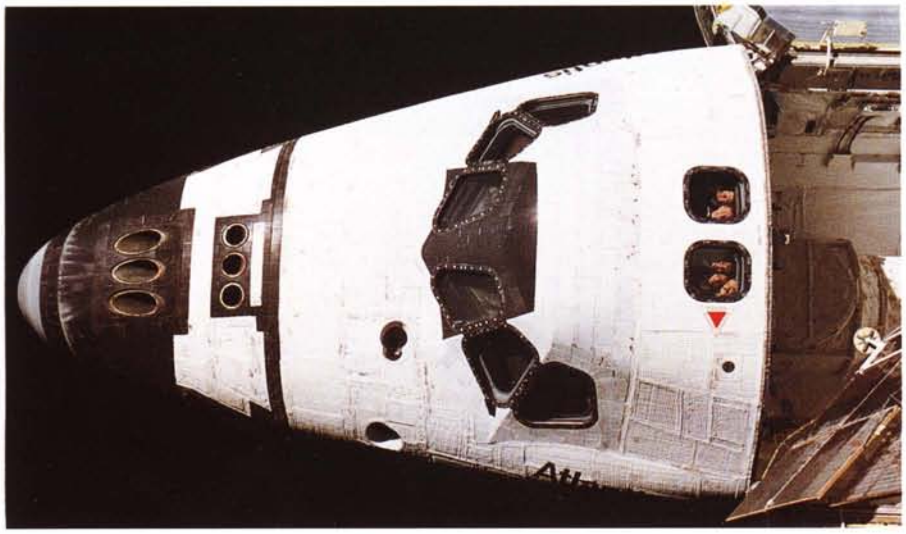
A structure subjected to this pressure front will therefore receive a very high positive load of very short duration (analogous to an impact), followed by a suction load of smaller intensity and longer duration. The effect of this loading is to set the structure and its elements into motions, which may result in distortion past material survival limits. The latter may involve displacements above or below the limits of permanent distortion.

In considering this phenomenon in the context of glazing, the objective of the engineer is to be able to quantify with some confidence the response of, for example, a window of given parameters to a blast wave of given parameters. The approach to this problem may be on the basis of empirical tests or by mathematical analysis.

On any installation the factors that influence the choice of bomb-blast resistant glazing will vary and may include:

- the threat
- the degree of protection required (safety of people/minimisation of damage)
- the extent of the building area to be protected
- architectural constraints, including any opening requirements
- manufacturing and installation limitations
- budget

Fig. 15.1 The windows of the space shuttle (courtesy of Genesis Space Photo Library)



Costs of different glasses should not be considered in isolation from the framing and installation costs. Anti-shatter film or thin laminated glass can be installed in standard frames with the objective of providing some hazard mitigation by limiting the spread of loose fragments. For more comprehensive blast resistance or thicker panes it is pointless to upgrade glass into a frame which is not strong enough to carry the reactions generated by the new glass.

The range of briefs for providing blast resistance to glazing may vary from providing complete protection to specified rooms under a specified threat (bomb size and distance), to enhancing the resistance or hazard mitigation properties of existing windows over a large facade by a nominal amount by adding film and curtains. Intermediate levels of upgrading may consist of reglazing with stronger glass, or replacing with stronger frames and stronger glass, but for an unspecified threat.

Between these two approaches lies the transition from a deterministic approach (i.e. against a specific defined threat) to a stochastic (i.e. risk, or statistical) approach influenced by pragmatic policy and cost decisions. It is easy but confusing to mix the two philosophies.

The predicted threat itself can only be an estimate even if it is carried out by those who have information to enable them to do so. The threat may change with time and there will always be a chance that the predicted value will be exceeded.

Rapid and efficient methods of estimating maximum structural response and damage are very desirable in preliminary dynamic structural design and also in 'reverse-engineering' calculations related to assessing the severity of an explosion. Baker *et al.* (1992) describe the basic principles of energy balance methods, with several practical examples. Leach and Codd (1992) describe the development of a cladding system to resist an external explosion but capable of relieving the pressure of an internal explosion before it becomes high enough to harm the occupants.

The design of blast-resistant glazing is well covered in TM5-1300 (1990) and in Mays and Smith

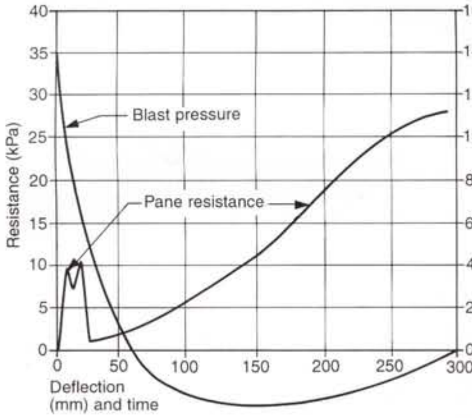
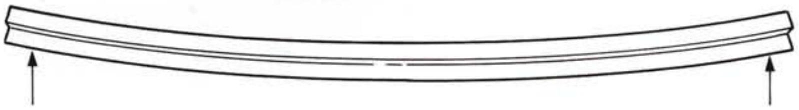


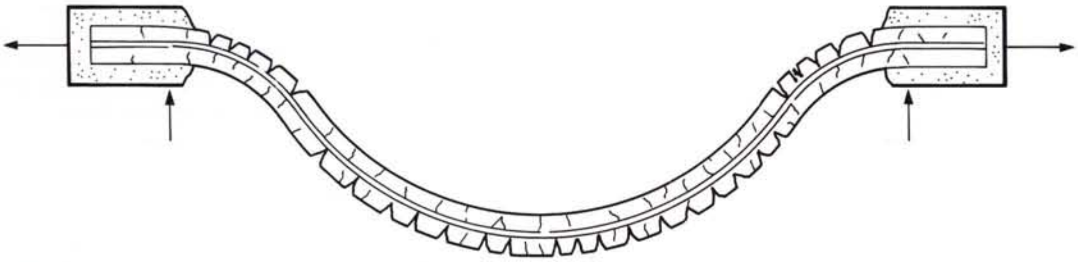
Fig. 15.2 A typical blast pressure–time curve (courtesy N. F. Johnson)

Table 15.1 Minimum rebate depths recommended by the UK Ministry of Defence

Glass span	Rebate
< 0.75m	25mm
0.75m < span< 1.5m	35mm
> 1.5m	Minimum bearing depth = 15mm + span/100 Minimum rebate depth = bearing depth + 5mm



(a) In thin plate bending mode



(b) In membrane deflection mode

Fig. 15.3 Laminated glass (a) in plate bending and (b) in membrane deflection (catenary) (courtesy of N. F. Johnson)

(1995). The Security Facilities Executive (SAFE) is a UK Government Agency of the Cabinet Office that provides security services to public clients. Within SAFE the Special Services Group (SSG) has an Explosion Protection Team that focuses on protective security measures against blast and weapon effects. Johnson (1998) describes some aspects of its work.

In the absence of any specific threat information it is suggested that the designer should incorporate a 1.52mm pvb interlayer in the glass and support the panes with deep rebates. Advice on rebate depths is given in Table 15.1. It is also worth recalling that the stiffness and strength of pvb laminates reduce as temperature increases. Unfortunately its ductility reduces below 0°C.

It is often necessary to provide or assess the blast resistance of materials that have been selected for other security purposes, such as resistance to bullet or manual attack. See section 15.3 for more details.

15.2.2 Performance in use

Annealed glass breaks into jagged irregular fragments that are extremely dangerous. Toughened glass is several times stronger than annealed glass and it breaks into cube-shaped 'dice'. Laminated glass is generally held together after the glass has broken by the plastic or resin interlayer.

The plastic interlayer normally used for blast resistance is polyvinylbutyral (pvb) but specialist applications can use polyurethane. Glass can also be laminated with layers of polycarbonate using polyurethane as a bonding layer. Acrylic resin bonded laminates are also available but have generally been developed for use when pvb foils cannot be used, such as with toughened glass.

Pvb is highly ductile except at or below 0°C and has significant tensile strength and high recovery after deformation. It bonds well to glass. Under blast load, after the glass has broken, the pvb acts as a ductile membrane in catenary and is capable of stretching a significant amount. As the threat increases the material will stretch further until failure initiates by tearing of the pvb or by pulling out from the frame rebates.

Under blast, laminated glass behaves in a fundamentally different way to plain glass. Blast energy will cause brittle fracture of annealed glass, converting it into high velocity hazardous shards. Laminated glass can absorb considerable blast energy while retaining integrity as a flexible membrane. At the same time it softens the blast shock impact transmitted to the glass supports. An essential part of laminated pane design is in the edge retention detailing and frame strength to support the glass.

An alternative interlayer material is polyurethane which is as strong and ductile as pvb and which retains these properties at sub-zero temperatures. It also retains its stiffness at high temperatures. Being more expensive than pvb, it is used for special critical applications such as aircraft windows.

Polycarbonate can be laminated with glass, combining the toughness of polycarbonate with the stiffness of glass. Polyurethane is used as the interlayer because it can cope with the differential thermal movements of glass and polycarbonate. Glass-polycarbonate can resist blasts effectively but the outer glass layers are liable to be thrown off as hazardous fragments even though the inner layers of polycarbonate remain held in the frame. The high strength and stiffness of the composite pane can load its frame severely.

Resin-laminated glass is formed by pouring liq-

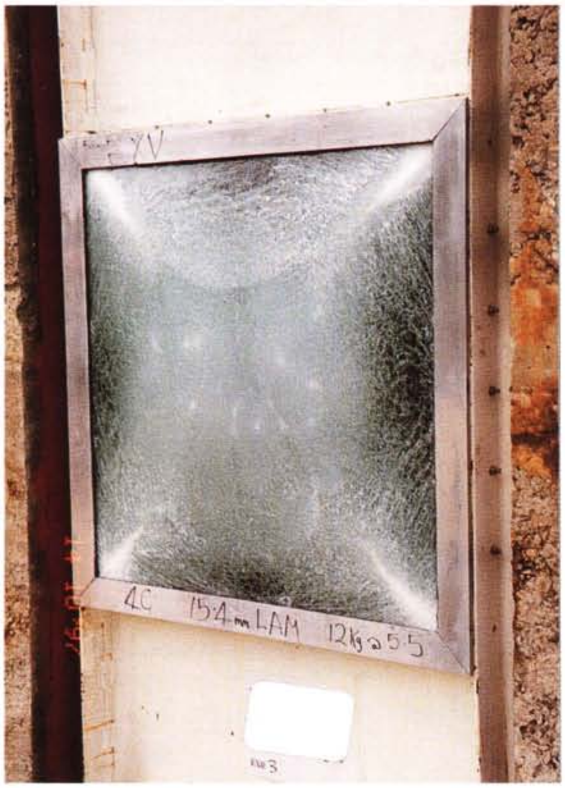


Fig. 15.4 Laminated glass panel after being blast tested (courtesy of Security Facilities Executive)

uid resin into the gap between two sheets of glass held in a jig. It is well suited to coping with the surface waves found in toughened glass.

The manufacturers make no specific claims for blast resistance of resin laminates. However the adhesive properties of resins are capable of holding shattered glass together to satisfy some defined impact safety tests.

Point-supported glass (such as Pilkington's Planar or St Gobain's Spider) is inevitably less blast resistant than fully edge supported glass. In comparative blast tests a single thickness toughened pane with four corner point supports shattered at twice the distance from a bomb (i. e. less than half the pressure and impulse) at which a same thickness four edge supported toughened pane survived. The semiflexible corner supports had the effect of reducing the blast resistance of the toughened pane to approximately that of a fully edge supported annealed float glass pane of the same thickness, though producing less hazardous fragments.

Double-glazed point-supported glass, including thick toughened leaves and heat-strengthened laminated with acrylic resin, have been demonstrated to offer a measurable resistance to blast without cracking. When subjected to more onerous blasts the resin has some capacity to hold shattered fragments together for short periods, after which the weight of glass pulls away from the support and it falls.

Anti-shatter film is a transparent polyester film which is glued *in situ* onto the inside face of existing panes with the objective of bonding the glass fragments together when broken under blast. Because the film edge necessarily stops short of the rebates in retrofit applications there is a potential failure line around the edges of the film.

There is a certain small range of blast levels over which the film alone will make the difference between the pane falling as fragments or being held in the frame. Above that level the filmed pane will be blown in. Tests show that filmed panes then give a general reduction in hazard inside a building for blast up to certain further levels, limiting the spread of fragments and dropping to the floor sooner, nearly halving the distance from the test bombs at which hazardous lacerations occur. Above these levels, i.e. at closer distances, the hazard is not significantly reduced. When used with bomb-blast net curtains the flying panes bonded to film may be more easily arrested or slowed down by the curtain gathering the fragments and slowing down their trajectories.

If the pane is unfilmed the small shards of annealed glass are more likely to cut through the curtain material, so curtains without filmed glass are not recommended.

15.3 Bullet and manual attack and vandal-resistant materials

15.3.1 Rules of thumb

Laminated glass is effective against bullets and manual attack when correctly selected. When selected for bullet resistance the glass construction can be very thick, sometimes more than 50mm. This overrides the usual requirements of blast resistance. Such a thick pane is capable of resisting blast loads for which the frame support will have to be much stronger than needed to resist the bullet or manual attack threat.

Even if only required to resist a lesser blast threat than its full capacity a thick, stiff, bullet-resistant pane can transmit higher shock loads to the frame than a thinner, more flexible, laminated pane capable of resisting that threat. It is therefore important to assess the capacity and if necessary modify the strength and edge retention details of bullet-and vandal-resistant frames if they are also required to resist blast.

15.3.2 Performance in use

BS 5544 defines impactor drop tests to demonstrate that glass can survive a series of impacts. A draft European standard (prEN 357) classifies glass products according to the height of drop that the glass can resist without penetration, the most severe being a 4kg steel ball dropped from 9m.

Attack with objects having sharp cutting edges and swung using a handle causes a very different type of damage to that from a relatively blunt thrown object. prEN 357 also contains a simulated axe attack.

Anti-bandit glass comes in different forms with different levels of resistance. It may be sufficient to deter a housebreaker by persuading him or her that it will take too long (and hence increase the risk of detection). Even wired glass can sometimes act as an effective deterrent. For more sustained and energetic assaults it will be necessary to provide a higher level of resistance. The evaluation of the threat is not a matter for guesswork by an amateur.

Toughened glass is susceptible to impact from sharp-pointed objects, such as axes. Annealed glass, although weaker, leaves jagged edge pieces that can deter or delay entry. Laminated annealed glass often provides the right level of protection, with multiple layers for high security areas.

The framing system for anti-bandit glazing is just as important as the glass. There is no point in providing strong glass in a weak frame, or in providing strong glass that can easily be removed. The principles of security glazing are covered in BS 5357.

Bullet-resistant glazing must, of course, prevent the passage of bullets from defined weapons. Another criterion is the nature of the splinters of glass ejected from the rear face of the glass.

Table 15.2 Typical thicknesses of bullet-resistant glass
Source: Pilkington Glass Consultants' Guidance Note 'Glass and Security'

Weapon	Thickness
9mm Parabellum	20-30mm laminated glass
.44 Magnum revolver	40-60mm laminated glass
NATO rifle (armour piercing)	50-80mm laminated glass
Shotgun	40-50mm laminated glass

The construction will depend on the degree of spall or splintering that is acceptable

BS 5051 covers bullet-resistant glazing.

Table 15.2 gives a general range of thicknesses for bullet-resistant glass to resist particular weapons.

Polycarbonate on its own has good resistance to impact attack. BS 6262: Part 4: 1994 describes it as 'very difficult to break'. Polycarbonate laminated with glass has excellent resistance to bullets and physical attack. Though it is expensive it can be used to save weight and thickness or achieve increased performance over pvb laminated glass (it is particularly useful in aerospace and rail applications). These advantages may be combined with use for blast resistance.

15.4 Hydrostatic pressures

15.4.1 Rules of thumb

Glass has been used for a long time for observation windows in swimming pools and aquaria and for the walls of aquaria. The glass is subjected to long-term high pressures and the consequences of failure can be disastrous.

Traditionally annealed glass has been used to resist water pressures for a number of reasons. When it breaks it cracks but may well stay in place, limiting the rate of leakage. By contrast, toughened glass, when broken, offers no resistance at all to the flow of water. Toughened glass is not as flat as annealed glass and is therefore harder to laminate, although cast resin laminating has now overcome this problem. For equal strength, toughened glass will be significantly thinner than annealed glass, which can lead to deflection and hence distortion problems.

In order to cater for the possibility of accidental or deliberate damage, it is customary when using toughened glass to provide redundancy by laminating two or more panes of equal thickness, each of which is capable of withstanding the design pressure alone.

Where the design indicates that the thickest toughened pane (usually 19mm) is insufficiently strong on its own then the design can of course rely on multiple layers. However, given the uncertainties about long-term composite action of laminated panes, the load should be distributed between the panes assuming no composite action whatsoever. In any laminate system there should always be at least one redundant pane, of the same thickness as the others, and ignored for the purposes of resistance to water pressure.

Figs 15.5 and 15.6 assist a designer in establishing the minimum thickness of annealed glass needed to resist hydrostatic pressure on the sides of a tank. Section 15.6 provides a worked example in their use. These charts apply to 4 edge supported glass where the top of the water is not above the top of the glass. They do not, therefore, apply to observation panels installed below the surface of the water. Impact considerations may also need to be accounted for.

Figs. 15.7 to 15.9 assist a designer in establishing the minimum thickness of annealed glass to be used in the base of a tank of water.

Figs. 15.5 to 15.9 are figures 1 to 5 from Pilkington's *Aquaria and Underwater Observation Panels*.

15.4.2 Performance in use

Glass up to 10mm thick can have clean cut edges. If the glass is more than 10mm thick or the edges are not clean cut then the edges must be ground by a wet process, working along the edge and not across it.

The glass is usually glazed into metal frames or directly into a concrete structure. The concrete should not be porous and should have a good surface in the rebate, which may need treatment to prevent deterioration of the glazing compound, which should be impervious to water.

The edge cover should be at least equal to the thickness of the glass and if possible the glazing should be installed from the inside so that water pressure will force the glass towards the back check.

If laminated glass is used then the exposed edges of the interlayer must be protected from contact with the water and any glazing compound used must be compatible with the interlayer material.

From Fig 15.5 it is clear that a small increase in water depth or panel width can require a significant increase in glass thickness. To minimise costs it is worth considering whether, for example:

- two small windows could be used instead of one larger one (a line of portholes, for example)
- could a corner position be used instead of the middle of a side? (better field of view)

A note of caution during maintenance: several instances have occurred of thick glass observation panels in open air swimming pools cracking while the pool was drained. Direct exposure to sunlight had warmed the bulk of the panel while the edges remained in shadow and in contact with the cool mass of the pool structure. The resulting thermal stresses cracked the glass. Thermal stress is covered in more detail in Chapter 6, where it can be seen that the causes of the problems encountered feature in the chart of factors contributing to thermal stress.

Fig. 15.5 Recommended minimum thicknesses for vertically glazed, four edges supported annealed float glass where water line is level with the top of the glass (from Pilkington's *Aquaria and Underwater Observation Panels*)

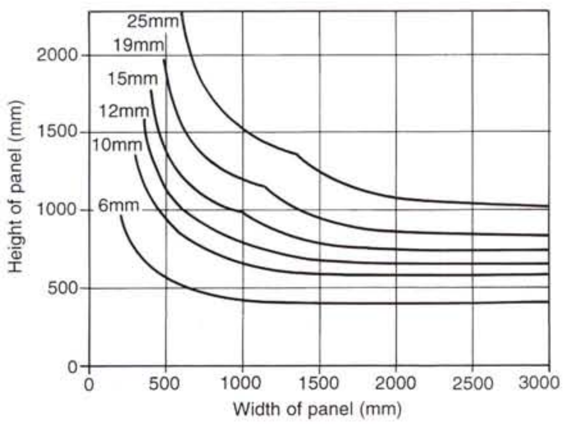


Fig. 15.6 Factors for reduced water levels (from Pilkington's *Aquaria and Underwater Observation Panels*)

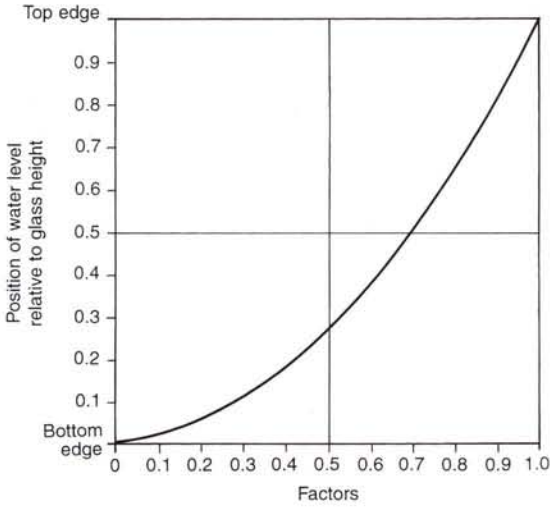
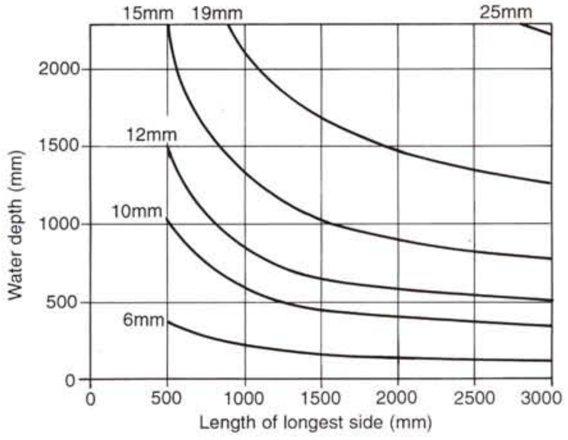


Fig. 15.7 Minimum thickness for base glass length of shortest side not exceeding 500mm (from Pilkington's *Aquaria and Underwater Observation Panels*)



15.5 Design details

Fig 15.10 shows a blast-resisting double-glazed unit, taken from page 13 of Pilkington's *Glass and Security*.

15.6 Worked example

See page 134.

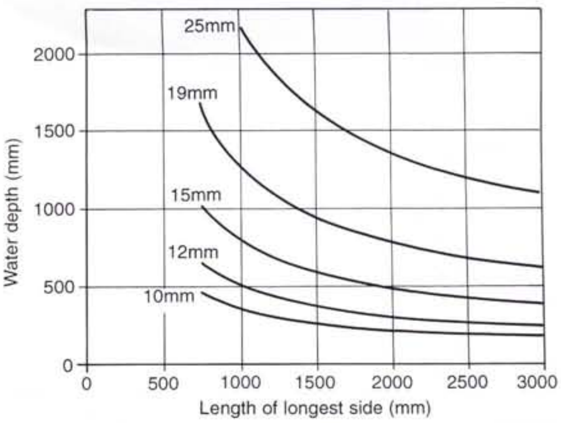


Fig. 15.8 Minimum thickness for base glass length of shortest side not exceeding 750mm (from Pilkington's *Aquaria and Underwater Observation Panels*)

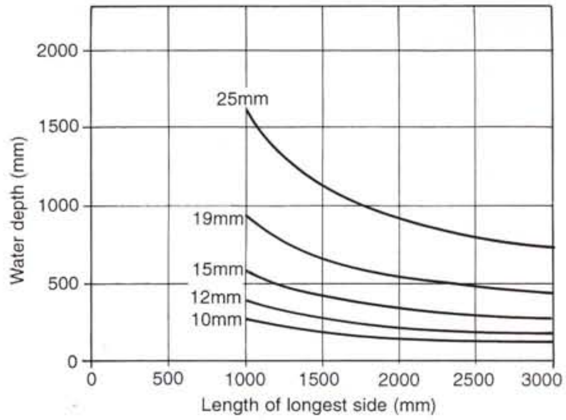
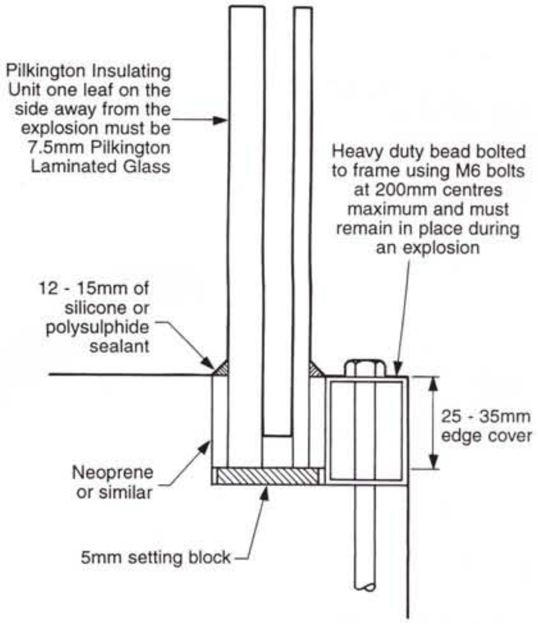


Fig. 15.9 Minimum thickness for base glass length of shortest side not exceeding 1000mm (from Pilkington's *Aquaria and Underwater Observation Panels*)

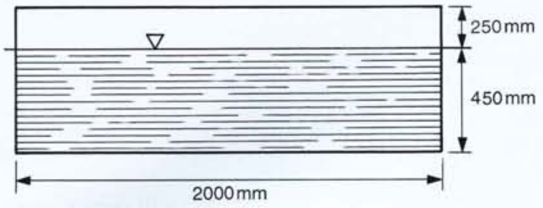


Frame must be securely fixed to the building structure; all elements must be designed to resist the blast forces

Fig. 15.10 possible design for blast-resistant glazing incorporating Pilkington Insulation Units (courtesy of Pilkington Group)

Worked example

What thickness of annealed glass is required for an aquarium panel 2000mm wide by 700mm high when the water level will not be more than 450mm above the bottom of the glass? All four edges of the glass are supported and there is no possibility of the water level going any higher.



From Fig. 15.5, for a panel 2000 × 450mm, required thickness = 15mm.

From Fig. 15.6, for water level 450/700 = 0.64, factor = 0.8

Hence required glass thickness = 0.8 × 15 = 12mm.

It is up to the designer to decide how many layers are required to provide adequate redundancy in case of breakage. Section 15.4.2 warns against thermal cracking.

15.7 References

Mays, G. C. and Smith, P. D., editors: (1995): *Blast effects on buildings*. Thomas Telford.

Baker, W. E., Spivey, K. H. and Baker, Q. A. (1992): 'Energy-balance methods for structural response and damage analysis under transient loads'. pp 229-237 *In* Clarke, J. L., Garas, F K and Armer, G. S. T. (eds.) *Structural design for hazardous loads*, E & F N Spon, p229

BSI (1978): *Specification for anti-bandit glazing (Glazing resistant to manual attack)*. BS 5544: 1978 (1994)

BSI (1988): *Security glazing. Part 1. Bullet-resistant glazing for interior use and Part 2. Bullet-resistant glazing for exterior use*. BS 5051: 1988 (1994).

BSI (1994): *Code of practice for glazing for buildings. Part 4. Safety related to human impact*. BS 6262: Part 4: 1994

BSI (1995): *Code of practice for installation of security glazing*. BS 5357: 1995

BSI (1996): 'Glass in buildings: Fire-resistant glazed elements'. prEN 357: 1996

Johnson, N. F. (1998): *Design for glazing protection*. In IStructE. Seminar on 'Structures and blast loading', 29 January 1998.

Leach, P. and Codd, M. R.(1992): 'The design of cladding panels for offshore structures subject to blast loading'. *In* Clarke, J. L., Garas, F. K. and Armer, G. S. T. (eds.) *Structural design for hazardous loads*. E & F N Spon, p197.

Pilkington's *Aquaria and underwater observation panels*

Pilkington's *Glass and security*

United States Departments of the Army, the Navy and the Air Force (1990): *Structures to resist the effects of accidental explosions*. Army TM 5-1300, Navy NAVFAC P-397, Air Force AFR 88-22, November 1990.

16 Specification

16.1 Specification writing

The specification is a document included in the contract documents which contains the instructions of the designers or specifiers to the contractor. It may include requirements for materials and workmanship, sometimes known as a prescriptive specification; or it may contain requirements for the performance of the glass; or it may combine the two. A specification needs to be:

- complete
- clear
- precise
- enforceable
- co-ordinated with other project information (it should not conflict with drawn information, for example), including other contract documents

It is most important that the requirements of the specification can be objectively verified, that is to say that they can be measured or tested according to clearly defined standards. Tables 16.1 and 16.2 list documents which could be useful.

16.1.1 Materials and workmanship

This is the traditional specification, in which all required materials are described as well as any reference standards. The quality of workmanship is clearly defined with reference to Codes of Practice, accepted industry standards or even samples if this is appropriate.

16.1.2 Performance

With this approach, the contractor is responsible for the design, or the completion of the design, in response to criteria laid down by the designer or specifier. Visual acceptance criteria are not easy to define. The terms 'consultant designer' and 'specialist designer' are sometimes used to distinguish between the different parties involved in this process.

16.1.3 Specification checklist (not exhaustive)

Note that some of the items in this checklist apply to glass used as part of the external envelope of a building. They are therefore not necessarily appropriate when glass is to be used in a different application, for example as a structural floor within a building.

CONTENTS OF SAMPLE SPECIFICATION CHECKLIST

PRELIMINARIES

The building
The role and function of the building, its appearance, form and size as related to the cladding (if the glass is used for cladding), including its relationship to its neighbours.

The internal climate, standard of comfort and working conditions as well as external climate and atmospheric conditions.

The glazing
The extent of the glazing, its geometry, how it is attached to the building, its intended solidity, lightness, texture, contrast and colour.

GENERAL REQUIREMENTS

Pressure equalised cavities, locations of weather seals, thermal bridging, accommodation of cleaning/maintenance gantries, ease of removal/replacement.

System descriptions
Types of framing, types of glass, support and attachment to the building.

Design requirements
Responsibilities, Codes, Regulations, Health and Safety, programme.

Performance requirements
Acoustic transmission
Air permeability
Applied loads
Brackety and fixings
Condensation
Corrosion
Design life
Fire and smoke stopping
Fire performance
General requirements for enclosure, durability, attachment to the building, adjustment, movement, ease of removal.
Infestation
Ironmongery
Lightning protection and electrical safety
Locked-in stresses
Movement
Noise generation
Robustness
Safety
Solar control
Strength, stability, stiffness
Thermal transmittance
Vibration
Weathertightness
Wind resistance – safety
Wind resistance – serviceability

Submittals
With tender
Post contract

Quality assurance
Quality plan
Quality control procedures

Technical procedures
Air permeability tests
Assessing thermal performance
Attachments to concrete
Checking flatness
Checking sizes
Erection and dismantling
Factory-assembled mock up samples
General
Impact tests
Load tests
On-site quality control samples and testing
Reporting
Sizing movement joints
Sources of information

Testing
Testing procedures
The test rig
The testing authority
Thermal load test
Watertightness tests
Weathering performance test specimens
Wind resistance test

PRODUCTS

General standards of quality
Accuracy and flatness
Aluminium
Annealed glass
Anodising
Carbon steel
Double-glazed units
Fabrication
Gaskets
General
Glass
Heat strengthened glass
Insulation
Laminated glass
Low emissivity coatings
Non-structural sealants
Polyester powder coat finishes
Safety
Screen printing
Setting blocks
Sizes
Stainless steel
Stainless steel finishes
Structural silicone glazing
Thermal stresses
Toughened glass
Vapour control layers
Visual acceptance criteria
Waterproofing membranes

EXECUTION

Accuracy of erection
Accuracy of joints between components
Erection tolerances
Finishes
Fixings
Gaskets
Glazing
Handling and storage
Health and Safety File
Inspection and testing
Installation
Insulation
Protection and cleaning
Setting blocks
Vapour control layers and waterproof membranes

Table 16.1 British and European (CEN) standards

Aluminium extruded section	BS 1161, BS 1474, BS EN 754, BS EN 755
Aluminium plate, sheet & strip	BS EN 485, BS EN 573
Aluminium windows	BS 4873
Anti-bandit glazing	BS 5544
Barriers in and about buildings	BS 6180
Bimetallic corrosion	PD 6484
Bullet-resistant glazing	BS 5051: Part 1
Carbon steel angles	BS 4848: Part 4, BS EN 10056-2
Carbon steel beams, joints and channels	BS 4
Carbon steel bolts and nuts	BS EN 24032, BS EN 24034, BS EN 24016, BS EN 24018, BS EN 24014, BS EN 24017
Carbon steel hollow sections	BS 4848: Part 2
Carbon steel plate, sheet & strip	BS 1449: Part 1
Carbon steel washers	BS 4320
Double glazed units	BS 5713, prEN 1279
Durability	BS 7543
Gaskets	BS 4255
Glass	BS EN 572-1, BS EN 572-2, BS EN 572-4, BS 952: Part 1, BS 952: Part 2, prEN 1863, prEN 12150, prEN 12543 and prEN 12725
Glazing for buildings	BS 6262: Parts 1 to 7
Impact performance of glass	BS 6206, prEN 12600
Lightning protection	BS 6651

Table 16.1 (continued)

Non-loadbearing vertical enclosures	BS 8200 (no longer maintained)
Performance of windows	BS 6375: Part 1, BS 6375: Part 2
Polyester powder coating	BS 6496
Sealants	BS 5889, BS 6213
Sound insulation	BS 5821 Part 3, BS EN ISO 140-3
Stainless steel fasteners	BS 6105
Stainless steel plate, sheet & strip	BS 1449: Part2
Structural fixings in concrete	BS 5080
Structural use of aluminium	BS 8118
Structural use of steelwork	BS 5950
Superimposed loading	BS 6399: Part 1
Suspended access equipment	BS 6037
Testing of windows	BS 5368: Parts 1 to 4
Testing thermal performance	BS 874: Part 3
Thermal modelling	BS EN ISO 12011-1, BS EN 6946, prEN 10077
Thin vulcanised fibre sheet	BS 2768 (now withdrawn)
Vulcanised fibre for electrical purposes	BS 6091: Part 1, BS 6091: Part 2
Welding of aluminium	BS 8118: Part 1, BS 8118: Part 2
Welding of stainless steel	BS 7475
Welding of steel	BS 4870, BS 4871, BS 4872, BS 5135
Wind loading	BS 6399: Part 2
Window safety	BS 8213: Part 1
Workmanship on building sites: Part 7: Code of Practice for glazing	BS 8000: Part 7

Table 16.2 Guides, reports and codes of practice

American Society for Testing and Materials	Standard test methods for strength of glass by flexure (determination of modulus of rupture). ASTM C158
	Standard terminology of glass and glass products. ASTM C162
	Standard test method for annealing point and strain point of glass by fiber elongation. ASTM C336
	Standard test method for annealing point and strain point of glass by beam bending. ASTM C598
	Standard specification for flat glass. ASTM C1036
	Standard specification for heat-treated glass. ASTM C1048
	Standard test method for determining tensile adhesion properties of structural sealants. ASTM C1135
	Standard specification for laminated architectural flat glass. ASTM C 1172
	Standard test method for shear strength of adhesive bonds between rigid substrates by the block-shear method. ASTM D4501
	Standard test method for rate of air leakage through exterior windows, curtain walls and doors. ASTM E283

Table 16.2 (continued)

	Standard test method for structural performance of exterior windows, curtain walls and doors by uniform static air pressure difference. ASTM E330
	Standard test method for water penetration of exterior windows, curtain walls and doors by uniform static air pressure difference. ASTM E331
	Standard test method for structural performance of glass in exterior windows, curtain walls and doors under the influence of uniform static loads by destructive methods. ASTM E997
	Standard test method for structural performance of glass in windows, curtain walls and doors under the influence of uniform static loads by non-destructive methods. ASTM E 998.
	Standard practice for determining the minimum thickness and type of glass required to resist a specified load. ASTM E 1300
	Standard test methods for bond integrity of transparent laminates. ASTM F521
	Standard guide for selection of test methods for interlayer materials for aerospace transparent enclosures. ASTM F942
American Welding Society	Recommended practices for stud welding
American Architectural Manufacturers' Association	Field checks of metal curtain walls for water leaking. AAMA 501.2
	Glass design for sloped glazing
	Structural properties of glass
British Board of Agrément	Methods of assessment and testing
Building Research Establishment	Ergonomic requirements for windows and doors. Information Paper 2/82
Canadian General Standards Board	Structural design of glass for buildings. CAN/CGSB-12.20-M89
Centre for Window and Cladding Technology	Guide to the design of thermally improved glazing frames
	Standard and guide to good practice for curtain walling
CIRIA	Manual of good practice in sealant application. Special publication 80
	Sealant joints in the external envelope of buildings: a guide on design, specification and construction. Funders' report CP/39
Cook, N	The designer's guide to wind loading of structures
Department of Environment, Transport and the Regions	The Building Regulations Approved Document N — Glazing — safety in relation to impact, opening and cleaning

Table 16.2 (continued)	
Deutsche Norm	Back-ventilated, non-loadbearing external enclosures of buildings, made from tempered safety glass panels. DIN 18516: Part 4: February 1990
Glass Association of North America	Glazing Manual
Institution of Structural Engineers	Aspects of cladding
The Steel Construction Institute	Concise guide to the structural design of stainless steel. SCI 123
	Design of stainless steel fixings and ancillary components. SCI 119
Ryan, P., Otlet, M. and Ogden, R. G.	Steel supported glazing systems. SCI 193
Standards Australia	Glass in buildings — Selection and installation. AS 1288-1994
UEAtc	Technical guide for the approval of structural sealant glazing systems (bonded external glazing systems). MOAT No 52

17 Contract and procurement, inspection and maintenance

This section draws heavily on Arup Research and Development (1993). For a more detailed exposition, the reader is advised to refer to chapters 19, 20 and 21 of that publication.

Whole life or lifecycle costing of a facade or roof can contribute to the design of a building by providing a means of ensuring the right mix of capital and running costs to best suit the client's requirements. Section 2 draws a distinction between those components that are designed to be replaceable, maintainable or lifelong. Inspection and maintenance play an important part in this. BS 7543 provides guidance on durability and defines terms such as 'service life'.

Brand (1994) points out that buildings are constantly being refined and reshaped by their occupants. Nowadays the skin of a commercial building changes every 20 years or so, to keep up with fashion or technology.

17.1 Approaches to contract

The principal aim of a contract is to set down the rights and obligations of the parties. The consultant designer (i.e. the client's primary engineer or architect) will need to assess the costs and other implications of specialist design input (i.e. design by a specialist subcontractor's designers). Procurement can be traditional, where design, tendering and construction are consecutive activities or it can be fast-track where design and construction overlaps.

The critical factors are:

- clarification of liabilities and allocation of risk
- understanding of recent amendments to standard forms of contract
- contractual relationships where specialist design input precedes the letting of the main contract
- selection of the form of contract appropriate for the project.

Just like a specification, the detailed conditions of contract need to be:

- complete
- clear
- precise
- enforceable
- co-ordinated with other project information or contract documents
- explicit.

17.2 Review of contracts and sub-contracts

Traditional procedures and contracts are used where the design, tendering and construction are consecutive. Traditional tenders are supposed to be based on completed designs and do not in principle allow for specialist design input via the contract.

The construction of glass elements will usually be subcontracted to a specialist firm.

The most common forms of fast-track contract are construction management (CM) and management contracts and under such contracts the glass elements will be, or will be part of, a contract between the specialist and the employer or the management contractor respectively. These are generally known as trade contracts for CM projects and works contracts in the case of management contracting.

Latham (1994) provides a succinct comparison of the strengths and weaknesses of the major UK forms of contract.

17.3 Tendering, certificates, warranties, insurance and defects

The procurement procedure will be determined largely by the size of the project, the extent to which specialist design is required and the placement of risk. The consultant designer must exercise skill and care in the selection of specialists to fabricate and install the glass (and perhaps to carry out detailed design as well). Where specialist design is required, a design warranty should be entered into between the specialist designer and the client, although this may not be needed where there is already a direct contract

The specialist should discharge all its contractual obligations before the issue of the final certificate.

The critical factors are:

- contractual responsibilities of the named parties in the contract
- warranties create contractual links where otherwise there would be none
- careful assessment of manufacturers' and contractors' guarantees
- investigation of defects for cause and responsibility and their resolution

17.4 Competence and resources of potential glass suppliers

The following is a list of items that may be checked when choosing potential glass suppliers.

Company information
- Turnover
- Number of staff
- Number and locations of offices and factories
- Main activities (manufacture, fabrication, installation)
- Project references

Design capability
- ISO 9001 accreditation
- CAD facilities
- Number of directly employed design staff
- Qualifications of design staff
- In-house/subcontracted design
- Knowledge of standards and design codes
- Procedures for complying with CDM Regulations

Raw materials
- Sources of supply
- Quality controls and certificates of conformity
- Stock levels
- Lead times

Processing and manufacture

- ISO 9002 accreditation
- Number of directly employed staff
- Production facilities (toughening, cutting, polishing, drilling, heat soaking, (on-line or off-line), bending, laminating, coating)
- Extent of subcontracted work

Installation

- Number of directly employed glaziers
- CVs of staff and management
- Extent of subcontracted work
- Safety policy and performance

17.5 Inspection of the works

Inspection is not the same as supervision, although the two can overlap. The aim of inspection during construction is to determine that the installation is carried out in accordance with the contract. The aim of inspection during the life of the building is to determine if cleaning or repair or replacement is needed ahead of its planned date.

Those carrying out inspections should record their observations and the results of any tests carried out. Buildings completed since 1994 will have a Health and Safety File. This is an appropriate place to keep records of the design and construction methods used for the glazing systems incorporated within the building. For those carrying out inspection, maintenance and repair activities reference will first be made to the Health and Safety File. Subsequent observations and test results will then be included in the building's Operation and Maintenance Manuals, which often form part of the Health and Safety File.

Inspection requires safe access and must therefore be planned carefully. A glass roof may be relatively easily accessible from scaffolding during installation but difficult to access during the life of the building. Chapter 2 provides some checklists for designers when considering access, installation, cleaning, inspection, maintenance, repair and replacement.

17.6 The role of the contractor

The main contractor may have responsibility for providing information relevant to inspection, especially where the main contractor has design responsibility. Attention to the quality of the preceding works is important, to ensure progressive and satisfactory installation of the glazing. Samples and mock-ups can demonstrate conformity with the design intent, can allow resolution of difficult details and can provide a reference for acceptable quality on site.

17.7 Health and safety

The health and safety of the construction workforce and those affected by the construction workforce is very important. Much glazing involves working at height and working with large, heavy brittle objects. Ove Arup & Partners (1997) provides guidance to designers on discharging their responsibilities under the CDM regulations.

17.8 Materials handling and storage

Suppliers and manufacturers should be consulted about storage and handling of glass. It is a material that is susceptible to damage if not handled properly. If the designer wants the manufacturer's or supplier's instructions to be followed then this should be stated explicitly.

Fig. 17.1 Mechanical handling on site of a large pane of glass (courtesy of M. Elkan Photo)

Fig. 17.2 A suspended access cradle (courtesy of John Young)

17.9 Site processes

A typical glass facade or roof may contain a large number of components:

- glass
- insulation
- shading
- fixings
- cover plates
- sub-frames
- sealants and adhesives
- gaskets
- flashings
- openings

Works on site give rise to requirements including:

- correct sequencing of inter-related trades, to ensure continuity of operations
- correct programming of the roof or facade installation, to ensure no backtracking over completed work
- sufficient time for inspection and testing, plus contingency for remedial work and retesting

The designer can help the contractor by having these issues in mind when designing the glazing installation. If, for example, sub-assemblies can be built and tested at ground level, then the contractor's life may be made easier.

The specification of remedial work should follow a proper diagnostic sequence. There is no point in carrying out a repair until the defect and its cause or causes have been identified. Testing of materials is only worth doing if action can be taken as a result of the tests. Therefore the methods and criteria for testing should be clearly established and agreed in good time.

17.10 Planned maintenance

Maintenance of the facade and roof and any other glass elements should be part of a comprehensive maintenance programme (and budget) for the whole building. Maintenance of large areas of roof or facade may significantly affect their performance over the life of the building and should be considered during the design process.

Preventative maintenance should be undertaken in a programmed and thought-through manner, with regular inspections and early and correct attention to problems.

Maintenance contracts should be considered as should the requirements for maintenance activities of warranties and guarantees.

The maintenance of a large glazed facade may well involve the use of suspended access cradles. One-person cradles are often seen as attractive because they are cheaper than larger cradles, can negotiate re-entrant corners more easily and can fit between the glass fins of a suspended facade. (If inadequately padded they can also damage the fins). A one-person cradle is no use if a pane of glass is to be replaced, which requires a two-person cradle with the capacity to carry the glass as well. Designers should also consider the (usually extremely unlikely) possibility of, for example, the person in a one-person cradle suffering a heart attack or other disabling event. How would such a person be brought safely to the ground?

Rice and Dutton (1995) show that the maintenance equipment, if properly designed, can be integrated into the design, rather than appear to be an afterthought. Lattunen (1999) provides an overview of permanently installed systems that enable access to various glass surfaces of a building

17.11 Diagnosing defects and remedies

Before any remedial action is taken defects should be diagnosed to determine the cause(s) and extent of failure. Are they, for example, related to the complete installation or just to a local detail? What is the scale and urgency of the problem?

Diagnosis of defects or failures can be a complicated matter and should be approached systematically. The Institution of Structural Engineers report *Aspects of cladding* (1995) provides a useful checklist of headings for investigation of problems in the cladding envelope of a building.

Any remedial proposals should be thought of as new design work and evaluated as part of a life-cycle cost. As always, the designer must consider the health and safety not only of the people carrying out the repair or replacement but also the health and safety of those affected by the work. This will usually include both the general public walking past the building and also the occupants of the building.

17.12 References

Arup Research and Development: *Flat Roofing: Design and Good Practice*. CIRIA/BFRC, 1993.

Brand, S.: *How Buildings Learn*. Phoenix Illustrated/Viking, 1994

British Standards Institution: *Guide to durability of buildings and building elements, products and components*. BS 7543: 1992

Institution of Structural Engineers: *Aspects of cladding*. SETO, August 1995

British Standards Institution (1994): *Quality systems. Model for quality assurance in design, development, production, installation and servicing*. BS EN ISO 9001

British Standards Institution (1994): *Quality systems. Model for quality assurance in production, installation and servicing*. BS EN ISO 9002

Latham, M.: *Constructing the Team*. HMSO. 1994

Lattunen, P.: 'Permanent Access Systems – Natural Part of Modern Glass Architecture'. *Proceedings of The Sixth International Conference on Architectural and Automotive Glass*, Tampere, Finland, 13-16 June 1999.

Ove Arup & Partners: *CDM Regulations – work sector guidance for designers*. CIRIA Report 166, February 1997.

Rice, P. and Dutton, H.: *Structural Glass*. E & FN Spon, 2nd edition, 1995

Appendix A History of glass

The oldest finds of glass date from around 10 000 BC in Egypt. Hollow glass vessels date from about 1500BC and glass vessels as we know them date from the first century BC.

Glass making was developed by the Romans, the Syrians and the Venetians and then by the French, Germans and English. There was a glass industry in Britain as early as 680AD around Jarrow and Wearmouth. Lead glass was invented by George Ravenscroft in the 1670s and the British Plate Glass Company was founded in 1773. The first American glassmaking innovation was a glass-pressing machine that was patented in 1825.

Until 19th century glass panes were made by the 'crown' process, which declined in mid-century after 150 years of development. It could produce panes of up to 0.5m × 0.75m but they were usually smaller. In the 'crown' method the glassmaker blew a large bubble of glass, which he then spun rapidly while the glass was still soft, producing a disc of glass that was then cooled gently.

Developments in structural engineering made increasingly larger window openings available for all types of buildings, not just great cathedrals. This stimulated demand for bigger and better panes of glass.

The 19th century invention of the Siemens-Martin firing method that recovered the heat from waste gases made possible the higher temperatures needed for better quality glass.

The first half of the 19th century was the era of the great iron and glass glasshouses, described by Woods and Warren (1990) as a time of glass roofs and graceful curves. Notable examples include:

- A cast-iron framed glass house at Chiselhampton, Oxfordshire, c.1800 (architect unknown)
- Mrs Beaumont's 60 ft tall circular dome at Bretton in Yorkshire, built by W. and D. Bailey in 1827, in which the glass provided in-plane shear stiffness and two inch by one half inch wrought iron bars provided out-of-plane stiffness.
- The Curvilinear range at the National Botanic Garden in Dublin by William Clancey and Richard Turner, completed 1848
- The Palm House at Kew, by Decimus Burton and Richard Turner, also completed in 1848
- Paxton's astounding Crystal Palace, 1851, which used 900 000 square feet of sheet glass in its patented ridge and furrow construction.

Cast iron greenhouse at Chislehampton (courtesy of May Woods)

The cylinder process (also known as the broad process) provided glass of more uniform thickness up to 1.0m × 1.3m. This involved blowing a bubble of glass, then swinging it into a cylindrical shape. The ends of the cylinder were cut off, it was slit longitudinally and it was then reheated and opened out into a flat sheet. In 1871 William Pilkington invented a machine which automated the production of plate glass made using the cylinder method. A mechanical cylinder drawing machine was first introduced in 1910.

The beginning of 20th century saw the development of various drawn flat sheet processes, notably the Belgian Fourcault and the American Colburn processes. These drew molten glass from the furnace in a thin stream, then flattened and cooled it by pulling it between asbestos rollers into panes up to 1.9m wide.

The rolling process (first produced by Chance Brothers in 1870) is used for the manufacture of patterned flat glass and wired glass. A continuous stream of molten glass is poured between water-cooled rollers. Patterned glass is made in a single pass process and wired glass by a double pass process. Wired glass was first made in 1898.

Plate glass is the name given to glass rolled from the furnace into a ribbon and then ground and polished. This was costly and incurred wastage of 20%. The Bicheroux process for casting, grinding and polishing the glass dates from 1918.

In the mid-20th century Pilkington developed the float glass process, which is described in Chapter 2. Float glass combines the best features of sheet and plate glass — the brilliant surfaces of sheet glass and the flat parallel surfaces of polished plate. Since then the glass industry has responded to concerns about energy efficiency by developing new coatings to tune the performance of the glass to reduce energy consumption, most notably among which are the low-emissivity coatings whose sales have grown by an average of 13% per year throughout the 1990s.

In the early 20th century A. A. Griffith carried out pioneering experiments in which he drew thinner and thinner glass fibres and measured their tensile strengths. He found that as they got thinner, so they became stronger. Today, silica glass filaments, with diameters measured in microns, exhibit strengths of up to 14 000N/mm^2. Continuous glass fibre is a continuous strand, made up of a large number of individual filaments of glass and finds widespread application in glass fibre reinforced polymers and in high performance architectural fabrics.

Glass is also now available as tube and rod and block.

Reference

Woods, M. and Warren, A.: *Glass houses*. Aurum Press, 1990

Appendix B Regulatory framework

National and European Standards

Many national standards exist for glass products and the use of glass. European Standards are being prepared or already exist and are issued in the UK under the prefix BS EN. Draft European Standards are prefixed prEN and are issued by CEN, the European Committee for Standardisation. Table B.1 Listed below are some of the basic British and European Standards.

Selected British and European Standards for glass

BSI: *British Standard Specification for Hermetically sealed flat double glazing units. BS* 5713: 1979.

BSI: *Specification for Impact performance requirements for flat safety glass and safety plastics for use in buildings*. BS 6206: 1981

BSI: *British Standard Code of Practice for Glazing for Buildings*. BS 6262: 1982

BSI: *Glass in building – Basic soda lime silicate glass products*

Part 1. *Definitions and general physical and mechanical properties*. BS EN 572-1: 1995

Part 2. *Float glass*. BS EN 572-2: 1995

Part 3. *Polished wired glass*. BS EN 572-3: 1995

Part 4. *Drawn sheet glass*. BS EN 572-4 : 1995

Part 5. *Patterned glass*. BS EN 572-5 : 1995

Part 6. *Wired patterned glass*. BS EN 572-6 : 1995

Part 7. *Wired or unwired channel shaped glass*. BS EN 572-7 : 1995

CEN: *Glass in building – Insulating glass units*. prEN 1279

CEN: *Glass in building – Heat-strengthened glass*. prEN 1863

CEN: *Glass in building – Thermally toughened safety glass*. prEN 12150

CEN: *Glass in building – Chemical strengthened glass*. prEN 12337

CEN: Glass in building – Laminated glass and laminated safety glass. prEN 12543 Parts 1, 2 and 3

CEN: *Glass in building – Glass block walls - Dimensions and performances. prEN 12725*

CEN: *Glass in building – Glazing and airborne sound insulation* Part 1: *Definitions and determination of properties*. prEN 12758-1

Products
Arup Research and Development (1993) provides a succinct summary of the key issues relating to the EC Construction Products Directive, products that achieve European Technical Approval and Agrément Certificates.

The Building Regulations
If it is intended to erect a new building, or to alter an existing building, or to change the use of a building in the UK, The Building Regulations will probably apply. Separate Regulations apply to England and Wales, to Scotland and to Northern Ireland. These are listed in Table B.1.

Table B.1 The UK Building Regulations

England and Wales	The Building Regulations 1991
Scotland	The Building Standards (Scotland) Regulations 1990
Northern Ireland	The Building Regulations (Northern Ireland) 1990

Health and Safety
Designers in the UK should be aware of their duties under the various health and safety regulations. These include *The Management of Health and Safety at Work Regulations 1992* and *The Construction (Design and Management) Regulations 1994*, better known as the CDM Regulations.

Reference

Arup Research and Development: *Flat roofing: design and good practice*. CIRIA/BFRC, 1993

Appendix C Stability of narrow fins and beams

The following six pages of this Appendix are reproduced from Appendix H of Australian Standard AS 1288 – 1994, *Glass in buildings – Selection and installation,* with the kind permission of Standards Australia.

For further information about this or other Australian Standards the reader should contact:

Standards Australia
Head Office
1 The Crescent
Homebush 2140
(PO Box 1055 Strathfield 2155)
New South Wales
Australia
Telephone
Administration (02) 746 4700
Information Centre (02) 746 4748
Sales (02) 746 4600
Facsimile
Administration (02) 746 8450
Sales (02) 746 3333

Appendix E The effects of atmospheric pressure and temperature on insulating units

When sealed insulating units are manufactured, the panes of glass are generally flat and are separated by edge spacers. Air or another gas (for example, Argon) is trapped inside the unit.

A consequence of this is that changes in temperature or pressure will apply inward or outward pressures on the panes. Changes in pressure may arise from changes in meteorological conditions or changes in altitude.

Moving the unit from production at low temperature and high pressure (sometimes called the winter condition) to use at high temperature and low pressure (sometimes called the summer condition) will cause the panes to bow outwards. The converse is also true. The pressures caused by these changes are referred to as isochore pressures in the August 1997 draft European Standard on glass panes CEN/TC129/WG8 for 'Design of glass panes Part 2: Design for uniformly distributed load'and the following values are recommended in the absence of better information.

Chapter 6 provides guidance on calculating the stresses and deflections caused by these pressure changes.

Table E.1 Isochore pressures — Climatic action
(Source: Draft European Standard on Glass Panes (August 1997))

Condition at place of use	Parameters for place of use		Parameters for production (final sealing)		Isochore pressure – climatic action
	Temperature	Meteorological pressure	Temperature	Meteorological pressure	
Summer	+45°C	100kN/m^2	+18°C	103kN/m^2	+12kN/m^2
Winter	+3°C	104kN/m^2	+30°C	98kN/m^2	-15kN/m^2

Table E.2 Isochore pressures — Altitude action
(Source: Draft European Standard on Glass Panes (August 1997))

Altitude change	Isochore pressure—Altitude action
Up to 400m	+/-3.6kN/m^2
Up to 700m	+/-8.4kN/m^2

Secondary seal
See dual seal system.

Security
Depending on the context this means either:

- the ability of glass to withstand manual attack or armed attack, or
- blast resistance, or
- electromagnetic shielding, or
- one way vision.

Security glass
A glass that assists in giving security.

Security glazing
A glazing system including security glass that assists in giving security.

Setting blocks
Small packers, usually of hardwood, hard rubber or plastics, placed under the bottom edge of the glass to support it off the glazing platform and allow clearance for drainage and ventilation.

Shading coefficients
The total shading coefficient is a measure of the total amount of heat passing through the glazing (known as the total solar heat transmittance) compared with that through a single clear glass. Glass lets heat through in two ways; a proportion of the short wavelength radiation is transmitted straight through, while some is absorbed by the glass and re-radiated as long wavelength radiation. The total shading coefficient is split into two parts relating to the proportions of the total solar heat transmittance which are short wavelength – the short wave shading coefficient, and long wavelength – the long wave shading coefficient.

Sheet glass
Flat glass made by continuous drawing.

Short wavelength energy
An alternative term for short wavelength radiation.

Short wavelength radiation
That part of electromagnetic radiation (i.e. from 280nm to 2500nm wavelength), which is radiated by the sun. The main components of glass are transparent to the majority of this short wave radiation.

Short wave shading coefficient
See shading coefficients.

Silicone sealant
A type of glazing compound made from silicone material which is gunned into position and cures into an elastic solid.

Silvering
Depositing silver on glass to form a mirror.

Single glazed
Fitted with only one pane of glass, neither an insulating unit nor a double window.

Sloping glazing
An alternative term for inclined glazing.

Soda lime silicate glass
Ordinary window glass, including float glass, patterned glass and wired glass and any products made from these.

Solar control
The effectiveness of glass in limiting solar heat gain. Solar control can be described in terms of the total shading coefficient of the glass, as being low (shading coefficient > 50%), medium (35% < shading coefficient ≤ 50%), or high (shading coefficient ≤ 35%).

Solar direct transmittance
The proportion of incident solar radiation that passes straight through the glass, expressed as a fraction. See solar properties.

Solar energy
An alternative term for solar radiation.

Solar gain factors
Numbers related to and derived from shading coefficients, which also describe the ability of the glazing to reduce solar heat gain.

Solar heat gain
The amount of heat from the sun which passes through the glass into a building.

Solar properties
Those properties of glass related to solar radiation, i.e. reflectance, absorptance, solar direct transmittance, total solar heat transmittance, shading coefficients and solar gain factors. The term is also used occasionally to include emissivities and optical properties.

Solar radiant heat properties
See solar properties.

Solar radiation
The heat, light and UV emitted by the sun as received at the surface of the earth.

Solar spectrum
The electromagnetic radiation emitted by the sun and its variation with the wavelength of the radiation. The solar spectrum effectively has a range of wavelengths from 280nm to 2500nm, with the largest proportion present as visible light.

Sound insulation
See acoustic properties.

Spacer
An alternative term for spacer bar.

Spacer bar
The preformed section, usually aluminium or steel, which spaces apart the panes of an insulating unit in order to form the cavity. The spacer bar usually also acts as a container for the desiccant in the insulating unit.

Spall
The pieces of glass ejected from one face of a pane of glass when it is impacted from the opposite face. This term is commonly used in connection with bullet resistance, where a requirement for reduced spall may be part of the classification system.

Spandrel panel
A glass panel, commonly in a curtain wall, which is made of an enamelled glass or an opacified glass in order to hide parts of a building structure, such as the edge of floor slabs.

Spectral distribution
The proportion of different wavelengths of a spectrum.

Spectrum
The wavelengths contained within a particular type

APPENDIX H

BASIS FOR DETERMINATION OF FIN DESIGN TO PREVENT BUCKLING

(Informative)

H1 INTRODUCTION In glass facades which use glass stiffening fins located on the inside to provide the necessary support for the facade panels, it is necessary to ensure that buckling of the fin will not occur when it is subjected to the design loads.

Since there are many possible configurations for glass stiffening fins, it is not practicable to provide a simplified design approach. Consequently, each design must be analysed in accordance with accepted engineering principles.

The analysis requires a knowledge of the critical elastic buckling moment (M_{CR}), and values for particular situations can be obtained from standard texts on structural analysis. However, as an aid to design, some values of the critical elastic moment are presented in this Appendix.

The design moment for a particular structural situation shall not exceed more than the critical elastic buckling moment (M_{CR}) divided by a factor of safety of 1.7.

The following recommendations are applicable to end-supported beams of bisymmetrical cross-section for which the contribution of warping stiffness to the buckling strength may be neglected.

The ends at supports are assumed to be effectively restrained against twisting. This condition will be satisfied if the supports possess a torsional stiffness in excess of $20GJ/L$, where GJ is the torsional rigidity of the beam and L is its length.

For information on more general sections, including the effects of warping stiffness, a useful reference is the following:

> NETHERCOT, D.A. AND ROCKNEY, K.C. Unified Approach to the Elastic Lateral Buckling of Beams, *The Structural Engineer*, Vol. 49, No. 7, July 1971, pp. 321–30. (For erratum, see Vol. 51, No. 4, April 1973, pp. 138–9.)

H2 BEAMS WITH INTERMEDIATE BUCKLING RESTRAINTS The critical elastic value of the maximum moment between two buckling restraints may be taken as:

$$M_{\mathrm{CR}} = (g_1/L_{\mathrm{ay}})\left[(EI)_{\mathrm{y}}(GJ)\right]^{1/2} \qquad \ldots \mathrm{H2(1)}$$

where

M_{CR} = critical elastic buckling moment

g_1 = constant obtained from Table H1

L_{ay} = distance between effectively rigid buckling restraints

$(EI)_{\mathrm{y}}$ = effective rigidity for bending about the minor axis

(GJ) = effective torsional rigidity

NOTE: In computing the effective torsional rigidity of beams of solid rectangular cross-section, the value of the torsional moment of inertia (J) may be taken as:

$$J = \frac{db^3}{3}\left(1 - 0.63\frac{b}{d}\right)$$

where

d and b are the depth and breadth of the fin respectively.

The value of torsional elastic modulus (G) may be taken as 28.3 GPa for glass fins.

The value of the linear elastic modulus (E) may be taken as 69.0 GPa for glass fins.

TABLE H1

COEFFICIENTS FOR SLENDERNESS FACTOR OF BISYMMETRICAL BEAMS WITH INTERMEDIATE BUCKLING RESTRAINTS

Moment parameter (β) (see Figure H1(c))	Slenderness factor (g_1)	
	Free restraint condition*	Fixed restraint condition*
1.0	3.1	6.3
0.5	4.1	8.2
0.0	5.5	11.1
−0.5	7.3	14.0
−1.0	8.0	14.0

* The buckling restraints must prevent rotation of the beam about the z-axis. The terms 'free' and 'fixed' restraint condition refer to the possibility for rotation of the beam about y-y axis at the restraint locations, as shown in Figure H1.

H3 BEAMS WITH NO INTERMEDIATE BUCKLING RESTRAINTS The critical elastic value of maximum moment of beams with no intermediate buckling restraints may be taken as—

$$M_{CR} = (g_2/L_{ay})\,[(EI)_y\,(GJ)]^{1/2}\,[1 - g_3\,(y_h/L_{ay})\,[(EI)_y/(GJ)]^{1/2}] \qquad \ldots \text{H3(1)}$$

where

M_{CR} = critical elastic buckling moment

g_2, g_3 = constants obtained from Table H2

L_{ay} = distance between effectively rigid buckling restraints (span of beam)

(EI_y) = effective rigidity for bending about the minor axis

(GJ) = effective torsional rigidity

y_h = height above centroid of the point of load application

NOTE: In Table H2, the values of the coefficients g_2 and g_3 apply to beams with lateral restraints only at their end points. However, these coefficients may be used for any other beam load system that has a similar shape of bending moment diagram between points of lateral restraint.

H4 CONTINUOUSLY RESTRAINED BEAMS For beams of bisymmetrical cross-section continuously restrained against lateral displacement at a distance y_o below the neutral axis, the critical elastic moment M_{CR} may be taken as—

$$M_{CR} = \frac{(\pi/L_{a_\varphi})^2\,(EI)_y\left[\dfrac{d^2}{4} + y_0^2\right] + (GJ)}{(2_{y_0} + y_h)} \qquad \ldots \text{H4(1)}$$

where

M_{CR} = critical elastic buckling moment

L_{a_ϕ} = distance between points of effective rigid rotational restraints

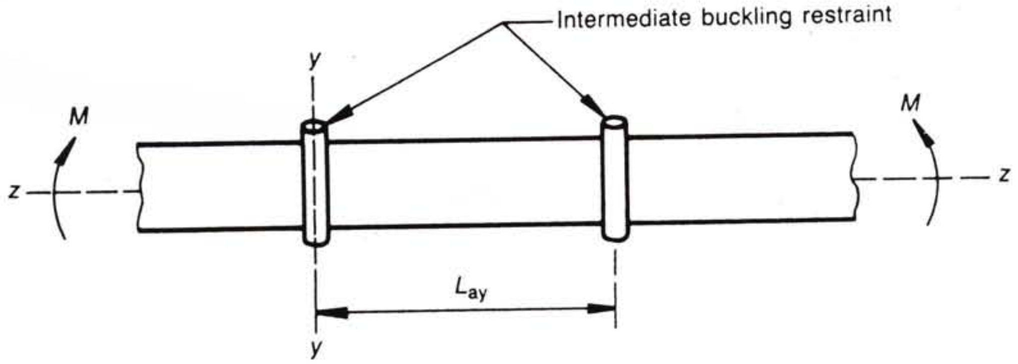
$(EI)_y$ = effective rigidity for bending about the minor axis

d = depth of beam

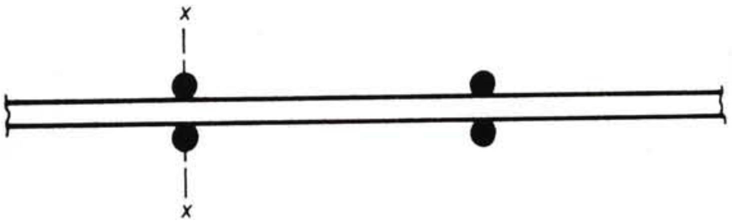
(GJ) = effective torsional rigidity

y_h = location above the neutral axis of the loading point

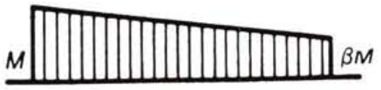
NOTE: The parameter y_h may take on negative values.



(a) Side view of beam



(b) Top view of beam



(c) Diagram of bending moment between buckling restraints

FIGURE H1 NOTATION FOR BEAMS WITH INTERMEDIATE BUCKLING RESTRAINTS

H5 BUCKLING RESTRAINTS For most design situations, no check need be made on the effectiveness of buckling restraints. However, for an unusually light restraint system being used for a critical (i.e. non-load-sharing) engineered structure, it may be advisable to assess the effect and the capacity of the restraints.

For a design of slender beams having equally spaced buckling restraints, the restraint system is considered a lateral one as shown in Figure H2 where the restraint stiffness (K_A) is defined as follows:

$$P_R = K_A \Delta_A \qquad \ldots \text{H5(1)}$$

where

P_R = restraint force

K_A = restraint stiffness

Δ_A = beam displacement

The restraint force (P_R) occurs when the point of attachment of the restraint to the beam undergoes a displacement (Δ_A). It is assumed that the ends of beams are effectively restrained against torsional rotation.

The design force (P_R) on the lateral restraints is given by the following equation:

$$P_R = \frac{0.1\,M_a}{d(n+1)}\,g_4 \qquad \ldots \text{H5(2)}$$

where

M_a = the applied bending moment on the beam

g_4 = constant
= lesser of $(m + 1)/2$ and 5

d = depth of beam

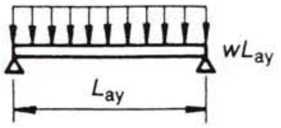
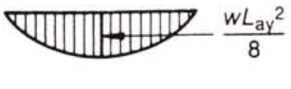
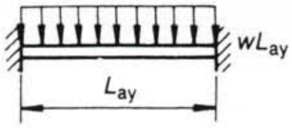
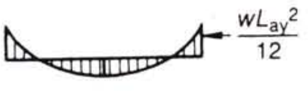
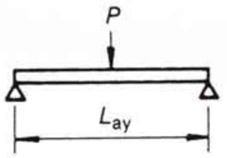
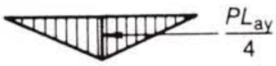
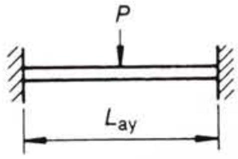
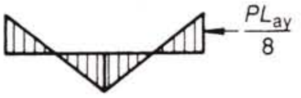
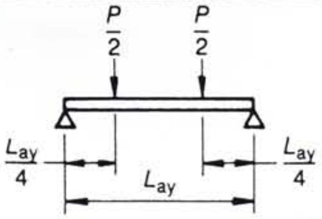
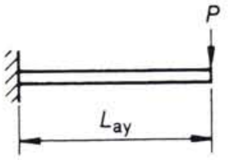
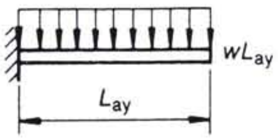
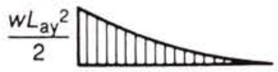
n = number of equally spaced intermediate restraints

m = number of members supported by each restraint system

NOTE: Equation H5(2) is for members of rectangular section and for box beams.

TABLE H2

COEFFICIENTS FOR SLENDERNESS FACTORS OF BISYMMETRICAL BEAMS WITH NO INTERMEDIATE BUCKLING RESTRAINTS

Loading	Bending moment (M)	Condition of end restraint against rotation about y-y axis*	Slenderness factors	
			g_2	g_3
		Free Fixed	3.6 6.1	1.4 1.8
		Free Fixed	4.1 5.4	4.9 5.2
		Free Fixed	4.2 6.7	1.7 2.6
		Free Fixed	5.3 6.5	4.5 5.3
		Free Fixed	3.3 —	1.3 —
		Fixed	4.0	2.0
		Fixed	6.4	2.0

* For direction of y-y axis, see diagram in Figure H1 (free ends of cantilevers excepted).

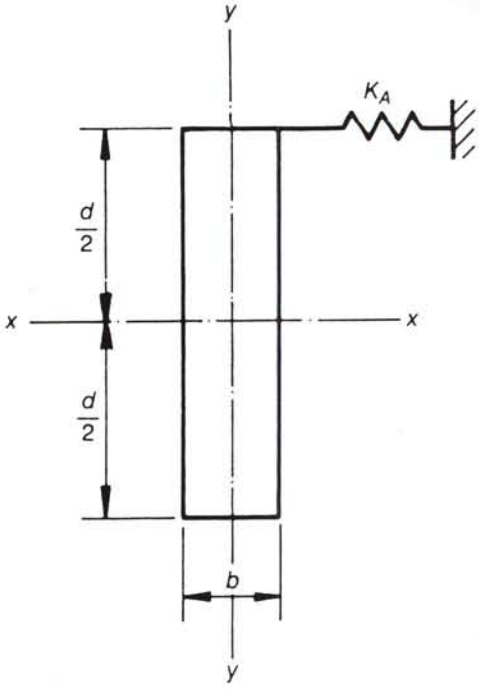


FIGURE H2 BEAM INTERMEDIATE LATERAL RESTRAINTS

Appendix D Load sharing

Chapter 2 raises the question: do the panes of an insulated unit share loads? The example below answers that question.

Load sharing in double glazed units

Consider an insulating unit 1.5m   1.5m and assume that an increase in pressure of 2.5kN/m^2 is applied to the outer surface. At sea level atmospheric pressure is around 100kN/m^2.

We can state with confidence that the pressure in the cavity will be somewhere between 100kN/m^2 and 102.5kN/m^2.

Therefore the maximum variation in cavity pressure will be 2.5kN/m^2 or 2.5%.

By Boyle's Law, Pressure   Volume / Temperature = Constant

Therefore the maximum variation in volume will be less than 2.5%.

The length and width of a cavity do not change, but the depth can, as the glass deflects under pressure changes.

Therefore the maximum variation in cavity depth will be less than 2.5%.

In a standard 12mm cavity, this variation will be 12   2.5/100, which equals 0.3mm.

Now compare this with the midspan deflection of 6mm annealed glass in a pane 1.5m square. Under 2.5kN/m^2 it will deflect about 15–20mm.

This deflection is so much greater than the variation in cavity depth under a pressure change of 2.5kN/m^2 that it is clear that the panes will share the load. How they share it will be determined by their relative stiffnesses.

This conclusion is, of course, not valid for small stiff panes separated by deep cavities.

Some national standards (for example the Netherlands, the USA, Canada) allow only partial load sharing when calculating the load-carrying ability of insulating units.

Appendix E The effects of atmospheric pressure and temperature on insulating units

When sealed insulating units are manufactured, the panes of glass are generally flat and are separated by edge spacers. Air or another gas (for example, Argon) is trapped inside the unit.

A consequence of this is that changes in temperature or pressure will apply inward or outward pressures on the panes. Changes in pressure may arise from changes in meteorological conditions or changes in altitude.

Moving the unit from production at low temperature and high pressure (sometimes called the winter condition) to use at high temperature and low pressure (sometimes called the summer condition) will cause the panes to bow outwards. The converse is also true. The pressures caused by these changes are referred to as isochore pressures in the August 1997 draft European Standard on glass panes CEN/TC129/WG8 for 'Design of glass panes Part 2: Design for uniformly distributed load'and the following values are recommended in the absence of better information.

Chapter 6 provides guidance on calculating the stresses and deflections caused by these pressure changes.

Table E.1 Isochore pressures — Climatic action
(Source: Draft European Standard on Glass Panes (August 1997))

Condition at place of use	Parameters for place of use		Parameters for production (final sealing)		Isochore pressure – climatic action
	Temperature	Meteorological pressure	Temperature	Meteorological pressure	
Summer	+45°C	100kN/m^2	+18°C	103kN/m^2	+12kN/m^2
Winter	+3°C	104kN/m^2	+30°C	98kN/m^2	-15kN/m^2

Table E.2 Isochore pressures — Altitude action
(Source: Draft European Standard on Glass Panes (August 1997))

Altitude change	Isochore pressure—Altitude action
Up to 400m	+/-3.6kN/m^2
Up to 700m	+/-8.4kN/m^2

Appendix F Glossary of terms and symbols

The glossary is based on one provided by Pilkington Glass Consultants. For a comprehensive US glossary the reader is referred to ASTM Standard C162—95b *Standard Terminology of Glass and Glass Products*. For a glossary of terms relating to the repair and maintenance of historical glass, see 'The repair and maintenance of historic glass' by Jane Kerr, which is chapter 2 of *Practical Building Conservation, Volume 5, Wood, Glass and Resins*, by John and Nicola Ashurst, Gower Technical Press, 1988.

3 ply
See laminated glass.

5 ply
See laminated glass.

AA
See reaction to fire.

Absorptance
The proportion of incident solar radiation absorbed by the glass, expressed as a fraction. See solar properties.

Absorption
An alternative word for absorptance, expressed as a percentage.

Acid etching
A process whereby the polished surface of glass is made matt by exposure to hydrofluoric acid.

Acoustic laminate
A laminated glass with special interlayers with better acoustic performance.

Acoustic performance
The properties of a glass or glazing product which describe its airborne sound insulation, as measured by the reduction or attenuation of sound, at specific pitches or frequencies, in decibels (dB), or by sound reduction indexes, such as the mean sound reduction index (R_m), the weighted sound reduction index (R_w), or the road traffic sound reduction index (R_{TRA}).

Air mass 2
A particular definition of the solar spectrum. See also relative spectral distribution.

Airborne sound insulation
The correct term for the type of sound insulation given by glass. See also acoustic performance.

Anneal
To attain acceptably low stresses, or desired structure, or both, in glass by controlled cooling from a suitable temperature.

Antique glass
Common name for handmade glass blown by the muff method.

Airspace
An alternative term for cavity.

Annealed glass
Ordinary glass that can be cut by scoring and snapping. Annealed glass, if broken, gives large fragments with sharp edges.

Anti-bandit glazing
A form of security glazing resistant to manual attack.

Applied film
An organic (plastic) film stuck on to glass to give it additional properties, e.g. a safety film.

Applied leading
Strips of lead adhered to both surfaces of a pane of glass to give the appearance of a leaded light.

Armed attack
An attack using firearms.

Arrissed edge
An edge finish to the glass where the sharp corners of the edge have been removed.

Aspect ratio
The ratio of the long edge of a pane to the short edge.

Attenuation
The reduction of either sound (see acoustic performance) or electromagnetic radiation (see electromagnetic shielding).

Backing paint
A form of opacifier, or a protective coating applied to mirrors.

Balustrade
A term commonly used for a barrier, protecting a drop, which comes up to about waist height.

Barrier
A structure designed either to guide the direction of pedestrian traffic or to provide guarding to the edges of drops.

Base glass
A term used to describe the glass which is subsequently processed, e.g. acid etching, sand blasting or forming coated glass.

Bead
See glazing bead.

Bent glass
An old term for curved glass.

Bevelling
The manufacture of polished shallowly chamfered edges to glass.

Blast resistance
The ability of a particular type of glass to withstand explosion pressure waves.

Bow
One form of distortion of toughened glass or heat strengthened glass.

Break safely
See safe breakage.

Brewster's Fringes
An effect like a rainbow, visible under certain lighting conditions, produced in an insulating unit when the two panes of glass are almost identical in thickness.

Brilliant cutting
The manufacture of a decorative polished V-shaped notch in the surface of the glass. The notch may be straight or curved.

Brise soleil
A partial shading device, usually above a window on the exterior of a building.

Bullet resistance
The ability of a particular type of glass to withstand armed attack using a particular type of weapon, not just by stopping the bullets, but also in terms of the spall ejected from the opposite face by the impact. BS 5051 grades bullet resistance with reduced spall (RS) from G0 through G1 and G2, for hand guns, to R1 and R2 for rifles in order of stopping power, with a separate grade S86 for shotguns.

Bushes
Nylon or hard fibre ferrules used round the shanks of bolts in bolted connections, to prevent direct contact between the bolt and the glass.

Butt joint
A joint between the edges of adjacent panes, which has no frame, but is filled with adhesive sealant, commonly silicone sealant.

Cast-in-place (CIP)
A type of interlayer used in the manufacture of laminated glass, by pouring a liquid resin between two panes of glass and curing it either chemically or by exposure to UV light.

Cavity
The gap between the panes of an insulating unit also known as the airspace.

Ceramic coating
The enamel finish applied to toughened glass.

Class 0
See reaction to fire.

Classes A, Ao, B, Bo, C, Co
See safety glass.

Clear float
Untinted float glass (but which may have a slight green tinge to it, usually noticeable only when looking at the edge of the glass).

Coated glass
A base glass to which an inorganic coating has been applied, either a pyrolytic coating, usually applied on-line (i.e. during the manufacture of the float glass) or a sputtered coating applied off-line to stock sizes or cut sizes.

Cold radiation
A description of the apparent effect felt when sitting near to a cold window surface, e.g. single glazing in cold weather.

Coloured film
Decorative applied film stuck on to the glass, usually in conjunction with applied leading to give the appearance of a leaded light.

Comfort
See thermal comfort.

Condensation
The formation of water droplets on cold surfaces. Condensation is regularly seen on the room surfaces of single glazing, but its incidence is reduced by the use of insulating units and particularly those that contain low E glass. See also external condensation.

Conduction
One of the methods of heat transfer through glass or through the gas in the cavity of insulating units.

Conduction heat gain
The transfer of heat from outside the building to the inside when the external air temperature is hotter than the internal air temperature.

Containment
The ability of a glass or glazing product to prevent persons who accidentally fall against it from falling through. See also guarding and barriers.

Convection
One of the methods of heat transfer by the gas in the cavity of an insulating unit.

Copper light
An old type of glazing using relatively small panes of glass fixed together with small copper bars, called cames, similar in appearance to a leaded light but having a limited fire resistance.

Critical locations
Those areas of a building, e.g. doors, adjacent to doors, or low-level glazing, where glazing is most vulnerable to accidental human impact and which may require the use of safety glass.

Cross bar
A support for the lead cames in large traditional leaded lights.

Cullet
Broken glass recycled for use in the glass-making process

Curtain walling
A glazing system in which the complete facade is glazed into frames attached to the building structure. The glazing may include both vision areas and spandrel panels.

Curved glass
Glass which has been heated past its softening point and formed into a curved shape, usually by draping the softened glass over or into a mould. The shaped glass is subsequently cooled slowly to form annealed glass or it may be rapidly chilled to form toughened glass.

Cut sizes
Panes of glass cut to the final size for glazing.

CVMA
Corpus Vitrearum Medii Aevi.

Cylinder glass
Glass produced by blowing a balloon of molten glass, then spinning it to elongate it into a cylindrical shape and cutting off the ends of the cylinder; then cutting along its length and unfolding into a rectangular sheet. Also known as muff glass.

Dalles de verre
Thick slabs of glass produced by casting in moulds.

Decibel (dB)
The scale used to measure or describe:

- loudness of sound, or
- sound insulation and sound reduction indexes

(see acoustic performance), or
- attenuation of radar and radio waves (see electromagnetic shielding).

Delamination
The coming apart of laminated glass, by the interlayer losing its adhesion to the glass in adverse environments.

Diffusing
Randomly scattering the incident light while still allowing transmission. Usually applied to the effects on light of acid etching, sand blasting and white interlayers. See also translucent.

Diffusion
See diffusing.

Dimensions
The length and width or other appropriate descriptions of the size of a pane of glass. The glass thickness is not usually referred to as a dimension of the glass.

Direct transmittance
The proportion of solar radiation that goes straight through the glass without being absorbed. See also solar properties.

Distance pieces
Sections of material used to space the pane of glass away from the upstand of the rebate in a frame, in order that an appropriate face clearance and an appropriate amount of sealant is present between the glass and the frame.

Double glazing
An old name for insulating units comprising two panes of glass.

Double window
A window containing two panes of glass in the same vision area, but which are glazed separately, not formed into an insulating unit. It is sometimes described as secondary sash glazing.

Drained and ventilated glazing
Drained glazing where the rebates are deliberately vented so external air circulates around the edge of the glass to assist in keeping the edges dry.

Drained glazing
A glazing system in which any lodged water is channelled out of the rebates.

Drawn glass
Glass made by a continuous drawing operation.

dsr
Differential surface refractometer: optical instrument used for measuring stress in glass (less precise than gasp).

Dual seal system
The edge seal of an insulating unit that comprises primary seals between the spacer bar and the panes of glass and a secondary seal between the two panes outside the spacer bar.

Edge clearance
The distance between the edge of a pane and the frame in which it is glazed. The clearance is required to allow for tolerances, avoid contact between the glass and its framing and, in the case of drained glazing, to give sufficient room for water to drain away.

Edge cover
The amount of glass within the rebate, i.e. covered by the glazing bead. This is required to ensure the pane is effectively secured (i.e. a mechanical requirement) and also to ensure the edge seal of an insulating unit is protected from the weather.

Edge seal
The hermetic seal around the edge of an insulating unit, designed to limit the rate at which water vapour penetrates into the cavity. The better edge seals are usually dual seal systems.

Effective U-value
A measure of the performance of glass as an energy-saving wall construction when its ability to let in useful solar heat gains is combined with its capability for thermal insulation as described by the U-value.

Electromagnetic attenuation
See electromagnetic shielding.

Electromagnetic radiation
The full spectrum ranges from gamma rays with very short wavelength, through X-rays, UV light (generally described as 280nm to 380nm wavelength), visible spectrum (generally described as 380nm to 780nm) and infrared, to radio waves with very long wavelength.

Electromagnetic shielding
The use of a Faraday Cage to reduce or prevent the passage of the longer wavelengths of electromagnetic radiation, usually at the frequencies of radar and radio waves. The electromagnetic attenuation given by the Faraday Cage is measured in decibels.

Emissivity
The ability of a surface to absorb or emit electromagnetic radiation. In terms of glass, emissivity is only important with respect to long wavelength radiation (in the range 5000nm to 50000nm) produced as radiated heat by objects at around room temperature. Glass naturally has a high emissivity. However, when made into low emissivity glass (low E glass), the glass surface does not absorb the radiated heat, but reflects it back into the room, enhancing the U-value of the glazing.

Enamel
A glassy material that is melted into the surface of the base glass at high temperatures to form a ceramic coating.

Enamelled glass
Glass with enamel applied.

Energy balance value
Also known as the effective U-value.

Environmental control
A term used to describe a glass or glazing product which is used for a particular effect on the environment inside a building. Often used as a euphemism for solar control, it could also refer to sound insulation, thermal insulation, and control of lighting levels or combinations of all of these.

Epoxypolysulphide
A sealant that sets very hard.

Explosion resistance
See blast resistance.

Ext. AA
See reaction to fire.

External applications
Applications where glass or glazing products are used in positions exposed to natural weather.

External condensation
Condensation forming on the external face (surface 1) of glazing with very low U-values. The effect requires particular combinations of high external humidity, average temperatures and exposure of the glass to clear night sky.

Facade
The face of a building, or the cladding covering it.

Facade element
A part of the facade, such as a window or spandrel panel.

Face clearance
The distance between the glass and the rebate upstand. This is usually filled with a gasket or sealant.

Fanlight
The glazing immediately above a door.

Film
See applied film.

Fin box
The glazing system used at the ends of glass mullions to retain them.

Fire barrier
An element of construction, such as a wall, partition or glazed screen, which gives an appropriate level of fire resistance.

Fire performance
The length of time an element of construction, such as a wall, partition or glazed screen, continues to give fire resistance when tested under simulated fire conditions according to BS 476: Part 20.

Fire propagation
See reaction to fire.

Fire protection
The action of a fire barrier in containing a fire.

Fire resistance
The ability of an element of construction, such as a wall, partition or glazed screen, to maintain integrity and/or insulation when tested under simulated fire conditions according to BS 476: Part 20.

Fire-resistant glass
A glass which, in an appropriate glazing system, allows the glazed screen or door to achieve fire-resistance for more than 30 minutes. The fire resistant glass may be a non-insulating glass, i.e. it satisfies only the integrity requirements of BS 476 for the time recorded during the test, or it may be a fully insulating glass, i.e. it satisfies both the integrity and insulation requirements of BS 476 for the time recorded during the test.

Fire safety
See fire protection.

Fired-on transfer
An applied transfer containing ceramic material or enamel that is melted into the glass surface at high temperature.

Fixing
Depending on the context this may mean either:

- the method of retaining the glass in position on the building, or
- the action of installing the glass (glazing it).

Flat ground edge
A glass edge that has been completely flattened by a grinding machine, after which the sharp corners are arrissed. The surface appearance is similar to sand blasting.

Flexible compound
A type of glazing material or sealant that remains permanently elastic, such as polysulphide or silicone sealant.

Float glass
Glass which has been manufactured by floating the molten glass on a bed of molten tin until it sets, producing a product with surfaces which are flat and parallel.

Flush glazing
Glazing which has no fixings or parts of the glazing system protruding beyond the outer surface (surface 1) of the glass.

Fragments
Pieces of broken glass.

Framed
Supported by a frame along the full length of an edge. Typical descriptions of glazing systems would be 4-edge framed or 2-edge framed.

Frameless
Not supported by a frame on any of the edges. The alternative to framing is by using bolted connections which could be described as structural glass.

Framing system
The type of material and the design of the frame supporting the glass. See also glazing system.

Free path
The distance that a person can move directly towards a barrier. This is used as a measure of how much energy can be developed by accidental impact in order to determine the appropriate containment level for glass in the barrier.

Freestanding glass protective barrier
A balustrade in which the glass performs all the mechanical functions. There are no posts or balusters; the glass is cantilevered from the floor and has a continuous handrail mounted on the top edge.

Frequency
The rate of vibration of a sound wave in Hz, also known as the pitch, or the rate of vibration of electromagnetic radiation, particular radio waves, usually in MHz.

Frit
An alternative name for enamel.

G0
See bullet resistance.

G1
See bullet resistance.

G2
See bullet resistance.

Gaskets
Solid, preformed glazing materials used to separate glass from other parts of the fixing or frame.

Gasp
Grazing angle surface polarimeter: optical instrument used for measuring stress in glass (more precise than dsr).

Glare
Excessive illumination or excessive contrast between lit and unlit areas which causes difficulty with vision.

Glare reduction
The ability to reduce glare problems, either by reducing the overall illumination or by diffusing direct light or a combination of both.

Glass mullion
A mullion support for glass panes made entirely from glass or from glass beams splice jointed with metal (or other) connectors. Also known as a fin.

Glass transition temperature
On heating, temperature at which a glass transforms from an elastic to a viscoeleastic material, characterised by the onset of a rapid change in thermal expansivity.

Glazing
Depending on the context it is either:

- the complete element of construction comprising the glass, the glazing materials and the fixing or frame, or
- the glass or glass product itself, or
- the act of installing the glass or glass product.

Glazing attenuation
See attenuation.

Glazing bead
The common mechanism used to retain glass in a frame.

Glazing compound
A glazing material which is soft and pliable, such as putty or silicone sealant, and can be used as a gap filler.

Glazing factors
Another term for radiometric properties, i.e. solar properties and optical properties.

Glazing materials
The gaskets, glazing tapes, glazing compounds, bushes, sealants and other items required for the purpose of glazing a glass product.

Glazing platform
The horizontal leg of the rebate in a frame, upon which the glass sits (on setting blocks) when it is glazed.

Glazing seal
Another term for glazing compound or sealant.

Glazing system
The frame and the design or method of fixing the glass into the frame.

Greenhouse effect
The retaining of solar heat by glass, for two reasons. Firstly, the presence of the glass prevents the wind from removing the heat rapidly. Secondly, the glass lets through the short wavelength radiation direct from the sun, but is opaque to the long wavelength radiation emitted by the warmed items inside the greenhouse, so the heat takes a lot longer to escape than it does to enter the greenhouse, resulting in the greenhouse getting warm inside. See also effective U-value.

Guarding
The prevention of persons falling, by means of barriers and balustrades. Any glass glazed into or forming such a barrier or balustrade is required to give containment.

Handling
All the activities involved in transferring the glass from factory to the site and into position in the building ready for glazing.

Hard coating
A term for a coating that is very durable, i.e. resistant to abrasion. It is a term usually applied to pyrolytic coatings.

Hazardous areas
Aan alternative term for critical locations.

Heat gain
See solar heat gain.

Heat soaked toughened glass
Toughened glass that has been heated for a period of time at moderately high temperatures to reduce the possibility of spontaneous fractures in service.

Heat-strengthened glass
Glass which has been heated past its softening point and chilled rapidly to increase its strength, but which breaks like annealed glass.

Heat transfer coefficient
A measure of the rate at which heat can cross a boundary or surface (whether it is by conduction, convection or radiation). The heat transfer coefficients at surface 1 and surface 4 of an insulating unit, as well as the heat transfer coefficient across the cavity, are required to calculate the U-value of the insulating unit.

Hermetic seal
An edge seal that is designed to prevent gas passing. The edge seal of an insulating unit is a hermetic seal to minimise the rate at which water vapour can penetrate into the cavity.

Hot box
A device which is used to measure the U-value of insulating units or the overall U-value of windows, including the frame.

Horizontally toughened glass
Glass that has been toughened in the horizontal position, supported on rollers. Although the glass is kept moving during the process, when it is soft it tends to sag between the rollers. The final product shows traces of this sagging as a phenomenon called roller wave, which may manifest itself as a regular distortion of images reflected in the glass surface.

Impact performance
The impact resistance of a safety glass when tested according to BS 6206.

Impact resistance
The classification according to BS 6206.

Impact resistant
A euphemism for being a safety glass.

Impact safety
An alternative term to impact resistance.

Inclined glazing
Glazing which is either horizontal or sloping up to 75° from the horizontal. Glazing within 15° of vertical is defined as vertical glazing.

Incombustible
An alternative word for non-combustible.

Infill panel
Depending on the context, this could mean:

- an alternative term for spandrel panel, or
- a panel underneath the handrail in a barrier.

Inner glass
See inner pane.

Inner leaf
See inner pane.

Inner pane
The pane on the room side of an insulating unit or double window.

Installation
Depending on the context this is either:

- the act of glazing, or
- the finished glazing.

Insulated panel
A spandrel panel with insulation in the form of organic foam or mineral wool attached to the rear face.

Insulating glass
A fire-resistant glass that gives both integrity and insulation for a specific period of time greater than 30 minutes. Do not confuse insulating glass with insulating units.

Insulating unit
A construction consisting of two or more panes of glass spaced apart with spacer bars to form a cavity between the panes. An edge seal is applied around each cavity to form a hermetic seal, minimising the ingress of the moisture into the cavity. A desiccant is incorporated in the spacer bar to dry up any residual moisture. Insulating units are assessed in their effectiveness at resisting moisture penetration by BS 5713. The air in the cavity can be replaced by another gas to give the unit specific thermal insulation or sound insulation properties. An insulating unit does NOT normally have any fire resistance properties unless it incorporates at least one pane of fire-resistant glass.

Insulation
Depending on the context, this may mean either:

- the material applied to the back of spandrel panels to increase the thermal insulation of the panels, or
- an alternative word for thermal insulation, or
- the length of time that a construction can give fire resistance in relation to the passage of heat, as defined in BS 476: Part 20.

Integrity
Depending on the context, this may mean:

- the ability of the glass to hold together after fracture, or
- the length of time that a construction can give fire resistance in relation to the passage of flames and smoke, as defined in BS 476: Part 20

Integrity-only glass
Another term for non-insulating glass.

Interlayer
The material used to separate and bond the plies of glass in laminated glass. The interlayer can be pvb, cast-in-place, or intumescent.

Internal applications
Applications where glass or glazing products are not exposed to natural weather.

Intumescent
Capable of expanding. In terms of glass and glazing, intumescent means specifically that the material expands with heat. The term is applied to glazing materials as well as interlayers.

Intumescent interlayer
An interlayer which intumesces in fire conditions, not only holding the laminated glass together, but also creating an effective barrier to smoke, flames and heat.

ISO range
The part of electromagnetic radiation which is UV light according to the ISO definition (between 280nm and 380nm).

Laminate
Another (non-preferred) term for laminated glass.

Laminated glass
Two or more panes of glass separated and bonded by interlayers. The panes can be any type of glass, but the commonest is float glass. The laminated glass may be described by the number of plies, e.g. 3 ply (2 panes + 1 interlayer) and 5 ply (3 panes + 2 interlayers).

Laminated toughened glass
Laminated glass made with all the panes toughened glass.

Lead cames
The lead used in traditional leaded lights to hold the individual small panes of glass in position. The lead cames are relatively flexible, so large leaded lights may need additional support from cross bars attached at intervals to the lead cames.

Leaded glass
An alternative name for leaded lights.

Leaded light
Glazing which is formed either:

- in the traditional manner by using lead cames to fix small panes of glass, or
- by sticking applied leading on to the surface of a single pane.

Lehr
A long, tunnel-shaped oven for heat treating glass by continuous passage

Light diffusion
see diffusing.

Light reflectance
The proportion of the visible spectrum which is reflected by the glass, expressed as a fraction. See optical properties.

Light reflection
An alternative term for light reflectance, expressed as a percentage. Light reflection can be described as low (≤ 15%) or high (> 15%)

Light shelf
A reflective device (possibly a partial mirror), placed in a position near the upper edge of a window, which redirects light from the sun and sky on to the ceiling or towards the back of the room, in order to improve the natural illumination within the room.

Light transmittance
The proportion of the visible spectrum which is transmitted by the glass, expressed as a fraction. See optical properties.

Light transmission
An alternative term for light transmittance, expressed as a percentage. Light transmission can be described as low (≤ 25%), medium (> 25% and ≤ 50%), or high (> 50%)

Lighting conditions
The level of illumination, specifically the illumination on the public side and the private side in relation to one way vision effects.

Linseed oil putty
The traditional glazing compound for single glazed timber windows. Linseed oil putty is NOT suitable for insulating units.

Lite or light
A panel or sheet of glass (US terminology).

Location blocks
Small separators placed between the frame and the edge of the glass to maintain the edge clearance between the glass and the frame. The separators are called location blocks when positioned on the vertical and top edges of the pane. At the bottom edge their equivalents are setting blocks. Location blocks are not required in every instance, but are commonly used in opening windows, where they may be a tendency for the glass to move in the frame.

Long wavelength energy
An alternative term for long wavelength radiation.

Long wavelength radiation
That part of the electromagnetic spectrum (i.e. from 5000nm to 50000nm wavelength), which is produced by objects at around room temperatures. Glass is opaque to this radiation so short wave radiation from the sun is trapped by glass, giving the greenhouse effect. It is possible to design coatings which are transparent to visible light, but which are highly reflective, i.e. have a low emissivity, to long wavelength radiation. Glass with such a coating is called low E glass.

Long wave shading coefficient
See shading coefficients.

Low E glass
See low emissivity glass.

Low emissivity glass
Glass coated with a material that has an emissivity less than 0.2 in the long wavelength radiation part of electromagnetic radiation. Uncoated glass has an emissivity of around 0.9. The purpose of low E glass is to reduce the radiation component of heat transfer across the cavity of an insulating unit. Since radiation is a significant component of the heat transfer across a cavity, insulating units incorporating low E glass have much improved thermal insulation properties when compared to units without low E glass.

Low-level glazing
Glazing which is wholly or partly within the critical location up to 800mm from finished floor level.

LWSC
Long wave shading coefficient.

Manifestation
Making panes of glass, whose presence may not be immediately obvious, easily visible by the application of permanent patterns, logos or other markings, in order that persons should not walk into them without noticing.

Manual attack
Attack using manually held implements or thrown objects, but not firearms.

Marked
Having a permanent inscription indicating the performance of the product and other information. The most common marks are those related to safety glass classification and to insulating unit performance.

Marking
The permanent inscription marked on the glass.

Mean sound reduction index (R_m)
The average of 16 sound insulation values over the frequency range 100–3150Hz (see acoustic properties).

Metal casement putty
The traditional glazing compound for single glazed steel windows. Metal casement putty is NOT suitable for insulating units.

Metallic glass
Also known as glassy metals or alloys, or metglass. Glassy (i.e. non-crystalline) solids made of elements or mixtures which normally occur as metals or alloys. A very high cooling rate is essential for their production. The great tendency towards crystallisation means that only relatively thin films or wires can be produced.

Mirror
A glass which is highly reflective and opaque. Silvering followed by an application of backing paint forms the commonest type of mirror.

Muff method
Another name for the method used to produce cylinder glass.

Multi-laminated
Containing more than two plies of glass in the laminate.

Multi-pane
A term applied to fire-resistant glazing which has been tested with more than one pane of glass in the assembly. It does NOT indicate double windows or insulating units.

Multiple glazing
An old term for an insulating unit comprising two or more panes.

Nickel sulphide inclusion
A small impurity in the glass which can cause spontaneous fracture of toughened glass some time after toughening.

Noise attenuation
An alternative term for sound insulation.

Non-combustible
See reaction to fire.

Non-insulating glass
A fire resistant glass which gives integrity for at least 30 minutes, but which does not give insulation for 30 minutes.

Non-loadbearing element
An element of construction that plays no part in supporting the building structure or part of the structure.

Observed side
See public side.

Observing side
See private side.

Octave band
The range of sound frequencies over which the frequency is doubled, e.g. 200Hz to 400Hz.

Off-line
See coated glass.

On-line
See coated glass.

One way vision
An optical effect resulting from the relative luminance of transmitted and reflected light, which allows vision through a window from only one side.

Opacified
Made opaque by the application of a backing paint or other backing material, a term related closely to spandrel panels.

Optical properties
The light transmittance and light reflectance of glass products.

Optical quality
The presence or absence of visual distortion or small blemishes in the glass.

Outer glass
See outer pane.

Outer leaf
See outer pane.

Outer pane
The pane on the external side of an insulating unit or double window.

Overall U-value
The U-value of a window, i.e. the combination of glass and frame.

Overhead glazing
Sloping glazing or horizontal glazing, usually in roofs.

Pallet
A packaging method for transporting and storing glass. See also rack and stillage.

Pane
A piece of glass.

Parry Moon range
The part of electromagnetic radiation which is UV light according to the Parry Moon definition (between 300nm and 400nm)

Patent glazing
A system of drained glazing which is formed from lightweight framing sections incorporating a built-in gutter in the rebate, commonly used for roof glazing.

Patterned glass
Glass manufactured by passing between two rollers (hence it used to be called rolled glass), one of which forms an impression or pattern into the glass.

Pinhole
A small defect where a coating, enamel or backing paint is missing.

Pitch
The frequency of a sound.

Plate glass
Flat glass formed by a rolling or casting process, ground and polished on both sides, with surfaces essentially plane and parallel

Polarised light
Light waves which are vibrating in a specific orientation, either after passing through a polarising filter, or after being reflected from a surface or from the sky.

Polished wired glass
Wired patterned glass that has subsequently been ground and polished on both surfaces to make it transparent.

*Polyvinyl butyral (*pvb)
A type of interlayer used in the manufacture of laminated glass, by placing a sheet of the material between two panes of glass and curing under heat and pressure.

Primary seal
See dual seal system.

Private side
The side of a one way vision glass from which the other, public side is clearly visible.

Public side
The side of a one way vision glass from which the other, private side is not visible.

pvb
See polyvinyl butyral.

Pyrolitic
Applied at high temperature. In relation to glass, this term is usually applied to coatings applied online when the ribbon of float glass is around 500°C to 600°C.

Radiation
Depending on the context it could mean:

- one of the methods of heat transfer across the cavity of an insulating unit, or
- electromagnetic radiation.
- one of the forms in which heat from a fire gets through non-insulating glass.

Radiative combustion
See reaction to fire.

Radiometric properties
The combined sets of optical properties and solar properties of a glass product.

R1
See bullet resistance.

R2
See bullet resistance.

Rack
A packaging method for transporting and storing glass. See also pallet and stillage.

Reaction to fire
The way in which a material or product behaves in a fire situation. There are four major classifications used to define the behaviour. Radiative combustion relates to whether fire can pass through a material when used as a roof covering subject to heat from an adjacent fire. Glass generally obtains the highest rating, described as AA or Ext. AA. However, cast-in-place laminated glass has not been tested.

Materials are also classified by surface spread of flame, the ability or otherwise of fire to spread along its surface.

Materials are also assessed for being non-combustible, i.e. that they do not burn, and for their fire propagation, i.e. whether they contribute to a fire. Glass is non-combustible, except for laminated glass, which generally(1) achieves the highest rating for fire propagation. Materials that are non-combustible, or achieve the highest rating for fire propagation are designated Class 0 according to Building Regulations.

Rebate
The part of a frame that holds the glass.

Rebate depth
The depth of the rebate in a frame, being the sum of the edge clearance and the edge cover of the glass.

Reduced spall
See spall.

Reflectance
The proportion of incident light or solar radiation reflected by the glass, expressed as a fraction. See optical properties and solar properties.

Reflection
An alternative word for reflectance, expressed as a percentage.

Reflective glass
Glass with a coating that reflects light or short wavelength infra-red radiation.

Refraction
The distortion of the path of light as it passes through a glass/air interface.

Relative spectral distribution
A specific description of the solar spectrum used to determine the radiometric properties of glass.

R_{m}
Mean sound reduction index.

Robustness
The ability of a pane of glass to resist breakage (under accidental human impact).

Rolled glass
An old name for patterned glass.

Roller wave
See horizontally toughened glass.

RS
Reduced spall.

R_{TRA}
Traffic sound reduction index.

R_{w}
Weighted sound reduction index.

S86
See bullet resistance.

Safe breakage
Either cracking without producing large openings or separate large sharp edged pieces (i.e. in a manner similar to laminated glass), or cracking into many small fragments (i.e. in a manner similar to toughened glass). Safe breakage is precisely defined in BS 6206.

Safety
Depending on the context, this may be either:

- the ability of glass to reduce the possibility of piercing and cutting injuries when subjected to accidental human impact, or
- the reduction of hazard from breakage of glass in overhead glazing, or
- fire protection.

Safety backing
An alternative term for safety film, usually used in connection with mirrors.

Safety film
A plastics film adhered to one surface of the glass with the intention of holding it together after fracture, so that the glass can be classified as a safety glass.

Safety glass (UK)
A glass or glazing product which conforms to BS 6206, which classifies the product as giving no break or safe breakage when the glass is tested, classifying the glass as Class C, Class B or Class A (or Class Co, Class Bo or Class Ao, if the test is from one side only of an asymmetric product) according to the drop height achieved in the test.

Safety glass (USA)
Glass so constructed, treated or combined with other materials as to reduce, in comparison with ordinary sheet, plate or float glass, the likelihood of injury to persons whether these safety glasses are broken or unbroken. Types of safety glass include laminated safety glass, tempered glass and wire glass.

Safety rating
The classification achieved for a safety glass to BS 6206.

Sand blasting
A process whereby the polished surface of glass is made matt by exposure to air blown sand or grit.

Screen printed glass
Glass which has been given a decorative surface finish of either ceramic ink (a type of enamel), which is subsequently fired onto the glass, or epoxy-based ink.

Sealant
A glazing compound that sets after application into a rubbery consistency.

Secondary glazing
See secondary sash glazing.

Secondary processing
Subsequent processing of glass after initial manufacture, e.g. manufacture into laminated glass, toughened glass, or insulating units.

Secondary sash glazing
A double window.

of electromagnetic radiation, such as the solar spectrum.

Spontaneous breakage
An alternative term for spontaneous fracture.

Spontaneous fracture
The breakage of glass for no immediately obvious reason. The term is more often associated with fracture of toughened glass than any other type, because the mode of fracture of toughened glass tends to disguise the cause.

Spread of flame
See reaction to fire.

Stained glass
Depending on the context, this may mean:

- a traditional leaded light made with glass of different colours to form a picture or decorative pattern, or
- a pane of glass with coloured applied film and applied leading which looks like a traditional leaded light
- a piece of glass of the type used in a leaded light.

Steady state
Under constant conditions. This is usually associated with environmental properties. Since the environment (temperature, wind, and sun) is in a constant state of flux, this makes calculations of the glass performance very difficult. The solar properties and U-value of the glass are therefore calculated with a steady state set of conditions.

Stepped unit
An insulating unit with one pane larger than the other. The unit may be stepped on only one edge (often used at the bottom edge of roof glazing) or it may be stepped on more than one edge.

Stillage
A packaging method for transporting and storing glass. See also rack and pallet.

Stock plate
An alternative term for stock sizes.

Stock sizes
The glass as manufactured and stored ready for cutting down to cut sizes.

Stress pattern
The effect seen in toughened glass when it is viewed under polarised light or through a polarising filter, which shows a patterning of spots or bars due to slight non-uniformity of the surface compressive stress in the glass.

Structural glass
Glass used in a manner where it may be supporting other building components (e.g. glass mullions) or where it performs a semi-structural role (e.g. free-standing glass protective barriers). The term may also be used for glass fixed using bolted connections (frameless glazing), even if it performs no structural function.

Surface 1
The surface of glass exposed to the weather.

Surface 2
The room side surface of single glazing, or the cavity surface of the outer glass in an insulating unit.

Surface 3
The cavity surface of the inner glass in an insulating unit.

Surface 4
The room side surface of double-glazing.

Surface coated glass
See coated glass.

Compressive surface stress
See toughened glass.

Surface resistances
The inverse of the heat transfer coefficients at a surface.

Surface spread of flame
See reaction to fire.

SWSC
Short wave shading coefficient.

Tempered glass
Glass that has been subjected to a thermal treatment characterised by rapid cooling to produce a compressively stressed surface layer (US term equivalent to UK's 'thermally toughened').

Template
An exact size physical model of the shape of the glass to be manufactured.

Thermal break
A gap or a portion of low thermal conductivity in a metal frame, separating the inner and outer parts of the frame, designed to increase the thermal insulation of the frame.

Thermal comfort
The physical feeling of comfort in relation to the absence of cold radiation and down draughts from window surfaces of insulating units with low U-value.

Thermal fracture
See thermal stress and thermal safety.

Thermal insulation
The ability to restrict the flow of heat. The lower is the U-value, the better is the thermal insulation.

Thermal properties
Depending on the context this could mean either:

- the U-value, or
- the solar properties, or
- both of the above.

Thermal safety
The determination of whether annealed glass is thermally safe, given that it has good quality edges.

Thermal stress
Stress developed in glass due to differences in temperature across its surface. In buildings, this is commonly related to glass exposed to the sun, where the central part is heated, but the edges, in the frame, remain relatively cool. Too high a temperature difference can result in thermal fracture of the glass.

Thermal transmittance
An alternative term for U-value.

Thermally safe
Has a risk of thermal fracture sufficiently low to be acceptable.

Third octave band
A range of sound frequencies which is 1/3 of an octave band. Note that this is not a numerical 1/3. For example, the octave band from 200Hz to 400Hz is split at 250Hz and 320Hz.

Third octave band centre frequency
The frequency commonly used by sound engineers to ascribe the average loudness or sound insulation over that third octave band.

Tight size
The size of the opening in a frame into which glass is to be glazed. The glass should be smaller than the tight size, to allow a suitable edge clearance.

Time/temperature curve
The prescribed temperature rise in a fire test furnace as a function of the duration of the BS 476 test.

Tinted float
Float glass that has small amounts of colorants added to the glass to give it solar control properties. Also called body-tinted float.

Tinted interlayer
An interlayer in laminated glass that is tinted to give the glass solar control properties.

Total shading coefficient
See shading coefficients.

Total solar energy transmittance
An alternative term for total solar heat transmittance.

Total solar heat transmittance
The proportion of incident solar radiation transmitted by the glass, including both the solar direct transmittance and a portion of the absorbed radiation which is re-radiated, expressed as a fraction. See solar properties.

Total transmittance
An alternative term for total solar heat transmittance.

Toughened glass
Glass which has been heated past its softening point and chilled rapidly to build in a surface compressive stress which gives it greatly increased strength and makes it break into small fragments if broken.

Traffic noise reduction index (R_{TRA})
This derived by taking into account a typical spectrum of road traffic noise (see acoustic properties).

Translucent
Letting light through, but obscuring clear vision.

Transmission
An alternative word for transmittance, expressed as a percentage.

Transmittance
The proportion of incident light or solar radiation transmitted by the glass, expressed as a fraction. See optical properties and solar properties.

Transparent
Allowing through vision.

Triple glazing
An old name for insulating units comprising three panes of glass.

U-value
A measure of the rate of heat loss through the wall or a component in a wall of a building, also described as thermal transmittance. U-values depend on several different variable factors, such as wind speed and temperature, so they are usually quoted in relation to a specific set of steady state environmental conditions

Ultraviolet transmittance
The proportion of incident UV radiation transmitted by the glass, expressed as a fraction.

UV filter interlayer
An interlayer in a laminated glass that blocks the majority of the UV radiation.

UV filter layer
An alternative term for UV filter interlayer.

UV light
An alternative term for UV radiation.

UV protection
An alternative term for UV reduction.

UV radiation
The part of the electromagnetic spectrum with a slightly shorter wavelength than visible light, within the UV range, known as ultraviolet light or UV light.

UV range
The wavelengths of the electromagnetic spectrum usually described as being UV radiation. There are two common descriptions, the ISO range and the Parry Moon range.

UV reduction
The proportion of UV radiation that is blocked by the glass.

UV transmission
An alternative expression for UV transmittance, expressed as a percentage.

UV transmittance
The proportion of incident UV radiation transmitted by the glass, expressed as a fraction.

Vandal resistance
The ability to resist damage, as opposed to the ability to resist penetration. Glass commonly does not have high vandal resistance.

Vertical glazing
Glazing which is either true vertical or within 15° of true vertical.

Visible spectrum
That part of the electromagnetic spectrum which is visible to the human eye, i.e. at wavelengths between 380nm and 780nm.

Vision area
Depending on context, either:

- an oval with axes equal to the height and width of the pane, or
- the parts of a building facade or curtain wall which are intended for the passage of light.

Vision panel
A term used to distinguish a part of curtain walling as being distinct from a spandrel panel.

Visual distortion
The warping of images when seen through the glass, due to the surfaces of the glass being not exactly flat and parallel. The term is also sometimes applied to reflected images.

Visual quality
An alternative term for optical quality.

Wavelength
A character of electromagnetic radiation, by which it can be described. Usually used to discriminate between different types of electromagnetic radiation, such as visible, UV and infrared (heat).

Weight
The area density of a pane of glass, expressed in kg/m^2.

Weighted sound reduction index (R_W)
Incorporates a correction for the ear's response and has been derived in accordance with BS 5821: 1984. See acoustic properties.

Wind resistance
The ability of the glass to withstand wind loads.

Wired glass
Generic name which covers polished wired glass and wired patterned glass.

Wired patterned glass
Glass with a welded steel mesh incorporated within the body of the semi-molten glass and formed by passing between two rollers, one of which forms an impression or pattern into the glass.

Glossary of symbols

Symbol	Meaning	SI Unit
a	Half length of a crack	m
a, b	Short and long dimensions of a pane of glass	m
E	Young's Modulus	MPa or GPa
G_c	Toughness $= \dfrac{K_{1c}^2}{E\,(1+\nu)}$	kJ/m^2
h	Glass thickness	m
I	Second moment of area	m^4
K_{1c}	Fracture toughness, or critical stress intensity factor	MPa m$^{0.5}$ or MN/m$^{1.5}$
l	Span of beam	m
M	Bending moment	kNm or Nmm
m	Exponent used in section 5.7	dimensionless
N	No of cycles	dimensionless
P_x	Probability integral	dimensionless
p	Pressure	N/m^2
r_0, r_1, r_2	Coefficients used in section 6.2.2	dimensionless
S	Surface area	m^2
t	Thickness of a pane	mm
n	Exponent used in section 5.7	dimensionless
β	Exponent used in section 5.7	dimensionless
$\Delta\sigma$	Stress amplitude	N/mm^2
ρ	Density	kg/m^3
ν	Poisson's ratio	dimensionless
σ	Stress	N/mm^2

Structural use of glass in buildings

Glass remains an elusive material for engineers, feared because it is brittle, under-used because design data is so hard to find. This is especially vexatious because it is a material much sought after by architects. It is hard to think of any modern building in which glass does not play an important part. Transparency and translucency are essential features of modern architecture.

There are many books and many precedents that inspire designers to use glass but the data designers need is not easy to find. It exists but it is not available from a single source. This guide attempts to assemble the information that structural engineers will need. In doing so it touches on many issues that influence design but which are not necessarily themselves structural, for example condensation, colour and acoustical behaviour.

The guide is aimed at two distinct groups of users:

- Those who want straightforward advice on how to do something in glass with guidance on the applicability of the designs or details that are offered.
- Those who want to design in glass from first principles.

As far as possible the guide compares and contrasts the structural behaviour of glass with that of other, better known, structural materials.

Whilst primarily aimed at structural engineers the guide will be of interest to a wide variety of professionals within the construction industry.