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Chapter 6
Glass in facades and other applications

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6.1. Introduction

Glass has been used as a glazing material (i.e. in windows) since the Roman times and it is ubiquitous in buildings (try thinking of a building that uses no glass!). Yet, despite its long traditions and popularity, glass is often regarded as a mysterious material like no other. In fact, glass is an engineering material that in many respects can and should be treated like other engineering materials, but like other construction materials it has particular properties that must be considered carefully in the design process.

Glass components and structures can be designed to safely resist the forces to which they may be subjected in a resource-efficient (i.e. sustainable) manner. The process involves knowledge and creativity to: conceive optimal glass solutions at early design stages; develop and test (numerically and/or physically) the solutions at detailed design stages; interact with others in the design/fabrication/construction team to produce a safe, buildable and sustainable glass design solution that is well integrated with the architectural intent and the rest of the building. This process is informed by knowledge of the following:

- The manufacturing processes and resulting mechanical properties of glass (Section 6.2).
- The different uses of glass components and types of connections in buildings (Section 6.3).
- The engineering design process, including limit state design and risk analysis (Section 6.4).
- Designing environmentally sustainable glass components and structures (Section 6.5).

Throughout the design process it is essential to remember the peculiarities of glass that affect the structural design process and decisions. In particular:

- Glass is inherently brittle, thereby requiring special measures to prevent catastrophic collapse and human injury by means of manufacturing safety glass products, minimising stress concentrations and by introducing fail-safe systems in the design of components, assemblies and connections.
- Glass is generally transparent or translucent, and is not normally covered up by other finishes. Aesthetic qualities therefore play a very important role and must be taken into account through the design/detailing process. Similarly, glass is often used in building envelope applications and other performance requirements – for example, thermal performance, light transmission, acoustic performance, occupant comfort, and so forth – play a significant role in the design process.

This chapter endeavours to summarise the salient information about the above-mentioned aspects for designing safe and sustainable glass elements and structures.

6.2. Manufacture and mechanical properties

A basic understanding of the glass manufacturing processes is essential because they underpin the mechanical properties and the corresponding structural design decisions. Further detail on the manufacturing processes is available in Haldimann *et al*. (2008), O'Regan (2014) and Rawson (1991).

Glass can be manufactured in various ways. Mainly, extrusion for producing glass fibres, moulding for producing glass containers, casting for solid volumetric elements, or floating for sheet elements. The latter process is used for the vast majority of architectural and automotive applications.

The principal steps in glass production, irrespective of the manufacturing method used, are: melting at approximately 1500–1800°C; forming at 800–1500°C; cooling at 100–600°C.

In the float process, flat soda-lime-silica glass is produced by melting the raw materials, namely: silicon dioxide (silica); sodium carbonate (soda); and dolomite at approximately 1500°C in a furnace, and a continuous ribbon of molten glass is fed onto and floats on a bath of molten tin. As the glass cools rapidly from 1100°C to 800°C in the float bath, its viscosity increases and prevents crystallisation, effectively becoming an amorphous isotropic solid. This rapid cooling and incomplete crystallisation is what gives glass its distinctive transparency and the corresponding absence of slip planes or dislocations (such as those found in steel) produces an almost perfectly elastic, isotropic behaviour and brittle fracture. The continuous ribbon of glass is then fed into the annealing lehr (see Figure 6.1) where the glass is cooled in a gradual and controlled manner to minimise the residual thermal stress in the glass. This allows the glass to be cut without shattering. This is known as annealed float glass and is the base product for most architectural glass applications in buildings.

Annealed glass of about 6 m long by 3 m wide can be produced by the float process, but even longer sections may be obtained by special order. The thickness of the glass sheets may range between 2 and 25 mm, but 6 to 12 mm thick are more readily available.

The intrinsic tensile strength (i.e. strength based on the intermolecular forces) of annealed glass is exceptionally high and may reach 32GPa (Haldimann *et al.*, 2008). However, the extrinsic (i.e. actual) tensile strength is several orders of magnitude lower – for example, the long-term tensile strength can be as low as 7 MPa for annealed glass. The reason for this discrepancy is the presence of stress-raising flaws, known as Griffith flaws. Such flaws cannot propagate in the presence of compression. Therefore, the compressive strength of glass is much larger than the tensile strength. The compressive strength is generally irrelevant for structural applications because transverse tensile stresses, arising from Poisson's ratio effects or from buckling, tend to govern the design of glass elements when subjected to a compressive stress.

Other physical properties of glass are easier to establish and are shown Table 6.1.

Figure 6.1 The float glass production process. (Haldimann *et al.*, 2008)

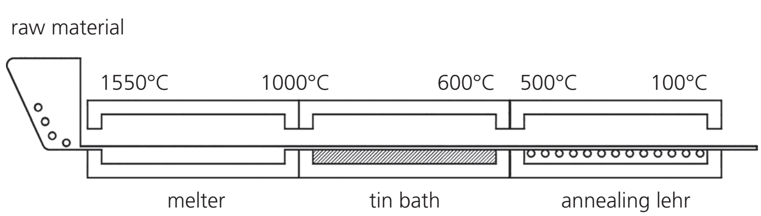


Table 6.1 Physical properties of soda-lime-silica glass. (CEN, 2021; Haldimann *et al.*, 2008)

Density	2500 kgm^{-3}
Young's modulus	70 GPa – 74 GPa
Poisson's ratio	0.22 – 0.24
Fracture toughness	0.78 MPa $m^{1/2}$
Knoop hardness	6 GPa
Annealing point	$10^{13.5}$ Pa s (520°C)
Thermal conductivity	1 W m^{-1} K^{-1}
Coefficient of thermal expansion	7.7×10^{-6} K^{-1} – 9 $\times10^{-6}$ K^{-1}

6.2.1 Design strength and performance of float glass

The strength of glass may be calculated directly from linear elastic fracture mechanics, but this requires knowledge of the location and size of the critical flaw, which in most structural design applications is unknown. Consequently, the strength of glass is often determined statistically. The latter approach is similar to that used in other construction materials, except that the strength of glass is very sensitive to the following extrinsic factors, which must be assessed carefully.

- Surface condition (larger flaws in high stress areas results in lower strength).
- Surface area exposed to tensile stress (larger stressed area results in lower strength).
- Surface stress history (i.e. magnitude and duration) and environmental conditions.
- Thermal or chemical prestressing.
- Lamination.

6.2.1.1 Surface condition

A large scatter of strength data is always obtained when a batch of nominally identical test pieces of a glass are broken in a carefully controlled way. This dispersion is a result of the variations in surface flaw characteristics and cannot be adequately captured by normal (Gaussian) distributions used in other loadbearing materials. Therefore, a 2-parameter Weibull distribution is often used to describe the availability in glass strength data and to derive the characteristic and design strengths from a set of glass load tests (see Figure 6.2). Further details on the basis of Weibull statistics for representing the strength of glass are available in Haldimann *et al.* (2008), Overend *et al.* (2012) and Datsiou *et al.* (2017).

The characteristic (bending or tensile) strength of glass is affected by flaws resulting from the manufacturing process as well as the subsequent accumulation of flaws from handling, weathering, and so forth. Typical values are shown in Table 6.2.

Additional flaws are generated during cutting of edges and drilling of holes in the glass. If the edges or holes are in an area of high tensile stress, the strength of the glass element will be governed by the strength or these edges or holes. This strength-reducing effect can be expressed by an edge or hole modification factor k_e (Table 6.3).

Figure 6.2 Probability density functions of tensile strength of annealed glass and fully toughened glass and compressive strength of concrete. (Author's own)

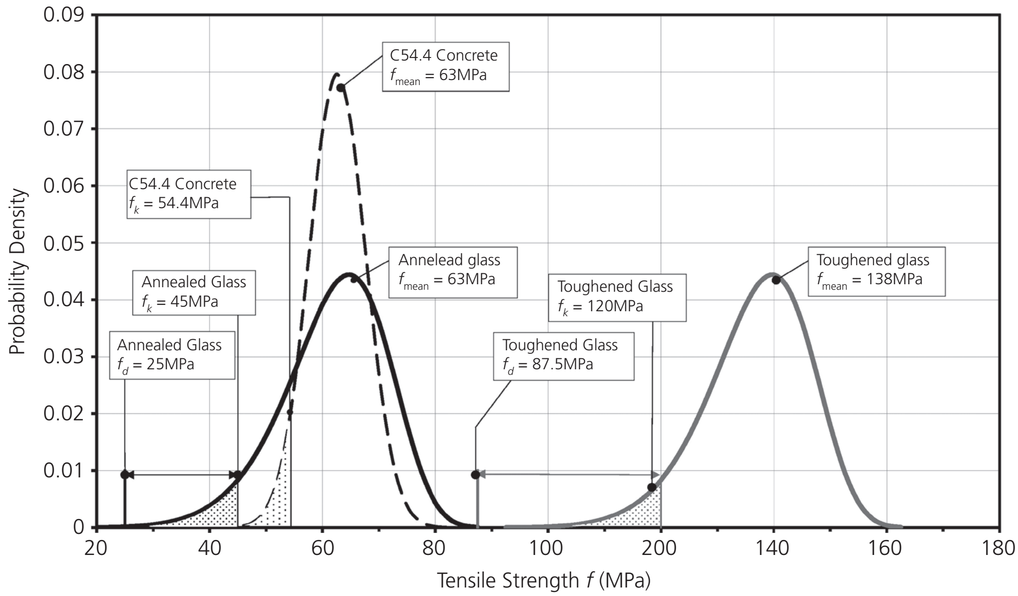


Table 6.2 Characteristic bending (tensile) strength $f_{g,k}$ for design for basic soda-lime-silicate float glass. (CEN, 2021)

Type of glass	Standard	$f_{g,k}$ N/mm²
Float glass	EN 572-2	45
Polished wired glass	EN 572-3	33
Drawn sheet glass	EN 572-4	45
Patterned glass	EN 572-5	33
Wired patterned glass	EN 572-6	27

6.2.1.2 Surface area

Surface flaws of different sizes are generally randomly distributed over the surface of the glass, therefore the probability of encountering larger surface flaws increases when large surface areas are exposed to a high stress. This effect is negligible for most small-scale applications of glass, but it should be taken into account, by the following area modification factor (k_A), when large surface areas of glass are in a state of high tensile stress:

$$k_A = \frac{f_g}{f_{ref}} = \left(\frac{A_{ref}}{A_f}\right)^{1/\beta} \tag{6.1}$$

where f_{ref} is the tensile strength for a reference surface area A_{ref} and m is a surface strength parameter that describes the variability of the surface flaws. $b \approx 7$ for normal conditions, but it can range from 25 for glass with a very uniform degree of damage to 3 for very random damage. The reference surface area A_{ref} is the surface area of glass tested in the process of obtaining f_g; for instance, the $f_{g,k}$ values shown in Table 6.2 were obtained by co-axial double ring tests specified in EN ISO 1288-5 (ISO, 2016), wherein the test surface area $A_{ref} = 314\text{cm}^2$, therefore with $b = 7$, $k_A = 2.27 A_f^{-1/\beta}$ where A is expressed in cm^2.

Table 6.3 Edge finishing factor k_e near edges and holes under tension. (CEN, 2021)

	Edge finishing factor k_e[a]		
	As-cut, arrissed or ground edges[b]	Seamed edges[c]	Polished edges
Float glass	0.8	0.9	1.0
Patterned glass	0.8	0.8	0.8
Polished wired glass	0.8	0.8	0.8
Wired patterned glass	0.8	0.8	0.8

[a]Values to be used for verifications within a distance *d* measured from the edge of the pane or of the hole towards the interior of the glass surface. The value of the distance d is d = h+c, where:
- h is the thickness of the glass ply and
- c is the distance of the cutting edge of the chamfer with the glass surface to the edge of the glass or of the hole.
[b]Arrissed or ground edges by machine or by hand where the abrasive action is across the edge.
[c]Arrissed or ground edges by machine or by hand where the abrasive action is along the length of the edge.

6.2.1.3 Surface stress history and environmental conditions

When glass is subjected to net tensile stress without causing instantaneous fracture, cracks and flaws may still grow slowly over time, eventually reaching a critical value when failure occurs. This is known as stress-corrosion and, as a result, the tensile strength decreases with stress duration. This strength-reducing effect can be accounted for by means of a load duration factor (k_{mod}). For constant loads, the relationship between the time to failure t_f and tensile strength f_g is given by:

$$k_{mod} = \frac{f_g}{f_{ref}} = \left(\frac{t_{ref}}{t_f}\right)^{1/n} \tag{6.2}$$

where f_{ref} is the tensile strength at the reference time t_{ref} (generally taken as 3s) and n is the static fatigue constant ≈ 16 for normal conditions, but can be as high as 30 for glass immersed in water. The variation of k_{mod} or relative strength with time, for a constant stress history is shown in Figure 6.3 and specific k_{mod} values can be obtained from Table 6.4. Alternatively, load duration effects may be grouped into long-, medium- and short-term load durations (Table 6.5), which makes it easier to apply in engineering design. This grouping is represented by the dashed line in Figure 6.3.

Annealed glass fails at relatively low stresses and typically fractures into large, sharp shards (Figure 6.4); it is therefore generally used for relatively low-stress glass elements, where the risk and consequence of failure is low.

Table 6.4 Load duration factor k_{mod}. (CEN, 2021)

Type	Load duration	Action	k_{mod}
Permanent	Permanent	Self-weight, difference in altitude, permanent cold bending	0.29
	Intermediate	Snow (3 to 4 weeks)[c]	0.43
		Imposed vertical action (1 week)	0.45
		Temperature change and change in the meteorological barometric pressure (8 h)[d]	0.58
Variable	Short	Maintenance load (30 min)	0.69
		Wind (10 min)[a]	0.74
		Barrier personnel loads – crowds (5 min)	0.77
		Barrier personnel loads – normal duty (30 s)[b]	0.89
	Very short	Wind (3 s)	1.00
	Dynamic	Impact (100 ms)	1.20

[a]The value of $k_{mod} = 0.74$ is based on a cumulative equivalent duration of 10 min, considered representative of the effect of a storm which may last several hours. Higher values of k_{mod} can be considered for wind.
[b]The value of $k_{mod} = 0.89$ is based on a personnel load of 30 s duration. Other values can be considered depending on the type of personnel load being evaluated and also the building use.
[c]$k_{mod} = 0.43$ can be considered representative for snow loads lasting between 5 days ($k_{mod} = 0.49$) and 3 months ($k_{mod} = 0.41$). Other values of k_{mod} can be appropriate depending on local climate.
[d]$k_{mod} = 0.58$ can be considered representative for climatic loads lasting between 6 h ($k_{mod} = 0.59$) and 12 h ($k_{mod} = 0.57$). Other values of k_{mod} can be appropriate depending on local climate.

Table 6.5 Load duration factors. (Adapted from CEN, 2021)

Design combination	Stress duration	Stress duration factor. k_{mod}
Long-term combination, F_{dL} e.g. self-weight	$t_f > 6$ weeks	0.29
Medium-term combination, F_{dM} e.g. sustained imposed loads, seasonal temperature, snow and self-weight	6 weeks $\geq t_f >$ 10 minutes	0.43
Short-term combination, F_{dS} e.g. wind, access loads, sustained imposed loads, wind, temperature, snow and self-weight	$t_f \leq$ 10 minutes	0.74

Figure 6.3 Relative strength vs. Log_{10} stress duration. (Adapted from Overend *et al.*, 2007)

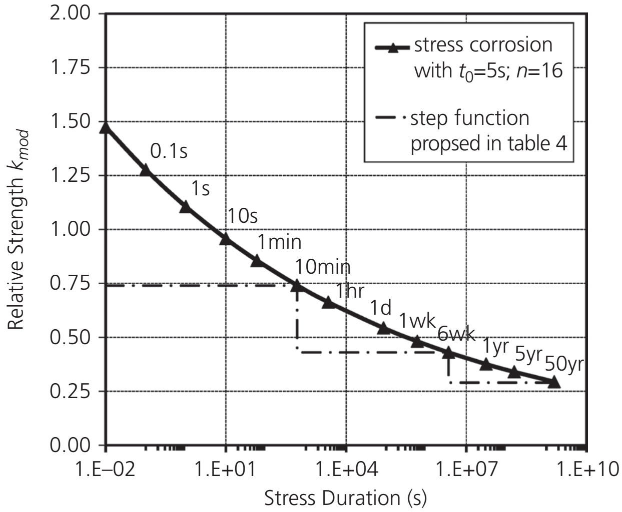
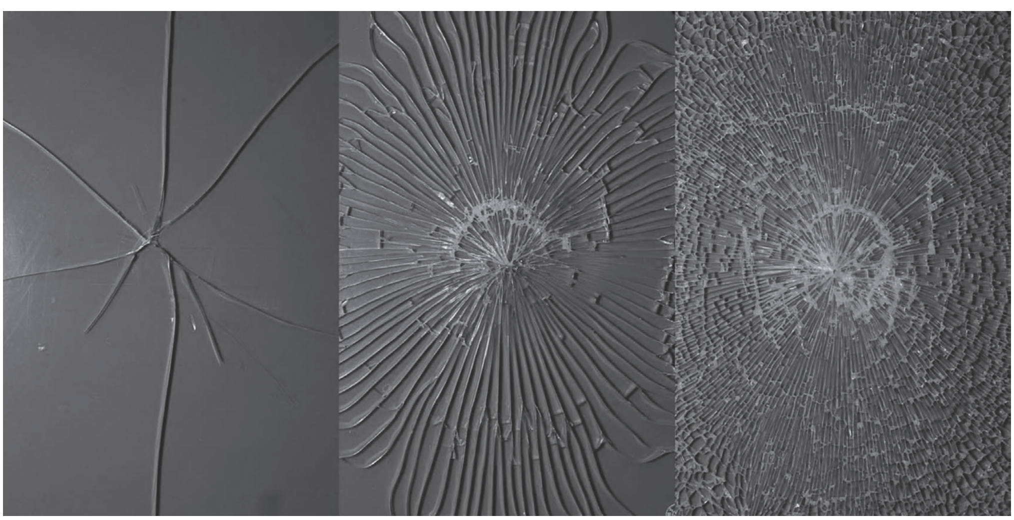


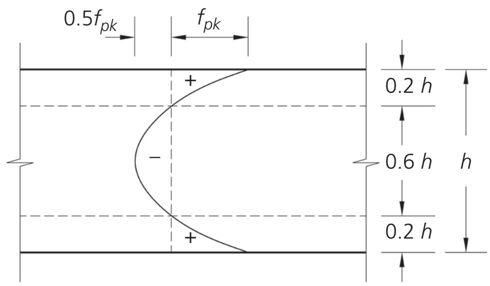
Figure 6.4 Typical fracture patterns for annealed glass (left), heat-strengthened glass (middle) and fully toughened (aka tempered) glass (right). (Courtesy of International Association of Bridge & Structural Engineering)



6.2.1.4 Thermal or chemical prestressing

Heat-treated glass overcomes some of the limitations of annealed glass. In fact, glass can be either thermally (heat) or chemically treated, but the latter is not commonly used in the construction industry. In the thermal treatment process (sometimes called thermal toughening), annealed glass is heated to 625°C and then the surfaces are cooled rapidly. As the inner core of the glass cools and contracts it puts the outer surface into compression. This results in a parabolic residual stress

Figure 6.5 Residual stresses profile in thermally toughened glass. (Adapted from verend, *et al.*, 2007)



distribution through the thickness h of the glass, where the glass surface is in compression f_{pk} (Figure 6.5). The toughening of glass is analogous to the prestressing of concrete.

The magnitude of surface pre-compression, f_{pk}, is affected by the rate of cooling – that is, the quality and type of heat treatment process ($k_p = 1.0$ for horizontal heat-treatment process; $k_p = 0.6$ for vertical heat-treatment process) and the presence of free edges and/or holes ($k_{ep} = 0.75$ for edges; $k_{ep} = 0.6$ for holes). Note only ground and polished edges should be used – that is, as-cut edges should be avoided.

Two distinct classes of thermally treated glass are available: heat-strengthened glass and the stronger fully toughened glass (also known as tempered glass). The difference is largely due to the rate of cooling applied in the heat-treatment process. In fully toughened glass the surface pre-compression is approximately ≈ 90MPa. Whereas for heat strengthened glass the far-field pre-compression is between 24MPa and 52MPa. The characteristic bending strength of typical prestressed glass products is shown in Table 6.6; the strength values represent the thermally or chemically induced prestress in addition to the inherent strength of the annealed glass.

In heat-treated glass, surface cracks may only propagate after the surface pre-compression has been overcome. This effectively shifts the probability density function by f_{pk}, as shown in Figure 6.2.

Furthermore, when compared with annealed glass, heat-treated glass has a superior resistance to impact. Furthermore, fully toughened glass breaks into small dice (≈ 1cm^2), whereas heat strengthened glass breaks into larger shards, similar to annealed glass (Figure 6.4). The fracture pattern of chemically strengthened glass is similar to that of annealed glass.

6.2.1.5 Design strength of monolithic glass

The design strength of heat-treated (thermally toughened or heat-strengthened) glass is therefore calculated by accounting for the above-mentioned factors as follows:

$$f_{gd} = k_e k_A k_{mod} \frac{f_{gk}}{\gamma_m} + k_p k_{ep} \frac{f_{pk} - f_{gk}}{\gamma_p} \tag{6.3}$$

where γ_m and γ_p are the partial factor for basic annealed glass and the prestressing process, respectively (Table 6.7).

Table 6.6 Characteristic bending (tensile) strength $f_{p,k}$ for design of prestressed glass products

Glass material per product (whichever composition)	Values for characteristic bending strength $f_{p,k}$ for prestressed glass processed from:		
	thermally toughened safety glass to EN 12150-1, and heat-soaked thermally toughened safety glass to EN 14179-1 (CEN, 2016)	heat-strengthened glass to EN 1863-1 (CEN, 2011)	chemically strengthened glass to EN 12337-1 (CEN, 2000a)
float glass or drawn sheet glass	120 N/mm^2	70 N/mm^2	150 N/mm^2
patterned glass	90 N/mm^2	55 N/mm^2	100 N/mm^2
enamelled float or drawn sheet glass	75 N/mm^2	45 N/mm^2	
enamelled patterned glass	75 N/mm^2	45 N/mm^2	

Table 6.7 Partial factor γ_m and γ_p for glass

Design situations		
Persistent & Transient (fundamental combination)	Basic material γ_M	1.8
	Surface prestress γ_P	1.2
Accidental	Basic material γ_M	1.1
	Surface prestress γ_P	1.0

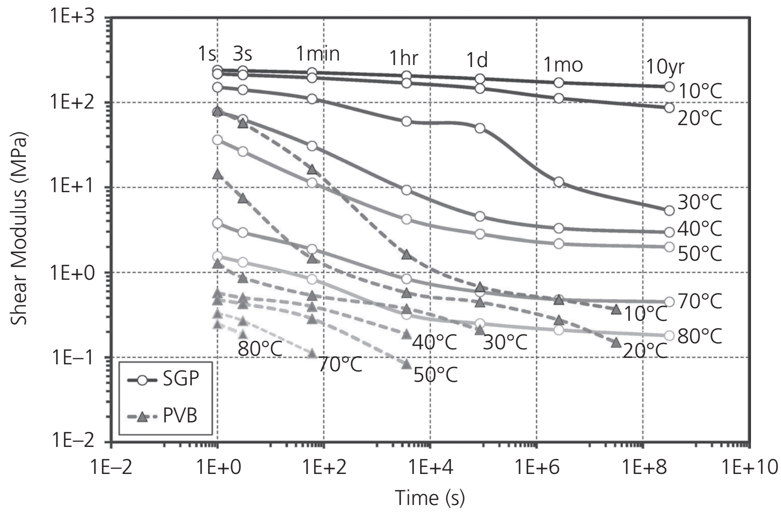
6.2.1.6 Laminated glass

Laminated glass consists of two or more glass plates bonded together by a transparent polymer interlayer, normally polyvinyl butyral (PVB). The nominal thickness of a single PVB foil is 0.38 mm and it is normally applied in two layers (0.76 mm) or four layers (1.52 mm). Laminating the glass has no observable effect on the crack propagation, but has a significant influence on the post-fracture performance

PVB is a visco-elastic material and is susceptible to creep. The stiffness of the interlayer and the flexural behaviour of laminated glass are therefore influenced by the magnitude and duration of loading and temperature (Figure 6.6). At room temperature, PVB is comparatively soft with an elongation at breakage of more than 200%. At temperatures below 0°C and for short load durations, PVB is sufficiently stiff ($G \approx$ 1GPa) and transfers longitudinal shear from one pane of glass to another. At higher temperatures and long load durations, the shear transfer is greatly reduced. It is common practice to assume some degree of shear transfer ($\approx$ 20%) for short-term loading of PVB and to ignore shear transfer for medium- and long-term loading.

Alternative stiffer and stronger interlayers such as SentryGlas (SGP) provide enhanced post-fracture performance: SGP is 30 to 100 times stiffer than PVB and has the ability to absorb 500%

Figure 6.6 Shear Modulus (*G*) of PVB and SentryGlas interlayers as a function of time and temperature. (Source: Author's own)



the tear energy of PVB. However, the higher stiffness at high strain rates of SGP compared with PVB means that a larger proportion of the incident shock loads will be transmitted to the supporting structure. Therefore, PVB is normally the better choice for blast loading, whereas SentryGlas is better for smalls impacts.

In structural design it is often convenient to express the actual build-up of laminated glass as an equivalent monolithic glass thickness.

The equivalent thickness for calculating the bending deflection is given by:

$$h_{eq,\delta} = \sqrt[3]{\left(1-\varpi\right)\sum\nolimits_i h_i^3 + \varpi\left(\sum\nolimits_i h_i\right)^3} \qquad (6.4)$$

and the equivalent thickness for calculating the bending stress in the i^{th} ply is given by:

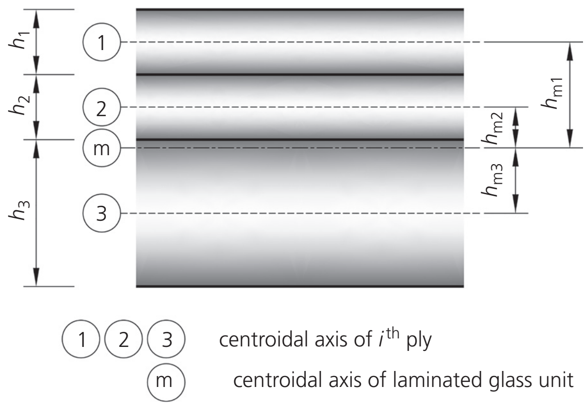
$$h_{eq,\sigma} = \sqrt{\frac{\left(h_{eq,\delta}\right)^3}{\left(h_i + 2\varpi h_{m,\mathrm{i}}\right)}} \qquad (6.5)$$

where $0 \leq \varpi \leq 1$ represents no shear transfer (0) and full shear transfer (1); h_i is the thickness of the i^{th} glass plies; $h_{m,i}$ is the distance between the mid-plane of ply *i* and the mid-plane of the laminated glass unit, ignoring the thickness of the interlayers (Figure 6.7).

6.2.2 Float glass products

There are various processes and treatments that can be applied during the float process (on-line) or subsequently (off-line). These include, coating (on-line or off-line), heat treating, laminating, bending, surface working and assembling into insulated glazing units (IGUs). Multiple treatments

Figure 6.7 Dimensions for equivalent thickness calculations of laminated glass. (EN 16612:2019; CEN, 2019)



and processes may be applied to the same glass panel, for example basic float glass may be clear, tinted or coated, which in turn can then be heat treated and/or bent. It can subsequently be printed, laminated and double glazed. This gives rise to a very large number of possible product permutations which increase in number as new processes become available. There are, however, some permutations that are not possible, namely:

- Deeply patterned or deeply worked glass cannot be heat treated.
- Fully toughened glass cannot be subsequently surface worked or cut.

Glass panel sizes are governed by the size of the equipment used in their production. This tends to change regularly as manufacturers and glass processors invest in larger plant.

Float glass forms the basis for all other glass products discussed in this chapter. It is produced in thicknesses of 3, 4, 5, 6, 8, 10, 12, 15, 19 and 25 mm. These thicknesses can be processed into other glass products as shown in Table 6.8, with the exception of toughened and heat-strengthened glass that must be $\geq$ 4 mm thick. Table 6.8 provides a summary of indicative panel sizes, but manufacturers and processors should be consulted for up-to-date information.

In addition, when compared with annealed glass, heat-treated glass has a superior resistance to impact. Furthermore, fully toughened glass breaks into small dice ($\approx 1cm^2$) whereas heat-strengthened glass breaks into larger shards, similar to annealed glass.

The size of the toughening oven will limit the dimensions of toughened glass panels. 4.2 m $\times$ 2.4 m are readily available, but larger 'over-size' panels are available at a cost. Also, heat-treated glass panels will deflect more than annealed glass since they will be thinner for supporting a similar load. Drilling of holes and cutting must be completed before heat treating.

Float glass can normally be cut within $\pm$2 mm and $\pm$ 4 mm of the specified length or squareness. The surface of a glass pane is not perfectly flat and it normally contains some imperfections that

Table 6.8 Glass panel sizes

Glass product	Maximum panel size (mm)	Comments
Monolithic annealed float glass	6000 × 3210	• Glass width (3210 mm) governed by width of float bath. Lengths above. 6000 mm available by special order
Monolithic toughened glass	4500 × 2150 or 7000 × 1670 or 6000 × 2700	• Size governed by toughening furnace which varies from one manufacturer to another. • Length-to-width aspect ratio is generally limited to 1:10.
PVB laminated glass	3800 × 2400 or 4000 × 2000 or 7000 × 1800	• Size limited by size of autoclave which varies from one manufacturer to another. • Super-size laminated glass measuring 2800 × 13000 mm is available from some manufacturers, but can be limited by size of monolithic glass used to built laminated unit.
Insulated glazing units	6000 × 2700	• Limited by size of monolithic glass used to build up IGU

Note: Super-size glass panels, including laminated glass and IGUs, measuring 3600 ×18 000 mm are available from a very small number of specialist manufacturers

are measured optically in annealed glass as specified in EN 572 (CEN, 2012a). In toughened glass the imperfections are limited to roller wave distortion ≤ 1 mm and overall bow ≤ 5 mm; the two can occur simultaneously and are additive.

Curved glass is produced by either heating flat glass beyond its softening point or by bending the glass at ambient temperature (cold-bending). The most popular heat-bending process is sag bending where the glass is heated to 600°C–700°C and the softened glass relaxes onto a mould. Single curvature sag-bent glass is limited to a radius of curvature of:

- 100 mm for 6 mm thick glass
- 300 mm for 10 mm thick glass
- 750 mm for 12 mm thick glass
- 1000 mm for 15 mm thick glass
- 1500 mm for 19 mm thick glass.

Double curvature bending is available from specialist glass processors.

In order to improve the heat-transfer (conductive and radiative) performance, glass is coated and/or assembled into IGUs.

Various types of thin-film coatings are applied to glass to change the reflectance, emissivity and radiation transmittance, generally without significantly affecting the visible light transmittance.

Coating is broadly classified as hard or soft, depending on whether they can resist aggressive cleaning and weathering or whether they need to be protected in-use.

IGUs incorporate two or more panes, separated by continuous spacers around the perimeter (aka edge spacers) to create a hermetically sealed cavity between the glass panes. The cavity is filled with desiccated air, argon or krypton and the edge spacer contains desiccant material to prevent moisture from accumulating and condensing on the inner surfaces of the IGU cavity.

6.2.3 Other types of glass

The overwhelming majority of glass used in buildings (and in the automotive sector) is soda-lime-silica produced through the float process. Alternative manufacturing processes and chemical compositions of glass are used for other niche products. The glass forming principles described in Section 6.2 of melting constituent materials followed by rapid cooling to prevent (or reduce) crystallisation apply to these different types of glasses, but the precise properties of density, strength, thermal shock resistance and so forth, will vary from one glass type to another. But the end result is still a brittle, generally transparent or translucent material that is theoretically very strong, but much weaker in practice due to unavoidable flaws.

Some alterative processes for manufacturing glass, including non-planar (volumetric) glass, are as follows.

- **Rolled (flat) glass** is produced through the overflow process and fed through rollers that impart a profiled surface on the glass and/or where a metal sire mesh is embedded into the glass to produce wired glass. After this, the rolled glass is taken off the rollers, annealed and cut.
- **Channel glass** is produced by casting glass into a U-Shape. It is especially useful where a relatively high bending stiffness – for example, to span large distances – is required but where optical quality (transparency) is not essential.
- **Hollow and solid cast glass blocks** are both produced by depositing molten glass into a mould where it cools in a controlled manner. The casting process allows for considerable freedom in the size, shape, colour and transparency of the glass component. Hollow blocks are produced by moulding molten glass in two individual shells, which are subsequently thermally fused along the edges to form a hollow block. The air cavity can be filled with argon to improve thermal insulation. Solid cast glass is produced in a similar manner, but the mass of the solid cast glass unit requires careful consideration because it has a significant effect on the annealing time.
- **Extruded glass** such as hollow tubes or solid rods have a constant cross section and are produced with glass recipes that crystallise or a have a relatively high softening point, such as silica glass or borosilicate glass. They are mainly used in interior architecture, art, design and lighting solutions.

Thin (flat) glass, typically below 3 mm, is produced in one of the following ways.

- The **modified float process,** which involves modifications to the raw materials in the batch while keeping similar furnace temperatures. Glass can be produced in thicknesses as low as 0.5 mm and 3.21 m wide, but the maximum size can be limited by the available equipment to handle the glass.

- The **down-draw process**, where the glass is drawn vertically from the bottom of a tank of molten glass, which produces glass in widths of up to 0.5 m and thicknesses ranging from 1.1 mm to 0.03 mm.
- The **overflow fusion down-draw process**, where the glass flows over the top edges of a reservoir, forming two thin streams along the outer surfaces before converging and fusing into a single sheet at the bottom. This process currently produces glass sizes of up to 3 m wide and thicknesses from 0.5 mm to 0.05 mm.

6.3. Use of glass in buildings

6.3.1 Structural versus non-structural

The term ‘structural glass’ is ambiguous. It implies that glass is either structural or non-structural. In fact, all glass components bear some loads (e.g. glazing in small windows must resist wind loads and support self-weight). It is therefore more useful to classify glass components in terms of the significance of their structural role and the corresponding consequence of failure, as follows.

- **Primary structure:** glass elements that contribute to the loadbearing capacity of the main structure. Failure of the glass member would compromise the stability of the structure and/or of other elements in the structure. Failure of a primary structural element has a consequence for loss of human life/injury or very significant economic, social or environmental consequences (Consequence Class 3). Glass members in this category include columns, floor elements and shear walls and other large glass elements used in high-occupancy buildings.
- **Secondary structure**: glass elements that either contribute to the loadbearing capacity of the infill panels, building services or finishes. Failure of the glass element has a considerable consequence for human injury and/or economic, social or environmental consequences (Consequence Class 2). Glass elements in this category include glass fins, frameless balustrades, top-hung frameless glazing systems, and medium-sized glass elements used in normal-occupancy buildings.
- **Infill panels:** glass elements whose failure would not affect any other elements of the structure and where there is a low consequence of failure on injury and the economic, social or environmental consequences are negligible (Consequence Class 1). Members in this category are normally relatively small glazing panels that are supported by a frame at two or more edges or glass components used in buildings where people do not normally enter.

6.3.2 Types of glass structure

Over the last 50 years, the use of glass has evolved from small flat infill panels in windows to large complex assemblies (Figure 6.8) where the glass elements fulfil a significant structural function. Glass elements may therefore be classified in terms of their structural action.

- **Struts or ties** (including loadbearing walls): where the glass element is predominantly in uniaxial tension or compression (Figure 6.9).
- **Beams** (including facade fins): where the members transmit the applied loads in bending about their cross-sectional axes and shear parallel and perpendicular to their cross section (Figure 6.10).
- **Plates**: which transmit the applied loads in biaxial bending and twisting moments and shear forces (Figure 6.11).
- **Shells**: which transmit the applied loads as membrane stresses acting on a tangential plane at a given point to the surface (Figure 6.12).

Figure 6.8 Loadbearing glass staircase, Apple store, Fifth Avenue, New York. (Image courtesy of Bohlin Cywinski Jackson & Apple Inc.)

Figure 6.9 Glass struts and ties in (a) ZipTruss, Delft, courtesy of Ate Snijder and (b) glass loadbearing walls in Steve Jobs Theatre, Cupertino, USA. (Courtesy of Foster & Partners and Apple Inc.)

(a) (b)

6.3.3 Connections

There are several ways of connecting glass elements to each other or to components made of other materials. These joints are necessary for providing support/transferring loads as well as for other non-structural purposes – for example, water and airtightness, acoustic isolation, and so forth. This section deals with loadbearing connections.

As shown in Table 6.9, loadbearing connections (including those that merely support the self-weight of the glass component) can be classified by their geometry (linear or point) and by their load transfer (mechanical or adhesive).

Figure 6.10 Glass beams in (a) roof over the Victoria and Albert Museum, London. (Courtesy of Octatube BV), and (b) glass fin facade. (Author's own)

(a) (b)

Figure 6.11 Glass plates in (a) glass floor in the New Acropolis Museum, Athens, Greece, and (b) unitised curtain wall facade. (Author's own)

(a) (b)

Figure 6.12 Glass shell structure in (a) Bombay Sapphire Distillery glasshouses, Hampshire, UK (Courtesy of Bellapart), and (b) Qaammat glass pavilion, Greenland (Courtesy of Julien Lanoo)

(a) (b)

Table 6.9 Loadbearing connection typologies

		Support geometry	
		Linear	Point
Interface Type	Mechanical	• external cap glazing (Figure 6.13(a)) • toggle glazing (Figure 6.13(b))	• clamped patch plate with / without hole (Figure 6.14) • bolted semi-rigid (Figure 6.15(a), Figure 6.15(b)) • bolted articulated (Figure 6.15(c))
	Adhesive	• structural silcone glazing (Figure 6.13(c))	• embedded laminated with thin / thick insert (Figure 6.16(a), Figure 6.16(b)) • surface bonded (Figure 6.16(c))

In linear connections, also known as framed systems, glass is often used as an infill panel (e.g. in a glazed curtain wall facade) and is supported on a framework of rectilinear elements known as profiles and generally made of timber, aluminium alloy or steel. There are two main variations: mechanically fixed framing (Figure 6.13(a), 6.13(b)) and structural silicone glazing (Figure 6.13(c)). In the former, also known as ‘dry glazing’, the panels are held in position between the profile and an external capping (aka pressure plate) (Figure 6.13(a)) or by a shear key known as a toggle (Figure 6.13(b)), wherein polymer gaskets are used to avoid direct contact between the glass and the frame. Whereas, the structural silicone glazing, also knowns as ‘wet glazing’, has no capping strip and the glass is bonded to the profiles by means of an elastomeric silicone adhesive.

Frameless glazing (aka point connections) consists of one of the following.

- Clamped connections known as **patch plate connections** (Figure 6.14), where the glass is clamped by small rectangular stainless steel or aluminium plates close to the edges of the glass. The clamping force is generated by bolts with oversize holes in the glass or by placing the bolt in the gap between adjacent glass panels, thereby preventing direct bearing of the bolt on the glass.
- **Bolted connections** where the in-plane and lateral forces to the glass are transmitted as transverse shear and direct forces to the bolt respectively. The bolts are generally made of stainless steel and rely on bushings, made of aluminium, stiff polymers or injected two-component mortars, between the bolt and the glass, for reducing bearing stress concentrations. There are a variety of bolted connections ranging from semi-rigid bolted connections (Figures 6.15(a), 6.15(b)), where the glass is partially restrained from rotating out of plane, to fully articulated bolted connections (Figure 6.15(c)), where the glass is free to rotate with respect to the bolt. The bolts can either have a conventional or a countersunk head, as shown in Figure 6.15, and the support structure can consist of standard steel profile or special cast steel brackets also known as spider brackets.
- There is a growing interest in **localised adhesive connections** for frameless applications. These have the advantage of lower stress concentrations compared with bolted connections. A particular form of adhesive connection that has gained popularity is the embedded laminated connection (Figure 6.16), which consists of a metallic insert, typically stainless steel or titanium, that is embedded into the stiff interlayer during the lamination process and provides a means of connecting the glass by bolts to the insert.

Figure 6.13 Linear connections for glazed curtain wall systems: (a) external cap system; (b) toggle system; (c) structural silicone glazing system. (Courtesy of Menandros Ioannidis)

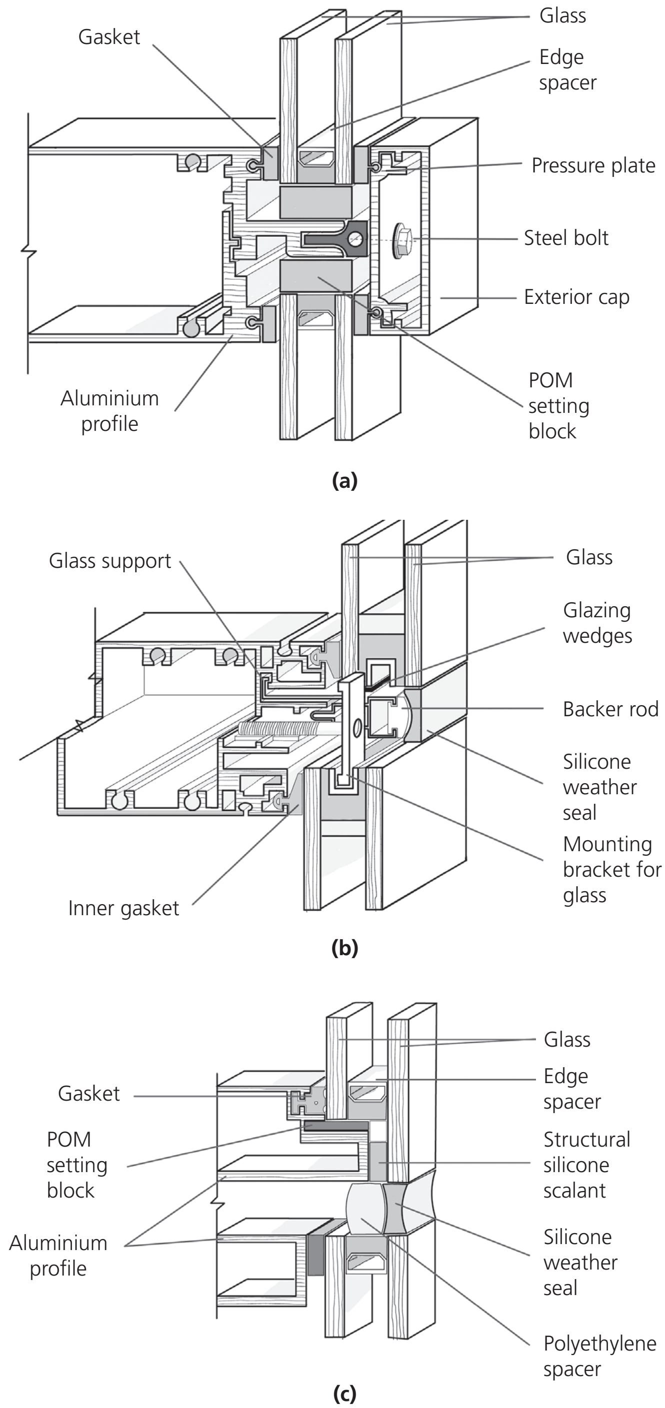
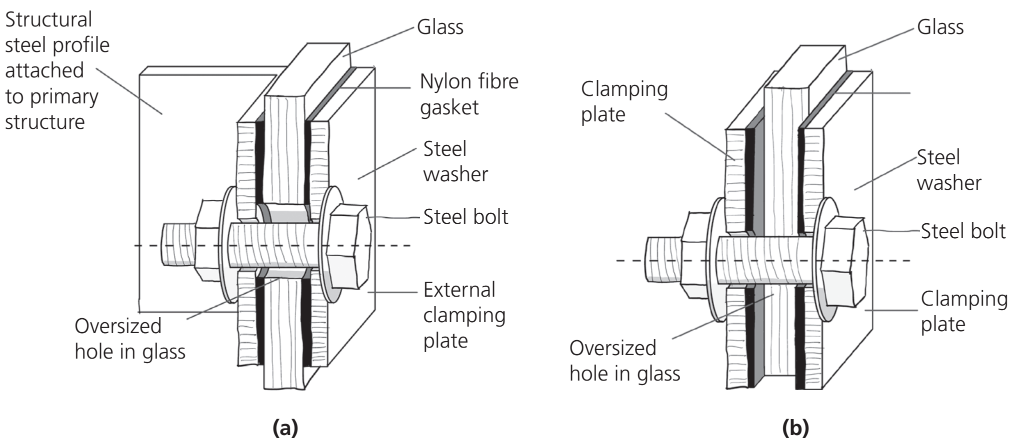


Figure 6.14 Clamped connections: (a) through-bolt; (b) without bolt hole. (Courtesy of Menandros Ioannidis)



6.4. Engineering design of glass

The mechanical performance of glass components is governed by the material properties described in Section 6.2. In general, it is important to select/design a glass component that meets an acceptable level of performance in terms of safety and stability, serviceability, durability and environmental sustainability. The acceptable safety, stability and serviceability performance levels of glass used in relatively small window glazing applications is achieved through product certification that ensures that the glass component complies with national/international product standards – for example, EN 1279 Glass in building. Insulating glass units (CEN, 2018). However, larger and more complex glass glazing applications require explicit and bespoke engineering design. The engineering design choices for these more complex glass components/structures, such as the selection of the system typology, the type of glass used, the type of connection between glass components, the size (e.g. thickness) of glass components used, and so forth, often involve the use of the following.

- Rules of thumb.
- More detailed calculations based on the limit state principles.
- Risk analysis.
- Prototype testing (also known as design assisted by testing).

Each of these is described in the sub-sections below. In addition, when designing loadbearing glass components and structures, it is important to do the following.

- Make the components simple with direct load paths.
- Consider interfaces and connections very carefully.
- Consider consequence of failure of plies and panel.
- Use appropriate lamination material.
- Consider whether the glass panel size and geometry (e.g. curved glass) are compatible with the treatments (e.g. thermal toughening, coating, etc.) applied to the glass.

Figure 6.15 Bolted connections: (a) through hole semi-rigid; (b) countersunk hole semi-rigid; (c) articulated countersunk. (Courtesy of Menandros Ioannidis)

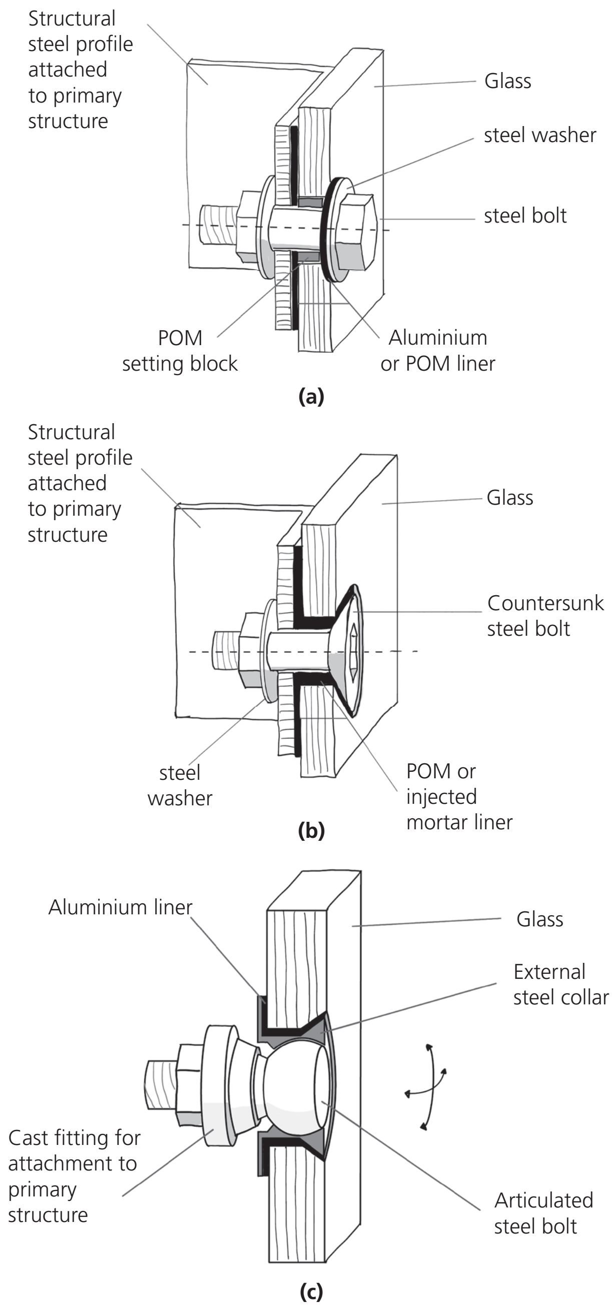
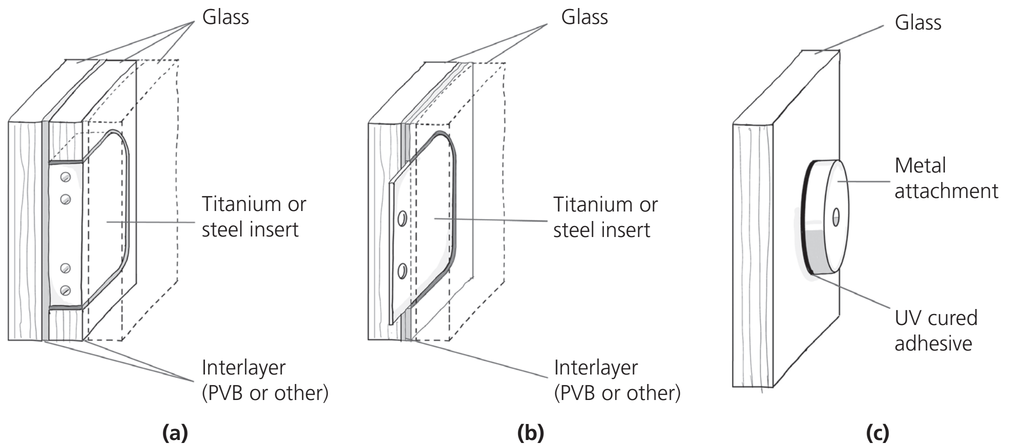


Figure 6.16 Adhesive connections: (a) embedded laminated connection with thick insert; (b) embedded laminated connection with thin insert; (c) surface bonded connection. (Courtesy of Menandros Ioannidis)



- Consider cleaning and maintenance strategies, including the replacement of a panel after construction.
- Consider possible conflicts between the structural design and other performance criteria – for example, thermal, acoustic and so forth.

6.4.1 Rules of thumb

This section provides guidelines on the use of approximate methods for the design of structural glass. These are not a replacement for more detailed calculations, but they can be very useful at early-stage design or as a quick check for the latter more detailed stages of the design process (e.g. sanity check when performing detailed numerical analysis).

6.4.1.1 Strength and other physical properties

Calculating the strength of glass and the mechanical properties of the polymer interlayers can be laborious (see Section 6.2). Tables 6.10 to 6.12 provide the salient mechanical characteristics of glass interlayers and silicones that can be used for preliminary sizing.

6.4.1.2 Initial sizing of glass components

Table 6.13 shows approximate span-to-thickness ratios useful for initial sizing of laterally loaded glass plates.

6.4.2 Stability

Glass is predominantly manufactured in thin flat sheets and is therefore susceptible to buckling instability. Buckling theory is well established and used extensively in the structural design of other materials. This is applicable to glass design, but in addition the engineer must be aware of (a) the manufacturing tolerance and initial imperfections in glass and (b) the visco-elastic and temperature-dependent behaviour of the interlayers used in laminated glass.

Table 6.10 Approximate design strength of glass for preliminary design purposes.

Stress duration and load type	Approximate design strength					
	Annealed glass		Heat-strengthened glass‡		Fully toughened glass ‡	
	Far-field (MPa)	Edge or hole (MPa)	Far-field (MPa)	Edge or hole (MPa)	Far-field (MPa)	Edge or hole (MPa)
Short term (e.g. wind action)	18	15†	39	27†	82	52†
Medium-term stress (e.g. snow load, human traffic)	11	9†	32	21†	73	46†
Long term (e.g. self-weight, superimposed dead)	7	5†	28	18†	70	43†

† With ground or arrissed glass edges

‡ Heat-strengthened and tempered glass complying with EN 12600 (CEN, 2002a) using a horizontal heat treatment process.

Table 6.11 Approximate shear modulus (*G*) of interlayers

Interlayer	3 seconds	1 hour	1 year
PVB @ 30°C	1.0	0.4	0.1
SentryGlas @ 30°C	141	60	6.8

Table 6.12 Approximate properties of two-part structural silicone adhesives (note: strength values are permissible strengths)

Short-term tensile strength	0.14 MPa
Long-term tensile strength	0.014 MPa
Short-term shear strength	0.07–0.128 MPa
Long-term shear strength	0.007–0.011 MPa
Short-term Young's modulus	1.0–1.25 MPa
Long-term Young's modulus	0.9 MPa
Poisson's ratio	0.49

6.4.2.1 Column buckling

The load-carrying behaviour of a monolithic glass column with effective length L_e, cross-sectional area A, initial imperfection δ_0 and axial compression N applied at an eccentricity e can be derived directly from the second order differential equation.

The elastic critical (Euler) buckling load is:

$$N_{cr} = \frac{\pi^2 EI}{L_e^{\,2}} \tag{6.6}$$

Table 6.13 Typical span/thickness ratios

Glass type	Maximum span / thickness	
	Vertical	Sloping or horizontal
Annealed glass	150	100
Fully tempered glass	200	150
Laminated annealed glass	150	100
Laminated tempered glass	150	100

The maximum deflection at mid span is:

$$\delta_{\max} = \frac{e}{\cos\left(L_e / 2\sqrt{N / N_{Cr}}\right)} + \frac{\delta_0}{1 - N / N_{Cr}} \tag{6.7}$$

and the maximum surface stress is:

$$\sigma_{max} = \frac{N}{A} \pm \frac{N}{W_e}\left(\delta_{max} + \delta_0 + e\right) \tag{6.8}$$

where W_e is the elastic section modulus about which buckling will occur.

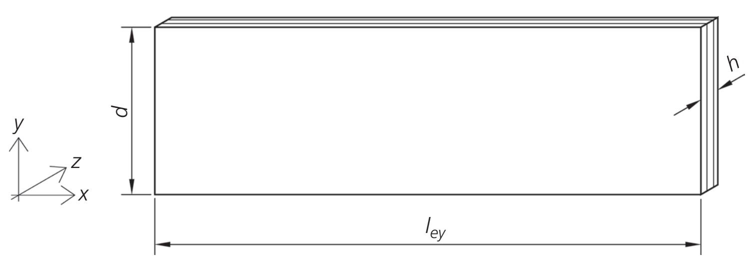
The initial imperfections in annealed glass are very small (typically $\delta_0 \leq$ L/2500), but the thermal toughening process causes roller wave distortions and an overall bow in glass, with a combined $\delta_0 \leq$ L/300.

In laminated glass columns, the interlayer provides a shear connection between the glass plates. The complex time and temperature relationship may be simplified by using elastic sandwich theory and by considering the interlayer as a perfectly elastic material with a constant shear modulus for a given temperature and stress duration. Equations for critical load, maximum deflection and maximum surface stress are available in Haldimann *et al*. (2008). For long-term loads and/or high temperature environments, it is sensible to ignore the contribution of the interlayer altogether. The initial imperfections in laminated glass are the same as those for the constituent glass plates. Further details on the performance of laminated glass under compressive loads are provided in Haldimann *et al.* (2008).

6.4.2.2 Lateral torsional and local buckling

Slender glass members such as fins subjected to bending about their major axis are particularly susceptible to lateral torsional buckling and local buckling (Figure 6.17).

Figure 6.17 Sign convention for lateral torsional buckling. (Author's own.)



For rectangular fins with a cross-section width b and depth d subjected to pure bending M_x, with torsional restraints M_z located l_{ey} apart: the critical elastic bending moment is given by:

$$M_{Cr,\,LT} = \frac{\pi h^3 d}{6 I_{ey}} \sqrt{EG\left(1 - 0.63\frac{h}{d}\right)} \tag{6.9}$$

For fins with torsional restraints M_z and rotational restraints M_y located l_{ey} apart: the critical elastic bending moment is given by:

$$M_{Cr,\,LT} = \frac{\pi h^3 d}{3 I_{ey}} \sqrt{EG\left(1 - 0.63\frac{h}{d}\right)} \tag{6.10}$$

Guidelines for fins subjected to non-uniform bending moments are provided in AS (2021).

Local buckling often governs the sizing of a glass fin; this can be determined approximately from:

$$M_{Cr} = \frac{Eh^3}{6\left(1 + v\right)} \tag{6.11}$$

Equations 6.9, 6.10 and 6.11 ignore initial imperfections and the presence of the PVB interlayer that are normally encountered in glass fins. They should therefore be regarded as approximate and used for preliminary design purposes only. Guidelines for calculating the lateral torsional buckling of glass components, including different boundary conditions and loading configurations, are available in O'Regan (2014) and AS (2021).

6.4.2.3 Connections

The loadbearing capacity of glass members is often governed by the stress concentrations at the connections, particularly when point connections, such as the frameless glazing connections shown in Figure 6.15 and Figure 6.16.

BOLTED CONNECTIONS

If there is a sufficient end distance c, edge distance (d-H)/2 and an adequate intermediate liner is placed between the steel bolt and the glass to reduce hard contact, the strength of bolted connection is governed by the tensile stresses generated by the elongation of the hole. This peak stress occurs at the rim of the hole approximately perpendicular to the direction of the force (Overend *et al.*, 2013).

The peak tensile stress around a bolt hole is often determined by modelling the connection as a contact problem (involving gap elements or similar) and performing nonlinear finite element analysis. Approximate values of the stress concentration K_t around a bolt hole can also be estimated from stress concentration charts (Pilkey and Pilkey, 2008) or from empirical formulae. For a loading configuration, shown in Figure 6.18, the empirical formulae given by Duerr (2006) is:

$$K_t = 1.5 + 1.25\left(\frac{H}{d} - 1\right) - 0.0675\left(\frac{H}{d} - 1\right)^2 \tag{6.12}$$

Where the stress concentration factor K_t is defined as:

$$K_t = \frac{\sigma_{\max}\left(H - d\right)t}{P} \tag{6.13}$$

Figure 6.18 Pin and lug notation. (Overend *et al.*, 2013.)

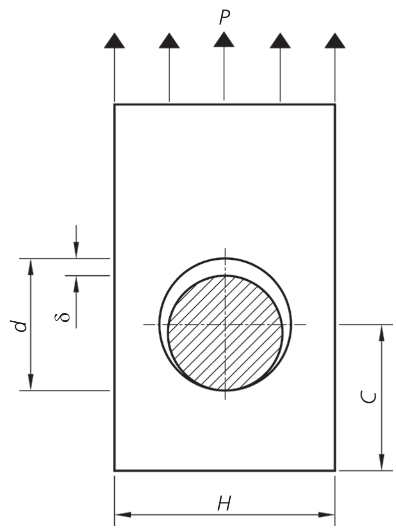
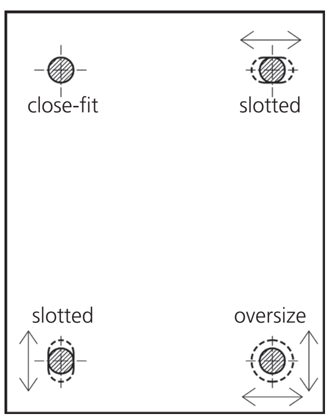


Figure 6.19 Provision for movement in point supported glazing panel. (Haldimann *et al.*, 2008.)



These approximate approaches are only valid for preliminary design of very simple cases and a finite element analysis of the bolted connection is generally required.

Allowance must be made for thermal movements and the articulation of glass structures. This is particularly important in point supported glass, where thermal expansion can lead to very high stress concentrations. A typical solution to accommodate this movement is shown in Figure 6.19.

ADHESIVE CONNECTIONS

Adhesive connections provide the opportunity to distribute the loads onto a large surface area of the glass, thereby reducing stress concentrations. In addition, unlike bolted connections, adhesive connections do not require flaw-inducing surface preparation such as hole drilling, and therefore do not adversely affect the strength of the glass in the vicinity of the connection. Structural silicone, the adhesive used in structural silicone glazing (Figure 6.13) is an elastomeric adhesive that has been used for more than 30 years in the facade industry. Its use is regulated by standardised tests (EOTA, 1998). Typical design properties for structural silicone adhesives are shown in Table 6.12.

The low stiffness and low strength of structural silicones is generally unsuitable for point connections (e.g. as shown in Figure 6.16(c)). There are a number of adhesives that have a suitably high strength and stiffness, but their long-term performance is the subject of ongoing research. A useful summary of properties is shown in Table 6.14. It is important to note that the values in this table are based on experimental tests involving short-term loads and cannot be used directly in design.

One major disadvantage of adhesive connections, however, is that the long-term performance of several adhesives (with the exception of structural silicone) is as yet unproven. They should therefore be used with caution, particularly where long-term loads or high temperatures are present. In addition, high-strength high-stiffness adhesives are a barrier to disassembly, reuse/recycling at end of life (see Section 6.5).

Table 6.14 highlights some important aspects for structural design of bonded glass connections, namely the following.

Adhesives are visco-elastic. As a result, the shear (and Young's) moduli of the adhesives consist of two components: (1) The visco-elastic component and (2) the residual component. The latter is independent of load duration, but the former decays to zero with stress duration. The apparent stiffness, and the resulting stress concentrations, will therefore be higher for short-term loads such as wind loads, impact and blast. In some adhesives, such as epoxies, the short-term shear modulus is more than 700% the long-term shear modulus.

Table 6.14 Short-term mechanical properties of adhesives. (Overend *et al.*, 2011).

	Mean shear strength[a] (MPa)	Visco-elastic Shear Modulus G_v (MPa)	Residual Shear Modulus G_r (MPa)	Mean Pull-Out Strength[c] (MPa)	Ductility	Ease of Preparation and Tooling	Strength Variability[d]
silicone	0.58	0.031	0.55	1.07	high	med.	low
polyurethane	0.97	1.50	2.09	0.98	high	low	high
epoxy	7.21	201.88	32. 10	3.57	med.	high	med.
2P-acryclic	15.30[b]	195.89	161 .00	7.47	low	high	low
UV-acryclic	9.83[b]	386.23	347.81	10.56	v. low	med.	med.

Note: Unlike Table 6.12, strengths shown here are mean strength, rather than permissible strengths.
[a]based on short-term loading and equivalent constant shear stress along the 26 mm long single-lap shear joint.
[b]goverened by glass failure.
[c]based on short-term loading and equivalent constant tensile stress across the T-peel joint.
[d]based on single-lap shear and T-peel joints.

The stronger adhesives, particularly the acrylics, are sufficiently strong and stiff that on loading, failure of the joint is governed by the failure of the tempered glass in the vicinity of the adhesive rather than failure of the adhesive.

The stronger adhesives tend to be less ductile than the weaker adhesives.

An alternative to the above-mentioned pot adhesives is to use a stiff interlayer for bonding steel-to-glass or glass-to-glass, as shown in Figure 6.16(a) and Figure 6.16(b). This interlayer is sufficiently stiff and strong to provide a discrete loadbearing connection, but the assembly process is more demanding than pot adhesives as the bonding must be performed in an autoclave.

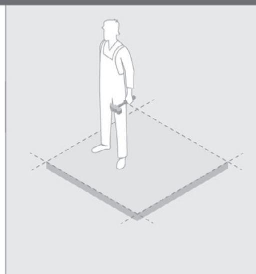
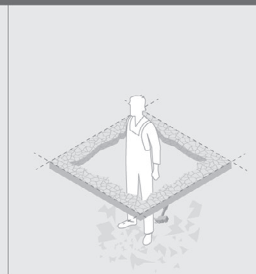
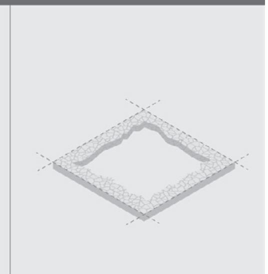
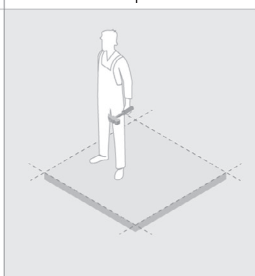
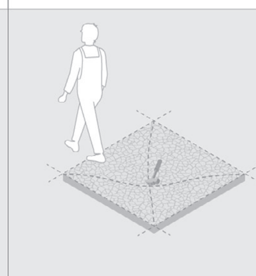
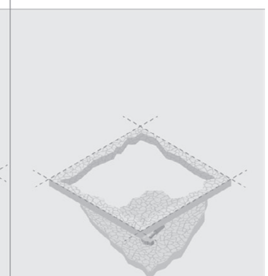
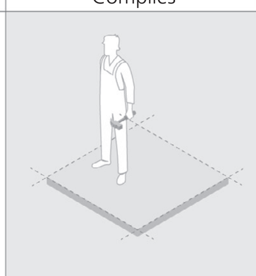
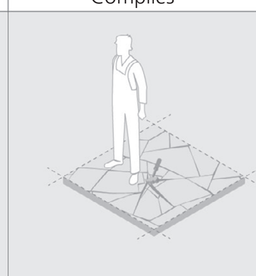
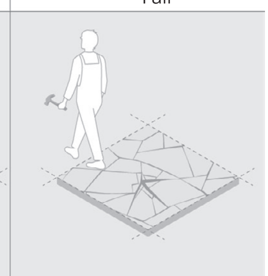
6.4.3 Limit state design and actions on glass structures

As with other materials, glass structures must be designed and constructed to minimise injury and loss of property/business. Due to its brittle nature, glass has some specific requirements for considering fracture and post-fracture scenarios during the design process, in addition to the normal ultimate and serviceability limits states. Depending on the intended end use and the consequence of failure, some glass components will need to satisfy the ultimate limit state (ULS) and the serviceability limits state in the unfractured state (SLS) requirements, while others will need to also satisfy the fracture limit state (FLS) and the post-fracture limit state (PFLS). The approach is summarised in Figure 6.20 and described below.

- **ULS** – that is, that the resistance of the glass structure or glass component exceeds the loads applied to it. This is performed in a similar manner to other construction materials by considering realistic loading scenarios (action combinations with appropriate load factors γ_f) – for example, combination of self-weight, live loads, wind loads and so forth.
- **SLS** – that is, that the deflection and movement caused by normal operating loads do not cause excessive deflection. This is performed in a similar manner to other construction materials by considering realistic loading scenarios (action combinations with load factors $\gamma_f = 1.0$) – for example, combination of live loads, wind loads and so forth.
- **FLS and PFLS for accidental actions** – where parts of the entire glass component fractures. This includes the situation during the event of fracture (e.g. do the size and shape of the glass shards constitute an unacceptable risk of human injury?) and the situation after fracture (e.g. does the fractured glass have a sufficient loadbearing capacity to allow safe operation until the glass is replaced?). This approach is very rarely needed with other construction materials, but is often crucial in glass.

In order to perform limit state design of glass components/structures, it is essential to determine the actions expected during the design life. The actions on glass structures are largely similar to those on other construction materials and must be established on a case-by-case basis from the intended use of the glass component. As described in Section 6.2, the strength of glass is sensitive to surface condition and sub-critical crack growth, therefore in addition to the magnitude of the action, it is also important to consider the action history – that is, the duration of the action and whether the surface of the glass is damaged by the action. It is not always possible to assess the mechanical response of glass components by desktop methods (e.g. analytical, numerical, etc.) alone. In such cases it is necessary to perform porotype testing. A summary of typical actions on glass components and the corresponding verification methods is shown in Table 6.15.

Figure 6.20 Summary of limit states used in design of glass components. (Courtesy of Eckersley O'Callaghan)

Loadcase consideration Time	ULS | SLS T_0	FLS $T_{+\text{ sec}}$	PFLS $T_{+\text{ hours}}$
Monolithic thermally toughened glass			
Status	Complies	Fail	Fail
Laminated thermally toughened glass			
Status	Complies	Complies	Fail
Laminated heat-strengthened glass			
Status	Complies	Complies	Complies

The design loads F_d for ULS arising from normal use may be determined by combining the relevant actions as follows:

$$F_d = \gamma_G \cdot G + \gamma_Q \cdot Q_{k,1} + \gamma_Q \sum_i \psi_{0,i} Q_{k,i} \tag{6.14}$$

where γ_G is the partial factor for permanent actions, G is the value of permanent actions (e.g. self-weight load, permanent equipment), γ_Q is the partial factor for variable actions, $Q_{k,1}$ is the characteristic value of the leading variable action (e.g. imposed load on floor, wind, snow) and $\psi_{0,i}$ is the combination factor for accompanying variable actions. Combination factors for loadbearing glass components can be obtained from EN 1991-1 and for non-loadbearing facade applications from CWCT Guidance on the actions on non-loadbearing building envelopes. For example, in the case of barrier load, and wind load, it is sufficient to consider only the largest of the two for glass in residential buildings, but for buildings where people may congregate it is necessary to consider wind load plus 0.5 occupancy load or 0.5 wind load plus occupancy load, whichever gives the most severe action.

Table 6.15 Summary of typical actions and corresponding guidelines

Action	Guidelines
Self-weight	0.25kN/m^3
Static imposed loads	Vertical static loads to national / international codes (e.g. EN 1991-1-1) (CEN, 2002a).
	Horizontal area and line loads representing static load on parapets, partitions and full-height glazed facades to prevent occupants falling from height, including in buildings susceptible to large crowds consult EN 1991-1-1 (CEN, 2002b), PD6688-1-1 (BSI, 2011a) BS 6180 (BSI, 2011b) and Building Regulations Document K (MHCLG, 2013)
Wind load	Wind pressure calculations based on national / international wind codes (e.g. EN 1991-1-4 (CEN, 2005) for simple / low-rise buildings). In facade applications it is essential to consider the net pressure (i.e. external and internal pressure) on the glazing. For complex geometries / intricate facades refer to PD6688 1-1 (BSI, 2015) or perform wind tunnel testing.
Internal pressure in IGUs	Pressure difference between the cavity of a sealed IGU and ambient air pressure (also known as Isochore pressure) arises from when there is either a difference in altitude between the place of production and the place of installation of the IGU and also when the temperature of the sealed cavity changes from the original temperature, thereby causing an expansion/ contraction of the cavity. See CEN/TS 19100 (CEN, 2021) for details.
Snow load	Snow load and snow drift from national and international codes.
Thermal stress / strain	Provide adequate movement joints for thermal movement between glass and other materials.
	The thermal stress in a glass component depends on the temperature difference between the hottest part (often the central part, which receives solar radiation) and the coolest part (often near the edges and close to the frame). Coloured glass can reach a temperature of 90°C when exposed to solar radiation. The edge strength can be checked from Section 6.2. See CWCT TN 65 (CWCT, 2020) for details.
Human impact (including maintenance)	Barriers and partitions: soft body impact test on vertical barriers and partition performed with 50kg impactor to EN 12600 (CEN, 2020a) to meet recommended application-specific classification to national codes.
	Roofs for maintenance access or public access: Sequence of: soft body impact, hard body impact and a static load test to assess post-fracture performance. See CWCT TN66 (CWCT, 2010a) and TN 67 (CWCT, 2010b) for further details.
Wind-borne debris	Generally required in hurricane / typhoon-prone regions. Timber missile impact tests to ASTM E1886 (ASTM, 2019) and ASTM E1996 (ASTM, 2020).
Hail	Test described in EN 13583 (CEN, 2012b) if required.
Intrusion	Hard body impact test and swinging axe test to EN 356 (CEN, 2000b).
Blast	Preliminary sizing using pressure-impulse charts generally verified by arena blast tests EN 13541 (CEN, 2012c) or GSA 2003 (GSA, 2003).
Movement of sub-structure	Provide adequate movement joints.

The strength of annealed glass is very sensitive to stress history. It is therefore sensible to assemble three fundamental combinations.

- The worst combination of actions F_{dS} that is expected to occur within any time period t_s during the service life of the structure, where $0 < t_S \leq 10$ minutes resulting in a major principal surface stress $\sigma_{I,\,S}$.
- The worst combination of actions F_{dM} that is expected to occur within any time period t_s during the service life of the structure, where 10 minutes $< t_M \leq 6$ weeks resulting in a major principal surface stress $\sigma_{I,\,M}$.
- The worst combination of actions F_{dL} that is expected to occur within any time period t_s during the service life of the structure, where 6 weeks $< t_L \leq 50$ years resulting in a major principal surface stress $\sigma_{I,\,L}$.

The short-, medium- and long-term principal stresses, $\sigma_{I,\,S}$, $\sigma_{I,\,M}$ and $\sigma_{I,\,L}$, resulting from these loads may then be compared with the corresponding time-resolved design strengths $f_{gd,\,S}$, $f_{gd,\,M}$ and $f_{gd,\,L}$, obtained from Equation 6.2 by means of the stress-history interaction equation:

$$\frac{\sigma_{1,\,S}}{f_{gd,\,S}} + \frac{\sigma_{1,\,M}}{f_{gd,\,M}} + \frac{\sigma_{1,\,L}}{f_{gd,\,L}} \leq 1 \tag{6.15}$$

The interaction equation accounts for the fact that the strength of glass at any point in its service life is a function of the stress corrosion (sub-critical crack growth) caused by the preceding actions.

The design loads for SLS arising from normal use may be determined from:

$$F_d = G \text{ "+" } \psi_1 \cdot Q_{k,1} \text{ "+"} \sum_i \psi_{2,i} Q_{k,i} \tag{6.16}$$

where ψ_1 is the factor for frequent value of a variable action and $\psi_{2,i}$ is the factor for quasi-permanent value of a variable action. Recommended values for the partial load factors ψ_1 and ψ_2 are obtained from EN 1991 (CEN, 2002b) or from CWCT Guidance on the actions on glass in building envelopes (CWCT, 2017).

Exceptional actions are normally considered separately by performing action-specific tests, as described in Table 6.15. In the absence of specific test recommendations, the design loads for exceptional/accidental actions may be determined from:

$$F_d = G \text{ "+" } A_d \text{ "+" } \psi_1 \cdot Q_{k,1} \text{ "+"} \sum_i \psi_{2,i} Q_{k,i} \tag{6.17}$$

where A_d is the design value of an accidental action.

In glass structures, an adequate post-fracture performance – that is, subsequent to the exceptional event – is often required. The residual post-fracture capacity may be determined by subjecting the fractured glass to a post-breakage design load of F_d - A_d in Equation 6.17.

6.4.4 Risk analysis

A risk analysis is essential when designing glass components and structures. It is not merely a form-filling exercise, but requires careful consideration of the specific components/structure and the hazard scenarios. The outcomes of the risk analysis will directly influence the key design choices or other measures that must be taken to reduce the risks.

A range of different hazard scenarios should be considered – for example, the risk of accidental impact from objects dropped during cleaning and maintenance operations, the risk of hard objects thrown in vandalism attacks, and so forth, and the risk rating of these hazard scenarios should be quantified in turn.

A method commonly used for determining the risk ratings for specific glass components/structures exposed to hazard scenarios is the Fine and Kinney method, where the risk rating is calculated from:

$$R = P * E * S \tag{6.18}$$

where R is the risk of injury or death, P is the probability that the hazard will occur, E is the exposure to or frequency of the hazard and S is the severity of the injury sustained if the hazard occurs. The indices for each of these aspects are obtained from Table 6.16.

The above can therefore be used to assemble a table listing all hazard scenarios and their corresponding risk rating. Risk ratings below 75 are deemed safe. Risk ratings greater than 75 are unacceptable and require measures for reducing the risk rating to 75 or lower. This can be achieved by introducing fail-safe measures (e.g. switching to safety glass), limiting the exposure by restricting access through barriers, and so forth.

6.5. Designing environmentally sustainable glass

Life-cycle assessment (LCA) methods are used to quantitatively evaluate the environmental performance of products and services, but their use in practical glass design is still in its infancy.

The first step is to define a functional unit as a reference, for example, 1 m^2 of glass. A system boundary that includes predefined LCA stages, as shown in Figure 6.21, can then be selected, and subsequently evaluated with reference to the functional unit. The output from the LCA can be in the form of environmental impact indicators, such as global warming potential (GWP).

Table 6.16 Risk-rating indices for probability, exposure and consequence

Probability (P)		Exposure (E)		Consequence (S)	
intentionally or unintentionally		of structural element		at complete failure	
virtually impossible	0.1	very rarely	0.5	first aid	1
practically impossible	0.2	several times a year	1	minor injury	3
possible, but very unlikely	0.5	monthly	2	serious injury	7
only possible in the longer term	1	weekly	3	one dead	15
uncommon but possible	3	daily	6	more than one dead	40
quite possible	6	constantly	10	catastrophe, many deaths	100
can be expected	10				

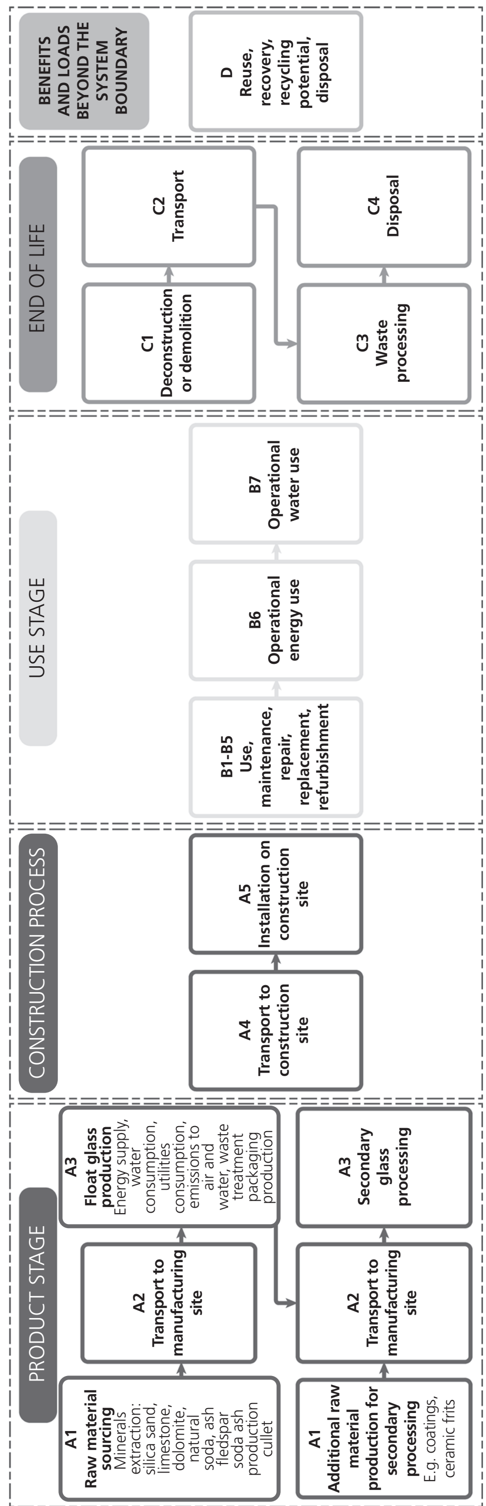


Figure 6.21 Life-cycle assessment stages for a flat glass product based on ISO 14040. (ISO, 2006)

The energy inputs and emissions associated with stages A1–A5 are often referred to as *embodied.* Stages B1–B7 relate to the energy and emissions associated with the use phase of the glass product including maintenance, repair, replacement, refurbishment and water use and operational energy. Life-cycle stages C1–C4 refer to the energy and emissions associated with deconstruction or demolition, transportation of materials from site, waste processing and disposal. Stage D is associated with the energy and/or emission savings that may be achieved by some form of recovery process when the unit is removed at the end of its initial service life.

Stage D deserves equal levels of attention at the design stage (e.g. design for disassembly/reuse/recycling strategies), to ensure that the highest-value recovery method can be achieved at the end-of-life stage. However, tools and methods for evaluating reuse and recycling (stage D) options are not yet established and are the subject of ongoing research (Beurskens *et al.*, 2016; Hartwell *et al.*, 2020).

Figure 6.22 shows the energy inputs and emissions from the energy-intensive process of melting constituent raw materials and cullet, and subsequent primary and secondary forming/processing methods. The efficiency and mix of fuels will vary from one flat line to another. Similarly, the secondary processing methods that are required for different glass products vary and the corresponding energy inputs and associated emissions used in an LCA will also differ accordingly. Typical cradle-to-gate embodied energy and carbon for common glass products are shown in Table 6.17.

Nearly none of post-consumer flat glass is currently reused or recycled to flat glass. Therefore, the recycled content often stated by manufacturers (e.g. in Table 6.17) refers to pre-consumer glass cullet. Two major barriers to closed-loop recycling of post-consumer glass are (1) the presence of contaminants (e.g. from coatings) in the post-consumer glass, which will emerge as unacceptable imperfections in the recycled flat glass, and (2) the difficulties in dissembling multi-material glass products such as laminated glass.

Some glass production processes and glass products are more tolerant to contaminants than the float process and are therefore more accepting of post-consumer glass cullet. For example, there

Figure 6.22 Flat glass processing: relevant energy inputs and associated emissions. (Hartwell, 2022)

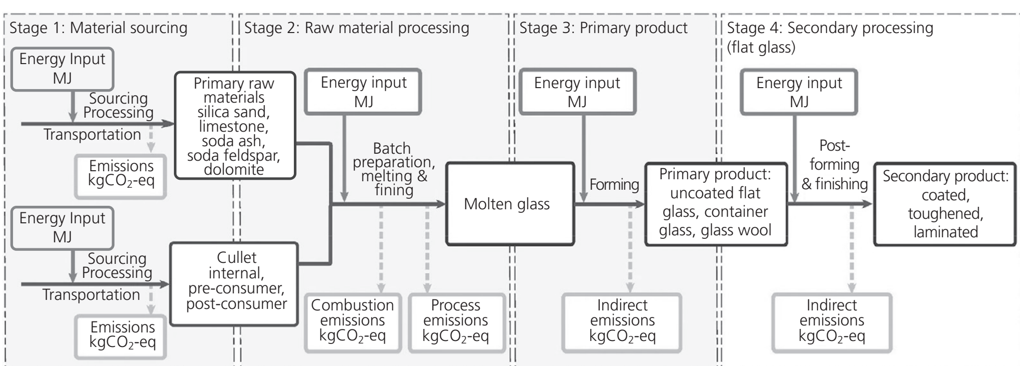


Table 6.17 Typical values of embodied energy and carbon for life-cycle stages A1–A3, raw materials to final glass product

Product (%RC = % Recycled Content)	Embodied Energy (MJ/kg)	Embodied Carbon ($kgCO_2$-eq/kg)
Float glass (23% RC)	14.32	1.09
Low-E coated glass (23% RC)	15.99	1.35
PVB laminated glass (23% RC)	22.61	1.39
Toughened glass (23% RC)	23.77	1.35
Concrete 32/40 MPa	0.88	0.13
Extruded Aluminium (0% RC)	214	12.5
Extruded Aluminium (100% RC)	34	2.12

are several sites for reprocessing end-of-life flat glass into ‘furnace-ready’ cullet for use in container glass (bottles and jars) production, glass-fibre production for insulation products or foam glass or glass abrasives. Glass casting is also very well placed for recycling the difficult-to-recycle glass into high-value glass products, but techniques for doing so are not yet well established in industry and are the subject of ongoing research (Bristogianni *et al.*, 2018, 2020).

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