Introduction on use of glass in modern buildings

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Rapport ICOM 462

INTRODUCTION ON USE OF GLASS IN MODERN BUILDINGS

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ABSTRACT

Contemporary architecture has an increasing demand for transparent building elements such as facades or roof structures, predominantly as steel and glass constructions. While materials such as steel, stainless steel or aluminium have been well studied in the past, relatively little is known about glass, its properties, connections and design in modern building applications. This article gives an overview about glazing applications from a façade and structural engineering point of view, with built examples and recent research activities.

RÉSUMÉ

L'architecture contemporaine fait appel de plus en plus à des éléments de construction transparents pour la réalisation des façades et des toitures de bâtiment, plus particulièrement à des éléments constitués de verre et de métal. Les matériaux métalliques tels que l'acier, l'acier inoxydable ou les alliages d'aluminium ont été largement étudiés par le passé, alors que le verre est encore un matériau de construction relativement mal connu quant à ses propriétés, ses moyens d'assemblage et son dimensionnement propres au domaine des bâtiments modernes. Ce rapport donne un aperçu de l'application du verre en tant qu'élément structural de façade et de toiture, des exemples de réalisation de bâtiments ainsi qu'un résumé des recherches en cours dans ce domaine.

ZUSAMMENFASSUNG

Die Architektur der Gegenwart zeigt eine zunehmende Nachfrage nach transparenten Bauelementen wie etwa Fassaden oder Dachstrukturen, die im wesentlichen Stahl- Glas- Konstruktionen sind. Während die Materialien Stahl, Edelstahl oder Aluminium in der Vergangenheit bereits gut erforscht wurden, ist über den Werkstoff Glas, seine Eigenschaften, Verbindungstechniken und Bemessung in moderner Bauanwendung noch relativ wenig bekannt. Der folgende Artikel gibt daher einen Überblick über Glasanwendungen im Fassadenbau aus Sicht des Konstruktiven Ingenieurbaus, einschließlich einiger gebauter Beispiele und gegenwärtiger Forschungsaktivitäten.

1 INTRODUCTION

Glass may be defined as an "inorganic melt product, which solidifies without crystallization". Soda-lime-silica glass is said to be a "frozen liquid". That is a visco-elastic material which is solid at room temperature, but liquid at temperatures above its transition zone (above ~580 °C). Due to the lack of a lattice structure, light may pass through the material without being blocked, which leads to the qualities of transparency and translucency of glass in buildings. At the same time, however, glass is a brittle material. A single sheet of glass once broken offers minimal redundancy, which is why load-carrying glass elements should be designed from an engineering point of view in order to avoid spontaneous failure.

Traditionally glass has only been used as single panes in conjunction with a load-carrying frame, but today glazing may be locally fixed by means of point-supports, or even used as a primary structural member, as glass fins (Figure 1), beams or columns. The use of glass in structural engineering needs further investigation of the causes and effects of its brittleness, to be able to account for the glass material characteristics in safety assessments and in structural detailing. When consequences of drastic failure are expected, additional measures have to be taken to compensate for the fact that glass gives no pre-warning of material failure. These aspects are considered in the following sections.

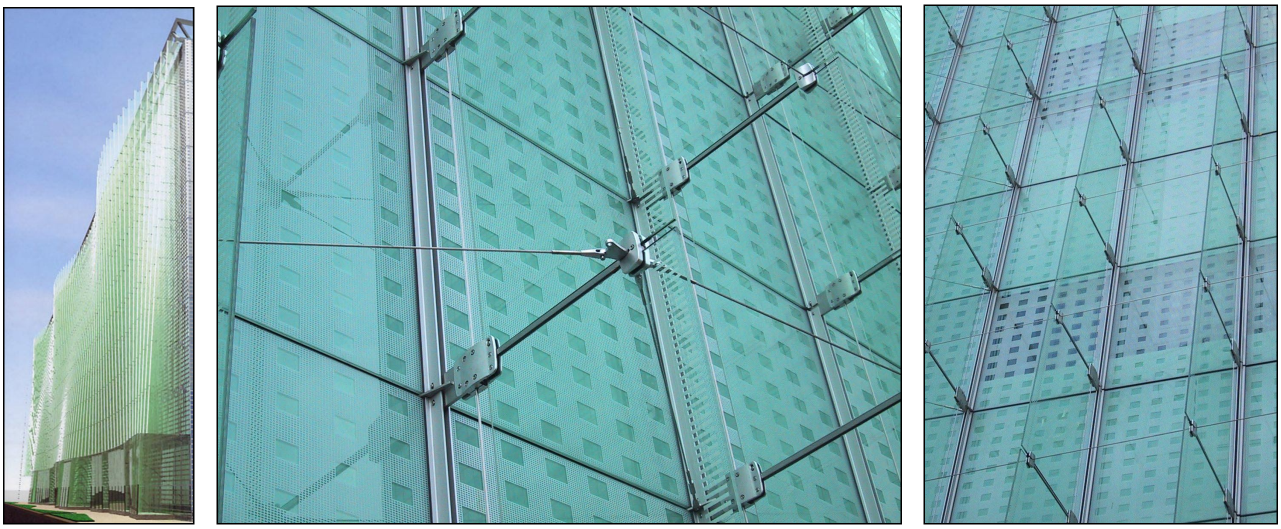


Figure 1 - *Example of an "oscillating glass façade" with point-supported and locally clamped glass fins, supported by horizontal cables [1]*

2 GLASS PRODUCTS

2.1 SHAPE

Different types of glazing are standardized in EN 572. The most common manufacturing process is the float glass process, where flat glass of thicknesses 3,4,5,6,8,10,12,15, 19 and 25mm is produced. The hot glass melt is poured onto a zinc bath, slowly cooled down and cut for further processing. The initial glass size dimension is about 6.0m x 3.2m (maximum). Different glass edge qualities are available, see Figure 2. While a cut edge might be sufficient for traditional window applications, higher quality edge treatments are required as soon as the panel edges are subject to bending or local load transfer. This is because the grinding wheel application reduces the risk of micro-or macro-cracks on the glass edge surface. Also rounded joints or beveled edges are possible for aesthetic reasons.

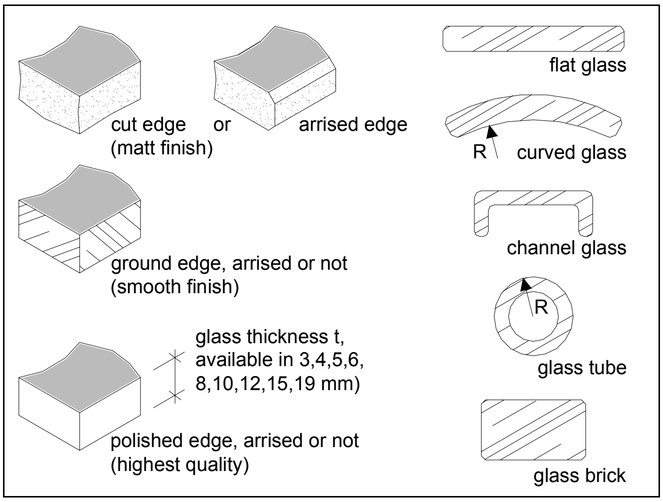


Figure 2 - *Basic edge qualities and available glass product shapes*

In order give the glass surface a special pattern, the hot glass melt may also be poured out and pressed between two rollers, which is the process for manufacturing ornamented glass (Figure 3). It is formed by a reversal of the pattern on the roller, cooled down to room temperature. Patterned glass is only available in certain thicknesses and should be checked with manufacturers data. It offers a variety of architectural appearance, but is not as clear and flat as float glass.

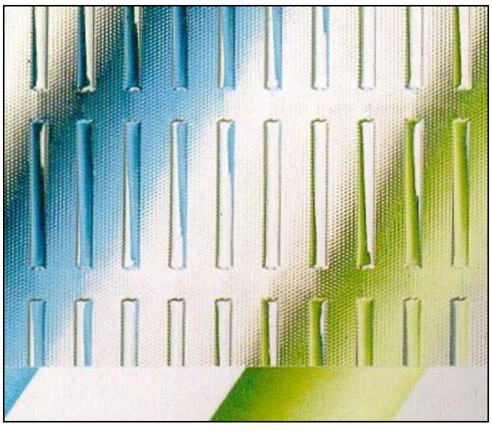


Figure 3 - *Example of patterned glass surface (ornamented glass)*

The sides of the hot glass may also be further bent by means of additional rollers on either side to form C-or U-channel sections up to approximately 6.0m length. Circular glass tubes are also available, with wall thicknesses of about t= 0.7 to 10.0 mm and diameters ~ Ø = 3 to 325 mm. Translucent glass bricks (EN 1051) may be manufactured as standard ranges or according to project needs. Curved glass might be made with the help of special ceramic moulds, where initially flat float glass is placed onto them horizontally and slowly reheated. When warm enough, the glass panel then sags into or over the shape of the mould by means of its self-weight. Possible radii vary from about R= 300 mm to ∞, but depend on the type and thickness of glass. Bends can be created in one or two planes. Various irregular curved shapes might be manufactured, depending on the shape of mould (Figure 4).

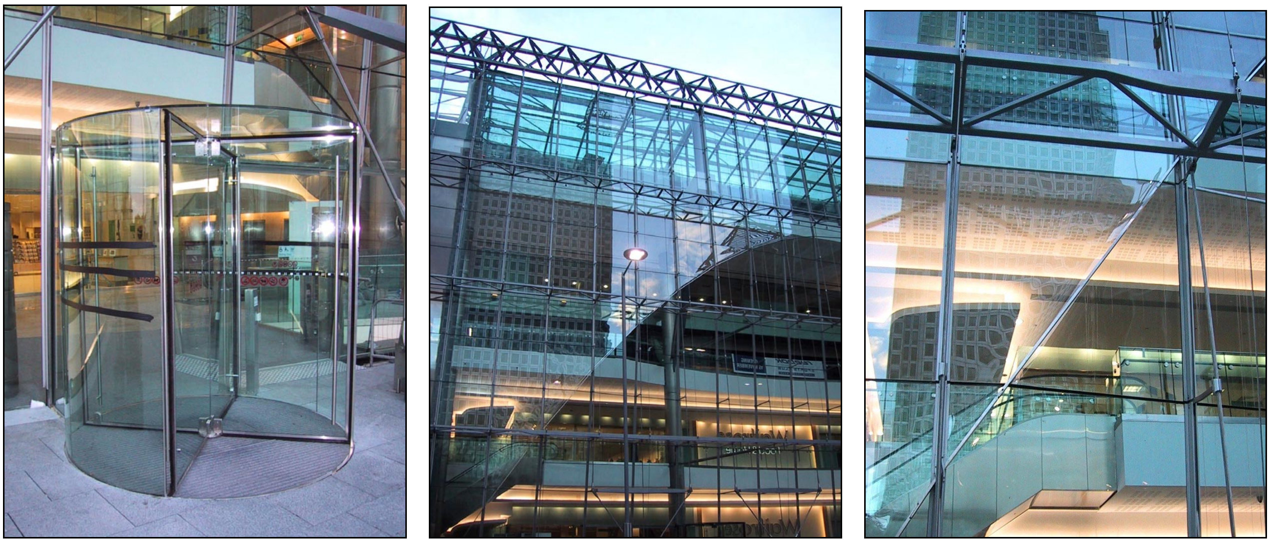


Figure 4 - *Curved glazing revolving door (left); partially bent façade glazing to form transition zone between a straight façade with a cone area (center and right) [1]*

2.2 STRENGTH-REFINED GLASS

Glass products may be divided into three different basic types with regard to their strengths and fracture patterns according to Figure 5. Annealed glass often does not give sufficient strength for modern applications. Fully toughened glass with high strength does not stay in position in the event of fracture because of its fine fragments once broken. For that reason, heat-strengthened glass was developed to give both high allowable strength values as well as a large breakage pattern in case of failure.

During the tempering process, basic annealed glass is heated up to >600°C in a furnace and then rapidly cooled, using air nozzles from both sides down to room temperature. High temperature gradients between the colder surfaces and the inside of the glazing panel temporarily occur. Together with interaction of the viscous material properties of glass, an invisible, internal 3D pre-stress is induced, where all panel surfaces are put in compression, held in equilibrium by inner tension. Tempered glass must be cut to size, edge treated and hole drilled before being subjected to toughening, because attempts to work the glass after toughening will usually cause the glass to shatter [2].

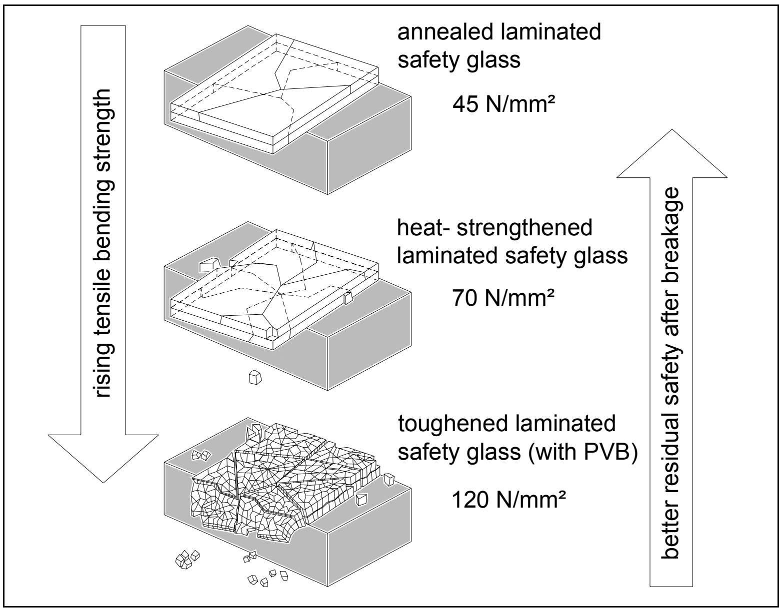


Figure 5 - *Standard glazing types with their corresponding breakage patterns (laminated with PVB) and 5%-fractile characteristic tensile bending stress values (with 95% probability level)*

2.3 LAMINATED GLASS

2.3.1 Principal

Laminated (safety) glass consists of two or more annealed or tempered or heat-strengthened glass panes which are joined by a transparent intermediate layer of plastic, in general one or more foils of Poly-Vinyl-Butyral (PVB-foil) with a basic thickness of t= 0.39 mm or cast resin in between the sheets. When the panes are destroyed the broken glass pieces stick to the foil, and large deflections and energy absorption are possible before the foil fails. The main application fields are for overhead glass, wind screens, bullet proof glass, glass beams and glass columns. Laminated glass is standardised in EN ISO 12543.

2.3.2 PVB-Interlayer

The manufacturing process involves washing, pre-positioning, pre-heating and an autoclave in which the glass panels with the PVB interlayers in between are superimposed onto each other and then laminated under incremented pressure (~12 bar) and temperature (~140°C). This process locally may lead to a certain offset of adjacent glass edges. Durability against weathering (water/UV) is generally sufficient, but exposed horizontal edges of laminated glass could be weather-sealed with PVB-compatible silicone, if required. PVB density is 1070 kg/m3, its poisson's ratio close to 0.5 and its thermal expansion coefficient might be taken to be 8 x 10^{-5} 1/K. The PVB-foil should have a minimum rupture strength ≥ 20 N/mm^2 and a PVB minimum rupture strain (elongation) ≥ 300 % to offer sufficient strength and ductility.

2.3.3 Resin interlayer

Another lamination method involves cast resin, where two glass panels are closely positioned next to each other vertically and the defined remaining gap (i.e. 2 mm) is filled with an injection of liquid cast resin, which cures with time under UV ("cast-in-place"). Therefore, very large panel sizes may be realized, as no additional autoclave etc. is required. Cast resin density is 1700 kg/m^3, its poisson's ratio about 0.45 and its thermal expansion coefficient might be taken to be 4 x 10^{-5} 1/K. Young's modulus E varies from product to product and is around 10 N/mm^2 for cast resin. Compared with PVB, resin offers better acoustic insulation, but once a laminated glass is broken, there is less residual safety available, see Figure 6. It is not recommended to be used for overhead glazing, unless 1:1 testing is performed with sufficient results.

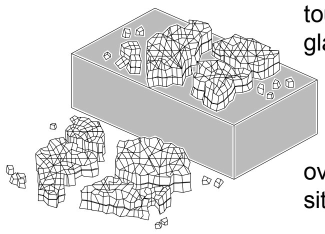


Figure 6 - *Typical insufficient breakage pattern of a laminated toughened glass with cast resin*

2.3.4 Other Laminated Products

Glass may be laminated to other materials such as stone (i.e. glass/resin/marble) or opaque insulated panels as well. New interlayers with higher strength than PVB, such as polycarbonate, have also been introduced on the market more recently to make use of a higher shear interaction of the interlayer as well as an improved post-failure behaviour of laminated safety glass. Increasingly, also photovoltaic elements are embedded within glazing elements in high-transparency resin to transform solar energy into electricity. The cells are connected to each other within the module and hence generate a direct electrical current. Mono-crystalline solar cells (colour: black, silver, blue) may convert up to 16% of solar energy into electricity, each cell with a size of about 100 x 100 mm. Multi-crystalline solar cells (colour: pale blue, grey shades, bronze silver) comprise crystals oriented in different directions, converting about 14% of solar energy.

More recent developments use thin film layer technologies, where the PV consist of very thin layers of cadmium-sulfide and cadmium telluride, which are electro-deposited on the glass (i.e. a laser-scribing procedure forming the individual solar cells). Even though energy efficiency is lower than for crystalline solar cells, production costs are less expensive, such that thin film technology might be more economical. All intercell electrical connections (metallic conductive paths) are internal to the module, which forms a monolithic structure. Between the layers and metallic conductive path there is an EVA interlayer (Ethylene Vinyl Acetate). The total thickness between the two outer glass panels is approximately 0.80 [mm], where the thin film itself only makes up 1.5 to 3.0 µm. No additional diode is necessary for “hot spots” due to possible short circuits or local overheating, because no “reverse flow” is possible within this system. At the glass panel edges, a danger of water penetration is precluded, as the thin film interlayer stops short and is covered by the EVA. The interlayer is a transparent thermoplastic, amorphous elastomer, which remains flexible at low temperatures and resists cracking. EVA density is similar to PVB, its poisson’s ratio 0.4 to 0.5, its Young’s modulus around 60 N/mm^2 and its thermal expansion coefficient might be taken to be 9 x 10^{-5} 1/K. The EVA-foil offers a minimum rupture strength ≥ 10 N/mm^2 and an EVA minimum rupture strain (elongation) ≥ 500 % for sufficient strength and ductility.

2.3.5 Overhead glazing

Overhead glazing may be defined as all glass that people pass below, including glass canopies, glass roofs and glass facades under which people can pass. In some countries it is defined as all glazing inclined ≥ 10° to the vertical. For safety reasons, the glazing shall be laminated, consisting of either two or more annealed or preferably of two or more heat-strengthened panels or a combination of heat-strengthened and fully toughened glass panels. This is to assure that in the case of glass breakage no dangerous glass fragments can fall down, because they are bonded to the PVB or other interlayer for a sufficiently long time. As the broken glass behaviour depends on its size, type, thickness and support conditions of the glazing, a full size test has to be carried out for the most critical cases. The test is passed, if a broken panel with all individual panels broken may remain in position for at least 24h (to be agreed with local authority in detail). This is to assure sufficient time to close the area underneath the broken glass so it can be replaced safely. In practice, this information is gained by 1:1-testing (Figure 7).

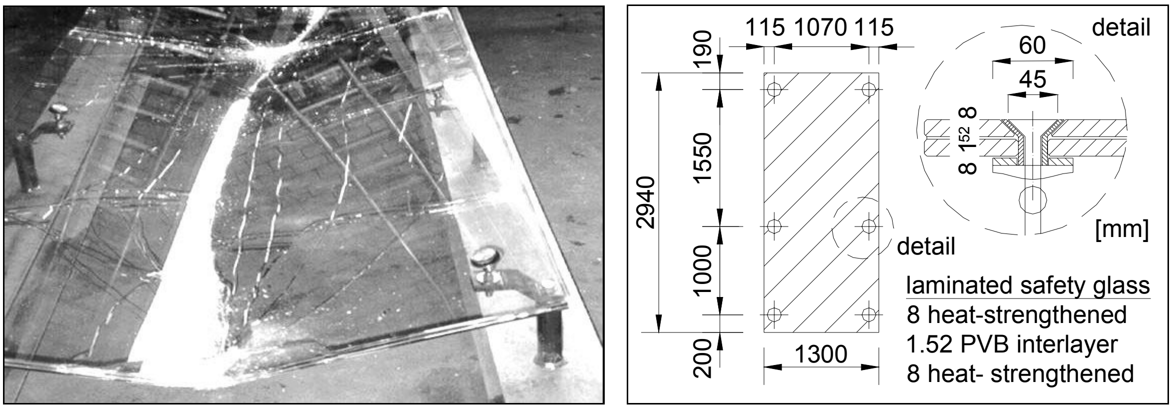


***Figure** 7 - Example of an overhead-glazing test to determine residual safety after breakage (destruction of both panes under additional loading UDL = 0.5 kN/m^2, removed here) [2]*

2.4 DOUBLE GLAZED UNITS

Double glazed units (EN 1279) consist of two or more glass panels enclosing a cavity space of about 12 to 16mm width (filled with air or rare gas), created by an aluminium spacer along the glass edges, such that insulation properties compared to single glazing are considerably increased. In order to eliminate the thermal bridge effect of the standard spacer, new spacers made of less thermally conductive materials i.e. low thermal conductivity plastics or fibre-glass reinforced materials have been recently developed. To prevent the cavity from condensation, a hygroscopic dehydrating medium is placed within the spacer (desiccant). Normally the primary seal along the spacers is achieved by means of a thin butyral layer, which is further weather-sealed and protected on the outside (secondary seal). If the outside air pressure differs from the initially induced inner cavity pressure, an additional load case is induced [3].

2.5 FIRE RESISTANT GLAZING

Special modern glazing products allow for a fire protection of up to 120 minutes. The transparent glazing is protective by becoming opaque when subjected to heat above ~120°C. This is achieved with the help of special transparent gels or intumescent (swelling) interlayers carrying chemically bound water, i.e. such as alkali-silicates, which are transparent at room temperatures, but foaming above a certain temperature, such that heat waves are blocked and spread of fire is avoided (Figure 8). It might be distinguished between fire protective systems that shall only stop smoke and flames from spreading through the glazing or additionally also block heat radiation through the glass, where no flames on the side opposite the fire are allowed to develop; the surface facing away from the fire shall stay below 140K (area-averaged increase above room temperature) and locally not heat up more than 180K (local maximum); these temperature levels are intended to ensure that any combustible material in contact with the unexposed face will not ignite.

The glazing might break, but shall stay in position after breakage without falling down. 1:1 testing of a fire-protective glazing with its particular framing system as one unit has to be performed and certificated by independent testing authorities. Glasses with low thermal expansion coefficients such as borosilicate glass experience lower tensile stresses caused by temperature gradients within the panel and hence might withstand smoke and flames up to 30 minutes without additional interlayers.

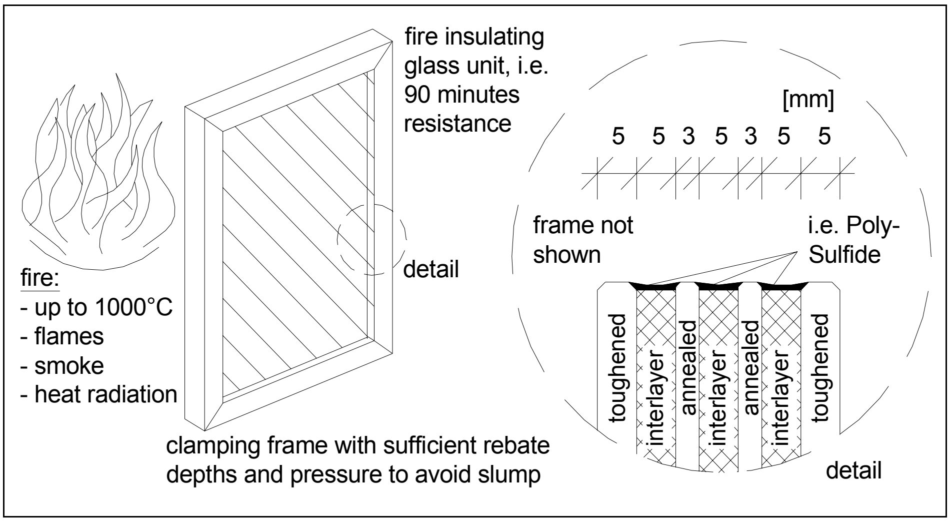


***Figure 8 -** Build-up of a fire protective glazing, resistant against heat radiation, spread of flames and smoke for at least 90 minutes*

2.6 GLASS APPEARANCE/COATINGS

2.6.1 Low iron glass

Within the glass melt for normal annealed glass, the presence of a small amount of iron oxide (~0.05 to 0.1% FeO and Fe_2O_3) causes a slightly greenish appearance, because its complementary color magenta is blocked to some extend. To achieve a very clear, almost "white" glass, a special glass melt with hardly any iron oxide is used to produce low-iron glass, which is more expensive than regular float glass, but increasingly popular due to aesthetic reasons, namely its colorless appearance and good light transmittance, see Figure 9. It might be further manufactured in the same way as regular float glass.

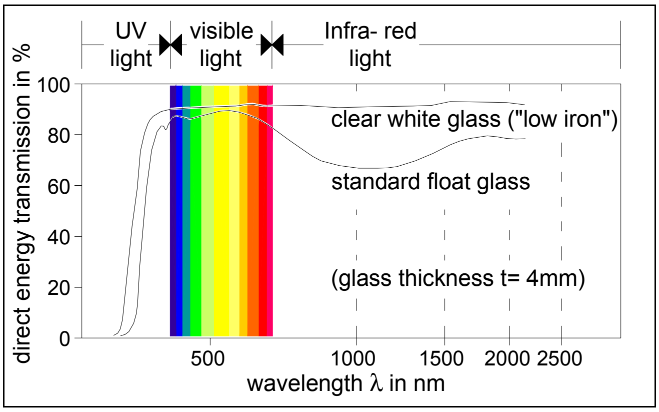


***Figure 9 -** Wave lengths transmission of regular float glass and low-iron glass in comparison*

2.6.2 Coating techniques

Different coating types might be distinguished in architectural glazing as follows [4][5]:

hard coatings

The coating materials are fired into the glass surface while it is under very high temperatures. For this reason the so-called on-line coating process is integrated in the float process or in the annealing lehr. The applied coating materials are metallic oxides that fuse by pyrolysis into the glass surface at 600-650°C. The advantage is their hardness so that the coated surface can be glazed also to exterior sides of the glass unit. On-line coatings show good economics in fabrication, but have the disadvantage of having to be integrated in the float process and therefore they are not as flexible as off-line coatings. Only a maximum number of two layers can be applied at once. Dip coating is another method to apply hard coatings on glass surfaces. In this process the glass is dipped into the coating solution and then heated up to 650 °C to create a hard transparent oxide coating.

soft coating

There are different application methods such as dip coating, chemical or physical vapour deposition to apply soft coatings onto glass surfaces. Currently, the DC-magnetron sputtering process is the most common technique. In this process the glass is placed in a vacuum chamber that contains the cathode target and a sputter gas. A negative charge is applied to the cathode, and a glowing plasma ignites in the vacuum chamber. The target is now bombarded by ions of the sputter gas which rip off atoms from it and deposit them on the glass surface. The coating is carried out in several vacuum chambers with a certain number of different cathodes targets. It is possible to apply up to 15 different target materials to be sputtered onto the glazing and therefore to vary the coating composition as well. Typical coating materials for a low-e coating are tin oxide and silver. The total coating thickness is only about 0.01 to 0.1 µm. The magnetron sputtering is a very precise, flexible and modern technique that enables very constant coating quality. It makes it even possible to reproduce exactly the same coating with the same technical properties after many years and the color adjustment is very simple.

The disadvantage of soft coatings is their susceptibility to aggressive air pollution and mechanical damage. This makes it necessary to protect the soft coating with a protective layer or assemble them into double glazing units, with the coating on face 2 (for optimum solar control performance) or face 3 (heat insulation, low-e). The magnetron sputtering coating of curved glass is not yet fully developed. In this case the glass units have to be made of laminated glass with a special plastic interlayer to monitor the transmission and reflection. Very recently, a high rate reactive mid frequency magnetron sputtering is used for glass coatings more often. Advantages of the so-called MF-magnetron sputtering are harder coatings, higher sputtering rates (up to 3-9 more compared to DC-sputtering) and lower costs.

2.6.3 Aesthetic coatings

Most commonly, colored aesthetic glazing patterns are produced using an enameled frit technique, where a ceramic color is sprayed onto the glass surface through a screen (with embossing the negative pattern) and then burned into the glazing surface during toughening. It is possible to further laminate surfaces with ceramic frit pattern with PVB or resin, but its tensile bending strength is somewhat reduced by about 25%.

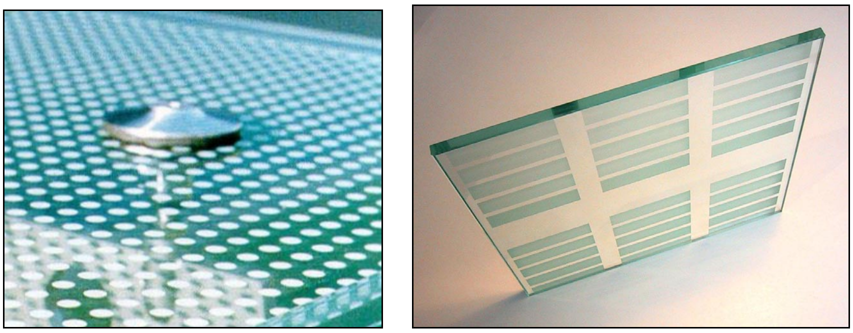


Figure 10 - *Enameled finish, white ceramic frit on face 2, laminated safety glass (left); surface treatment with a partially acid etching pattern, t= 10 mm (right)*

A rough surface might be generated using a sandblasting technique, where the glazing surface is roughened and hence an engraved, translucent pattern is created. An abrasive is blasted under pressure onto the surface of the glass. With acid etching (either with liquid acid baths or acid pastes/screens) very durable patterns with warranties up to 10 years can be produced (Figure 10), where the surface durability is only affected by dirt which can be cleaned, but not by means of any chemical reactions as for ceramic frit, when used on face 1 in direct contact to weathering. Acid etching relies on the fact that glass is subject to attack by some acids (i.e. hydrofluoric acid), such that a consistent translucent obscuring surface of different depths may be created.

2.6.4 Solar control coatings

Solar sky radiation that reaches the earth consists of 3% short-wave ultra-violet rays (UV), 42% visible light (wavelengths from ~380 nm to 780 nm) and 55% long-wave infra-red radiation (IR). As the energy is particularly high for infra-red light above the visible wavelengths, the strategy for solar protective glazing is to block as much light in that range as possible, but without reducing visible light transmission too much, see Figure 11. Solar coatings reflect and absorb a large amount of energy, such that the total energy transmission of the glazing is significantly reduced. When solar glazing alone is not sufficient, alternative shading strategies such as external moveable blinds may have to be considered additionally.

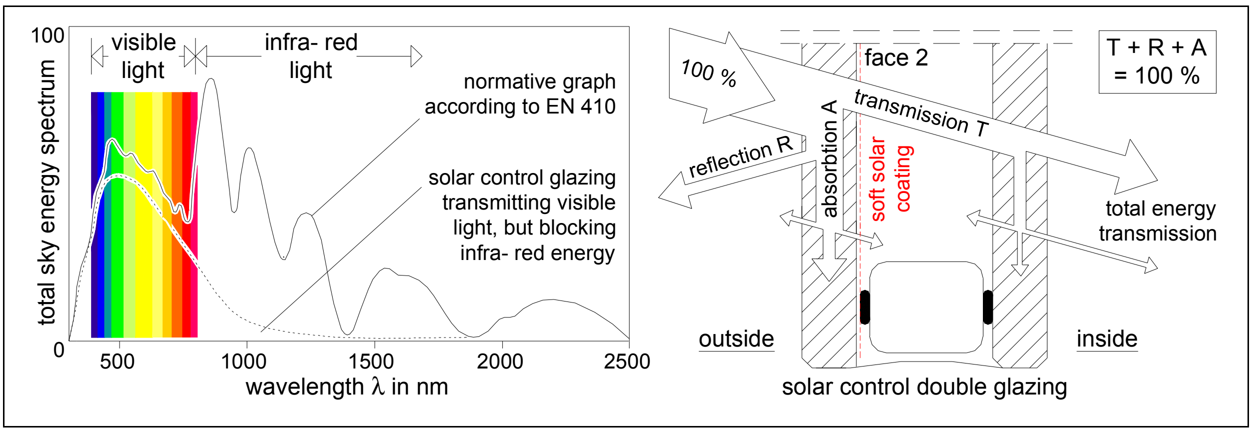


Figure 11 - *Principle function of a solar control coated glazing panel*

2.6.5 Heat insulating coatings

Heat insulating coatings have the objective to reduce the high emission coefficient of glass for thermal radiation from $\varepsilon = 0.89$ down to ~0.05. These coatings are therefore called low-e coatings and can either be a hard or a soft coating. They are predominantly transparent over the visible wavelength, but reflective in the long-wave infra-red range. It is possible to reduce the infra-red radiation down to 20 % with a light transmittance greater than 0.70. In temperate climates where a high thermal insulation with simultaneous solar control is required, it is possible to combine the functions of heat insulating coatings with solar control coatings within one single coating. For a regular double glazed unit with no further coatings, about 1/3 of heat exchange is due to conduction and convection, while 2/3 is due to heat radiation. With a low-e coating on face 3 the radiation heat loss is significantly reduced (Figure 12).

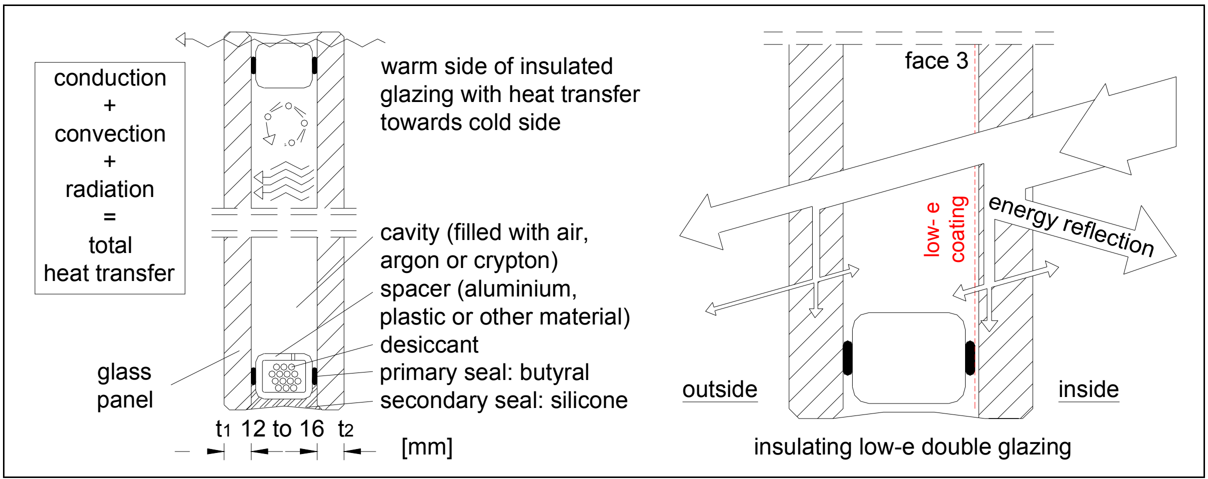


Figure 12 - *Principle build-up and heat transfer mechanisms of a double glazed insulating unit with low-e coating*

2.7 AVAILABLE PANEL SIZES

For orientation, Table 1 shows some useful values with regard to available glass panel sizes, depending on type and refinement.

Table 1 - *Available glass panel sizes (check with manufacturer's data in more detail)*

Glass product/refinement	panel size [mm] x [mm]	Comment
Single basic annealed float glass	6000 x 3210	Restricted by float plant (maximum band width)
Single basic patterned glass	4500 x 2040	Thicknesses 4 to 10 mm
Basic insulated glass	6000 x 2700	
Toughened glass	6000 x 2700 or 7000 x 1670 or 4500 x 2150	Restricted by temper furnace
Laminated safety glass (PVB)	7000 x 1800 or 4000 x 2000 or 3800 x 2400	Restricted by autoclave size
Laminated glass (resin)	6000 x 3210	Limited by injection facility

3 MATERIAL PROPERTIES

3.1 PHYSICAL CHARACTERISTIC VALUES

Some relevant physical values of glass panels are given in Table 2.

Table 2 - *Design-relevant physical data for glass panels used in buildings*

Glass property	Value	Unit
Density σ	2500	kg/m^3
Young's modulus of elasticity E	70000	N/mm^2
Poisson's ratio (transverse contraction) μ	0.23	-
Thermal expansion coefficient β	9×10^{-6}	1/K
Thermal conductivity λ	1.0	W/(mK)
Emissivity ε	0.89	-

3.2 GLASS STRENGTH

3.2.1 General

Glass is very strong under compression (up to 500 N/mm^2), but rather weak in tension. Traditionally, the concept of "allowable stresses" has been used, where a defined characteristic bending strength value is defined for each type of glazing, which is then divided by a global safety factor. The bending strength might be determined by a four-point-bending test or a coaxial double ring test (EN 1288), where short term bending stresses are determined and then statistically evaluated (i.e. 5% fractile values for 95% probability level).

3.2.2 Annealed glass

Due to the brittle material behavior of glass, strength of annealed glass is not a constant, but influenced by its micro- and macro-cracks at the surfaces and hence fracture mechanics is applicable. Under bending, the glass resistance (tensile strength) depends on various factors: the area under tension and its surface condition, load duration and distribution of stresses, the stress rate and environmental conditions.

3.2.3 Fully toughened glass

Toughened glass (EN 12150) has a higher breakage resistance than annealed glass, but once broken it bursts into small pieces. Such a spontaneous failure may also occur due to small nickel sulfide inclusions (NiS), which expand their volume within the glass even up to about 2 years after production. A so-called destructive heat-soak test (i.e. according to DIN 18516, part 4) should therefore be performed before delivery to determine those inclusions within the toughened glass.

Fully toughened glass panels exhibit high values of bending strength, composed of the frozen-in compressive surface stress in addition to the tensile strength of the annealed float glass, that is effective after decompression by loading. As the compressive surface stress is not influenced by surface defects, the tensile strength of a single pane safety glass may be approximately considered to be independent of the surface condition, the size of the surface, the distribution of stresses, the stress-rate and the environmental conditions, if the tensile strength of the annealed glass is neglected. Toughened glass might withstand local temperature differences of up to 150K, i.e. due to local heat. As the pre-stress is not equally distributed over the surface of a toughened glass panel, the safety verifications should be performed according to a zonation [6] that takes the design situation for pre-stress into account (Figure 13).

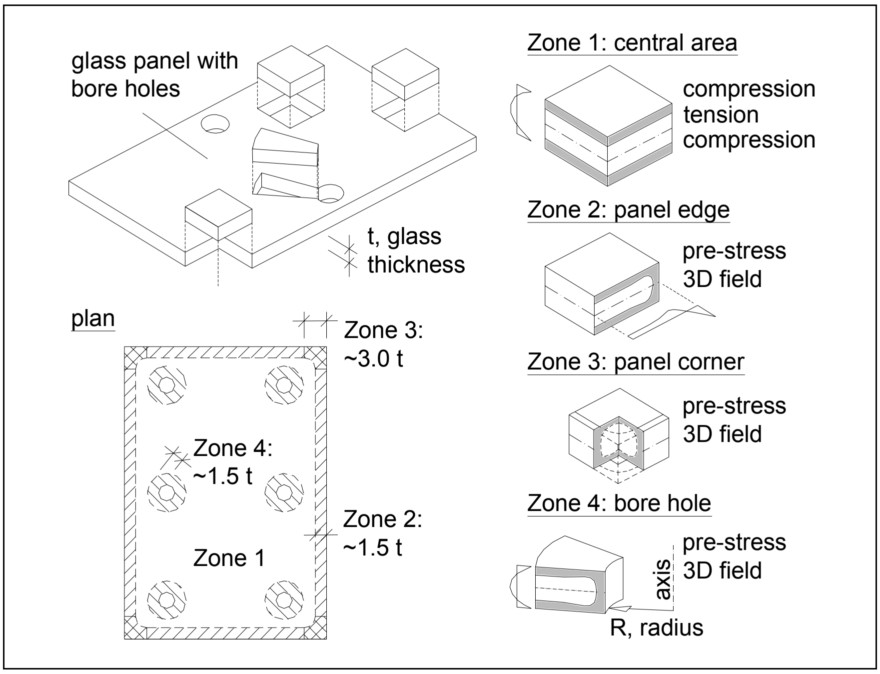


***Figure 13** - Zonation of a toughened glass panel with regard to different pre-stress distributions, compressive areas marked*

Edges or the areas around holes should be treated differently from the central area of a glass panel. As an example, the principal pre-stress distribution for a bore hole with a cone is given in Figure 14. The reliability of pre-stress can be checked by quality control measures that include optical measurements. It might be distinguished between out of plane or in-plane loading [7].

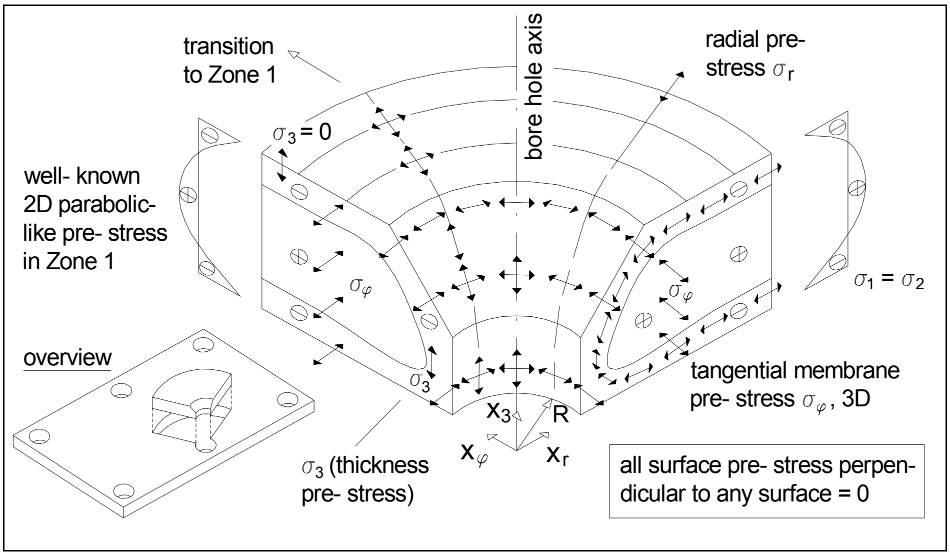


***Figure 14** - Principle of thermal pre-stress distribution near a bore hole with a cone (Zone 4)*

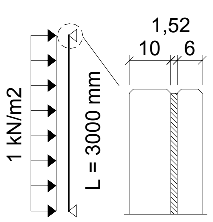
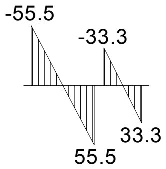
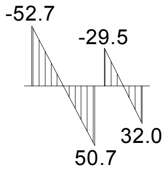
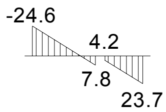
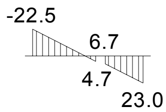
3.2.4 Heat-strengthened glass

In many cases there are reasons to reduce the surface pre-stress level in the toughening process to about -55 to -35 MPa for heat-strengthened glass (EN 1863) instead of -140 to -90 MPa for fully toughened glass (zone 1). The fragmentation is similar to that of annealed glass; that keeps the panes in position after cracking when they are framed or laminated and hence the residual safety is sufficient. Heat-strengthened glass is manufactured in a similar way than fully toughened glass, but no spontaneous failures do to NiS-inclusions have been observed in the past, such that no heat-soak test is necessary. Heat-strengthened glass might withstand local temperature differences of up to 100K, compared to annealed float glass of up to 40K. The safety assessment for heat-strengthened glass is performed in the same way as for tempered glass taking lower pre-stress values into account. Particular quality control is necessary to avoid a too high or too small level of compressive pre-stress, i. e. non-destructive optical measurements.

3.2.6 Laminated safety glass

In general, at least for long-term actions, the composite action by the foil is not taken into account in design. Therefore, for a laminated safety glass, e.g. with a total thickness of 20.78 mm, that is composed of two single glass panes, only the sum of the strength and stiffness of the single 10 mm panes may be considered in order to allow for creep effects at elevated temperatures and for longer load duration. However, recent tests with laminated safety glass have given evidence that for short-term loading, such as from wind gust or impact the composite action is significant. Depending on load duration and temperature, the shear modulus G of the foil may be taken according to Table 3. For shorter spans differences of stress distribution might be even more significant.

***Table 3** - Influence of PVB interlayer shear modulus G on mid-span deflection and bending stresses in a laminated safety glass with asymmetrical composition (10mm/1.52mm PVB/6 mm)*

Load duration [s]	unknown	long	short < 180 s	very short < 10 s
Temperature [°C]	unknown	~22	~22	~22
Comment	Safe side always: “no shear interaction”	i.e. self- weight	i.e. wind gust loads	i.e. impact loads, almost „full shear interaction“
Effective PVB shear modulus G [N/mm^2]	0	0.01	1	4
mid-deflection f_{max} [mm]	148.7	138.3	44.4	36.9
 bending stress in the glass layers [N/mm^2]				

4 GLASS CONNECTIONS

4.1 GENERAL

In general, a direct steel–glass contact should be avoided with the help of separating intermediate materials. Normally self-weight is taken by plastic setting blocks or by epdm/silicone layers with hardness 60 to 80 Shore A, separating the glazing from the frame. For the loading perpendicular to the panel, different fixing possibilities exist, see Figure 15 [8]. These are described in the following in more detail.

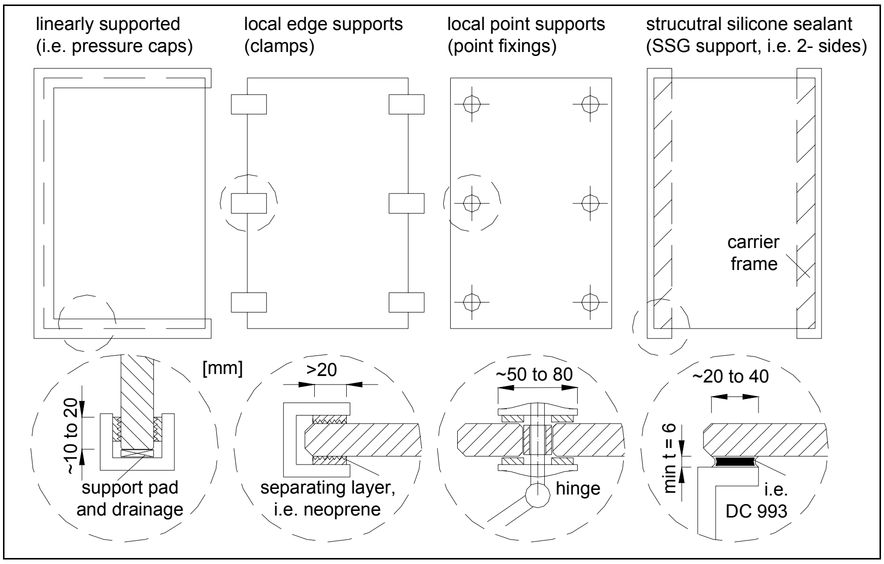


Figure 15 *- Overview of common glazing support possibilities*

4.2 LINEAR SUPPORT

Linearly supported glazing is usually framed, where its self-weight is transferred through support pads either side at the horizontal bottom glass edge (Figure 15). The frame size is larger than the glass pane, such that production tolerances as well as temperature movements can be taken without any in-plane constraint. Wind pressure and suction is taken by the frame system (i.e. pressure caps) and transferred to the main structure.

4.3 LOCAL EDGE CLAMP

In order to minimise the visual impact of linearly supporting frames or pressure cap profiles, panel edges may be fixed only locally by means of clamps that are fixed to the sub-structure, where there is a frame-like structure only on the inside of the glazing (Figure 16). In addition to the visual impact it may also be beneficial for overhead glazing where certain rainwater ways are required.

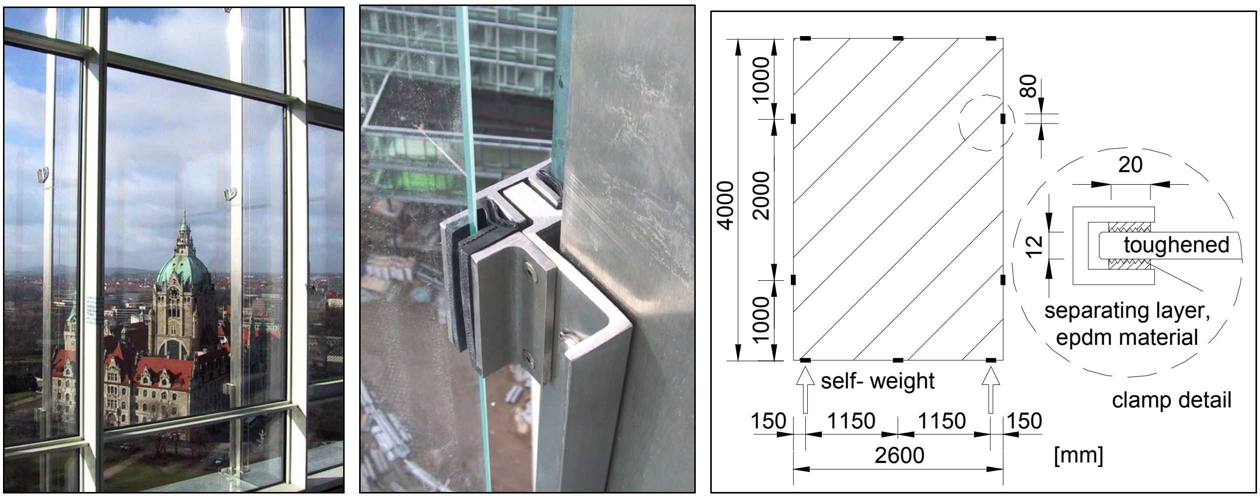


Figure16 - *Example of a locally clamped triple façade outer glazing panel, t= 12mm toughened glass*

4.4 POINT SUPPORT

Normally point-supported structures are driven by aesthetic requirements to minimize the visual impact of the glass panel support. One of the key problems of structural detailing is to solve the connection problem in such a way that unforeseen peak stresses and extreme stress concentrations as well as a direct steel-glass-contact are avoided. This is achieved by plastic interface elements such as bushings or pads or injected resin that avoids direct glass-metal-contact and acts as a buffer. To allow for proper assembly and to avoid unfavourable in-plane constraints (i.e. due to temperature), the point-support pins should be tightened carefully (i.e. torque screw moment < 30 Nm) and fixed into slot/wide holes of the sub-structure with suitable low-friction interlayers (i.e. teflon) according to Figure 17. Annealed glass should always be avoided here, because its insufficient strength around the holes may lead to breakage under loading.

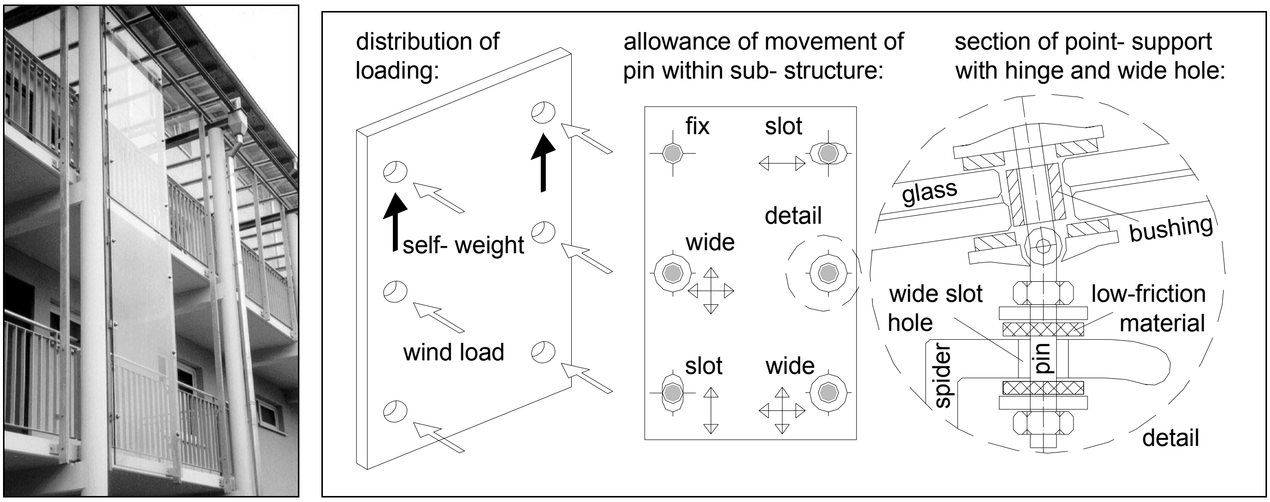


Figure 17 - *Example of a point-supported glazing panel and its support conditions (sub-structure)*

Numerical modelling should be performed in a way to find the maximum tensile stress on all glass surfaces, especially near the connections with high stress concentrations. Point-supported glass structures might be modelled numerically with the help of finite 3D-shell-elements. Suitable FEM-detailing for local stress concentrations have to generate all holes or other geometric irregularities.

4.5 STRUCTURAL SILICONE SEALANT

For linearly supported glazing sometimes there is an aesthetic demand to achieve a flush façade surface. Mainly for that reason, linear structural silicone sealant glazing supports have been developed (SSG), where the glass panel edges are silicone-bonded to a sub-structure ("carrier frame") which is then fixed to the main building structure (Figure 18). There are specific quality procedure requirements for both factory-applied as well as on site-applied SSG, see EOTA. Some relevant values are given in Table 4. It is important to state that SSG might only be glued to special surfaces other than glass, such as anodized aluminium or stainless steel profiles, but not to pure or painted mild steel or standard polyester powder coated materials. SSG is UV-stable and compatible with PVB and resin interlayers. In some countries building authorities ask for additional fail safes in case of failure of the silicone, which may lead to local edge clamps around the glazing panes and therefore such requirements should be discussed during the design process already.

Table 4 - *Structural silicone sealant glazing properties*

SSG property	Value
Minimum recommended thickness t	6.0 mm
Allowable normal stress σ for dynamic loading such as wind, includes global safety $\gamma = 6$	0.14 N/mm^2 (perpendicular to glazing surface)
Allowable normal stress σ for static loading such as self-weight, includes global safety $\gamma = 6$	0.015 N/mm^2 (perpendicular to glazing surface)
Allowable shear stress τ for dynamic loading such as wind, includes global safety $\gamma = 6$	0.07 N/mm^2 (parallel to glazing surface)
Allowable shear stress τ for static loading such as self-weight, includes global safety $\gamma = 6$	0.007 N/mm^2 (parallel to glazing surface)

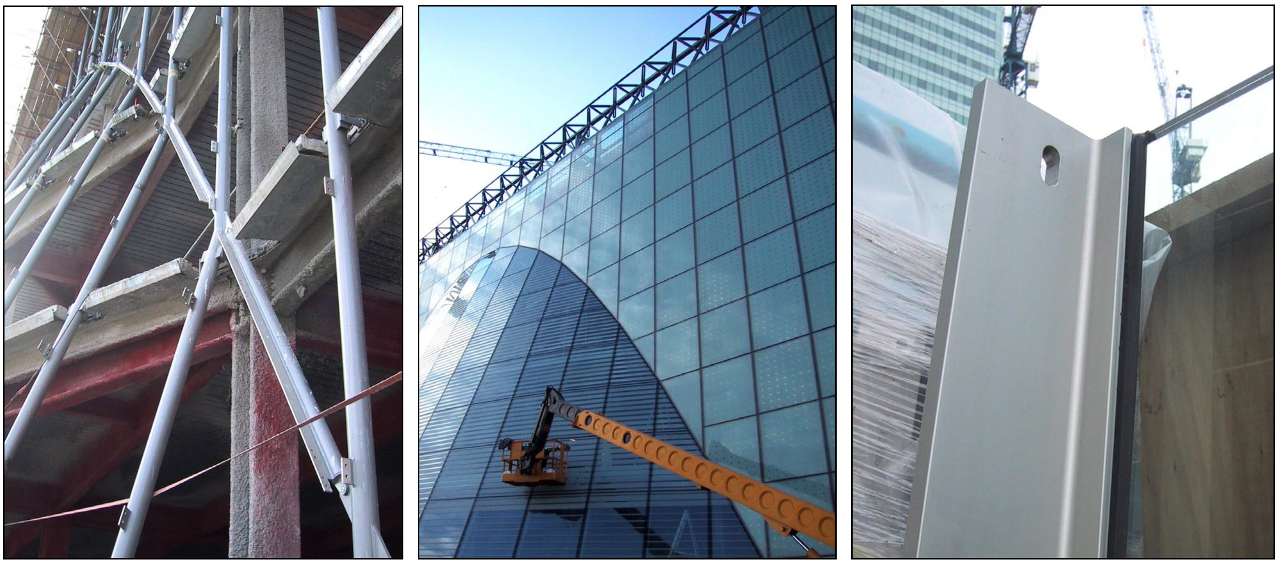


Figure 18 - *Example of a structural silicone glazing façade, main sub-structure mullions before glazing (left); finished façade (center) and anodized aluminium carrier-frame (right) [1]*

4.6 GLUED CONNECTIONS

In glass furniture production, acrylate glues have been used for many years, but they generally carry only minor loads and are only used internally (with minor temperature changes only, little environmental impact such as UV-light). In order to develop a durable suitable glued connection for external structural use, suitable glue compositions and required testing are still under development and in general not yet ready for applications. From a structural point of view the aspects of any adhesive to be used as a permanent glazing connection shall be examined by means of testing, calculations and further careful examinations with regard to durability, strength, dynamic loading and ease of application.

4.7 LOCALISED LOAD INTRODUCTION

In new modern constructions where glass is often used as a structural element, localized load introductions made of plastic or neoprene pads are no longer sufficient to resist high compressive stresses between the glass edges and the intermediate material. In this case soft aluminum may be used instead. The advantage of aluminum is a Young's modulus almost identical with glass and a yield strength lower than the compressive strength of glass. Preliminary tests [9] with hard intermediate materials showed a good behavior and capability of aluminum to introduce in-plane forces into the glass panels. The tests also showed the high compressive strength of glass that caused even plastic deformation of the steel and aluminum plates (Figure 19). The edges of the glass panels have to be at least grounded with chamfers (arrised) to avoid a local stress concentration and failure of the glass. A load introduction within a distance less than 2 times the glass panel thickness away from the weaker corners of heat-strengthened and fully toughened glass should be avoided. Due to the lower residual stresses around the corners their load capacity is relatively low compared to the rest of the glass edge.

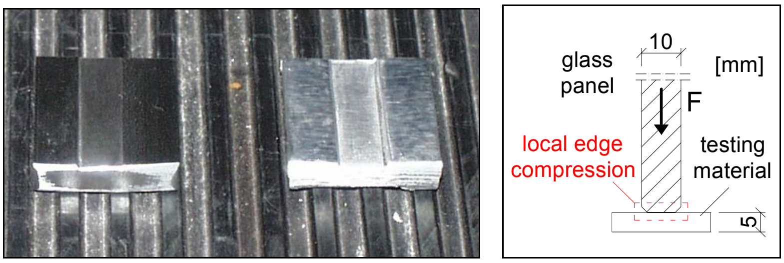


Figure 19 - *Plastic deformation by a grounded 10 mm glass edge with chamfer of: steel t = 30mm (σ_{max} = 580 N/mm^2, left) and aluminum t = 30 mm (σ_{max} = 540 N/mm^2, center); section (right)*

The lamination process normally leads to glass edges that are not absolutely flush with each other and therefore a homogenous load introduction into both panels is no longer guaranteed. Hard materials extending over the full width of the laminated glass should not be used to introduce forces in more than one layer of laminated safety glass consisting of tempered glass layers, because toughened glass can not be treated after toughening any more. In this case steel shoes should support laminated glass, where the space between the steel shoe and the glass edge might be filled with a special injection mortar (i.e. epoxy resin) or two-component glue to adjust the glass edges. Further research to develop high performance load introductions and design methods for laminated safety glass will be necessary.

5 ENGINEERING DESIGN

5.1 RELEVANT LOAD CASES

Relevant load cases for façade or roof glazing are given in Table 5.

Table 5 - Summary of relevant load cases in structural glazing applications

Load case	Example/comment
Self-weight g	i.e. 0.25 kN/m^2 for 1m^2 of t = 10 mm panel
Wind load w	wind pressure/suction, see national codes
Snow load s	snow/snow drift, see national codes
Temperature loading ΔT	i.e. summer: ΔT = 30K; i.e. winter: ΔT = -20K
Local panel heating	i.e. due to shadowing/solarisation ΔT = +/-10 K
Climate loading c	For insulated glass units only: i.e. +/-16 kN/m^2 isochore pressure (then further calculations for pressure onto glazing [3])
Human impact	i.e. horizontal line load of 1.5 kN/m at railing height; i.e. point load of 1.0 kN onto 100 x 100 mm^2 area; or more advanced dynamic calculation and 1:1 testing
man-load cleaning operation	i.e. man load 1.5 kN onto 100 x 100 mm^2 area of roof glazing
Movement of supporting sub-structure Δs	Consider tolerances in all directions, possible blocking of local supports etc.
Blast loading	For bomb blast resistant glazing only, Perform advanced dynamic calculations and 1:1 testing
Accidental/after-failure behavior (laminated glass units only)	Add self-weight of broken panels onto remaining panels Perform 1:1 testing or refer to existing testing data

5.2 IMPACT RESISTANT GLAZING

Glazing balustrades, glass doors or wall elements might be designed to resist dynamic human impact. A standard testing procedure according to prEN 12600 has been developed which uses a twin tyre around a 50kg pendulum, which is released from certain dropping heights in order to determine whether glass breakage occurs and how a broken glass pattern may affect human health. However, this test method is restricted to one single panel size with a four- sided linear support only. Therefore, great care shall be taken, when results of this standard testing method are to be used for impact resistant glazing of different sizes or support conditions, i.e. point-supported glazing might behave more critically than linearly supported glazing. Also, smaller glazing sizes are not necessarily more secure under dynamic impact due to their possibility to be "punched-out" of their supports as a whole (Figure 20). 1:1 testing with original glass size and support stiffness is therefore strongly recommended. It is also advised that bottom-clamped glass balustrades with no further handrails or posts in front of the glazing should not be made of a single toughened sheet only. Detailed and practical advice might be gained from [10].

Figure 20 - *Impact test EN 12600 (left), sufficient impact resistance of a curved laminated safety glazing balustrade with additional handrail at the top (center), failure example of a rather small, locally clamped, toughened glazing balustrade, punched-out as a whole (right) [2]*

5.3 CONSTRUCTION PRINCIPLES

In order to avoid severe failure consequences in case of damage of a single glass element with load carrying functions (i. e. car crash), global safety concepts have to be developed by the design engineer that include redundancies. Those might be the protection of the load-bearing glass by additional glass panels with no load-bearing function or the use of statically undetermined systems with the possibility of load-redistribution or certain owner regulations like inspection intervals of the building. Vandalism or other failure reasons of the glass should always be taken as important load cases to deal with in design. E.g. for roofs, laminated glass should stay in position for at least 24 hours to have enough time to change the panels. Also, a cleaning strategy should always be developed to reach all glazing everywhere for cleaning purposes as well as glass replacement.

5.4 GLASS PANEL MODELING

For stress and deflection design, the finite element method is a powerful tool to determine design decisive maximum tensile stresses and deformation patterns. 3D-isoparametric shell elements might be used and connected to 3D volume-elements near point-supports or local load introduction points. An example of such a FE-calculation is given in Figure 21.

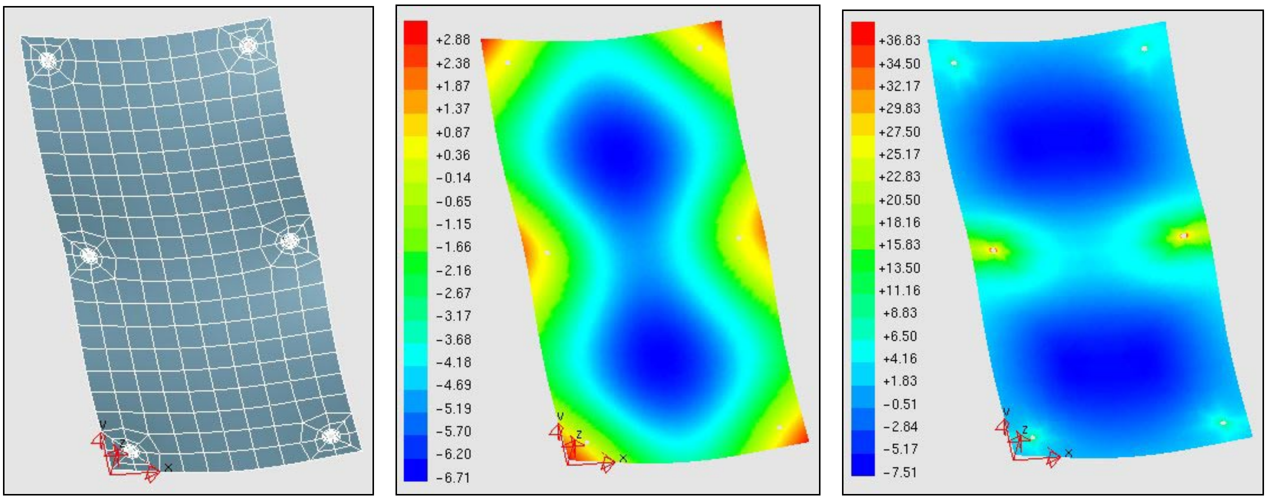


Figure 21 - *FE-mesh for a point-supported toughened glazing 1.5 x 3.0 m, (left); deflection (center) and maximum tensile stress near the center holes (right); wind loading w= 1.0 kN/m^2, t= 10mm*

5.5 ULS

Until now only few design codes [11] [12] and safety concepts [3] [13] for glass in buildings are available. As glass panels were used mainly as a filling material in windows, most of the design methods are restricted for wind and climate loading only. Most of the existing design codes are still based on maximum allowable tensile stresses of the glass panels that do not represent the brittle breakage behavior of glass sufficiently. Glass is an ideal-elastic material until fracture occurs without any plastic deformation like common building materials. The maximum tensile stress glass can resist is the sum of the thermal pre-stress and the maximum tensile strength of glass. The maximum tensile strength of glass is unfortunately a high scattering value dependent on:

- size of micro cracks and the damages occurring during lifetime on the glass surface
- environmental conditions (humidity, temperature)
- load distribution and load duration

Fracture mechanic models have been developed in the past to determine this value. For example the tensile strength of annealed glass with a 0.1 mm large surface crack is 26 N/mm^2 for a load duration of 1s and only 6 N/mm^2 for a load duration of 30 years. A future safety concept for glass therefore has to take into account the possible glass damages and the accumulated load duration during lifetime.

Existing and currently developed safety concepts [3][11][13] [14] for ultimate limit state design (ULS) are based on the method of separate partial safety factors for load and resistance corresponding to the Eurocode (EC) design philosophy. The three concepts compare a so-called effective stress, which is a weighted average value of the distributed main stresses on the glass surface, with a maximum tensile resistance of the glass. The tensile resistance contains the influence of size and quality of the glass surface, accumulated load duration and environmental conditions. In [11], for example, the verification equation reads:

$$\sigma_{eff} \leq f_{g,d}$$

$$f_{g,d} = \left(k_{\text{mod}} \frac{f_{g,k}}{\gamma_m \, k_a} + \frac{f_{b,k} - f_{g,k}}{\gamma_V} \right) \cdot \gamma_N$$

σ_{eff}: effective stress

$f_{g,d}$: design resistance

k_{mod} : load duration influence

$f_{g,k}$: characteristic glass strength

γ_M : partial safety factor for glass

k_a : influence of the glass surface size

$f_{b,k}$: characteristic glass strength of pre-stressed glass

γ_V : partial safety factor for pre-stress

γ_N : national coefficient

5.6 SLS

Verifications necessary for the serviceability limit state (SLS) concern glazing deflections, movement of the glass elements within the structure and the structure itself as well as vibrations (normally uncritical). Only some indications [15] concerning deflection limits currently exist for glass design (Table 6). An important part in verification of a glass element also is its post-breakage behavior. Glass panels have to remain in place for a certain time even if all glass layers are already broken (see chapter 2.3.5).

Table 6 - *Allowable deflections according to [15]*

type of glass	type of linear supports	Deflection limit	Definitions
single glass		f ≤ l/100	l: span in main load-carrying direction d: glass thickness *)
insulated glass unit	four sides	f ≤ l/100 and f ≤ d	
	two or three sides	f ≤ l/100, f ≤ d and f ≤ 8 mm	l: length of free glass edge d: glass thickness *)
*) the nominal glass thickness of a laminated safety glass unit is $d = \sqrt[3]{d_1^{\,3} + d_2^{\,3}}$			

The maximum allowable deflections of a structural glass element should be more severe than the values given in Table 6. Deflection limits given for steel structures might be values of orientation for glass elements as well here. Supports should be flexible enough to follow these deformations without creating secondary bending moments. In façade construction deflection limits can be more restrictive because of architectural aspects to avoid negative lens effects of the façade surface, for example. Relative displacements between different glass panels should also be checked, because they can lead to high shear stresses in the silicone sealant joints, glass-glass or glass-steel-contact might occur.

5.7 TOLERANCES

The structure should always be able to allow for tolerances in the glass production as well as tolerances of the sub-structure. Movements of the glass in the direction of the panel should be made possible to avoid the case of severe temperature load or other likely eventualities. Tolerances of glazing dimensions might be calculated from the given allowable size deviations in the codes or specifications. More importantly, tolerances of the sub-structure should be taken from calculations or specifications of the main building structure. Taken together these allow for the design of required joint widths and local adjustment devices such as slot holes or adjustable brackets for the supports of the glazing. Constraint-free assembly on site should be achieved for all glazing types.

6 CURRENT STRUCTURAL STABILITY RESEARCH ACTIVITIES

Transparency in conjunction with allowable high compressive glazing stresses make the use of glass sheets as primary load-carrying elements such as beams, columns and shear panels both attractive and possible. Due to their high slenderness such load carrying elements tend to fail because of structural instability (Figure 22). Therefore, one aspect of the research works in progress [16] consists of the experimental and theoretical study of fundamental glass stability problems for single-layered as well as laminated safety glass. This is leading to the development of a safety concept for structural glass design. The brittle, linear-elastic behavior of the material means that glass lacks the properties of steel, which plastic deformability or strain hardening effect has to be compensated for through the composite action of laminated safety glass, subjected to compressive and bending stress due to the foil which creates a „ductile“ behaviour for columns, on which tests were performed with initial imperfections.

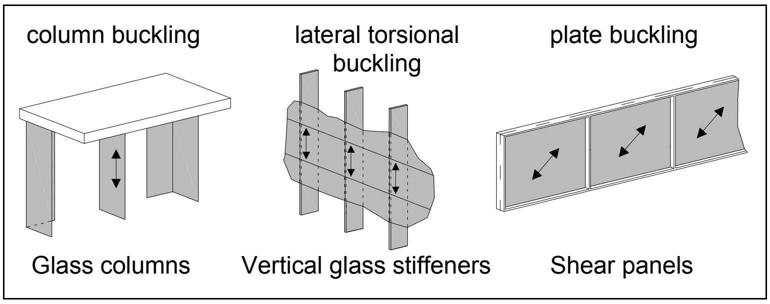


***Figure 22 -** Example for load-carrying glass elements subject to different stability problems*

Existing design methods, such as the use of buckling curves for steel or timber structures cannot be directly transferred to glass panels [17]. The influence of production tolerances, initial deformations due to the tempering process, and the breaking stress in glass have to be investigated for glass in a different way. This is not due to the material property, but depends on the residual stresses due the tempering process, the degree of damage of the glass surface, the distribution of stresses on the glass surface, humidity and the load history For the experimental study, column buckling tests on upright glass strips were performed. A total of 60 displacement- and force-controlled tests were carried out (Figure 23).

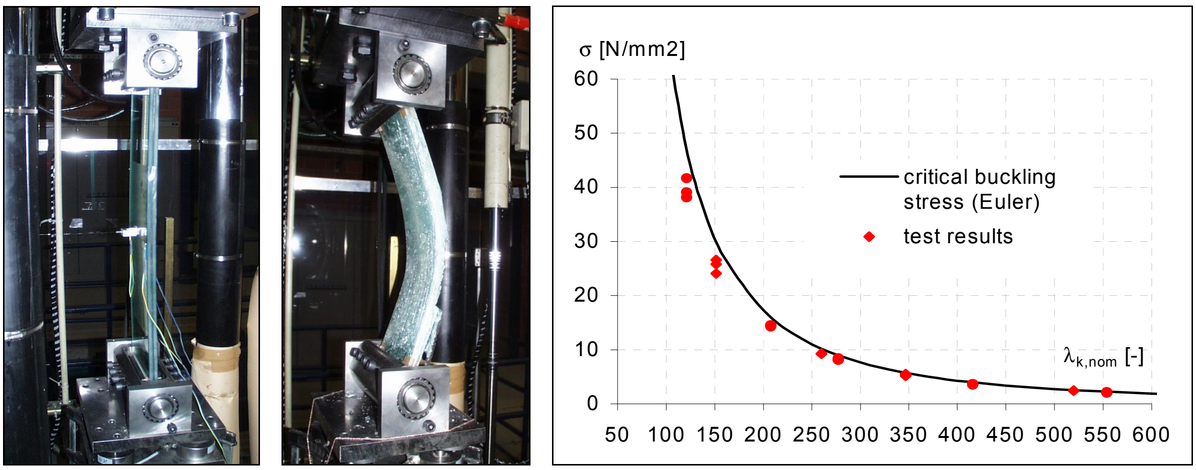


***Figure 23 -** Test set-up for laminated safety glass unit (2x 10 mm heat-strengthened), L x w = 800 x 200 mm (left); failure in Euler mode 2 (center) and derived buckling curve for glass (right)*

To simulate the sandwich behavior of laminated safety glass a finite element model was constructed with the PVB interlayer represented by linear visco-elastic solid elements. Initial deformation w_0 was found to be the most important influence on the load-carrying behavior, together with load eccentricity and breaking tensile stress of the glass. A very good conformity between experimental and numerical results was obtained [18].

7 SUMMARY AND FUTURE TRENDS

Clearly, glass in structural building applications has not yet reached its full potential. In the future, glass panels might be used more regularly as a load-carrying element in conjunction with well-known materials. Best practice experiences may be transformed into accessible codes and safety regulations. New glazing materials such as integrated light sources within laminated glazing, testing results and improved coating performances will offer new possibilities within the field of façade engineering.

Façade engineering has developed into an engineering discipline in its own right, where close attention can be given to the glass material and its applications. It is a specialized service integrating engineering and architectural skills, combining analysis, specification, the customizing of commercial systems, bespoke design and detailing. As various interdisciplinary aspects play its part here, the European initiative COST C13 “Glass and Interactive Building Envelopes” is currently collecting available relevant research results.

REFERENCES

[1] Steel-glass facades of DS8 building, Canary Wharf London, façade engineering by Whitby Bird & Partners (WBP), England, 2002.

[2] *ZiE-Report for overhead glazing, Trube und Kings*, Institute of steel constructions, RWTH Aachen, 1998.

[3] Sedlacek, G., Blank, K., Laufs, W., Güsgen, J., *Glas im Konstruktiven Ingenieurbau*, Verlag Ernst&Sohn, 1999.

[4] *Glass Guide*, Saint Gobain Glass UK, edition 2000.

[5] *Glass in Building*, edited by D. Button and B. Rye, Butterworth architecture, Pilkington Glass Limited, 1993.

[6] Laufs, W., Sedlacek, G.: *Stress distribution in thermally tempered glass panes near the edges, corners and holes*, Glass, Science and Technology, 01 and 02/1999.

[7] Laufs, W., *Ein Bemessungskonzept zur Festigkeit thermisch vorgespannter Gläser*, dissertation at the Institute of steel construction, RWTH Aachen, Shaker Verlag, 2000.

[8] Laufs, W., Luible, A., Mohren, R., *Etude préliminaire sur le verre comme élément de construction dans le bâtiment*, ICOM Rapport 403F + 403D, EPFL, Lausanne, 2001.

[9] Luible, A., *Lasteinleitung in Glaskanten*, ICOM Rapport 463, EPFL, Lausanne 2002.

[10] DIBt : *Technische Regeln für die Verwendung von absturzsichernden Verglasungen*, 03/2001, DIBt-Mitteilungen (German national rule).

[11] DIN EN 13474-1, *Glass in building - Design of glass panes - Part 1: General basis of design*; (Draft standard).

[12] *Standard Practise for Determining Load Resistance of Glass in Buildings*, ASTM Designation: E 1300-97, American Society for Testing Materials.

[13] Wörner, J.D., Schneider, J., Fink, A., *Glasbau*, Springer Verlag, 2001.

[14] Haldimann, M.: *Safety of steel-glass structures*, dissertation EPFL-ICOM, Lausanne, currently in progress.

[15] DIBt : *Technische Regeln für die Verwendung von linienförmig gelagerten Verglasungen*, 12/1998, DIBt-Mitteilungen (German national rule).

[16] Luible, A.: *Stabilität von tragenden Glaselementen*, dissertation EPFL-ICOM, Lausanne, currently in progress.

[17] Laufs, W., Kasper, Th.: *Biegedrillknickverhalten thermisch vorgespannter Gläser*, Bautechnik, 05, Berlin, 2001.

[18] Luible, A., Crisinel, M., *Auf Biegen und Brechen*, tec21, Zürich, N° 12, 2002.