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Applications for curved glass in buildings

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Abstract. In the last years an increase of the number of building projects with built-in curved glass can be observed. The applications can principally be curved monolithic glass, laminated safety glass or insulated glass. This fact makes it absolute of interest to make more investigations in this field. The investigations can be focused on e.g. the process of the bending of the glass to bring it into a certain shape, or the very difficult topic of pre-stressing it. The state of the art of the production process of such glass shows some different ways to produce curved glass. The most used way is to bend the glass at a high temperature of more than 550° Celsius. Another kind of curved glass can be achieved in combination with the laminating process. With the cooling down at the end of the laminating process the interlayer becomes stiff enough to hold the shape by activated shear forces between the glass layers. Another possibility is to produce flat glass and bend it while mounting the glass. The question how to pre-stress curved glass is on the very first beginning of investigations. All these different processes are on the first view very easy but very difficult in the detail.

Keywords: Cold bent glass, hot bent glass, curved insulated glass

1. Introduction

The tendency to use curved glass in buildings shows an increasing number of realized outstanding projects like the ‘Nordkettenbahn’ in Innsbruck (Austria), designed by the famous architect Zaha Hadid. The new cable railway substituted the old railway, which connects the city of Innsbruck with the area Hungerburg located in the north of the city. This cable railway consists of four stops – ‘Congress’ next to the city centre, ‘Löwenhaus’, next at the riverside of the river Inn, ‘Alpenzoo’, which is on the half way up to the final station at the very steep hillside and the ‘Hungerburg’ which is the final destination on the very top.

The principle glass geometry follows the raster of the steel grid, which is the main structure in the inner of the glass sculptures. All of the different glass elements are free form bent glass, as can be seen in Fig. 1 below.

With a special stainless steel supporting system, which is glued to the surface, the glass elements were assembled to the steel substructure.

2. Cold bent glass by assembling

2.1. General

A possibility is to produce the glass planar. The demanded shape is achieved during the mounting of the glass. The simple process can very simply be described as a glass which shall be fixed with

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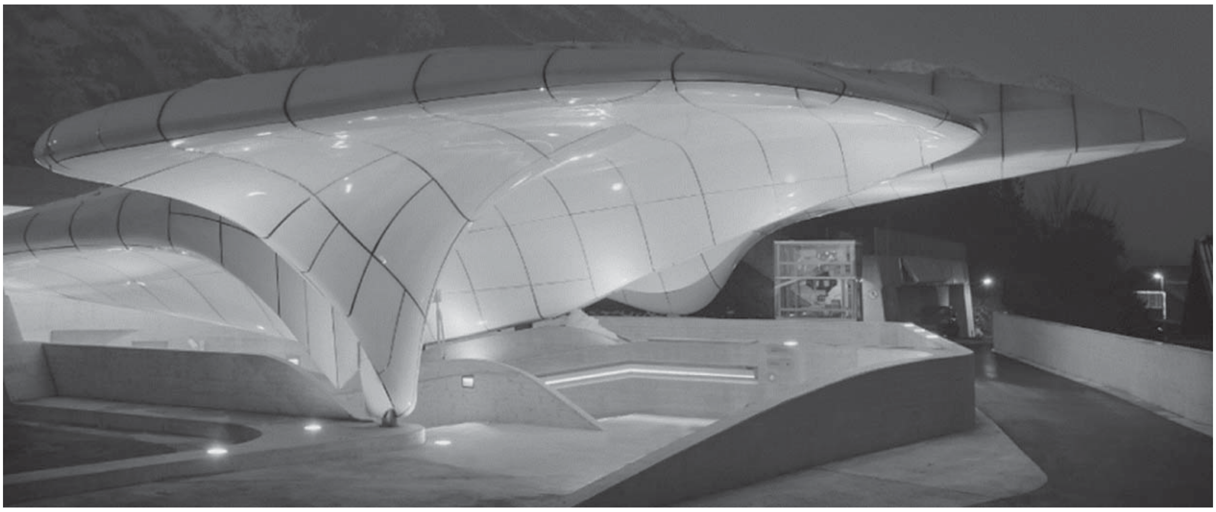

Fig. 1. 'Nordkettenbahn' station Hungerburg, Innsbruck (Strabag).

four glass fittings, as shown in Fig. 2 below. The glass, e.g. a laminated safety glass, is produced as a planar panel. In the first step all four glass fittings are in the same plane surface. If one of these glass fittings is moved out of this plane surface, a curved surface of the glass occurs. The maximum curvature is limited by the bending strength of the used glass.

2.2. TGV railway station, Strasbourg

One wonderful example for such technique with cold bent glass by assembling, is the TGV railway station in Strasbourg, see in Fig. 3 below. The laminated safety glass was produced planar and these big glass panes were mounted at the building site into their demanded curved shape.

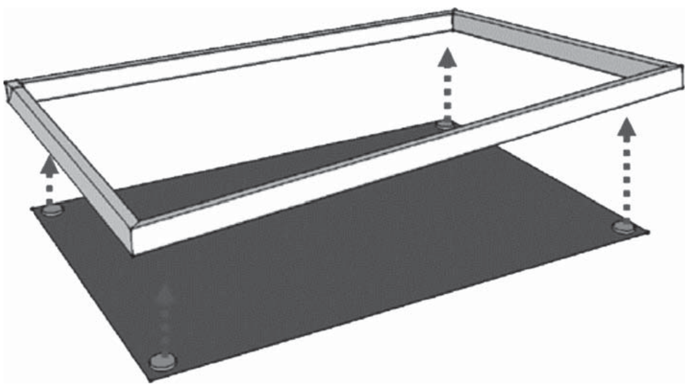

Fig. 2. Cold bent glass by assembling.

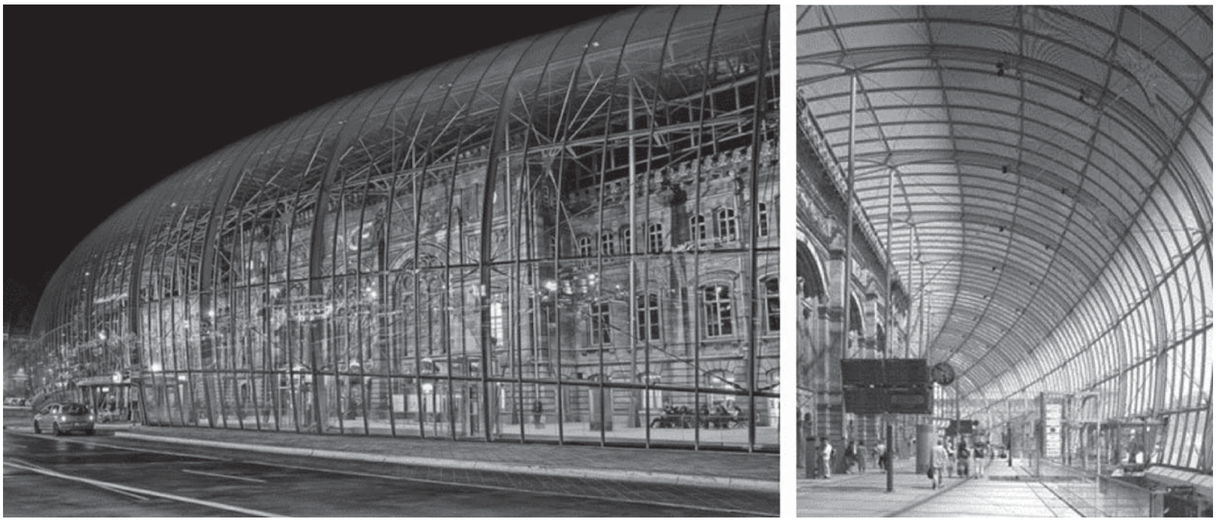

Fig. 3. Example for cold bent glass by assembling (Fildhuth, 2014).

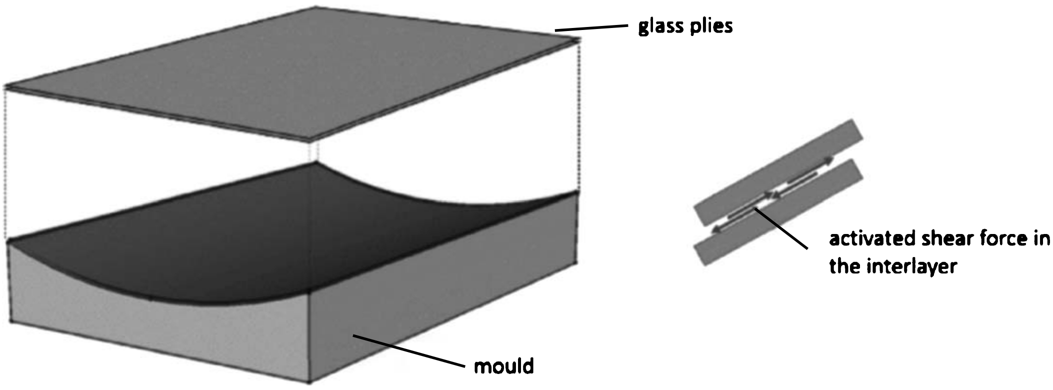

Fig. 4. Cold bent glass by lamination.

3. Cold bent glass by lamination

3.1. General

Another kind of curved glass can be produced in combination with the laminating process. The glass layers are fixed in there demanded shape in special moulds. The typical laminating process will be started. At a temperature of approximately 120°C and a pressure of 1 bar up to 12 bar (depends on the kind of process) the interlayer, e.g. polyvinylbutyral (PVB), will become soft and the glass layers will be connected. During the cooling down at the end of the laminating process the interlayer becomes stiff enough to hold the shape by shear forces which are activated between the glass layers. When releasing the laminate from the production jig (e.g. the mould) the bending energy stored in the laminated glass is partially released. This effect can be described by the following

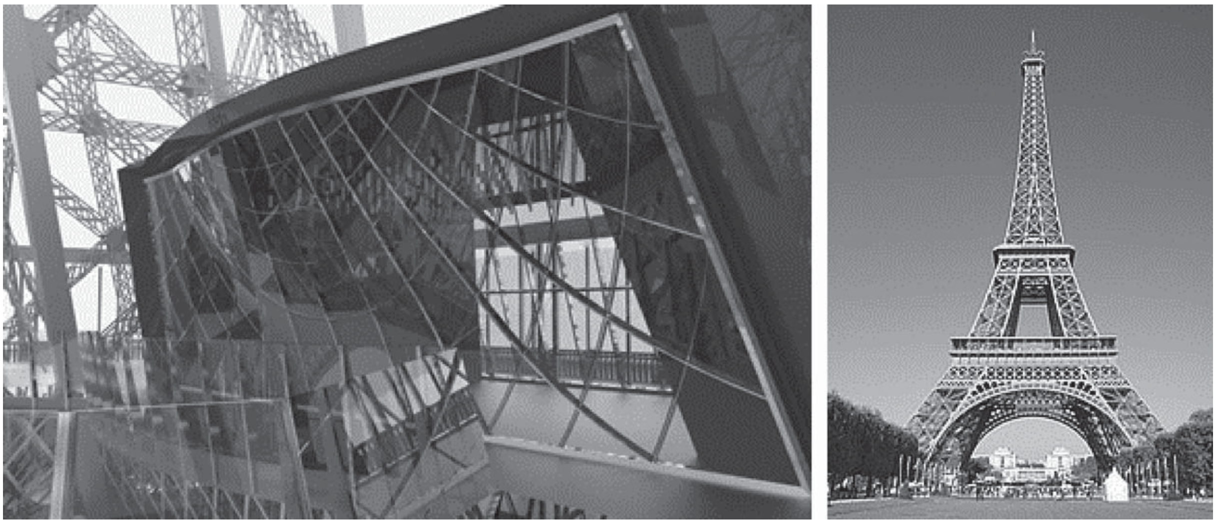

Fig. 5. Pavilions at Eiffel tower (Leduc, 2012).

two phenomena. A quasi-instantaneous, elastic spring back and a continuous long-term spring back, i.e. the decreasing relaxation of the laminate related to the viscoelastic interlayer properties including time and temperature (Fildhuth, 2014).

3.2. Eiffel tower

One excellent project, as shown in Fig. 5, is the replacement of the Gustave Eiffel and Ferrié pavilions with two new pavilion housings and exhibition space, along with the facade renovation of the restaurant 58, designed by Moatti & Rivière Architecture et Scènographie. The glass panels are insulated glass units consisting of toughened laminated safety glass on the external public side and a single tempered glass on the inner side. The traditional method to fabricate the glass as a hot bent

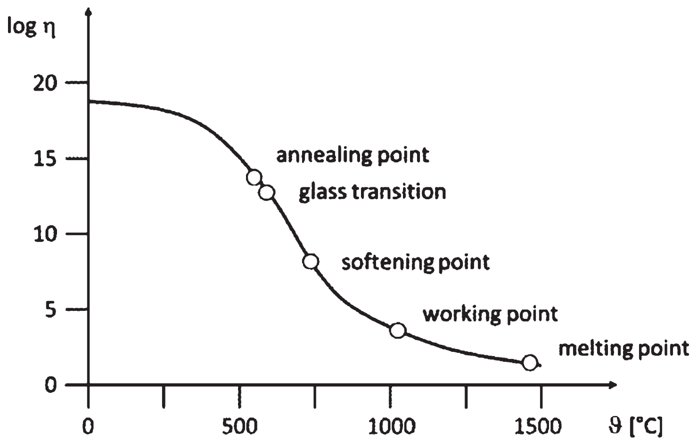

Fig. 6. Viscosity behaviour of glass at high temperature.

glass was not appropriate because of two reasons. Firstly the costs for all different geometries would have been too high and secondly such a double curved glass is not producible as a toughened glass by heat treatment (Leduc, 2012).

4. Hot bent glass

4.1. General

The most used procedure is the bending of glass at a high temperature with more than 550°C. In this case there is a change of the viscosity in connection with decreasing of the Young´s modulus at such high temperatures. Due to the gravity effect, the softer glass sags down into special designed moulds and gets its demanded geometry.

The process of the deformation of a flat glass pane at high temperatures is the opposite process of the very old technique of glass blowing. The glass is again and again brought in a furnace on a temperature of over 600°C, in order to form it by blowing to a cylinder. The ends of the cylinder are cut. In the second step the glass is reheated in another furnace and made flat.

At temperatures above the temperature of transformation of approximately 550°C, the glass becomes softer. A physical description of the procedure is possible with the viscosity. The viscosity designates the strength, which is required, in order to shift two parallel surfaces in a certain distance with a certain speed. One recognizes the meaning of the viscosity, if one regards the formation of a

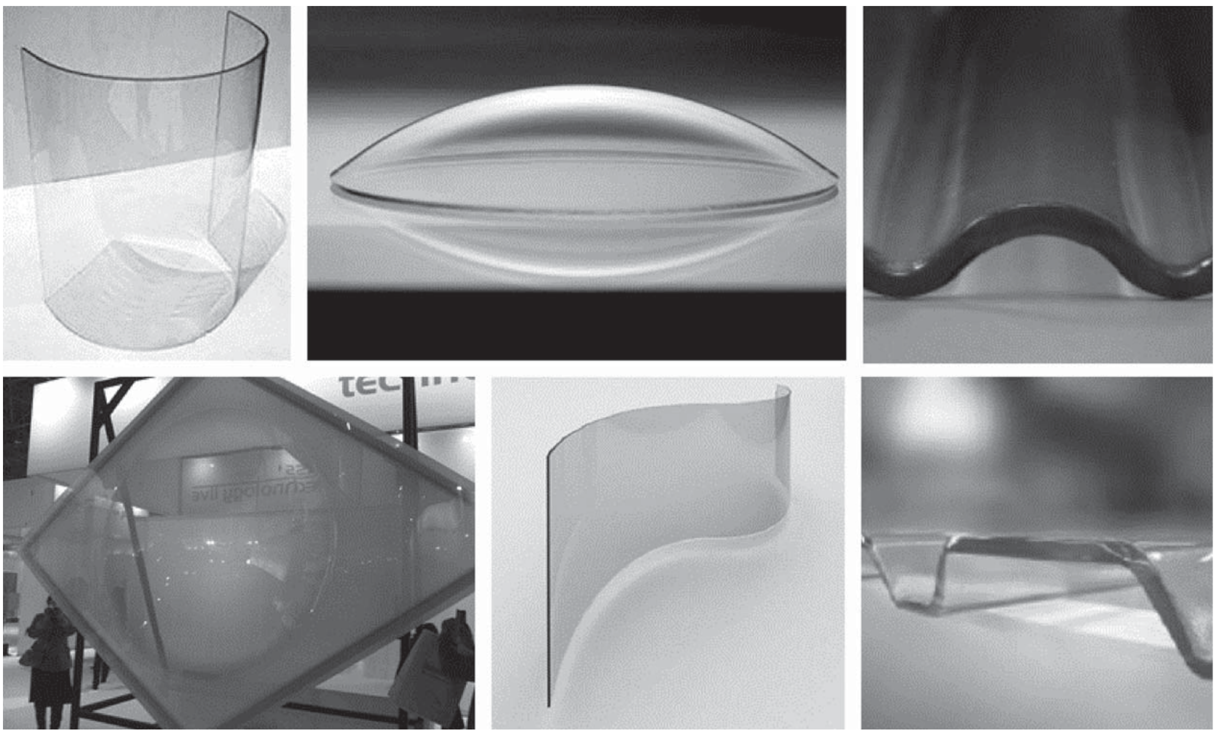

Fig. 7. Hot bent glass products.

glass. Melted glass is a liquid and differs from the solid state by the fact that the bonds between the molecule particles are missing. If individual particles move, then the bonds between these molecule particles must be blown up. The energy needed to blow up bonds between the molecule particles is supplied by thermal energy (Neugebauer, 2007).

The higher the temperature is, the more bonds between the particles are blown up and the glass matrix becomes softer. This effect results in more curvature in the glass and smaller bending radii. At a temperature of approximately 800°C it is possible to produce such extreme curved glass with e.g. a corrugated or trapezoidal shape as shown in Fig. 7 below (Neugebauer, 2013).

4.2. Vivarium Maria Hof

An example of a special application of curved laminated safety glass is the glass tunnel for the 'Vivarium' in Maria Hof in Austria, shown in Fig. 8 below. It is a tunnel made from glass for an aquarium containing piranhas. The tunnel with a total length of 6 m was built with five cylindrical curved glass sections. Each cylinder has a radius of approximately 2.0 m, a width of 1.2 and an arc length of 3.6 m. The lower edge of the glass lies in a water depth of 3.0 m. For this very high load of (30 kN/m²) a laminated safety glass, consisting of 4×12 mm bent glass, was needed. Due to the big differences of the loads between the lower and the upper edge a stainless steel sub-construction for the stabilisation of the glass elements was used. This project very impressively demonstrates how the thickness of the glass can be reduced by activating membrane forces in the glass due to a special supporting system of the glass at the lower and the upper edges (Neugebauer, 2007).

4.3. JCDecaux

An extraordinary transformed glass was used for a project in London. A tower for advertising for the company – JCDecaux in Brentford, 1000 Great West Road, Middlesex, United Kingdom TW8.9 – was planned by the famous architect Lord Norman Foster; see in Fig. 9 below. The tower for advertising is situated directly at the exit road to the airport Heathrow in Brentford. With its height of

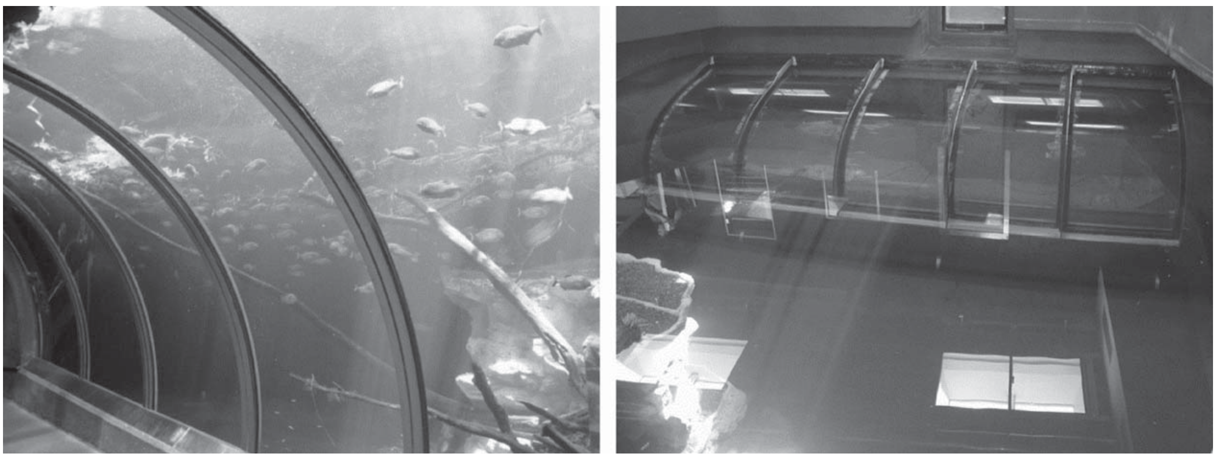

Fig. 8. Glass tunnel 'Vivarium' Maria Hof, Austria.

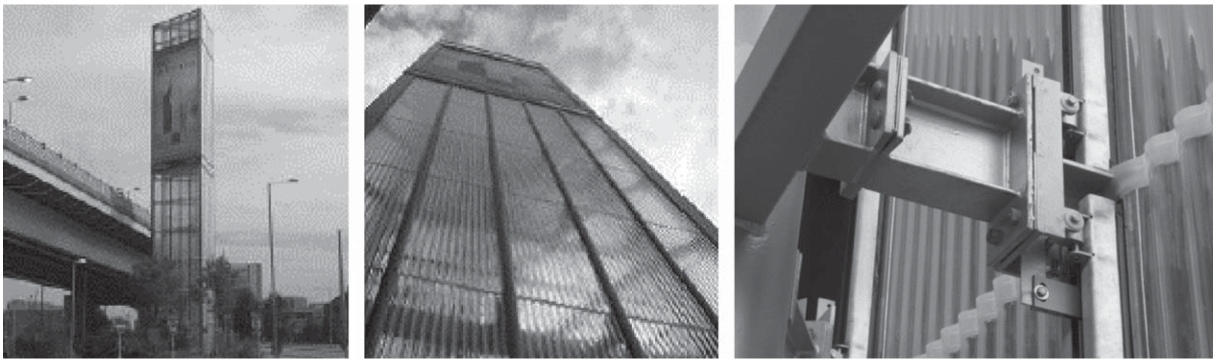

Fig. 9. View of the JCDecaux Tower London.

approximately 29 m the tower has a triangular ground plan form. The lengths of all sides of the triangle are approximately 6 m. The tower has two large light boxes for advertising at the sides arranged to the road. A structural steelwork is situated in the interior on which the cladding is fastened. The structural steelwork consists of three vertical columns in the corners and horizontal girders at each glass gap with a vertical clearance of approximately 3 m. With diagonals the steel construction became stiffer due to the wind loads. The whole tower was shrouded in this corrugated glass. The corrugated glass with an average thickness of 8 mm has a wave-length of 76 mm and a difference between valley and peak of 20 mm (Neugebauer, 2007).

4.4. Joanneumsviertel, Graz

A very interesting project, finished at the end of 2011, is the new entrance of the museum quarter 'Joanneumsviertel' in the historical centre of Graz in Austria. This project is so important, because it shows different kinds of curved glass applications like curved laminated glass and curved insulated glass. The museum was founded in the year 1811 and on the occasion of the 200 year jubilee the government of Styria had decided to renovate this museum. The complex of the museum's building consists of two wings (Museum of Natural Science and the Museum of Modern Art) of the existing structure. For the connection of those old parts of the museum the architects – eep architekten, Graz, Austria and Nieto Sobejano Arquitectos, Madrid, Spain – designed the new entrance between them. The visitors of the museum can reach the biggest cone designed as the museum entrance via a specially designed public place. The picture below (Fig. 10) shows this new entrance with an escalator marked with an arrow.

The basement with a depth of approximately 10 m was excavated and the two levels were covered with wide spanned reinforced concrete slabs. An architectural challenge of this project was to bring daylight into these two lower floors. The concept of the architects was to let natural daylight flow into the basement via vertical funnels.

These funnels have the form of small round courtyards with different diameters of up to approximately 16 m. Laminated safety glass and insulated glass were used for the cladding of these conical-shaped funnels.

The cones have a central axis which are inclined up to 15° from the vertical. For this reason the inclination of the glass panes vary from the vertical position to an inclined position of up to 30° from

Fig. 10. New entrance – 'Joanneumsviertel' (Neugebauer, 2012).

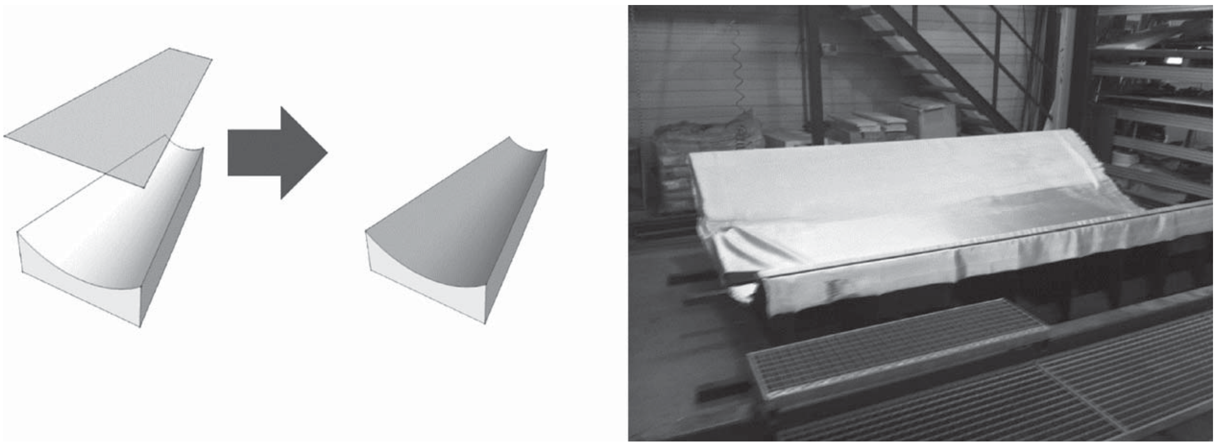

Fig. 11. Production of conical shaped insulated glass.

the vertical. Two of the six cones interpenetrate and another one is posed on its top and situated in the centre of a larger one (Neugebauer, 2012).

4.4.1. Production of conical shaped insulated glass

The usual way to produce the conical shaped glass is by the process of a high temperature of more than 550° Celsius and with the usage of gravity. In this case there is a change of the viscosity in connection with decreasing of the Young´s modulus at such high temperatures. Due to the gravity effect the softer glass sags down into special designed moulds and gets its demanded geometry.

The procedure of the production of such conical shaped insulated glass (IGU) can be described with the following steps. The first step was to cut out the glass to the demanded geometry and the edge treatment. After this first step the glass had to be brought into the furnace for the bending process. The bent glass must be laminated, if needed. The final step was the assembling of the insulated glass unit, by usage of soft-spacers for the edge sealing. The laminated safety glass and insulated glass were glued onto the stainless steel sections.

Fig. 12. Cones 1 & 2 (Neugebauer, 2012).

4.4.2. Cone 1 & 2

Cones 1 & 2 are the cones with an interpenetration located on the northern part of the public place. Cone 1, with a diameter of approximately 9 m, extends into the first basement level and Cone 2, with a diameter of approximately 6 m, extends into the second basement level (see in Fig. 12 below). For the balustrade, laminated safety glass with a total thickness of 24 mm, which consists of 2×12 mm conical-curved annealed glass panes, was used. The cladding in the basement levels consists of insulated glass with conical-curved 12 mm glass on the outer side, a 16 mm space, and laminated safety glass, which consists of 2×8 mm conical-curved annealed glass on the inner side.

A special detail is the interpenetration of these two cones. The guarantee of the tightness against the rain for the parabolic curve of the interpenetration was a difficult part, as well as the geometrical challenge which had to be solved. The gap between the glass panes of the different cones was covered with a specially formed stainless steel profile with approximately the same U-shaped cross section as used for the stainless steel handrails of the balustrade.

4.4.3. Cone 3 & 4

Cone 3 has its larger diameter on the upper side in comparison with cone 4, which was posed on its top and has the larger radius on its bottom edge. The smaller cone number 4 is situated in the centre of cone 3, which is larger. For the balustrade, laminated glass with a thickness of 24 mm consisting of two 12 mm conical-curved annealed glass panes was used. The cladding in the first basement level was made for both cones of insulated glass with conical-curved 12 mm glass on the outer side, a 16 mm space, and a laminated safety glass, which consists of 2×8 mm conical-curved annealed glass on the inner side. The glazing in the second basement level, which is used as a depot for the exhibits, was designed as laminated safety glass with a total thickness of 24 mm. Cone 6 is equal to Cone 3 (Neugebauer, 2012).

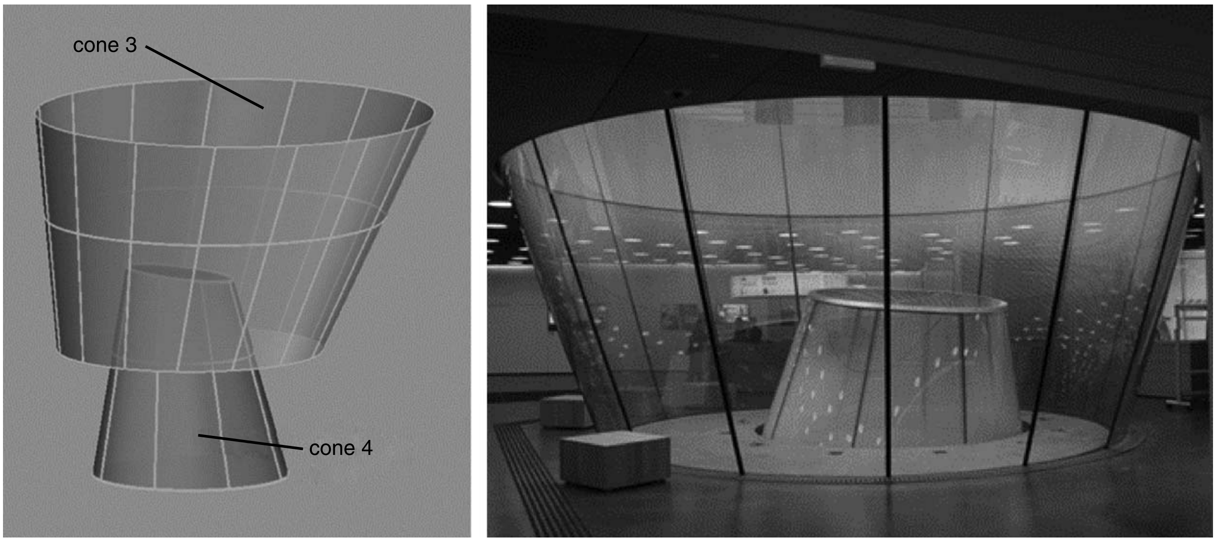

Fig. 13. Cones 3 & 4 (Neugebauer, 2012).

The picture of Fig. 13 shows the view from the inner of the museum in the first basement level through the insulated glass units of cone 3 to top off the insulated glass of cone 4. The top of cone 4 is covered with an elliptical, but flat, insulated glass pane. A very slender steel construction positioned in the gaps between the conical glass units carries this insulated glass of the top and is supported on the concrete slab.

4.4.4. Cone 5

The biggest cone – Cone 5 – with a diameter of approximately 16 m was designed as the new entrance for the visitors of the museum. Via an escalator the people reach the first basement level and enter the museum through a sliding door. The central axis of this cone is inclined by approximately 15° from the vertical and for this reason the inclination of the glass panes vary from a vertical position up to an angle of 30° from the vertical (near to the escalator). For the balustrade, laminated safety glass with a total thickness of 24 mm, which consists of two 12 mm conical-curved annealed glass panes, was used. In the balustrade, a gap for installation of the escalator was positioned (see Fig. 14 below, left).

4.4.5. Principle concept of glazing

The special boundary condition of the great deformation of the wide span concrete slabs of more than 30 mm (for the long-term deformation) causes the special structural system of all the cladding. The glass panes of the balustrade had to be stacked on the insulated glass of the level below. This means that the lower glass has to carry the vertical loads, e.g. the dead loads of the glass above. To keep the distance between the upper and the lower glass level, synthetic blocks were used. The calculations made during the design process showed that the additional stresses due to the dead load of the upper glass were not very high and in this case absolutely acceptable. At the lower edge of the insulated glass pane the dead load is supported by steel consoles, which were mounted on the concrete slab.

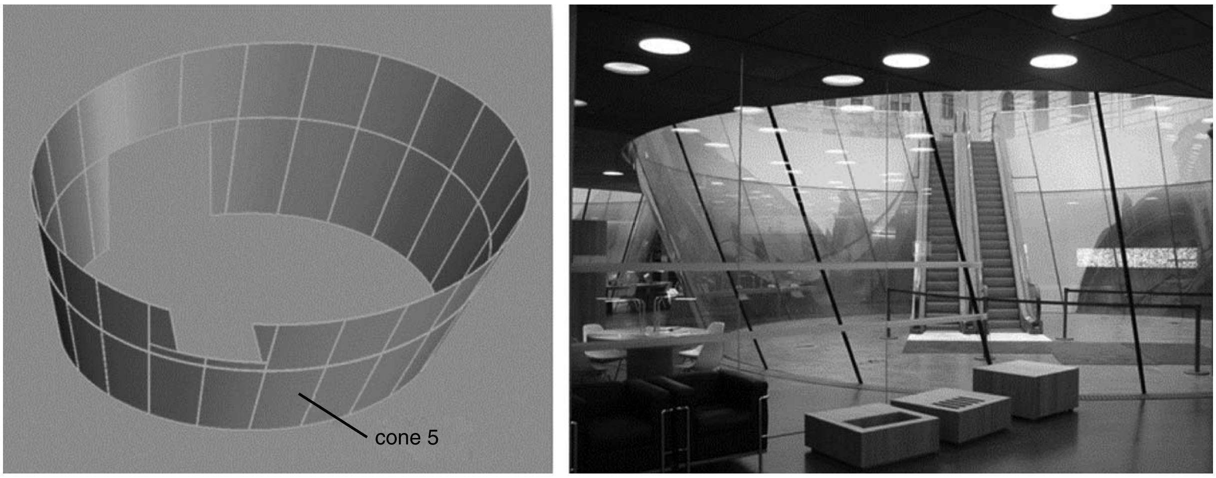

Fig. 14. Cone 5.

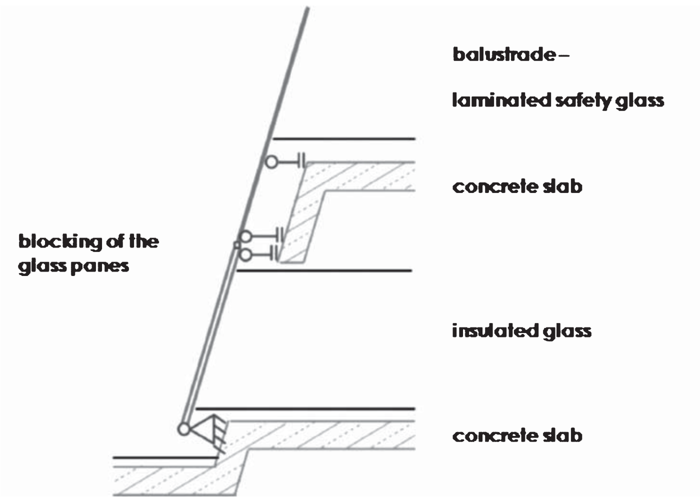

Fig. 15. Principle concept of glazing (Neugebauer, 2012).

For the horizontal loads, the glass panes were glued to stiff stainless steel ring sections, which were discretely supported at their ends. These hinged supported systems transfer the horizontal loads, e.g. wind or human impact, to the concrete slabs and guarantee the freedom of vertical movements of the concrete slabs (see in Fig. 15 above).

4.4.6. Design of cones

All the different cones were designed with a finite element model which covers all glass panes. The loads were defined with dead loads, wind loads and horizontal loads due to human impact. For the design of the balustrade in the public area a horizontal load of h = 3.0 kN/m was used. This high level of the load is based on the possibility of a big gathering of people. Beside these mechanical loads the

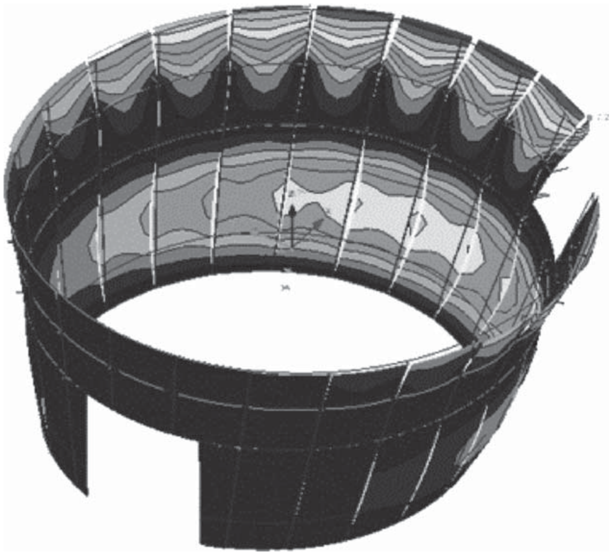

Fig. 16. Finite elements model of cone 5 (Neugebauer, 2012).

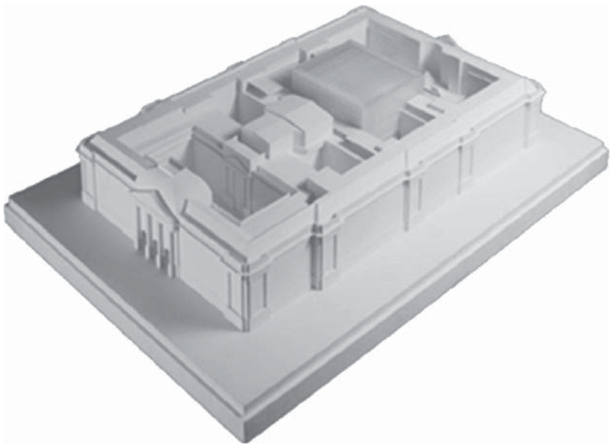

Fig. 17. Modell of the Berlin State Library (Neugebauer, 2009).

climatic loads in the insulated glass units were taken into account. These climatic loads include the difference in temperature (summer and winter), the difference in the meteorological air pressure and the difference in the altitude (between the production site and the building site). All these internal and external loads were superposed in the finite element model (Neugebauer, 2012).

4.5. State library, berlin

The thirteen storeys old building complex of the Berlin State Library with a length of 170 m and a width of 107 m is located in the heart of Berlin. For the, in the Second World War partly destroyed, a call for tenders was realized by the city council of Berlin. The famous German architect HG Merz won

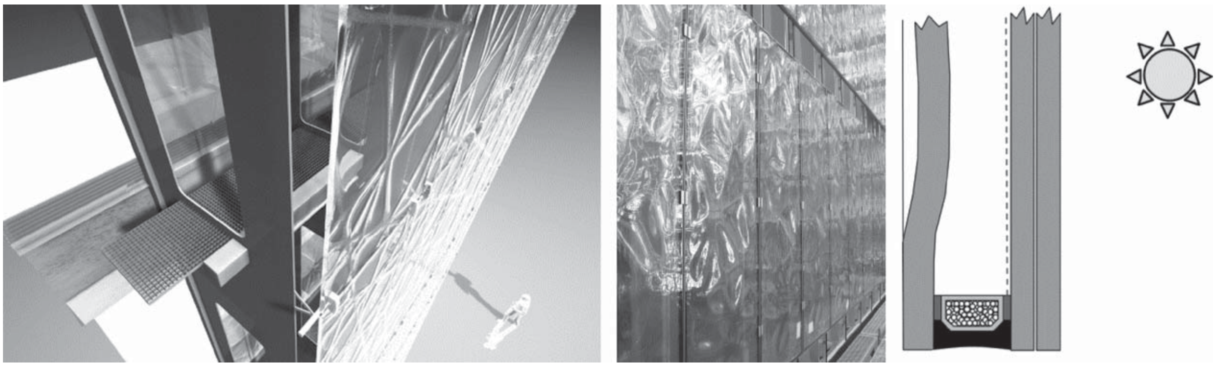

Fig. 18. Concept of the double skin facade (Neugebauer, 2009) and view of the outer skin on the site (right), cross section.

this architectural competition. The cubical structure of the new reading room was situated between two courtyards in the middle of the old building complex. The design concept of the architect was to bring as much daylight as possible into the reading room. So glass was used for the facade (Neugebauer, 2009).

The vertical cladding of the reading room was designed as a double skin facade. For the outer, secondary skin of the double skin facade, 8 mm heat-formed toughened glass panes with a lot of small dents, according to a special design of the architect, were used. The depths of these dents were designed up to approximately 20 mm. For the outer skin with a size of 2834 m² 1215 glass elements were produced. All glass elements were glued and sealed into aluminium frames. These aluminium frames were mounted at the outer side of the vertical steel structure of the facade.

The space in between the two skins is used for maintenance. The distance between the inner and the outer skin given by the architect is approximately 1 m. The gangway for the maintenance staff is covered with a steel grid, and runs in each storey through cut-outs of the vertical steel-beam (see in Fig. 18, below).

The inner, primary skin consists of insulated glass units with a 2×6 mm laminated safety tempered glass on the outer side, and 8 mm heat formed toughened glass with a lot of small dents on the inner side. The depths of these dents at the inner skin are up to approximately 10 mm. All insulated glass units were glued and sealed into aluminium frames. The aluminium frames were mounted at the inner side to the vertical steel structure of the facade. For the inner skin with a size of 1560 m² 661 insulated glass units were produced.

The picture in the middle in Fig. 18 shows the outer skin during the process of assembling. The picture shows very well the nature of the cladding with the hot deformed glass.

5. Pre-stressing

In some cases, e.g. for glass with boreholes, pre-stressed glass is demanded. Two techniques are currently available. The first possibility is thermal pre-stressing and the second is chemical treatment. A special technique is the production of e.g. front shields for cars. Very special and expensive ceramic moulds are used for such glass. This is only possible because such moulds are used for many thousands of front shields. For thermally heat treated glass there is a geometrical limit. Only for cylindrical shaped glass a thermal pre-stress is possible.

5.1. Thermal pre-stressing

At the market big machines are available to thermally strengthen and bend the glass in the same step of the process. At first the flat glass is heated up to approximately 550°C. The hot glass is moved to the next part of the machine. In this part the glass will be bent and pre-stressed. Instead of stiff roles a flexible kind of chain is used to bend the glass. Depending on the direction of these chains with regards to the axis of the machine the glass can be defined as b-shaped or c-shaped. After bending of the glass the surface is blown off with air. In principle the pre-stress process is the same as for flat glass. Thermally pre-stressed cylindrical shaped glass comes out at the end of the machine, see in Fig. 19 below.

5.2. Chemical pre-stressing

Chemically strengthened glass is a type of glass that has increased strength as a result of a post-production chemical process. When broken, it still shatters in long pointed splinters similar to float glass. For this reason, it is not considered a safety glass and must be laminated if a safety glass is required. However, chemically strengthened glass has typically a six to eight times higher bending strength in comparison to annealed glass.

The glass is chemically strengthened by a surface finishing process. Glass is submerged in a bath containing a potassium salt (typically potassium nitrate) at 300° up to 400°C. This causes sodium ions (Na) in the glass surface to be replaced by potassium ions (K) from the bath solution, see in Fig. 20 below.

These potassium ions are larger than the sodium ions and therefore wedge into the gaps left by the smaller sodium ions when they migrate to the potassium nitrate solution. This replacement of ions causes the surface of the glass to be in a state of compression and the core in compensating tension. The surface compression of chemically strengthened glass may reach up to 690 MPa, see in Fig. 20 below.

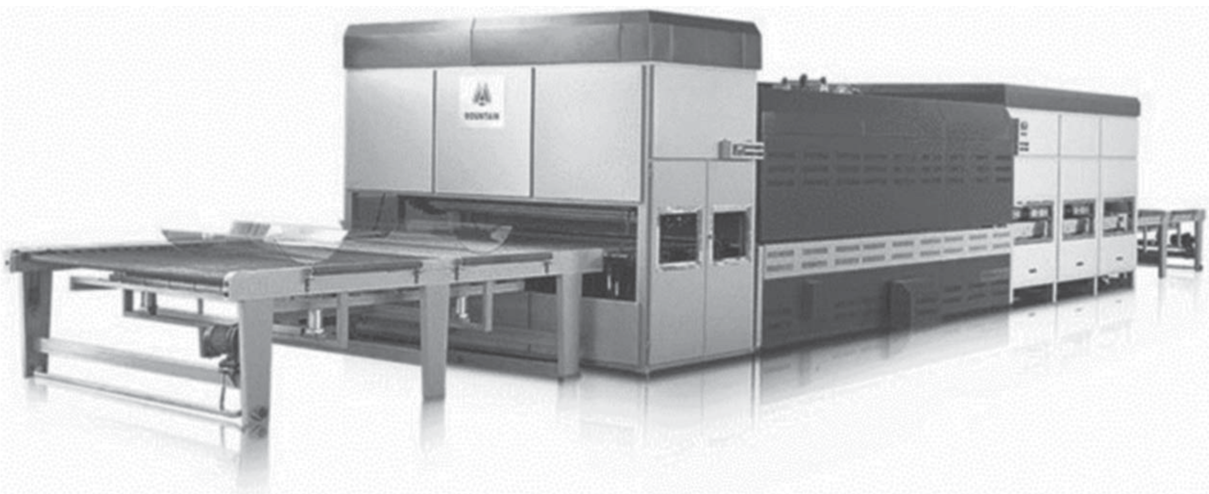

Fig. 19. Machine for thermally pre-stressed glass (Neugebauer, 2013).

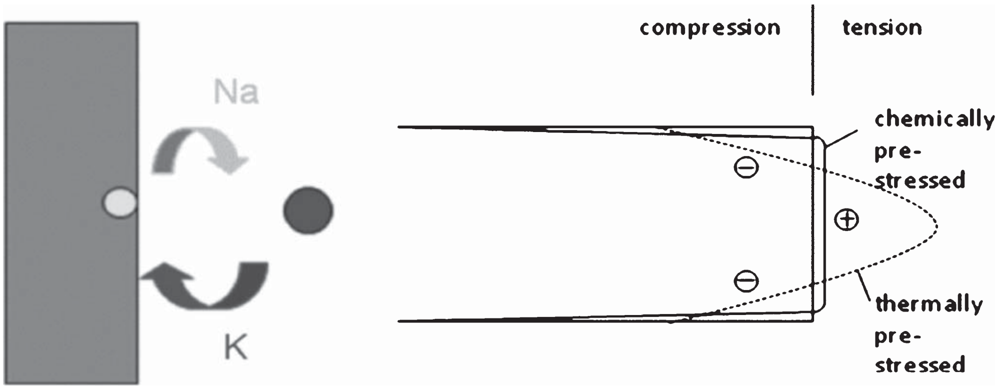

Fig. 20. Principle of chemical strengthening.

Chemical strengthening results in a strengthening similar to toughened glass. However, the process does not use extreme variations of temperature, and therefore chemically strengthened glass has little or no bow or warp, optical distortion or strain pattern. This differs from toughened glass, in which slender pieces can be significantly found (Karlson, 2010).

6. Failure

In various projects curved glass with defects can be observed. These failures can be less critical optical ones or very critical mechanical ones.

6.1. Optical failure

An example of a failure in the production method is the cylindrical shaped heat strengthened glass of a shop window found in Graz. This glass is mounted with glass fittings at the substructure of the masonry. Figure 21 below shows this window with the distorted glass. These distortions are the so called roller waves in the glass. The reason of these waves is the too high adjusted temperature in the furnace during the heat treatment. Due to the too high temperature the glass is too soft and the waves can occur (Neugebauer, 2013).

6.2. Mechanical failure

In Bolsward, The Netherlands, the 'Broerekerk' (church of the brothers), founded before the 13th century was completely ruined by a fire in 1980. In 2004 works were started to pre-serve the ruin, and it was decided to fit a new roof, designed mainly from steel and glass, onto the old church, see in Fig. 22. Cylindrical shaped heat-treated laminated safety glass was used for the glass of the roof.

While assembling the glass on the roof a glass breakage of some glass elements could be observed. After investigation of this problem the failure could be described. It was a failure happening while bending and pre-stressing the glass. The flat glass panel is placed on top of the mould and put into the furnace. As the glass is heated up, it sags into the mould until it just touches the heat resisting fabric. The deformed panel is not moved in the mould, neither the mould is moved in the airflow.

Fig. 21. Shop window with optical failures.

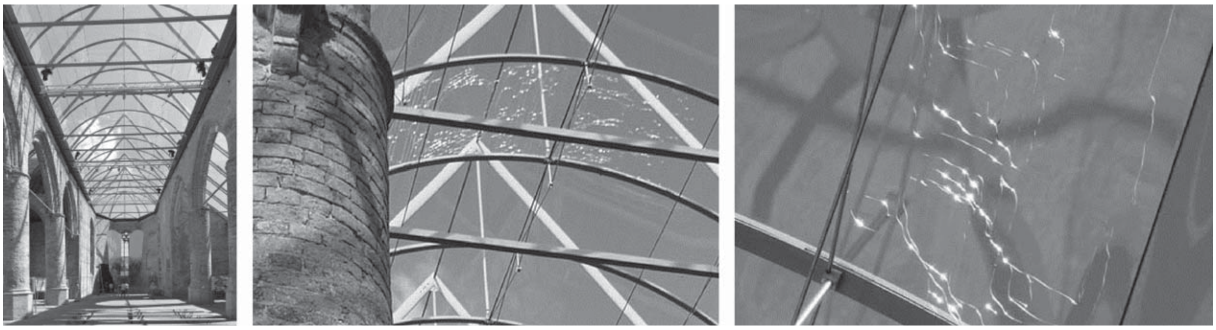

Fig. 22. Church 'Broerekerk' in Bolsward (The Netherlands) with broken glass panels.

The panel is directly cooled by cold air from the top. But from the bottom the air is hindered by the steel mould and the resisting fabric. At the supporting point no cold air reaches the hot glass pane and zones of tension instead of pressure occur on the surface of the glass. These cause an opposite effect of the pre-stress of the glass and results in much less bending strength (Niderehe, 2008).

To avoid such failures it is absolutely necessary to have the detailed knowledge about the behaviour of glass during the process at high temperature. There is a strong relationship between the size and the mass of the glass on the one hand and the duration and temperature of the production process on the other hand. Only with the combination of the right duration and temperature it is possible to produce a good quality.

7. Summary

In a lot of realized projects around the world one can find curved glass in many different applications with a big number of different geometries. These applications can principally be curved monolithic glass, laminated safety glass or insulated glass. Our focus was on the process of bringing the bended glass into a certain shape and the very difficult topic of pre-stressing it. The most used way is to bend the glass at a high temperature of more than 550° Celsius. Another kind of curved glass can be achieved in combination with the laminating process. With the cooling down at the end of the laminating process the interlayer becomes stiff enough to hold the shape by activated shear forces between the glass layers. Another possibility is to produce flat glass and bend it while mounting the glass.

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