

The Cold Bent Glass Roof of the Victoria & Albert Museum, London

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The Victoria & Albert Museum in London was recently extended with its Medieval and Renaissance Galleries. Designed by MUMA Architects (London), an existing outside courtyard has been transformed by the addition of a glass roof into a light filled exhibition space. Due to the existing geometry of the surrounding buildings, and several boundary conditions set by the architects, the surface of the roof could not be flat. Instead, it had to be twisted into an undevelopable hypar surface. Pre-engineering by Dewhurst Macfarlane (London) indicated the possibility of achieving this surface with cold bent glass panels. The experience of Octatube with this kind of surfaces as well as the development of a theory of cold bent glass panels, transformed the possibility into a reality. A further complication of the design rested in the fact that the load bearing construction of the glass roof panels was unusually long, triple laminated glass beams. To provide a suitable fail safe concept for the glass roof, it was insufficient to consider only the separate members of the construction. Instead, to describe the fail safe behaviour of the structure, all parts had to be considered to work together during an emergency situation.

Keywords: cold bent glass, hypar surface, glass beams, fail safe

1. Introduction

In 2001 Octatube introduced the use of twisted tempered glass panels in the realization of the City Hall of Alphen aan den Rijn (NL). Since then further research of the structural behaviour of twisted glass panels had been carried out by Dries Staaks, leading to a profound knowledge about its quantitative behaviour as well as quantitative approach on stresses and stability. The latter is referred to as the “Law of Staaks” [Ref. 1,2]. On the basis of the developed theory the application of twisted panels has been extended and proven to be a valuable contribution in order to realise free form twisted glass envelopes. Although the theory was investigated and set up after the first application in the town hall of Alphen, it was only after establishment of this very theory that several buildings could be provided with accurately engineered twisted roofs and flat roofs with twisted parts, where the glass panels were even insulated / laminated glass panels. Practice precludes theory in this case, but then theory opens up more opportunities in practice. A prominent building design with twisted glass was the bus station at Zuidpoort in Delft, designed by architect Mick Eekhout. The maximum cold

twisting possibilities of laminated glass were established and led to the maximum possible undulating shape of this roof.

The design by MUMA architects for the day-lit gallery roof of the Victoria & Albert Museum indicated cold twisted glass panels, not only laminated but also insulated. These panels are more rigid than laminated panels and require more twisting tensions in order to be twisted into the desired form. On top of that the architect and structural engineer designed these insulated glass panels to be supported by vulnerable glass fins. These boundary condition dictated the development of the design.

1.1. First experiences with cold twisting of glass

In 2001/2002 Octatube designed, engineered and realized its first permanent 'Blob' or 'Free Form Design' building (Town Hall of Alphen aan den Rijn) with a façade consisting of circular, conical and hyperboloidal planes. The development was during the childhood of 'blob' architecture and 'blob' management and absorbed much energy to get proper relations in a process where all designers, engineers, co-makers and contractors had to trust each other in a close collaboration. The result still did cost the client 25% more budget than initially anticipated.

This design of architect Erick van Egeraat and ABT engineers is a pre-runner of Free Form Design Architecture. The main load bearing structure has not a single piece of repetition. Octatube was selected for the engineering, production & installation of the frameless glazing façades. This building has a façade of frameless glass panels, fully screened with graphical motives of trees, leaves and flowers in quite an ad hoc fashion. The panels are supported by elliptical façade mullions 75x150 and 110x220 up to 20m height, spaced at around 1.8m, with glass support nodes in between. The high yield, slender hot rolled elliptical mullions are excellent in freestanding use of frameless glazing. Their use in Quattro façades, either vertically or horizontally and suspended from the roof, is a standard system. The glass panels, around 850 pieces, are all unique in form and print design. The glass panels have been screened on surface 2 and have a low E coating on side 3. Most of the panels are 10-spacer-10 double glazed units in fully-tempered clear glass panels; the roof panels have laminated lower panels 6.6. All panels are fully tempered.



Figure 1: Overall view of the town hall façade.

In the 'semi-Blob' geometry, parts of the façade are conical upward and downward, cylindrical, spherical, anti-clastical and only some parts are straight. However, all glass panels of these façade parts were designed to be flat, twisting was not applied here. Because of the geometrical differences between lining of the façade mullions and glass panels, the columns are positioned in varying angles to the glass panels. The glass connectors are irregular. Not one of the 90 mullions is equal to another. In the anti-clastical surface (roughly 10x10m²) the rectangular glass panels are twisted and the elliptical mullions have up to 9 bents in their longitudinal axis, which are cut and welded on jigs in the factory straight from the engineering drawings. They fitted perfectly.

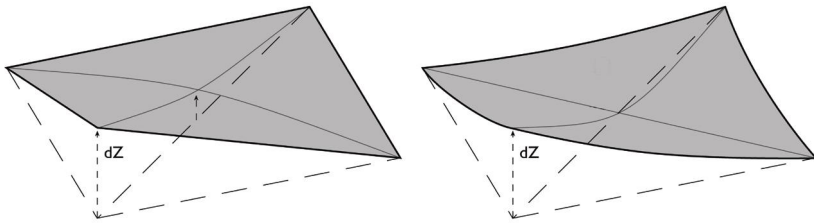


Figure 2 and 3: Schematic representation of the first and second deformation mode

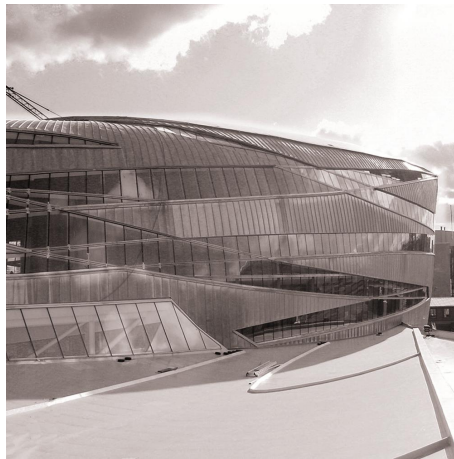


Figure 4: Spaghetti facade with cold twisted glass in the Town Hall of Alphen a/d Rijn

The back part of the town hall of Alphen aan den Rijn had a double curved surface over which glass lintels were designed by the architect EEA. As these glass lintels did not run concentrically, many of the composing glass panels had to be twisted. This was solved by cold twisting of the glass panels on site. Upper and lower profiles were U-channels. The insulated glass panels were maximally 900x2000mm large and consisted of 8 mm outer blade fully tempered and inner blade of also fully tempered 4.4.2. The silicone seals were normal butt seals. The glass was twisted out of its plane maximally

40mm. This work proved to be realizable at very economical costs, with larger risks than normal (3% breaking of panels on site during installation compared to much less than 1% for normal practice). After having completed the job, we wondered what we had done. It took the then student Dries Staaks (now one of Octatube's valued engineers) one full year to discover and describe the regularity's of cold twisting of glass panels.

1.2. Dries Staaks developed his 'Theory of Staaks' in 2003

Dries Staaks was a student at the Faculty of Architecture in Eindhoven, who did his final studies at Octatube, during the installation of the twisted glass panels in the 'spaghetti' strips at the back of the Town Hall of Alphen. He became involved with the application of practical cold twisting on site and was motivated to spend his graduation year towards analyzing and establishing a theoretical foundation for twisting of (insulated) glass panels [2]. One of the remarks of the project architect of Erick van Egeraat Architects after completion of the spaghetti strips was that the cold twisting apparently produced not a regular pattern of deformation, as was indicated by the reflections of the glass. Reflections will ruthlessly betray the flatness/continuity or deformations in the glass. Insulated glass can show bulging forms even when the apparent overpressure in the inter-space only produced a camber of a few millimetre over the glass length of 1,5 m. All defects are visible. Also in the spaghetti strips there were defects.

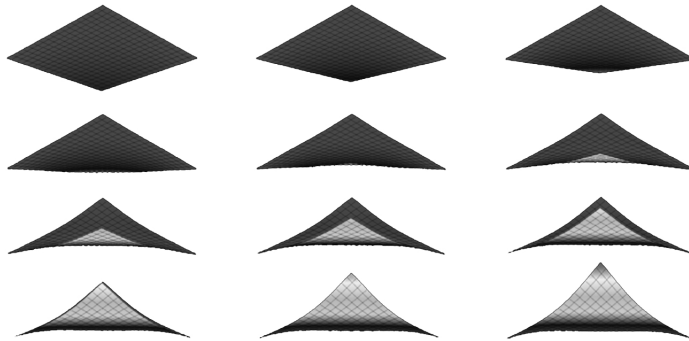


Figure 5: Staaks theory

Dries Staaks' assignment was to investigate the laws and regulations behind the deformations in twisting glass panels. His view was that glass panels are flat panels and can be bent easily cylindrically when the radius of bending curvature is constant or conically when the radius is diverging but positive. This can easily be verified with a flat piece of paper, that can also be easily curved cylindrically or conically. But when one tries to counter-form the glass, twisting the glass panel unnaturally, the resulting form results initially in an elastic deformation, but after a certain point the panel will buckle along one of the diagonal lines, depending on the shape of the panel. Similar deformation behaviour can be observed with a piece paper. Allowable deformations do not give large abnormalities and visual disturbances but when twisting further towards larger deformations all of a sudden a sharper diagonal deformations could result. In case of large continuous surfaces with cold deformed twisted glass panels in visual position

(i.e. façades, often not roofs), one has to study whether it is possible to develop a method of cold deformation that produces continuity and does not produce unpleasant irregular surprises. If this proves to be impossible, the penalty would be that all glass panels have to be made on moulds in ovens, an expensive process that is also called ‘hot-deformed’.

The law of Staaks analyses the stresses in the glass and gives an indication how far the deformations can be brought without visual disturbances. Further development between the theory and the practice of cold twisting of glass is needed in order to arrive at a point where the designing engineer safely can predict that with the limited twisting in the glass panels, the resulting reflections would produce a smooth surface.

1.3. Tramstation Zuidpoort: twisted laminated glass

The outcome of the theory of Staaks was employed in the undulating glass roof of tram station ‘Zuidpoort’ in Delft, designed by architect Mick Eekhout. The Delft tram stop roof has been designed using the maximum possibilities of cold warping in vision, resulting in a continuously warped roof which has such a size in length and height to be in harmony with the shopping centre complex building Zuidpoort in Delft.



Figure 6: Top view Tramstation Zuidpoort.

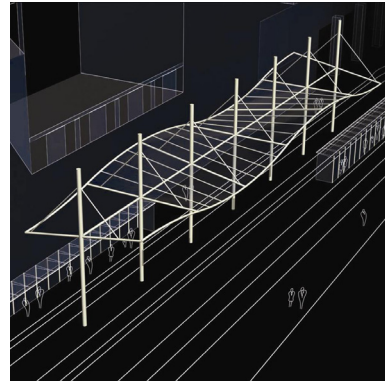


Figure 7: Draft Tramstation Zuidpoort.



Figure 8: Tramstation Zuidpoort.

2. Victoria and Albert Museum – twisted, laminated insulated glass panels on glass beams

In the following years several projects with cold twisted glass have been engineered and built, also with insulation glass. The latest project of this range has been inaugurated in December 2009 in London. The V&A Museum is one of the world's most renowned museums for art, design and crafts. It is situated in the heart of London, in South Kensington. The Medieval and Renaissance Galleries are extended and refurbished. As the space at the site of the museum is quite limited, an unused courtyard of the museum was being converted into a glass covered exhibition space.

Architecture office MUMA together with Dewhurst Macfarlane Engineers designed for this purpose a spectacular glass roof (see figures 8 and 9). The main structure of the roof is formed by laminated glass beams, heat strengthened with a maximum length of 10m. The surface of the roof is formed by insulation glass panels, which are fixed by point connectors in the glass seams to a continuous stainless steel profile on top of the glass beams (see figure 10: inside picture of mock-up of day lit gallery roof). Total area of the glass roof is approximately 370m².

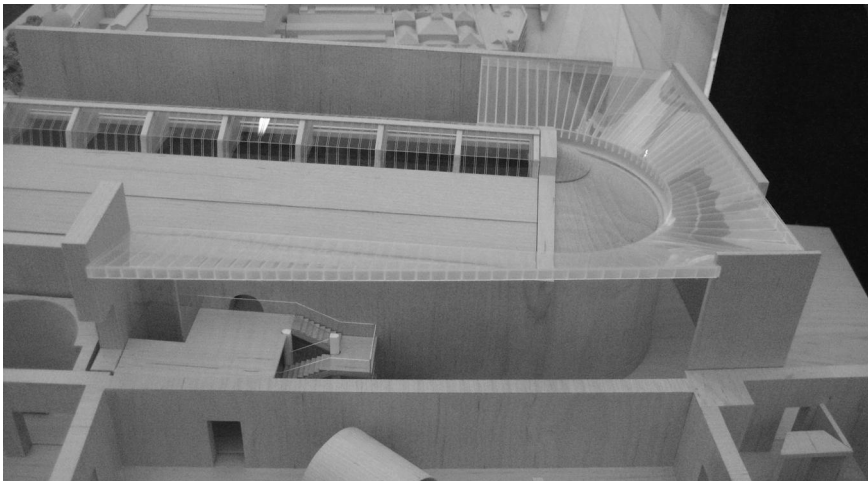


Figure 9: Model of glass roof Victoria & Albert Museum.

The design provided several challenges. Some of them were of a geometrical nature, some were concerning the safety concept. The first consideration during design phase of the project was finding a suitable safety concept for the glass roof. As the main construction is made up from laminated glass beams, damages to singular glass panes of these beams as well as failure of a whole beam have to be considered. For each of these possible failure types both the likelihood of occurrence, as well as the consequences of this occurrence were reviewed.

For failure of a single pane of a beam the likelihood of occurrence is very low. The beams are made up of heat-strengthened glass, which is considered to be almost immune against spontaneous breakage due to nickel-sulfide inclusions. But even if a failure of a single pane of a beam would occur for whatever reason, the consequences

would stay mainly monetary. The remaining panes of the beam will be sufficiently strong to carry the forces into the supports until the damage is detected by regular inspections. The glass beam can then be replaced within a couple of weeks. During these weeks the beam will be closely monitored, and if any unexpected behaviour should be noticed within this beam, the area below the beam will be closed off as a safety precaution or the beam is reinforced by steel U-channels temporarily. The risk (likelihood multiplied by consequence) of endangering people underneath is therefore sufficiently small to be acceptable.

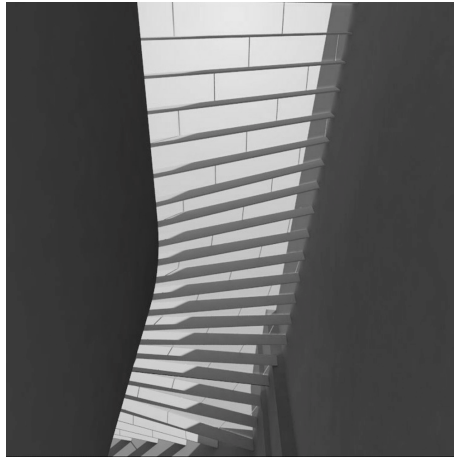


Figure 10: Internal rendering of glass roof Victoria & Albert Museum.

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For failure of all three panes of a glass beam at the same moment the likelihood of occurrence due to internal causes is even lower than for a single pane. The only reasonable cause for all 3 panes to fail simultaneously would be a direct hit by a heavy object. As this is impossible during normal opening hours of the museum (nobody has direct access to any of the glass beams during opening hours), the risk to the public by a failing glass beam is sufficiently small.

However, during maintenance work inside access to the glass roof is provided by an aerial platform. This platform could cause extensive damage to a glass beam when

handled in a wrong way. Several precautions have therefore been taken in the safety concept. The first precaution is the exclusion of all people from the Day-Lit Gallery during maintenance work, only the workers themselves are allowed to be in the area. In this way possible consequences are already limited to a small group of people. As a second precaution all hard surfaces of the aerial platform will be covered by shock absorbing material, to minimize the risk of damaging a glass beam during accidental contact. However, the necessary safety of the workers needed design impulses for the event of a completely failing glass beam. Unfortunately the workers will be always in the aerial platform, which damages the glass beam, and therefore under or at least in the vicinity of the damaged beam. They therefore need at least sufficient time to be able to leave the direct surroundings of the calamity, before the possibility of collapse of a beam arises.



Figure 11: Full scale test assembly glass roof Victoria & Albert Museum.

Here the design of the roof system becomes important. A single glass beam, without any connection to a glass roof, will fail almost instantly if all of its panes are damaged. The time for people under such a failing beam to evacuate themselves is almost nonexistent. As lives are in danger, this is not acceptable. However, if the complete system of the roof is considered, the time for evacuation is increased manifold. The glass panels forming the surface of the roof are connected to each other by silicone seams, and by special clamping plates in the seams to the top of the glass fins. These seams normally only provide the weatherproofing of the roof. In case of complete failure of a glass beam this beam will sag and hang under the glass roof surface. The glass surface of the roof will start to act as a membrane, with the silicone seams in tension. The stresses in the silicone will be sufficiently low to resist this mechanism for quite some time. The exact time is difficult to quantify from tests, as a lot of variables have an impact. The necessary time to evacuate all personnel is definitely available. The risk to the workers by a failing glass beam is therefore also sufficiently small. After the safety concept of the design was established, the other challenges of the project could be tackled.

The major geometrical challenge is the shape of the surface of the roof. Both the top and the bottom end of the roof are placed horizontally. As both lines do not run parallel in plan view, but follow two completely different shapes of the adjacent buildings (see figure 10), the surface of the roof has to be saddle shaped. This shape, also called 'hypar surface', is best known from tent structures, where this special counter curving form provides necessary stability for the tent membrane.

In case of the V&A museum it was chosen to bend the IGU (insulated Glass Units) on site into the desired shape. This process is also called 'cold bending', as the panels are fabricated as ordinary flat IGU's. The other possible option, giving the IGU the desired shape during production (also called 'hot bending', as the glass panel is placed on a mould and then heated up almost to the melting point, around 600°C), was discarded for several reasons. The first reason is the high cost for this option. Every panel would have to receive a different shape, as the hypar surface is changing its curvature continuously. About 200 different moulds would have to be made for this process. The second reason is the visual quality. During the hot bending process the surface of the glass panel will not display a completely smooth surface, but will appear slightly faceted due to the type of mould used. The tempering process itself would result in relatively strong anisotropies (if it would have been possible at all with the special hypar shape). Both aberrations are visually not desirable.

The chosen option for creating the hypar surface of the roof, 'cold bending' of the IGU's, needed careful engineering before execution could start. The stresses due to the cold bending process together with the stresses due to external forces were not to exceed the maximum allowable stresses for the used glass quality. As the cold bending process of the glass panel into a hypar shape creates compression zones in the surface of the glass panel, stability of the shape has to be checked early in the process. Depending on the shape of the glass panel as well as its support conditions the glass panel could snap through due to local instability, and display an uniaxially bent shape. Octatube calibrated their FEM models with extensive physical tests, to be able to determine this snap through point by numerical analysis. As can be seen in figure 11, the surfaces of the IGU's display a perfect hypar shape, exactly as envisioned by the architects.



Figure 12: Hypar surface of mock-up.

Another major geometrical issue was the irregular shape of the old buildings surrounding the roof area. As the detailing of the roof left only very narrow tolerance adjustment possibilities, the complete courtyard area was laser scanned and stored as a three dimensional CAD model. From this model Octatube was able to engineer and produce all parts months before starting assembly on site.

3. Conclusion

Assembly of the glass roof started in May 2009, and was finished in summer 2009. The Medieval and Renaissance Galleries were opened to the public in December 2009, displaying their famous artefacts in the beautifully designed galleries, including the spectacular new top-lit space. The super long triple laminated heat-strengthened glass fins could, without any breakage on site, be covered by cold twisted insulated glass panels, thanks to a metal channel on top of the fins that distributed local supporting forces on the complete length of the top of the laminated beams. The realized system is a safe system for use for the museums visitors and even for maintenance crews.

4. References

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