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Design and Build of a Warped Tram Station Roof in Delft

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In 1992 Walter Lockefeer and Mick Eekhout designed an office for the Glass Association in Gouda with a flamboyant glass envelope, which ended as runner-up in an architectural competition. The design was classical in architectural sense and futuristic in technical sense: it contained a pre-stressed glass membrane. In 2002 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 has 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". 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 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. The 1992 design, which was not chosen out of disbelief concerning the innovative state of its glass façade, could be entirely built today from the trustworthy glass technology. The integral innovation approach as a bridge between fundamental research, technical development and application design, each with its own habits and peculiarities, but in mutual understanding and support, shows that integral incremental developments on many levels pay off and produce new technologies for use in architecture. This contribution ends with the application of a glass roof for a warped glass roof surface, making use of the maximum cold warping possibilities of laminated glass panels.

Keywords: cold-twisted, blob-design, cold-bent, double curved architecture, blob architecture

1. Introduction

In 1991/1992 the Dutch Glass Association located in Gouda, NL, developed an architectural competition for the new headquarters of the Glass Association to be built in Woerden, near Utrecht NL. The competition jury elected the architectural firm of CPZ as the winner, as the jury was of the opinion that the 2nd price winner with its far more technically advanced proposal was not technically feasible. The second winning design was made by Walter Lockefeer and Mick Eekhout, who had collaborated earlier in the first horizontal under-spanned glass roof for a flower shop in the Netherlands in Hulst. They joined forces as Lockefeer was a specialist architect on classic buildings and Eekhout was developing glass technology for applications and structural glass. In 1990 together with architect Pieter Zaanen he had designed, engineered and build the Glass Music Hall in the Berlage Exchange in Amsterdam with the first frameless glazing in the Netherlands. He had worked as a student at the Institute of Light weight Structures of Frei Otto at Stuttgart in 1970, and having started his company Octatube in 1982 with a number of stretched membrane structures. Since then he worked on space frames, domes and developed the technology for frameless glass structures and lately glass fibre reinforced polyester structures.

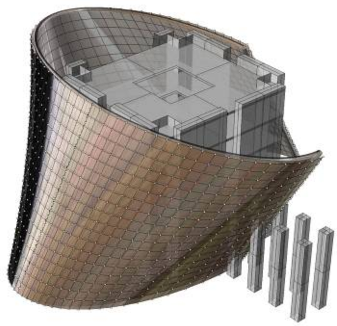

Figure 1: Design of the Glass Association House by Walter Lockefeer and Mick Eekhout 1992

Figure 2: Glass roofs Olympic Stadium by Günther Benisch and Frei Otto

Figure 3: Glass music Hall in the Exchange of Berlage

The architectural idea was to make an urban office surrounded by a glass atrium which would make the glass impression and the message for the world from the Glass Association to the world. The glass envelope would be like an all-glass stretched cable net or membrane structure, reinforced by pre-stressed steel cables. The idea was perfectly feasible in a technical sense with a proper development time planned in. Alas the jury did not realize these conditions. It was only after opening of the envelopes that the jury came to realize its mistake, but was unable to change the outcome by then. The office design of CPZ (rectangular blocks) was never realized due to a lack of funding from the side of the client. The design of Lockefeer & Eekhout was stored in history. It plays its role here as the architectural ambition directing technical research and development.

It was not until after the start of the PhD study of Lockefeer in 2006 under supervision of prof. Eekhout that the concerned Glass Association Design with the block office and the waving glass envelope received their renewed interest because of the free form design shape of the glass envelope. The shape of the glass skin, symbolic for a new future of the glass industry, proved to be a composition of 2D and 3D curved glass panels, inclusive cold bent panels and cold twisted panels in rough sizes of maximum 2x2m. (The design displays sizes of 1,2x1.2m).

Figure 4: The original designs for the Glass Association House

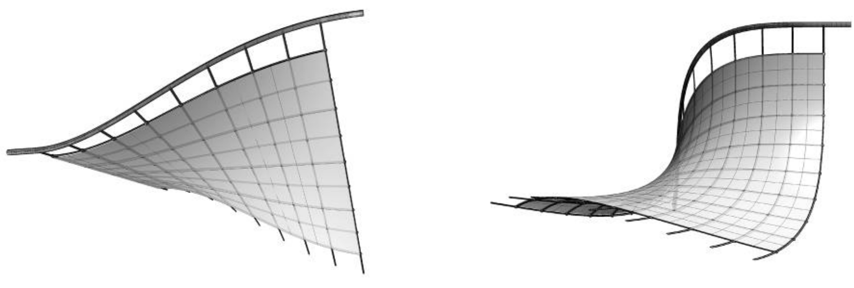

Figure 5: Details and a wild view on the waving glass envelope

In the early 'zero' years of the new millennium a sequence of Octatube projects had caused and accelerated the development of cold bent glass and cold twisted glass panels, usually laminated fully tempered glass but also insulated glass panels as well. It took 10 years before the new technical assumptions of the glass stretched membrane structures of the 1992 design were realized in different projects. Only in 2002 the back spaghetti lintels of the town Hall of Alphen were realized. These steps in the development are illustrated in this contribution and at the end a proposal is given how a pre-stressed glass membrane could be made in reality these days, bridging the gap in time of 18 years development and making sense of these incremental developments and using state-of-the-art technology.

The glass envelope was conceived in double glass units with laminated panels for safety and fully tempered glass instead of heat-strengthened glass, as is the case in an number of European norms for overhead glazing. The required strengths for cold twisting and bending would be high enough to absorb 25 to 50% of the allowable pre-stress tensions. The colour of the glass would be greenish as a low solar admission factor and a low light transmission factor would have to be chosen for the envelope.

2. 'Free Form Design' Buildings with all-glass facades

In 2002/2003 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 hyparboloidical 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. This still would cost the client 25% more budget than initially anticipated. The resulting glass façade with straight panels would show a similar appearance as the polygonal glass façade envisaged in the 1992 Glass Office design.


Figure 6 : Overall view and detail view of the town hall façade

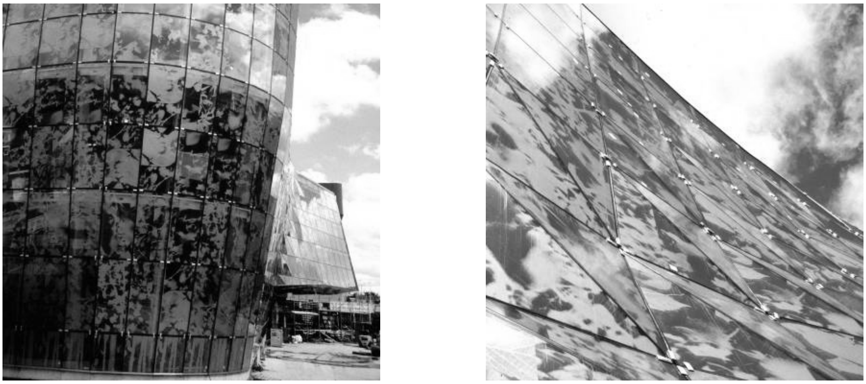

Figure 7: The triangulated and twisted façade part overall and in detail

3. The dissertation of dr.Karel Vollers in 2001: 'Twist & Build'

In 2001 Karel Vollers received his PhD with a brilliant piece of work *'Twist and Build, Creating Non-orthogonal Architecture'* in which Mick Eekhout had the privilege to be one of the two scientific supervisors. Vollers departed from urban design considerations, jumped over to the scale of the building in its architecture, then to the technological scale of the technical composition of the elements and components and related this technology to the material technology and production technology to make free form design elements and components. After that he went back all the way to urban design by proposing buildings in an urban environment. In case of glass panels one has to depart from industrially produced float glass, which could be put in its position either by pressure or by heating.

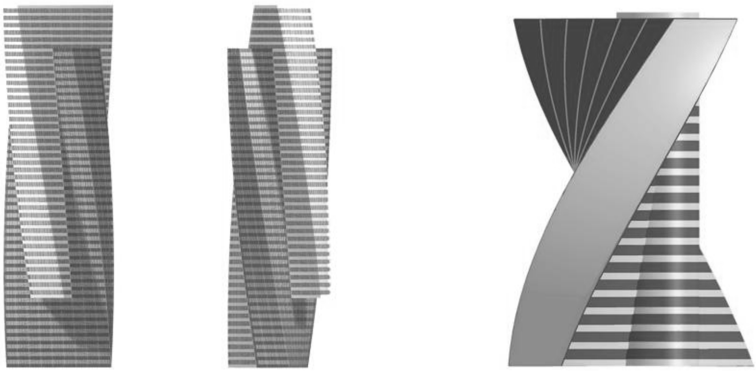

Figure 8: Two examples of Karel Vollers designs from 2001

Vollers idea was to use hot bent glass panels and he is still conducting research in the field. The author was more in favour of cold bent glass panels out of economic considerations. The glass industry did not allow this, since they do not want to encourage new developments with small turnovers and high risk profiles. From that time the ideas of Vollers were published and discussed in various conferences. As a consequence of his work major architectural firms have produced designs of twisted high-rise buildings. His contribution to the architectural vocabulary has been confirmed, although his name is seldom mentioned by the architects involved as the source of inspiration. In the modest opinion of the author Vollers stands in front of many twisted buildings in the world nowadays.

4. Blobs research group at TU Delft

The author initiated in 2001 a new research group at the department of Building technology, Faculty of Architecture of the TU Delft, called ‘Blobs’, around the person of dr. Karel Vollers and later extended this ‘Blobs’ program to 15 to 20 researchers who all were working in one of the three subprograms of Blobs / Structures, Blobs / Claddings or Blobs / Wind. In this Blobs program Vollers is performing his research on curved glass, the continuity of curved glass panels in a large glazing façade and he also executes bending experiments and tests. His recent reports witness these results. This Challenging Glass conference paper illustrates the incremental progress in multiple levels of the chain of 6 rings (as displayed in Figure 10) of related sciences which in integral collaboration can produce better results than many individual and isolated researches would do individually, without relationship towards the demanding side of architecture. The scheme involves on the left hand side fundamental research (in this case the theory of Staaks), cold twisting glass panels, the central part of technology and system development in frameless glazing and the modus operandi of twisting on site and on the right hand side the architectural application designs of the 1992 Glass Association House and on the extreme right the free re-design of the 2007 Glass Office House.

5. First experiences with cold twisting of glass

After the successful engineering and testing of the frameless glass façade of the Town Hall of Alphen, Octatube also developed the twisted ‘spaghetti’ glass lintels in the back windows of the Town Hall. Here the glass panels were 1x2m in size, triple layered (laminated inside, outside single; all 3 panels in fully tempered glass), where the glass panels were twisted roughly 50 mm out of its plane. The percentage of breaking on the building site was 5%, 5x more than the usual 1%, but acceptable at the time.

Figure 10: Overall view of the spaghetti strips

The glass panels 6+6.6.2 were produced as flat sealed glass panels and twisted on site in between a lower u-formed brim and an upper one, which would restrain the twisting forces from the glass panels. In general the structural analysis proved that 25% of the available stresses in the glass panels were consumed by the cold twisting, while the other 75% would be left for the stresses due to wind loads. One of the unforeseen consequences of the cold twisting was that the glass panels had, tangentially seen, a 'funny' form, a sort of arbitrary bulging seemed to appear.

6. 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 millimeters over the glass length of 1,5 m. All defects are visible. Also in the spaghetti strips there were defects.

So 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. A flat piece of paper can be curved cylindrically of conically. But when one tries to counter-form the glass, twisting the glass panel unnaturally, the resulting form results initially in an elastic deformation and up to a certain point the panel will buckle along one of the diagonal lines, depending of the shape of the panel. Allowable deformations do not give large abnormalities and visual disturbances but when twisting 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. The penalty is that all glass panels have to be made on a jig, a mould and have to be hot-deformed, which has other problems as described by Mick Eekhout et al in Tampere 2007 [3].

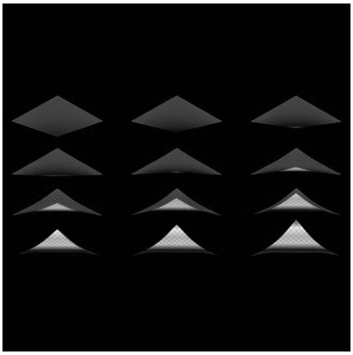

Figure 11: Staaks theory

The law of Staaks' analysis the tensions 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.

7. Applications of theory and practice in the Tram Station Canopy in Delft

The outside of the South Gate shopping centre in Delft was to be provided with station for trams and busses, which basically was conceived by the master plan architect Bob van Reeth (B) as a flat roof on columns. Mick Eekhout made an architectural design on the basis of the town coat of arms of Delft which contains waving breast as Delft used to be a harbour town in the 16th and 17th century (with Delftshaven, the place where the Pilgrim Fathers took off to New England) as their harbour. This Delftshaven harbour is now enclosed by and a part of Rotterdam). He designed a waving roof in the scale of the building behind it: much larger and higher than necessary for the users of public transport. The roof was entirely covered with glass panels, fixed on a tubular steel structure and stabilized by 7 tapered masts, which would stabilize the outrigging steel structures by guy rods.

Figure 13: Glass canopy of "South Gate" tram stop

The glass panels had a deformation of 70 mm per panel of 2x2m, depending of the location in the roof, the panels would have form hardly any to maximum torsional deformation. Using flat panels would be much cheaper that hot deformed glass panels and would make the project feasible with the client's budget. as the size of the panels had to be 8.8.2 in heat strengthened glass. Even rectangular panels would offer economic advantages over conically shaped panels, whatever the small the tapering would be as the tapering would change industrial production back to handicraft production. the panels could be kept rectangular. The actual deformation in the plane of the glass was found in the seams, which were 10 to 20 mm wide, diverging over the lengths of the glass panels. The roof is at a height of 6 m (because of the electrical installation on top of the tram) and the diverging seams are hardly noticeable for the specialist, let alone for the bystander. The top roof view from the balcony of the nearby housing apartments show that the glass reflections are not yet continuous as one can follow the lines of masts and guy rods: they are not continuous over the twisted panels. Nevertheless they give a comfortable view.

Figure 14: Glass roof from above

8. Towards a trustworthy free form curved glass façade for the 1992 Design

The original design of 1992 contained a more or less traditional building block of roughly $20x20x20m^3$, surrounded by the freely positioned glass envelope roughly 25x50m in plan and 20m height. The ellipse form has a 90^o twist over the surface of 25x50m. The glass enveloping form could be constructed in several ways, from a cable net between an upper ring and bottom foundation, to a single layered space frame in vertical and horizontal direction or a simple structure of more or less vertical tubular poles directly stabilizing the glass panels, fixed at the top by a top circular ring, elliptical in plan and stabilized to the building volume at points. The structural design is not the subject of this conference so will be held as global as described.

The glass envelope, when easily to be made, could inspire architects to design new envelopes in the spirit that Karel Vollers worked out in his dissertation [1] and still is researching on. Architect Walter Lockefeer made some more drawings glass buildings with twisted elliptical envelopes, playing with the cubical mass, the rotation and twisted envelope, the reflections on the glass panels and the supporting tubular steel structure. It is even possible to think of a complete office building with a central glass covered atrium and the glass façade could be the office outside skin. Independent tubular steel structures would enable the architectural designer, thinking as a sculptor, to play with masses and elegance, with continuity and interruptions.

The enveloping glass façade could of course be made in flat panels, giving the envelope a diamante-like shape because of its polygonal reflections. But seen the above described technological innovations, it is possible to design an continuous smooth glass surface where each panel is pre-curved, which would make a more abstract outlook for the glass shape, a giant green glass sculpture. Although for site-curving the cable net has to be strengthened by a tubular space frame, and this means an internal continuous space frame of tubes, on which stools or saddles are fixed for fixing the glass panels to this frame on as many places as the twisting requires. On the outside one would seen the small glass connection pads and the façade would be a continuous green of greenish surface, depending of the choice of coatings and glass colours. Other colours could be used as well like grey, which would make the elliptical cylinder black of even silverfish reflective to get a maximum solar reflection but also a ruthless judgment on possible deformations due to the cold bending.

9. Conclusion

The progress in 18 years of incremental development in cold bent and cold twisted glass towards autonomous glass envelopes is accelerated by the pulling and pushing forces of theory and praxis, of ideas and new concepts (with design and engineering capabilities) on the one side and hands and tools (with industrial production and installation capabilities) on the other side and a firm and continuous belief in inventions which would lead to successful innovations in the long run, in this case over a period of 15 years, half a generation. Sometimes ideas from dreaming architects could be too early in time and the industry has to bridge the gap between the dream and reality by taking steps towards that goal and only after awhile realization on economic grounds is feasible. The industry could also dream and develop possibilities which are not used by the consuming field of architects if these ideas do not match with or do not inspire architect's wishes.

At this point in time it could be said that cold bent glass and cold twisted glass has been developed up to a point where the application in buildings is feasible, but it requires utmost engineering care as the experiences are limited. 'Me-too' followers will no doubt generate their own problems if they do not take the extensive precautions that (in the experience of the authors) usually accommodate these developments in projects.

10. References

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