30 years of Dutch Glass Developments and Innovations

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Abstract

Octatube has been on the forefronts of innovations of glass structures since 25 years. Beginning with the Glass Music Hall (1990) in Amsterdam 10x10x22m3 with tensile loaded glass, as the first structural glass project in the Netherlands; a 10x10m2 canopy in Eindhoven with compressed glass panels; the highest glass façade with tensile truss stabilizations 52m high and 16 m width in Tel Aviv. Different Quattro glass nodes were developed. Even one system for seismic resistant applications in Japan. This system of tensile stabilizations was also applied in flat glass roofs often 30x30m2 with a macro stabilization system and a mini system to cover modules of 8x8m2. The connection from the earlier single glass, laminated glass and insulated glass units is fully bolted, in later innovations half bolted/half glued connections are developed and applied as also completely glued connections. Added to these developments of structural tensile stabilizations, Quattro connections and glued connections is the elegance of slenderness and beauty. Round tubes even are developed to elliptical cross sections of different form. Strong to withhold wind forces and slender in its silhouette, likes mast of sailing ships, but far stronger. The current experiments are towards the use of glass fins in roofs and facades covered with flat IGU panels, cold bent IGU panels or cold twisted glass IGU panels, for which use special details were developed that reinforce those glass fins to resist those details and loadings. Also the safety behavior of glass fins is a major concern in order to increase the safe use of overhead glazing.

1. Introduction

More than 30 years of continuous glass developments have passed in my design and build company Octatube. Looking over back in history a long process of incremental inventions, innovations, developments on different technical levels, continuous research and applications of new knowledge and insight has been endured, which still is continuing these days. What stays is the quest for incremental innovations from a designer's point of view, with the absolute wish to realize dreams. The vehicle is a design & build company, led by a designer, at the same time responsible for realization. I have built spatial structures since 1975 as an architect and illegal builder. In 1983 Octatube was initiated as a design & build company. At the moment with 90 staff a medium sized company working in many places over the world. The last 30 years many inventions were developed and realized, so they became innovations. From 1992 to 2015 I held the position of part-time fill professor of Product Development at the faculty of Architecture, which gave possibilities to have more fundamental problems be studied in the Chair by staff and students. They resulted in for example: structural connections between glass panels (by Rik Grashoff), in twisted glass panels in twisted buildings (dr. Karel Vollers), in a theory of cold warping of glass (by Dries Staaks), in strong glass columns (by Joost Pastunnik) and in a connection system for glass panels (by Fokke van Gijn). Their inventions were published widely in my articles and books.

2. Early period of glass claddings

- Laminated glass façade OZ Building Tel Aviv, 1994 52 m high and 16 m wide, with horizontal tensile stabilizations and vertical deadweight suspensions upward to the roof of the building, laminated 6.6.2 fully tempered glass with mechanical Quattro fixings (arch. Avram Yaski). Laminated glass also because of the war-like environment. The steel structure is an open system, connected between the floors at each 3.6m vertically. The building houses the Dutch embassy.

Figure 1: Façade of the OZ building

- Typhoon resistant glass façade with steel stabilizations in the City Corp skyscraper, Hong Kong, 1994 for laminated 20.3.2 glass panels, fully tempered 12 m wide and 32 m high with typhoon loading of 5,5kN/m² (arch. Rocco Jim). Again an open structural system. The skyscraper was built in a velocity of 1 storey each 24 h, in order to attain a super short building period and complete writing off of the building before the handing over of Hong Kong to the republic of China in 1997. However the building is still occupied as anticipated originally.

-Seismic resistant Quattro node for Central Glass of Japan in a test rig with 6.6.2 mm glass panels (2x2m2) to become the Quattro SR (Seismic Resistant) system, able to cope with horizontal deformation of rows of panels on top of each other shifting more than 20 mm between rows of glass panels. One application for an hospital in Tokyo, 1996. the application survived the Hanshin Earthquake of 1995 (with 6.400 casualties and 200.000 buildings destroyed, mainly in Kobe).

- Horizontal roof for the Natural History Museum (arch. Jelle de Jong) in Leeuwarden, NL, with an independently stabilized steel structure (table model on 4 masts), macro and mini system of tensile stabilizations and insulated glass panels 10 + 6.6.2. fully tempered; 2004 Closed structural system. The 4 masts are stabilized by upper and lower stabilizers connecting the masts to an horizontal framework of round tubes, between which the mini-stabilization is connected. The atrium steel structure touches the existing timber roof structure only at the edges with a neoprene flashing.

Figure 2: Atrium covering Natural History Museum, Leeuwaarden

- Glass cube for the Santander Bank, Madrid, 30x30m in plan, 21m high with tensile stabilized tubular columns and trusses, (closed structural system) connections with Quattro nodes and covering with insulated glass panels in the facades and laminated insulated glass panels in the roof. The drainage of the glass panels via a glass gutter and internally down the columns in separate internal drainpipes.

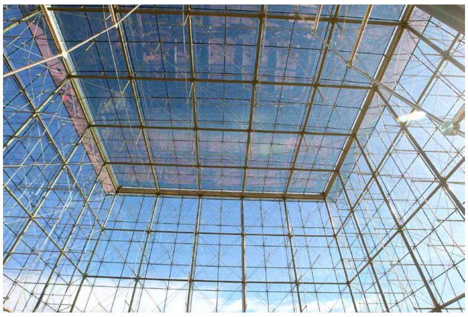


Figure 3 + 4: Glass cube, Madrid

3. Quattro Glass Connection systems

In line with the developments of the late 80s the original connections were designed by RFR in the Serres of la Villette. They were H shaped to connect vertical panels mainly. My first connections were X-shaped not to interfere with the design of RFR. They were called ' Quattro' nodes. Connecting 4 glass panels at their corner areas, around 100 x 100 mm from the corners, to be exact, so that the nodes were roughly 200x200mm sized. The first applications were single glass panels, later followed by laminated panels, insulated panels and insulated laminated glass panels.

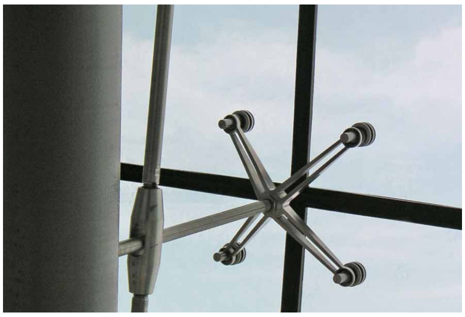


Figure 5: Detail of glass connection

The principle of connection stayed in all of these cases point corner connections at 100x100mm distances (150x150mm in the Madrid cube). These connections came out of architectural considerations to make glass planes without aluminum or steel frames. The point connections at 100 mm from the corner tips of the glass panels were more efficient that the extreme corners, the center of vertical and horizontal seams in terms of bending moment in the glass panels. For panels 2x2m² the bending moment of 1.8x1.8m² is 80% less.

In times of wealth more glass is understandable. Yin the near future the embedded energy in buildings will have to be reduced, which will bring back this theme in the table. The historical development was as follows:

- The first connectors coped with the steel bolt connections on the inside of the glass holes. The first application were pre-stressed connections, with increased shear surface friction by sand paper washers. This could only be done with solid glass panels like the 8 mm panels of the Glass Music Hall. And could only be done inside, without rain, snow or frost.

- The alternative connection is with shear friction against the glass hole, form the stem of the bolt and an interlayer of deformable material like POM of nylon, so that the steel shaft should not break the glass in the surface of the glass hole. Several materials were researched and tested.

- This is valid solution both for solid glass as well as for laminated glass panels.

- Initially when insulated glass panels were targeted, the first attempts by others were done in making holes in both panes of the double glass panel and making a watertight and gastight connection between both panes, so that the air-tightness of the air-cavity was guaranteed. However how can the industry guarantee such solutions when they are only done on project base?

- So in 1995 for the project of the Netherlands Architectural Institute (NAi) in Rotterdam the double glass penetration was brought back to only penetration of the inner pane. The outer pane was connected by silicone sealant to the inside pane. So research and tests were done. The air-tightness of these panels was only guaranteed by Octatube, the glass manufacturers did not. Only after 5 years of projects with this type of connections and no damages or failures, they took over the guarantees.

- When 2 glass holes was the obvious solution and 1 hole out of 2 was experimental and innovative, there would be one step further to make: no holes at all. The solution was to glue a stainless steel saucer to the inside face of the inner pane of the double glass panel. In the inner pane a threaded hole would function as a flat and deformed nut, glued to the glass surface. The inner panel would then be chemically connected to the connecting element. The outside panel would be structurally sealed to the inner pane.

4. Cold bending and twisting of glass panels

The early projects of 'Free Form Architecture' just after the millennium turn showed glass planes that were not flat but bent or twisted. The normal way of doing would be to heat the glass panels, deform them and cool them down and make the required laminated of insulated glass panels out of these hot bent or twisted panels. Hot treatment is expensive, requires molding and much attention.

Up to a certain degree glass panels, like each flat panel can be bent or distorted. The thinner the panel, the easier this can be done. The Municipal Pavilion at the Floriade of 2002 in Hoofddorp (near Schiphol) as designed by Asymptote Architects contained curved glass panels. The project had a tight budget and many other problems. The proposal was made to buy flat laminated glass panels 6.6.2 of fully tempered glass, 2x2m² and to bend them on site on the substructure. Structural analysis showed that 50% of the maximum bending stresses would be consumed by cold bending and maximum stressed caused by wind loadings was less than the other 50%.

Figure 6 + 7: Municipal pavilion at the Floriade of 2002, Hoofddorp

For the Town Hall in Alphen aan den Rijn, NL, (arch Erik van Egeraat) ribbon formed glass windows were designed on a more or less free form spherical surface. This resulted in 'spaghetti-lintels' of which the individual panels were twisted in form around 50 mm out of the plane of a panel 1 x 2m².

Experimentation in the Octatube factory showed that deformation was possible by cold twisting. The upper and lower supporting line had to be rigid and consisted of double U-profiles. We had to slide the panel into the U profile, twist the upper part of the panel and force it in the upper panel. I have to admit that we had 500 % more breakage during installation (i.e. 5 panels in stead of only one). This project was realized on site , sealed and no breakages or leakages were detected ever since the installation in 2003. One year later student Dries Staaks would develop his cold bending 'Theory of Staaks', which was published in GPD symposium days of 2007. Cold bending was possible and could be engineered trustworthy since 2003.

Figure 8: Town Hall in Alphen aan den Rijn

In 2008 a warped glass roof for the bus and tram station 'Zuidpoort' in Delft was designed and realized. Flat panels were used to show the maximum deformation of flat glass panels to become a fluently bent and curving roof surface. The distortion between the rectangular panels was taken up entirely in the width of the silicone seams.

Figure 9: Tram station roof, Delft

5. Glass fin structures

After the initial investments of Seele and China to produce for Apple stores larger fins, production possibilities grew. The Seele fins are perfectly made, but expensive. The China fins require an engineer to supervise the project production in order to assure the proper quality. And there is the question of shipment and transport over a long distance and with 4 weeks of time from China overseas to Europe. In the mean time glass fins are made in triple laminations: on either side a glass pane can be damaged and inactive and still the central one has to function. Anyway, fins of different and larger lengths are possible.

First major project with fins of different lengths and angles in the roof was for the Victoria & Albert Museum in London, arch. Muma, where insulated and laminated glass panels were forces in warped form in the fins. For that purpose the fins got a stainless steel top profile so that local tensions form twisting the roof panels would be distributed more evenly on the glass fins. The translucent PVB film in the laminated beams resulted in an astonishing beauty from the beams as wings.

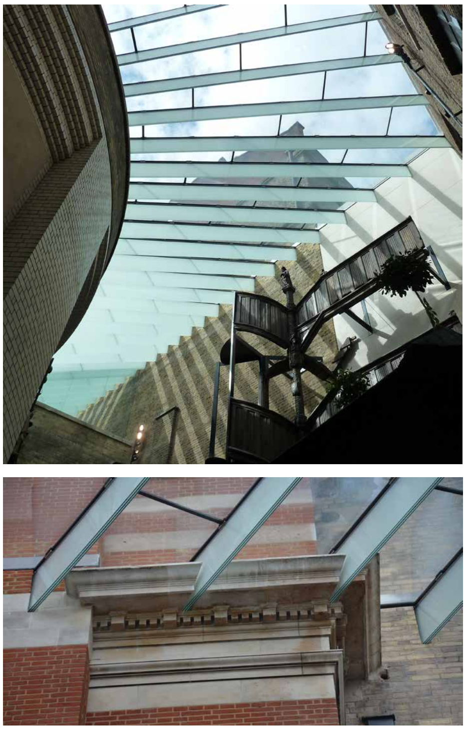
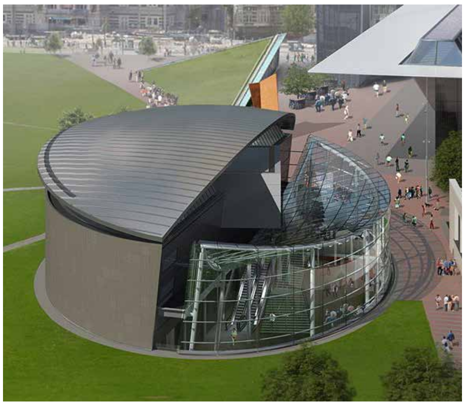


Figure 10 + 11: Laminated glass fins in the Victoria & Albert Museum, London

In the atrium covering of the municipal museum of The Hague similar glass fins were employed as the whitish secondary beams, while the primary beams were made in low iron glass, quadruple laminated, spanning 13 m in a width of 10m, so heavy loaded glass fins. In counter light they are almost invisible.

Figure 12: Atrium covering Municipal Museum The Hague

For the Van Gogh museum entrance in Amsterdam similar glass fins were employed, but this time completely transparent, in low iron glass, over which the roof panels and the cold bent insulated façade panels were forced from flat into in curved form by an electrical robot embrace.



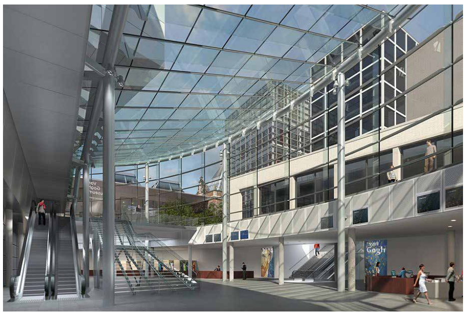


Figure 13 + 14: Exterior and interior view of the extension of the Van Gogh Museum, Amsterdam

6. Cable stayed glass facades

The INHolland poly-technical school in Delft, arch. Rijk Rietveld, has 3 facades of 13 m high in single pre-stressed Aramid cables for stabilization against wind loading (2009). These Aramid cables were designed and engineered to run vertically in carbon fiber tubes, fixed in between the metal air spacers between inner and outer panels. Both faces of the insulated glass panels were chosen as laminated fully tempered glass panes. At the last moment, just before starting the production the glass producing company refused the guarantee on the perforations of the carbon fiber trough the spacers, basically as there had been too short time to do extensive testing. As a result of which 2 large facades were made in insulated glass panels, while the Aramid cables would run through the fabricated carbon fiber tubes, but all on the inside of the glass façade. So a traditional solution, be it that the single cable was an innovation. The poly-technical school has a Composite Laboratory, for that reason they wanted as much composites as possible. The third façade has been made as originally planned, even with a carbon fiber spacer and separate hydrating tubes visible in the cab very, and all details as designed and engineered. The deadweight of the glass panels is suspended by stainless steel hangers in the vertical seams upward to the roof structure. The statical analysis of the cable stayed façade showed that the maximal horizontal deformation due to wind load would be 300 mm inward and outward. This was the reason why the corners were tailored with an insulated rubber membrane in lens form, so that both façade would not touch one another during maximum wind loading and cause any cracking of the glass panels.

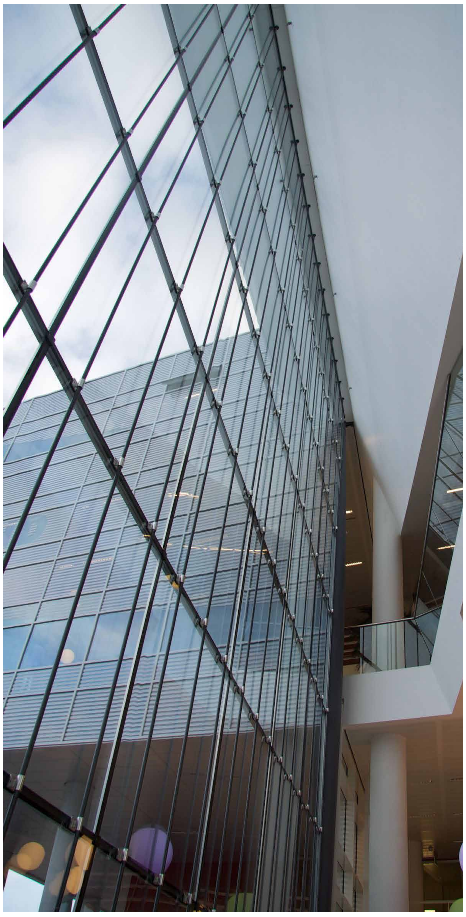


Figure 15 + 16: Facade of the INHolland poly-technical school, Delft

The latest cable stayed structure are the two glass facades of the Markthal in Rotterdam, sized 42 m wide and 34 m high, arch. Winy Maas / MVRDV. Stabilizing structure is a cable net of 30 mm diameter galvanized steel cables spaced 1.5 m, so that each second pair would directly lead in its pre-stress forces in a floor of the surrounding apartments. The level of pre-stress in the steel cables is 30kN. After that relative relaxation the analyzed deformation of the cable net will be 700 mm inward and outward, depending of the wind loading. Glass panels are laminated 6.6.2mm heat-strengthened glass panels fixed at the 4 corner tips in a circular cable-and-glass connector.

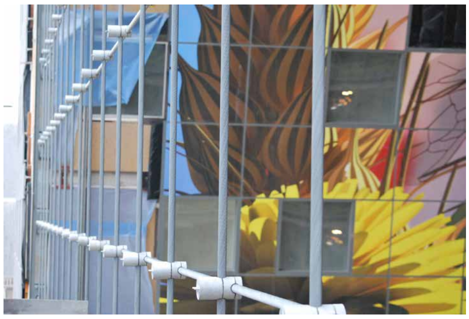


Figure 17 + 18: Glass facade of the Market hall, Rotterdam (upper image not yet glazed)

7.GRP sandwich shell structures

For the Rabin Center in Tel Aviv a system of Free Form sandwich shells was developed, prototyped, engineered, produced and realized on the designated site. It was a highly innovative adventure, caused by as much as 8 innovations in one process. The specific innovations were:

- Free form geometry of the building;
- Juggling with a number of non-connected computer programs in use;
- Use of glass fibre reinforced polyester as building material;
- Vacuum injection production methode for composite segments;
- Structural system pf sandwich type shell structures;
- Complex interlocking of prefabricated components;
- Main production off shored to a composite yachting industry;
- Complicated site activities out of view at 5000 km from Delft;
- Building in a critical governmental approval environment.

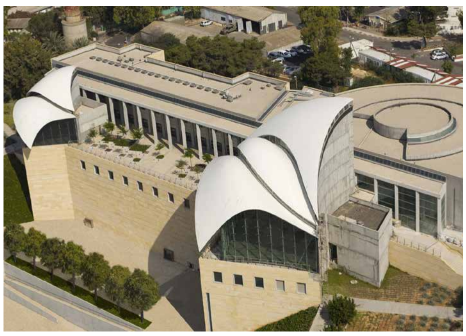


Figure 19: Rabin Center in Tel Aviv

The principle idea was the result of in-house brainstorms with the co-makers and their experienced advisors under the leading spirit of Octatube, influenced by the industrial glass fibre reinforced polyester (GRP) production processes from the yachting industry and discussed with some of the colleague-professors of TU Delft. The process of design & engineering, made use of state-of-the-art design and engineering computer programs, on transfer and adaptation of technology from the yachting industry but relied even more on the abilities and imagination of the technical designer to develop this complex process diligently. A Building Information Model (BIM) was made in this project out of absolute geometical necessity. This project can only be described exactly in all of its elements and components, otherwise the components will never fit.
So the free form geometry of the total building (roof+facades of the Library and Great Hall) is composed of the free form components and elements with their specifically described geometry. The tolerances between these components is a next point of ever lasting attention.

The production phases were greatly influenced by the transfer of technology from yachting industry, although the architectural application, mainly in its size as roof wings, but also in transport, shipment and assembly, had to be adapted and developed on the building industry's level of technology and pricing. Juggling with tolerances during production and installation was of prime importance.

The result marks a new era, the renaissance of the shell structures, once popular in architecture in the 1960-ies when Felix Candela built his thin concrete shells in Mexico, but they disappeared since. 'Liquid design' architecture enhances another and completely free form geometry of buildings. The building industry calls these projects 'liquid design nightmares'. Realising free form design dreams requires the highest skills available.

8. Conclusions

Thirty years of incremental glass innovations both on the level of the load-bearing tensile main structures, the glass panels connectors and the glass panels, with an increasing technical function of the glass panels has enlarged the possibilities of glass in a structural sense. The attitude was based on architectural concepts of complete transparency, working this out in a climate comforting and technically feasible way. And always within the constraints of fixed project budgets. The 'design & build' approach of a specialized company for facades and roof structure has paid off in quicker solutions than designers can design, engineer can engineer and producers can imagine how to realize these dreams of which they usually get all responsibilities and liabilities and hardly the fame. But this evolution of experimenting on the forefront of glass innovations was worth while.