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Editorial

Structural Glass is defined as an application of the material glass in a main bearing structure of for example a building or a bridge. Involvement started for the author in 1986, with designing and building of the Sonsbeek pavilion and continues, up to present, with the completion of the Taipei Performing Arts Centre expected in 2019. This editorial is divided in four chapters; the first one concentrates on bridges, the second on facades, the third on cast glass and the last chapter is on future developments. Ongoing research is discussed at the end of each chapter.

One could say that the Roman, bronzed framed, glass panels, known from excavations in Pompeii, were the first application of glass as “structure”: they had to withstand wind load and the influences of the outside climate. However, this is a secondary structure, what we are now looking for is the use of glass in primary structures and, very important, because glass is a delicate material, these primary glass structures have to be robust, according to the demands of the Eurocodes.

1 Concept: Bridge

1.1 *Bridge Rotterdam, realized in 1994, architect Dirk Jan Postel of Kraayvanger*

A glass food bridge spans a 3.5-meter-wide space between two buildings in the city of Rotterdam, the Netherlands (fig. 1). The architect wished that all structural components were made of glass. For safety reasons we used laminated glass, mostly float glass; only for the floor and the two walls tempered, laminated glass was used. Small stainless steel connectors were installed to guarantee structural coherence. The bridge survived two serious attacks by hooligans throwing stones but did not fall apart or crash down. The only results of these vandal acts were the costly repairs that had to be undertaken.

1.2 *Bridge Hoofddorp, study 1999-2002, architect Joris Luchinger*

For a large horticultural exhibition, the Floriade, an entrance bridge over a 20-meter canal was necessary (fig. 2). A design competition for young architects was held for a very special bridge. Inspired by an art work by Andy Goldsworthy (a bridge formed by icicles) he designed a glass bridge with big icicles made from glass panels. The icicles were clamped in the abutments at the banks of the canal, each cantilevering about 10 meter from



Figure 1. Bridge Rotterdam, the Netherlands

there. Each icicle was formed by 3 triangularly shaped glass panels. Four sets of big beams were laid out at a centre to centre distance of 1 meter. Perpendicular to the big beams 3000 small beams were placed. The bridge was tendered out and proved to be ten times as expensive as a standard steel bridge. A political decision was quickly made and this beautiful design disappeared in the future as un-build. Not everything was lost; for the

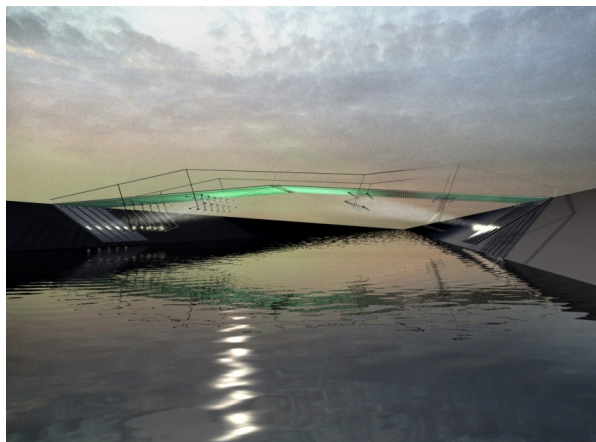


Figure 2. Bridge design for the Floriade in Hoofddorp, the Netherlands

technique of the holes was later used in a big staircase in the Heerema office building in Leiden.

1.3 Glass Truss Bridge, architect/ engineer Delft University of Technology

In 2016 a competition was held for technicians of the Delft University to design a bridge over a 14-meter-wide canal for the Green Village (fig. 3, 4). The Green Village is an area of the campus of the Delft University where studies in sustainable techniques are employed. Consequently, this bridge had to be as sustainable as possible. The design team led by the author decided to propose an arch bridge made from massive cast glass blocks. This concept will be explained in the chapter 3 (p. 10). An arch only starts to work properly when the last stone is put in his place. So a supporting structure was necessary to make the Glass Arch Bridge. This was the Glass Truss Bridge; a lenticular shaped Warren truss with glass diagonals. The glass diagonals are formed by a bundle of six massive glass bars of 20 mm diameter with a steel bar of 12 mm in the middle. The Glass Truss Bridge was built in the Stevin II lab close by the building site by technicians of the Delft University. To take all doubts away regarding the structural safety of this experimental bridge a group of 60 students from the Delft University marched over the bridge, proofing that the Glass Truss Bridge is very strong and capable of carrying large loads.

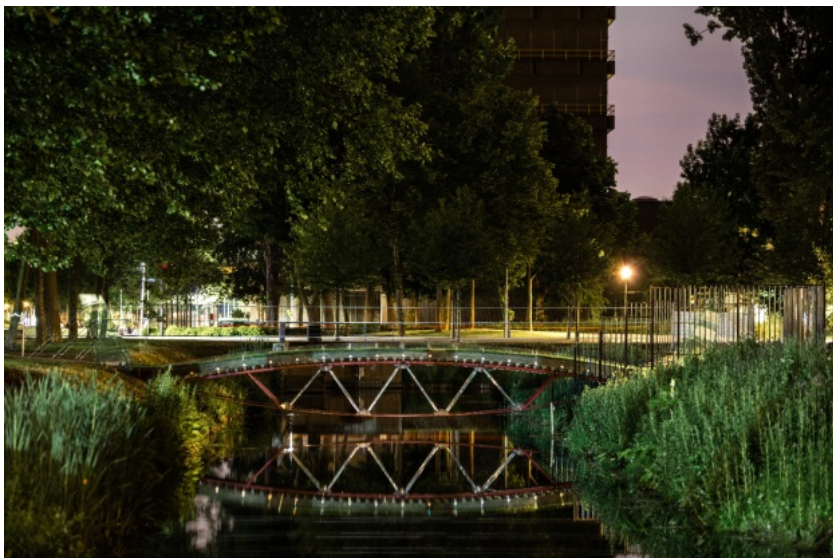


Figure 3. The Glass Truss Bridge at Delft University campus, the Netherlands



Figure 4. Test loading the Glass Truss Bridge

1.4 *Glass Swing for the 2018 Glastec, architect/ engineer Delft University of Technology*

Continuing on the strategy of making glass bundle columns with a central steel bar as applied in the Glass Truss Bridge we i.e. Delft University, wanted to make a special object to exhibit a special structure for the 2018 Glastec. We decide to make a swing, since this is not only a fun structure but also subjected to a very special dynamic load case. To make the optimal structure we decide to make a parametric design with the computer programs Rhino and Karamba. An initial shape was slowly transformed into the optimal patron of glass bundle columns. For the essential structural nodes, we chose for 3D printed ones made out of steel or PETG. This special structure was submitted to very serious tests by students before it was sent off to the Glastec. Also we connected to the swing devices to measure stresses and deformations while using the swing.

2 **Concept: Facade**

2.1 *Sonsbeek Pavilion, realized in 1986, architect Benthem & Crouwel*

For an large sculpture exhibition in the Sonsbeek park in Arnhem, the Netherlands it was specified that also vulnerable art objects were exhibited in the park (fig. 5). A competition under (then) young architects resulted in a winning design being a tunnel of glass panels.

The architects and engineers worked out the structural design for this temporary structure (March to October 1986). It was composed of glass portal frames, centre to centre 2.5 meter, made from two vertical glass fins and a horizontal, very light, steel truss. The fins gave support against the wind forces, the steel truss supported the glass panels that formed the roof. The transversal stability was given by the portal frame action of the two glass fins and the steel truss, the lateral stability was provided by the Vierendeel (shear force) action between the glass panels in the facades, the connecting silicone joint provided the structural connection between the glass panels.



Figure 5. Sonsbeek Pavilion, the Netherlands

2.2 *Façade Casa da Musica, Porto (P), realized in 2005, architect OMA*

In 1998 OMA won an architectural competition for a theatre in Porto, Portugal. Their design was a white concrete rough diamond shape with very big “windows” (fig. 6). To fill these windows, the architects asked for an all glass solution. After a lot of design efforts, we came up with a solution the architects liked very much: corrugated glass panels. When we showed these to the architects they fell immediately in love with it for the following reasons: a) Structure; they are very thin but also very stiff due to their 3D shape, b) Architecture; they have a beautiful water-like surface that shines and shimmers, c) Function; they are very present, the corrugated shape deforms the view.



Figure 6. Façade Casa da Musica, Porto, Portugal

2.3 Façade Museum MAS, Antwerp (B), realized in 2008, architect Neutelings Riedijk

The city of Antwerp, Belgium had a number of small museums housed in circumstances not fit for museum objects. It was decided to concentrate all these museums in a little island in the old harbour of Antwerp (fig. 7). An international competition was held and the architectural firm Neutelings Riedijk won. Their design was a stack of concrete rectangular boxes, each rotated 90 degrees to its neighbour. In this way the public could walk up slowly in a big spiral staircase, visiting each box i.e. museum, one by one. To protect people from rain, cold and wind the architects decided to use the same corrugated



Figure 7. Façade of museum MAS, Antwerp, Belgium

glass as in the Porto project as façade of this spiral staircase. The standard size could be 5.5 meter but at the corners two on top of each other: 11-meter high. Also laminated corrugated glass panels were now possible. In this way the safety against falling through was better guaranteed.

2.4 Façade National Library, Doha, Qatar, realized in 2018, architect OMA

In the newly founded University of Doha in Qatar required a library building. The architectural firm OMA made a design for this Qatar National Library, as it is called now (fig. 8). The architects were inspired by a folding paper form that is made from two flat planes, each creased along the centre, and pulled apart to create a diamond shaped void. The diamond shaped facades of the Qatar National Library, 80 meter long and 17 meter high, were clad with corrugated glass panels. This time insulated and laminated glass units (IGU) were created, especially to limit the energy need for cooling during desert daytime. The solar gain was mitigated with a reflective 50% cover of silver frit on the external face of the IGUs. In order to allow movement caused by wind loads, shrinkage and expansion due to temperature and earthquakes, all connecting details in the facades can accommodate these movements, both in horizontal and in vertical direction.

In 2019 another building with these corrugated glass walls of the architect OMA will be finished: the Taipei Performing Arts Centre in Taiwan. A large theatre complex with a central cube like building of 60 x 60 x 60 meter clad with the corrugated glass panels as we know from Porto and Doha.



Figure 8. Façade National Library, Doha, Qatar

3 Concept: Cast Glass

3.1 *Shopfront PC Hooftstraat Amsterdam, realized in 2016, architect MVRDV*

Architect Winy Maas of MVRDV had a brilliant idea for rebuilding a brick building from the 19th century in the most expensive shopping street in Amsterdam: the PC Hooftstraat. He proposed to the client, a project developer, who wanted something “special” on this location, to remake the building with on the first two floors everything: bricks, window frames, doors etc., made out of glass (fig. 9).

The client found this an intriguing, beautiful proposal and commissioned Delft University to investigate all critical technological issues like strength, stiffness, water tightness, insulation value, temperature/ sun radiation induced movement etc. After this research the choice was made for cast glass massive bricks and window frames. The bricks are glued together by an adhesive that hardens in a few minutes under ultra violet light. An extra small layer of silicone in each joint is used to safeguard the water tightness. Since this is the first time that on this scale, in outside conditions, a façade composed of glass bricks is built, the quality control, both in the factory and on the building site, was done by Delft University.



Figure 9. Shopfront in the PC Hooftstraat, Amsterdam, the Netherlands

3.2 *Glass Arch Bridge, Green Village Delft, project, still to be built, architect Delft University of Technology*

Based on the experience with the glass brick work designed for the PC Hooftstraat, we came up with the concept to emphasize the best structural property of glass: its resistance against compressive forces. The concepts “compression” and “bridge” automatically lead to an arch (fig. 10). An arch, if detailed correctly, transfers all loads on the bridge by compressive stresses. The large dead load of glass also leads to significant compressive forces. However, we must make a shallow arch to let people cross this bridge in a comfortable way. This shallowness of the arch can cause dangerous “buckling” behaviour.

Therefore, a rather thick layer of glass stones must be installed to produce such a big compression that tensile stresses caused by big local point loads are always eliminated. We entered a competition for a “sustainable” bridge for the Green Village of Delft University of Technology which we won (see section 1.3). We are now (spring 2018) running all kinds of research to prove the technical issues regarding an all glass arch with a thin layer of plastic in each joint, no adhesive, to make it demountable and reusable.



Figure 10. Artist impression of the Glass Arch Bridge

4 Concept: Future developments

4.1 *New Marble, the collaboration between glass and concrete. Architect MVRDV*

Concrete and glass are family; both are based on the chemical elementary material silicium. We discovered in our Glass Laboratory at Delft University of Technology that glass and concrete can, under certain conditions, develop a bonding. Although this bond is still weak we expect that further research will show us ways to improve the strength of this bond. In a competition for a new façade for their flagship stores the Italian luxury goods, especially jewellery, firm Bvlgari, wanted surprising and beautiful designs and asked a number of architects to think about this. Jacob van Rijs of MVRDV suggested a combination of a “poor” material: concrete and a “rich” material: gold coloured glass. The glass should not be transparent but include veins as one can see in marble. Delft University was asked to make prototypes to demonstrate the architectural potential of this “New Marble” (fig. 11). First we casted a flat glass panel with on top of the panel the required veins of glass sticking out. After solidifying of this glass panel black coloured concrete was poured on the glass panel, leaving the glass veins open.

The results impressed both the architects and the client. We asked for a half year period to work out all possible technical issues since it was to be built in the tropical climate of South Asia. Also we wanted to produce a sizeable mock up with all technical connections. Marketing interest were weighted higher then technical safety, so this project was stopped. Nonetheless, both architect and University are looking for possibilities to continue research in this promising and beautiful direction.



Figure 11. New Marble made of glass and concrete

4.2 Cast glass = cast concrete?

Figure 12 shows a vision of a City of the Future from the 1950s drawn by a craftsman with a lot of imagination, but no technical knowledge. Would not it be wonderful to be able to make a pylon for a bridge, like in the figure, not from ordinary concrete but from the, imagined, transparent “concrete”: glass? At the moment this not possible; especially the controlled cooling down after pouring of the molten glass in a “formwork” proves “a bridge too far”. However, with electrically heated steel formwork this controlled cooling down might be possible. Also we discovered that the addition of certain chemicals to the molten glass mass can change the properties of the solidified glass. Strength, fire resistance and, there it is: required cooling down time can be influenced. But a lot of creative research is still necessary.

Rob Nijse

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Figure 12. *City of the Future*¹

¹ Obtained from a science fiction magazine published in the 1950s.

