Challenging Glass 2 – Conference on Architectural and Structural Applications of Glass,
Bos, Louter, Veer (Eds.), TU Delft, May 2010.

Segmented Barrel-Vaulted Glass Roof

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A structural system for segmented barrel-vaulted glass roofs has been developed, aiming at maximum transparency due to structural optimization. This has led to a structural system with small connections, integrated into the glass, as well as clear, transparent joints. Finite element analysis and a full-scale test has been performed, showing PVB-laminated glass, 101010.4, could be sufficient to create spans up to 20 meters with slightly prestressed cables measuring just 3 mm in diameter.

Keywords: Glass, barrel-vaulted, cylindrical, roof, connection, transparent joint

1. Introduction

A barrel-vaulted glass roof, constructed with nearly invisible connections and transparent joints. An almost utopian vision, and therefore an interesting subject of study. As a result, a unique transparent barrel-vaulted roof has been developed, based on optimized integration of form and structure.

2. Development of the structural system

2.1. Preliminary research

In the past, transparent barrel-vaulted roofs have already been constructed. Worth mentioning is the Maximilian Museum's roof, Augsburg Germany (figure 1). However, a more transparent structure with smaller steel connections as well as less visible cables

Figure 1: Maximilian Museum, Augsburg, 2000
(source: Seele GmbH)

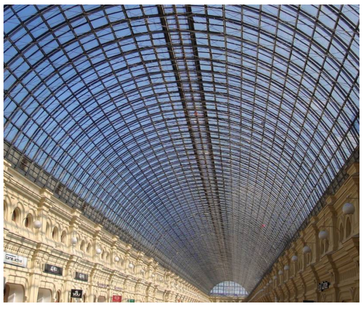

Figure 2: GUM, Moscow, 1893

was preferred. Therefore, alternative barrel-vaulted structures have been evaluated during preliminary research. Based on comparison of several known and self-developed barrel-vaulted structures, it was found that a structure developed by Vladimir Shukhov, applied late 19th century in Moscow's GUM, would be the most interesting option for further research (figure 2-3). This structure is stabilized with cables, connecting each joint of the structure separately to the supports. Furthermore, the structure consists of a series of connected arches, due to supports along its full length in axial direction. Reducing the amount of non-transparent structural components was presumed to be possible by structural use of the glass panes.

2.2. Conceptual approach

A closer look at the cable structure reveals that all connections are hinged. In stead of transferring all forces in a single connection, suggestions were made to transfer normal and shear forces completely separately. As a consequence, normal forces can be transferred by pane-wide rubber parts, distributing the normal forces over both the surface of the rubber and the glass edge. This leads to exceptionally low normal stresses in the structure. In addition, small shear forces can be transferred by slender steel elements, placed at the corners of the glass panes. These measure about 90x60x6 mm^3 and will be located between the top layers of a triple laminated glass panel (figure 4). When the glass panels are aligned at an angle to each other, normal forces will be introduced into the glass panes due to vertical (cable) forces on the steel elements (figure 5). Normal stresses remain low, as a result of the orientation of the smaller inner glass pane.

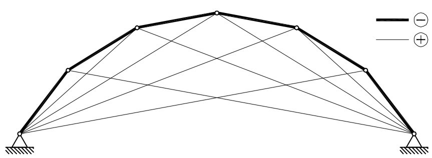

Figure 3: Configuration of stabilizing cables, developed by Vladimir Shukhov

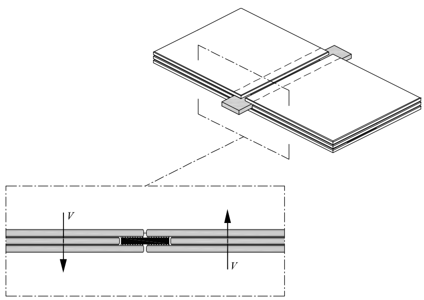

Figure 4: Steel elements at the corners

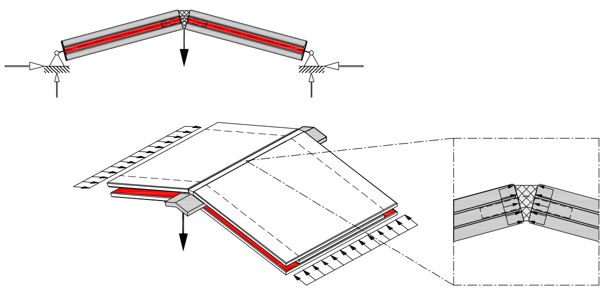

Figure 5: Normal forces in glass panes due to vertical forces on the steel element

2.3. Final design

The conceptual approach can be expanded to an entire arch-structure. Based on a semi-circular arch, all connections will have an equal geometry. This means large barrel-vaulted roofs can be constructed with mass-produced steel elements. In order to avoid horizontal movement, as well as to connect the cables, the steel elements have been designed in a T-shape (figure 6-7). The perpendicular part of the element extends barely 10 mm underneath the glass surface, leading to an optical almost flat surface at the inside of the roof (figure 8). While cables measure just 3 mm in diameter for spans up to 20 meters, only the glass structure and steel connections will be visible at the first glance. Furthermore, the application of clear, transparent polyurethane between the glass panes will contribute to a unique degree of transparency, as can be seen from the constructed prototype (figure 12). The durable polyurethane joint filler possesses a high compressive strength, but is also flexible, thereby able to compensate small imperfections in the glass edges. Application of the material in building purposes is a novelty, for which reason experiments have been performed to determine the material properties for use in engineering calculations.

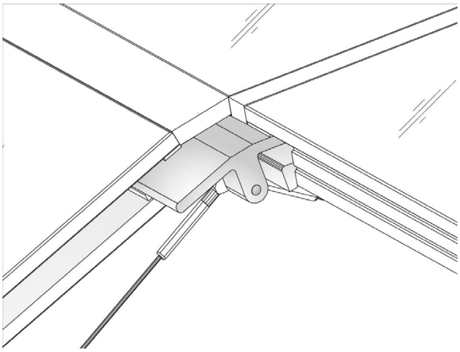

Figure 6: Steel element, connecting four glass elements

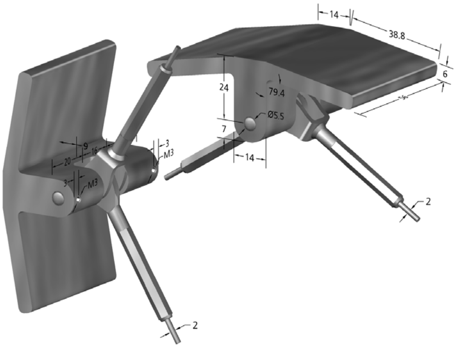

Figure 7: Steel element in detail

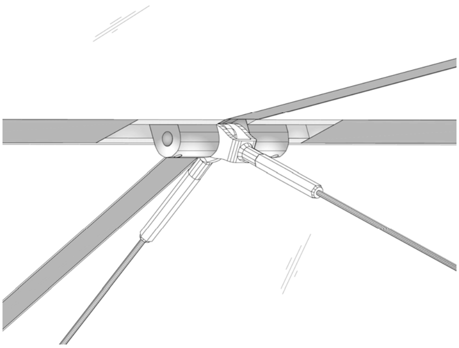

Figure 8: Detail view from underneath the roof.

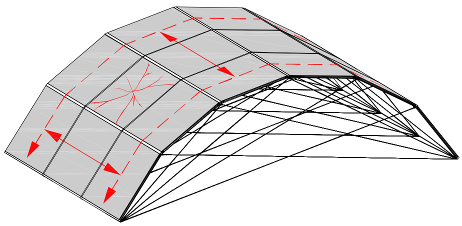

Figure 9: Behaviour after breakage of one glass panel

By positioning the steel elements on the corners of four glass panes, post-failure structural capacity is ensured. In case of failure of one glass element, forces can redistribute to adjacent intact arches (figure 9). By applying annealed or partly toughened glass, broken glass panes will remain in position due to adherence of the PVB interlayer.

3. System analysis

3.1. Finite element model

In order to analyze the structural behaviour of the system, both finite element analysis and a full-scale test has been conducted (figure 14). Finite element analysis was performed by using a parametric finite element model, developed in ANSYS, allowing to vary the dimensions and material properties. Due to the three-dimensional model, all stresses and displacements could be evaluated, including shear- and peel stresses in the interlayers, as well as friction stresses between steel elements and the polyurethane. Since the highly non-linear geometric behaviour increases the amount of calculations, an arch with symmetry constraints on both sides is modeled. The full-scale prototype was used to validate these finite element models.

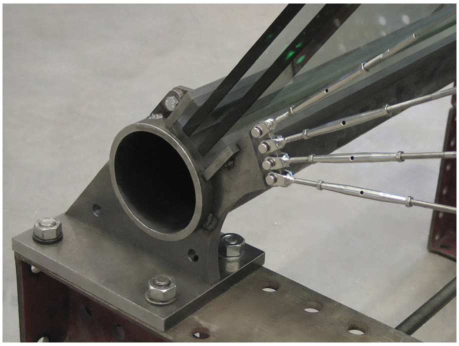

Figure 10: Support of the constructed prototype

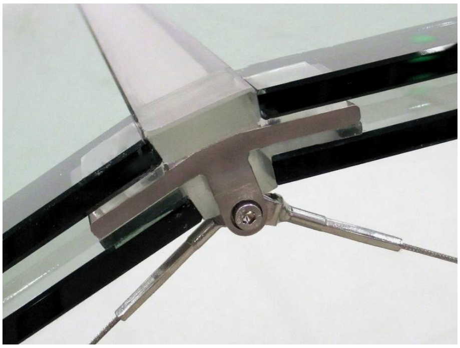

Figure 11: Front view of the prototype

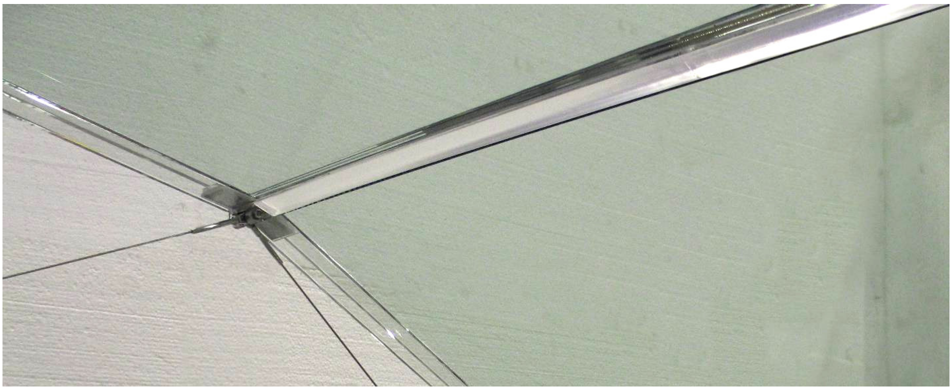

Figure 12: View from underneath the prototype: Full transparent joints

3.2. Structural behaviour

In principle, the behaviour of the developed connection is equal at every position in the structure. Critical stresses occur at the bottom glass pane, that tends to 'peel off' from the upper glass panes (figure 13). As a consequence, bending stresses can be found up to 3,4 N/mm^2 by an arbitrary span of 5 meters and 101010.4 (1.52 mm) PVB laminated glass. These stresses were caused by a maximum cable force of 620 N, distributed over two connected arches. In case of eccentric snow loading, equivalent stresses occur up to 4,4 N/mm^2. Without changing glass dimensions, spans up to 20 meters can be created. Increasing the span even further is possible by increasing the glass panes thickness, which will prohibit buckling of the glass elements. Structural optimization in an elegant way can be achieved whenever buckling capacities and local tensile strengths are reached simultaneously.

Bending stresses in the bottom glass pane also trigger tensile stresses in the lower interlayer. These 'peel stresses' seems to remain relatively low, about 2 N/mm^2. However, the true peel strength of the interlayer is unknown. This strength depends on the intrinsic tensile strength of the interlayer, as well as on the bonding strength upon the glass. Further research is necessary in order to obtain these values. During this research stresses up to an arbitrary value of 5 N/mm^2 are found to be acceptable.

Due to slightly prestressed cables, the system stiffens substantially. Hence, system displacements remain quite low: Displacements as small as 5,4 mm have been calculated by a 5 m span and eccentric snow loading. This means displacements do not exceed about 1/1000th of the total span.

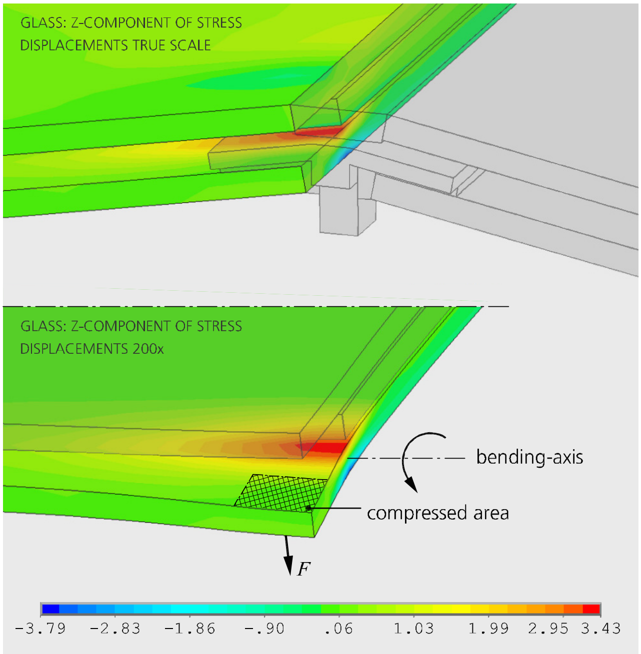

Figure 13: Stresses in the glass panes due to transversal force at the connection

4. System optimization

In order to optimize dimensions and properties of the chosen materials, a parametric finite element study has been performed. Tensile stresses in the glass panes, peel stresses in the interlayer, compressive stresses in polyurethane parts and deformations were taking into account, leading to the dimensions as described above. As a result, the interlayer has been determined to consist of conventional PVB foils, resulting in lower tensile stresses in the glass panes and strongly decreased peel stresses in the interlayer. Regarding the stresses in the glass panes, a stiff (stainless) steel element appears to be more favorable than similar elements in aluminum.

5. Construction method

The barrel-vaulted glass roof can be realized by using wooden arches, acting as centrings to position glass and polyurethane elements side by side to each other (figure 14). Subsequently, the steel elements and cables can be placed in position. After slightly prestressing the cables, a stable glass arch is established and the centrings can be removed. With just a small hex L-key and a wrench the remaining prestress can be applied to the cables. However, prestressing a single cable can influence tension stresses in all other cables. This would undoubtedly result in unwanted cable forces. Fortunately, only the lower, most tensioned cable will determine the maximum tensile stress in the glass pane, while calculated prestress values in all other cables may vary by plus or minus 25%, only effecting (small) displacements. During construction, this means only the lower cable has to be carefully checked on the calculated prestressing force.

Figure 14: Constructing the prototype for testing

6. Full-scale test on prototype

In order to validate the finite element models, experimental research has been performed at Eindhoven University of Technology in cooperation with ABT bv. Based on a 5 m span, a full-scale prototype has been constructed out of six glass elements, PVB triple laminated, 101010.4, measuring 1 x 1 m^2. Glass strains were measured at 20 locations, all placed in the compressive area of the critical bending zone (figure 16). Additionally, transversal displacements were recorded through 14 digital indicators.

After removing the centrings, prestresses were introduced into the cables up to 630 N. These were about 200% of the actually required prestresses, thereby ensuring a continuous sustained tensile stress in the cables during the test. At this first load step, only strains were measured. Critical stresses were expected to be located at the most right and left connections, defined as locations 1 and 5, connected by just one cable (figure 16). Finite element analysis indicated that stresses up to 3,9 N/mm^2 could appear at these locations. Test results showed 17% higher stresses of about 4,6 N/mm^2 (figure 17).

Snow loads, both centric as eccentric, were applied by sand bags (figure 15). As a result, stresses up to 5,6 N/mm^2 appeared nearby the expected critical locations. Compared to the finite element model, these stresses were underestimated by a maximum of 15% (figure 17). On the other hand, finite element results overestimated the averaged test results by just 1%.

Unfortunately, higher stresses were measured at other locations, as a result of incorrect prestressed cables. These prestresses were caused by an attempt to equal calculated prestresses exactly, which resulted in a permanently, non-correctable deformation (figure 15). As a consequence, only cables connected to the assumed critical locations 1 and 5 were correctly prestressed, allowing a proper comparison between measurements and FEM results. At locations 2, 3 and 4, stresses varied from 4,8 to even 22 N/mm^2 after loading the model.

Figure 15ab: Test setup, before (left) and during (right) centric snow loading

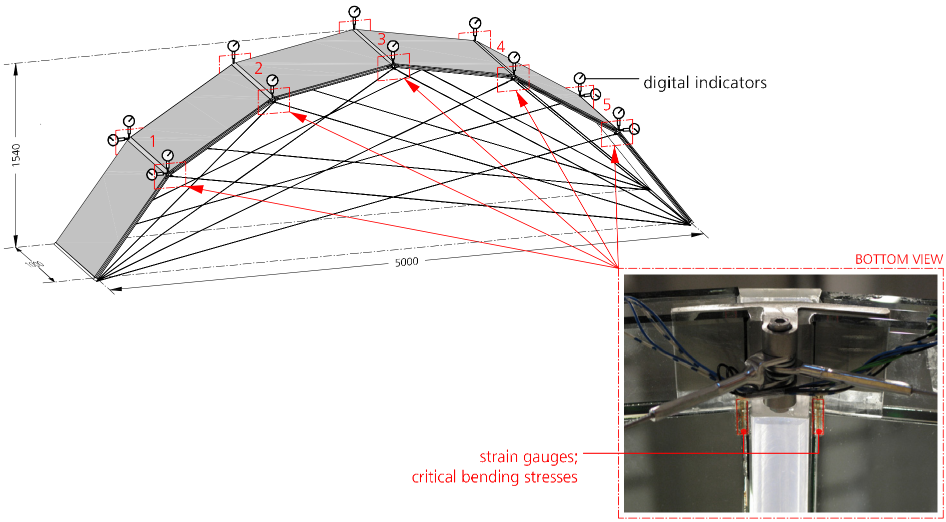

Figure 16: Measurement locations

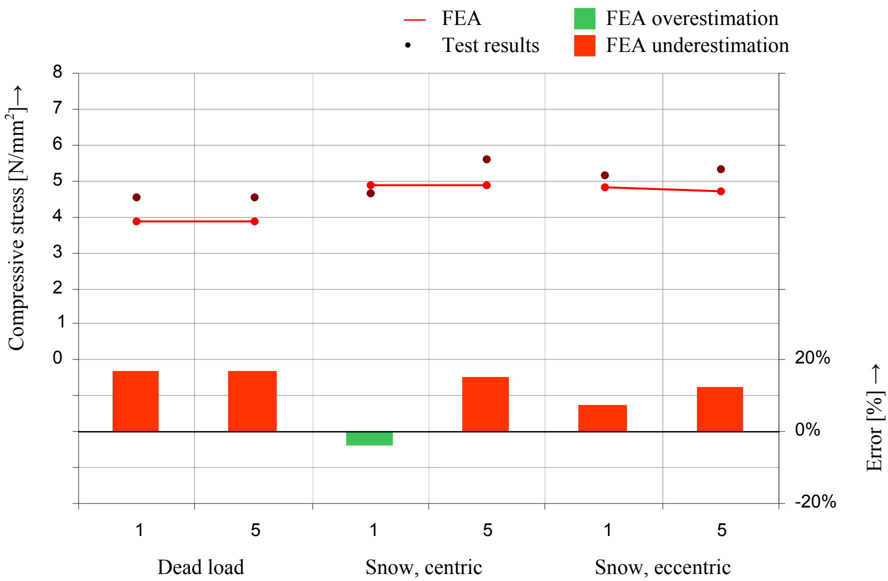

Figure 17: Compressive stresses at expected critical locations:
Calculated stresses compared to measurements

Deformations turned out to be even smaller than expected. In case of centric snow loading, a maximum displacement of 2,9 mm has been calculated, while during the experiment only 1,05 mm was measured (~1/5000th of the span). Eccentric snow loading leads to maximum displacements of 2,5 mm, equal to the calculated value.

Although theoretically only compressive stresses were to be expected at the measured locations, two strain gauges indicate tensile stresses. These stresses ranged up to 6 N/mm^2, or just disappeared during the test. These results were possibly caused by torsional stresses at the glass edges. Unfortunately, these were not measured during the experiments. Therefore, further research related to this aspect is recommended.

Figure 18: Prototype used for testing

6. Conclusions

Overall, the developed system seems to fulfill initial goals. Transparency of barrel-vaulted glass roofs has been given an extra dimension, due to an optimized glass structure, constructed with small connections, integrated into the glass. Even more transparency is obtained by clear, transparent polyurethane joint fillers and barely visible steel cables.

Both the experimental behaviour and stresses compare quite reasonably with the finite element model at the expected critical locations. Furthermore, calculated displacements showed close resemblance to the experimental values. This indicates that the finite element model properly represents the actual system's capacity, even though further research is needed to evaluate stresses at non-critical locations. As a result, spans up to 20 m could become reality someday (figure 19).

Figure 19: Artist's impression of the developed system, based on the GUM-facades (14 m span)

7. References

[1] Haarhuis, K.J. (2010) Master's thesis: *Cilindrische Schaalconstructie in Glas: Ontwikkeling van een Maximaal Transparant Constructiesysteem, Eindhoven: Eindhoven University of Technology*