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Testing for individual approval of a vault roof with in-plane loaded glass panes

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Abstract

At the IASS conferences in 2007 [1] and 2008 the concept and testing results of a sustainable and transparent roof construction were presented. These transparent space grid structures base on a double layer grid in which all bars in the upper layer, the compression layer, are replaced by glass panes. The glazing is part of the primary load bearing system and transfers significant in-plane forces. In 2007 the first realisation project using this new concept was launched and will be finished this year. With a dimension of 13.5 m x 21 m and an arch rise of 3.50 m it covers the courtyard of one of the Berlin palaces. The design process was attended with extensive testing to obtain an individual approval. This contribution describes the testing at single panes and the full-scale arch of 13.5 m span necessary for the individual approval of the building authorities. Plastics for the in-plane load application into the glass edge and their creeping behaviour were investigated in first tests. The stability behaviour against glass pane buckling was tested at relevant load combinations and the post breakage robustness and the walk-on ability of the overhead glazing ensured by suitable test. Load bearing tests with a total load of 13 tons were conducted at one 13.5 m arch and finished the test series. The successfully finished testing is the basis for the individual approval and the realisation of the roof construction within the next month.

Keywords: Glass, Individual Approval, Space Structure, Roof, Testing, Mock-up

1. Introduction

At Technische Universität Dresden the Institute of Building Construction is decisively involved in the development of transparent space grid structures. The recently conducted testing series of full-scale mock-up for individual approval accelerated this development process. This describes the testing of a transparent double layer grid in vault geometry for individual approval. The system possesses half-Vierendeel geometry [1].

The concept of transparent space grid structures is characterized by the activation of the glazing as part of the primary load-bearing system. Using the example of a double layer grid the utilisation of the glazing as compression layer, roof stabilisation and roof covering is proven. The structure is material-efficient as the glazing fulfils a double function: it serves for the primary load transfer and as roof covering.

Beside conducted standard test, like walk-on tests or post breakage robustness tests the main focus of this contribution is on load capacity tests at the 13.50 m spanning mock-up, buckling tests at single panes and tests of the contact material for load application into glass panes.

2. Spatial geometry and structural system of transparent space grid structures

Figure 1 shows two double layer grids of the geometry half-octahedron + tetrahedron. From the steel double layer grid at the left hand side all bar elements in the compression layer are replaced by glass panes to form the transparent double layer grid. The panes are only connected at their corners with steel knots; there is no linear connection between them. The transfer of significant compression forces in the compression layer is ensured by the glass panes due to their high compressive strength. The glazing fulfils a double function: they serve for the load transfer and for the roof covering. The steel bars in the tension layer and the diagonal bars keep the same function as they have at a traditional steel space grid [2].

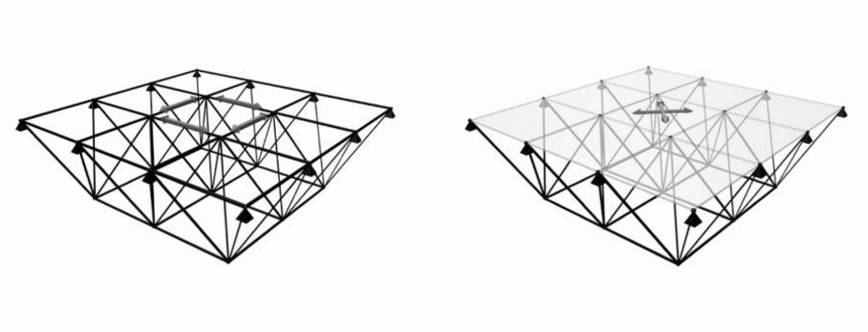

Figure 1: Compression elements in the upper layer in a traditional space grid structures and a space grid structure with glass panes as load bearing element

3. Structure half-Vierendeel

3.1 Structure geometry

The structure half-Vierendeel is a double layer grid with restraint bar connection. Despite no diagonal bars the structure is stable. At this structure the upper and the lower layer have the geometry of square grids and are congruently situated to each other. The connection of upper and lower grid is achieved by vertical posts between the knots. The stability is achieved by restraint bar connections at the tension layer. The link between glass panes and the post is a hinged connection.

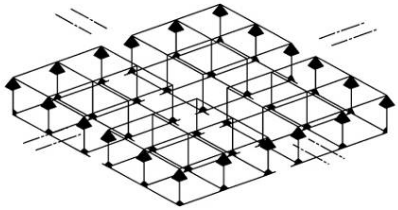

Figure 2: Structure half-Vierendeel

3.2 Design of the full scale mock-up

Objective of the conducted tests is the obtaining of an individual approval for a glass roof construction; build as transparent space grid structure. The roof should cover an inner courtyard and was intended as uni-axial curved geometry by the architectural concept. The built environment did not allow the dealing with horizontal reaction forces. Therefore the glass roof is a bending structure in vault geometry. The system slides on its supports; therefore, no membrane forces can be transferred by the curved shape. The structure possesses a complete modularity consisting of arches.

The largest arch of the roof was chosen to be used as a mock-up. Also the mock-up can slide on its supports; therefore the arch functions as bending system, as single beam.

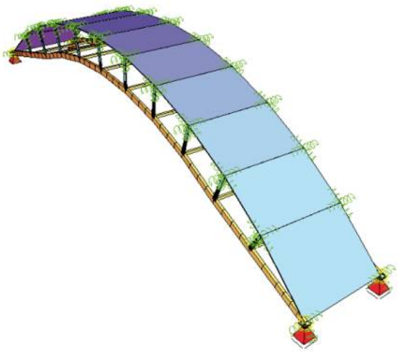

Figure 3: FE-model of a vault strip half-Vierendeel

The mock-up consists of a eleven glass panes, half knots on the vertical posts, four tension rods below the glass edges of each pane, the vertical posts and the steel bars in the tension layer. The dimensions of the glass panes are 1.80 m x 1.26 m. The panes consist of insulating glass made of 8 mm toughened glass and a laminated glass of 19 mm toughened glass and 8 mm heat-strengthened glass with PVB-interlayer. All in-plane load is transferred by the 19 mm toughened glass pane. The 8 mm heat-strengthened glass pane of the laminated glass serves for safety reasons, e.g. walk-on and post-breakage behaviour, only. The load input from the glass pane into the knot was realised by plastic blocks [3].

3.3 Assembling

The modularity of the roof allowed a prefabrication of single arches to be bolted at the site. The steel structure of each arch comprising the tension layer members and the vertical posts is a welded and stable construction. The mock-up possesses a span of 13.50 m and a width of 1.80 m. The knots are bolted on the top of the vertical posts. The glass panes are laid into the knots. The load application construction with its contact material and the tension rods connect knots and pane to one single unit and ensure the load transfer between steel knot and pane without slipping.

4. Testing to obtain individual approval

4.1 Assembling

The knots are the crucial and most important part of the entire structure. They have to fulfil several requirements regarding load transfer between vertical posts and glass panes, feasibility and tolerance adjustment. The load application from the glass pane into the knot is realised by plastic blocks that are integrated inside the knot.

Extensive testing including tests under permanent load and creeping tests was carried out to identify an appropriate block material. The results are described more detailed in [3].

Figure 4: Knot design with plastic blocks

The principal behaviour of the glass-block contact at large compression forces was investigated in the testing facility shown below. Identical test specimens of aluminium F28, POM-C and glass fibre reinforced POM-C were investigated in mechanical load transfer tests.

The mechanical tests identified both POM-C materials as more appropriate than aluminium. The respective properties of both un-strengthened POM-C and glass fibre reinforced POM-C GF25 were investigated in a subsequent creeping test. Its purpose was to identify the better creeping behaviour between the materials in terms of long-term shortening and accompanied load relocations within the structure. The result was that POM-C GF25 possesses more proper properties under the aspect of a less creeping ratio.

Figure 5+6: Devices for testing the block materials

After identification of the appropriate material POM-C GF25 additional tests were conducted at small specimens with ring geometry having an outer diameter of 11.1 mm, 5.1 mm inner diameter and 6 mm height. A compressive stress of 27.5 N/mm² was applied to the specimens at ambient temperature and increased temperature of 45 °C. This temperature range represents the conditions which are likely to occur during the lifetime of the structure.

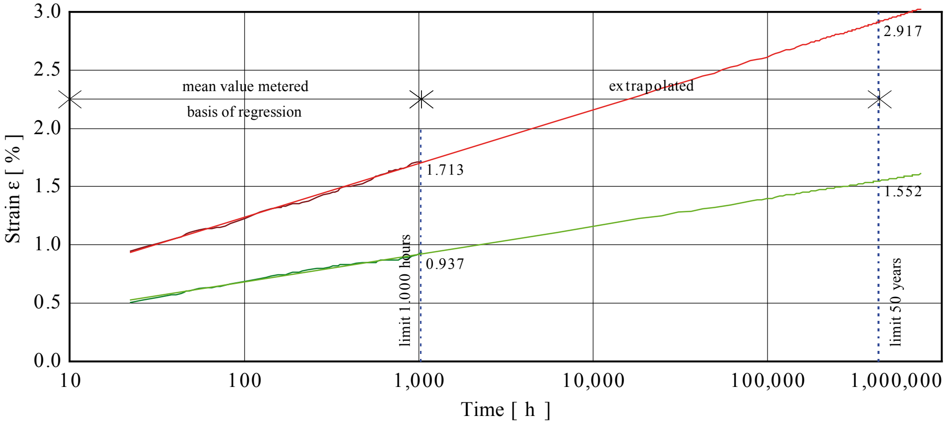

Figure 7: Regression analysis for creeping behaviour

At the creeping specimens the load is applied perpendicular to the extrusion direction and, therefore, to the principle order of glass fibres [3]. The gained data were statistically evaluated by means of a regression analysis. The measured time-strain-curve shows the typical developing of materials subjected to creep. The regression was done utilising a logarithmic approach. Such a procedure is mentioned in [6] comprising the following equation:

$$y = b_0 + b_1 \cdot \log x \tag{1}$$

After monitoring the data over a time of 1,000 hours the regression analysis was done and extrapolated to the proposed lifetime of the structure of 50 years. The result is shown in figure 7 for both ambient and increased temperature.

The long-term E-modulus of the material POM-C GF25 was able to be derived from the results gained. The long-term E-modulus is approximately one third of the initial value.

4.2 In-plane Stability

Many tests were executed to determine the in-plane stability of glass panes. For this, only the 19 mm thick fully toughened pane was tested isolated. The other component of the laminated safety glass, the 8 mm thick heat strengthened pane, remained unconsidered. In real situation this will work as an additional safety factor. The IGU glazing is structurally not applied within the test series.

The tests include amongst others the check of the single panes pertaining to geometrical consistency and tolerances of the dimensions and thickness compared to the governing code [7] as well as the identification of in-plane distortions.

On the one hand these tests should proof the sufficient stability of such panes under the given loading condition and secondly provide data for verification of the FE calculation models. Therefore, the surface stresses due to the pre-stressing procedure at the edge and in plane were additionally ascertained to check the homogeneity of these stresses and their values.

The results of testing the homogeneity of the surface stresses and geometrical conditions showed that all values were within the range of the tolerances allowed by the applicable code. The average surface stress was more than the required 75 N/mm²; the average thickness of 18.42 mm was within the tolerances for 19 mm thick panels. The stress at locations of discontinuities (edge and corner) was able to be approximated by a regression analysis with an exponential function (figure 8). Normally, such stress developing should be assumed as a polynomial function to be approximated as per [8]. But the evaluation showed that a polynomial approximation is less appropriate than an exponential one and generates meaningless or negative values by extrapolating the trend. Moreover, the coefficient of determination was less as well. Finally, the exponential function approximated the test results better.

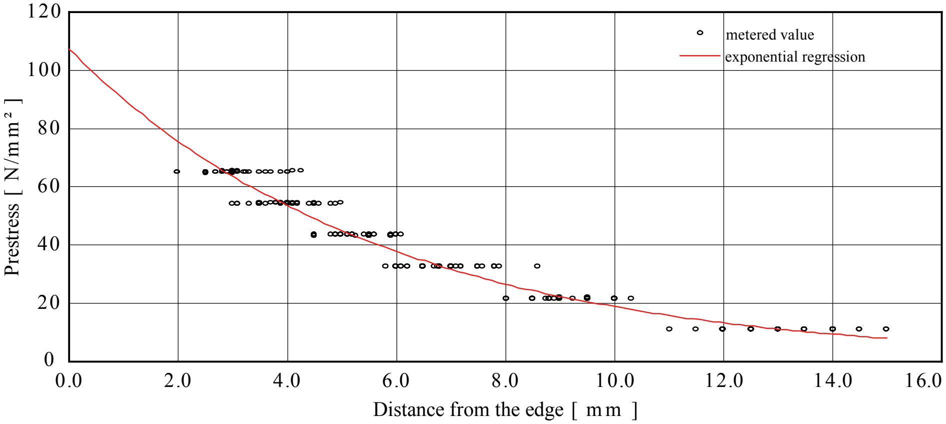

Figure 8: Regression of edge stresses at location 2

The axial load was applied by hand-driven presses at each corner of the pane. The forces were previously determined in a structural calculation of the entire roof structure. The result was that at each corner different forces had to be applied. The compression was measured exactly by load cells at each press. The deflections were taken at the middle of the edges of the long side and in the middle of the pane by inductive displacement transducers (abbreviation DT in figure 9).

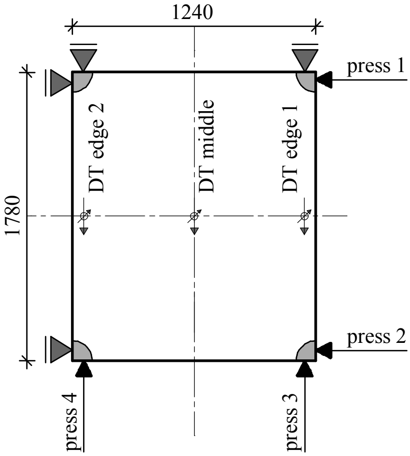

Figure 9+10: Arrangement of testing devices and pre-load by sand bags

The testing rig consisted of stiff and heavy steel profiles to carry the applied forces without disturbing relative deformations. In each line of the presses steel beams were arranged to short the forces.

As per the real installation of the glazing in the roof structure the panes were pointy supported at each corner in vertical direction. The support was able to slide due to the arrangement of greased Teflon-plates. The pane was installed with the in-plane distortion facing downwards. This initial deflection in a type of an imperfection was amplified by the loading of the pane with the weight of the one-time snow load as per the structural calculation (figure 10). The snow load was simulated by sand bags. After arranging the snow load the axial forces were applied according to a testing schedule which was previously coordinated with the approving authority. The axial load was applied by several steps and 15 seconds and 1 minute hold time respectively between two steps. Figure 11 shows a typical load-deflection-diagram.

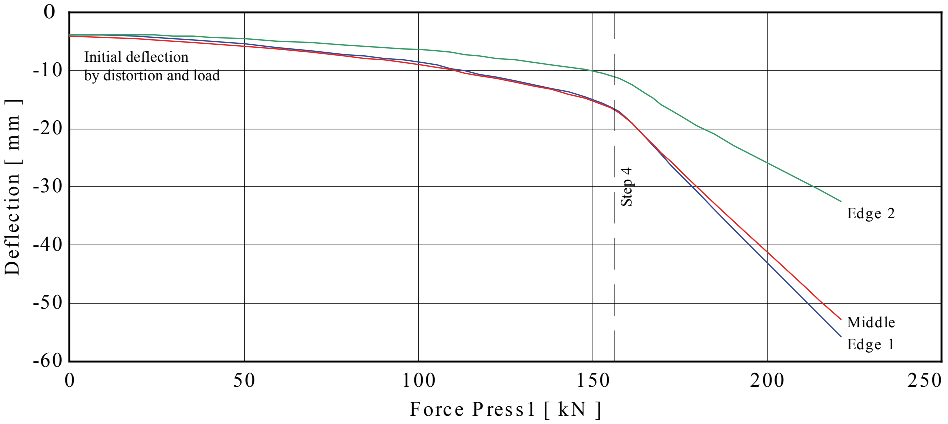

Figure 11: Load-deflection diagram due to in-plane forces

The initial first order deflection is clearly visible at the beginning of the test. The increasing deformation resulted from P-Δ-effects due to the high axial in-plane forces. The average maximum deflection in the middle of the pane at the state of 4 times the characteristic load was 17.50 mm and at the state of breakage 56.90 mm (that is more than l/32). The three measuring points are showing different values in figure 10 due to the different axial forces at each corner and in each direction and, therefore, varying P-Δ-effects.

It is remarkable that the gradient of the force-deflection-curve became more steeply from load step 4. The stiffness of the pane seems to be decreased what definitely can not be possible. The reason for such a behaviour has not been investigated yet and is still part of further research. The main goal within these tests was to experimentally proof the sufficient safety of such structures and not as much to do detailed research regarding plate buckling of glass.

It could be stated as the main result that all test specimens reached a safety level of at least 4 and was therefore higher than the required factor of 3.

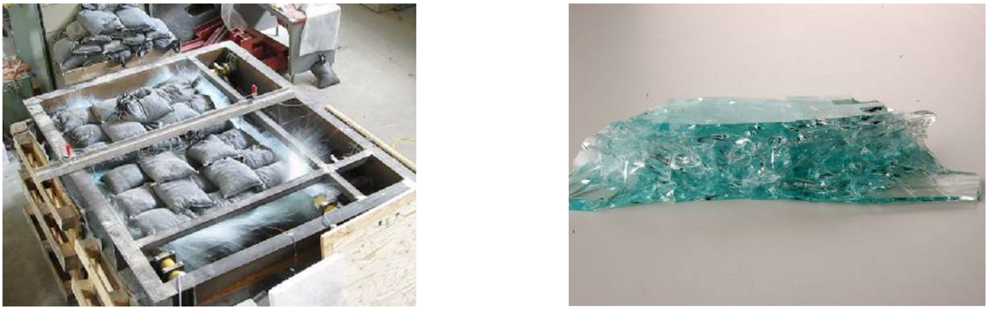

Figure 12+13: Begin of breakage and Fracture pattern

Apart from the typical fracture pattern of fully tempered glass with small and blunted pieces the glass was broken horizontally in-plane parallel to the surfaces with partially long and sharp splinters (figure 13). This is a sign of very high energy stored in the material due to the axial compression forces in addition to the ordinary implemented pre-stressing. Therefore, the fracture origin was indeterminable.

The results and data gained were a valuable tool to verify the calculation models pertaining to buckling and local load transfer.

4.3 Walk-on Test and Post-Breakage Behaviour

The roof is accessible for maintenance and cleaning purposes and, therefore, must be proven according to certain work safety guidelines. The test includes falling glass ball bags to simulate a falling person and steel balls to approximate falling tools. The post-breakage behaviour must be investigated to ensure that the entire glazing will remain in its supports after breakage, that the glazing will not be penetrated or the size of the penetration is limited respectively, and that no dangerous splinters will fall down in occupied areas or walk ways.

All dimensions, geometries and additional construction members such as tension rods matched exactly the future situation. The testing schedule stipulated a dropping of the bag with an altitude of 1.20 m and of the steel ball with a an altitude of 4.00 m on different points of the glazing. After that, a static weight was placed during a range of 15 minutes to simulate an unconscious person. Both the IGU top-pane and the laminated safety glass had to be tested. The several panes were destructed ordinary with a hammer and centre punch if the pane of the IGU was not destroyed by such a dropping or static loading. The location was cleared for the next step of testing by dropping and static loading (figure 14). In each case it was necessary to break the glazing manually. No pane was destroyed by dropping the bag or ball.

The test of post-breakage shall show the behaviour of a totally destroyed glazing under certain load conditions during a certain time range. It is crucial for such tests that the entire future construction is simulated exactly. In this specific case the broken glazing laid on the tension rods and the former pointy supported system changed to a linearly supported one (figure 15). Such an altering of the support system and structural system was evident and necessary to pass the test.

Figure 14+15: Cleaned dropping location and support by the tension rods

4.4 Testing on a Life-size Mock-up

All previous tests and investigations were the basis for the built-up of a life-size mock-up in the line of one single strip of the roof. The dimensions are 13.50 m length and 1.80 m width. Load tests and investigations of the post-breakage behaviour were carried out under real installation conditions at this mock-up to determine the exact performance of the roof. The results processed to load-deformation-diagrams (figure 16) were a valuable tool to check, improve, and verify the calculation model.

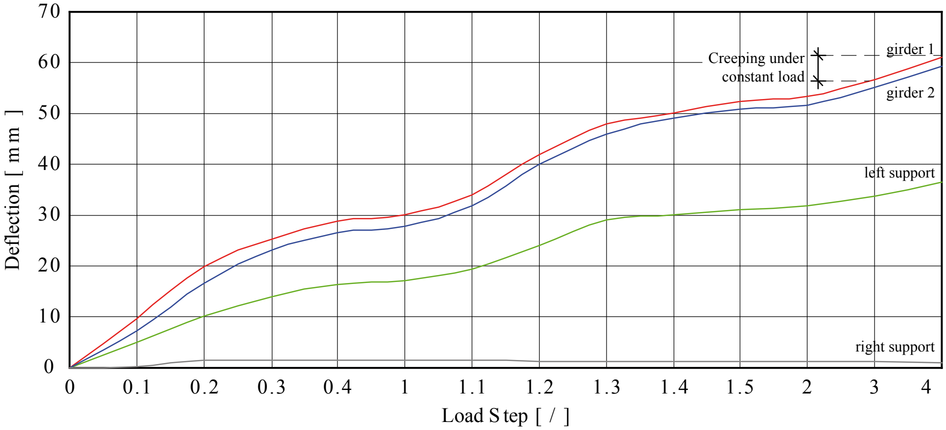

Figure 16: Load-deflection diagram of the mock-up

The testing procedure followed the already above mentioned coordinated schedule. To proof the sufficient capacity of the entire structure a safety factor of at least 3 was required. The governing load case was snow with conglomerations to adjacent roofs and structures. This load was applied with sand bags with a total weight of 13 tons onto the mock-up.

The dimensions of the steel members were increased by 100 % due to the required safety factor of 3. The steel structure must be strengthened because of the lower overall safety factor for steel of approximately 1.40 x 1.10 = 1.54. The different safety concepts such as LRFD and ASD must be considered and complied with each other.

The deflection in the middle and at the base point were measured with digital displacement transducers and recorded after each load step (figure 16 and 17). Altogether 3 tests had to be conducted along with an exchange of the maximum loaded glazing in the middle of the arch.

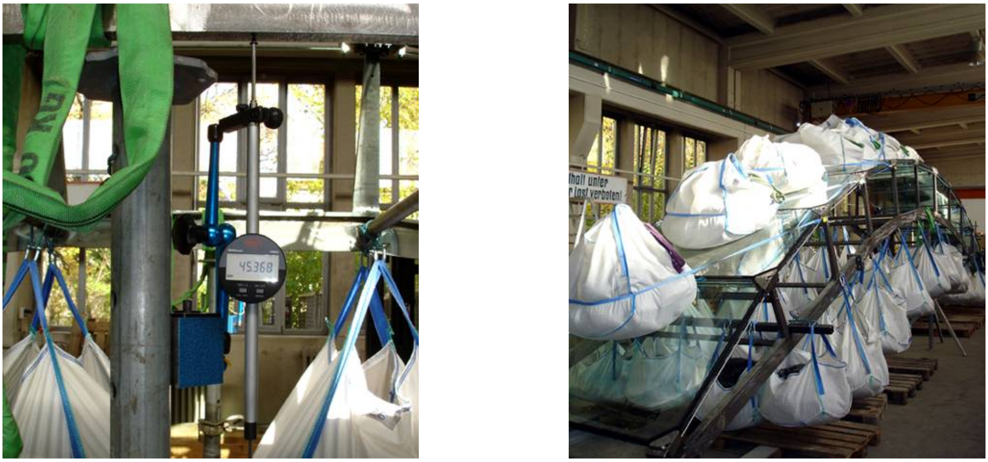

Figure 17 and 18: Digital displacement transducer in the middle of the girder and loaded girder

The mock-up had to withstand all loads during a time of at least 24 h to pass the test. Not only the overall stability had to be intact but the local parts such as glass panes, knots, blocks and steel structure must not have shown damages. An extraordinary deflection after 24 hours loading time would have been a failure criterion as well. The POM-C blocks were not ordinary changed during the entire testing time except for the replaced glazing in the middle of the arch.

The increase of the deformation after the application of the last load step shown in the diagram figure 15 arises from creeping properties of the blocking material (step 4). The previous tests of the blocking material consisting of glass-fibre reinforced POM-C showed that the material is able to creep up to a ratio of 3 % under dead loads by a temperature of 45 °C. The creeping of the blocking material was during this test much higher because of the 3 times higher total loads. But this effect must not be taken into account because the service load is less compared to the ultimate state and the snow load is considered as a short term load. The measured deflection values matched quite well with the calculated values.

All tests and verifications were fulfilled in such a way that there were no further (major technical) objections against the erection and installation of such a roof in a real structure.

5. Conclusion

The full-scale mock-ups of a double layer space grid structure in half-Vierendeel geometry demonstrated the feasibility and structural principle.

Comprehensive testing was conducted at an arch with a span of 13.50 m to obtain an individual approval. This included small-size testing of block elements for the local load application into the glass edge, in-plane stability tests, walk-on and post breakage behaviour tests and load bearing tests on the arch. The glazing had to resist a load with a safety factor of 3.0 while the structural test. The achieved safety factor was higher than this in the most cases. The results of the testing on a real-size mock-up encourage the authors to continue with their research and to pursue realisation plans.

Acknowledgments

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