



Challenging Glass 7  
Conference on Architectural and Structural Applications of Glass  
Belis, Bos & Louter (Eds.), Ghent University, September 2020.  
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ISBN 978-94-6366-296-3, <https://doi.org/10.7480/cgc.7.4488>



# The Development and Testing of Large Sandwich Panels

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The TU Delft glass group designed, developed and build three glass sandwich panels for the Glasstec 2018 in collaboration with ARUP. These were composed of heat strengthened laminated float glass with Schott glass tubes as the core. Initial small scale tests were used to determine the parameters for the digital design by ARUP. Based on these results form-finding was used to determine the optimum configuration of the glass tubes in the panel. This was verified by further scale model experiments which led to more refinements in the form finding algorithm. The small scale tests were extend to full scale prototypes which were proof tested at TU delft using a static and dynamic load of standing or dancing students. The full scale panels were then exhibited at the Glasstec 2018 where they were walked over by thousands of people. Finally one of the panels was tested to destruction. It was found to be very resilient and failed in a safe way. The test results are compared with FEM models. The important lessons learned from this for the design and production are explained.

**Keywords:** Sandwich panel, Spanning structure, Testing, Formfinding

## 1. Introduction

When float glass is used as a spanning horizontal structure either very thick plates are needed or a supporting structure to reduce the span. Thick plates are heavy and inefficient. The supporting structure reduces the transparency. In many materials the problem is solved by creating a sandwich panel. The honeycomb panel used in aerospace is a typical example combining span and light weight.

Adding transparency as a requirement however complicates the design as the spacer reduces the transparency. In theory laminated float glass elements can be adhesively bonded to glass spacers to create a safe all glass sandwich panel that has high transparency and is an mechanically efficient spanning structure.

Vitalis did introductory research into this for his master's thesis, Vitalis 2017. Using standard glass bowls and laminated float glass plates prototypes were made and tested. These were optimized using form finding to find the optimum configuration of the spacers combining mechanical efficiency and transparency. Examples of the results are shown in figures 1, 2 and 3. The final design concept is shown in figure 4.



Fig. 1 stacked prototype panels.

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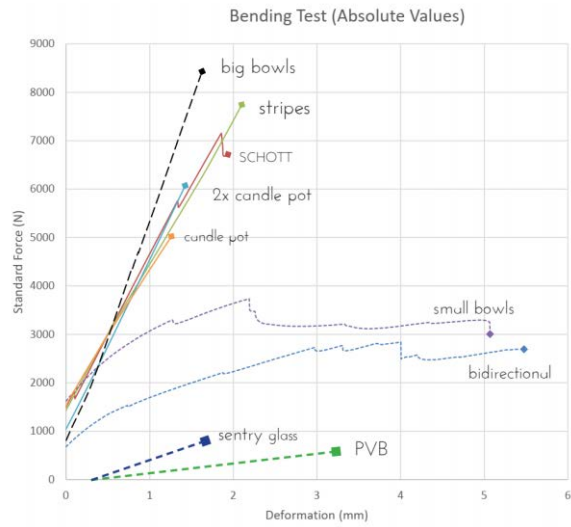


Fig. 2 bending test results for prototype panels.

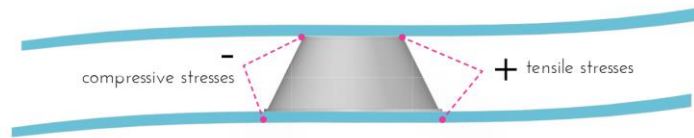


Figure 145 Strain-->Stress

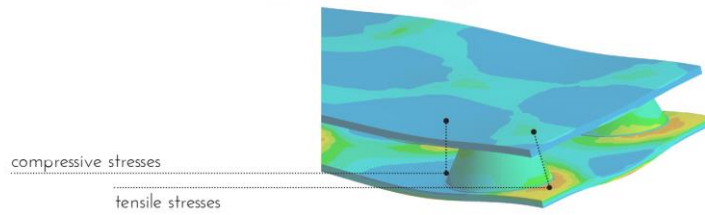


Figure 146 Strain-->Stress

Fig. 3 FEM modelling.

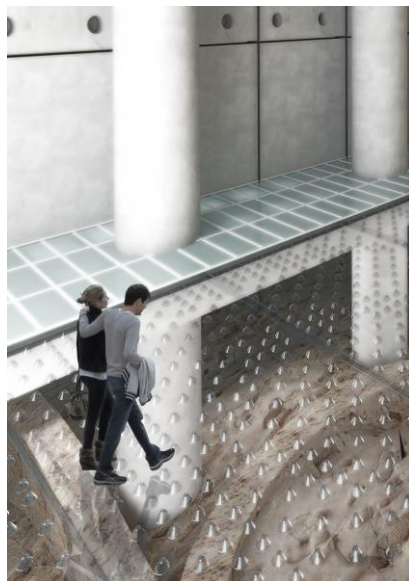


Fig. 4 Final design concept.

## 2. Evolution of the design concept

In 2018 the structural glass research group of TU Delft was invited to exhibit in the university section of the Glasstec 2018 exhibition in Dusseldorf. For this it was decided to develop the glass sandwich panel concept further and to exhibit a glass swing, Snijder 2019. 6 m length glass sandwich panels which were supported at the end and spanning at least 5 m and which could be walked on were necessary. Arup collaborated with TU Delft providing expertise in form finding to find the optimum pattern of spacers. TU Delft providing the expertise and facilities to make and test the panels. Schott sponsored the project by providing the glass spacers. These were carefully cut and flame polished DURAN tubes. The spacers were tubular, 210 mm long, with wall thicknesses of 5 or 9 mm depending on the location in the panel.

Preliminary calculations indicated a laminate of two layers of heat strengthened 10 mm thick glass in a PVB laminate should be more than sufficient. Heat strengthened PVB laminated 10.10.3 glass panels 6 m long and 1.5 m wide were ordered. During the three month delivery period experiments were conducted using 2\*0.5 m panels of 8.8.3 annealed PVB laminated glass.

The biggest problem was finding the adhesive for this design. The adhesive needs to connect the spacer with the float glass panels. The float glass panels are in essence flat excepting roller wave distortion, which was so low it could not be measured after the glass panels were delivered. The tolerance problem thus lies in the spacer. To determine this a set of 20 flame polished 210 mm long tubular spacers were accurately measured using a 300 mm digital caliper. The height distribution is shown in figure 5. This was found to be a non-gaussian distribution, possibly due to different machines being used cutting the tubes. The tubes were found to vary between 149.7 and 150.9 mm. Although as a percentage this is a small tolerance in terms of adhesive thickness this is a big problem. TU Delft had good results using DELO photobond adhesives in the past, Oikonomopoulou 2019, and prefers to use these for glass to glass connections. After discussion with the supplier the DELO photobond 4494 was selected. This cannot bridge a tolerance of 1.4 mm. However by measuring all tubes and placing the shorter ones on one side of the panel and the larger one on the other side, as illustrated in figure 6, the effective tolerance is reduced to 0.5 mm which the DELO photobond 4494 can bridge.

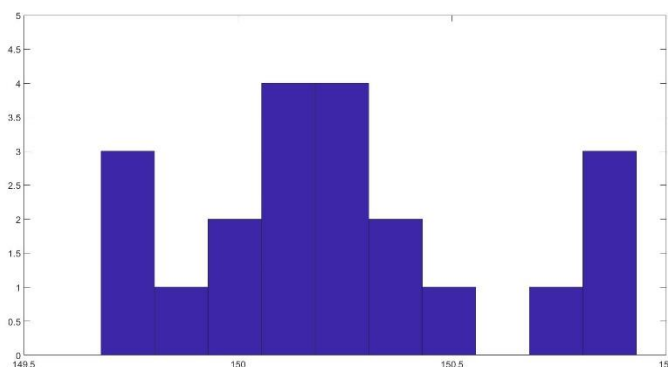


Fig. 5 distribution of measured height of 20 tubular spacers.

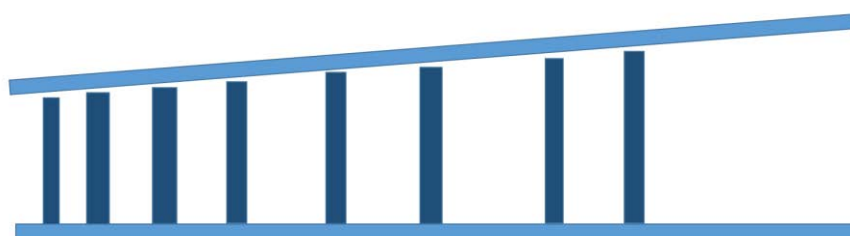


Fig. 6 Placement of spacers in the panel, short ones on the left, taller ones on the right, scale is exaggerated.

## 3. Prototyping, form finding and testing

Having determined the components and adhesive the next step is to find the ideal configuration of the spacers within the panel. This was done by making 2\*0.5 m prototypes. Initial experiments were done to optimize the production process. These panels were then tested in 4 point bending using a Zwick Z100 universal testing machine as shown in figures 7 and 8. After some trial and error panels could be made consistently and reasonably fast. The test results were

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compared to numerical modelling done by ARUP, see figure 9. After some fine tuning the ARUP models gave a good description in terms of stiffness and failure point of the experimental models. The numerical process is not described in this paper as the details are proprietary to ARUP. Based on these test result numerical modelling was used to form find the optimum configuration of spacers. This was verified on a small prototype, the data was used to refine the model which resulted in a design for the full scale panel.



Fig. 7 Production of prototype panel.



Fig. 8 Testing of prototype panel.

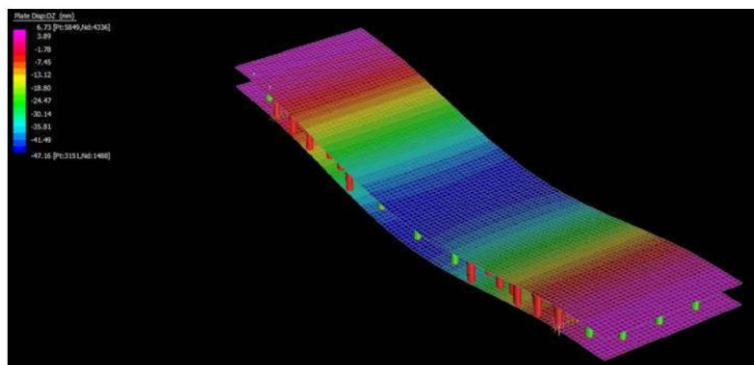


Fig. 9 Numerical modelling of prototype panel tests by ARUP.



#### **4. Making the full scale prototypes**

The float glass panels of the small scale models weighed 40 kg each. The panels for the full scale model weigh 450 kg each. Obviously this cannot be lifted by hand. Additionally the 6 m long panels are flexible and if supported in the middle flex some 8 cm at the ends.

This necessitated a totally different approach to production. As the panels had to be transported from Delft to Dusseldorf in crates, the base of the crates was used as a support for the bottom plate. The plate was cleaned with 2-propanol. Guides for the placement of the spacers were placed. The spacers organized in the right order on a table. The spacers were taken from the table, cleaned with 2-propanol, adhesive was applied on the surface and the spacer was placed at the correct position on the bottom glass plate. The joint was then illuminated to cure the adhesive. Figure 10 shows this part of the process.

After all spacers were bonded to the bottom plate, the top plate was taken from the crate using a crane with a vacuum suction clamp. The to be bonded panel surface was cleaned with 2-propanol. The top of the spacers are all cleaned with 2-propanol. Adhesive is applied by an organized team on all spacers within a 5 minute period, as shown in figure 11. The top plate is then placed on wooden supports resting on hydraulic jacks as shown in figure 12. By simultaneously lowering the hydraulic jacks the top plate is put in one single movement and completely flat on top of the adhesive on the spacers. All joints are now cured as quickly as possible by a team using multiple UV curing lamps.

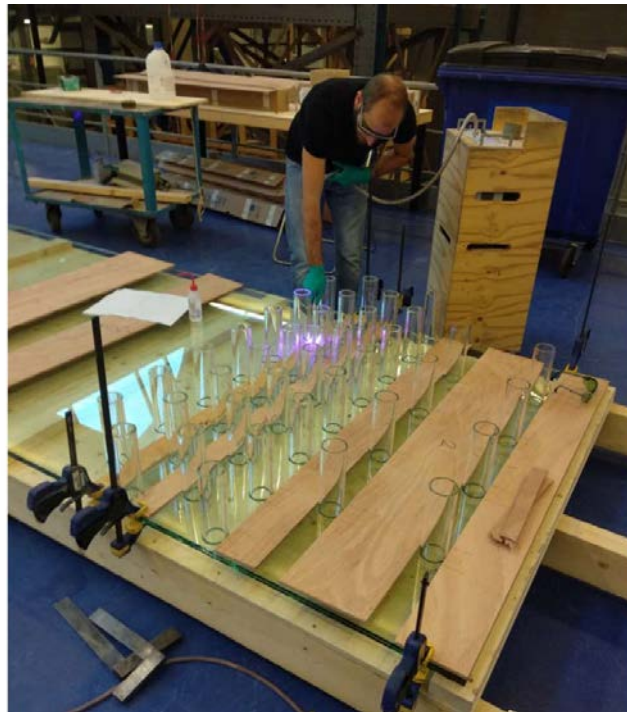


Fig. 10 production of bottom part of sandwich panel.



Fig. 11 applying adhesive to top of cylinder before placing top panel.



Fig. 12 placement of top panel.

### 5. Non-destructive testing of the full-scale prototypes

The glasstec 2018 insisted that the full-scale prototypes were tested before they could be exhibited. To validate the performance of the panels one of the prototypes was used to conduct experiments with dynamic and static response to loads. The dynamic response was validated by having students first walk, then march in step on it and then jump on it. The static response was determined by loading the panel with as many students that could fit on it. This is illustrated in figures 13 and 14. The panel was instrumented with strain gauges on some spacers and on the bottom plate. The strains measured were not excessive and in the expected range. Visual inspection of all adhesive joints after the tests revealed no problems.



Fig. 13 Non-destructive test of large prototype panel using dynamic load.



Fig. 14 Non-destructive test of large prototype panel using a static load exceeding the normal service load.



## **6. Exhibiting at the glasstec 2018**

The sandwich panels were moved to Dusseldorf for the glasstec 2018. They were exhibited in a triangle so people could walk on them going from panel to panel. Figure 15 shows the panels as exhibited. Figure 16 shows the panels with visitors on them. There was a very positive reaction from the visitors to the panels. Thousands of people walked over them without reluctance or hesitation. This proves the concept that a spanning glass structure will work psychologically.



Fig. 15 Full size panel at glasstec 2018.

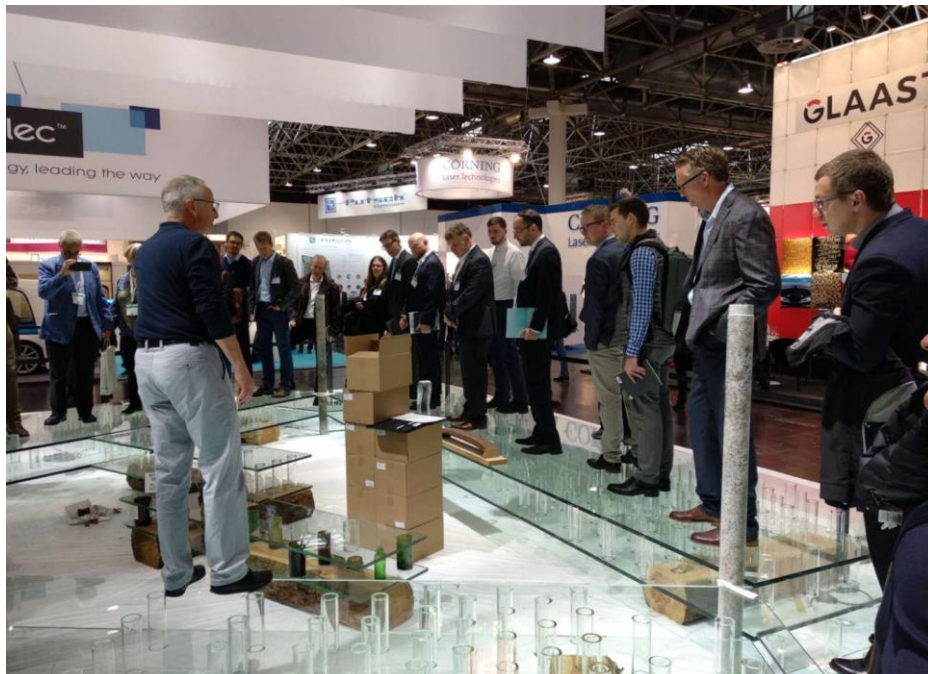


Fig. 16 Panel loaded with visitors at glasstec 2018.

## **7. Destructive testing of a full scale prototype**

After the glasstec 2018 exhibition was finished one of the three sandwich panels was available for a 4 p bending test to destruction. Considering the size of the specimen standard machines could not be used. A test rig which was used for bridge panels where the center rollers were fixed and the outer rollers hydraulically pushed up as available. This

was used with wooden beams as the intermediary between the steel frame and the glass. Figure 17 shows the test setup from above. The specimen was wrapped in plastic foil for safety reasons to prevent shards flying around the laboratory.

The specimen showed considerable deformation, as can be seen in figure 18. The bottom plate cracked at the location of a spacer, shown in figure 19. This did not seriously affect the strength and safety and further loading produced considerable deformation. The test had to be halted and the supports heightened to allow for a bigger displacement. The spacers let loose only locally and rotated slightly, as can be seen in figure 20. The load displacement curves are shown in figure 21.

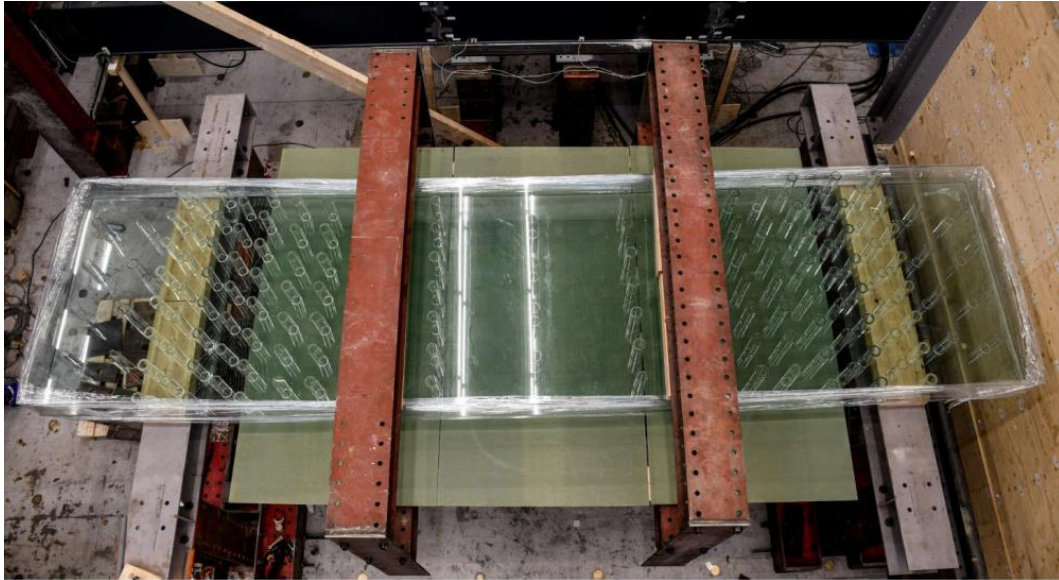


Fig. 17 Test setup from above, also showing the transparency of the glass sandwich panel.



Fig. 18 Side view of test after first loading sequence.



Fig. 19 cracks in bottom plate originating from a spacer.



Fig. 20 Details of spacers at end of test.



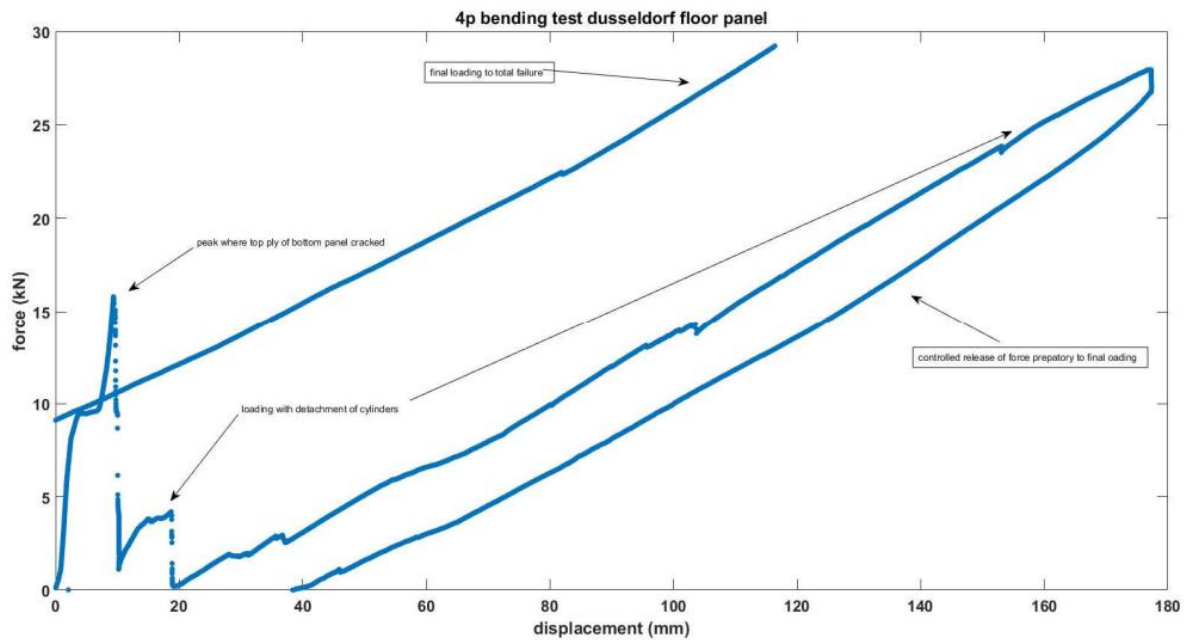


Fig. 21 Force displacement diagram of test.

## 8. Discussion

The results show that a glass sandwich panel made from heat strengthened float glass panels and tubular glass spacers can work efficiently, spanning a space transparently while providing stiffness and safety. Considering the large number of people who walked over these panels the panels provide enough psychological safety.

Mechanically the panels are very safe. As the load displacement data shows that even after local damage there is a high level of residual strength. The panels have a high structural safety and behave ductile, partly due to the nature of the laminated heat strengthened glass skin panels as well as the use of an adhesive that allows local de-bonding of the spacer while still maintaining some shear force transfer. The nature of the design is thus intrinsically safe allowing for a deformation of the comparable to the panel thickness while still carrying a considerable load.

The behavior of the panel can be modelled in Finite Element Modelling and the predicted behavior is quite close to the actual behavior as shown in figure 22. This allows for optimized design of these panels adapting the spacer configuration to the specific demands of the design.

Important lessons from the manufacturing perspective are that production of the spacers needs to be closely controlled. Assembly is not complicated but requires great care in terms of :

- keeping everything clean.
- sorting out the spacers for length
- Placing the top panel in a single movement without bending the plate
- Using a team of trained staff with enough UV lamps to quickly cure all the spacer-upper panel adhesive joints

This requires preparation, training and enough skill of the team doing this.

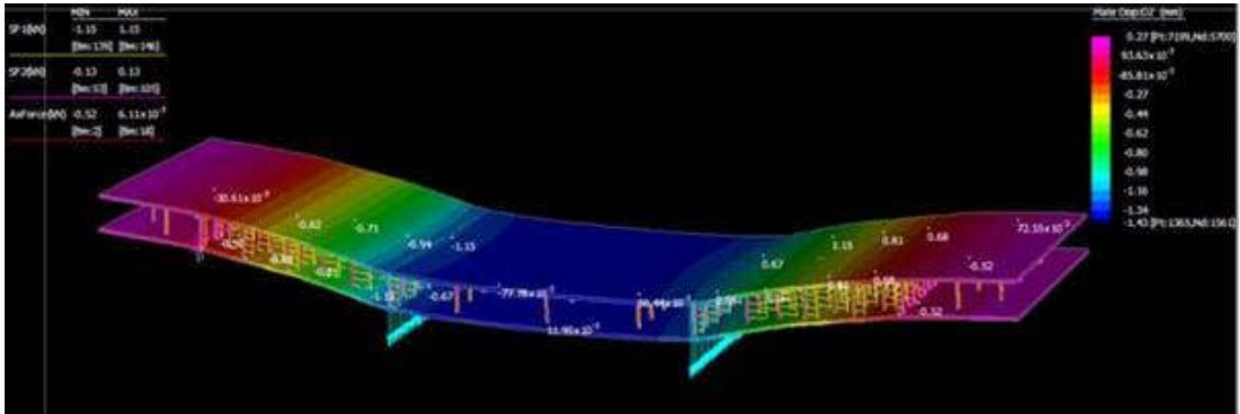


Fig. 22 FEM model of final panel in 4p bending test, model and test results corresponding closely.

## 9. Conclusions

Sandwich panels made from tubular glass spacers and heat strengthened float glass using a proper adhesive:

- combine transparency, low weight and high stiffness
- are structurally safe with good residual strength and good ductility
- can be made safely and economically using existing technologies if proper attention is paid to team training and process control.
- are psychologically acceptable for people to walk over.
- can be used in innovating ways in buildings and other structures.

## 10. Acknowledgements

The authors acknowledge the critical support of Schott in providing the necessary spacers and technical data.

The assistance of the building technology and building engineering students of Delft University of Technology who helped in manufacturing the sandwich panels and who acted as human test subjects is gratefully acknowledged.

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