

Linear connection system for structural application of glass panels in fully-transparent pavilions

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Utilizing glass facade as unique vertical structural element in fully-transparent pavilions, the individual glass panels are subjected to in-plane shear loading, in-plane compression and out-of-plane bending. The upper glass boundary is connecting to the roof; bottom part is supported by the foundation while the side boundaries are support free. A concept of glass panel linearly glued by structural silicon sealant to roof and foundation on two shorter edges was developed with seating blocks made of mortar. Preliminary investigations on local behaviour of the connection system gave results which provided the bases for research on global behaviour of glass panels under in-plane shear loading with in-plane compression and out-of plane bending interaction.

Keywords: Fully-transparent pavilion, In-plane shear loading, Structural adhesive, Glass panel-structural behaviour, Shear buckling

1. Introduction

Nowadays tendency using transparent and new material in modern architecture, leads to the idea of utilizing glass not only as a window element but also as a structural material able to carry the loads. Increasing the window areas and glazing surface more and more, and making the load bearing structure finer and finer but still rigid enough to sustain the loads, transparency and lightness of the structure can be increased. Further improvement will be to entirely dismiss the traditional load bearing structure and to use the glass not only for this transparency but also in a structural manner as primary structural element capable to carry and transfer the loads [1], [2].

In fully-transparent pavilions (Fig. 1), glass panels can be used as unique vertical structural element able to carry the vertical load imposed by the roof and to stabilize the structure [3]. An individual glass panel is therefore subjected to in-plane shear force (lateral wind), in-plane compression (roof self weight, snow, etc.) and out-of-plane bending moment (perpendicular wind). Connection system should be able to transfer the load from the roof through the glass panel to the foundation smoothly avoiding stress peak and stress concentration in the surrounding glass [4], [5].



Figure 1: Fully transparent pavilions a) Rheinbach glass pavilion b) Novartis campus entrance building

Primary idea is to develop a suitable connection system, to investigate its local behaviour and its influence on the global structural behaviour of glass panels. For this reason two structural concepts are developed and studied: **point support system** where glass panel is connected by bolts to the substructure [6] and **linear support system** where glass panel is linearly attached to the substructure by adhesive where mortar is used as seating block. This paper presents the development of linear support system and explains the main results of the experimental investigation.

2. Connection test – local behaviour

2.1. Specimens

The objective of the connection test is to study the shear behaviour of the adhesive used to glue the glass to the substructure. The specimen consists of glass plate (220x490mm), adhesive (structural silicon sealant DC 993) and substructure (stainless steel). Regarding the load direction, two tests were recognized:

Transversal shear test - adhesive is subjected to transversal shear stresses (Fig. 2a)

Longitudinal shear test - adhesive is subjected to longitudinal shear stresses (Fig. 2b)

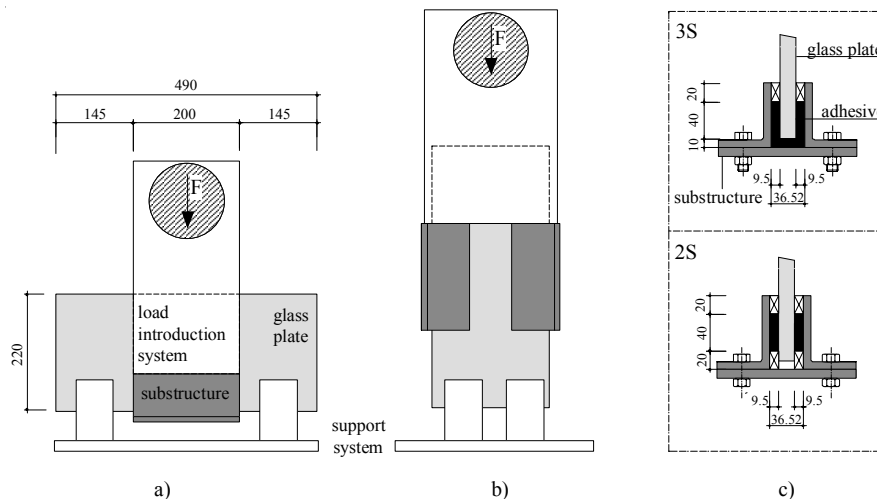


Figure 2: Connection test a) transversal shear test b) longitudinal shear test c) connection details

Regarding the geometry of the adhesive connection, three sides gluing (3S) and two sides gluing (2S) are distinguished (Fig. 2c). The force on the specimen is introduced by two steel plates which transfer the force from the testing machine to the substructure and through the adhesive into the glass plate.

2.2. Connection test results

Force vs. specimen displacement. Substructure displacement due to adhesive deformation (δ) in relation to the applied force (F) in transversal and longitudinal shear test can be seen in Figure 3.

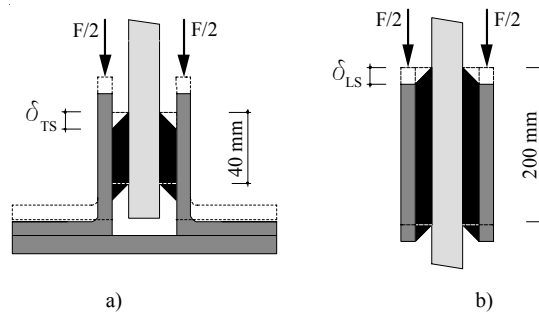


Figure 3: Adhesive deformation a) transversal shear test b) longitudinal shear test

Figure 4a shows the specimen displacement in relation to the applied force in transversal shear tests. Adhesive behaviour can be divided in three zones: linear-elastic zone, non linear zone and softening zone when adhesive loses its resistance. The non linear zone in two side gluing is much greater than the one with three side gluing. Resistance of 3S is higher than the 2S while the adhesive deformation is smaller.

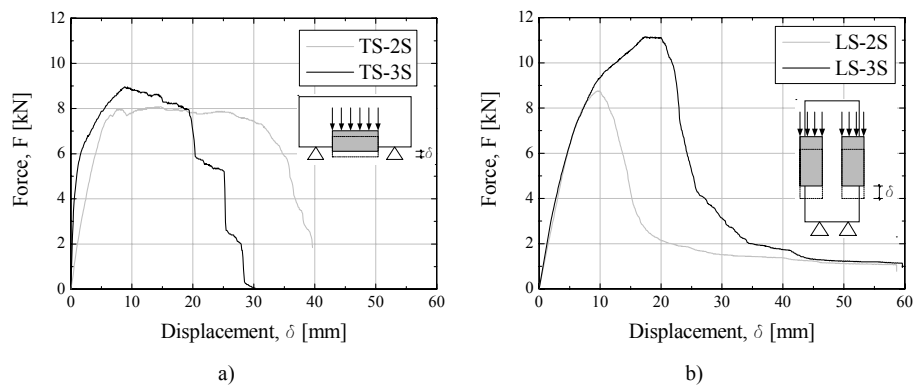


Figure 4: Force vs. displacement a) transversal shear test b) longitudinal shear test

Figure 4b shows the specimen displacement in relation to the applied force in longitudinal shear tests. Adhesive behaviour can be divided in three zones: linear, non linear and softening zone, with the fact that non linear zone is very small, almost negligible for some test series. On the other hand, the softening zone is greater than in transversal shear test. 3S specimens show higher resistance and deformation than 2S.

Failure mode. Specimens in transversal and longitudinal shear tests failed in the adhesive interlayer. So called cohesive type of failure took place - the rupture happens inside the adhesive (Fig. 5). Adhesive failure (rupture due to separation of adhesive from the metal/glass in the contact area) didn't occur.

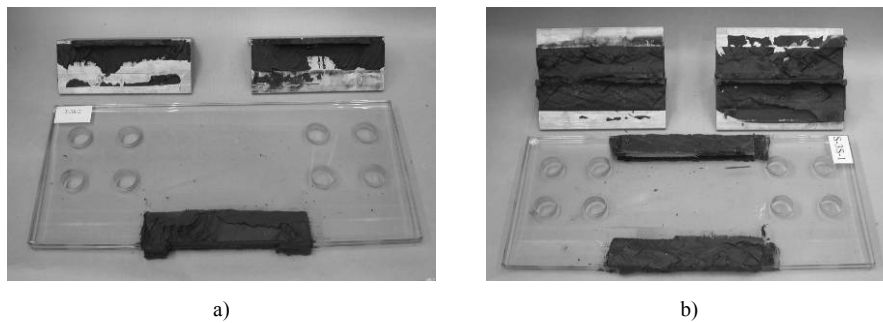


Figure 5: Specimen failure a) transversal shear test b) longitudinal shear test

3. Panel test – global behaviour

3.1. Specimens

The behaviour of the adhesive layer under different shear loading orientation was given by the connection tests. Although showing less resistance, two sides gluing is chosen for panel tests due to easiest gluing process and clearer stress distribution. The objective of panel tests is to study the global behaviour of full-size glass panels supported linearly on two shortest edges under different load cases.

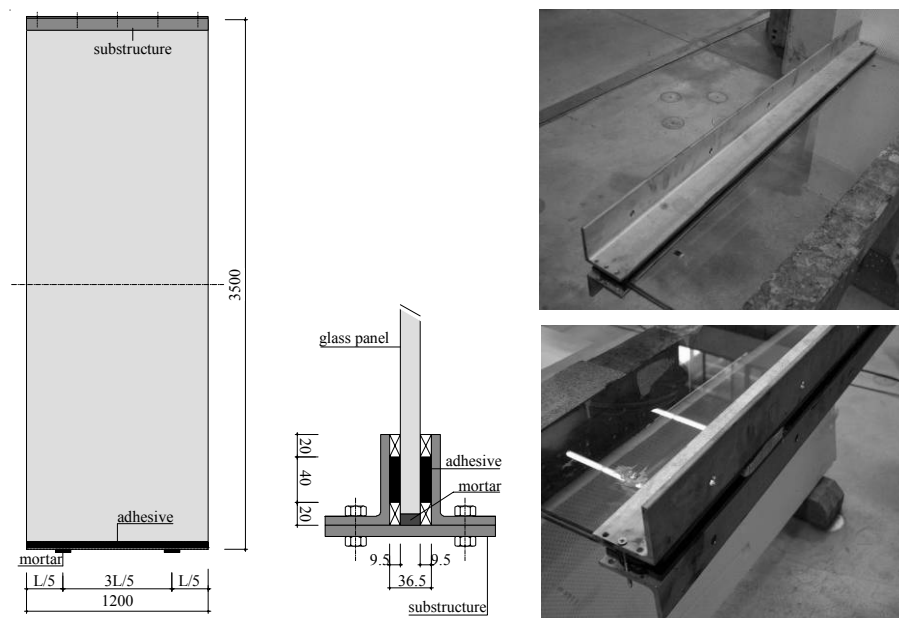


Figure 6: Panel test specimen with connection details

Three full size specimens were built and each subjected to different load cases:

Test 1 (T1): specimen is subjected to variable in-plane shear force (V).

Test 2 (T2): specimen was simultaneously subjected to variable in-plane shear force (V) and constant out-of-plane bending ($q = 0.4 \text{ kN/m}^2$).

Test 3 (T3): specimen was simultaneously subjected to variable in-plane shear force (V) and constant in-plane compression ($N = 20 \text{ kN}$).

The specimen consists of heat strengthened laminated glass panel (dimension 1200x3500mm, thickness 8/1.52/8), adhesive (structural silicon sealant DC993), mortar (HIT HY 70) as seating blocks and two substructures (stainless steel). The substructures were glued to the glass panel by adhesive on two shortest edges. Adhesive has the function of transferring in-plane shear force from the support (substructure) to the glass panel. As the structural silicon is not allowed to carry the permanent load, seating blocks made of injected mortar were added (Fig. 6).

3.2. Panel test load frame

For the experimental investigation purpose, a load frame was constructed (Fig. 7). The load frame was placed in horizontal position. It consists of four steel profiles HEB 180 (named North, East, South, West), articulated connection at four angles (A, B, C and D) able to transfer the force but not the moment and three supports (longitudinal C and D, transversal C).

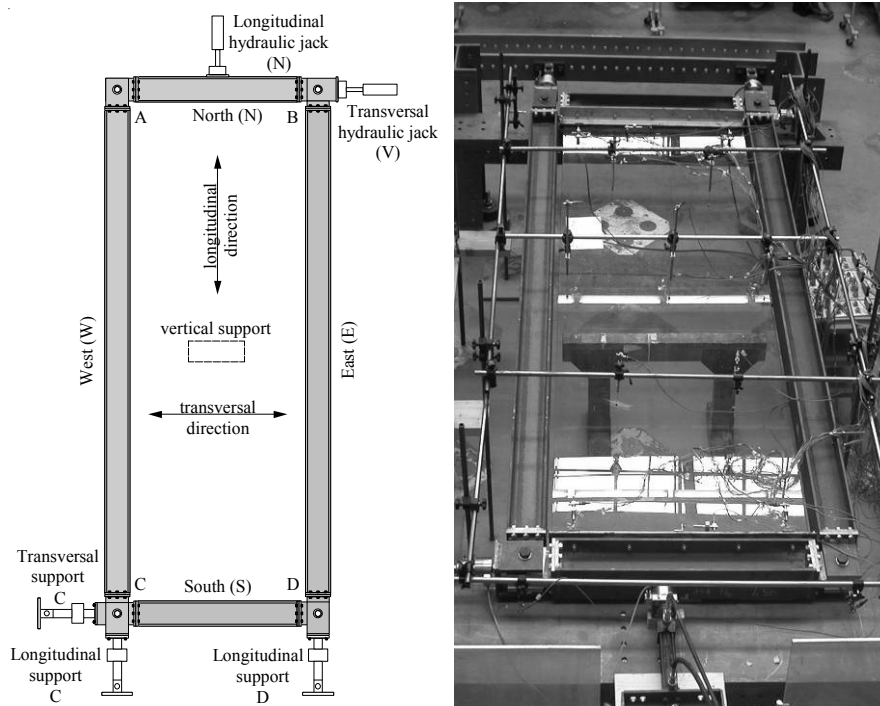


Figure 7: Panel test load frame

Being cinematically unstable under in-plane shear force, the load frame is stabilized only once the glass panel is positioned in the frame. In-plane shear loading (V) is introduced by transversal hydraulic jack (point B), in-plane compression loading (N) by longitudinal hydraulic jack (middle of steel bar N) while the out-of-plane bending (q) is simulated by the self-weight of the glass panel. To avoid the out-of-plane influence during Test 1 and Test 3, additional vertical support was placed in the middle of the glass panel.

3.3. Panel test results

Specimen subjected to in-plane shear force (Fig. 8a) showed membrane effect - compressive and tensile diagonals in the glass panel crossing each other (Fig 8b). The compressive diagonal takes place between two opposite seating blocks (B and C), whereas the tensile diagonal (between blocks A and D) occurs due to shear strength of the adhesive that try to keep the glass panel in position. In the same time, the transversal slip of the glass panel with respect to the substructure take place.

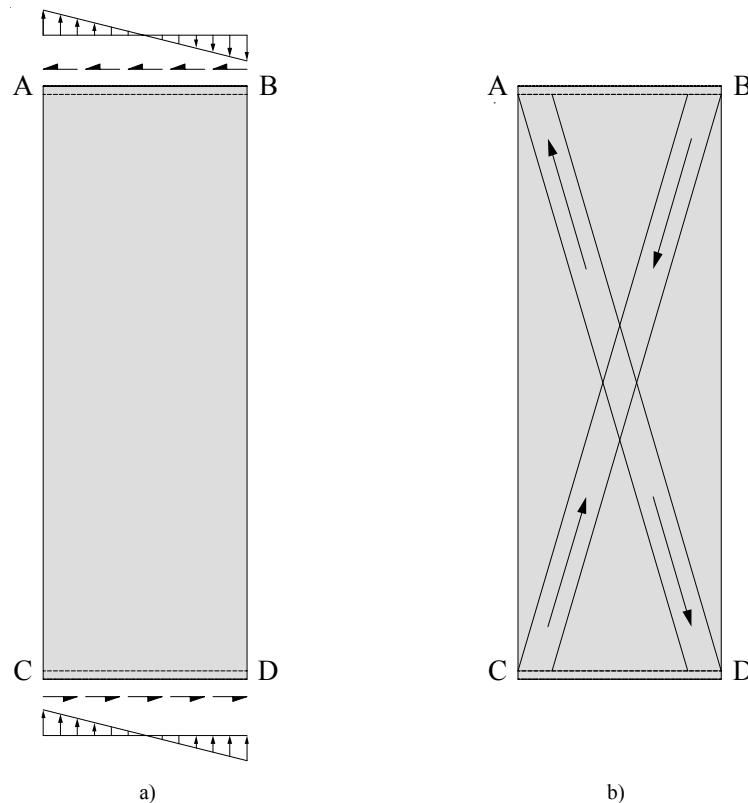


Figure 8: Glass panel a) actions b) internal force distribution

Force vs. displacement. Figure 9 shows the transversal specimen displacement (Δ) that contains the deformation of glass panel (Δ_{gp}) and the deformation of adhesive layer (Δ_{al}) plotted against the in-plane shear force (V). Initial linear-elastic zone can be recognised. After a certain load, non linear behaviour is visible. The resistance of

specimen under in-plane shear force (Test 1) is higher than the specimens under in-plane shear/out-of-plane bending and in-plane shear/in-plane compression interaction (Test 2 / Test 3). The elastic displacements of the specimens are in serviceability range ($< L/150$). Table 10 is representing the shear force, transversal specimen displacement of the system, of the glass panel and of adhesive layer at failure of the specimens.

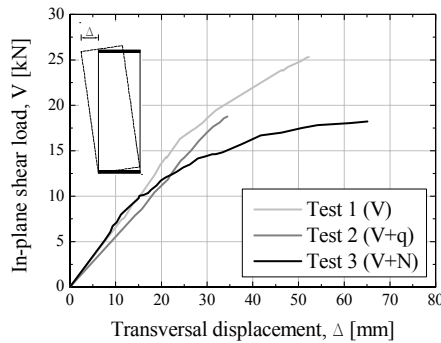


Figure 9: Force vs. transversal specimen displacement

Test	V [kN]	Δ [mm]	Δ _{gp} [mm]	Δ _{al} [mm]
Test 1	25.29	52.3	3.7	48.6
Test 2	18.22	65.1	4.2	60.9
Test 3	18.77	34.5	2.3	32.2

Table 10: Panel test recapitulation

Figure 11 shows the perpendicular deflection (w) in the middle of the glass panel span under constant out-of plane load (0.4 kN/m^2) in Test 2, measured in the period of 24 hours. Due to PVB creep effect, the deflection increased during the time. Most of the deflection variation happened in the first 15 minutes, while after 24 hours the deflection remained constant. Keeping this out-of-plane bending constant, the in plane-shear load was applied. The perpendicular deflection of the glass panel for different in-plane shear force steps of 3 kN is represented in Figure 12. The deflection is not linear regarding the applied in-plane shear force - for each successive load step, the larger deflection increment is visible.

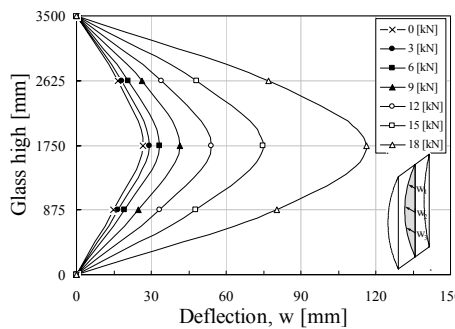


Figure 11: Perpendicular deflection in the middle of glass span vs. time

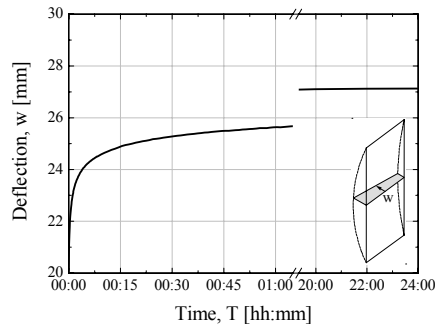


Figure 12: Glass panel deflection curve for different in-plane shear load steps

Failure mode. The failure of the glass panels under in-plane shear force happened due to splitting tension. Perpendicular to the compressive stresses in the compressive diagonal B-C, Poisson ratio causes high tensile stresses which lead to the failure. The crack initiation point in the glass panel is on the contact surface with seating blocks. The crack path is clearly visible in the upper glass of the panel (Figure 13).

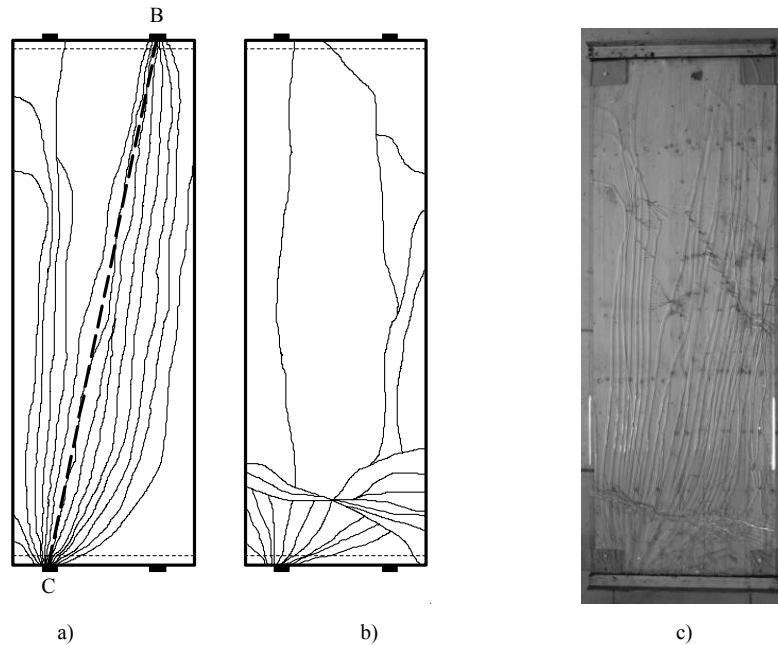


Figure 13: Failure mode of Test 3 a) upper panel b) lower panel c) failed specimen

4. Conclusions

4.1. Connection test – local shear behaviour

Specimens under longitudinal shear force are showing ductile behaviour with large non linear zone which depend of the glue geometry. On the other hand, specimens under transversal longitudinal shear force are showing very small non linear zone, but with large softening zone. The resistance of the three side gluing specimens is higher than the two side ones. The specimens failed due to cohesive rupture in the adhesive.

4.2. Panel test – global shear behaviour

The specimen subjected to in-plane shear force showed initial linear-elastic behaviour. Reaching certain load amplitude, the specimen started showing ductility caused by the adhesive non linear behaviour. A tensile diagonal is caused by the shear resistance of the adhesive, whereas a compressive diagonal takes place between the opposite seating blocks. Specimen failure occurs due to splitting tension - a tensile force caused by Poisson ratio perpendicular to the compressive stresses in the compressive diagonal.

4.3. Future work

Analytical and numerical models of the linear support system will be developed and furthermore compared and verified with the results obtained from the experimental investigation. Intensive parametrical study, in order to identify the main parameters governing the phenomena, will be conducted. At the end, design procedure and practical recommendations for implementation of glass panel as primary structural element in fully-transparent pavilions will be given.

5. Acknowledgements

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6. References

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