Glass panel under in-plane shear loading: Experimental investigation on structural glass panel point support

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Keywords

1=structural glass 2=building stabilization 3=in-plane loading 4=point support 5=bolted connection

Abstract

The latest trend in contemporary architecture is fully-transparent pavilions in which glass "walls" can be used as vertical structural elements to support the roof and as wind bracing elements to stabilize and strengthen the building. In these applications, the individual glass panels are subjected to in-plane (compression and shear) and out-of-plane (bending) loading. An adequate connection system ensuring uniform load transfer through the glass panels should be developed, before the global glass panel-structural behaviour can be analyzed.

This contribution describes laboratory tests studying local behaviour of structural glass bolted connections. These connections represent rigid and pinned panel point supports under axial and eccentric in-plane loading. Innovation lies in the use of injected mortar as a glass drill hole filling material instead of classical liner material. Laboratory test results, system deformations, stress distribution as well as failure modes for different load actions and boundary conditions are presented.

These results provide a foundation for further research on glass panel global behaviour under in-plane shear loading.

Introduction

The main problem of structural use of glass panels lies in the difficulty of transferring the load from the glazing system to the main building structure. Once an adequate connection is established, glass panels can be used as structural elements and substitute classical construction elements such as steel bracing or concrete walls (Figure 1)

The typical connection system used in glass facade building envelopes is comprised of bolted connections. Glass panels are supported by the substructure using bolts. If such glazing systems are to be employed as stabilization elements, the in-plane load should be adequately introduced in the glass panel to provide sufficient shear load-carrying capacity. The critical part in the glass panels will be the area around the drilled holes where complex stress fields and large stress concentrations will appear [1].

Aluminium or POM (Polyoxymethylene) material are usually employed as liner material in bolted connections to avoid the direct contact between steel bolt and glass, but they are unable to uniformly transfer the in-plane load in laminated glass due to production tolerances [2]. The proposed concept assumes the use of injected mortar in the bolted connection as a liner material which is able to homogenously transfer the load from the glass to the structure and vice versa, as well as assure the serviceability and structural safety of the building structure.

This contribution presents laboratory investigations on the local behaviour of glass specimens (Figure 2) with bolted connections using mortar as a liner material.

Specimen and test lay-out

Heat strengthened glass specimens of different thicknesses (6 mm of monolithic glass, 6/1.52/6 and 8/1.52/8 of laminated glass) with two drilled holes were tested (Figure 2b). Injected mortar HIT HY 50 (Hilti) was used as a liner material between the glass and the bolt (Figure 2c)

All specimens were tested 24 hours after injection of the mortar, under the same environmental conditions – humidity (60%) and temperature (23°). For each test, three specimens were tested under displacement control with constant increments of 2.4 mm/min. Figure 3 and Figure 4 shows the positioning of the specimens in the testing machine.

Three test types are distinguished (Figure 5 and Table 1)

- Axial test (A): the load is introduced on both sides of the bolt (M20); glass is subjected only to the normal force (Figure 5a).

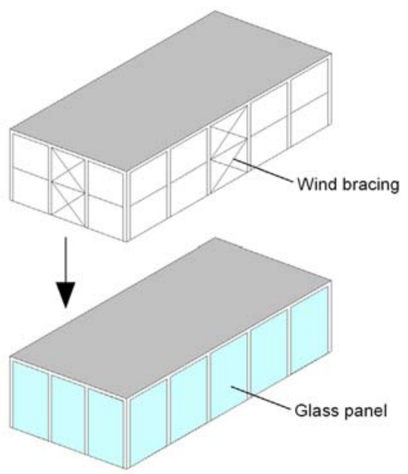
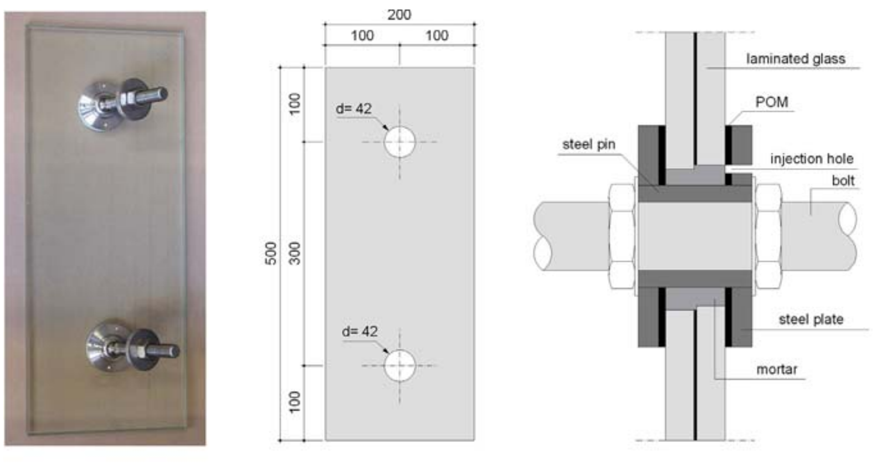


Figure 1
Stabilization by glass panel



a) glass specimen b) glass plate c) connection detail

Figure 2
Test specimen

- Eccentric rigid test (ER): the load is introduced 60 mm eccentrically from the centre line of the glass plates. The connection between glass and bolts is rigid; the glass is subjected to normal force with additional moment due to eccentricity. Bolts M16 and M20 were used (Figure 5b)
- Eccentric pinned test (EP): the load is introduced 60 mm eccentrically from the centre line of the glass plates. The bolt heads have an articulation. Bolts M16 were used (Figure 5c)

Test type	Axial (A)	Eccentric rigid (ER)		Eccent. pinned (EP)
Bolt diameters	M20	M20	M16	M16
Glass thickness	1x6	1x6	1x6	1x6
	2x6	2x6	2x6	2x6
	2x8	2x8	2x8	2x8

Table 1

Test types

Figure 3 and Figure 4

Specimens in the testing machine - axially and eccentrically applied load

Test results

Force and system displacement

Figure 6 shows the force/system displacement results of the tests under tensile loading.

The axial tests, where glass panels were subjected only to the normal force, showed higher resistance with smaller system displacement than the eccentric tests in which the glass was subjected simultaneously to axial force and bending.

Eccentric rigid connection with stronger bolts (M20) gave the system a higher rigidity than the one with weaker bolts (M16), as well as higher resistance and smaller displacement.

It can be seen that rigidity does not depend on the support condition, but on the bolt diameter: the eccentric pinned connection with M16 has the same rigidity as eccentric rigid connection with M16. On the other hand, the eccentric pinned connection demonstrates higher resistance but greater deformation.

For each of the connections types, three specimens were tested. The mean value of the ultimate resistance, with minimum and maximum values as well as standard deviations are represented in Table 2.

	Axial (A)	Eccentric rigid (ER)		Eccent. pinned (EP)
	M20	M20	M16	M16
	[kN]	[kN]	[kN]	[kN]
Mean	42.73	14.03	10.43	15.28
Maximum	49.8	16.84	11.68	17.28
Minimum	38.92	10.80	9.76	12.64
Standard deviation	6.13	3.04	1.09	2.39

Table 2

Ultimate resistance result of tensile test

In Figure 7, the force/system displacement results of the specimens under compression loading are represented.

Again, the axial connection demonstrates higher resistance and smaller displacement than the eccentric connection. The strongest bolt in the eccentric test gives higher rigidity and higher resistance to the specimen.

Table 3 summarizes the compression test results.

	Axial (A)	Eccentric rigid (ER)		Eccen. pinned (EP)
	M20	M20	M16	M16
	[kN]	[kN]	[kN]	[kN]
Mean	48.68	20.96	13.64	16.08
Maximum	51.12	22.8	14.96	17.04
Minimum	46.04	19.00	12.84	15.12
Standard deviation	2.55	1.90	1.15	1.36

Table 3

Ultimate resistance results of compression test

The resistance of axial and eccentric rigid connections is quite higher under compression than under tensile loading, what is not the case for eccentric pinned connection where the resistance under compression and tensile loading are almost the same.

Glass panels with eccentric rigid connections demonstrate a residual resistance – in laminate glass one glass sheet failed initially, but the system had sufficient resistance to withstand further loading until failure of the second glass sheet which corresponded to system failure. However, in the axial test and eccentric pinned test the failure of both glass sheets in laminated glass occurred at the same time.

Although glass is a linear-elastic material, in some tests ductile behaviour

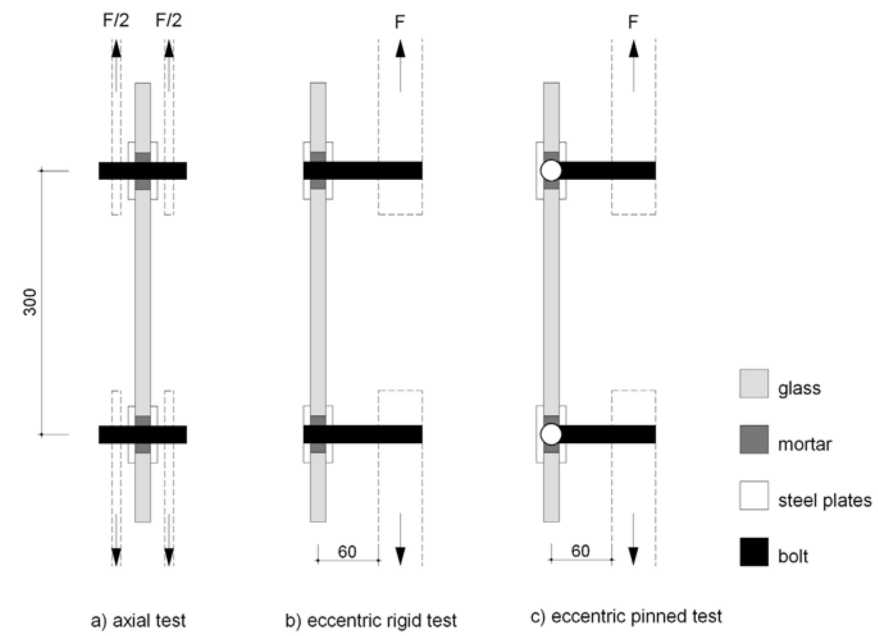


Figure 5

Test types

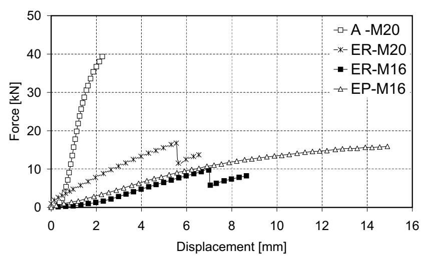


Figure 6

Force/system displacement results of tensile test

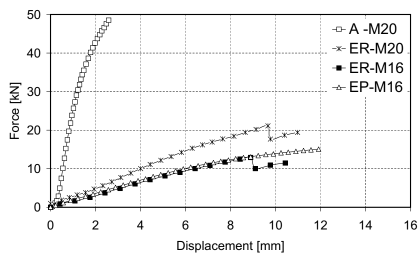


Figure 7

Force/system displacement results of compression test of the system can be identified. There is a point after which the force/system displacement curve is no longer linear. This occurs in specimen with weaker bolts, where steel yielding of the bolts take place due to high bending.

Stresses

During the tests, strain was measured radially around the drilled holes, 45 mm from the centre, on both sides of the glass plate (Figure 8). The strains obtained from the rosette were converted to the stresses by adopting a modulus of elasticity of 70'000 N/mm^2.

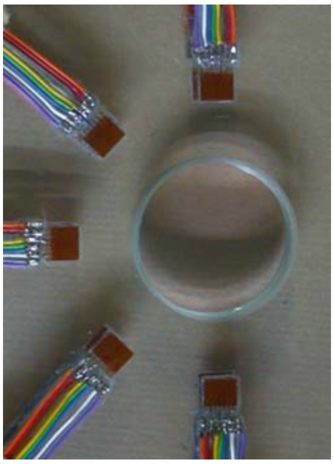


Figure 8

Strain gauges arrangements

Figure 9 to Figure 12 show the radial stresses measurements in laminated glass specimens (thickness 8/1.52/8 mm) subjected to tension load of 8 kN (that correspond to stress of σ_N=2.5 N/mm^2 in the middle of the glass plate due to normal force).

In the axial tests, the stresses on both sides are the same due to the fact that only normal force is present. The point at +90° is in compression, whereas the opposite point at -90° is under tension.

In the eccentric tests, the additional bending due to eccentricity causes a different stress distribution on each side of the glass specimen. For the same load magnitude, tensile stresses are higher in the specimen with weaker bolts (stress concentration is higher)

Failure modes

Initial fracture of the glass always occurs under tensile strength. Depending on the test type and load direction, different failure modes were recognized.

In the axial test under compression loading, no instability phenomenons were observed due to the slenderness of the specimen. Splitting tension failure mode took place. High compressive force introduced between the bolts caused perpendicular tensile stress that led to crack propagation in the longitudinal direction of the specimen (due to Poisson's ratio). After the first occurrence of a longitudinal crack in the middle of the glass panel, the specimen was still able to resist additional force. As the load increased, more longitudinal cracks occurred (Figure 13).

In the axial test under tensile loading the specimen failed due to tension in net section. Initial failure occurred at the edge of the glass hole, perpendicular to the load direction, due to stress concentration (Figure 14).

In the eccentric test under compression loading (Figure 15 and Figure 17), failure mode combination (splitting tension and bending) was observed. In the rigid connection, the first crack occurred longitudinally between the bolts, but the final failure occurred transversally in the middle of the glass plates where the highest tensile stress occurred due to the glass curvature. However, in the pinned connection, where normal force has more influence than the bending, the cracks propagated mainly in longitudinal direction due to splitting tension.

Similarly, in the eccentric test under tensile loading (Figure 16 and Figure 18), failure mode combination (tension in net section and bending) were observed. In the rigid connection test the bending has more influence than in the pinned test.

In the specimen with weaker bolts and stronger glass, plastic deformation of bolts was observed. In the most extreme case (stiffest glass 8/1.52/8 with the weakest bolt M16), the instability phenomenon in the bolts took place.

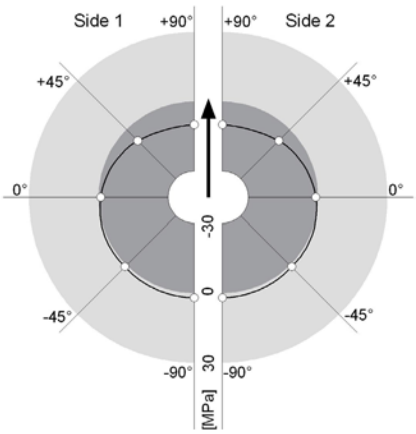


Figure 9

Radial stresses in axial test with M20

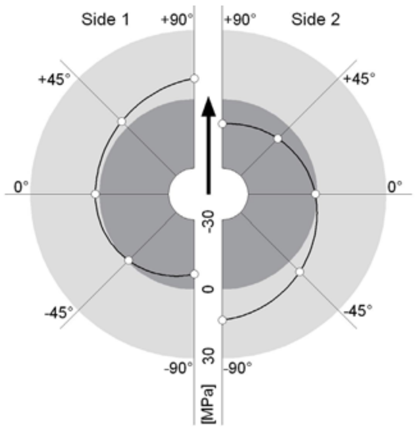


Figure 10

Radial stresses in eccentric rigid test with M20

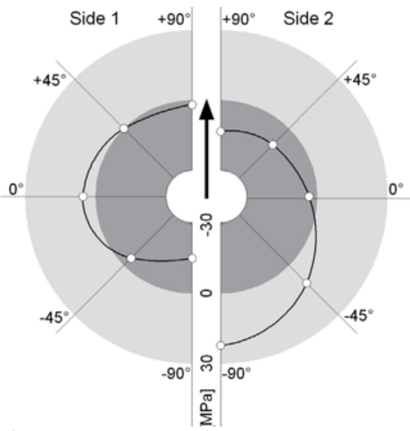


Figure 11

Radial stresses in eccentric rigid test with M16

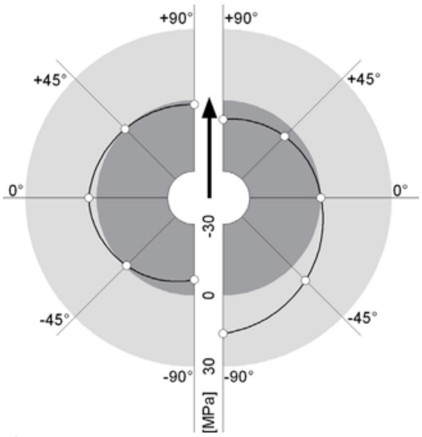


Figure 12

Radial stresses in eccentric pinned test with M16

Potential practical applications

Each test type showed different behaviour and consequently different potential applications in practice. Glass specimens with axial connections demonstrated high resistance with small system deformation and are therefore applicable for higher design loads than the glass panels with eccentric connections. Glass specimens with eccentric connections with stronger bolts gave the system higher rigidity and as a result higher resistance. On the other hand the specimen with weaker bolts exhibited ductility (the plastic deformation of the bolts occurs before the brittle failure of the glass) giving potential applications in seismic areas. The advantage of the eccentric rigid connection is its residual resistance giving additional safety to the structure. The eccentric pinned connection demonstrated very high deformation and therefore would only be useful for small serviceability loads.

Conclusions

When using glazing as a stabilizing element in buildings, the load should be adequately introduced in the glass panel providing sufficient shear load-carrying capacity. A concept of bolted connection system with injected mortar as liner material was developed. The local behaviour of glass panels near the drilled hole was studied experimentally.

Figure 15 and Figure 16

Failure modes of eccentric rigid tests under compression and tension

Figure 13 and Figure 14

Failure modes of axial tests under compression and tension

Figure 17 and Figure 18

Failure modes of eccentric pinned tests under compression and tension

Glass specimens were tested under axially and eccentrically applied load, with rigid and pinned point supports, under compression and tension. It was found that the specimen's behaviour was particularly sensitive to the loading eccentricity – the axial test demonstrates higher resistance with less deformation than the eccentric test. The rigidity of the system depends on the bolt diameters, but not on the support conditions. The eccentric rigid system demonstrates additional safety due to the residual resistance. The weak bolt in the eccentric test gives the system ductility. The failure modes were found to be a function of the loading direction, boundary conditions and specimen geometry. The use of injected mortar was found to be an adequate solution for uniform load introduction in the laminated glass as well as for load transferring from the bolts to the glass panel.

This experimental investigation was used as the basis for a future study of the global behaviour of full scale glass panels with bolted connections under in-plane shear load and its suitability for use in building stabilization.

Acknowledgements

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