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Mechanical Modelling of In-Plane Loaded Glass Panes

Paulo J. S. Cruz, José Pequeno
School of Architecture, University of Minho, Portugal, pcruz@arquitectura.uminho.pt
Jean-Paul Lebet
ICOM – EPFL, Switzerland, jean-paul.lebet@epfl.ch
Danijel Mocibob
Institute IGH, Croatia, danijel.mocibob@igh.hr

Glass panes are increasingly being used to the stabilization of one storey buildings by acting as shear walls and thus replacing conventional bracings. This is the case of glass pavilions and some timber or steel frames or facades. The behaviour of such structural systems mainly depends on the stiffness of the connections. This research focuses on the prediction of the in-plane structural behaviour of steel and timber frames with a single pane fixed by circumferentially glued joints or by point support connectors. Mechanical models have been implemented and validated. The results obtained clearly demonstrate that the models can be applicable for the purpose of the non-cracking pre-design of panes acting as a shear wall because they are able to predict the in-plane stiffness and the force necessary to obtain a certain horizontal in-plane displacement at the top.

Keywords: Glass Pane, Shear Wall, Building Stabilization, Mechanical Model

1. Introduction

Facades, as the transparent face of buildings, gain nowadays a high significance in architectural design, construction and material technology, as well as functionality.

The potential of glued joints is not entirely exploited in glass facades. Possible applications of glued joints could be point supports or linear bearings to carry single facade elements or connect them to plates, columns and beams. Circumferentially glued joints are generally classified in three different types as shown in Figure 1.

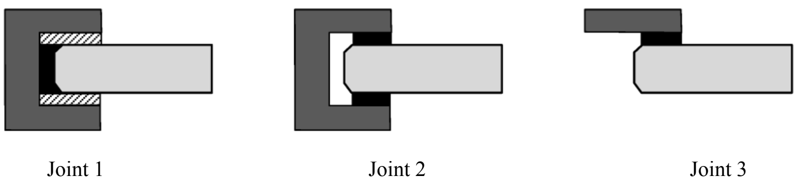


Figure 1: Adhesive joint types.

Glazing elements in facades are usually designed only to support out-of-plane loads. However glazing elements can also support high in-plane loads and, thus, contributing to minimize the number of steel elements and their cross sections. Several authors exploited the in-plane shear-strength of glass panel elements in combination with steel and timber frame constructions [1] to [4].

The lesser the support system, the more complicated the transference of loads and actions from glass into the substructure will be. If high loads have to be transferred by small dimensions, the corresponding fixing system plays a key role in this field and different strategies have to be balanced in order to avoid unpredictable and brittle failure.

The use of mechanical models to predict the behaviour of joints has a long tradition in the fields of steel and composite structures. The component method proposed in Eurocode 3 [5] and Eurocode 4 [6] is based on the association of springs that model the different components of a joint.

The present research focuses on the use of simple mechanical models to simulate the in-plane structural behaviour of steel and timber frames, having a single pane fixed by circumferentially glued joints or by point support connectors.

2. Mechanical model

2.1. In-plane behavior of circumferentially adhesive bonded glass panes

Huveners et al. [7] have recently proposed a mechanical model of twelve springs to simulate the in-plane behavior of circumferentially adhesive bonded glass panes (Figure 2).

2.2. Type 1

The normal stiffness of the adhesive joint is constant and the normal springs are placed in the centre of the assumed linear distribution, considering a linear distribution of the normal stresses. Consequently, the stiffness of the normal and shear springs can be derived from equations (1) to (4).

$$K_1 = K_2 = K_3 = K_4 = \frac{3}{8}\, k_{f,1}\, t_g\, w_g \tag{1}$$

$$K_7 = K_8 = K_9 = K_{10} = \frac{3}{8}\, k_{f,1}\, t_g\, h_g \tag{2}$$

$$K_5 = K_6 = k_{f,2}\, t_g\, h_g \tag{3}$$

$$K_{11} = K_{12} = k_{f,2}\, t_g\, w_g \tag{4}$$

in which t_g, w_g and h_g are the thickness, width and height of the glass pane, respectively.

The continuous normal stiffness and shear stiffness ($k_{f,1}$ and $k_1(f,2))$ are dependent of the adhesive properties (Young's modulus, E_a and shear modulus, G_a) and of the joint thickness (t_j):

$$k_{f,1} = \frac{E_a}{t_j} \tag{5}$$

$$k_{f,s} = \frac{G_a}{t_f} \tag{6}$$

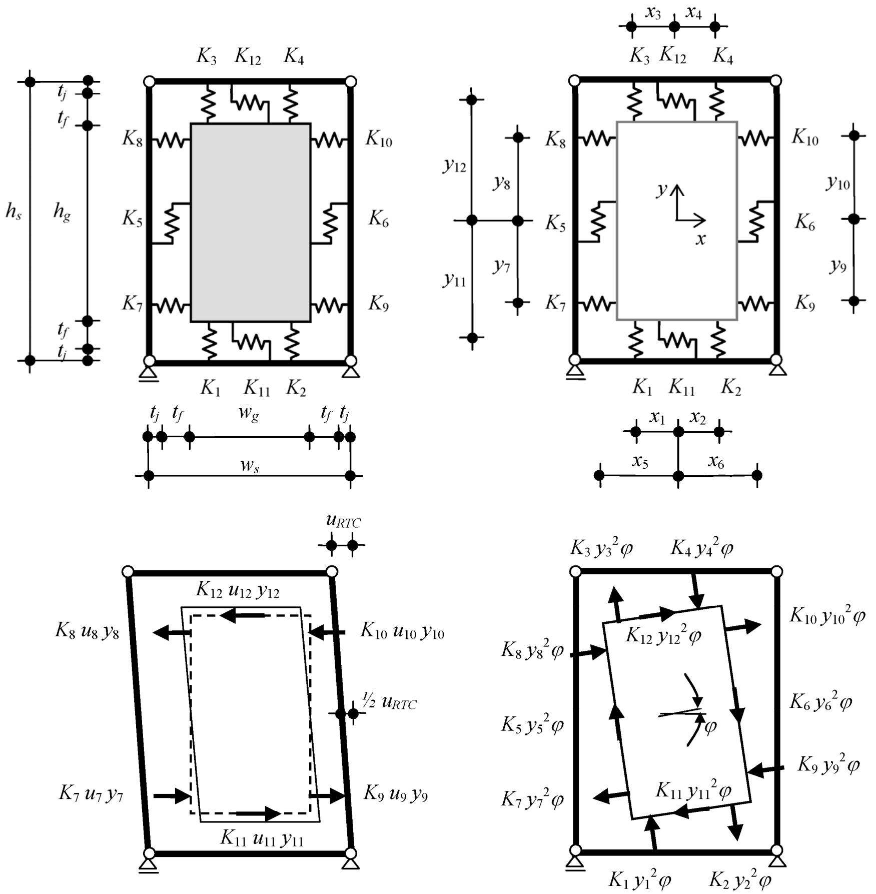


Figure 2: Mechanical model (adapted from [7]).

Furthermore, the rotation of the glass pane and the in-plane stiffness of the system are given by the following equations:

$$\varphi(u_{RTC}) = \left(\frac{\sum K_{xri}\, y_i^2}{\sum\left(K_{xri}\, y_i^2 + K_{yri}\, x_i^2\right)}\right) \frac{u_{RTC}}{h_s} \tag{7}$$

$$K_S = \left(\frac{2\sum K_{yri}\, x_i^2}{h_S^2 \sum\left(K_{xri}\, y_i^2 + K_{yri}\, x_i^2\right)}\right) \sum_{i=9,10,12} K_{xri}\, y_i^2 \tag{8}$$

Equations (7) and (8) can be complemented with other equations to compute the maximum relative in-plane displacements, the maximum stresses in the adhesive and the largest maximum principal stress at the right bottom corner of the glass pane [7].

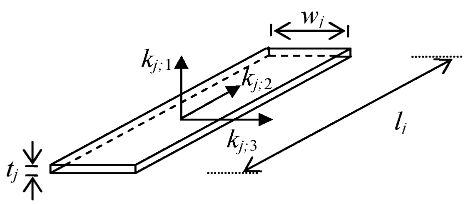
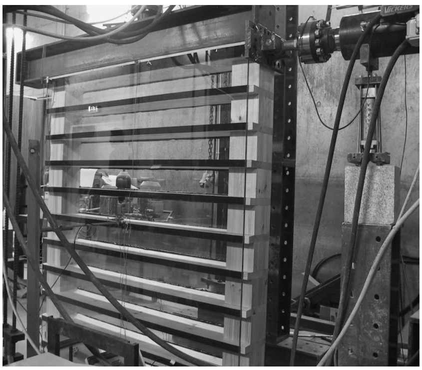


Figure 3: Notations for adhesive bonded joint.

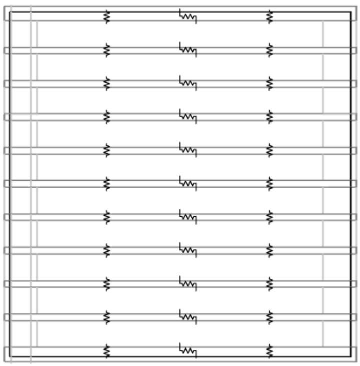
2.3. Types 2 and 3

The continuous normal stiffness ($k_{j,1}$) has to be replaced by the transversal shear stiffness ($k_{j,3}$) and the thickness of the glass (t_g) must be replaced by the joint width (w_j), in the case of joint type 3 (Figure 3). In joint type 2 the horizontal in-plane force is two times the one of joint type 3.

The model can be easily generalized to simulate the behavior of much more complex systems, such as the timber-glass composite structural panel [8] illustrated in Figure 4a. In this case the mechanical model illustrated in Figure 4b includes 33 springs.



a) Test set-up.



b) Mechanical model.

Figure 4: Timber-glass composite structural panel.

2.4. Extension of the model to glass panes fixed with point support connectors

Eight springs are enough to simulate the in-plane behaviour of the glass pane fixed with four-point support connectors (Figure 5). Equation (8) must be replaced by equation (9).

The stiffness of the springs can be obtained with pull-off and push-out tests of the connection device.

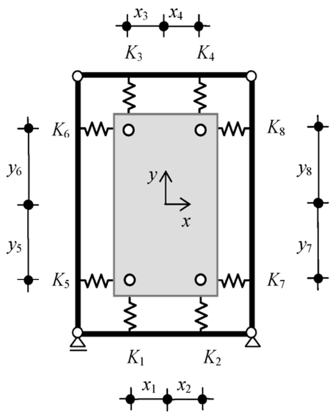


Figure 5: Notations for adhesive bonded joint.

$$K_S = \left(\frac{2 \sum K_{yri}\, x_i^2}{h_S^2 \sum \left(K_{xri}\, y_i^2 + K_{yri}\, x_i^2 \right)} \right) \sum_{i=6,8} K_{xri}\, y_i^2 \tag{9}$$

3. Simulation of circumferentially adhesive bonded glass panes

3.1. Stabilization of a steel frame

Huveners et al. [2] studied the experimental and analytical use of in-plane stiffness of glass panels to stabilize a steel framework in a facade (Figure 6). The square glass panel was circumferentially structurally bonded with adhesive to the steel framework by means of a joint type 1 of 5 mm thickness polyurethane - SIKAFLEX-252, laterally supported by a hard synthetic material.

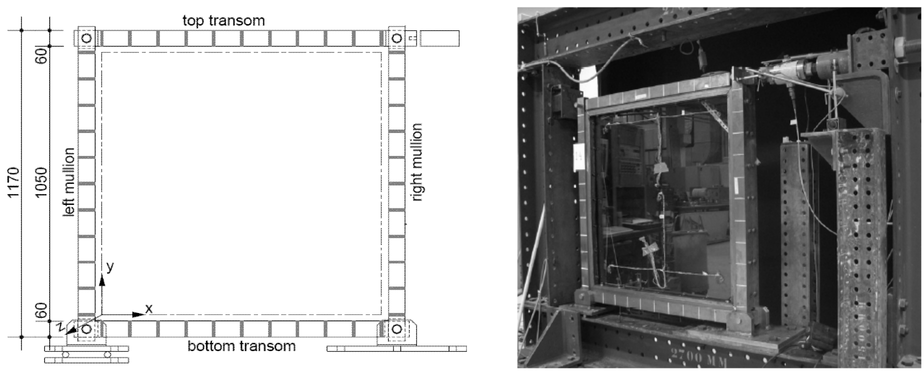


Figure 6: Drawing and photo of the test set-up [2].

The square pane consisted of a 12 mm annealed single float glass with ground edges with a dimension of 1000 mm. The steel frame consists of four steel beams of 120 mm wide and 59 mm high. The beams were pinned connected.

The results of the in-plane stiffness and the horizontal in-plane load at the first glass-steel contact are given in table 1 and are exactly the same of those obtained by Huveners et al. [2].

Table 1: In-plane stiffness and horizontal in-plane load obtained for different panel dimensions.

w_g [mm]	h_g [mm]	K_S [kN/mm]	F [kN]
1000	**1000**	**1,14**	**4,22**
1500	1500	1,83	9,81
1000	1500	0,88	4,72
1000	3000	0,37	3,88
1500	1000	1,85	6,84
3000	1000	2,94	10,86

3.2. Stabilization of a timber frame

Niedermaier [1] studied the shear-strength of glass panel elements in combination with timber frame constructions. He tested stiffening glass panel elements which were 800 mm wide and 1600 mm high (Figure 7). The glass pane was fixed to the timber frame with a joint type 3, 12 mm wide and 6 mm thick (Figure 8). A horizontal load of 1 kN was applied on the top member.

Figure 7: The test set-up [9].

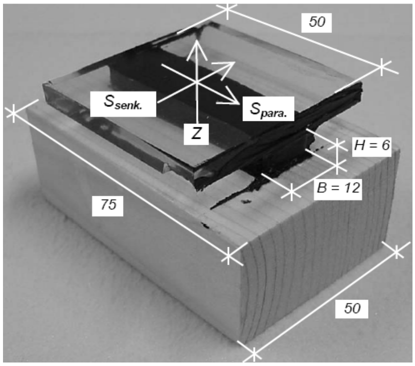


Figure 8: Specimens of a structural sealant glazing system with timber [10].

The results of the in-plane stiffness and the horizontal in-plane displacement for the glue with Silicon are given in table 2, assuming that the timber elements are pinned connected.

The in-plane horizontal displacement of the reference panel is in good accordance with the experimental results: 4.0 mm (first loading) and 5.8 mm (second loading).

3.3. Stabilization of a timber panel

Each composite panel was 224 mm thick and consisted of two 6.6.1 laminated glass bonded on both faces of the timber structure, made of four *Pinus Sylvestris* timber boards, with 200x30 mm^2 of cross section [11]. The adhesive is a Dow Corning 895 with a thickness of 2,5 mm and a G modulus of 0,37 N/mm^2.

Table 2: In-plane stiffness and displacement of the system obtained for different panel dimensions.

w_g [mm]	h_g [mm]	K_S [kN/mm]	d [mm]
800	800	0,45	2,23
800	1200	0,29	3,39
1200	1200	0,64	1,56
800	**1600**	**0,19**	**5,34**
1200	1600	0,5	2,02
1600	1600	0,83	1,20

The application of the mechanical model illustrated in Figure 4b leads to an horizontal in-plane force of 34,64 kN, considering an imposed displacement of 5 mm and neglecting the in-plane stiffness of the timber panel. The in-plane stiffness of the timber panel increases the horizontal in-plane force to 35,65 kN. The experimental value in-plane force is significantly lower (13,3 kN). However, this difference is justified by the lift of the timber frame in the right bottom support, as illustrated in Figure 9.

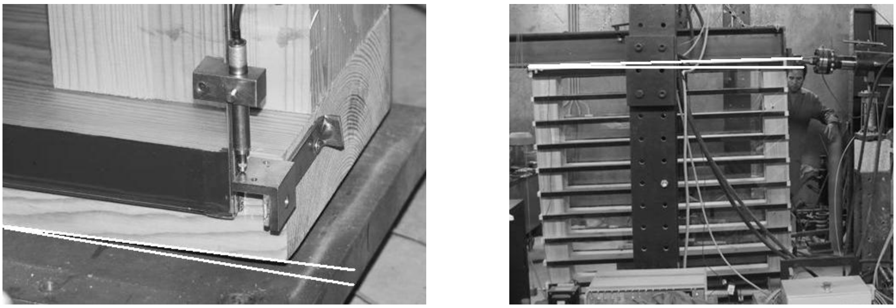


Figure 9: Lift of the timber frame on the right bottom support.

4. Simulation of one-point supported panel

Aiming at estimating the shear buckling behaviour of glass panels, Mocibob [12] carried out tests on full size glass panels of 1200 × 3500 mm made of two layered laminated heat strengthened glasses (Figure 10). The thickness of each glass sheet was 8 mm and the thickness of the PVB interlayer was 1.52mm. Before heat strengthening and lamination of glass panels, four holes (d=42mm) were drilled in the corners of each glass sheet at 100 mm from the edges.

A steel pin and a bolt M20 were placed in the middle of each glass hole and they were fixed to the glass panel by a steel cylinder. Between the steel cylinder and the glass panel the gasket made of POM was placed to avoid direct contact between the glass and the steel cylinder. A mortar Hilti HIT HY 70 was injected through the hole into the steel cylinder to fill the space between the pin and the hole.

Figure 11 illustrates the specimens tested by Mocibob et al. [12], which consisted of heat strengthened glass plates that measured 200 × 500 mm, with two holes (Ø 42mm) and bolted connection devices. In those tests the mortar injected was the Hilti HIT HY 50.

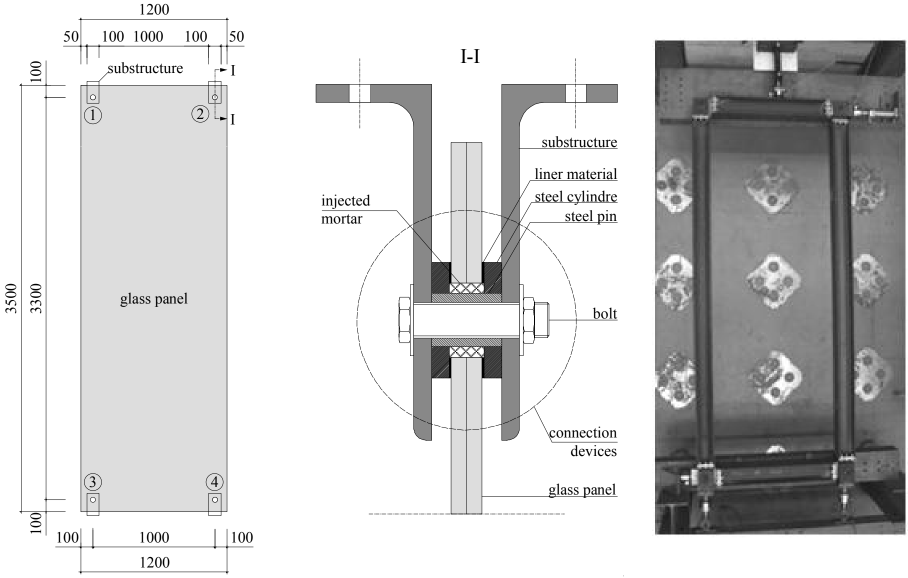


Figure 10: One-point supported panel test: specimen, substructures and testing frame [12].

The specimens were tested under displacement control with constant increments of 2.4 mm/min. The applied force F and the longitudinal displacement (consisting of glass plate elongation and deformation of the connection devices) were measured directly by the testing machine.

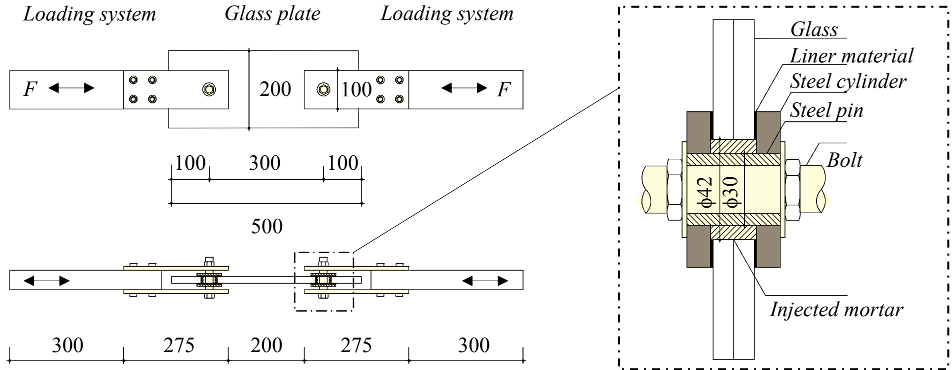


Figure 11: Axial rigid connection: plan view, side view and connection devices [12].

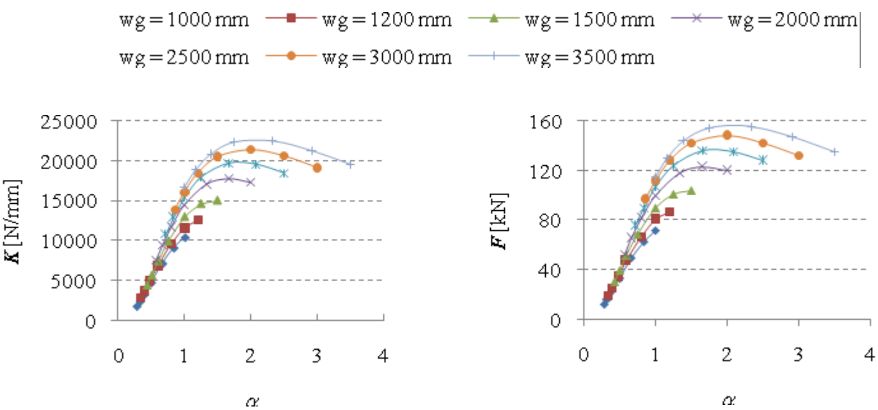
Table 3 shows the value of the force at failure, F, and the longitudinal specimen displacement at failure, ä, for the three specimens, and the corresponding average values.

By deducting the glass plate elongation between the connectors (0,061 mm) to the average value of the displacement of the compression and tension tests (2,35 mm), the resulting displacement of each fixing support is 1,14 mm. The corresponding stiffness is 39,998 kN/mm.

Table 3: Axial rigid connection tests results.

Specimen	Compression		Tension	
	F [kN]	δ [mm]	***F*** [kN]	δ [mm]
1	48,88	2,34	38,92	1,58
2	46,04	2,64	39,48	2,23
3	51,12	2,51	49,8	2,78
Average	**48,68**	**2,50**	**42,73**	**2,20**

Figure 12a shows the in-plane stiffness obtained with equation (9) in relation to the geometrical ratio á=w_g/h_g, for seven values of w_g and h_g (1000 mm, 1200 mm, 1500 mm, 2000 mm, 2500 mm, 3000 mm and 3500 mm).



a) In-plane stiffness.

b) Horizontal in-plane force.

Figure 12: Parameter influence.

Figure 12b shows the horizontal in-plane force in relation to the geometrical ratio á=w_g/h_g, for the same values of w_g and h_g described above and for an imposed horizontal in-plane displacement of 6,9 mm. The predicted in-plane horizontal force in the reference panel is 19,39 kN, in reasonably good agreement with the value of 27,54 kN obtained in the experimental test. The difference can be explained basically by the fact that the mortar used in the test of the panel is different than that used in the tests of the connection devices. Furthermore, the glass panel was tested in the horizontal position, with an out-of-plan support in the middle of the panel.

5. Conclusions

Mechanical models have been used to predict the in-plane structural behaviour of steel and timber frames with a single pane fixed by circumferentially glued joints or by point support connectors.

The simulation of the experimental tests, recently presented by other authors, makes evident the potential of those models to be used in pre-design of glass panes acting as shear walls. The cracking and buckling of glass panes were not considered in this research.

The models can predict the in-plane stiffness and the force necessary to obtain a certain horizontal in-plane displacement at the top. Furthermore, they can be easily adapted to simulate the behaviour of non-rectangular glass panes or under different boundary conditions.

Much more complex mechanical models can be developed to introduce non-linear and time-dependent effects.

6. Acknowledgements

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7. References

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