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Keywords

1=building stabilization 2=glass pane 3=steel frame 4=adhesive bonded joint 5=in-plane loads

Abstract

Circumferentially adhesive bonded glass panes in steel frames of façades can take over the structural function of steel braces for the stabilization of one-storey buildings. A system, built up of a steel frame, a single glass pane and a flexible adhesive bonded joint across the full thickness of the glass pane was subjected to a concentrated horizontal in-plane load at the top. Experiments with square glass pane sizes showed that the system had a very small in-plane stiffness, a glass-steel contact at large horizontal in-plane loads and a good residual capacity. The parametric studies by means of finite element models only focused on the variation of the geometry of the glass pane. The behaviour of the system mainly depends on the stiffness of the adhesive bonded joint. At larger horizontal in-plane displacements, systems with rectangular glass pane sizes have two glass-steel contacts. The mechanic models well predict the in-plane stiffness of the system, the largest maximum principle stress and the maximum normal and shear stresses in the adhesive bonded joint. The horizontal in-plane load and the horizontal in-plane displacement at the top at the first glass-steel contact are also well predicted. The criteria are the limitation of the horizontal in-plane displacement at the top (serviceability) or the strain rate of the adhesive bonded joint (strength). To guarantee the stability of a building all glass panes in the façade have to be mobilized to transfer in-plane load.

Introduction

Contemporary architecture desires large glass surfaces in the building envelop with a minimum of non transparent members such as steel braces needed for the stability of buildings. Actually, glass panes have the capacity to resist in-plane loads and can replace the steel braces [1,2,3]. The idea is not new to stabilize a building by glass panes. The slender iron structure of the 19th century green house in Bicton Garden (UK) [1] was stabilized by small single glass panes which were circumferentially bonded with putty to the iron structure of the building envelope. The putty made it possible to transfer in-plane loads. Nowadays, structural adhesives take over the outmoded putty to mobilize glass panes in-plane. For the research, a steel frame, a single annealed glass pane and three joint types form the system which is only subjected to a concentrated horizontal in-plane load at the top. The research methodology consisted of experiments, finite element simulations, parametric studies and the set-up of mechanic models for systems with joint type 1 to 3 to get more insight in the structural behaviour of the systems. This paper deals with the results and the mechanic models for systems with joint type 1.

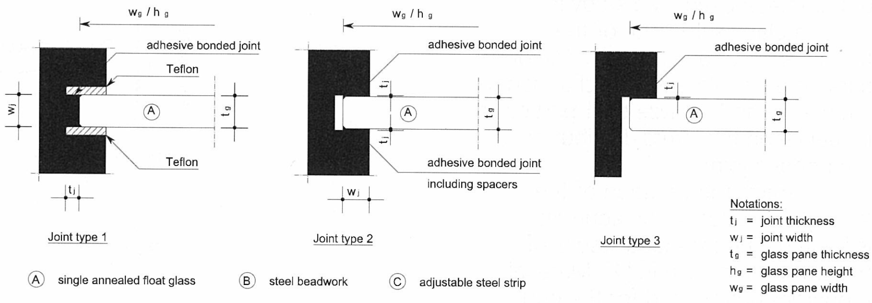

Figure 1
Joint type 1 to 3

Joint types

A circumferentially adhesive bonded joint is a suitable connection technique to transfer the in-plane load between the steel frame and the glass pane, because the adhesive bonded joint spreads the in-plane load over the glass pane and is an interlayer which prevents direct glass-steel contact. For the research three joint types were defined (figure 1). The basic assumption was that the adhesive bonded joints had to be as small as possible to increase transparency. Joint type 1 is a flexible adhesive bonded joint across the full thickness of the glass pane. Joint type 2 is a two-sided stiff adhesive bonded joint along the edges on both faces of the glass pane. Joint type 3 is a one-sided stiff adhesive bonded joint along the edges on one face of the glass pane. The applied adhesive for joint type 1 was a polyurethane adhesive (Sikaflex-252) [4,5]. The polyurethane adhesive is a gap filling sealant which has a flexible behaviour at room temperature. The applied adhesive for joint types 2 and 3 was an epoxy adhesive (Scotch Weld 9392 B/A) [4,6]. The epoxy adhesive has a stiff and toughened behaviour at room temperature.

Experiments

Figure 2 shows the test set-up of the system. The system was built up of four outside beams provided with hinges at the ends, four joint dependent beadworks bolted to the outside beam, a single glass pane and a circumferentially flexible adhesive bonded joint (joint type 1). The system was connected to the test rig with a horizontal roller at the left bottom corner and a pinned connection at the right bottom corner. The steel frame was needed to redistribute the concentrated in-plane loads in the system. The concentrated horizontal in-plane load (F_h) was introduced on the top beam at the right top corner. A laminated annealed float glass unit which is four-sided supported has better residual capacity after glass breakage [7]. However, for the research was chosen for single annealed float glass panes to map the stress distribution in the glass pane by the adhesive bonded joint unequivocally. The glass pane had a square size of 1.0 m and a nominal thickness ($t_{g;n}$) of 12 mm. An overview of the measurements is given in figure 2. Moreover, a high speed camera was installed to record the crack initiation and propagation during the experiments.

The relation between the horizontal in-plane displacements at the top of the system (u_{RTC}) and the horizontal in-plane loads (F_h) was bi-linear (figure 3 left). The first stage had large horizontal in-plane displacements and small horizontal in-plane loads without cracking. The second stage (glass-steel contact) started at a horizontal in-plane displacement of $u_{RTC;1}$ = 21.84 mm with a horizontal in-plane load of $F_{h;1}$ = 38.42 kN and showed a quicker increase of the horizontal in-plane loads with smaller horizontal in-plane displacements accompanied with cracking at the right top and the left bottom corner of the glass pane. The out-of-plane displacements of the glass pane were small in the first stage and increased in the second stage. The minimum principle stresses at points 1, 3 and 5 more and more increased at increasing horizontal in-plane load. The adhesive bonded joint was intact till halfway the first stage and then it gradually started pulling off and pushing away. At the moment of the glass-steel contact the transoms and mullions were curved (bending). The residual capacity was good by the large horizontal in-plane displacements of the top of the system in the first stage (visual) as well as in the second stage (visual and audible). The experiments were presented in [8,9].

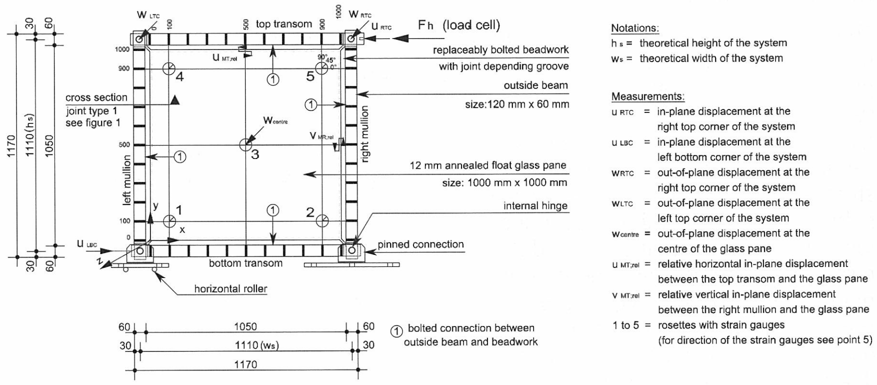

Figure 2

Test set-up and measuring devices

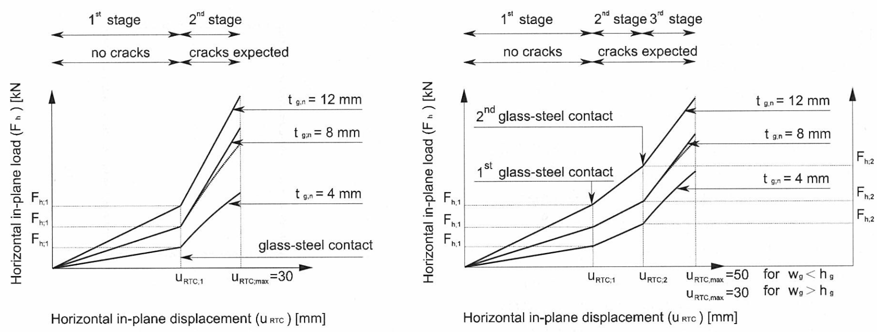

Figure 3

Schematic relation between the horizontal in-plane loads and the horizontal in-plane displacements at the top of the system for square (left) and rectangular glass pane sizes (right)

Finite element simulations

One finite element model was developed in the finite element programme DIANA [10] and was presented in [11,12]. Characteristic of the finite element model was that the finite element model contained all parts to simulate systems with joint type 1 to 3. Dependent on the joint type, the parts were by means of the material input activated or deactivated. The finite element simulation for systems with joint type 1 matched well with the experiments till the onset of the first crack.

Parametric studies

The parametric studies only focused on three nominal glass pane thicknesses and six glass pane sizes. The nominal glass pane thicknesses were 4 (3.8) mm, 8 (7.7) mm and 12 (11.7) mm. The values between the brackets are the minimal glass pane thicknesses in conformity with the European glass code [13] and were used in the finite element model. The glass pane sizes (w_g x h_g) are 1.0 m x 1.0 m, 1.5 m x 1.5 m, 1.0 m x 1.5 m, 1.0 m x 3.0 m, 1.5 m x 1.0 m and 3.0 m x 1.0 m. Furthermore, the value for the maximum initial out-of-plane imperfection at the centre of the glass pane for annealed float glass was based on the largest size of the glass pane divided by 2000 [14]. The parametric studies were presented in [12] and the main points have been summarized below. Table 1 gives an overview of the results at limited horizontal in-plane displacement (1/300 x h_s) [15] and at the first glass-steel contact obtained from the finite element simulations.

- The stiffness of the adhesive bonded joint mainly determines the in-plane stiffness of the system.
- The in-plane load is mainly transferred through the adhesive bonded joint in the compression zone than in the tension zone.
- The load transfer by in-plane shear increases at increasing joint length.
- The distribution of the relative in-plane displacements in normal direction is linear with the maximum at the ends of the adhesive bonded joint.
- The distribution of the normal stresses is linear or bi-linear and depends on the maximum relative in-plane displacement at the ends of the adhesive bonded joint.
- The distribution of the relative in-plane displacements in longitudinal direction of the adhesive bonded joint is uniform.
- The distribution of the shear stresses in the adhesive bonded joint is uniform.
- Systems with rectangular glass pane sizes have two glass-steel contacts (figure 3 right).
- Systems with rectangular glass pane sizes with a larger height than width firstly makes contact with the transoms and then with the mullions.
- Systems with rectangular glass pane sizes with a larger width than height firstly makes contact with the mullions and then with the transoms.
- The out-of-plane displacements of the glass pane are very small, but more and more increase at the moment of the glass-steel contact(s) especially for the nominal glass pane thickness of 4 mm.
- The values for the horizontal in-plane displacement at the glass-steel contact(s) are the same for all glass pane thicknesses in a certain size.
- The values for the horizontal in-plane load at the glass-steel contact(s) increase with the glass pane thickness, because the joint width corresponds with the glass pane thickness.
- The distributions of the normal stresses and the shear stresses in the adhesive bonded joint and the distribution of the principle stresses in the glass pane are the same for all glass pane thicknesses in a certain size.
- The largest maximum principle stress (tension stress) is located at the right bottom corner of the glass pane, but it is very small in comparison to the glass strength of annealed float glass.

Mechanic models

The points of interest for the mechanical models are the limited horizontal in-plane displacement at the top of the system (serviceability) and the first glass-steel contact (predictable residual capacity).The continuous normal stiffness ($k_{j;\xi}$) and the continuous shear stiffness ($k_{j;\eta}$) of the adhesive bonded joint are given in equations 1 and 2 respectively and are dependent on the material properties (E_a, G_a) [4,5,6] of the adhesive and the joint thickness (t_j). For the applied adhesive, figure 4 left gives the relation between the normal stresses and the relative in-plane displacements in normal direction of the adhesive bonded joint. The value for the continuous shear stiffness is 0.086 N/mm³. Figure 5 left top shows the principle of the mechanic model. The continuous normal and continuous shear stiffness of the adhesive bonded joint have been substituted by 12 springs (K_1 to K_{12}). The springs K_1 to K_4 (equation 3) are the normal springs in y-direction, the springs K_7 to K_{10} (equation 4) are the normal springs in x-direction, the springs K_5 and K_6 (equation 5) are the shear springs in y-direction and the springs K_{11} and K_{12} (equation 6) are the shear springs in x-direction. The distribution of the normal stresses at limited horizontal in-plane displacement at the top of the system is mainly linear and therefore, it is assumed that the normal stiffness of the adhesive bonded joint is constant, namely the initial normal stiffness ($k_{j;\xi;inil}$) (figure 4 left). So, the position of the normal springs is at the centre of the assumed linear distribution of the normal stresses (figure 5 right top). The position of the shear springs is halfway the joint thickness. Furthermore, the glass pane and the steel frame are assumed rigid.

The system has four generalized in-plane displacements, namely for the glass pane the horizontal in-plane displacements, the vertical in-plane displacements and the in-plane rotation and for the steel frame the horizontal in-plane displacements. Figure 5 left bottom shows the horizontal in-plane displacements of the springs K_7 to K_{12} imposed by the linear distribution of the horizontal in-plane displacements over the height of the steel frame with regard to the centre of the glass pane. The entire glass pane has a horizontal in-plane displacement which corresponds with the half of the horizontal in-plane displacement at the top of the system. Figure 5 right bottom shows the in-plane rotation of the glass pane (φ) around the centre of the glass pane within the non-displaced steel frame. The in-plane rotation of the glass pane results in horizontal in-plane displacements of the springs K_7 to K_{12} and vertical in-plane displacements of the springs K_1 to K_6. The sum of the moments around the centre of the glass pane of the horizontal in-plane loads imposed by the horizontal in-plane displacement of the steel frame is equalized with the sum of the moments around the centre of the glass pane of the in-plane loads imposed by the in-plane rotation of the glass pane (equation 7). However, the sum of the horizontal in-plane loads and the sum of the vertical in-plane loads are zero resulting in no horizontal and vertical in-plane displacements respectively.

The in-plane stiffness of the system (table 1) is given in equation 8 and is the sum of the moments around the centre of the glass pane of the horizontal in-plane loads at point 8, 10 and 12 and the horizontal in-plane load at the right top corner of the system (F_h). The maximum relative in-plane displacements in normal direction and in longitudinal direction are solved by equations 9 to 12 respectively and have to be checked with the allowable relative in-plane displacements of the adhesive bonded joint (strain rate). The maximum normal stresses in the adhesive bonded joint are the product of the maximum relative in-plane displacement in normal direction and the accompanying (non-linear) normal stiffness from figure 4 left (equations 13 and 14). The maximum shear stresses in the adhesive bonded joint are the product of the maximum relative in-plane displacement in longitudinal direction and the shear stiffness (equations 15 and 16). The normal tension stresses and the shear stresses of the adhesive bonded joint estimate the largest maximum principle stress

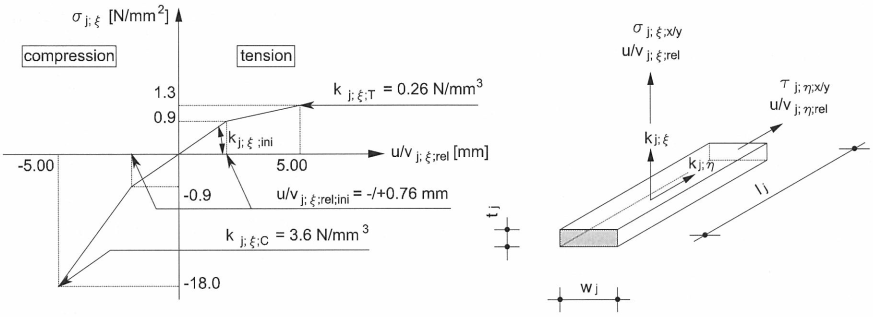

Figure 4

Relation between the normal stresses and the relative in-plane displacements of the adhesive bonded joint (left) and the notations for the adhesive bonded joint (right)

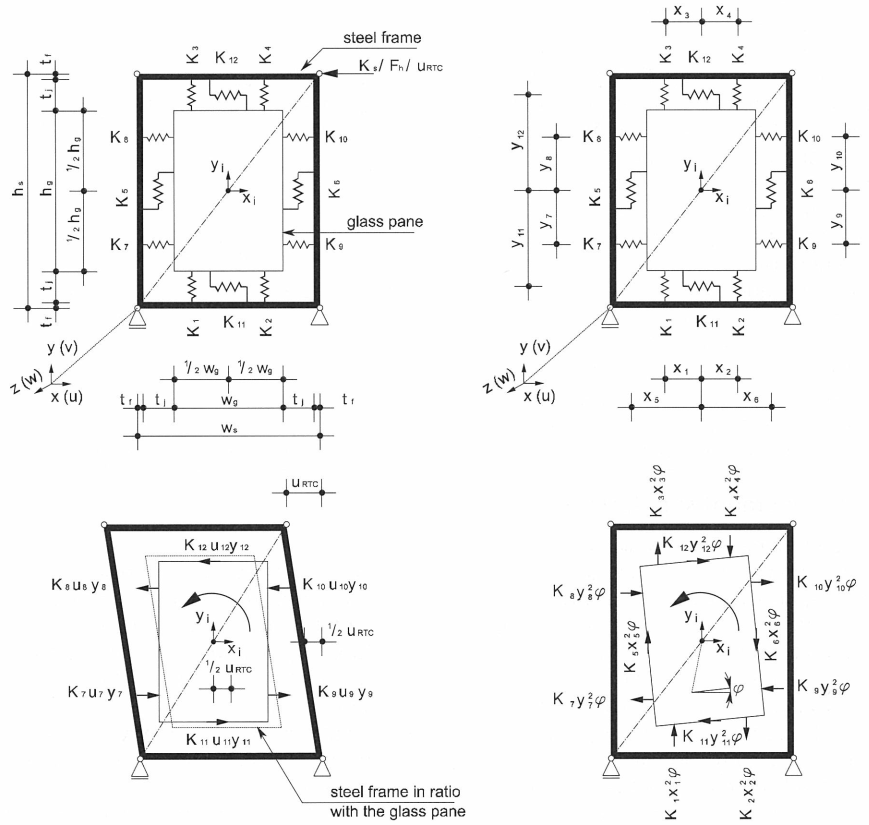

Figure 5

System with springs (left top), the position of the springs with regard to the centre of the glass pane (right top), the horizontal in-plane loads imposed by the horizontal in-plane displacements of the steel frame (left bottom) and all in-plane loads imposed by the in-plane rotation of the glass pane (right bottom)

$$k_{j;\xi} = \frac{E_a}{t_j} \quad \vee \quad k_{j;\xi} = \frac{\sigma_{j;\xi;x/y}}{u/v_{j;\xi;rel}} \tag{1}$$

$$k_{j;\eta} = \frac{G_a}{t_j} \quad \vee \quad k_{j;\eta} = \frac{\sigma_{j;\eta x/y}}{u/v_{j;\eta;rel}} \tag{2}$$

$$K_1 = K_2 = K_3 = K_4 = \tfrac{3}{8} k_{j;\xi} t_g w_g \tag{3}$$

$$K_7 = K_8 = K_9 = K_{10} = \tfrac{3}{8} k_{j;\xi} t_g h_g \tag{4}$$

$$K_5 = K_6 = k_{j;\eta} t_g h_g \tag{5}$$

$$K_{11} = K_{12} = k_{j;\eta} t_g w_g \tag{6}$$

$$\varphi_{(u_{RTC})} = \left(\frac{\sum K_{x;i} y_i^2}{\sum (K_{x;i} y_i^2 + K_{y;i} x_i^2)} \right) \frac{u_{RTC}}{h_s} \tag{7}$$

$$K_s = \left(\frac{2 \sum K_{y;i} x_i^2}{h_s^2 \sum (K_{x;i} y_i^2 + K_{y;i} x_i^2)} \right)_{i=8,10,12} \sum K_{x;i} y_i^2 \tag{8}$$

$$u_{j;\xi;rel;\max} = \frac{(u_{RTC} - h_s \varphi) h_g}{2 h_s} \tag{9}$$

$$v_{j;\xi;rel;\max} = \tfrac{1}{2} w_g \varphi \tag{10}$$

$$u_{j;\eta;rel;\max} = \tfrac{1}{2} (u_{RTC} - h_g \varphi) \tag{11}$$

$$v_{j;\eta;rel;\max} = \frac{(2 t_f u_{RTC} + h_s w_g \varphi)}{2 h_s} \tag{12}$$

$$\sigma_{j;\xi;x;\max} = k_{j;\xi;x} u_{j;\xi;rel;\max} \tag{13}$$

$$\sigma_{j;\xi;y;\max} = k_{j;\xi;y} v_{j;\xi;rel;\max} \tag{14}$$

$$\tau_{j;\eta;x;\max} = k_{j;\eta} u_{j;\eta;rel} \tag{15}$$

$$\tau_{j;\eta;y;\max} = k_{j;\eta} v_{j;\eta;rel} \tag{16}$$

$$\sigma_{g;1;\max} = \tfrac{1}{2}(\sigma_{j;\xi;x} + \sigma_{j;\xi;y}) + \tfrac{1}{2}\sqrt{(\sigma_{j;\xi;x} - \sigma_{j;\xi;y})^2 + 4\tau_{j;\eta}^2} \tag{17}$$

$$k_{j;\xi;equi;y} = \frac{(v_{j;\xi;rel;ini} v_{j;\xi;rel} + v_{j;\xi;rel;ini}^2)(2k_{j;\xi;ini;y} - k_{j;\xi;C;y} - k_{j;\xi;T;y}) + 2 v_{j;\xi;rel}^2 (k_{j;\xi;C;y} + k_{j;\xi;T;y})}{4 v_{j;\xi;rel}^2} \tag{18}$$

at the right bottom corner of the glass pane (equation 17).

For the estimation of the horizontal in-plane displacement at the top of the system, equations 9 and 10 are equalized in which the horizontal in-plane displacement at the right top corner is a function of the maximum relative horizontal and vertical in-plane displacements of the adhesive bonded joint. For square glass pane sizes and rectangular glass pane sizes with a larger height than width the maximum relative vertical in-plane displacement is substituted by the joint thickness. The accompanying maximum relative horizontal in-plane displacement is the ratio between the maximum relative horizontal and the vertical in-plane displacement of the adhesive bonded joint at limited horizontal in-plane displacement at the top multiplied with the joint thickness. For rectangular glass pane sizes with a smaller height than width the relative horizontal in-plane displacement is substituted by the joint thickness. The accompanying maximum relative vertical in-plane displacement is the ratio between the relative vertical and the horizontal in-plane displacement of the adhesive bonded joint at limited horizontal in-plane displacement at the top multiplied with the joint thickness. On the other hand, the normal stresses are non linear distributed. This non linear relation is transformed to a linear distribution with an equivalent continuous normal stiffness ($k_{;\xi;equi;x/y}$) (equation 18). The transformation is justified, because the horizontal in-plane load at the first glass-steel contact is the point of interest and is a global value. The horizontal in-plane load at the first glass-contact is solved with equation 8 multiplied with the horizontal in-plane displacement at the top at the first glass-steel contact in which the initial continuous normal stiffnesses of the adhesive bonded joint in equation 3 and 4 are replaced by the equivalent normal stiffnesses. The results of the horizontal in-plane displacement at the top of the system and the horizontal in-plane load at the first glass-steel contact are given in table 1.

Discussion of the results

The predicted in-plane stiffness of the system is smaller than the in-plane stiffness of the system obtained from the finite element simulations, because the increase of the normal stiffness at larger relative in-plane displacements in normal direction in the adhesive bonded joint is not involved in the mechanic models. At the first glass-steel contact, the prediction of the horizontal in-plane displacement at the top of the system and the horizontal in-plane load are smaller than obtained from the finite elements simulations, because of the linearization of the distribution of the non linear normal stresses which exactly behaves stiffer.

Conclusions

Systems with joint type 1, i.e. with flexible adhesive bonded joints across

		Parametric studies (FEM)				Mechanic models			
Size [m]	$t_{g;n}$ [mm]	$K_{s;lim}$ [kN/mm¹]	$F_{h;lim}$ [kN]	$u_{RTC;1}$ [mm]	$F_{h;1}$ [kN]	$K_{s;lim}$ [kN/mm¹](%)	$F_{h;lim}$ [kN]	$u_{RTC;1}$ [mm](%)	$F_{h;1}$ [kN](%)
1.0 x 1.0	4 8 12	0.39 0.80 1.20	1.45 2.92 4.41	23.25 23.15 23.65	14.80 25.70 37.70	0.37 (-5.1) 0.75 (-6.3) 1.14 (-5.0)	1.37 2.78 4.22	22.20 (-4.9)	12.12 (-18.1) 24.57 (-4.4) 37.33 (-1.0)
1.5 x 1.5	4 8 12	0.66 1.30 1.90	3.51 6.86 10.03	23.20 23.58 23.98	20.30 41.70 61.50	0.59 (-10.6) 1.20 (-7.7) 1.83 (-3.7)	3.19 6.46 9.81	21.47 (-9.0)	18.80 (-7.4) 38.09 (-8.7) 57.88 (-5.9)
1.0 x 1.5	4 8 12	0.32 0.63 0.92	1.69 3.37 4.88	23.21 23.61 24.39	9.11 18.40 29.20	0.29 (-9.4) 0.58 (-7.9) 0.88 (-4.4)	1.53 3.11 4.72	21.64 (-8.9)	8.77 (-3.7) 17.77 (-3.4) 27.00 (-7.5)
1.0 x 3.0	4 8 12	0.14 0.28 0.42	1.41 2.83 4.17	35.57 35.00 34.58	5.94 11.30 16.10	0.12 (-14.3) 0.25 (-10.7) 0.37 (-11.9)	1.26 2.55 3.88	32.88 (-6.2)	5.29 (-10.9) 10.73 (-5.0) 16.30 (1.2)
1.5 x 1.0	4 8 12	0.67 1.34 2.01	2.46 4.92 7.35	17.29 17.19 16.51	16.70 30.70 41.60	0.60 (-10.5) 1.22 (-9.0) 1.85 (-8.0)	2.22 4.50 6.84	14.92 (-12.3)	12.72 (-23.8) 25.78 (-16.0) 39.17 (-5.8)
3.0 x 1.0	4 8 12	1.11 2.20 3.36	4.10 8.12 12.42	12.80 13.16 13.20	15.50 30.90 44.30	0.95 (-14.4) 1.93 (-12.3) 2.94 (-12.5)	3.53 7.15 10.86	11.74 (-10.1)	14.84 (-4.3) 30.05 (-2.8) 45.67 (3.1)

Table 1

Overview of the results of the finite element simulations versus the mechanic models the full thickness of the glass pane, have been investigated by means of experiments, finite element simulations, parametric studies and mechanic models and the results were presented in this paper. The following conclusions can be drawn. The mechanic models well predict the in-plane stiffness, the largest maximum principle stress in the glass pane and the maximum normal and shear stresses in the adhesive bonded joint. The mechanic models yield lower values than obtained from the finite element simulations and therefore, a safe approach. The mechanical models for the prediction of the horizontal in-plane displacement at the top and the horizontal in-plane load at the first glass-steel contact are sufficient in case of residual capacity and it is also a safe approach. The criteria for systems with joint type 1 are the limitation of the horizontal in-plane displacement at the top (serviceability) or the limitation of the maximum relative in-plane displacements in normal and in longitudinal direction of the adhesive bonded joint (strength). To guarantee the stability of the building, all glass panes in the façade have to be structurally bonded to the steel frame, because of the small in-plane stiffness of the system. Finally, the residual capacity is good, because the system visibly and audibly warns for overloading.

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