Parametric Studies on Bracing Steel Frames with Glued Glass Panes

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Summary

Glass panes structurally bonded to a steel framework can be used as a stability system for buildings. A system built up of a single glass pane, a steel frame and a glued joint is only loaded by a concentrated monotonic in-plane load at the top. Three glued joint types are defined, namely a flexible joint on the end, a two-sided and a one-sided rigid joint. A finite element model was developed and calibrated with the experiments followed by varying the geometry of the glass pane. The applied criteria are the strength of glass for failure and the restricted in-plane displacement at the top. The system with a flexible joint on the end can be characterized by small loads, large in-plane displacements and small stiffnesses. The stiffness is the criterion. Systems with two-sided and one sided rigid joints can be characterized by larger loads, much smaller in-plane displacements and larger stiffnesses. The strength of glass is the criterion and is located on the glass pane's surface in the vicinity of the glued joint which anchors the tensile diagonal of the glass pane. These tensile stresses increase by the different in stiffness of the glued joint (rigid) and the less shear stiffness of the bolts between beadwork and outside beam of the frame. However, the stress distribution in the glass pane as well as in the glued joint is unfavourable for systems with one-sided rigid joint. The two-sided rigid glued joint is a promising joint type based on the geometric parameters of the glass pane and the good residual capacity after the first cracks as observed in the experiments.

Keywords: Glass pane, glued joint, steel frame epoxy, polyurethane, in-plane load, shear wall

1. Introduction

Glass is an indispensable material for the building envelope determined by aesthetics and regulations. One of the regulations is the structural performance of a glass pane to guarantee safety. The structural performance of glass panes established in codes is restricted to resist the usual uniformly distributed out-of-plane loads and excludes any in-plane loads. However, glass panes have the capability to transfer in-plane loads e.g. glass beams/fins and columns. Glass panes can also be used as transparent bracing elements to stiffen a framework e.g. a stability system of a building. A glued joint is needed to transfer smoothly the load between the frame and the glass pane. The first buildings stabilized by glass panes dated from the early 19th century e.g. green houses. The small single glass panes were bonded to the iron casings with putty. Some of these buildings stand the test of time and can be admired today e.g. Bicton Garden in England [3]. These 19th century buildings were designed without thorough calculation, but proof that glass panes still can be used as stiffened element. Moreover, these buildings appear more transparent than today's buildings and transparency is what architects really want. These two reasons are the underlying motive for scientific researches [1,2] and at Eindhoven University of Technology. The research focuses on a system consisting of a steel frame, a single glass pane and three different glued joint types. A finite element model is generated and validated with the results of experiments. The finite element model is an inevitable tool for further research to get more insight in the chosen systems. This paper starts with a short discussion of the experiments and the finite element model. The first results of the parametric studies of a steel frame loaded by a concentrated in-plane load at a top corner, braced by a circumferentially glued single glass pane are the subject of this paper.

2. Experiments

Figure 1 (left) shows the test set-up of the system. The system is built up of outside beams with hinged ends, a single glass pane and one of the three defined glued joint types (figure 1 right). The system is connected to the reaction frame at the left bottom corner with a roller and at the right bottom corner with a pin. The load is introduced on the top beam at the right top corner. A replaceable beadwork equipped with a joint type depending groove is bolted to the outside beam. The glass pane lines up with the centre of the outside beam. A glued laminated glass pane consisting of annealed float glass has a good post-failure behaviour [3]. In this research is chosen for a single glass pane to map a clear stress distribution in the glass pane induced by the glued joint. The glass pane was square in size ($w_g = h_g = 1.0$ m) and had a nominal thickness ($t_{g;n}$) of 12 mm. The glass pane's edge was polished and was provide with a facet. The three circumferentially glued joint types have a small joint width to increase transparency. Joint type 1 is a glued joint on end. The glass pane is supported laterally by a strip and a groove. The gap between glass pane and frame depends on tolerances and needs a gap filling sealant. The applied adhesive is Sikaflex-252 [4] and is a flexible polyurethane adhesive at room temperature. Joint type 2 is a two-sided glued joint. The joint's thickness can be very small and is guaranteed by spacers and adjustable strips. Joint type 3 is a one-sided glued joint and is an eccentric connection. The applied adhesive for joint type 2 and 3 is 3M Scotch Weld 9293 [4]. This epoxy has rigid and toughened properties at room temperature. Figure 1 (left) also shows the measurement programme. The load introduction (F_h), measured by a load cell, is displacement controlled with a velocity of 1 mm/min and can be considered as a static load. One of the measured in-plane displacement of the frame was point F (u_F). The out-of-plane displacement of the glass pane's centre was measured at point A (w_A). Points 1 to 5 are strain rosettes on the glass pane's front and measure the strain at 0°, 45° and 90°. A high speed camera was installed to record the crack initiation and propagation during the experiments.

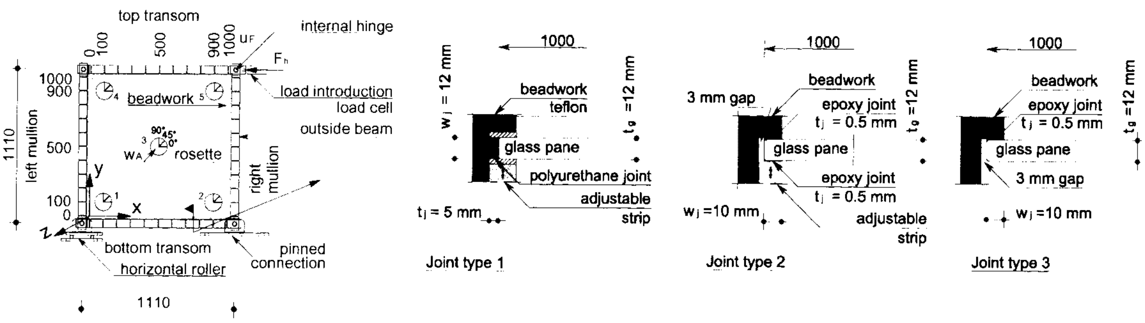

Fig. 1 Test set-up and measurement programme (left) and joint type 1 to 3 (right)

Systems with joint type 1 show a bilinear load-displacement relation. The first stage has large in-plane displacement and small load without cracking. The second stage starts at an in-plane displacement of $u_{F;ave} = 21.84$ mm and a load of $F_{h;ave.} = 38.42$ kN and shows a quicker increase of load with smaller in-plane displacement accompanied with cracking in the right top and left bottom corner (crushing the compression diagonal by glass-metal contact). The first stage is part of interest and the strength of glass was not critical. The residual capacity was good by large in-plane displacement (visual) in stage 1 and followed by stage 2 (visible and audible). Systems with joint type 2 show a slightly decrease of load increment at increasing in-plane displacement accompanied with cracking. The first crack occurred at the right bottom corner at a load of $F_{h;ave} = 46.00$ kN with a displacement of $u_{F;ave} = 1.00$ mm. The glued joint was intact after testing. Therefore, the strength of glass was the criterion. The residual capacity was good after the first crack (visible and audible). Systems with joint type 3 also show a slightly decrease of load increment at increasing in-plane displacement accompanied with cracking. The first crack occurred at the right bottom corner at a load of $F_{h;ave.}$ = 38.64 kN with a displacement of $u_{F;ave}$ = 0.97 mm. The glued joint was intact after testing and the strength of glass was also the criterion. The residual capacity was poor. Finally, the out-of-plane displacement (w_A) was negligible small for all joint types.

3. Finite element model

One finite element model was developed in the finite element programme DIANA and validated with the experiments [5]. The results of the finite element model matched well the experiments till the first series of cracks occur. Typical of this finite element model is that the model contains all elements needed to simulate joint type 1 to 3. Depending on the joint type the elements are activated or inactivated. This model was presented in [6], but is modified at two points. The first modification is the replacement of the modelled glass pane consisting of shell elements and solid elements along the edges by solid elements only (figure 2, left). The first modelled glass edge was modelled to use plane stress elements and corrected with solid elements to introduce eccentricities into the glass pane. This method of modelling led to a stress distribution along the glass pane's edges with no physical meaning. The modified glass pane is able to describe the three-dimensional stress state better. The consequence of this modification is that overlaps in the corners have been created between the horizontal and vertical interfaces (figure 2, right). The premature end of the all vertical interfaces led to large and unwanted stress concentrations which were no problem formerly. The second modification is a geometrically initial imperfection of the glass pane in stead of an imperfection by a uniformly distributed out-of-plane load. So, the glass pane investigated has no initial stresses by introducing imperfections. The initial imperfection of annealed float glass is small. The maximum initial imperfection has a value equal to the longest size of the glass pane divided by 2000 [7], directed to the rear side.

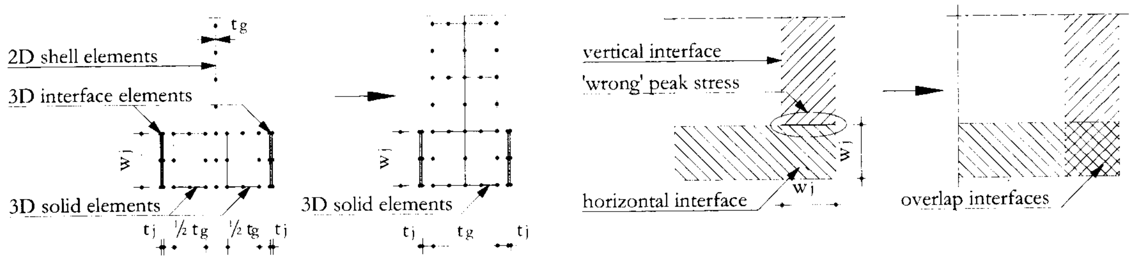

Fig. 2 Modification 1 of the model presented in [6]

4. Results of the parametric studies

The modified model described in section 3 is used for the parametric studies. These studies only deal with the geometry of the glass pane. The parameters are the thickness and size of the glass pane. The chosen nominal thicknesses ($t_{g;n}$) are 4 (3.8) mm, 8 (7.7) mm and 12 (11.7) mm. The values between the brackets are the minimal thickness of the glass pane in conformity with the European code EN-572-2 and used in the model. The sizes are grouped in three series. Series with constant width (w_g) of 1.0 m with three different heights (h_g), namely 1.0 m, 1.5 m and 3.0 m, series of constant height (h_g) of 1.0 m with three different widths (w_g) of 1.0 m, 1.5 m and 3.0 m and series of a square glass pane of 1.0 m and 1.5 m. The material properties of the adhesives, steel and glass are constant. The joint's length (l_j) and the frame's width (w_s) and height (h_s) adapt with the size of the glass pane. The cross section of the glued joints (see figure 1) and the frame are also constant. The criterion for strength of annealed float glass is the representative utmost bending tensile strength prescribed by the Dutch code [8] and given in equation 1. The criterion for maximum horizontally in-plane displacement at the top of the system is given by equation 2. This equation is prescribed in the Dutch code [9] and deals with serviceability of building structures.

$$\sigma_{1;FEM} \leq f_{mt;u;rep} = f_{g;k} \cdot k_b \cdot k_e \cdot k_{mod} = 45 \cdot 1 \cdot 1 \cdot 1 = 45 \text{ N/mm}^2 \quad (1)$$

$$u_{F;FEM} \leq u_{F;\max} = \tfrac{1}{300} h_s \qquad (2)$$

In which $f_{mt;u;rep}$ is the representative value for utmost bending tensile strength in N/mm^2, $f_{g;k}$ is the characteristic value for the utmost bending tensile strength of annealed float glass in N/mm^2, k_b is the factor for the glass pane's crack behaviour [-], k_e is the factor for the glass pane's edge quality [-], k_{mod} is the modification factor depending on load duration and reference period [-], $u_{F;max}$ is the maximum horizontal in-plane displacement at the top in mm and h_s is the system's height in mm, measured vertically between the internal hinges. The values in equation 1 belong to load case wind and provided with polished edges (section 2). $\sigma_{1;FEM}$ and $u_{F;FEM}$ are the maximum principle stress [N/mm^2] and horizontal in-plane displacement of the top beam [mm] respectively, calculated with the finite element model.

4.1 Load, displacement of the top and system's stiffness

Figure 3 (left) shows the loads (F_h) for systems with joint type 1 belonging to a limited in-plane displacement of the top ($u_{F;max}$) determined by equation 2. The maximum in-plane displacements are 3.70 mm, 5.37 mm and 10.73 mm for a system height (h_s) of 1110 mm, 1610 mm and 3110 mm respectively. The load almost doubles and triples at a nominal thickness of 8 mm and 12 mm respectively in comparison to the load at a nominal thickness of 4 mm with a certain size. The size series with a constant width (w_g) of 1.0 m and a variable height (h_g) of 1.0 m, 1.5 m and 3.0 m show a slightly increase of load at a height of 1.5 m and a slightly decrease of load at a height of 3.0 m in comparison to a height of 1.0 m for all nominal glass thicknesses. The size series with a variable width (w_g) of 1.0 m, 1.5 m and 3.0 m and a constant height (h_g) of 1.0 m show an increase of load in comparison to the height of 1.0 m for all nominal glass thicknesses. The square size series with scaling factor of 1.5 show an increase of load for all nominal glass thicknesses. Figure 3 (right) shows the system's stiffness with joint type 1. The glass pane with a size of 1.0 m x 3.0 m has a considerable small stiffness in comparison to the other sizes.

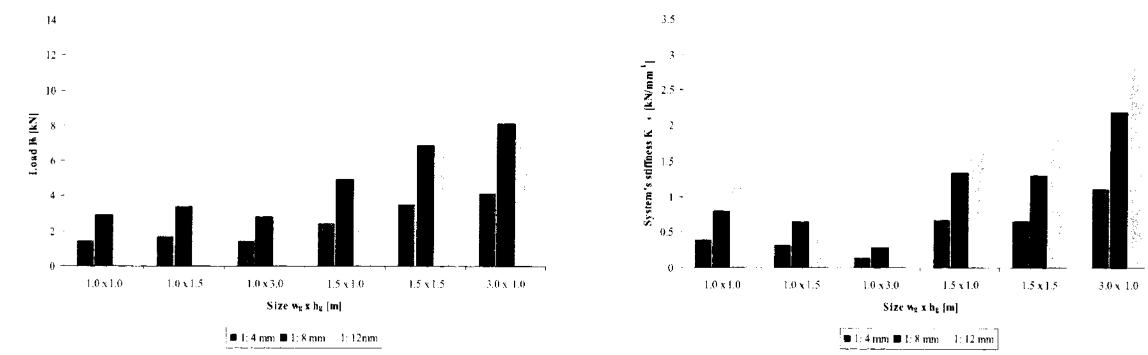

Fig. 3 Loads (left) and stiffness (right) based on $u_{F;max}$ for a system with joint type 1

Figure 4 shows at the left top side the loads (F_h) and in-plane displacement (u_F) and at the right top side the system's stiffness (K_s) for systems with joint type 2 belonging to the bending tensile strength determined by equation 1. The load and the in-plane displacement increase with increasing nominal thickness for each glass pane size. The size series with a constant width (w_g) of 1.0 m and a variable height (h_g) of 1.0 m, 1.5 m and 3.0 m show a decrease of load and a larger increment of in-plane displacement at increasing height for all nominal glass thicknesses. The size series with a variable width (w_g) of 1.0 m, 1.5 m and 3.0 m and a constant height (h_g) of 1.0 m show an increase of load and a slightly decrease of in-plane displacement at increasing width for all nominal glass thicknesses. The square size series with scaling factor of 1.5 show an increase of load and in-plane displacement for all nominal glass thicknesses. The glass pane with a size of 1.0 m x 3.0 m also has a small stiffness in comparison to the other sizes.

Figure 4 shows at the left bottom side the loads (F_h) and in-plane displacement (u_F) and at the right bottom side the system's stiffness (K_s) for systems with joint type 3 belonging to the bending tensile strength determined by equation 1. The load increases and the in-plane displacement decreases with increasing nominal thickness for each glass pane size. The size series with a constant width (w_g) of

1.0 m and a variable height (h_g) of 1.0 m, 1.5 m and 3.0 m show a decrease of load and an increase of in-plane displacement at increasing height for all nominal glass thicknesses. The size series with a variable width (w_g) of 1.0 m, 1.5 m and 3.0 m and a constant height (h_g) of 1.0 m show an increase of load and a decrease of in-plane displacement at increasing width for all nominal glass thicknesses. The square size series with scaling factor of 1.5 show a slightly increase of load and in-plane displacement for all nominal glass thicknesses. The glass pane with a size of 1.0 m x 3.0 m has a small stiffness in comparison to the other sizes.

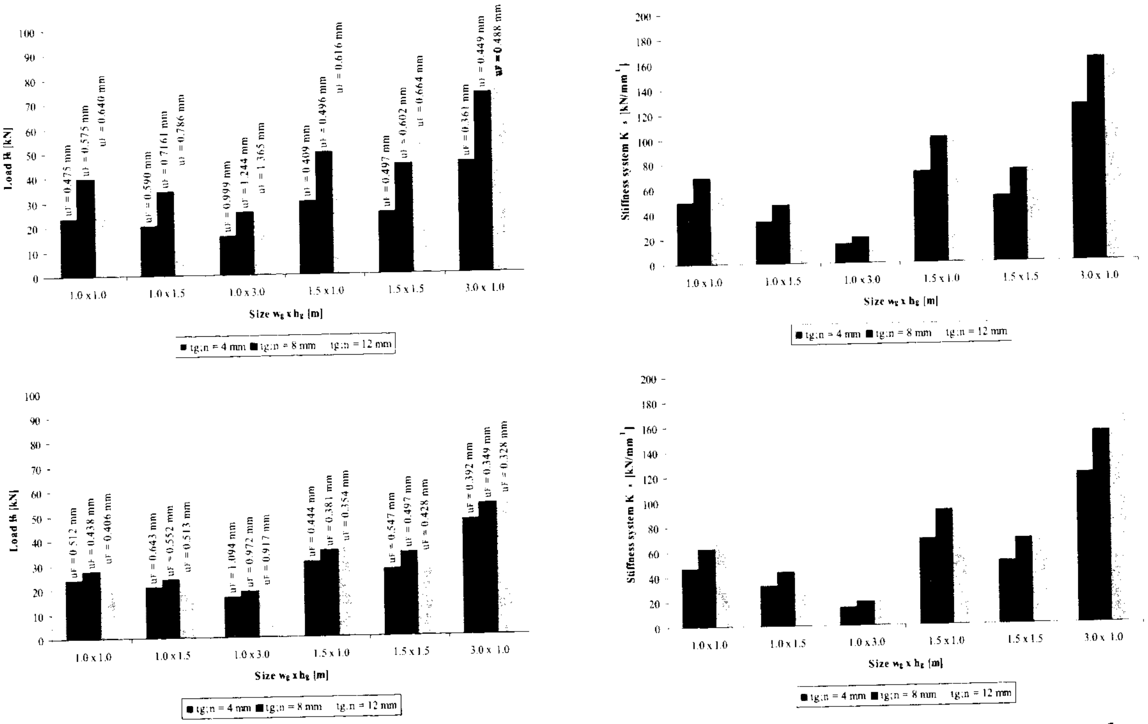

Fig. 4 Load (top left) based on $f_{mt;u;rep}$ and stiffness (top right) for systems with joint type 2 and load (bottom left) based on $f_{mt;u;rep}$ and stiffness (bottom right) for systems with joint type 3

4.2 Out-of-plane displacement

The out-of-plane displacements for all glass thicknesses and sizes for systems with joint type 1 are very small. The displacement image of the glass pane corresponds with displacement field B (figure 5). The out-of-plane displacements undulate along the diagonal from the left bottom corner to the right top corner. The out of plane displacements along the diagonal from the right bottom corner to the left bottom corner is a half sine.

The out-of-plane displacements for systems with joint type 2 correspond with displacement field A (figure 5). The out-of-plane displacement of the 1st and 3rd quadrant is directed to the positive z-axis (to the front) with its maximum in the quadrant's centre (position I). The out-of-plane displacement of the 2nd and 4th quadrant is directed to the negative z-axis (to the rear) with its minimum in the quadrant's centre (position I). The out-of-plane displacement of the glass pane's centre is negligible small and can be considered as zero. This system with nominal thickness of 4 mm and for all sizes shows slightly larger out-of-plane displacements. The out-of-plane displacement corresponds with displacement field B (figure 5) and table 1 gives the values. The out-of-plane displacement of the 1st and 3rd quadrant is directed to the positive z-axis (to the front) with its maximum in the quadrant's centre (position IV). The out-of-plane displacement of the 2nd and 4th quadrant is directed to the negative z-axis (to the rear) with its minimum in the glass pane's centre (position III).

The out-of-plane displacements for systems with joint type 3 correspond with systems with joint type 2 and also correspond with displacement field A, but the maximum positive as well as the negative out-of-plane displacement are located in the vicinity of the corners of the glass pane (position II). The out-of-plane displacement at the glass pane's centre is negligible small and can be considered as zero. This system also shows a slightly out-of-plane displacement for nominal thickness of 4 mm for all sizes and corresponds with displacement field B.

Table 1 Out-of-plane displacement of the glass pane based on $f_{mt;u;rep}$ for systems with joint type 2 and 3 with nominal thickness of 4 mm (for displacement field see figure 5)

Size [m]	Joint type 2 Out-of-plane displacement [mm]	Field/ position	Joint type 3 Out-of-plane displacement [mm]	Field/ position
1.0 x 1.0	-0.196	B/III	-0.175	B/III
1.0 x 1.5	-0.191	B/III	-0.232	B/III
1.0 x 3.0	-0.153/0.126	A/I	--	A/II
1.5 x 1.0	-0.400	B/III	-0.215	B/III
1.5 x 1.5	-1.520	B/III	-1.050	B/III
3.0 x 1.0	-0.197/0.158	A/I	--	A/II

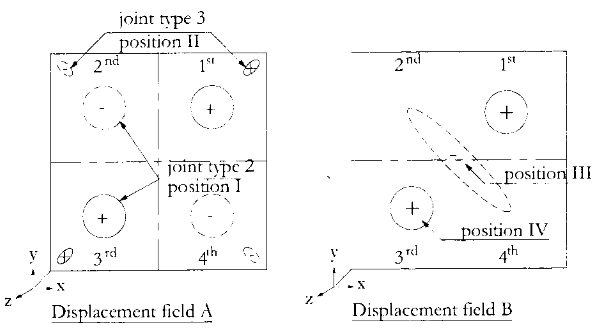

Fig. 5 Displacement fields of the glass pane based for systems with joint type 1 to 3 (principle)

4.3 Load distribution in the glass pane

The principle stress and its direction in points 1 to 5 for systems with joint type 1 are given in table 2 and figure 6. The stress state is two-dimensional. The principle stresses in points 1 and 5 are both compression stresses, in points 2 and 4 are both tensile stresses and in point 3 a tensile stress at an angle of -45° and a compression stress at an angle of 45° are found. The same is found for points 1 to 5 at the rear and for all glass panes and sizes. The magnitude, sign and direction are thickness independent within a size. The largest maximum principle stress is found at the right bottom corner with a three dimensional stress state (figure 6) and the value is small.

Table 2 Principle stresses and their directions at points 1 to 5 (front and rear) for all thicknesses for systems with joint type 1 based on $u_{F;max}$

Size	Point 1/5			Point 2/4			Point 3		
w_g x h_g [m]	σ_1 [N/mm²]	σ_2 [N/mm²]	α [°]	σ_1 [N/mm²]	σ_2 [N/mm²]	α [°]	σ_1 [N/mm²]	σ_2 [N/mm²]	α [°]
1.0 x 1.0	-0.55	-1.03	-44.37	0.86	0.58	-44.89	0.79	-0.87	-44.88
1.0 x 1.5	-0.52	-1.57	-16.00	0.93	0.61	-74.49	0.80	-0.95	-44.89
1.0 x 3.0	-0.23	-2.32	-7.04	0.98	0.37	-82.78	0.48	-0.76	-44.95
1.5 x 1.0	-0.53	-1.59	-72.42	0.93	0.60	-17.34	0.81	-0.98	-44.76
1.5 x 1.5	-1.34	-2.21	-43.95	1.01	0.84	-44.88	1.09	-1.32	-44.93
3.0 x 1.0	-0.28	-0.93	-50.85	0.74	0.38	-33.65	0.70	-0.68	-41.94

Table 3 Principle stresses and their directions at point 2 (F=front and R= rear) for systems with joint type 2 and 3 based on $f_{mt;u;rep}$ for sizes 1.0 m x 1.0 m, 1.0 m x 1.5 m and 1.5 m x 1.0 m

Size			$t_{g;n}$ = 4 mm			$t_{g;n}$ = 8 mm			$t_{g;n}$ = 12 mm		
	w_g x h_g [m]		σ_1 [N/mm²]	σ_2 [N/mm²]	α [°]	σ_1 [N/mm²]	σ_2 [N/mm²]	α [°]	σ_1 [N/mm²]	σ_2 [N/mm²]	α [°]
Joint type 2	1.0 x 1.0	F	12.21	-4.01	-44.98	12.65	-2.59	-44.96	12.20	-1.85	-44.91
		R	11.69	-3.30	-44.98	12.50	-2.34	-44.96	12.16	-1.70	-44.91
	1.0 x 1.5	F	11.36	-3.34	-42.38	11.98	-2.04	-41.89	11.44	-1.39	-41.62
		R	10.78	-2.63	-42.18	11.78	-1.80	-41.79	11.34	-1.23	-41.55
	1.5 x 1.0	F	11.47	-3.35	-42.37	12.03	-2.05	-41.79	13.03	-1.60	-41.47
		R	10.81	-2.65	-42.19	11.81	-1.79	-41.71	12.93	-1.42	-41.40
Joint type 3	1.0 x 1.0	F	12.22	-3.28	-45.00	7.75	-1.87	-45.00	5.44	-2.18	-45.00
		R	11.82	-1.89	-44.98	8.27	0.01	-45.00	6.88	0.01	-45.00
	1.0 x 1.5	F	11.37	-2.66	-42.10	7.65	-1.59	-42.11	5.17	-1.88	-41.45
		R	10.85	-1.34	-41.94	8.10	0.02	-41.94	6.45	0.02	-41.50
	1.5 x 1.0	F	10.85	-2.52	-42.12	7.52	-1.56	-41.45	5.36	-1.96	-41.02
		R	10.40	-1.29	-41.95	7.96	0.02	-41.52	6.71	0.02	-41.33

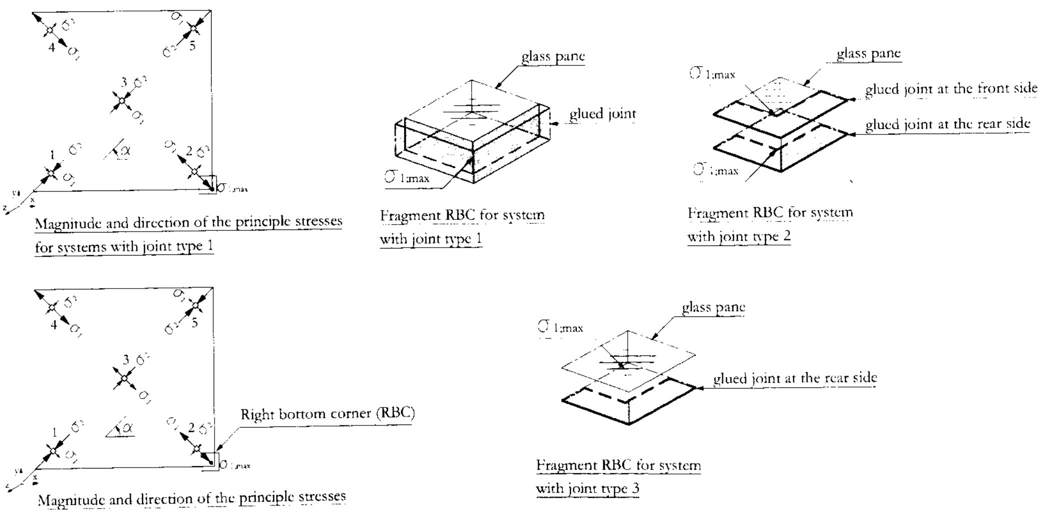

Fig. 6 Maximum and minimum principle stresses at points 1 to 5 and the position of the largest maximum principle stress for systems with joint type 1 to 3

The distribution of the principle stresses and their directions in points 1 to 5 on the front as well as on the rear for systems with joint type 2 show tensile stresses at an angle of -45° and compression stresses at an angle of +45° for all glass pane sizes and thicknesses (figure 6). The magnitude of the minimum principle stress in the points 1 and 5 is larger than the magnitude of the maximum principle stress (table 3). The magnitude of the maximum principle stresses in points 2 and 4 is larger than the magnitude of the minimum principle stresses. The maximum and minimum principle in point 3 is almost equal. The magnitude of the principle stresses on the rear is slightly smaller than the magnitude of the principle stresses on the front for all points, thicknesses and sizes of the glass pane. However, the principle stresses close to the inside corner of the glued joint show two-sided compression stresses at the left bottom corner as well as at the right top corner and two-sided tensile stress at the right bottom corner as well as at the left top corner. The gradient of the principle stress over the thickness of the glass pane is small (table 3). The largest maximum principle stress is located at the right bottom corner on the front and rear of the glass pane at the vicinity of the inside corner of the glued joint (figure 6). The stress state is three-dimensional.

The distribution, the magnitude and the stress state of the principle stresses and their directions in points 1 to 5 for systems with joint type 3 is comparable to systems with joint type 2 (figure 6). The principle stresses close to the inside corner of the glued joint also show two-sided compression stresses at the left bottom corner as well as at the right top corner and two-sided tensile stress at the right bottom corner as well as at the left top corner. The gradient of the principle stress over the thickness of the glass pane is smaller for the maximum principle stress than for the minimum principle stress (table 3). The largest maximum principle stress is located at the right bottom corner on the front only of the glass pane in the vicinity of the inside corner of the glued joint (figure 6). The stress state is also three-dimensional.

4.4 Stress distribution in the adhesive layer

The normal stress in the glued joint ($\sigma_{j;1}$) for systems with joint type 1 is a linear distribution between the joint's ends except for glass panes with a width or height of 3.0 m that show a non-linear distribution (figure 7 left top). At the joint's end the compression stress increases more and the tensile stress smoothes down. The distribution of the shear stresses ($\tau_{j;2}$) is constant over the joint's length. This is found at all glass thicknesses and sizes.

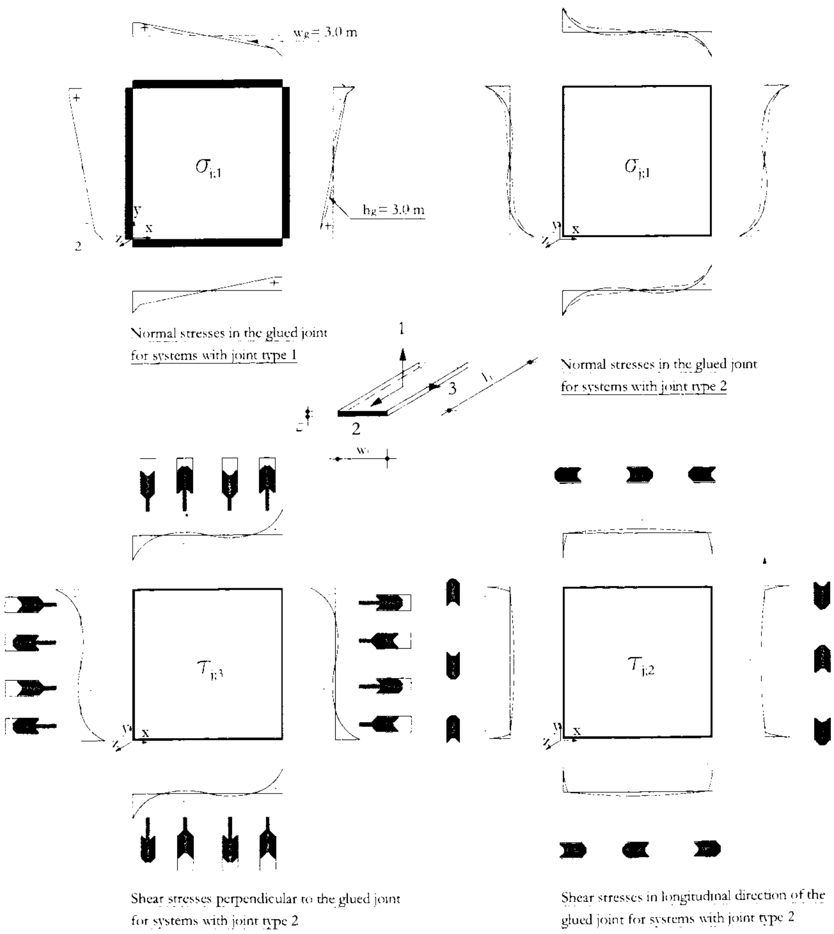

Fig. 7 The principle of the distribution of the normal stresses, shear stresses perpendicular to the joint's length and the shear stresses in longitudinal direction for systems with joint type 1 to 3 (systems with joint type 3 are not drawn)

The normal stress in the glued joint ($\sigma_{j;1}$) for systems with joint type 2 is given in figure 7 at the right top. The maximum compression stress is located at the joint's end at the left bottom corner and right top corner and the maximum tensile stress is located at the joint's ends at the right bottom corner and left top corner. This is found for both glued joints and for all glass pane thicknesses and sizes. Furthermore, the stress distribution and sign of the normal stresses between the ends varies over the length and width. The distribution of the shear stress perpendicular to the joint's length ($\tau_{j;3}$) shows an undulate image with peaks at the joint's end (figure 7 left bottom). This is found for both joints and for all glass pane thicknesses and sizes. The shear stress in longitudinal direction ($\tau_{j;2}$) is almost uniformly distributed over the joint's length and gradually decrease to the joint's end. The peaks are found at the joint's end with a change of sign (figure 7 right bottom). Moreover, the shear stress varies of the joint's width. This is also found for both glued joints and for all glass pane thicknesses and sizes.

The distribution of the normal stresses, shear stresses perpendicular to the joint's length and the shear distribution in longitudinal direction of the joint for systems with joint type 3 is comparable to systems with joint type 2, but than for one glued joint. The magnitude of these stresses is almost the same what is found for systems with joint type 2, but the normal stresses are larger.

5. Discussion

A concise overview of the results of the parametric studies by varying the width, the height and the thickness of the glass pane has been given in section 4 and the results will be discussed in this section.

Systems with joint type 1 have a flexible joint between the glass pane and the steel frame which clearly has the smallest stiffness and determines the system's stiffness. Increasing the thickness of the glass pane also entails an increasing of the width of the joint and therefore the joint's stiffness. This results in the doubling and tripling of the load (figure 3). Therefore, the stress distribution is independent of the glass pane's thickness, because the load is in ratio with the glass pane's thickness and the joint's width. The glass pane has small principle stresses and therefore, plate buckling does not occur. At large system's height the increment of the in-plane displacement increases, because of bending of the slender mullions. This leads to decrease of the system's stiffness and explains the decrease of load at increasing system's height (figure 3). The bending of the slender mullions or transoms reflects on the distribution of the normal stresses in the glued joint (figure 7 left top). The glass pane rotates and shifts within the frame. The rotation leads to normal stresses and the shift leads to shear stresses in the glued joint. The values of these stresses depend on the relative displacement between glass pane and frame (figure 7 left top). The larger the relative displacement in the compression zone, the larger is the increment of the compression stress (three dimensional stress state by lateral supports). The larger the relative displacement in the tensile zone and under shear, the slightly increase of the tensile stress and shear stress (the rearrangement of the chains). This results in more load transfer from the right top corner to the left bottom corner than from the left top corner to the right bottom corner (table 2).

Systems with joint type 2 are the two-sided rigid and toughened glued joint. The in-plane displacement at the top is the result of the deformation of the glued joint, the bolts between outside frame and beadwork and the glass pane. The contribution in the in-plane displacement of the glued joint is very small, because the large Young's modulus, shear modulus and small joint's thickness lead to a large joint's stiffness. On the other hand, the contribution in the in-plane displacement of the bolts between outside beam and beadwork is larger caused by clearing. Moreover, the horizontal in-plane displacement also increases by the vertical deformation of the bolts of the left and right mullion by bending (figure 4 left top). The contribution in the in-plane displacement of the glass pane is small, because the circumferentially glued joint restricts the deformation of the glass pane along the edges. Furthermore, systems with small width in comparison to their height are susceptible for bending (figure 4 left top) caused by the glass pane and the vertical deformation of the bolts of the mullions. The circumferentially glued joint clamps the glass pane at four sides. Therefore, the glass pane displaces more in the field (figure 5).

The local peaks of the normal stress ($\sigma_{j;1}$) at the glued joint's ends are the result of the traction of the glass pane perpendicular to the glass pane's thickness. Furthermore, the normal distribution in the rear and front glued joint depends on the pattern of the out-of-plane displacement of the glass pane (figure 5 and figure 7 right top). The distribution of the shear stress perpendicular to the joint's length ($\tau_{j;3}$) is the result of prevented rotation of the glass pane within the beadwork. The deformation of the bolts between outside beam and beadwork influences the rotation within the outside beam. The bolts have a large normal stiffness and transfers tensile and compression load from the rotating 'rigid' internal composite (glass pane, glued joint and beadwork). The glued joint also has to transfer these loads between beadwork and glass pane, which results in large shear stresses (figure 8). The curving and the undulated pattern between the joint's ends is the result of bending of the steel frame (figure 7 bottom left). This distribution belongs to a rigid glued joint.

The distribution of the shear stress in longitudinal direction ($\tau_{j;2}$) is the result of the prevented movement of the glass pane in vertical and horizontal direction within the frame. Remarkable are the peak stresses with sign change in a small region at the joint's ends. This is the consequence of the deformation of the bolts (shear) between the outside beam and the beadwork. Figure 8 shows the cause for the right top corner. Consider the top glued joint given in figure 8. The right mullion displaces to the glass pane (RM). The glass pane is forced to follow this horizontal displacement of the right mullion (stiff glued joint and large normal stiffness of the bolts) and therefore it displaces more than the beadwork of the top transom. The influence is local and it concerns for each corner in x- and y-direction (figure 7 right bottom).

The distribution of the normal stresses and the two shear stresses explains the principle stress distribution in the vicinity of the in the glass pane's corners. The change of sign of the shear stress in longitudinal direction (figure 7 right bottom) introduces additional tensile stress at the right bottom and left top corner and additional compression stresses at the left bottom and right top corner. The shear stress perpendicular to the glued joint's length leads to additional tensile stresses at the right bottom and left top corner and additional compression stresses at the left bottom and right top corner (figure 7 left bottom). Finally, the prevented deformation of the glass pane's edge leads to the three-dimensional stress state. All joint's stresses in the right bottom corner are slightly larger, because this corner of the frame behaves stiffer and thus more relative displacement between frame and glass pane than the`left top corner (deformations in the entire system).

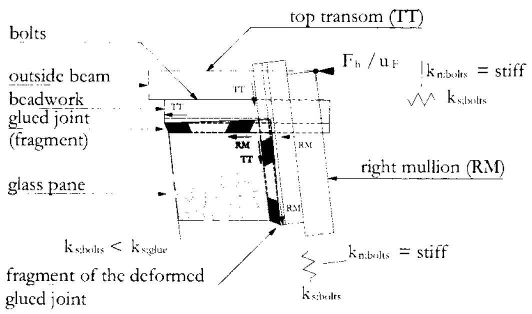

Fig. 8 Displaced situation of the right top corner

The discussion of the results for systems with joint type 3 is comparable to systems with joint type 2 with some deviations. These deviations are discussed here. Systems with joint type 3, the one-sided rigid and toughened glued joint, shows at increasing thickness of the glass pane a slightly increase of load accompanied with a slightly decrease of in-plane displacement (figure 4 left bottom). At increasing thickness of the glass pane the system behaves stiffer and resists more loads. But on the other hand, the eccentricity also increases at increasing thickness of the glass pane and leads to stronger bending in the glass pane (table 3). The one-sided rigid glued joint also prevents free rotation along the edges (clamped) and therefore the bending changes from sign above the glued joint's width (figure 5) accompanied with larger normal stresses in the joint.

6. Further work

The parametric studies with varying geometry of the glass pane have been finished. The next step is investigating the strength criterion for the applied adhesives. Finally, a design rule for systems with joint type 1 to 3 has to develop.

7. Conclusions

The response of the glass pane, glued joint and steel frame by varying the geometry of the glass pane has been described in this paper. The following can be concluded for each system and also takes into account the residual capacity after occurring of the first cracks.

Systems with joint type 1 are the stiffness the criterion. The system's stiffness depends on the stiffness of the glued joint. Glass pane sizes with a small width and a large height have the smallest stiffness. The largest maximum principle stress has been found in the right bottom corner, but is not the criterion. Through the small values of the principle stresses plate buckling does not occur. The load transfers more through the compressed glued joint than the stretched glued joint. A part of the load transfers along the glass pane's edges by shear. The bolted connection between outside beam and beadwork has no influence on the stress distribution of the glued joint. The residual capacity is comparatively good, because the system visually displaces enormously without cracking in the first stage of the glass pane followed by the second stage with cracking.

Systems with joint type 2 are the bending tensile strength the criterion. The largest maximum principle stress is found in the right bottom corner of the glass pane's surface at the inside corner of the glued joint. The tensile diagonal in the glass pane is anchored in this point and enlarges by the sign change of the shear stresses in longitudinal direction and the shear stresses perpendicular to the joint's length at the glued joint's corners. These large shear stresses are the result of the small shear stiffness of the bolts between outside beam and beadwork. The bending tensile stress is reached firstly before plate buckling occurs of a four-sided clamped glass pane. Glass pane sizes with a small width and a large height have the smallest stiffness by bending. The residual capacity is good, because the system resists more load after the first visible and audible cracks and the following cracks.

Systems with joint type 3 are comparable to systems with joint type 2. However, the distribution of the principle stress in the glass pane is influenced by the eccentric load transfer. Moreover, the normal stresses in the glued joint are large by bending of the glass pane. The residual capacity is poor, because the system has less residual capacity after the first visible and audible cracks.

8. References

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