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Huveners, E.M.P.; Hofmeyer, H.; van Herwijnen, F.; Soetens, F.

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Numerical Research on Glass Panes Acting as a Shear Wall

Edwin Huveners, Herm Hofmeyer, Frans van Herwijnen, Frans Soetens
Eindhoven University of Technology, Department of Architecture, Building and Planning, Unit Structural Design and Construction Technology, The Netherlands, e.m.p.huveners@tue.nl

Panes in the building envelope have the possibility to stabilize buildings. To use the pane as a shear wall, the connection between the pane and the casing has to be activated. This research focuses on a system consisting of a steel frame, a single pane and one of three defined circumferentially glued joint types, namely a polyurethane joint on end, a two-sided and a one-sided epoxy joint. A numerical model has been developed and validated for a parametric research. The validated models match well against the experimentally found results. The conclusion is that the numerical models are applicable for the purpose of the non-cracking design of panes acting as a shear wall.

Keywords: Glass, Circumferentially Glued Joint, Shear Wall, In-Plane Load, Finite Element Model

1. Introduction

Glass is a frequently applied building material, especially for building envelopes that is determined by architectural considerations and regulations. The structural performance of panes is one of the regulations and this concerns out-of-plane loads only. Panes also have good in-plane stiffness and offer the possibility for bracing a frame. So, panes can be used to stabilize a building e.g. one-storey buildings or a part of a building. The idea to use panes as stabilizing element is not new e.g. the cast-iron bearing structure of 19th century green houses was stabilized by single glass panes in the envelope [1]. The small panes were bonded to the casing with putty. However, nowadays the panes are flexibly enclosed by the casing.

To take advantage of the in-plane stiffness of panes, the presently used connecting detail between pane and its boundaries has to be changed. The glued joint is an eligible technique to connect glass to another material. The glued joint spreads stresses in the pane and forms an interlayer to prevent direct glass-metal contact. The glued joint is made of synthetic adhesive and replaces the former putty.

The research concentrates on a system consisting of a steel frame, a single glass pane, bonded to the frame with three different glued joints. Experimental research has been carried out and analyzed [2]. The next step is a numerical research to get more insight in the system. Numerical model of composed glass structure is an inevitable tool to find the critical tensile stress e.g. laminated glass [3], point fixed glass [4], uni-axially loaded glass [5] and shear wall [1]. This paper starts with a short discussion of the
experiments and continues with the development and validation of the numerical model of a frame loaded by a concentrated in-plane load at a top corner braced by a circumferentially glued single pane.

2. Experiments

2.1. Test set-up

The pane and one of the three defined joint types are placed in a frame and this is called the system (figure 1, left). The frame is built up of steel beams consisting of an outside beam and inside beam (figure 2, bottom left). The outside beam has a rectangular cross section and is connected with internal hinges. The inside beam is a replaceable beadwork equipped with a joint type depending groove and is bolted to the outside beam. The frame of the system is supported by a horizontal roller at the left bottom corner and pinned connection at the right bottom corner. The load is introduced on the top transom at the right top corner.

The applied type of glass is annealed float glass with a nominal thickness of 12 mm. The size of the pane is 1000 mm x 1000 mm. The edge is provided with a facet and is polished. The middle surface of the pane lines up with the centre of the outside beam.

The pane is structurally bonded to the beadwork of the frame with three different circumferentially glued joints (figure 1, right). Joint type 1 is a glued joint on end. The pane is supported laterally by a strip and a groove. The gap between pane and frame depends on tolerances and needs a gap filling sealant. Joint type 2 is a two-sided glued joint. The thickness of the joint can be very small and is guaranteed by spacers and adjustable strip. Joint type 3 is a one-sided glued joint and is an eccentric connection.

Figure 1: Test set-up of the system with measuring devices (left) and an overview of the joint types (right)

Two types of adhesive have been selected for the research and the shear stress-strain relation is determined experimentally under prescribed conditions [6,7]. The applied adhesive for joint type 1 is polyurethane (Sikaflex-252) and for joint type 2 and 3 epoxy (Scotch Weld 9323 B/A).

Figure 1 (left) also shows the measurement program. The load introduction, measured by a load cell, is displacement controlled with a velocity of 1 mm/min and can be considered as a static load. The in-plane displacement of the frame is measured at point F ($u_F$). The out-of-plane displacement of the centre of the pane is measured at point A.
Points 1 to 5 are strain rosettes on the pane's front and measure the strain at 0°, 45° and 90°. A high speed camera was installed and recorded the cracks.

2.2. Main observations

Figure 5, 6 and 7 (left top) show the load-displacement relation at the right top corner for systems with joint type 1 to 3. The load-displacement relation of systems with joint type 1 demonstrates an almost bi-linear behaviour. Till the intersection at $u_{F, ave} = 21.87$ mm the pane has no cracks and the glued joint is in tact. After this intersection the pane cracks at the left bottom corner and the right top corner. The glued joint is pushed away in the compression area and is pulled off in the tensile area. The load transfer from frame to pane changes by flaking off pieces of glass in these corners.

The load-displacement relation of systems with joint type 2 demonstrates a declining curve accompanied with cracking (discontinuities). The crack from the left bottom corner to the right top corner splits the pane and influences the load-displacement relation. At a few tests a fan-like pattern is observed at the right bottom corner which has a small influence on the load-displacement relation. The pane is uncracked at $u_{F, ave} = 1.00$ mm. After the test the epoxy joint is in tact.

The load-displacement relation of systems with joint type 3 shows a similar relation as described at systems with joint type 2. However, the maximum load is smaller. The crack from the left bottom corner to the right top corner leads to collapsing of the system. At a few tests a gradually propagating crack along the bottom of the right mullion is observed. The pane is uncracked at $u_{F, ave} = 1.07$ mm. The epoxy joint is also in tact.

The average out-of-plane displacement ($w_{F, ave}$) at average displacement of point F ($u_{F, ave}$) is 0.35 mm, 0.43 mm and 0.30 mm, directed to the negative z-axis (figure 1), for systems with joint type 1 to 3 respectively. The frame has negligible out-of-plane displacements.

3. Numerical model

3.1. Objective of the model

In the previous section the experimental results have been discussed. To give more insight in these systems a numerical model of the test set-up has been developed for a structural non linear calculation. The results are the basis for validation of the numerical model. Then the working model can be used for a parametric study to determine the maximum principle stress (failure criterion). The objective of the model is to simulate the system’s behaviour up to the onset of the first crack. The applied finite element package is DIANA 9.1 [8].

3.2. Geometrical model

The model consists of three groups (figure 2, right top), namely frame, pane and joints. The frame has four subgroups, namely two mullions and two transoms and these subgroups are divided into outside beam, bolted connection and beadwork. The pane has three subgroups, namely the glass panel and glass edges A and B. The group joints has three subgroups, namely interfaces A to C.
The frame has to fulfill eight conditions, namely the middle surface of the glass pane lines up with the centre of the outside beam (figure 2, right bottom), the transoms and mullions of the outside beam are connected hinged, the centre of the outside beam coincides with the centre of the internal hinges, the line of action of the load introduction at the right top corner coincides with the centre of the internal hinge and the outside top transom, the distance between the centre of the outside beam and the glass edge (figure 2, right bottom), the horizontal roller and pinned connection are fastened to the internal hinge of the left bottom corner and the right bottom corner respectively, the pinned connection is elastic in vertical direction and the clearance of the bolts of the bolted connection between the outside beam and the beadwork is elastic.

Figure 2: Pulled out of the numerical model (left), modeled cross section (right top) and real cross section (right bottom)

The outside beam is modeled by a beam element and a flat shell element (see table 2 for element overview). The beadwork is modeled as a “fork” to enclosure the pane edge and glued joints. The advantage of this way of modeling is that one numerical model can be made, which includes all the joint types. The fork consists of flat shell elements only. The properties of the real cross section correspond with the modeled cross section. The bolted connection between outside beam and beadwork is modeled by a two-dimensional interface element. At each corner the transom and mullion have an overlap with uncoupled nodes except the common node of the beam element. This node is coupled and also released for rotation around z-axis (internal hinge). The displacement controlled load is placed at the right side of the outside top transom in x-direction. The outside bottom transom has a horizontal roller at the left bottom corner and a pinned connection provided with a vertical spring element at the right bottom corner. The frame is fully supported in z-direction.
The pane is modeled by shell elements, because these elements also take into account the out-of-plane displacements. The edge of the pane is flanked by solid elements at both sides to model the thickness of the pane. So, an eccentric connection can be simulated, especially for joint type 3. The imperfections of the pane are simulated by introducing a small uniformly distributed load (0.001 N/mm²) directed to the negative z-direction.

Table 2: Element types applied and geometrical data

<table>
<thead>
<tr>
<th>Group</th>
<th>Subgroups</th>
<th>Number (fig. 3)</th>
<th>Element name</th>
<th>Element type</th>
<th>Thickness [mm]</th>
<th>Width [mm]</th>
<th>Height [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>Outside beam</td>
<td>1</td>
<td>Beam</td>
<td>L12BE</td>
<td>--</td>
<td>118</td>
<td>60</td>
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<tr>
<td></td>
<td></td>
<td>2</td>
<td>Flat shell</td>
<td>CQ40F</td>
<td>--</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Bolted connection</td>
<td>3</td>
<td>2D interface</td>
<td>CL12I</td>
<td>--</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>Beadwork</td>
<td></td>
<td>4</td>
<td>Flat shell</td>
<td>CQ40F</td>
<td>--</td>
<td>80</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>Flat shell</td>
<td>CQ40F</td>
<td>--</td>
<td>13</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>Flat shell</td>
<td>CQ40F</td>
<td>--</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>Vertical spring (fig. 3)</td>
<td></td>
<td>Discrete spring</td>
<td>SP1TR</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Pane</td>
<td>Glass panel</td>
<td>10</td>
<td>Curved shell</td>
<td>CQ40S</td>
<td>12</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Glass edge A and C</td>
<td>9</td>
<td>Solid</td>
<td>CHX60</td>
<td>6</td>
<td>10</td>
<td>--</td>
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<tr>
<td>Joints</td>
<td>Interface A and C</td>
<td>8</td>
<td>3D interface</td>
<td>CQ48I</td>
<td>0.5</td>
<td>10</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Interface B</td>
<td>6</td>
<td>2D interface</td>
<td>CL12I</td>
<td>12</td>
<td>5</td>
<td>--</td>
</tr>
</tbody>
</table>

Figure 3: The use of interfaces A to C for the systems with joint type 1 to 3.

Joint types 1 to 3 are represented by three interfaces which connect the pane to the fork of the frame. Interfaces A and C are solid interface elements placed between the glass edge and the inside of the fork. Interface B is a two dimensional interface element placed between the on end of the pane and the bottom of the fork. Joint type 1 (figure 3) uses polyurethane properties for interface B and Teflon properties for interfaces A.
and C. Joint type 2 (figure 3) uses epoxy properties for interfaces A and C and inactivates interface B. Joint type 3 (figure 3) only uses epoxy properties for interface C and inactivates interfaces A and B.

3.3. Material input

Table 3 gives linear material properties for glass, steel, stiffness of the vertical spring at the right bottom corner and the normal and shear stiffness of the bolted connection between the outside beam and beadwork. The latter two are determined experimentally. The group joints have a linear as well as a non-linear material input. The Teflon interlayer of systems with joint type 1 has a thickness of 3 mm and a Young’s modulus of 500 N/mm². Figure 4e gives the assumption relation between normal stress and relative displacement in the compression (contact) as well as in the tensile area (no contact). The shear stiffness is very small and is assumed to be constant (k_{Teflon} = 10^{-5} N/mm²).

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>E = 70000 N/mm²</td>
<td>Source: NEN 2806-2:2007 nl</td>
</tr>
<tr>
<td></td>
<td>v = 0.25 [-]</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>E = 210000 N/mm²</td>
<td>Source: NEN 6770:1997 nl –</td>
</tr>
<tr>
<td></td>
<td>v = 0.30 [-]</td>
<td>TGB 1990</td>
</tr>
<tr>
<td>Vertical spring (fig. 2)</td>
<td>k_{v,RBC} = 10³ N/mm³</td>
<td>Determined experimentally</td>
</tr>
<tr>
<td>Bolted connection</td>
<td>k_{s,bolt} = 10³ N/mm³</td>
<td>Large normal stiffness (assumption)</td>
</tr>
<tr>
<td></td>
<td>k_{s,bolt} = 10 N/mm³</td>
<td>Determined experimentally</td>
</tr>
</tbody>
</table>

Figure 4b shows the shear stress-relative displacement relation of epoxy converted from the experimentally found shear stress-strain relation and is assumed to be symmetrically. The Young’s modulus in the compression area as well as the tensile area is derived from the linear part of the shear stress-strain relation. The Poisson’s ratio is 0.30 [9]. The normal stiffness is assumed to be linear (k_{n,epoxy} = 1260 N/mm³).

Figure 4c shows the relation between normal stress-relative displacement of polyurethane. The stiffness of the flexible joint in the compression area increases at larger displacements till a relative displacement of 5 mm. After that, the stiffness is very large and simulates glass-frame contact. The relation in the tensile area shows the opposite. The stiffness slightly increases at increasing relative displacements. Then the stiffness reduces to a very small value. This simulates adhesion problems.

Figure 4d gives the shear stress-relative displacement of polyurethane converted from the experimentally found shear stress-strain relation and is assumed symmetrically. In the compression area the shear stiffness increases till a relative displacement of 5 mm. Then the joint has a very small shear stiffness, because the adhesive is pushed away. In the tensile area, the shear stress also increases till a relative displacement of 5 mm. Then the joint has a very small shear stiffness, because the adhesive is pulled off (adhesive failure).
4. Numerical model versus experimental results

This section deals with the validation of the numerical model with the experimentally found results of systems with joint type 1 to 3. Validation parameters are the load-displacement relation at the right top corner and the principle stress of point 1 to 5 (figure 5, 6 and 7). The measured strains are converted into principle stresses with the assumption that the Young's modulus and Poisson's ratio are 70000 N/mm² and 0.23 respectively.

The numerically found load-displacement relation of the system with joint type 1 matches well the experimentally found load-displacement relation (continuous). The first uncracked part coincides and the second cracked part has the same slope. The numerically found principle stresses also match the experimentally found principle stresses.

The first part of the load-displacement relation follows the material input of glass correctly. However, if the pane cracks at the left bottom and the right top corner, the material input of the second part is not valid anymore. Cracking of the right top corner (shattering pieces of broken glass) leads to lower the point of action on the pane. This is not modeled. The material input for the glued joint is valid for both parts of the load-displacement relation, because contact and adhesion problems are involved.

The numerically found load-displacement relation of the system with joint type 2 partly matches the results of the experiments (continuous). A good match is found till a displacement of $u_r = 1.8$ mm ($F_h = \pm 80$ kN). Then the experimentally found relation
gradually decreases at increasing displacement. The numerical model does not show this declining. The numerically found principle stresses match the experimentally found results well till a displacement of $u_r = 1.8$ mm.

![Graphs showing comparison between experimental and numerical results](image)

Figure 5: Comparison experimental results versus numerical results of the load displacement relation at the right top corner and the principle stresses at point 1 to 5 (see Figure 1) for the systems with joint type 1

The numerically found load-displacement relation of the system with joint type 3 matches the results of the experiments (continuous) well and the relation is linear. The numerically found principle stresses match the experimentally found results good.

The load-displacement of systems with joint type 2 and 3 also show a good match. This surely concerns for the uncracked pane. The applied material models can be used. The small cracks at the right bottom corner have small influences on the global behaviour of the system, just locally (point 2 of figures 6 and 7). If the crack occurs from the left bottom corner to the right top corner, the stiffness decreases by cracking and this phenomenon is not involved in the material models.
Figure 6: Comparison experimental results versus numerical results of the load displacement relation at the right top corner and the principle stresses at point 1 to 5 (see figure 1) for the systems with joint type 2.
5. Conclusions

One numerical model has been developed for the systems with joint type 1 to 3 and has been validated with the experimentally found load-displacement relation at the right top corner and the principle stresses of five points on the front of the pane. The results of the numerical model match well the experimental results till the first crack occurs. So, the model is applicable to simulate the system’s behaviour up to the onset of the first crack and therefore, the numerical model fulfils the objective. The model is suitable for non-cracking analyses and to determine the maximum principle stress which can be related to a failure criterion.

6. Further research

The experimental research and developing/validating of the numerical model have been carried out. The next step is refining the numerical model followed by a parametric study. This finally results in a design rule for a steel frame stabilized by a circumferentially glued pane.

7. Acknowledgement

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8. References