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

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In Plane Loaded Glass Panes in Façades
Temperature Loads in Fixed Bonded Glass Panes

Ir. Edwin Huveners, Prof. Ir. F. van Herwijnen, Prof. Ir. F. Soetens, Dr. Ir. H. Hofmeyer
Eindhoven University of Technology
Department of Architecture, Building and Planning, Group Structural Design
Den Dolech 2, Vertigo 9.08, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

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Abstract
The author discusses the use of glass panes as transparent stability elements in vertical façade structures subjected to in-plane loads including temperature loads. In the present façade architecture, glass is normally used non-structural. The only mechanical requirement is to resist transversal loads, which determines the thickness of the glass pane. Thus, glass panes are not used to stabilize the structural system. However, glass panes have excellent in-plane stiffness qualities, and providing appropriate connections between glass and the supporting structure, this in-plane stiffness can possibly attribute to the building’s stability. Temperature loads on the glass avoid making a totally stiff connection between glass and structure, whereas this would be required for the stability aspect.

To investigate this problem, this paper presents two conceptual connection designs between glass and structure. For temperature loads, these connections will be studied using the theory of plates. It is shown that a bond line as connection, having a large stiffness directly leads to a uniform distribution equal to almost the complete temperature load. If the shear stiffness of the bond line is taken into account, a complex stress pattern in the glass pane occurs, even for a geometrical and physical linear approach. Thus, the impact of the temperature loads is significant for all glass panes (plate level) and is independent on façade size and this in contrast with the collaboration of the glass panes and supporting structure to resist laterally mechanical loads (structure level). Research will continue with experiments to verify the theoretical derived results and with the development of finite element models to study the complex stress pattern in the glass pane, dependent on connection type and load case.

Introduction
Glass has always been a popular building material in architectural practice. The major function of glass panes is the transparent part in the building envelope. The present enclosing systems for fixing glass panes to the supporting structure behind are flexible systems for reducing unfavourably additional tensile or compression stresses, which can lead to collapse of the pane. Rubbery materials, such as neoprene, enclose a four-sided supported glass pane in the rebates. The glass pane is flexibly supported along the edges to transfer transversal load only and can move in plane freely. The only in plane load to be supported by blocks in the rebate is its own weight of the pane. So, no additional stresses in the glass pane can occur due to restricted deformation in plane along the edge of the pane.

Code [1] is used for dimensioning glass panes in building practise in the Netherlands. This code can only be used for linearly supported glass panes in façade and roof structures, which are loaded with uniformly distributed loads only. Furthermore, the prescribed mechanic models are based on geometrically and physically linear theory. Nevertheless, there are some developments to enlarge the field of this kind of glass applications.

For other supporting structures of a pane (such as point fixed), glass structures (such as beams, staircases and the like) and for non-uniformly distributed loads (such as concentrated loads) the common sense of the structural engineer is necessary to interpret the current codes and to make a properly mechanic model for reducing the tensile stresses to allowable values. The finite element method is a convenient tool for special glass applications.

The codes do not use the in plane stiffness of the glass pane. Unfortunately, the glass pane has good properties for transferring in plane loads. To design a building, which is stabilised with the help of glass panes,

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Figure 1
Kew garden, London, UK.

Figure 2
Glass panes as stiffening element in façade structures.
is a bridge to far for building practise and there is much of a chance that the local authorities, such as building inspection departments, reject it. But from the other hand, this is not a new application of glass. In former days, some buildings were stabilised with the help of glass, such as green houses in the nineteenth century in UK (figure 1). The comparatively small glass panes were structurally bonded to slender iron profiles with putty, in favour of transparency.

This leads to the investigation of the modern version of in plane loaded glass structures. To stabilise a façade structure (vertical diaphragm) an interaction has to occur between the glass panes and the linear supporting structure behind (see figure 2). The glass pane is continuously bonded to a beadwork with the help of modern adhesive technology and then this unit is connected to the supporting structure with mechanical fasteners. So, the structure can stabilize itself without annoying braces.

**Joint design**

Figure 3 shows two joint types that will be investigated. Joint type 1 is a comparatively simple joint, but the position of the bond line is not correct for connecting a glass pane to an adherent. This location is very sensitive for growing tensile stresses and can lead to premature failure. The investigation was started with this model for gathering information about the interaction between bond line and glass pane quickly with the help of analytical formulas before making a finite element model. Some results of this joint will be discussed in this paper. The location of the bond lines in joint type 2 is a more logical one, because it has two bond lines for transferring predominately shear stresses, it is symmetrical, it suppresses transversal tensile and compression stresses respectively by the beadwork, there is enough distance to the edge.

The joint has to fulfil more requirements than mechanical properties only. As stated before, production and construction are also very important design parameters. It is preferable to make the glass unit in a workshop under constant circumstances. The glass pane and beadwork undergoes the inevitable preparations for making a proper bond line. After curing, the beadwork protects the glass pane along the edges during transport and construction.

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**Load case temperature**

Beside transversal loads and in-plane loads due to mechanical load cases, the load case temperature also causes in-plane stresses, if the edges are prevented to move freely. Figure 4 shows a model with joint type 1. The glass pane is four-sided supported and enclosed by a bond line along the edges. The bond line has two kinds of stiffness (see figure 4), namely stiffness ($k_1$) and shear stiffness ($k_2$). The stiffness is determined by

$$k_1 = \frac{E}{t}$$

and by

$$k_2 = \frac{G}{t}$$

In which:

- $k_1$ is the normal stiffness in N/mm$^3$
- $k_2$ is the shear stiffness in N/mm$^3$
- $E$ is the Young's modulus of the adhesive in N/mm$^2$
- $G$ is the shear modulus of the adhesive in N/mm$^2$
- $t$ is the thickness of the bond line in mm

The stiffness $k_1$ (shear stiffness along the thickness of the pane) is assumed to be zero in this consideration.

The adhesive epoxy has an average Young's modulus in the order of 10,000 N/mm$^2$ for room temperature. If the epoxy behaves like a solid, the relation between Young's modulus and shear modulus is known. The relation is given by equation 3.

$$G = \frac{E}{2(1 + \nu)}$$

The Poisson's ratio ($\nu$) of epoxy is approximately 0.35 and the shear stiffness is in the order of 3700 N/mm$^2$. A bond line of epoxy has a thickness in the order of 0.5 mm. So the stiffness $k_1 = 20,000$ N/mm$^3$ and the shear stiffness $k_2 = 7400$ N/mm$^3$ respectively.

The relationship between modulus and thickness of the bond line is clear. A greater modulus and a smaller thickness give a greater stiffness. The adhesive epoxy has a greater value for the stiffness (greater modulus and a very small thickness of the bond line) than for instance polyurethane (smaller modulus and a comparatively large thickness of the bond line). The stiffness $k_1$ is based on the linear relation between stress and displacement of the bond line and this is a restriction of its application, because the bond line

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**Figure 3**

Two different types of investigated bond lines.

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**Figure 4**

Flexible enclosed glass pane with stiffness $k_1$ based on joint type 1.
strongly depends on force-deformation course and influences the stresses in the pane significantly. Thus, the compressed bond line shows another force deformation course than the bond line under tensile. Beside path-dependency, temperature and time are other adhesive properties, which influence the behaviour of the bond line and also the glass pane.

### Influence of stiffness $k_1$

The next derivations are based on glass panes, which are flexibly enclosed by stiffness $k_1$ only. If glass panes can move freely in plane, the strain $\varepsilon$ is the product of the linear thermal expansion coefficient and the uniformly distributed temperature ($a \Delta T$) for both directions and no shear stresses occur. If the glass pane is completely prevented to deform, the strains are suppressed to zero and the stresses are only shear stresses. If the glass pane is completely prevented to deform, the strains are suppressed to zero and the stresses are only shear stresses. If the glass pane is completely prevented to deform, the strains are suppressed to zero and the stresses are only shear stresses.

The stresses in both directions are the same and are independent of the pane size. No shear stresses occur in this case, because the strains along the edges are completely suppressed to zero and the stresses are thickness independence indeed.

The equation for uniformly distributed thermal stresses for plates [2,3,4] is

$$\sigma_{x,y} = -\alpha E (T - T_0) \quad (1)$$

Substituting the properties of glass, equation (1) can be rewritten as:

$$\sigma_{x,y} = -\frac{\alpha E T}{1 - \nu} \quad (2)$$

In which

$\sigma_{x,y}$ = the thermal stress in N/mm²

$\alpha$ = the linear thermal expansion coefficient of glass ($9\cdot 10^{-6}$ mm/mm°C)

$\nu$ = the Poisson's ratio of glass (0.23)

$E$ = the Young's modulus of glass (70,000 N/mm²)

$T_0$ = the initial temperature of the pane in °C

$T_e$ = the considered end temperature in °C

$\Delta T$ = the uniformly change of temperature in °C

$w$ = the width of the pane in mm

$\Delta T$ is reached immediately and is even dimension independent.

The linear relation of stiffness $k_1$ and the geometrical linear behaviour of the glass pane are not physically correct. If the glass pane is subjected to decreasing temperatures, the maximum occurred tensile stress is the utmost tensile stress reduced by factors such as time and the bond line has an allowable deformation belonging to its geometry and property. If the glass pane is subjected to increasing temperature, the bond line will be suppressed and leads to larger values for stiffness $k_1$. The compression stresses in the glass pane are large and in combination with its geometry (large size and small thickness) the pane will buckle. Small glass panes, which were applied in green houses, can better resist increasing of temperature, because the glass pane is completely under compression and stiff enough to resist buckling.

### Influence of shear stiffness $k_2$

In this consideration, the bond line has a linear stiffness along the edges, defined as $k_2$. This is the so-called shear stiffness of the bond line. It introduces stresses in the glass pane along the edges, which influences the entire plate. The stiffer the bond line, the larger is the shear stress especially at the corners, because the glass pane deforms from the centre of the plate outwards and the prevented deformations (distortion) is the largest at the corners. Shear stiffness $k_2$ also influence the stress distribution in x-direction as well as in y-direction. The centre of the edge is more prevented to deform by stiffness $k_2$, and leads to great normal stresses along and decrease to the corners. This leads to a complex stress distribution in the plate. The stress criterion for glass panes is the principle stress. The maximum as well as the minimum principle stress must be determined, because the maximum principle stress leads to failure of the utmost tensile stress and the minimum principle stress can lead to buckle of the glass pane.

### Summary

A bond line with a great stiffness $k_1$ (such as epoxy) directly leads to a uniformly distributed stress of approximately $-\nu^2 \Delta T$ and is independent from the size of the pane. A bond line with a small stiffness $k_2$ gives a lower uniformly distributed stress in the pane, but if the size of the pane increases, the prevented deformation also increases and leads to a stress of approximately $-\nu^2 \Delta T$ and is size dependent.

### References


