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The Influence of the Edge Sealing in Curved Insulated Glass

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An essential part of the structural analysis of insulated glass is, to find values for the inner pressure as a result the so called climatic load and the coupling effect in these curved insulated glass units. An interesting aspect of this analysis is the influence of the edge sealing. The edge sealing allows small movements and rotations of the glass at the edges. Depending on the load situation the distance between glass panes becomes longer or shorter. A range of displacements with a value of 0.1 mm up to 0.2 mm depending on the edge system used is possible. This displacement value is not big, but multiplied by the area of the glass panes a difference in the effective inner pressure results, which should not be neglected.

Keywords: Insulated Glass, Edge Sealing, Spacer

1. Introduction

A current tendency of architects is, to design the façades or the windows with curved insulated glass. Not only is the production of such glass a special topic, but the structural design is also very difficult. A difficult part of the analysis is to find values for the effective inner pressure depending on the so called climatic load and the coupling effect in these curved insulated glass units. The coupling effect describes the load distribution between the inner and the outer glass panes due to external loads, e.g. wind loads. The climatic loads result from differences in temperature, differences in meteorological air pressure and differences in height between the location of production and the construction site. Another important topic is the influence of the edge sealing. The edge sealing allows small movements and rotations of the glass at the edges. Depending on the load situation the distance between glass panes becomes longer or shorter. A range of displacements with a value of 0.1 mm up to 0.2 mm depending on edge system is possible. If soft spacers are used, it is possible to reach a value of more than 0.2 mm for the maximum deformation figure. This displacement is not big, but multiplied by the area of the glass panes a difference in volume results, which should not be neglected.

For the analysis of this effect many calculations were carried out. The results of the analysis showed that depending on the stiffness of the sealing the whole system of glass and sealing became softer. With this softening of the system, the difference in volume as a result of the internal pressure increased. This increase in difference in volume resulted in a decrease in the effective internal pressure.

2. Edge systems for curved insulated glass

Aluminium spacers or soft spacers can be used for the edge seals. For an application in curved insulated glass these aluminium profiles must be pre-shaped with the same geometry as the curved edges. The soft spacers consist of a flexible synthetic material and need not be pre-shaped. Figure 1 shows the cross section of edge sealing of the two principle types. [1]

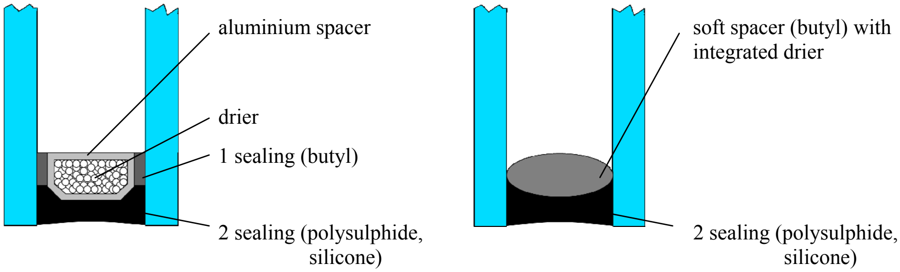

Figure 1: Edge systems.

3. Displacements and rotations

Because of the loads small displacements and rotations along the edges of an insulated glass unit are possible. For the description of the displacements a coordinate system (x, y, z) is assumed. These displacements between the glass panes can occur along the edges (δ_x) and in both directions orthogonal to the edges (δ_y and δ_z). The influences of rotation around the edges can be neglected. The reason for this is that the edge sealing is too weak for an effective support of the fixing moment [2]. Due to the very small deformations (δ_x and δ_y) in the direction x and y the influences of the sealing can be neglected. The most important displacement which results in a shortening or an elongation of the distance between the glass panes is defined as (δ_z).

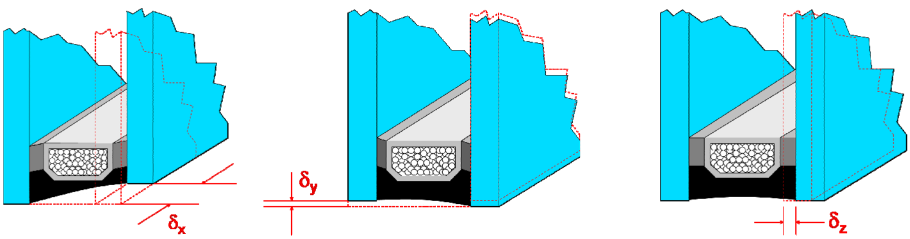

Figure 2: Displacements between the glass layers.

According to the stiffness of the edge sealing it is possible to define a stiffness of the springs in all directions of the coordinate system (C_x, C_y, C_z). The glass panes and the system of bearing-springs can be modelled in a finite elements program. One result of such a calculation is the value for difference in volume between the initial geometry and the deformed geometry and this value can be used as input data for the design concept described below.

4. Design concept for curved insulated glass

4.1. Internal loads

An aspect of the structural analysis of curved insulated glass is to find values of the internal pressure for the so-called climatic load in a curved insulated glass. One way is the definition of the two limits of the climatic load – the isochoric limit with the highest or lowest internal pressure in the insulated glass unit and the isobaric limit with no added increase or decrease in the internal pressure. Depending on the bending strength of the glass, the realistic pressure is between these two limits. For the differences in temperature, the differences in geographic height and the differences in the meteorological air pressure, it is possible to find the effective internal pressure in the bent insulated glass as the equilibrium of the bending strength of the glass and the internal pressure.

In figure 3 the principal concept for the climatic loads is shown. The left sketch is the isochoric state with the added internal pressure. The right sketch describes the isobaric limit with a bending strength of the glass panes of theoretically zero. The added internal pressure decreases to zero and the added volume increases to its maximum. The realistic behaviour of insulated glass is between these two limits, as shown in the sketch in the middle of figure 3. [3]

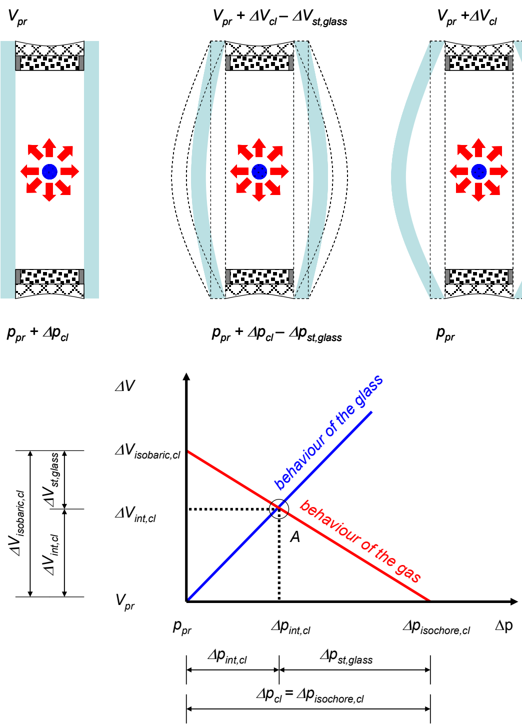

Figure 3: Internal pressure depending on internal “climatic” loads, pV-diagram for internal “climatic” loads.

With the following equations (1) and (2) the isochoric and the isobaric limit can be calculated. With knowledge of the bending strength of the glass pane the realistic pressure can be computed by the equation (3).

$$p_{pr} \cdot \left(V_{pr} + \Delta V_{cl}\right) = const. = isobaric \tag{1}$$

$$\left(p_{pr} + \Delta p_{cl}\right) \cdot V_{pr} = const. = isochoric \tag{2}$$

$$\begin{aligned} & p_{pr} \cdot \left(V_{pr} + \Delta V_{cl}\right) = \\ & \left(p_{pr} + \Delta p_{cl} - \Delta p_{st,glass}\right) \cdot \left(V_{pr} + \Delta V_{cl} - \Delta V_{st,glass}\right) = \\ & \left(p_{pr} + \Delta p_{cl}\right) \cdot V_{pr} \end{aligned} \tag{3}$$

p_{pr}	pressure at the production process
V_{pr}	volume at the production process
Δp_{cl}	added pressure due to the climatic loads (isochoric state)
ΔV_{cl}	added volume at the isobaric state
$\Delta p_{st,glass}$	difference in pressure due to the bending strength of the glass
$\Delta V_{st,glass}$	difference in volume due to the bending strength of the glass

One line in the pV-diagram in figure 3 describes the behaviour of the gas between the isochoric and the isobaric limits. The second line shows the bending strength behaviour of both panes of glass if a linear elastic theory is assumed. At the intersecting point of both lines, marked as point A the realistic internal pressure $\Delta p_{int,cl}$ can be read off. This pressure can be used as a load for the structural analysis and the verifications of the glass panes. With the following equation (4) it is possible to be computed the effective inner pressure $\Delta p_{int,cl}$. as the point of intersection of the two straight lines. [3]

$$\Delta p_{\text{int},cl} = \frac{\Delta V_{isobaric,cl}}{\frac{\Delta V_{isobaric,cl}}{\Delta p_{isochoric,cl}} + \Delta V_{st,glass}} \tag{4}$$

$\Delta p_{int,cl}$	effective internal pressure as a result of climatic loads
$\Delta p_{isochoric,cl}$	difference in pressure at the isochoric limit
$\Delta V_{isobaric,cl}$	difference in volume at the isobaric limit
$\Delta V_{st,glass}$	difference in volume due to the bending strength of the glass

4.2. External loads

In figure 4 the principal concept for the external loads is shown. In the left sketch an insulated glass with an external load is drawn. Due to the load a deflection results and the theoretical isobaric difference in volume can be calculated. As a consequence of this difference in volume the difference in internal pressure can be computed according to the ideal gas law. Because of the internal pressure a decrease in the deflection of the glass pane on the side of the load and an increase in deflection of the other glass pane results. This is the so-called coupling effect of the insulated glass units due to the external loads.

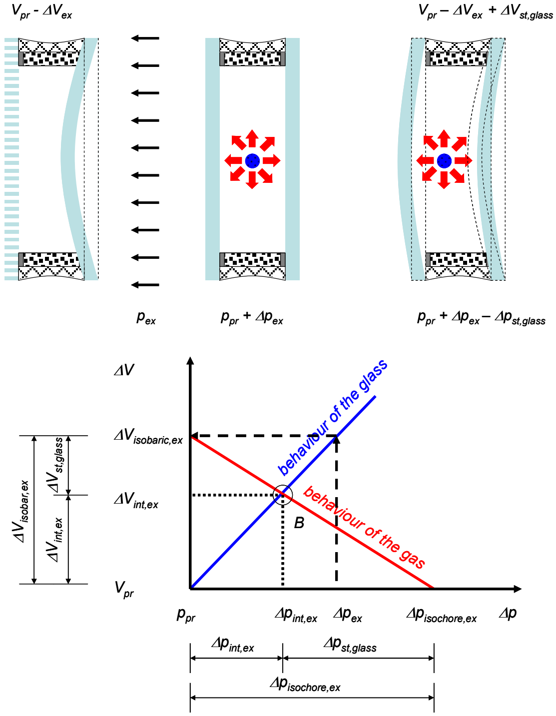

Figure 4: Internal pressure due to external loads, pV-diagram for external loads.

One line in the pV-diagram in figure 4 describes the behaviour of the gas between the isochoric and the isobaric limit. The second line shows the bending strength behaviour of both glass panes on the assumption of a linear elastic theory. At the intersection point of both lines, marked as point B the effective internal pressure $\Delta p_{int,ex}$ can be read off. At this point the inner pressure is in equilibrium with the bending strength of the glass panes. The sum of this internal pressure and of the external loads can be used as a load for the structural analysis and the verifications of the glass panes. With the following equation (5) it is possible to compute the effective inner pressure $\Delta p_{int,ex}$. as the point of intersection of the two straight lines.

$$\Delta p_{\mathrm{int},ex} = \frac{\Delta V_{isobaric,ex}}{\dfrac{\Delta V_{isobaric,ex}}{\Delta p_{isochoric,ex}} + \Delta V_{st,glass}} \tag{5}$$

$\Delta p_{int,ex}$	effective internal pressure due to external loads
$\Delta p_{isochoric,ex}$	difference in pressure at the isochoric limit
$\Delta V_{isobaric,ex}$	difference in volume at the isobaric limit
$\Delta V_{st,glass}$	difference in volume due to the bending strength of the glass

4.3. Superposition of internal and external loads

In reality there is a combination of both load situations. For a further structural analysis the climatic loads have to be superposed with the external loads. It is possible to define four load cases, shown in figure 5, namely two for the climatic loads *a* (excess pressure) and *b* (depression) and two for the external loads *c* (pressure) and *d* (suction).

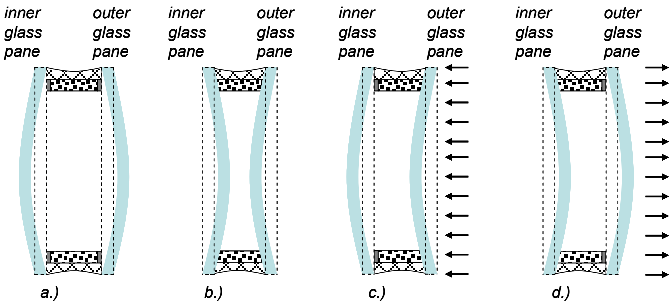

Figure 5: Superposition of internal and external loads.

For verifications of the inner and the outer glass panes the load cases can be superposed as shown in the following equations (6) and (7).

outer glass pane: $\Delta p_{eff} = \Delta p_{\text{int},cl} + \Delta p_{\text{int},ex} + \Delta p_{ex}$ (6)

inner glass pane: $\Delta p_{eff} = \Delta p_{\text{int},cl} + \Delta p_{\text{int},ex}$ (7)

5. Example

For the description of the behaviour of curved insulated glass and the influence of the edge sealing an example was analysed and documented. A glass with a length of b = 1000 mm and a height of h = 1000 mm was assumed. The thickness of both glass panes was defined with t = 6 mm. The bending radii R vary in four steps between a flat glass pane (R = ∞) as one limit and the radius of a semi-circle (R = 318 mm) as the other limit of the production (R = ∞, R = 2864 mm, R = 12374 mm, R = 636 mm, R = 318 mm). All the glass with the different radii have the same surface area. Figure 6 shows the main principle of the bending of glass in this example.

The example in this paper is focused on the variation of the most important displacement factor δ_z which describes the shortening or the enlargement of the distance between the glass panes. Due to the stiffness of the edge sealing it is possible to define a stiffness of the springs for a modelling of the supports of each glass pane. For all these glass panes with their different shapes the spring stiffness C_z was varied between $C_z = \infty$ (fixed) and C_z = 1.0 N/mm per mm edge length. These calculations were carried out according to the design concept described in chapter 4.

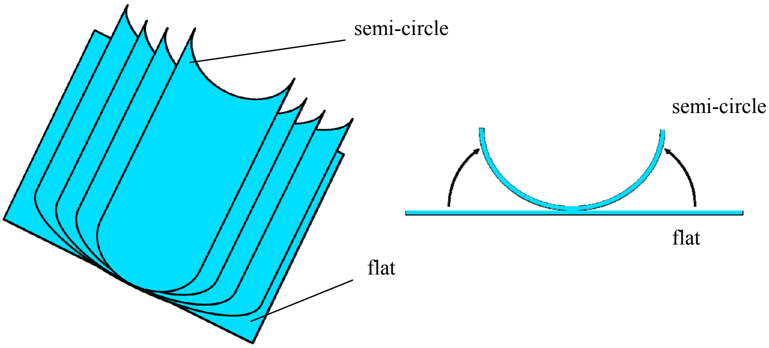

Figure 6: Concept of glass bending.

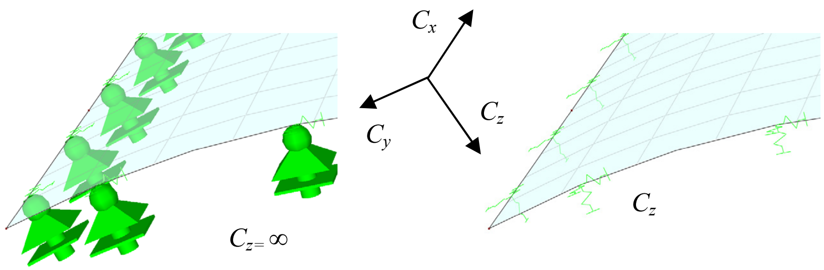

Figure 7: Displacements along the edge, R = ∞ (flat).

6. Results

The different shapes of glass with the variation of the spring stiffness were modelled with a finite element program.

6.1. Displacements along the edges

One result of the calculations is the displacement of each point along the edges of the glass pane. For the straight edges of the glass panes the results were documented. The results of the flat glass and the glass with a semi-circle shape were shown in figure 8 and 9. The middle of the glass edge is defined as the point of origin. The vector z gives the displacements δ_z in direction orthogonal to the surface.

Figure 8 shows the results for the flat glass. If a spring stiffness of 1.0 N/mm per mm edge length is used, in the middle of the glass edge the biggest displacement value of $\delta_z = 0.45\ mm$ resulted, as shown in figure 8. At the corners of the glass pane the calculation resulted in alternating (negative) deformations with $\delta_z = 0.26\ mm$.

The glass with a semi-circle shape is shown in figure 9. If a spring stiffness of 1.0 N/mm per mm edge length is used, the smallest deformations $\delta_z = 0.10\ mm$ resulted. In Comparison to the flat glass all displacement vectors δ_z have the same orientation. Depending on the shape of the glass pane and depending on the spring stiffness different deformations of the glass edges result.

Table 1 shows the results of the calculation of the displacements for the different glass shapes and the different spring stiffness.

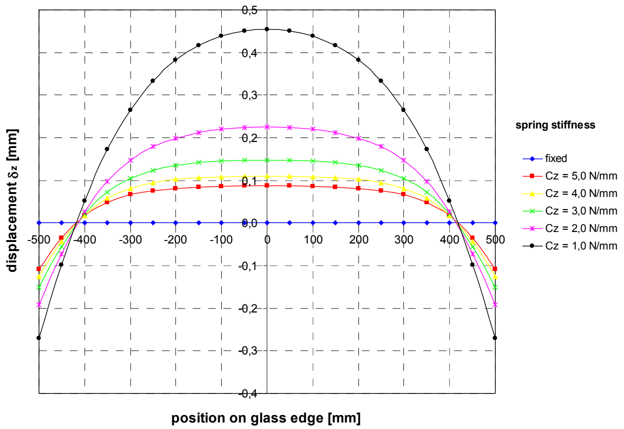

Figure 8: Displacements along the edge, R = ∞ (flat).

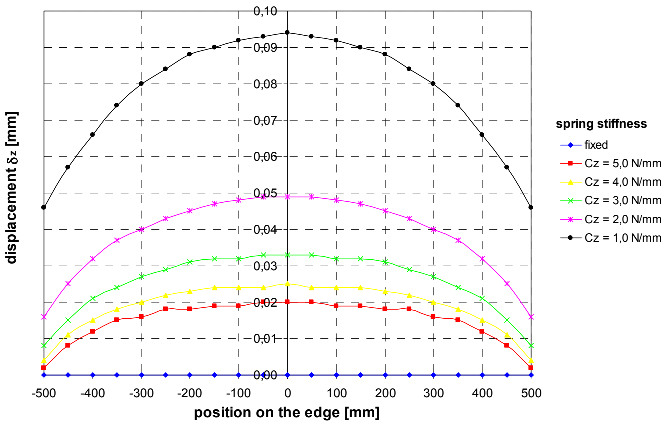

Figure 9: Displacements along the edge, R = 318 mm (semi-circle).

6.2. Effective inner pressure

Another result of the calculations is the effective inner pressure of the space between the glass panes. The results for the flat glass and the glass with a semi-circle shape were shown in figure 10 and 11.

Table 1: Displacements along the edges depending on the spring stiffness.

spring stiffness [N/mm]	R = ∞ (flat) [mm]	R = 2864 mm [mm]	R = 1237 mm [mm]	R = 636 mm [mm]	R = 318 mm [mm]
1	0.45	0.17	0.14	0.12	0.09
2	0.23	0.08	0.07	0.06	0.05
3	0.15	0.05	0.04	0.04	0.03
4	0.11	0.04	0.03	0.03	0.02
5	0.09	0.03	0.02	0.02	0.01
fixed	0.00	0.00	0.00	0.00	0.00

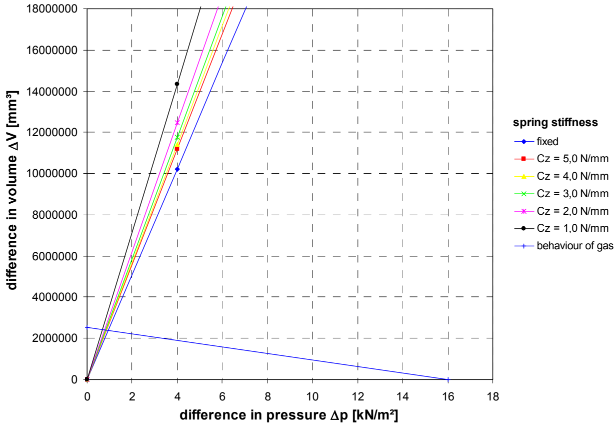

Figure 10: Effective inner pressure, R = ∞ (flat).

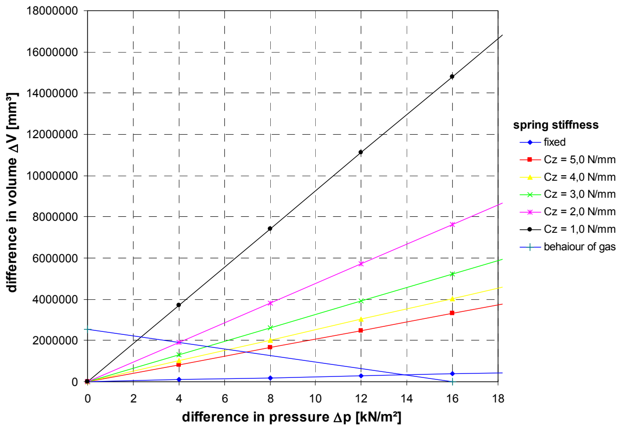

Figure 11: Effective inner pressure, R = 318 mm (semi-circle).

According to the before described design concept the different effective internal pressures Δp_{eff} were worked out. The flat glass with the less bending strength of the glass resulted in the lowest effective internal pressure. Figure 9 illustrate the results of the influence of the described variation of the spring stiffness for the flat glass. The results of the calculations with a value of the internal pressure of $\Delta p_{int} = 0.67\ kN/m^2$ up to $\Delta p_{int} = 0.93\ kN/m^2$ showed a small influence on the variation of the spring stiffness. In the case of glass with a semi-circle shape the results showed a big influence on the spring stiffness. The internal pressure varied between $\Delta p_{int} = 2.33\ kN/m^2$ for the weakest system of bearing-spring with a stiffness of 1.0 N/mm per mm edge length up to $\Delta p_{int} = 13.91\ kN/m^2$ for in direction z ($C_z = \infty$) fix supported glass.

Table 2 shows the whole results of the effective inner pressure for the different glass shapes and the variation of the spring stiffness.

Table 2: Effective inner pressure depending on the spring stiffness.

spring stiffness [N/mm]	R = ∞ (flat) [kN/m²]	R = 2864 mm [kN/m²]	R = 1237 mm [kN/m²]	R = 636 mm [kN/m²]	R = 318 mm [kN/m²]
1	0.67	1.77	2.19	2.31	2.33
2	0.77	2.47	3.46	3.84	3.98
3	0.81	2.87	4.31	4.94	5.21
4	0.84	3.12	4.92	5.77	6.17
5	0.85	3.29	5.38	6.42	6.94
fixed	0.93	4.33	8.66	11.76	13.91

7. Summary

The results of the analysis showed that depending on the stiffness of the sealing the whole system of glass and sealing became softer. Due to the internal pressure the glass panes are deformed. With a softening of the system, the difference in volume between the initial geometry and the deformed geometry increases. This increase in difference in volume resulted in a decrease in the effective internal pressure. The dimension of the influence on the results increases with a decrease of the bending radius.
With a finite element model of the glass pane and the accurate spring stiffness for the supporting system the insulated glass unit can be easily computed. The stresses in the glass can be analysed in accordance to the described design concept.

8. References

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