DEFORMATIONS IN THE GLUE LINE OF STRUCTURAL GLAZING ELEMENTS

VERFORMUNGEN IN DER KLEBEFUGE VON STRUCTURAL-GLAZING ELEMENTEN

DEFORMATIONS DES JOINTS DE COLLAGE DANS DES VITRAGES EXTERIEURS COLLES

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Summary
Silicon sealants are used in structural glazing elements as connection between the glass plate und the supporting frame. The silicone adhesive has to carry the loads acting on the glass plate such as dead weight, wind load or forces resulting from thermal expansion. Up until now the design of the glue line is performed using a simplified assumption on the load distribution in the glue line. It is the aim of the current investigation, to analyze the strain and stress state in the glue line more exactly. First results of finite element calculations and orientating test on a real structural glazing element show, that a multiaxial stress state exists in the glue line with sign changes of the displacements and forces along the edges of the plate.

Zusammenfassung
Silikonkleber bilden in Structural-Glazing Elementen die Verbindung zwischen der Glasscheibe und der Unterkonstruktion. Das Eigengewicht der Scheibe, die auf die Scheibe einwirkenden Kräfte sowie die thermischen Verformungen müssen von der Klebefuge aufgenommen werden. Die Bemessung erfolgt zur Zeit aufgrund einer sehr veinfachten Annahme über die Lastverteilung in der Fuge. Das Ziel der hier vorgenommenen Untersuchungen ist, den Verformungs- und Spannungszustand der Klebefuge genauer zu analysieren. Erste Ergebnisse von Finite-Elemente Berechnungen und orientierenden Versuchen zeigen, daß bei Belastung einer Glasplatte mit Windsog in der Klebefuge ein multaxialer Verformungs- und Spannungszustand mit Vorzeichenwechsel der Verformungen und Kräfte entlang des Plattenrandes entsteht.

Résumé
Dans les vitrages extérieurs collés la colle silicone constitue la connection entre le vitrage et la structure de support. Le joint de collage doit porter les charges qui agissent sur la vitre en tant que, p.ex. poids mort, charge due à la poussée du vent ou forces provenant de déformations

thermiques. Le calcul du joint de collage est basé sur une supposition très simplifiée de la répartition des charges dans le joint. Il est le but des investigations réalisées d'analyser plus exactement l'état de contraintes-déformations dans le joint de collage. Les premiers résultats des calculs d'éléments finis et essais d'orientation sur des vitrages extérieurs collés montrent qu'il existe un état contrainte-déformation multiaxial dans le joint de collage. Tandis que la tension domine dans le centre de la plaque, les coins sont soumis à des forces de pression.

Key words
Structural Glazing, silicone sealant, nonlinear glass plate, edge deformation, stress state

1. Introduction

The architecture of the last years shows an increasing use of glass facades as design features. The various possibilities to come to a typical design are highly appreciated. This method of construction is characterized by the use of prefabricated glass elements, that build the outer skin of a skeleton structure which appears as a continuous area only disturbed by small joints. All the beneficial properties of glass, for example transparency and reflection, now contribute to the design.

Neglecting some differences in detail the glass elements are composed of rigid aluminium frames with a single glass panel or an insulating glass unit glued by a silicone adhesive at the edge of the glass. This work is done only by experienced personel in a factory with adequate environmental conditions to assure a high quality. The elements are transported to the site and fixed to the structure. Finally the joints are filled with a weather sealing silicone [1],[2].

In order to fulfill the tasks of an outer skin the silicone adhesive has to carry the dead weight of the glass plates and all loads acting on the glass panel to the supporting structure. Additionally the movements caused by temperature have to be accommodated.

In the US this type of construction, which is called "Structural Glazing" has been used since 20 years. In Germany first steps toward a widespread use in civil engineering are underway. A lot of test series were carried out to check the load bearing behaviour and the durability against physical, chemical and biological influences in order to achieve an approval by the Institut für Bautechnik (IfBt).

Up until now the design of the structural silicone i.e. the determination of the width of the glue line is performed on the basis of a simplified assumption, that a uniform wind load causes trapezoidal distributed bearing forces along the glass edge [3]. This yields to a peak load of

$$q_1 = (b \cdot q_a)/2$$

(see fig.1), which is used for dimensioning the glue line with an allowable stress of $\sigma = 0.14$ N/mm²

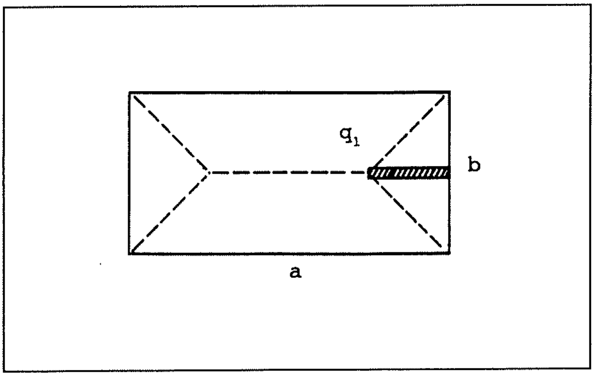

Fig.1 Trapezoidal distributed edge load q_1 due to uniform area load q_a - simplified assumption

This approach neglects

- the nonlinear distribution of the bearing forces along the edges with sign changes in the corner regions due to the plate bending behaviour,
- the finite width of the silicone and its capability to introduce bending moments into the glass plate and as a consequence the multiaxial stress state of the silicone,
- the deformations of the aluminium frame, on which the glass plate is glued and their effects on the stress distribution along the support line and
- the different mechanical properties of the silicones.

These shortcomings mean, that the safety level of the structural glazing elements can be predicted only with limitations.

In the literature some attempts are described to come to a more realistic approach [4],[5],[6]. The results based on finite difference calculations indicate the nonlinear distribution of the seal forces but some simplifying asumptions are still introduced, i.e. the structural seal has been modeled by elastic springs.

This was the initial situation, when the FMPA started a research project sponsored by the IfBT to investigate the stress state in the glue line of a structural glazing element by tests on full-scale elements and finite element calculations. The following parameters are to be taken into account:

- aspect ratio of the glass panel
- scale factor
- height and width of the glue line
- thickness of the glass
- rigidity of the supporting frame
- stress-strain characteristic of the silicone.

The research is still going on. In the following some preliminary results are reported.

2. The nonlinear problem of thin glass plates

The deflection behaviour of a thin glass plate is described by the von Karman nonlinear equations [7], where the nonlinearity makes allowance of the appearance of membrane forces at high pressure loads. The structural seal provides an deformable elastic support, in general with a nonlinear load-deflection characteristic.

Thus the structural glazing unit is a complex mechanical system, and some simplifying assumptions are suitable for a first contemplation. Neglecting the influence of the seal it is considered a glass plate bedded on a rigid frame. The out-of-plane displacements of the edges are assumed to be zero, while the in-plane displacements are not restrained.

In the case of small deflections the von Karman equations simplifiy to the linear plate equation, which can be solved analytically. Fig.2 gives the maximum nondimensional deflection $w^*=w/h$ at the centre of a quadratic plate versus the nondimensional load $q^*=(q\cdot a^4)/(E\cdot h^4)$ obtained from the analytic solution, where w, h, a, E, and q are the out-of-plane displacement, the plate thickness, the edge length, the Young's modulus and the pressure load.

The finite element technique was applied to the nonlinear problem considering geometric nonlinearity by an iterative process. The model used here was a plate with the dimensions $2000\cdot 2000\cdot 10\text{mm}^3$ and $E=7\cdot 10^{+4}\text{N/mm}^2$. Structural 3-dimensional elements with 8 nodes were choosen. It has to be taken into account that the results of the finite element computation are affected both by the grid size and the number of iterations. The results converge as the number of elements and the number of iterations increase (fig.2 and fig.3). It can be seen that for pressure values smaller than $2 \cdot 10^{-3} N/mm^2$ ($q^*<50$) nonlinear effects are not important.

The in-plane displacements and the boundary reaction forces in the normal direction along the edge of a quarter plate are given in fig.4 and fig.5 for (a) small ($q^*=23$) and (b) high ($q^*=460$) pressure load, characterizing the cases of the linear and the nonlinear response of the glass plate. The edge coordinate scales from 0 at the centre to 1 at the corner of the edge. It can be seen, that large inplane displacements occure at the centre of the edge and that the deflections increase nonlinearly with increasing load in particular at the corner regions.

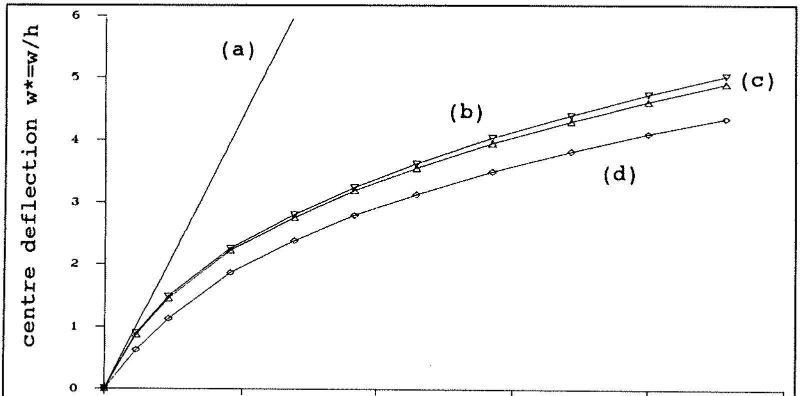

Fig.2 Centre deflection of a quadratic glass plate;
(a) linear solution, (b) 25 elements
(c) 100 elements, (d) 400 elements

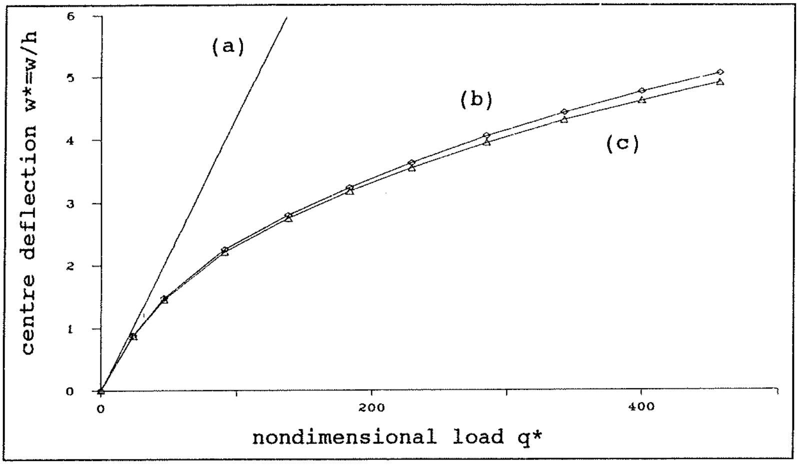

Fig.3 Centre deflection of a quadratic glass plate; influence of the number of iterations
(a) linear solution
(b) 5 iterations, (c) 20 iterations

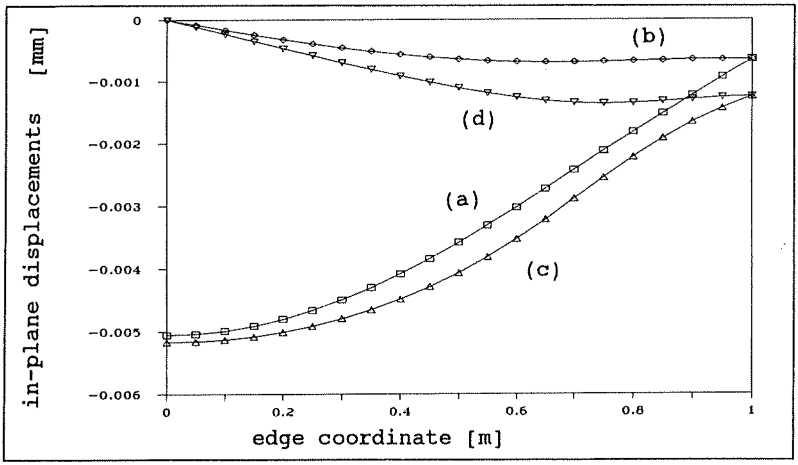

Fig.4 In-plane displacements u_x/q^*, u_y/q^* along the edge of a quadratic plate;
(a) u_x ($q^*=23$), (b) u_y ($q^*=23$)
(c) u_x ($q^*=460$), (d) u_y ($q^*=460$)

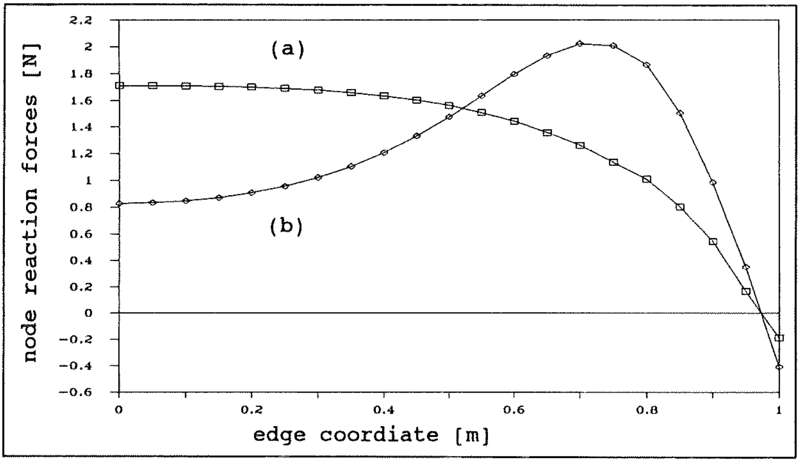

Fig.5 Node reaction forces F_z/q^* in normal direction along the edge of a quadratic plate; (a) F_z ($q^*=23$) (b) F_z ($q^*=460$)

While in the linear case the node reaction force at the edge continuously increases from the center to the corner, in the nonlinear case it takes an extremal value close to the corner and shows a significant change in sign. The value of the node reaction forces at the corner was determined from a linear extrapolation, because the value at this critical point is not given correctly due to the discretisation in the finite element calculation.

3. The deformation of the glue line

In the following it is assumed, that a glass plate is supported on four edges by a low modulus elastic sealant ($E=5N/mm^2$) with linear stress-strain characteristic. The glue line with the dimensions 10mm·10mm is assumed to be fixed to a stiff mullion. The linear response of the plate and the deformation of the glue line due to lateral pressure was calculated using the finite element model showed in fig.6.

The calculated out-of-plane and in-plane displacements at the inner and outer edge of the contact surface between the glass plate and the sealant are given in fig.7 and fig.8.

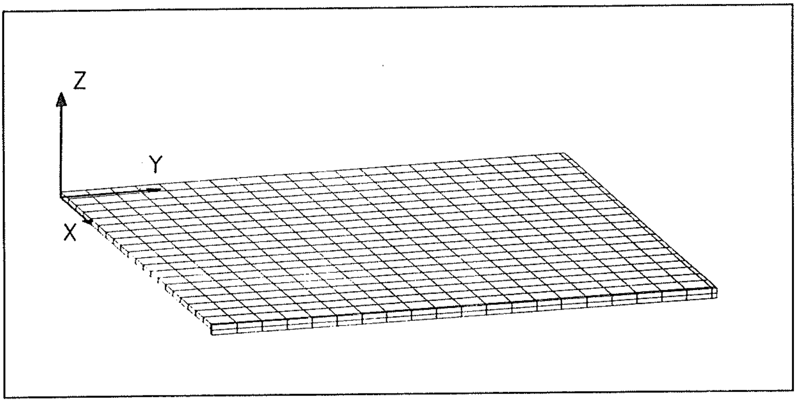

Fig.6 Finite element model of a quarter plate elastically supported along the edges

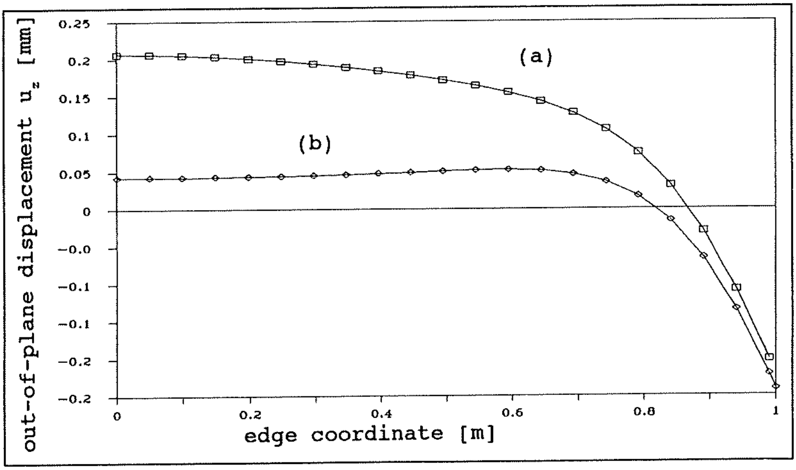

Fig.7 Out-of-plane displacements u_z at the edge of the the contact surface between the glass plate and the sealant
(a) u_z (inner edge), (b) u_z (outer edge)

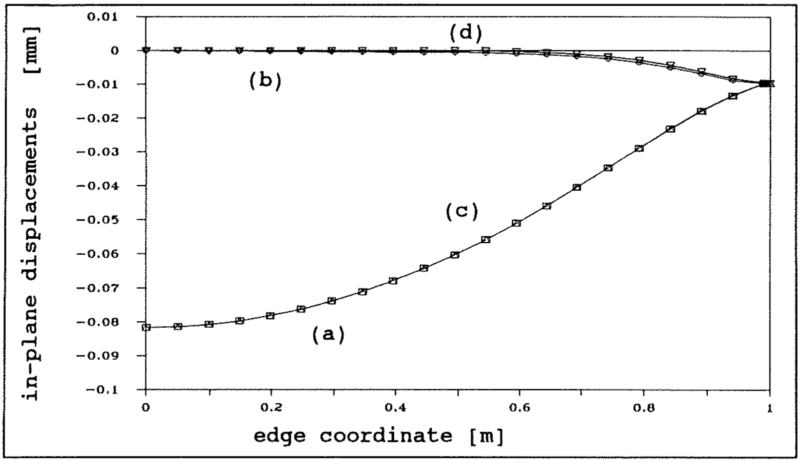

Fig.8 In-plane displacements u_x, u_y at the edge of the the contact surface between the glass plate and the sealant
(a) u_x (inner edge), (b) u_y (inner edge)
(c) u_x (outer edge), (d) u_y (outer edge)

As a result of lateral pressure a nonuniform multiaxial stress state with components of tension, pressure, torsion and shear exists in the glue line. Two regions with high stresses are located at the centre of the edge and at the corner. Large positive out-of-plane displacements just as negative negative in-plane displacements at the centre of the edge lead to a stress state dominated by tension and bending forces. In contrast to this the out-of-plane displacements at the the corner have a negative sign, while the inplane displacements are less important. Therefore the corner is the point of maximum pressure force in the glue line.

These preliminary results of the finite element calculations give an overview of the deformation behaviour of the glass plate and the glue line as a result of uniform wind suction. Further computations will be done to determine quantitatively the influence of the above-mentioned parameters.

4. Tests

Two tests on a real structural glazing element were performed to demonstrate the deformations of the silicone along the glass edge and to validate qualitatively the above calculations.

4.1 Test set-up

In both tests performed in the laboratory a structural glazing element with the dimensions 2250mm·1630mm comprising an insulating glass unit was used. Fig.9 shows a cross-section of the edge region of the element.

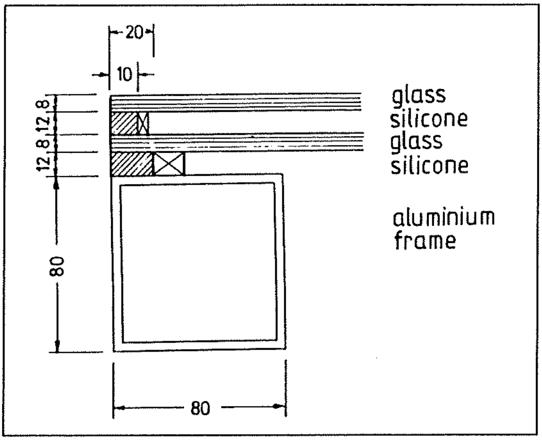

Fig.9 Cross-section of the tested structural glazing element

In the first part of the test four fixing points, located in the element corners were provided. In the second test six fixing points were added, two on each long edge and one on the short edges to simulate rigid support conditions.

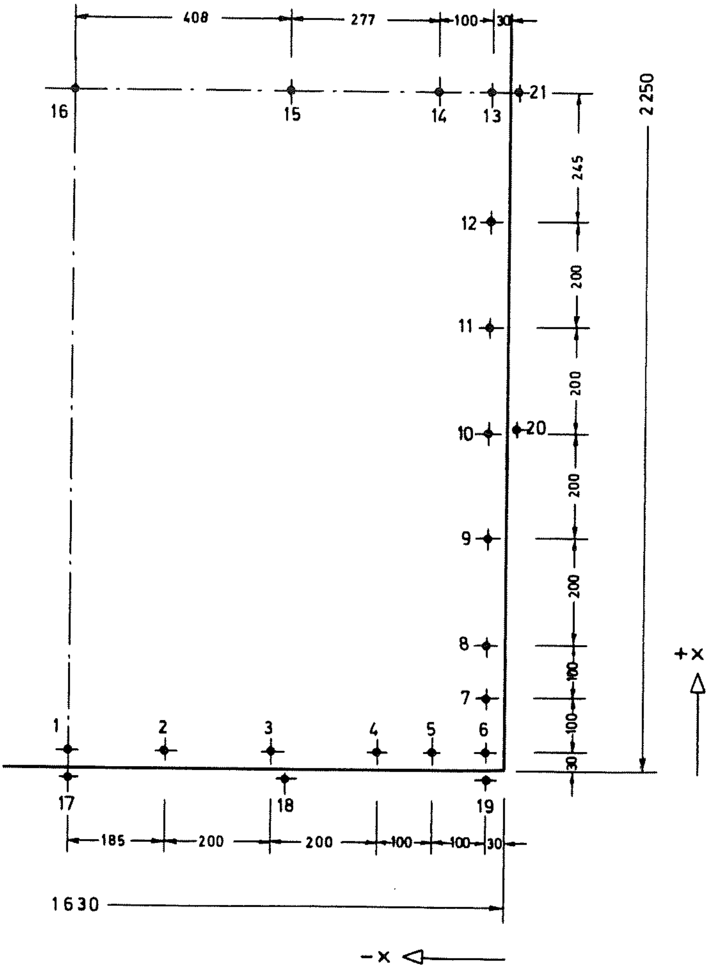

Fig.10 Location of the displacement transducers along the edges of a quater panel

A series of displacement transducers was arranged along the edge of a quater area of the glass plate and the short symmetry line. Additionally some transducers were used to measure the deflections of the aluminium frame (fig.10) A photograph of the test set-up is given in fig.11. The glass plate was loaded by rubber air bags to simulate uniformly distributed wind suction. The tests were performed in load steps of $0.4 kN/m^2$. The readings of the transducers were recorded by a data acquisition system.

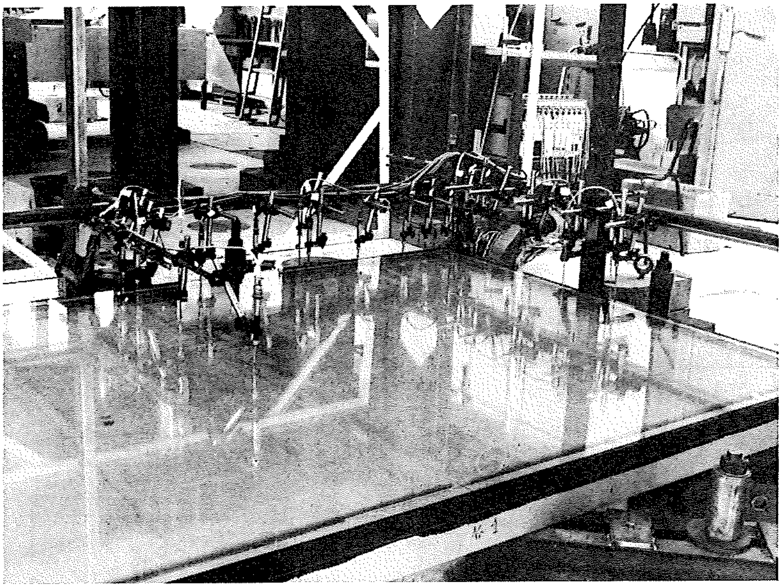

Fig.11 Test set-up

4.2 Test results

The plots in fig.12 and fig.13 show the deformation of the glass edges (continuous line) and the supporting frame (dashed line) indicating sign changes in the corner regions.

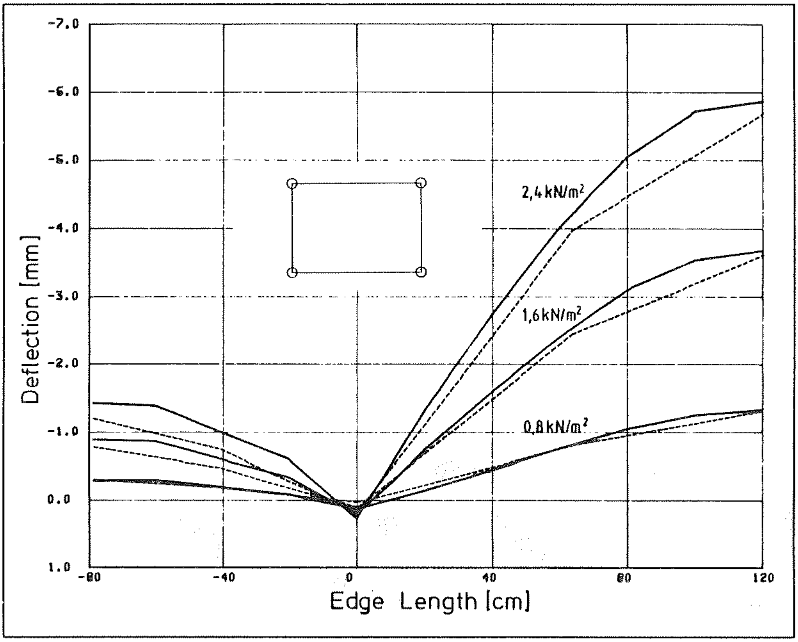

Fig.12 Deflections of the edges due to uniformly distributed loads in test no.1

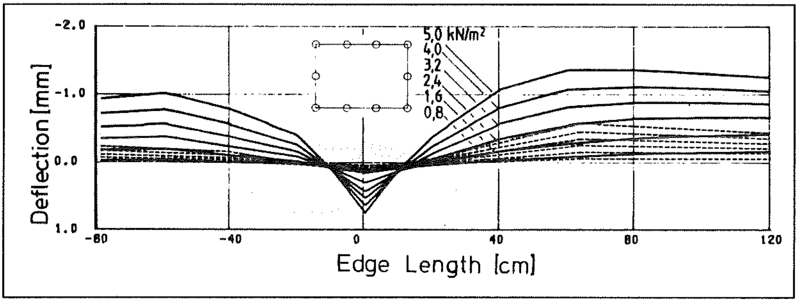

Fig.13 Deflections of the edges due to uniformly distributed loads in test no.2

The influence of the arrangement of fixing points i.e. the rigidity of the supporting frame is demonstrated by a significant increase of the global edge deflections in the four point support test. With increasing rigidity of the frame the glue line deformations and as a consequence the stresses in the silicone increase.

5. Conclusions

Some preliminary results of the current research on the deformation of the glue line in a structural glazing element due to wind load indicate, that

- the distribution of the edge forces shows sign changes close to the corners
- the glue line is in a multiaxial stress state
- the deformations of the glue line increase with increasing rigidity of the supporting frame

As consequence the safe design of the glue line on the basis of a simplified assumption is doubtful for all cases.

6. References

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