STRESS DISTRIBUTION IN HEAT-TOUGHENED GLASS

SPANNUNGSVERTEILUNG IN VORGESPANNTEM GLAS

DISTRIBUTION DES CONTRAINTES DANS LE VERRE TREMPE

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SUMMARY

In the last two decades an increasing use of glass and particularly heat-toughened glass in civil engineering has been witnessed. Actually there is the tendency to attach large-scale glass panes to the supporting structure by spot fixations. The structural analysis of glass panes with more than two spot fixations along the edge often yields maximum hoop stresses at the glass bore hole, which are relevant for the dimensioning of the glass thickness. But there is scarce knowledge on the state of stress of heat-toughened glass around a bore hole. In these cases, full-scale tests or detail tests are used to calibrate the calculations. In the following, a model is proposed to calculate the stress distribution on the basis of the temperature distribution at the transition from the viscous to the elastic material behaviour during the prestressing process. The procedure leads to a stress distribution which may be adapted to test results and can be used to investigate further topics.

ZUSAMMENFASSUNG

In den letzten beiden Jahrzehnten konnte eine stetige Zunahme der Verwendung von Glas und insbesondere von vorgespanntem Glas im Bauwesen festgestellt werden. Dabei ist neuerdings der Trend zu beobachten, daß die Befestigung großflächiger Glasscheiben mit punktförmigen Halterungen an Bedeutung zugenommen hat. Die statische Berechnung rechteckiger Glasscheiben mit mehr als zwei Halterungen entlang der Glaskante ergibt oft maximale Ringzugspannungen an den Durchgangsbohrungen im Glas. Da über den Spannungszustand im Glas in diesem Bereich noch sehr wenige Kenntnisse vorliegen, wird eine Dimensionierung schwierig. Man behilft sich in diesen Fällen, indem auf

Versuchsergebnisse aus Bauteil- oder Detailversuchen zurückgegriffen wird und die Rechenergebnisse entsprechend kalibriert werden. Nachfolgend wird ein Modell vorgeschlagen, das zu einer Spannungsverteilung aufgrund einer Temperaturverteilung im Glas zum Zeitpunkt des Übergangs vom viskosen zum elastischen Zustand während des Vorspannprozesses führt. Damit läßt sich eine Spannungsverteilung angeben, die leicht an Versuchsergebnisse angepaßt und für die Untersuchung weiterer Fragestellungen verwendet werden kann.

RESUME

Au courant des deux dernières décennies, on a constaté une utilisation croissante du verre et particulièrement du verre trempé dans le domaine du génie civil. Récemment on a pu observer la tendance à fixer des vitres de grandes dimensions à la structure portante par des fixations ponctuelles. Le calcul de résistance des vitres rectangulaires avec plus de deux fixations ponctuelles sur le bord fournit souvent des contraintes de traction annulaires maximales à proximité du trou fraisé dans la vitre. Le dimensionnement est difficile parce qu'il n'y a que peu de connaissances sur l'état des contraintes dans le verre à proximité du perçage. Dans ces cas, on a recours à des résultats d'essais pour calibrer les calculs. Dans la présente, un modèle est proposé, qui mène à une distribution des contraintes sur la base de la distribution de la température dans le verre au moment de la transition de l'état visqueux à l'état élastique pendant la trempe thermique. Il devient alors possible de calculer la distribution des contraintes, qui peut facilement être adaptée aux résultats des essais et utilisée pour d'autres investigations.

KEYWORDS

Glass construction, glass facade, glass pane, spot fixation, temperature distribution, prestress, finite element analysis.

1 INTRODUCTION

Glass has a theoretical strength of 10,000 N/mm² when pure silica glass is considered and 7,000 N/mm² for soda-lime-silica-glass, if the chemical bond forces are considered only [1]. Due to the excessive notch sensitivity, a real glass pane reaches a flexural strength of approximately 45 N/mm² [2]. The strength depends on the duration of the loading and the environmental conditions, and may be significantly lower. Strictly speaking, a strength for glass doesn't exist, but an arbitrary distribution of notches. Together with the loading, which as a rule is non-uniformly distributed, there is a location where a critical state is reached and failure will occur.

Heat-toughened glass panes are manufactured by heating beyond the weakening temperature and cooling down (quenching), which yields a prestressed state with compressive stresses at the surface and tensile stresses in the inner region. If the glass pane is subjected to a bending moment, first the prestress is equalized. Increasing the load will activate the intrinsic strength of the glass until failure. As a consequence, heat-toughened glass seems to have a higher strength.

In facade construction, there is a growing use of heat-toughened glass. In structural glazing constructions, the glass panes are glued on an aluminium frame along the edges. At present, architects give a particular preference to the use of single (spot) fixations to attach glass panes to the supporting structure. The fixations are inserted in bore holes with a conical shape. If a uniformly distributed load is acts on a rectangular glass pane with spot fixations in the corners, the stresses in the glass around the spot support are rather low and the critical stress is reached at midspan. The prestress state of the glass is well known and dimensioning is simple. If there are more than two supports along the edge, the maximum stresses (hoop stresses) occur in most cases at the middle fixation. The prestress state around the bore hole is not known and dimensioning is difficult. Up to now, dimensioning of those glass panes is performed on the basis of full-scale tests or detail tests and finite element calculation. The finite element model is calibrated by the detail tests. The same element mesh is then used to analyse the glass panes used on the site. In the following, a description of a simple model is given to simulate the state of stress of heat-toughened glass.

2 GENERAL IDEA

In [3], details are given on the temperature and stresses during the toughening process (fig. 1). In the initial state at time t = 0, the glass has a uniform temperature T_c beyond the weakening point. There are no stresses in the glass. When cooling down starts, low stresses develop at the surface, tensile stresses at first and compressive stresses afterwards. At the transition from viscous to elastic material behaviour (time t_2), low stresses have developed which increase with progressive cooling down. At time t = ∞ the glass has reached the final stress state and again has a uniform temperature.

3 ASSUMPTIONS

For the further consideration and for the sake of simplicity, it is assumed that at time t = t_2 there are no stresses in the glass.

$$\sigma(x,t_2) = 0 \tag{1}$$

The temperature difference between the central area (x = 0) and the surface (x = d/2) is

$$\Delta T = \Delta T_0 \tag{2}$$

Only temperature differences are taken into account because they contribute to the occurrence of stresses.

The distribution of the temperature differences is expressed by a quadratic parabola.

$$\Delta T = \Delta T_0\left(1-\left(\frac{x}{d/2}\right)^2\right) \tag{3}$$

As a consequence the temperature difference of an arbitrary point of the glass depends only on the edge distance.

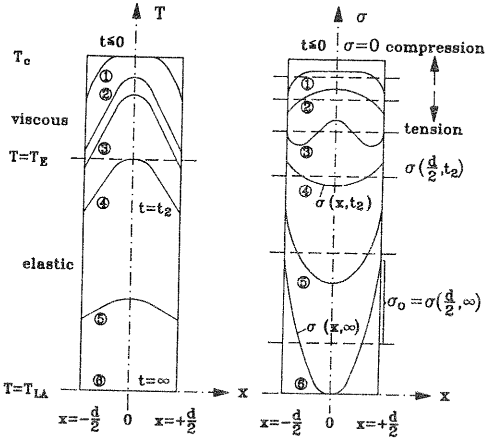

Fig. 1: Temperature and stress distribution in a glass pane during the thermal prestress process [3]

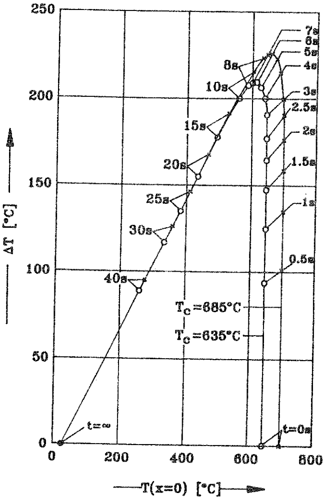

Fig. 2: Temperature difference between the central area and the surface area vs. temperature of the surface area [3]

4 APPLICATION

The general idea and the assumptions are introduced into a finite-element-analysis used to investigate the prestress state in the surroundings of a spot fixation in a glass pane with a thickness of 10 mm. The bore hole has a diameter of 30 mm in the cylindrical part, which increases up to 40 mm with an angle 45° in the conical part. The extension in x-direction is 300 mm.

The finite element model has rotational symmetry. The axis of revolution coincides with the axis of the bore hole. The x-y-plane is represented by the drawing plane. Hoop stresses have the direction perpendicular to the drawing plane (z-direction).

The element mesh consists of square elements with an edge length of $l = 0.5$ mm. At the edge of the conical part of the bore hole, triangular elements are inserted. Applicating equation (3), every node is assigned a temperature difference according to its edge distance. The maximum temperature difference is read from fig. 2 and $\Delta T_0 = 225$ K is assumed.

The following material properties are introduced into the analysis:

modulus of elasticity	$E = 70\,000$ N/mm^2
poisson´s ratio	$\mu = 0.23$
coefficient of thermal expansion	$\alpha_T = 0.000008$/K

5 RESULTS OF CALCULATION

Fig. 3 shows the vector plot of the principal stresses due to thermal loading only. Along the glass edge there are always compressive stresses. They cause diversion stresses in the surroundings of the transition from the flat glass surface to the bore hole. At some distance from the bore hole, there is a

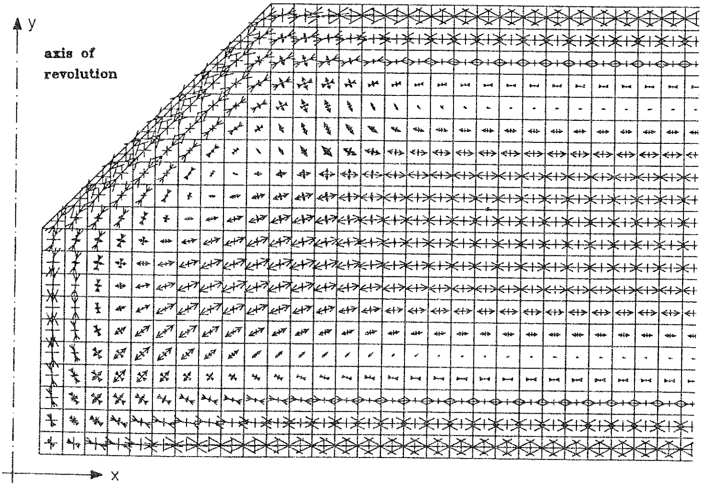

Fig. 3: Principal stresses in the drawing plane

constant stress distribution, comprising a compression zone at each glass surface with a depth of nearly 0.2d (d: depth of the glass pane). The remaining part of the glass section is the tensile zone.

The hoop stresses (z-direction) are shown in fig. 4. At the glass surfaces there are compressive stresses as well.

The finite element analysis provides the following peak stresses:

- flat glass surface area at a distance from the bore hole

$$\sigma_3 = \sigma_x = -109\ \mathrm{N/mm^2}$$
$$\sigma z \quad = -109\ \mathrm{N/mm^2}$$

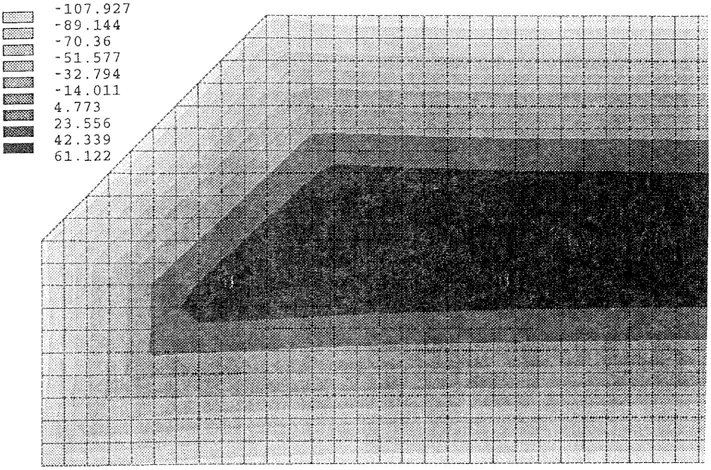

Fig. 4: Hoop stresses

- central area at a distance from the bore hole

$$\sigma_1 = \sigma_x = 55\ \mathrm{N/mm^2}$$
$$\sigma_z = 55\ \mathrm{N/mm^2}$$

- hoop stresses at the transition from the flat glass surface to the cylindrical part of the bore hole

$$\sigma_z = 87\ \mathrm{N/mm^2}$$

The calculation indicates that the hoop prestress around the bore hole is 20% lower than the prestress in the glass surface in the undisturbed area.

The calculated stresses are linearly related to the maximum temperature difference ΔT_0. As a consequence, the finite element model may be adjusted to a given prestress at the surface by converting the maximum temperature difference ΔTo in equation (3) into a variable:

$$\Delta T_0(\sigma_g) = \frac{225 \cdot \sigma_g}{109} \tag{4}$$

Equation (3) may be rewritten

$$\Delta T = \frac{225 \cdot \sigma_g}{109}\left(1 - \left(\frac{x}{d/2}\right)^2\right) \tag{5}$$

These temperature differences are now assigned to every node in the finite element model in order to get a prestress state with the surface prestress σ_g.

6 CONCLUSIONS

The distribution of prestress in heat-toughened glass around a bore hole is not known.

The prestress in this region is very important for the dimensioning of rectangular glass panes with more than two spot fixations along the edge.

A model for the calculation of the prestress is proposed. It is derived from the assumed temperature distribution during the prestress process, which,for every node of a finite element model, yields temperature differences depending on the edge distance only.

Temperature differences suitable to be introduced into the finite element model may be calculated in order to get a definite amount of prestress.

The finite element model may be used for further investigations, for example the calculation the carrying capacity of a spot fixation.

The main model parameter (amount and distribution of temperature differences) may be adjusted in order to correlate the computed values with test results. But up to now, suitable test results are not available.

7 REFERENCES

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