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Drilling in tempered glass – modelling and experiments

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Abstract

The present paper reports experimentally and numerically obtained results for the process of drilling in tempered glass. The experimental results are drilling depths on the edge in 19mm tempered glass with a known residual stress state measured by a scattered light polariscope.

The experiments have been modelled using a state-of-the-art model and compared with satisfying result to the performed experiments.

The numerical model has been used for a parametric study, investigating the redistribution of residual stresses during the process of drilling. This is done for investigating the possibility of applying forces in such holes and thereby being able to mechanically assemble tempered glass without the need of drilling holes before the tempering process.

The paper is the result of currently ongoing research and the results should be treated as so.

Keywords: Drilling, Tempered Glass, FE-simulation, Residual stresses, Joints, Connections.

1 Introduction

The main purpose of tempering glass is obviously to increase the apparent strength. However, all geometric features such as holes for assemble etc. have to be made before the tempering process,... or do they?

There is often a need to mechanically assemble tempered glass or attach brackets to it. This indicates that drilling and/or cutting the glass before the tempering is necessary, leading to inaccurate placement of holes etc. and, in certain cases, geometries which are difficult or impossible to fully temper without failure during the tempering process.

The ongoing research investigates the possibility to partially drill in tempered glass in order to mechanically attach brackets or assemble tempered glass parts without the need for pre

drilling of the glass. A principal sketch showing a possible attachment of a bracket is given in Figure 1.

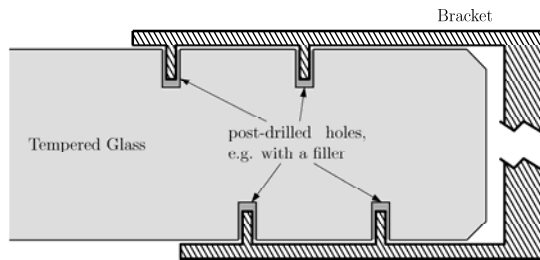


Figure 1 - Principal sketch for a possible way to attach a bracket to tempered glass with post drilled holes

2 Experimental work

Six square specimens with a side length of 300mm and a thickness of 19mm were investigated. Before the drilling, the residual stress was measured in nine different points on each specimen in two orthogonal directions, see Nielsen, et.al. [1], the average values of the measured residual stresses are given in Table 1. The residual stresses were measured using a scattered light polariscope (SCALP-04) which is described by Anton & Aben in [2]. The drilling of the specimens was done with a small diamond drill ($\varnothing 2.5$ mm) on the edge of the specimen, see Figure 2.

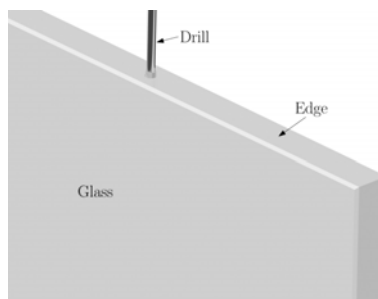


Figure 2 - Drilling at the edge with a 2.5 mm diamond drill

The drilling depth was measured during the process by mounting a displacement transducer on the drilling machine. The drilling was done in wet conditions, ensuring a proper cooling of the drill and removal of drill dust. The drilling depth at which the tempered glass specimen broke is reported in Table 1. The fragmentation process was recorded by high-speed cameras showing the development, however, that is outside the scope of this paper and instead references to Nielsen et. al. [3] are made.

Table 1 - Experimental results. Residual stresses are average values from 9 measurement points on each specimen. The drill depth is the depth at fracture.

Specimen	Thickness [mm]	Res. Stress. [MPa]	Drill depth [mm]
A1	19	-69.3	4.70
A2	19	-69.3	4.30
A3	19	-67.9	4.54
A4	19	-66.4	4.20
A5	19	-69.3	5.15
A6	19	-68.0	4.29
Mean:		-68.4	4.53

3 Numerical model for the drilling in tempered glass

Due to the lack of method for measuring the residual stress state at the edge of a hole and during the process of drilling, FE modelling is used for investigating the residual stress state influenced by removal of material, e.g. drilling.

This is done in two steps; first the residual stresses are modelled and then elements corresponding to the borehole in the model are removed successively.

The first step (the modelling of the residual stresses) is based on a model described thoroughly in [4], however, a schematic view of the model is given in Figure 3.

From the Figure 3 it is seen that modelling the temperature history is the driving force for the tempering. The structural relaxation, as described by Narayanaswamy in [5] is, provided the temperature, altering the thermal expansion coefficients (volume relaxation) used for calculating the thermal strains. At high temperatures the stress strain response is governed by a viscoelastic constitutive law. The viscoelasticity is treated as a thermorheologically simple¹ material in order to take the temperature into account. This leads to the stress state in the glass at a given time during the tempering process.

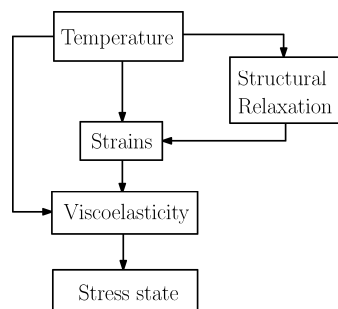


Figure 3 - Schematic view of modelling the tempering process.

¹ simple change of the time-scale according to the temperature

The process of drilling is modelled by successively removing one layer of elements and requiring equilibrium to be fulfilled in each step. Heat generated by the process of drilling is neglected; assuming that cooling water keeps the raise in temperature to a minimum, furthermore, the flaws introduced by the drill in the hole is disregarded.

3.1 Numerical model for comparison with experimental work

As seen in Figure 2 and Figure 4, the drilling was done on the edge of the specimens. For modelling this, a 3D solid model was needed. Symmetry was utilized in such manner that only 1/4 of the borehole was modelled. The model size was reduced further by applying constant displacement boundary conditions to one of the faces and symmetry on others; see Figure 4. It is therefore assuming that the size of the specimens in these directions was without influence on the results. The elements used were 20-node 3D brick elements with second order displacements fields and a corresponding first order temperature field. The analysis was carried out using ABAQUS along with a user subroutine for the tempering of the glass as described in Nielsen et.al. [4].

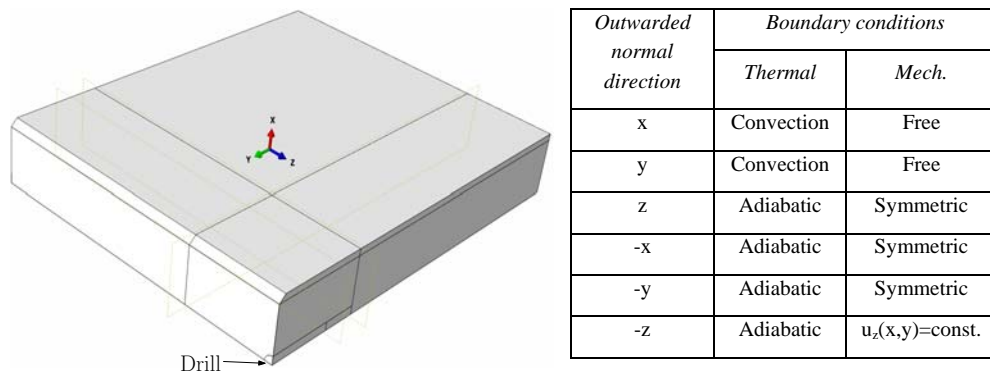


Figure 4 - Geometry and boundary conditions for the model of the experiments.

Figure 5 shows the distribution of the maximum principal stress at the bottom of the drilled hole. Different curves are given for different drill depths, d . From Table 1 the average drilling depth at failure for the experiments was $d=4.5\text{mm}$, and comparing this to the graph, it is seen that the maximum principal stress for this drilling depth is around 44 MPa, which is comparable to the tensile strength of glass.

Figure 5 - Max. principal stress at the bottom of the hole along the edge. Curves are given for different drilling depths, d .

4 Parametric investigation

In order to investigate some general tendencies of the stress state when drilling in tempered glass, a large plate with drilling in the center, far from the edges, were considered. Different diameters of the drills were investigated for different borehole depths, d .

4.1 Numerical model

An axis-symmetric model was used for this investigation. Only half the thickness of the glass was modelled, which indicates that drilling takes place from both sides of the specimen at the same time. It might be that only drilling from one side is preferable, however, this is not investigated here.

The geometry of the used model is shown in Figure 6. The axis of rotation is intersecting with the left vertical edge. The top surface (y axis as out warded normal) is subjected to a thermal convection boundary condition while all other surfaces are adiabatic. The bottom surface is modelled with a mechanical symmetry condition and on the right vertical surface; all displacements in the x -direction are constant. The drilling is taking place along the axis of rotation.

The compressive residual surface stresses (before drilling) are -102 MPa.

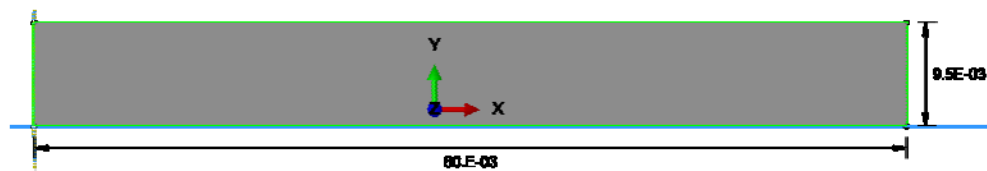


Figure 6 - Geometry of axis-symmetric model. All measures are in meters.

This section investigates the tangential stress at the top of a hole, point “*top*”, and at the bottom of the hole, point “*bot*”, as indicated on Figure 7.

The model uses axis-symmetric 8 node elements with second order displacement field and first order temperature field.

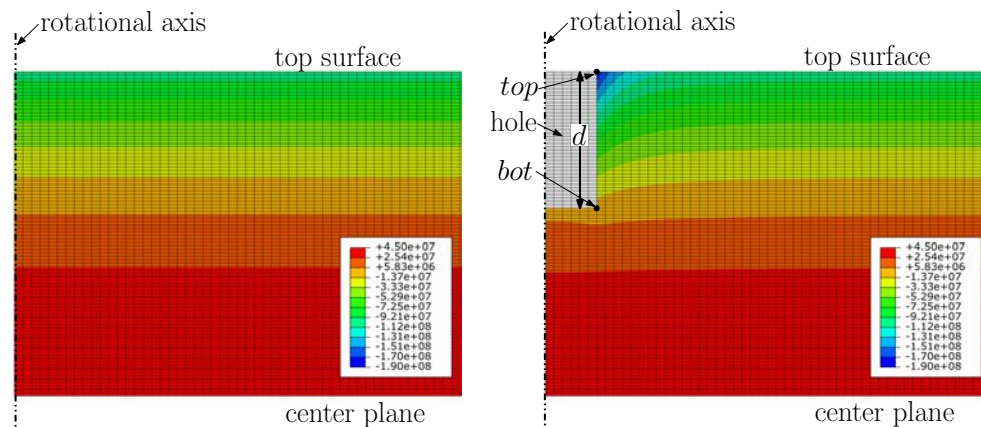


Figure 7 – Axis-symmetric model. Left: initial residual stress state (-102MPa compressive stress at the top surface). Right: Residual stress state after drilling with $\phi 3\text{mm}$ drill to a depth, $d=4\text{mm}$.

4.2 Results and discussion of the investigation

The results from the analysis is shown in Figure 8 and Figure 9, where the tangential stress at the bottom of the hole and the top of the hole is plotted against the borehole depth, d , respectively.

From Figure 8 it is seen that the depth, d , in the glass where tension is reached is actually increased by the drilling and drill size compared to the residual stress state before drilling. This indicates that one might be capable of drilling into the original tensile zone, without failure due to the redistribution of the stresses.

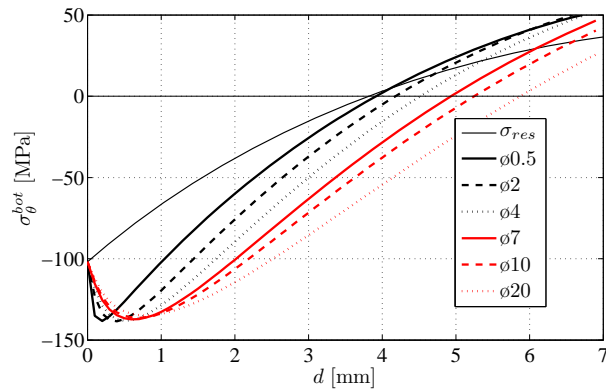


Figure 8 – The stress at the bottom of the borehole as a function of the drilling depth, d , for different size drills.

In order to utilize this technique for joints, the residual compressive tangential stress at the borehole boundary is needed, in particular at the top surface. From Figure 9 it is seen that extra compressive stresses are gained relatively fast, even for small borehole depths. The effect is seen to be most pronounced for small size drills, where the compressive stresses can be doubled, whereas for larger drills the effect is somewhat smaller.

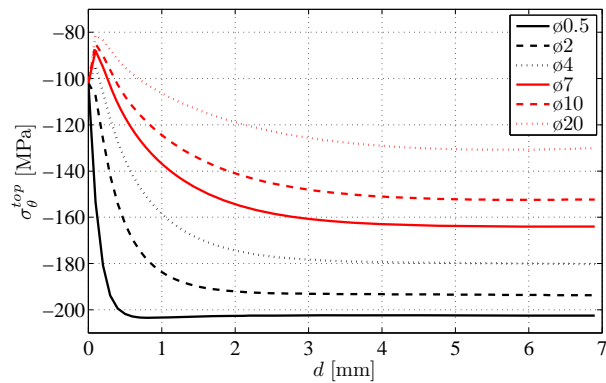


Figure 9 - The stress at the top of the borehole as a function of the drilling depth, d , for different size drills.

This investigation indicates that partly drilled holes in tempered glass are possible and might even be used transferring small forces. Due to the local increase in compressive stresses at the top of the borehole for small depths, d , it is suggested that a design of such a joint might be consisting of several small holes using small pins for transferring shear loads.

5 Conclusion

The present paper utilizes a model capable of determine the residual stresses in tempered glass and estimating the redistribution in stresses during drilling of the tempered glass. The model is valid until initial failure of the tempered glass, where other processes are governing the fragmentation of the tempered glass.

The model is compared with experiments where the borehole depth at failure was recorded. Good agreement between experiments and model is seen.

The model was used for studying the effect of drilling in the centre of a large plate far from the edges. It was shown that the depth where the tensile zone starts where increased when drilling. It was also observed that this effect was more pronounced using large drills compared to small ones.

It was also observed that the residual tangential stress at the surface around the borehole was increased considerably with up to 100% for small drills. This effect was obtained at relatively small borehole depths, compared to the depth of the compressive zone.

All in all it is concluded that drilling in tempered glass is possible, if the borehole depth is not too deep. Even at such small borehole depths, a beneficial redistribution of stress seems to occur around the borehole, indicating that this principle could be useful for transferring forces.

6 Litterature

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