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Joints in Tempered Glass Using Glass Dowel Discs

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Abstract

One of the major reasons for using glass in structures is its transparency; however, traditional mechanical joints such as friction joints and steel dowel pinned connections are compromising the transparency. The present paper describes a novel joint which is practically maintaining the complete transparency of the glass. This is achieved by using a dowel disc made entirely of tempered glass. The concept of the joint is proved by pilot tests and numerical models. From the work it is seen that the load-carrying capacity of such a connection is similar to what is found for traditionally in-plane loaded steel dowel pinned joints.

Keywords: Tempered Glass, Bolted Joints.

1 Introduction

One of the major advantages of glass is its transparency and architects are often using glass for creating structures with plenty of daylight and a simple appearance. Therefore, glass has been investigated for structural load-carrying purposes for the last couple of decades. One of the major issues in designing with glass is to transfer loads through joints. The most common ways to assembly glass is to use either adhesive joints or bolted joints. The adhesive joints lack from the uncertainties in the behavior of the adhesive exposed to long-term loading, U.V. radiation etc. The bolted joints are carried out using steel pins and inserts in order avoid the steel-glass contact and minimize the stress concentrations. However, such joints are often conspicuous and the goal is therefore to develop a joint which possesses both the transparency from the adhesive joint along with the more sound long term properties of the traditionally pinned joint, see Figure 1.

The present paper describes a concept for a transparent pinned joint using a circular piece of tempered glass as the dowel. The forces transferred in the tempered glass dowel are mainly in-plane and is therefore named a *Glass Dowel Disc* (GDD). The concept has been proved by two pilot tests revealing a load-capacity which is comparable to the more traditional pinned joint with soft inserts and steel pins.

Figure 1: Experimental setup for a glass dowel discs joint (left) and a traditional pinned joint [1] (right).

2 The Concept of the GDD Joint

The mechanics of the GDD joint is similar to a traditional pinned joint where the forces are transferred primarily by shear and bending in the dowel and contact pressure between dowel and lap plates. However, for the GDD the dowel is made of tempered glass which is a brittle material vulnerable to stress concentrations. In order to minimize the stress concentrations, the diameter to length ratio of the dowel is increased considerably compared to the traditional pinned joint. This will reduce the bending in the bolt to a minimum and the contact pressure should therefore be more uniformly distributed across the thickness of the glass panes. Furthermore, the force is transferred over a larger area along the perimeter of the hole, reducing the local contact pressure. In order to keep the GDD aligned with the plates, a thin layer of adhesive is applied along the perimeter of the bolt. A principal sketch of the GDD joint is shown in Figure 2, where the large glass dowel disc is seen.

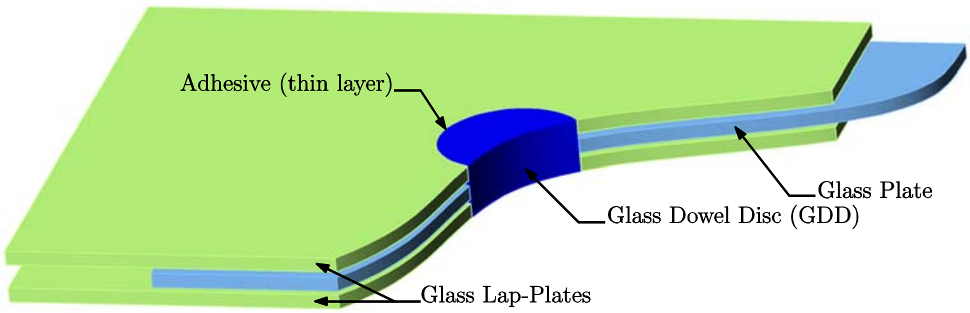

Figure 2: Components of a GDD joint. Note that the plates are slightly offset.

3 Experimental Validation of the Concept

In order to verify the concept, two pilot tests were carried out. One based on three 6mm plates and a 19mm GDD and a second one using three 10mm plates and a 30mm GDD. The setup is shown in Figure 3. The plates were supported along the edges in order to secure stability during loading. The tests were carried out at Technical University of Denmark, Department of Civil Engineering [2].

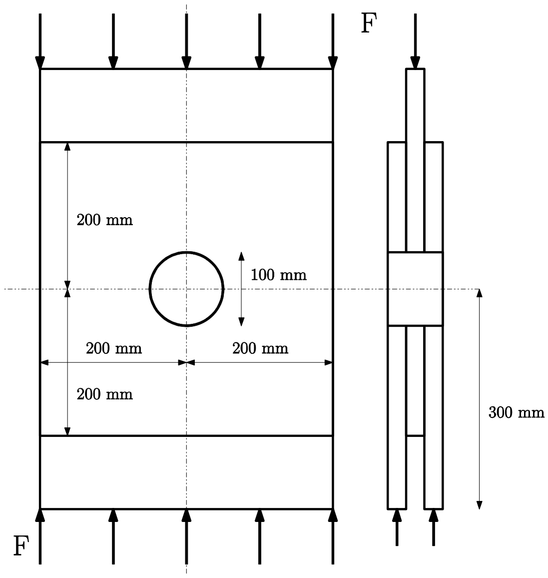

Figure 3: Left: sketch of the experimental setup, Right: Picture of the fractured specimen, note that the GDD has not failed.

The failure loads for the two pilot tests were 46,2kN for the 6mm plates and 168kN for the 10mm plates. In both pilot tests, the GDD remained intact as shown in Figure 3(right). In order to determine the initial point of fragmentation, a high-speed camera was recording the fragmentation.

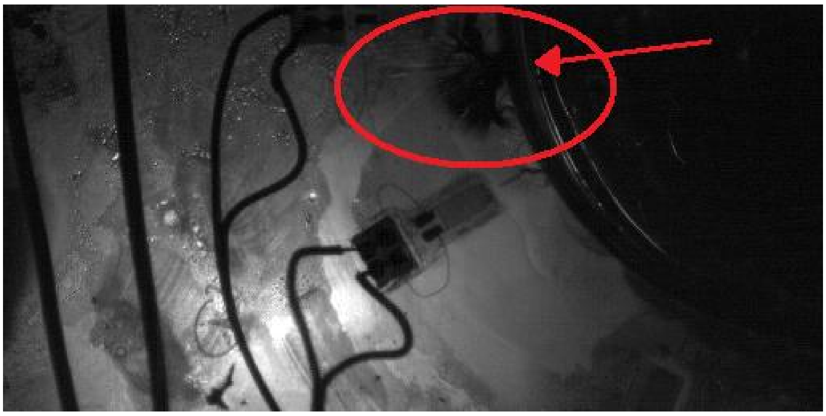

Figure 4: Image from the high-speed camera. The initial fragmentation is marked with the circle and arrow.

4 Analysis

This section describes how we have analyzed the parts of the joint in order to estimate the strength of the tempered glass and calculate the stresses arising from the external loading.

4.1 Strength of the Tempered Glass

The strength of the GDD and the plates has been estimated by first measuring the residual stress state at the center (far away from the edges) and then applying a numerical model of the tempering process in order to extrapolate the measurements to the edge of interest.

4.1.1 Measuring the residual stresses

The residual stress state was measured using a Scattered Light Polariscope (SCALP) as described in [3] using a photoelastic constant of 3.10 TPa^{-1} as found in [4]. A very brief description of the technique will be given here. In Figure 5 a principle sketch of the SCALP is shown. When a laser beam penetrates the glass, a scatter of the light will occur in the plane orthogonal to the beam and due to the so-called lattice effect, the retardation of the scatter changes according to the strain state in the glass. Applying Wertheim's law and stress transformation, the stress state in the glass plane can be determined. However, the approach assumes that the transverse stresses in the plate are zero which is not fulfilled near the edges and therefore reliable results are only obtained far from the edge.

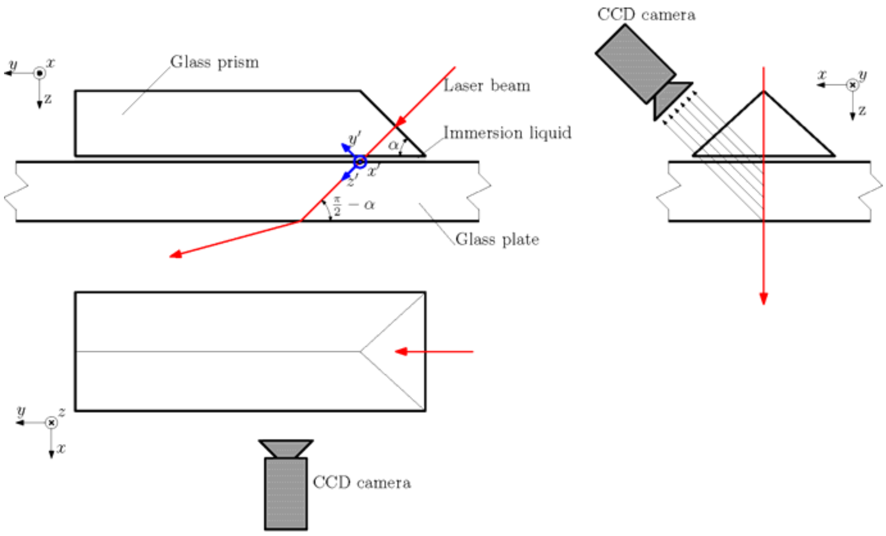

Figure 5: Principle sketch of the SCALP [5].

The residual stresses were measured in the Glass Dowel Disc (GDD) and the glass plates to be assembled. Five measurements were carried out at the center of each GDD using the SCALP. The residual stresses in the plates were determined in four locations (far from any edge) in each plate by four measurements in two orthogonal directions. The measured surface stresses are summarized in Table 1.

Table 1: Measured residual stresses (summarized).

Specimen	Dimensions (mm)	Residual Surface Stress Avg. (MPa)	Residual Surface Stress Plate Avg. (MPa)	Residual Stresses at the edge** (MPa)
Plate61	400x500x6	-118,8		-100
Plate62	400x500x6	-115,7	-112,1	
Plate63	400x500x6	-101,7		
Plate101	400x500x6	-93,2		-101
Plate102	400x500x10	-92,9	-92,4	
Plate103	400x500x10	-91,0		
Dorn19	Ø100x19	-129,8		-120
Dorn30	Ø100x30	-211,1*		-163

* *The SCALP can only measure up-to 19mm thick plates. However, the first 19mm were then used for the fit.*
** *The residual stresses at the edge are extrapolated from the numerical model described in Section 4.1.2.*

4.1.2 Modeling the tempering process

A FEM modeling of the tempering process was carried out in order to extrapolate the measured residual stresses to the edges of the hole.

The tempering model used will be briefly described here for a more in-depth description; the reader is referred to [6].

In the stress generating process of glass tempering, the main phenomena involved are the cooling (temperature), temperature dependent viscoelasticity, thermal strains and structural relaxation. These phenomena are coupled through the temperature as indicated in Figure 6.

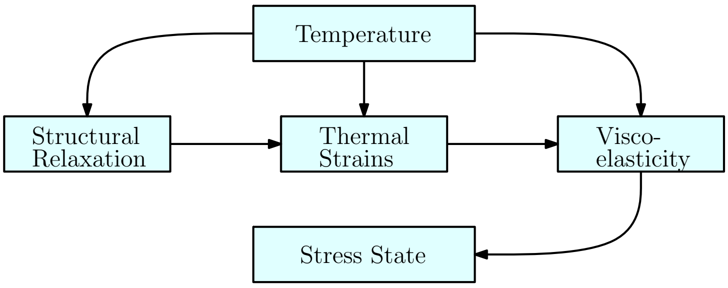

Figure 6: Coupling of phenomena in the glass tempering model.

From the figure it is seen that there is only a one-way coupling between the temperature and the strains. This enables us to solve the system of equations separately and thereby reduce the computational costs considerably. Such a model has been implemented as a user-subroutine in ABAQUS.

From the model, we have extrapolated the measured residual stresses to the edge of the hole in the tangential direction near the surface where the largest principal stresses occur due to the loading, see the right column in Table 1.

An alternative approach when designing is to estimate the residual stress from tables and figures given in [7].

4.2 Stresses from the Loading

In order to estimate the maximum stresses and thereby the approximate strength of the connection, ABAQUS has been used for a contact analysis of the joint consisting of 10mm glass plates. Since the GDD were intact in both pilot tests, the focus of the modeling is on the plates and therefore a 2D model is applied.

The effect of the adhesive is roughly included by performing calculations with and without a gap between the GDD and the plate. The force applied corresponded to the failure load in the experiment (168 kN). The first principal stress for the two cases can be seen in Figure 7, where it is found that the maximum principal stress is 105MPa for a joint without any gap and 180MPa when the gap is included. However, in the joint, the gap was filled with an adhesive.

The strength of glass at a hole cut by water jets at this size is difficult to find in the literature, however, for a smaller hole [8] reports a strength of 45.3MPa. Adding this to the residual stress state we have an apparent strength of approximately 146MPa at the edge of the hole, which is within the interval given above. A simple scaling of the results for the 10mm plate would yield a failure load of 100kN for the 6mm plate, however, the pilot test only showed a failure load of 46.2kN. This indicates a large scatter in the test results and a need for more tests.

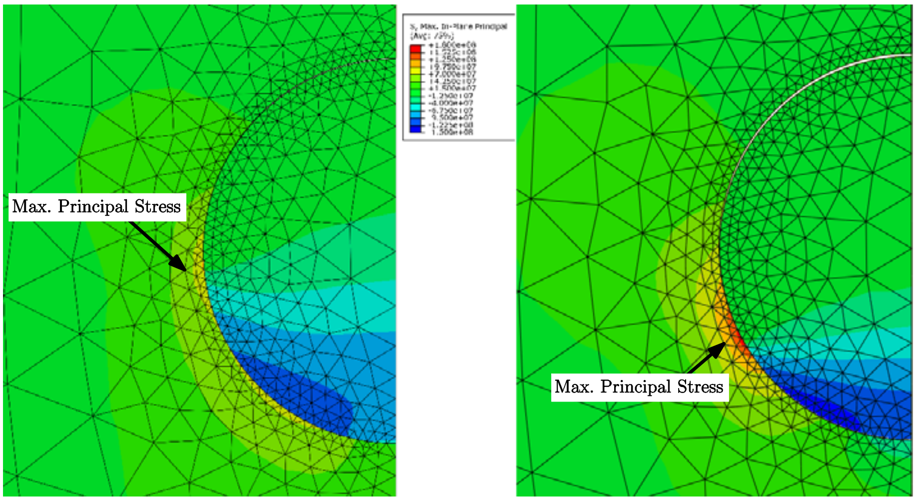

Figure 7: Stress from external loading of 168 kN. Left: no gap, max. principal stress is 105MPa, Right: gap of 0.235mm, max. principal stress is 180MPa.

Comparing Figure 4 with Figure 7 it is seen that the origin of the failure correspond reasonable to the model without the gap, which indicates that the adhesive is participating in the transferring of forces.

5 Conclusion

A new concept for assembling in-plane loaded glass structures has been presented. The concept has been tested in two pilot tests showing promising results. The initiation point of the fracture was recorded by high-speed cameras for comparison with the finite element results. Furthermore, the residual stress state in the tempered glass was measured far from edges and these results were extrapolated to the edges of the hole by means of a finite element model for the tempering process. The stresses arising from the external loading was modeled by a contact analysis using ABAQUS and showed reasonable results.

6 References

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