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# STATIC ANALYSIS OF THE STRESS STATE CAUSED BY HEATING-QUENCHING PROCESS IN TEMPERED GLASSES

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## ABSTRACT
*Tempered glass is widely used in many areas of the industry. Due to its high strength and fragmentation properties, it is the preferred choice for most designs in regard to safety. The production of tempered glass is such that flat glass are heated to about 600°C and rapidly cooled. The occurrence of high temperature differences through the plate causes the thermal stress problem. Especially, around holes and any possible defects on glass sheets, those differences cause the stress intensities. This destructively affects the quality of tempered glass in terms of the strength and surface reflection. In this study, a detailed analysis of the stress field around a hole due to the tempering process is presented. This thermal stress problem was statically modelled by the strain freezing method of the photo-thermo-elasticity.*
**Keywords:** Tempered glass, thermal stress, residual stress, photo-elasticity, FEM

## 1. INTRODUCTION
Glasses are used not only for decorative and packaging purpose but also for exterior structure covering as building material and for safety purposes in the automobile industry due to durability, light transmittance and aesthetic property. Automobile glasses are tempered in order to protect against external influences, changes in seasonal conditions, protection against abrasions and collisions, and fragmentation by separating small parts for the purpose of minimizing the fatal injuries caused by glass and glass parts in the event of an accident.
Tempering process of glass is an operation which includes heating the glass to over the glass transition temperature ($T_g$), 600-650 °C, and cooling by rapidly blowing air to its surface, homogeneously. Because of the difference of the temperature between the surface and interior the glass sheet, this process increases the mechanical strength against the effects coming on the surface by creating residual stresses in the direction of the thickness of the glass. Optical quality, light reflections, fragmentation and mechanical quality of the tempered glass highly depend on the correct cooling process [1].
Due to tempering, on the edges of the glass and around cuts and the holes for assembling the mounting parts, residual stresses occur. The stress field should be homogeneous on the surface of the glass plate after tempering process. However, this field is affected by some irregularities and holes mentioned above. So, the analysis of the stress singularities around these is a necessary.
To et al [2] investigated failure process of tempered glass with pin-loaded joints by experimental and numerical methods. In the study of the 3D calculation method for evaluating the effects of heat transfer to residual stresses in the float glass during the tempering, the relationship between the air

velocity and the inhomogeneity of the heat transfer and stress in the glass surface of the inhomogeneous diffusion of heat transfer during cooling was studied by Lochegnies et al [1] and that method was verified by photo-elasticity measurements in that work. Around cuts or holes on tempered glass, residual stress analysis was made by Pourmoghaddam et all [3] by Finite Elements Analysis. In that study, simulations were performed for the tempering of cylindrical holes and cuts of different geometries at different diameters [3]. Using the finite element method (FEM), Đurašković et al [4] demonstrated the safety of loaded glasses comparing the numerical and experimental results. Behmen et al [5] studied the development of relaxation of residual stress and strain in welded joints of large-size structures. The hole position requirements are standardized in the specification of EN 12150-1 [6] and ASTM C1048-12[e1] [7].

In this study, one suitable and one unsuitable hole according to the Refs. [6, 7] were created in the model throughout the thickness. Edge defects are also modeled by opening two spherical notches at two different depths. The stresses around the hole, which do not meet the hole specification requirements, have been investigated here. The stresses around the other hole and around the two spherical notches will be examined in future works.

The experimental results obtained here were compared with the results from the model of finite element package program, ABAQUS.

## 2. EXPERIMENTAL STUDY

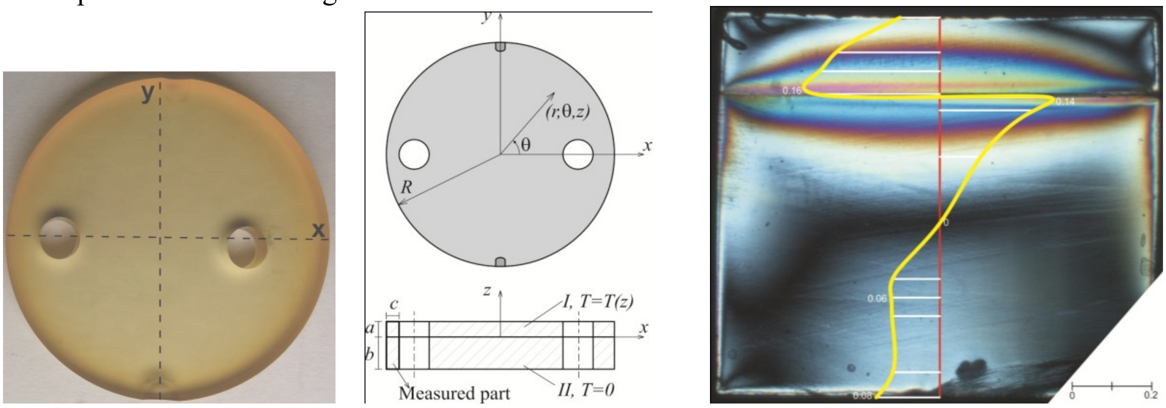
In the experimental study, mechanical modeling method of photothermoelasticity was used [8]. The experimental model was produced by two circular plates. The strains occurred in the surface region of the glass plate due to the sudden cooling of tempering process was obtained by mechanical strains in one part of the model. The other part represents the region having the constant temperature during the quenching. The optical sensitive material used is epoxy-based Araldite. That is homogeneous and isotropic, and linear-elastic behavior is considered here.

The thermal strain $\alpha\Delta T$, where $\alpha$ is the thermal expansion coefficient and $\Delta T$ is the temperature decrease, was formed by mechanical modeling method of photoelasticity and these strains, which were measured as $\alpha\Delta T$ =0.018, were fixed in the plate by freezing method of strain [8]. In order to obtain the part on which the mechanical strains were frozen, an axially loaded compressive specimen was used. This loading was performed in a furnace applying a heating-cooling process in order to freeze the strains. This heating is up to the viscoelastic temperature of 155°C at which the material behaves linear-elastic as like at room temperature.

From this specimen, a 1.07 mm thick plate was obtained by a precision cutting in order to create the thermal loaded part of the experimental model. The other plate having no mechanical effect was also produced with the thickness of 3.39 mm. This part has the same diameter with the diameter of the other part on which the mechanical strains are frozen. These parts were glued to each other by Epoxy resin with a special process.

Two elliptic holes were created on the model. One of them satisfies the position requirement of Refs. [6, 7] while the other one does not meet the specifications about the distance to the edge of the plate. Furthermore, edge defect was modeled by opening two spherical notches at two different depth levels. One of them has the depth up to the interface and the other one is 1 mm below the interface. In this study, just hole which is not at the suitable position according to Refs [6, 7] was analyzed. The other hole and two other notches will be studied in future works.

Dimensions of the model are $a$=1.07 mm, $b$=3.39 mm, $R$=24.86 mm, $c$=5.30 mm (distance from edge of the sample to edge of the unsuitable hole) shown in Fig 1.a. When the model was heated in the same heating regime up to the viscoelastic temperature, the strains on the first part, on which the thermal deformations were frozen, were released, but since the other part did not allow this, a new stress distribution occurred through the model. This stress distribution shows the thermal stress distribution in the prototype. Then, when the model was cooled to room temperature with the same special cooling regime, these deformations were fixed in the model. For thermal stress analysis, the slicing method of three-dimensional photoelasticity was used. A slice with a thickness of 1.13 mm was cut out along the diameter direction. As shown in the Fig 1.a, three slices were obtained because of this cutting. Here, one of them was considered. The stress measurement was performed on the model along three directions, at the left and right edges and along the thickness direction at the middle of the part. The distribution of thermal stress on this part in the direction along the thickness at middle of the part was shown in Fig 1.b.




*(a)* (b)

*Figure 1. (a) Experimental model of glass plate and (b) dimensionless stresses distribution.*

The stresses were measured at several points in terms of the number of fringe (*m*) by a polarizing microscope. The absolute value of the difference of the principal stress components can be calculated using the formula [8] given as

$$|\sigma_1 - \sigma_2| = \sigma_0^{1.0}\frac{m}{t} \qquad \text{... (1)}$$

Here, *t* is thickness and were measured at the related points by digital micrometer. Optical sensitivity coefficient of the material were obtained as $\sigma_0^{1.0}$=0.233 N/(mm.fringe) for the material used in the model. From those values, stress values can be find. The modulus of elasticity and Poisson's ratio were determined for the material as *E*=19.3 MPa and $\nu$= 0.49, respectively.

## 3. NUMERICAL ANALYSIS

A 3D finite element (FE) analysis method was performed using a finite element package program, ABAQUS. In the analysis, the mesh size was averagely chosen 1 mm. The type of mesh element was C3D10 (A 10-node, quadratic tetrahedron elements) and the total number of elements was 67071. The results obtained from FE analysis and from the experiment were compared.

## 4. RESULTS AND DISCUSSION

In this study, the thermal stress distribution in static case was obtained for the tempered glass because of the quenching process by using the photothermoelasticity. The stress distributions along the two edges of one part of the slice cut from the photoelastic model were obtained from the experiment and numerical analysis. The comparison of these were given in the Figs. 2 and 3 where *z* coordinates was started from the top of the first part in Fig 1.a and these values increases in the downward direction.

According to the graphs given in Figs. 2 and 3, the finite element analysis gave smaller values for the second part in Fig 1.a. Moreover, the finite element analyses gave a sign change for the stress in the second part while experimental results do not have any for this side.

The results obtained here show that the finite element model should be developed in order to obtain more convenient results with the experimental model. Furthermore, the numerical analysis should be verified by some other experimental works.

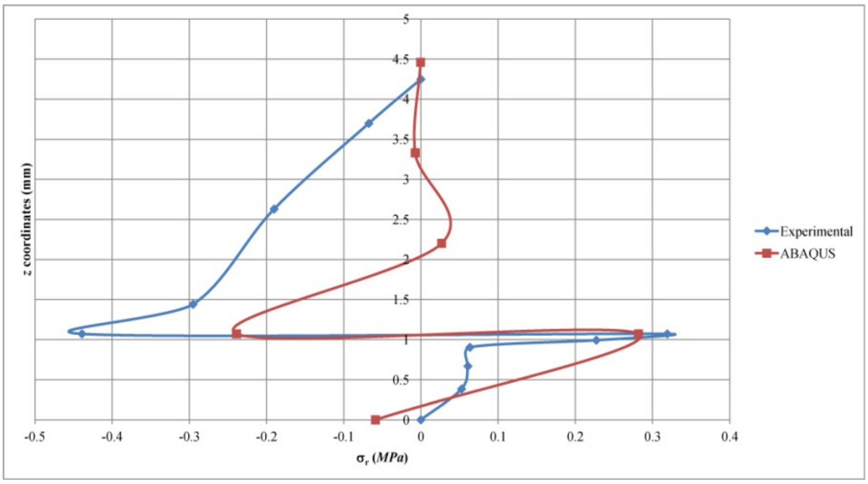



*Figure 2 Comparison of numerical and experimental stress values in the model (along the edge of the hole)*

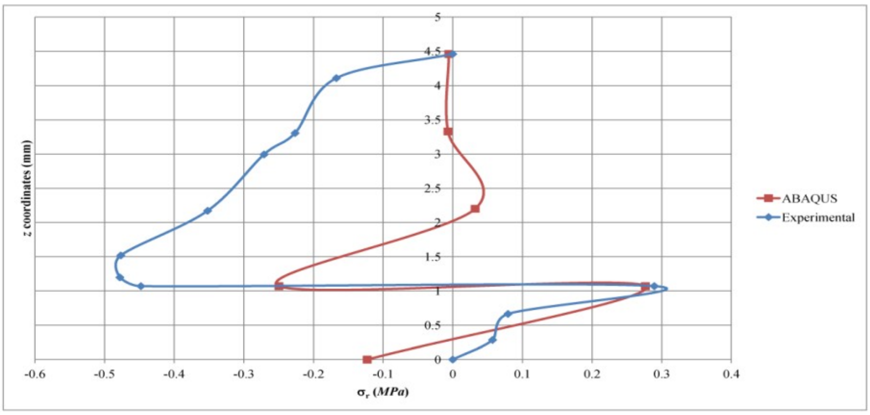



*Figure 3 Comparison of numerical and experimental stress values in the model (along the edge of the model)*

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