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Flexural strength improvement for structural glass: a numerical study

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Abstract. Glass is generally known as a fragile material. It is sensible to the cracks created from manufacturing or contact damage. The strength of a perfect glass without crack could reach 10 GPa. By mean of strengthening such as thermal tempering, glass can be safely use for building as architectural elements and very limited to the structural elements. The authors have been developing glass strengthening methods and structural design for large scale glass beam. Some influencing factors are considered: material, premature crack effect, geometry of sample and bolt. The mechanical behaviour of glass is modelled as elastic-plastic material, which show significant results in glass-bolt contact problem. The crack length, size and position provide information of a critical angle that allow to govern the crack effect in the beam connection.

1. Introduction

In construction building, the usage of glass material increases remarkably for architectural elements and also structural elements. We can see some innovative glass structures such as the Apple Glass Cube canopy in New York [1], the renovated pavilion of the Eiffel Tower's first floor [2], etc. To be a primary structural element, glass need to sustain safely with high load and the glass connections must be able to transfer the load to other elements of building. In the flexural strength of a glass beam, the connection strength is predominant over the bearing capacity of the beam itself. According to the previous studies [3], the load-carrying of glass connection is still limited because of the local failure at the contact areas. Fractography analyses by using SEM observation shown that the interaction between the glass and metal assembly excites a flaw on the lateral surface of the glass's hole. Furthermore, the distribution of principle stresses is also an important factor. A study on the geometrical optimization of the bolt and hole shape shows that, the conical bolt with chamfered glass hole presents the maximum stresses 1.5 times higher than the stiff cylindrical bolt with cylindrical glass hole [4]. Some experiments on a monolithic annealed glass shown in figure 1 and figure 2 confirmed that the origin of failure is initiated from where the principle stresses reach the maximum value, that is at the angle of 90° from the contact loading direction. Underneath the glass-bolt contact, a high compressive stress field is generated where the favourable densification phenomena could occur [5]. On the other hand, an observation on the hole's surface shows that the drilling process induced some crack and important roughness on the lateral face of the hole. The machining with cemented carbide or diamond bits causes chatter cracks similar to a scratch event on a brittle material [6]. The crack diameter is in a range of



300-400 μm [7]. This machining default is the main factor controlling the strength of glass-bolt connection. The polishing [8] and ion exchange [9] processes could decrease the crack size and thus improve the connection strength. The authors aim to study on the effects of connection conditions on the bearing capacity of the glass beam.

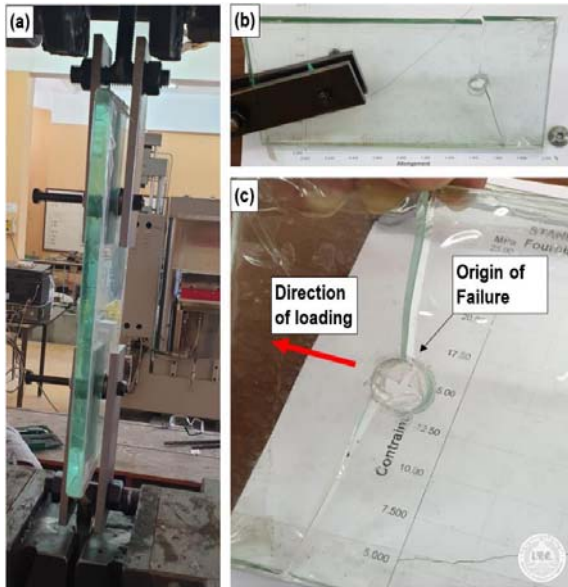


Figure 2. Glass-Bolt connection test: (a) testing assembly, (b) tested sample, (c) failure observation.



Figure 1. Glass drilling process.

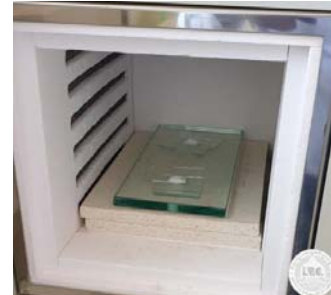


Figure 3. Glass hole strengthening by chemical tempering.

2. Methodology

The current studies are conducted to understand the behaviour of the glass-bolt connection and a way to improve its capacity. Some influencing factors are considered: material, premature crack effect, geometry of sample and bolt. Base on the 2-dimensional finite element analysis, the results of simulations such as the intermediate (middle) principal stress, are compared for a given loading.

2.1. Material

The common glass used in building is soda-lime-silica glass. Its macroscopic mechanical behaviour is known as isotropic elastic linear with Young modulus of 72 GPa and Poisson ratio of 0.21 [10]. The glass's strength is not intrinsic property because of the surface's flaws from which the glass failure is almost unpredictable. Though, a microscopic observation shows some permanent deformation without failure on a scratched glass's surface. There are two mechanisms involving in this deformation: densification and shear flow. According to Rouxel *et al.* [11], the initial densification threshold pressure of the soda-lime-silica glass is 3 GPa and the saturation level of densification is 6.3%. The shear flow threshold was identified by comparing the numerical simulations with a constitutive model of Keryvin *et al.* [12] and the experimental load-displacement curves and imprints of nano-indentations and nano-scratches. The equivalent yield strength is found to 3.81 GPa [13]. Due to the difficulty of numerical solution for a fully modelled behaviour of glass and small amount of the densification effect comparing to the global mechanical responses, the authors simplify the mechanical behaviour of the glass to be elastic linear and perfectly plastic with the yield strength of 3.81 GPa. The contact behaviour between glass and metal bolt is a hard contact with friction coefficient of 0.2.

2.2. *Glass strengthening effect*

Thermal and chemical tempering strengthens the glass by introducing the residual stresses in the glass volume. A chemical tempering by ion exchange modifies the composition of the glass from the surface to a deep less than 100µm ([14], [15]). This gradient of properties is assumed to have less effect on the study. The only one effect of the strengthening is the residual stresses. The surface’s compressive stresses induced by thermal and chemical strengthening are respectively 100 MPa and 250 MPa with the respective depths of one-fifth of the glass thickness and 90µm [16].

2.3. *Geometry and numerical modelling*

The glass specimen’s size is 150mm x 300mm x 12mm with two holes of diameter of 12mm drilled along the centre axis and the diameter of bolt is 10 mm. The crack’s opening is fixed $a = 0.050$ mm and the its depth, $b = [0.000 : 0.750]$ mm, is a parameter for glass strength observations. Another parameter from the premature crack is its position comparing to the loading direction, that is studied between 0° to 90°. Since the geometry and loading are symmetric for the axes perpendicular to the loading direction, the sample and bolt are modelled as a perforated square contacted to a circle. The meshes are gradually changed size from 0.170 mm to 6.00 mm with a 4-node bilinear plane stress quadrilateral, reduced integration, hourglass control, CPS4R mesh type.

3. **Results and discussion**

3.1. *Mechanical properties of glass*

The figure 4 shows the relationship between loading value and the corresponding maximum Mises stress in the sample. The properties of glass are discussed: purely elastic and elastic perfectly plastic. Prior to the shear threshold (3.810 GPa), the Mises stress-force responses of both cases are identical. However, from that point forward, it is obvious that the very small amount of plastic zone (figure 5.a.) need to be taken into account in the glass material modelling. In addition, we observed that the middle principal stresses illustrate the tensile stress field that would initiate the failure more clearer than the Mises stress (figure 5.b. and figure 6).

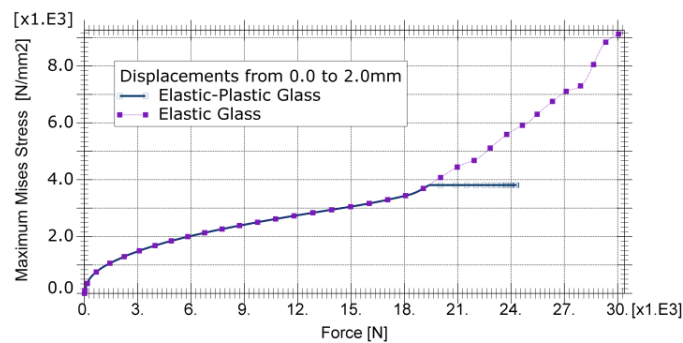


Figure 4. Comparison of Mises stress - Force responses of different behaviours of the glass sample. Loading by the imposed displacement on the perimeter of bolt.

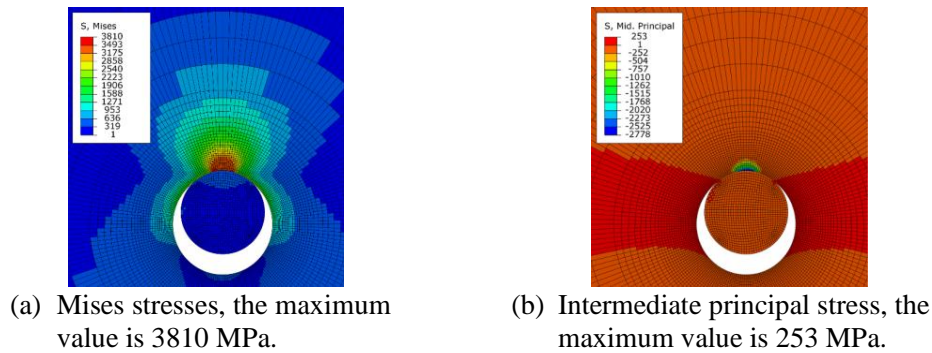


Figure 5. Stresses distributions in the glass for elastic-plastic behaviour with yield strength of 3810 MPa. The images in (a) and (b) are captured at the same time increment. The positive value of Mid. Principal stresses could be illustrated more clearer by graded more colours.

3.2. *Effect of the premature crack*

The parametric studies of the position and the depth of premature cracking along the perimeter of the glass hole are presented in figure 6 and figure 7. At a given load, the maximum value of the middle stresses presented in the glass increases importantly with the greater depth of the premature crack opening. On the other hand, the position of the crack comparing to the loading direction show two groups of tendency. The presence of a single crack at a vicinity of the contact area at an angle less than 30° has less effects on the glass failure. The region between 15° to 30° is where there are transitions of tensile and compressive zone due to the stress fields of the Hertzian contact and crack tip. The value of 30° is the critical angle which depends on the bolt-hole diameter ratio and the crack size and depth.

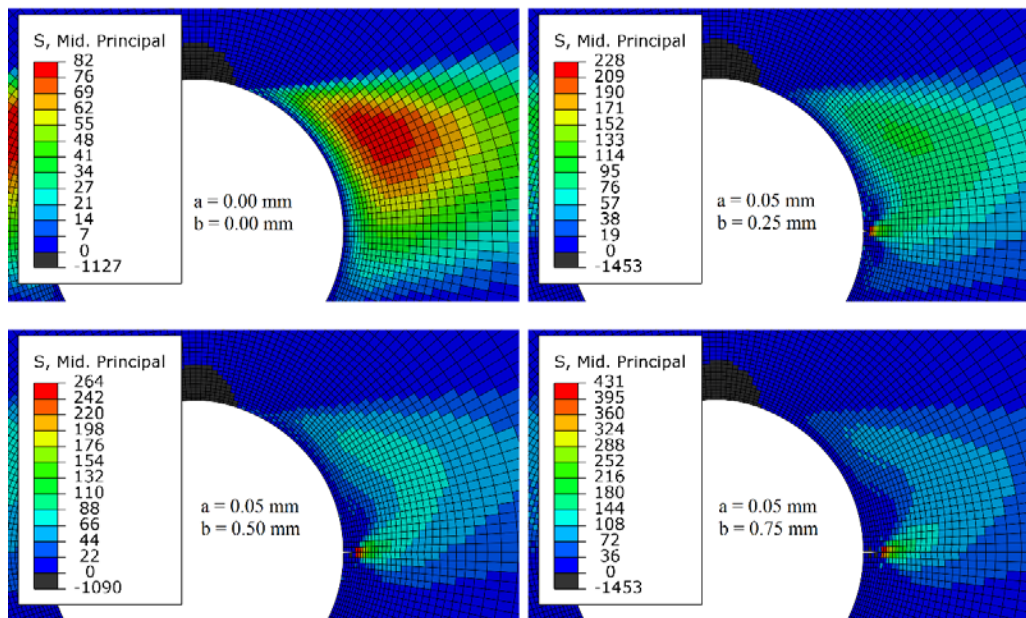


Figure 6. Intermediate (Mid.) principal stress distribution at load = 6kN on samples with different crack depth b . The crack openings are equal: $a = 0.05 \text{ mm}$.

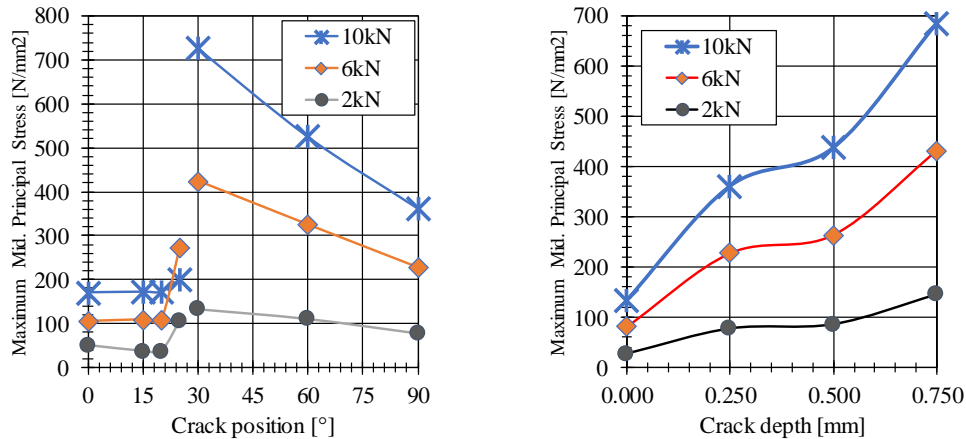


Figure 7. Observation on the maximum value of intermediate (Mid.) principal stresses for samples with different factors: (left) crack position of a 0.250 mm depth comparing to the loading direction, (right) cracks depth at 90° crack position.

4. Summary and conclusion

The studies have shown some important results for understanding and improving the flexural behaviour of structural glass. It is very important to model the plastic behaviour for glass material in the glass-bolt contact problem. In order to observe or compare the stress field in glass material that present very limited plastic zone, the intermediate principle stress is a better criterion comparing to the Mises stress. On the other hand, the crack length is predominant in failure mechanisms, which could be minimize thanks to the compressive residual stresses, e.g. in a tempered glass. The surface compressive stresses prevent crack's growth unless the external tensile stresses overpass their values. However, it is a challenge to model the effect of tempering in glass. The profiles of the residual stresses at the edge of a tempered glass, especially around a hole, are more appropriate with the 3-D modelling than the 2-D one. Another method to improve the glass connection strength is to govern the contact surface between the bolt and the glass's hole. The critical angle of 30° could be modified since the Hertzian contact provides stresses distribution depending on the radii of the both surfaces. It could be also suppressed by introducing multiple contact surfaces along the hole's perimeter.

Acknowledgments

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