The Effect of Openings on Stress Distribution in Glass Beams – Dependence on Diameter of Openings

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Abstract. Presented paper describes the behaviour of simply supported single ply glass beam with discontinuities in its geometry. Discontinuity is introduced by four openings symmetrically placed over the beam. This type of simplified structure represents cut out of real constructions where similar glass components are used as primary load bearing structures supporting glazing of roofs or decks of pedestrian bridges. The main focus of this article is in research of stress distribution around openings and how different diameter of a hole influences stresses in its close proximity. As Eurocode standards for glass structures are still not codified and most of the nowadays literature only provide suggested diameters of holes based on the thickness of the glass pane, this paper will provide the future designers of glass load bearing structures with closer look at stress distribution around mentioned area. In order to bring those informations to theirs seekers, both experimental analysis and numerical analysis together with parametric study were used.

1. Introduction
Among traditional materials used in constructions such as concrete, steel, timber and masonry, more often materials like glass emerged in last decades. Glass, substance used for centuries only as a fill of openings serving for bringing light into a building and creating transparent barrier between exterior and interior is nowadays, thanks to its unique properties used for constructions like slabs, beams and columns [1]. When used as a load bearing structure it not only transfers self-weight to other load bearing structures, but actively transfers loads like wind, snow or forces acting on structure during fire, to foundations and then to soil.

Glass, compared to other common materials used in building industry, has a unique mechanical and optical properties which open whole new range of construction details where it can be applied. Its high level of flatness allow engineers to design slender columns, beams and slabs, which also fulfil strict strength, reliability and safety requirements for buildings [4]. Relative to timber, glass is isotropic, which means, it has the same material properties in each point of a specimen. Moreover, it has equal tensile and compressive strength and strength of tempered glass exceeds compressive strength of commonly used concretes.

The aim of this work is to better understand stress distribution in glass beams with two or more vertical openings and help designers by providing them with information about stress distribution around holes depending on mutual distances between holes and on the diameter of openings.
2. Experimental analysis

The experiments were held indoor with room climate conditions. For the experimental analysis 3 specimens made out of heat-strengthened glass were used, numbered N01, N02 and N03. All three specimens were made out of heat-strengthened glass of thickness 12 mm with suggested minimal characteristic strength of glass 70 MPa. The beams were asked and fabricated in dimension 1000 x 200 mm. In the distance of 350 mm perpendicular to shorter edge two holes of diameter 20 mm were drilled above each other. From the longer edge the holes are 50 mm far and the distance between the centres of the openings is 80 mm. The specimens are symmetric, which means, that there are 4 openings in total. The centre to centre distance of supports is 900 mm. Cylindrical supports are placed 50 mm from the edge of the beam from both sides. The tested beams represent the cut of real structures. Beams of similar geometry as the tested ones can be found in structures of roof glazing or pedestrian bridges. Four point flexural bending test was used, which leads to constant moment in between the forces. The consequences of moment distribution as described is that the crack will appear in the weakest point of the specimen. Then, from the crack pattern of the broken specimen is obvious in which point stress exceeded the load bearing capacity of the specimen the first. The tests were running until the failure of a structure.

![Diagram of the loading assembly](attachment:loading_assembly.png)

**Figure 1.** Scheme of the loading assembly (distances in mm).

- **Number of strain gage**

The vertical deflection was measured by 4 rod extensometers. Two of them were placed in the middle of span from each side of the beam. Rod extensometers were placed on the horizontal plate of the two L-shaped steel components. Measuring the deflection from both sides allowed us to observe, if the beam buckles. Other 2 rod extensometers were placed on the top edge of the specimen in the point above the supports. As there were plastic washers from polyamide inserted between the steel supporting cylinder and the glass beam, the deformation of the polyamide showed as significant. To obtain the real deflection of the beam in the middle of its span, vertical deformation measured in the centre must be subtracted by the vertical deformation measured by extensometers placed in the points above the supports.

The failure of glass structures is brittle and occurs immediately after a maximum load bearing capacity of an element is reached. Shards of heat-strengthened glass are similar to those of float glass,
which allow us to fold the broken pieces of each specimen and determine where the crack was initiated, furthermore where the maximum stress was developed during the test. Ultimate limit state was reached for each beam at different force and deflection aligned to that load. Variety in maximum load applied to each specimen is presumably caused by the process of how heat-strengthened glass is produced. Comparison of values obtained from the tests and average value of force and deflection reached at breakage is shown in the table below.

| Specimen | Max. force [kN] | Max. deflection [mm] | Stiffness [kN/mm] |
|----------|-----------------|----------------------|------------------|
| N01      | 39.06           | 1.259                | 31.017           |
| N02      | 32.07           | 1.081                | 29.677           |
| N03      | 36.38           | 1.146                | 31.746           |
| Average  | 35.84           | 1.162                | 30.813           |

As shown in the diagram of comparison of force-deflection lines of all 3 specimens, the inclination of line of specimen N02 is different. The angle between the line and horizontal axis is lower which indicates lower stiffness. As all 3 tested beams have the same cross-section and length, Young’s modulus is lower too, compared to specimens N01 and N03 which stiffnesses are similar.

As observed from the crack pattern of specimens N02 and N03, the initiation of crack was found at the edge of low left opening which signals that during the tests maximum stresses occurred at the described point.

3. Numerical analysis
For numerical modelling was used ANSYS Workbench 19.0 (student license) software. Mentioned software as one of many uses finite elements method (FEM) for analysing the structures. The Workbench interface provide easy orientation alongside conserving the high standard of ANSYS software. A three-dimensional model was created which will represent tested beams. To define
geometry of same dimensions as specimens, the SpaceClaim interface was used. The shape of component allowed us to model only half of beam and use the symmetry of tested specimens.

![Figure 3. Geometry of used model.](image)

Numerical model reached during loading by force $F = 17.92 \, \text{kN}$ which is half of the total average force applied by loading arm in experiments, maximum vertical deflection of $1.155 \, \text{mm}$. Estimated stiffness as well as deflection corresponds with the average values stated in table 1. Calculated stiffness of numerical model is $K = 31.041 \, \text{kN/mm}$ which is almost identical as average stiffness of tested specimens, which is $K = 30.813 \, \text{kN/mm}$. In numerical model the maximum stress appears at the bottom edge of lower opening, at the point, where initial crack happened during the tests. As glass is elastic material, the force – deflection diagram of tested beam in ideal conditions should be linear as shown in the graph below.

![Figure 4. Comparison of ideal beam and numerical model.](image)

3.1. Parametric study
Validated numerical model with the same material characteristics and with unchanged way of support and load application, will be used in parametric study. Essential to this parametric study is to monitor changes in stress distribution around the openings, while using different radius of holes. The radiuses
used for this parametric study are shown in Table 2 together with maximum stress recorded at the bottom edge of lower opening and stiffness of modelled beam. Radiiuses of both openings were changed simultaneously and centre of rotation of holes remained unchanged.

| r [mm] | 5   | 8   | 9   | 10  | 11  | 12  | 13  | 15  | 20  | 25  | 30  |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Max σ [MPa] | 74,73 | 88,01 | 86,92 | 90,13 | 83,89 | 88,71 | 92,44 | 97,24 | 108,14 | 122,52 | 143,51 |
| K [kN/mm] | 31,36 | 31,19 | 31,12 | 31,04 | 30,95 | 30,85 | 30,73 | 30,48 | 29,66 | 28,48 | 26,82 |

Table 2. Input and output parametric quantities for variable radius of opening.

Influence of radius of the openings on stress distribution is shown in the diagram below. In presented diagram output quantity is stress at the bottom edge of lower opening. As centre of rotation of openings remained in the same position for all used diameters, the effect of increase respectively decrease in stress caused by linear distribution of stress alongside the height of the beam starting with zero at neutral axis and reaching its maximum at the edges is not involved in the following diagram.

Figure 5. Correlation between the radius of the opening and maximum stress at the edge of hole.

4. Conclusion
Experiments consisted of 3 specimens made out of heat-strengthened glass which were tested in four point flexural test. When the strength of specimens was exceeded, brittle failure characteristic for glass structures appeared immediately. Then, the crack pattern and shards were studied carefully and the bottom edge of lower opening was marked as the point of initiation of crack which spreaded promptly across the whole beam. The average stiffness of all 3 specimens was \( K = 30,813 \text{ kN/mm} \) and maximum average vertical deflection was \( \delta = 1,162 \text{ mm} \). Parametric study provided the data which will be compared to stated suggested diameters of openings in literature. As suggested by [1] diameter of a hole in a in-plane loaded glass pane should fulfil the formula \( D \geq S \), where \( D \) is diameter and \( S \) is thickness of glass pane. But from the perspective of stress quantity the most effective radius for openings in glass is around 11 mm (diameter 22 mm) as shown in chapter 3.1. Thickness of glass panes used for this research study is 12 mm. The parametric study not only confirms proposed formula, moreover adds new condition \( D \approx 2S \) in order to reach economic design with respect to maximum stress.
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