Load Bearing Innovative Construction from Glass

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Abstract. Glass plays an exceptional role in the modern architecture due to the optical properties and transparency. Structural elements from glass like beams, facades and roofs are relatively frequent in common practice [1]. Although glass has significantly higher compressive strength in comparison with tensile strength, load bearing glass elements are relatively rare. This opens up new opportunities for application of glass in such structures as transparent columns loaded by the axial force. This paper summarizes the experimental results of the tests on glass columns loaded by centric pressure, which were performed in the laboratories of the CTU in Prague, Faculty of Civil Engineering. The first set of experiments was composed of three specimens in a reduced scale 1:2 to verify real behaviour of the specimens with enclosed hollow cross-section. The main goal of the experiment was to determine force at the first breakage and consequently the maximal force at the collapse of this element.

1. Introduction

Glass columns subjected to compression must have sufficient strength, stiffness and residual load bearing capacity to be able to transfer loads (e.g. dead load, snow load, wind load) and to be safe even after first cracks have appeared. Design methods for other materials cannot be taken into account and used for glass elements without any modifications because it is necessary to consider the effect of manufacturing tolerances (glass thickness), initial deformation, PVB layers for laminated glass, glass elastic behaviour without hardening effect, the effect of load duration, damage of the glass surface and the impact strength of glass, which is not necessary for other materials (e.g. steel).

Due to fragility – the main property of glass, it is necessary to keep in mind proper design and assembly of details. Any local irregularities can cause stress concentrations and thus the failure of glass. In case of glass columns, the most important detail is the place where the force is transmitted from the slab to the glass part of the column. Project design should also consider load transfer from
horizontal structures to the other parts of structures and prevent progressive collapse of the building or its part due to the collapse of a single glass column.

Recently, a set of experimental studies at research centres in Europe has been focused on the behaviour of glass columns with different cross section. Experimentally verified glass structures were used in the practice, such as a glass pavilion in Rheinbach, where all vertical and horizontal forces were transmitted by glass columns [2]. Laminated glass columns of simple rectangular cross-section section were used. Another example is the glass foyer at the headquarters of an industrial company Nordborg in Denmark, where the architects used cruciform shape for the glass columns which support the glass roof beams [3]. Experimental verification of glass columns was also performed at EPFL in Lausanne, where the research was focused on the loss of stability of glass elements loaded by compression and on compiling of basic buckling curves for different strength of glass [4].

2. Glass columns

2.1. Design of glass columns

Within the research of glass structures, which takes place at the CTU in Prague, the first set of experiments contains three test specimens. These specimens were prepared in a reduced scale 1:2 from float single layered glass which had been selected with regard to simpler behaviour under loading without effect of polymer interlayers. In the real case laminated tempered glass will be used for such kinds of structural load bearing elements.

The test specimens consisted of four float glass panes of thickness 6 mm with the length 1750 mm and the width of 150 mm, which were connected to each other at the corners into a square hollow cross-section by acrylate adhesive Sikafast 5211 - NT, see figure 1, figure 2.

Special attention was paid to the detail of the end parts of glass columns. At this point, it was necessary to provide a uniform transfer of normal force into the glass part of the column by the plastic pad made from polyamide (PA). This plastic pad was designed as a two-stage plate to prevent potential torsion deflection of the cross-section at the edges. Plastic pad was placed at the bottom and the top of the column between the glass part and special steel shoes.

![Figure 1. Square hollow cross-section.](image1.png)

![Figure 2. Test specimen.](image2.png)
2.2. Test set-up
All test specimens were continuously loaded by centric force at the speed of 50 N/s until the first crack appeared. After the first breakage of glass pane, the columns were loaded until they collapsed. Total of 16 strain gauges LY11-10/120 were used for indirect measurement of stress, they were installed at the three levels of the column, see figure 3. Horizontal mid-span deflections were also recorded during the test by four potentiometers, which were fitted on each panel.

![Diagram of test setup](image)

**Figure 3.** Position of the measuring sensors.

The load bearing capacity of the glass column could be defined as force $F_{1st}$ in which the first crack has appeared but there is no total collapse of the column. The first cracks had been seen in all samples at the value of force $F_{1st} = 75$ kN. The first cracks appeared every time at the bottom of the column above the steel shoe and always had vertical direction. These cracks occurred due to the lateral tension. Thus, the column was still capable to transmit the normal force until it collapsed. We are talking about residual load bearing capacity. The residual load bearing capacity means the ability of partially broken column to transmit additional load without collapse. The residual load bearing capacity can be calculated as $F_{\text{residual}} = F_{\text{collapse}} - F_{1st}$, where $F_{\text{collapse}}$ is the ultimate loading force, see figure 4.

Columns were able to transfer additional load until they achieved forces in the range from $F_{\text{collapse}} = 85$ kN to $F_{\text{collapse}} = 168$ kN, i.e. columns had residual load bearing capacity in the range $F_{\text{residual}} = 13 - 93$ kN, see table 1.
Table 1. Experimental results.

| Specimen     | $N_{1st}$ [kN] | $N_{\text{collapse}}$ [kN] | $F_{\text{residual}} = F_{\text{collapse}} - F_{1st.}$ [kN] |
|--------------|----------------|-----------------------------|------------------------------------------------------------|
| Specimen 1.1 | 72             | 117.5                       | 45.5                                                       |
| Specimen 1.2 | 72             | 85                          | 13                                                         |
| Specimen 1.3 | 75             | 168                         | 93                                                         |

3. Analytical model

The real rod has lost its stability before the force reached the critical force $N_{cr}$. The behaviour of ideal compressed column with the length $L$ can be described by a known differential equation (1). The column is simply supported and loaded by axial force $N$ with initial imperfections $w$ in the shape of a sinusoidal wave, figure 5.

Figure 4. The basic behaviour of the glass column.

Figure 5. Eccentrically loaded compression rod with initial deformation [6].
\[ EIw'' + Nw = 0 \]  
(1)

For the real rod with initial geometric deflection \( w_0 \), the maximum bow imperfection in the middle of the length can be determined from the equation

\[ w = \frac{w_0}{1 - \frac{N}{N_{cr}}} \]  
(2)

The geometric deflection \( w_0 \) can be determined as the sum of material and structural imperfections according to the equation

\[ w_0 = w_{0,1} + w_{0,2} \]  
(3)

Material imperfection \( w_{0,1} \) for float glass can be considered according to [5] as the value \( L/2500 \) and structural imperfection \( w_{0,2} \) can be considered as \( L/400 \).

The critical Euler force for the ideal rod is equal

\[ N_{cr} = \frac{\pi \cdot EI}{L^2} \]  
(4)

where \( I \) is the moment of inertia.

Normal stresses in the middle of length and in the extreme fibers can be calculated by equation

\[ \sigma = \frac{N}{A} \pm \frac{M}{W} = \frac{N}{A} \pm \frac{N \cdot w}{W} \]  
(5)

where \( W \) is the section modulus.

The normal stress from the analytical model was determined according to the above mentioned equations and compared with the experimental data in the mid-span cross-section, see figure 6. Curves \( T_1 - T_2 \) represents the principal stress measured by stress strain gauges. Location and position of the stress strain gauges is shown in figure 3. The lines \( AM_{\text{pressure}}, AM_{\text{tensile}} \) are average values calculated by equation (5).

\[ T \text{ Model, tensile} – \text{The value of compressive normal stress reduced by the positive effect of the bending moment.} \]

\[ T \text{ Model, pressure} – \text{The value of compressive normal stress increased by the effect of the bending moment.} \]

**Figure 6.** Comparison of the analytical model with the experiments.
4. Numerical model
Program ANSYS ver. 14.5 was used for the numerical model. Each part of the column was created from volume elements SOLID. Glass was modeled as a linear isotropic material with Young’s modulus \( E_{\text{glass}} = 70 \text{ GPa} \) and Poisson coefficient 0.23. Plastic pad was defined as a linear isotropic material with Young's modulus \( E_{\text{pad}} = 3.5 \text{ GPa} \) and Poisson coefficient of 0.39.

The adhesive was modeled by using multi-linear stress-strain relation with Young’s modulus \( E_{\text{adh}} = 0.26 \text{ GPa} \) and Poisson coefficient 0.40. Stress-strain graph was based on tensile tests of adhesive joints performed at CTU, [6]. Initial geometric imperfection for the numerical model was set as \( w_0 = L/400 \).

The load bearing capacity was chosen for comparison of the test results obtained from numerical model and real measured data. Deformed shape and compressive stress \( \sigma_z \) in the glass is demonstrated in figure 7, which is scaled for illustration by 1000:1. The maximum of the measured horizontal deflection in the middle of the column was \( w_y,\text{real} = 0.22 \text{ mm} \). Deformation determined by the numerical model was by 25% lower, \( w_{\text{num},y} = 0.175 \text{ mm} \). Comparison of compressive stress obtained from experimental results and numerical and analytical model is shown in table 2.

![Deformed shape in the direction Uy (left); tension \( \sigma_z \) (right).](image)

**Figure 7.** Deformed shape in the direction Uy (left); tension \( \sigma_z \) (right).

**Table 2.** Comparison of principal stress obtained from the experiments, numerical and analytical model.

| Principal Stress | Analyt. model | Numer. model ANSYS 14.5 | Specimen 1.1 | Specimen 1.2 | Specimen 1.3 |
|------------------|---------------|-------------------------|--------------|--------------|--------------|
| \( \sigma_{\text{AN}} \) [MPa] | 24.6          | 25.4                    | 27.2         | 32.7         | 25.9         |
| \( \sigma_{\text{NUM}} \) [MPa] | 19.9          | 21.2                    | 16.5         | 14.2         | 16.8         |
| \( \sigma_{\text{exp}} \) [MPa] | 27.2          | 32.7                    | 25.9         |              |              |
From table 2 it can be seen that test specimen 1.2 has different values of the principal stress than the others. It is due to higher assembling imperfection and the fact that during the test a part of the glass corner felt out. Thus, a local bending moment increased.

5. Conclusion
In the first phase of experimental research of the behaviour of a glass column with hollow square cross-section was verified. Columns were assembled from four float glass panels with thickness 6 mm. They were bonded together along the length by acrylate adhesive. Results showed sufficient load bearing capacity of the glass columns. The first breakage occurred approximately at a force $F_{1st} = 75$ kN when the first crack occurred above the bottom basement of the test specimen. The column was still able to carry the increasing load thought cracks started to develop. The collapse was observed at average force $F_{collapse} = 123.5$ kN. The detail of transferring axial forces from steel shoe through the plastic pad into the glass column has had a significant influence on the load bearing capacity. In all cases, the first cracks showed above the steel shoe due to the lateral tensile but the column was still be able to carry the increased load. The average residual load bearing capacity was $F = 51$ kN.

The next phase of the research will be experimental verification of real scale specimens made from laminated glass.

6. References
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Acknowledgement
This research was supported by the grant GAČR 14-17950S.