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EXPERIMENTAL EVALUATION OF STRUCTURAL GLASS ELEMENTS UNDER COMPRESSION

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ABSTRACT

Nowadays glass is becoming more favourable material in a modern architecture, which has already changed its own meaning from filling material to material used for load-bearing structural elements. These elements are also able to transfer, apart from self-weight, dead load, snow or wind load as well as imposed load. While glass beams, staircases, floors are quite common, elements subjected to compression are still exceptional. This presented paper summarizes the results of experiments performed on glass columns with square hollow cross-section to verify the actual global behaviour under axial compressive pressure, as well as the estimation of the compressive loading ratios leading to first cracks opening and columns collapse, respectively.

Keywords: glass, column, adhesive, compression, buckling.

INTRODUCTION

Looking at the current architecture, there are a lot of examples of supporting glass structures such as beams, ribs, stairs and railings being subjected to bending. On the other hand glass columns subjected to compression are relatively rare despite the compressive strength of glass is significantly higher than its tensile strength. Insufficient knowledge about structural behavior of glass columns prevents greater use of these attractive structural elements. The load transmission from the floor or the roof to the compressed member is the main problem in case of glass columns. Any local irregularities may cause stress concentration peak or additional bending moments and thereby cause early failure of the element. Furthermore, there are insufficient information about global and local behaviour in compression in task of buckling, which means that glass columns are not used in practice more often. Glass column should also have high robustness against emergency situation or vandalism. It means that the design concept should consider the possibility of alternative load transfer from horizontal structures to other structures to avoid progressive collapse based on the breakage of one glass pillar.

Typical linear behavior with brittle failure occurring suddenly without any warning and the effect of the load duration or glass surface conditions are typical for a glass. During the assessment, it is necessary to keep in mind also other influences like manufacturing tolerances (glass thickness), type of glass and relevant initial deformation and material properties of used interlayer in case of laminated glass.

In the past few years, different experimental investigation, analytical and numerical research studies were performed to obtain fundamental knowledge about the structural behavior of glass columns with different cross-sections under compression, (Crisinel and Luible, 2004),

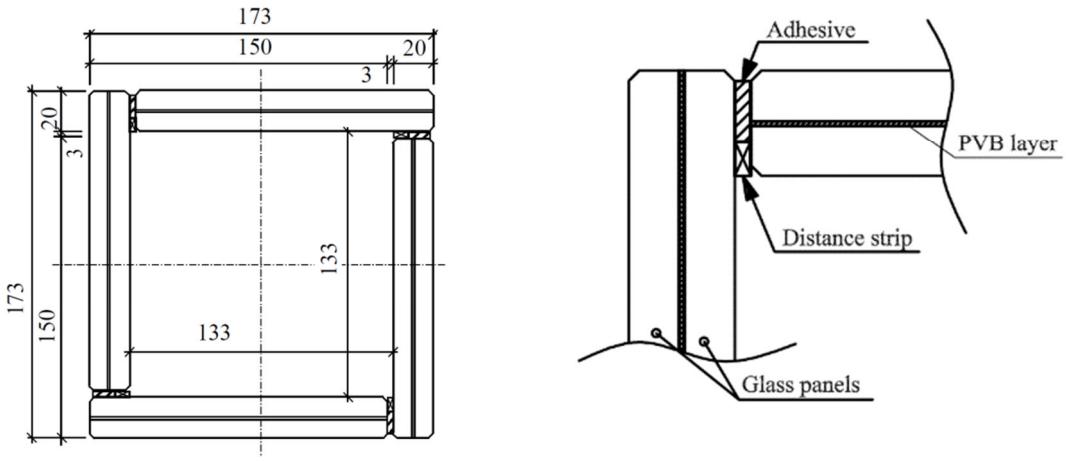
(Overend et al., 2005), (Foraboschi, 2009), (Amadio and Bedon, 2011). Performed tests were especially aimed to the rectangular cross-section and its structural behaviour under compression including verification and evaluation of the analytical models based on Euler's buckling calculation that were derived for a monolithic and laminated glass.

EXPERIMENTAL INVESTIGATION

Within the research of glass structures taking place at the Faculty of Civil Engineering CTU in Prague, the experimental programme contains five test specimens of glass column. Three specimens were subjected to axial compression tested up to the collapse and two specimens were subjected to the impact test. There are illustrated only three specimens subjected to axial compression in this paper. Obtained experimental results were used for the modified analytical model verification.

Description of test specimens

The typical specimen was composed of four double-layered panes of annealed glass with nominal thickness t = 20 mm, length L = 3000 mm and width h = 150 mm. The thickness of glass panels were t_{panels} = 2 x 10 mm and the interlayer was PVB foil with thickness t_{PVB} = 1 mm. The glass panels were bonded together at the corners with acrylic structural adhesive (type SikaFast®-5211NT) in order to obtain resistant square hollow cross-section, see Fig. 1a). To secure the thickness of the adhesive layers, special distance strips were used and installed in each corner, Fig. 1b).



(a) (b)

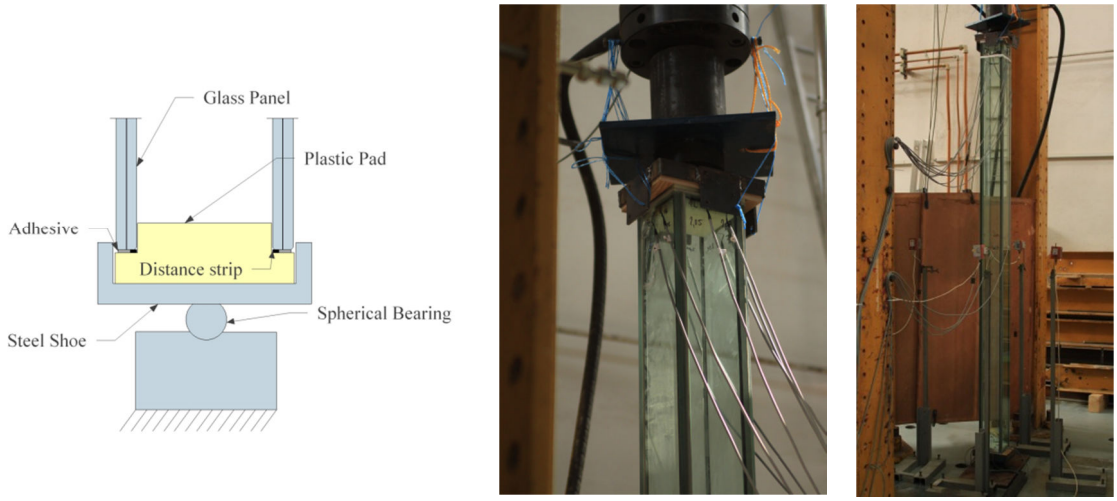
Fig. 1 - (a) Cross-section of glass column, (b) Detail of adhesive joint

Careful attention was paid to the detail of glass column connection with the bottom and the top supporting devices. In this part, it was necessary to provide the uniform normal force transfer into glass webs. The plastic pads with special shape were installed inside the hollow section to prevent direct contact between steel shoe and glass pane, see Fig. 2. These pads were designed from polyamide as two stage components to avoid potential torsion of cross-section at the edges.

Test set-up

Experiments were focused on load bearing behavior of glass column under axial force. All test specimens, totally three, were continuously loaded by loading rate 200 N/s until the first crack to determine the level of the load bearing capacity. Each test specimen was then loaded

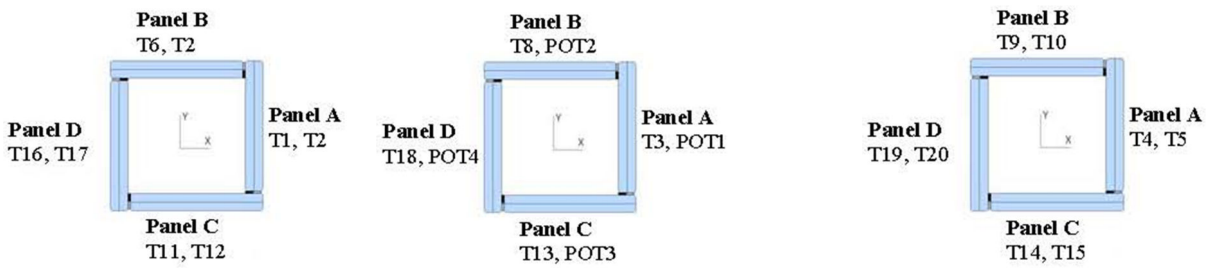
until collapse. To ensure the ideal boundary conditions at the bottom and the top part of the test specimen, steel shoe was supported by means of spherical bearing with diameter 60 mm, see Fig. 2a). Detail of the upper support is shown in Fig. 2b) and the whole test specimen is demonstrated in Fig. 2c).



(a) (b) (c)

Fig. 2 - (a) Detail of the bottom support, (b) Detail of the upper support, (c) test specimen of glass column

The stress distribution on the glass surface was measured indirectly by 20 strain gauges LY11-10/120 during the tests. Strain gauges were placed symmetrically at the top, mid-span and bottom cross-section on each glass panel in horizontal direction (strain gauges labeled T2, T5, T7, T10, T12, T15 T17 and T20) and vertical direction (T1, T3, T4, T6, T8, T9, T11, T13, T14, T16, T18 and T19) with the position depicted in Fig. 3. Horizontal mid-span deflections were also recorded by four potentiometers (POT1 up to POT4), which were fitted on each glass panel.



(a) (b) (c)

Fig. 3 – (a) Top cross-section, (b) Mid-span cross-section, (c) Bottom cross-section

Experimental results

Results from the experiments are summarized in Table 1. The first cracks caused by lateral tension always appeared at the bottom part of the column above the steel shoe in vertical direction. Different normal force N_{1st} magnitude was reached at the level of the first observed crack depending on the test specimen. No visible cracks were detected before the collapse in case of test specimen S2.4. Specimen S2.5 had lower value of N_{1st} caused by different plastic pad material properties leading to earlier breakage as well as earlier column collapse. First

cracks also appeared at the bottom cross-section but there were detected more than one crack spreading from one point.

Residual load bearing capacity was discovered by further overload. In this case, residual resistance means the ability of partially broken column to transmit additional load without a collapse. Columns were able to transfer submitted load until achieving normal force $N_{f,max}$, so the residual load bearing capacity can be calculated as the difference between $N_{f,max}$ and N_{1st}, see Table 1.

Table 1 - Experimental results at first cracking and post-cracked stage

Specimen	First cracking N_{1st} [kN]	Post-cracked stage $N_{f,max}$ [kN]	Residual capacity ΔN [kN]
S 2.1	580.14	864.23	284.09
S 2.4	-	856.66	-
S 2.5	160.02	459.24	299.22

ANALYTICAL MODEL

Modified analytical model was based on the preliminary model used in the first set of experiments (Kalamar and Eliášová, 2015) resulting from the stability of real rod with initial imperfection, Fig. 4. Corresponding material properties were considered for every used material: for glass as Young´s modulus E_{glass} = 70 GPa and Poisson´s coefficient ν_{glass} = 0.23, for plastic pad Young´s modulus E_{pad} = 3.5 GPa and Poisson´s coefficient ν_{pad} = 0.39. The adhesive can be similarly described by E_{adh} = 660 MPa and ν_{adh} = 0.34.

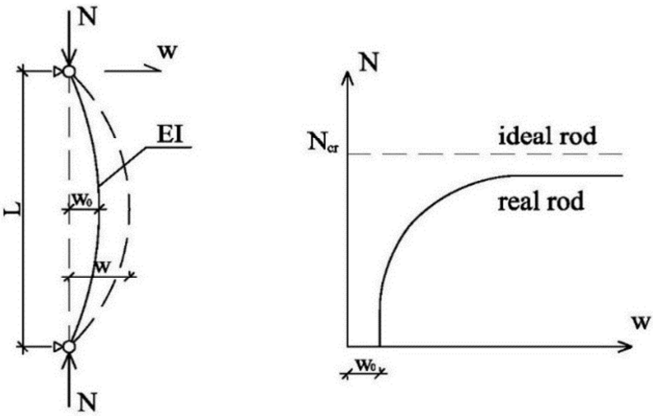


Fig. 4 - Simply supported column with initial and total deformation (Crisinel and Luible, 2004)

It is not possible to include all geometrical and physical properties thus smalli simplifications had to be accepted. The most important simplifications can be summarized as follows:

a) Cross-section along the entire length is considered as a rigid at the corners.
b) Nominal thickness of laminated glass panels were replaced by effective thickness.
c) All geometrical and material imperfection were considered in initial buckling shape.
d) Only one direction of buckling was considered.

Analytical solution for mid-span cross-section

Real rod loses the stability before the force reaches the critical force N_{cr}. Simply supported column and the first shape of buckling can be described by differential equation (1)

$$EI \cdot w'' + N \cdot w = 0 \,, \tag{1}$$

where E is represented by the Young´s modulus E_{glass} and I is effective moment of inertia $I_{y,eff,w}$ of the whole columns cross-section. This can be determined by equation (2)

$$I_{y,eff,w} = \sum\left(I_{y1,eff,w} + A_{1eff,w} \cdot z_{eff,w}^2\right), \tag{2}$$

where $I_{y1,eff,w}$ is effective moment of inertia for single panel, $A_{1,eff,w}$ represents the effective area for single panel and $z_{eff,w}$ is the centroid distance. All cross-sectional characteristics can be solved by following equations:

$$I_{y1,eff,w} = \frac{1}{12} \cdot h_{panel} \cdot t_{eff,w}^3, \tag{3}$$

$$A_{1,eff,w} = h_{panel} \cdot t_{eff,w}, \tag{4}$$

$$z_{1,eff,w} = 0.5 \cdot \left(h_{panel} + t_{glue} + 0.5 t_{eff,w}\right), \tag{5}$$

where h_{panel} - is the the glass panel height (i.e. h_{panel} = 150 mm), $t_{eff,w}$ - is the effective thickness replacing the nominal thickness of laminated glass panels for bending deflection calculation, (Draft prEN 16612). This simplification is based on the load duration and the effective transmission of shear forces between laminated panels, which was determined as ω = 0.5. The effective thickness can be then expressed by following equation

$$t_{eff,w} = \sqrt[3]{\sum_k t_k^3 + 12 \cdot \omega \cdot \left(\sum_i t_k \cdot t_{m,k}^2\right)}, \tag{6}$$

where t_{glue} - is the thickness of adhesive layer (i.e. t_{glue} = 3.0 mm).

The initial deflection w_0 in the middle of the cross-section can be determined as follows

$$w_0 = w_{0,1} + w_{0,2}, \tag{7}$$

where $w_{0,1}$ represents the initial material imperfection and was determined as a L_{panel} / 1250 mm, $w_{0,2}$ represents all geometrical imperfections which were in this case taken as L_{panel} / 300, where L_{panel} = 3000 mm.

Maximum deflection w can be calculated from equation (8)

$$w = \frac{w_0}{1 - \frac{N}{N_{cr}}}. \tag{8}$$

N_{cr} represents well known Euler´s critical force for the ideal column without initial deflections and the force can be obtained from equation (9)

$$N_{cr} = \frac{\pi^2 E I_{y,eff,w}}{L^2}. \tag{9}$$

Principal stress in the mid-span cross-section can be calculated by normal stress and additional bending strength combination. The principal stresses were in this analytical model calculated at the outer surface fibers by equation (10)

$$\sigma_{1,2} = \frac{N}{A_{tot,eff,\sigma}} + \frac{N \cdot \Delta w}{I_{y,eff,\sigma}} \cdot z', \tag{10}$$

where Δw is the difference between maximum deflection w and initial deflection w_0.

The effective moment of inertia of columns cross-section can be calculated by following equation

$$I_{y,eff,\sigma} = \sum \left(I_{y1,eff,\sigma} + A_{1eff,\sigma} \cdot z_{eff,\sigma}^2 \right), \tag{11}$$

where $I_{y1,eff,\sigma}$ is the effective moment of inertia of a single panel, $A_{1,eff,\sigma}$ represents the effective area of the single panel and $z_{eff,\sigma}$ is the centroid distance. All cross-sectional characteristics can be solved by following equations:

$$I_{y1,eff,\sigma} = \frac{1}{12} \cdot h_{panel} \cdot t_{eff,\sigma}^3 , \tag{12}$$

$$A_{1,eff,\sigma} = h_{panel} \cdot t_{eff,\sigma} , \tag{13}$$

$$z_{1,eff,\sigma} = 0.5 \cdot \left(h_{panel} + t_{glue} + 0.5 t_{eff,\sigma} \right), \tag{14}$$

where $t_{eff,\sigma}$ - is the effective thickness for stress calculation replacing the nominal laminated glass panels thickness (Draft prEN 16612). The effective thickness can be determined as

$$t_{eff,\sigma} = \sqrt{\frac{t_{eff,w}^3}{t_j + 2 \cdot \omega \cdot t_{m,j}}} . \tag{15}$$

Analytical model verification

Analytical model was compared with experimental results of specimens S2.1, S2.4 and S2.5 which were subjected to axial compression. Following figures represent force - stress relation with principal stresses measured by strain gauges in mid-span. Generally speaking, it can be seen that the model reflects the behavior until column collapse with safe reserve. Direction of the column buckling was determined on the basis of horizontal deflection measured by linear potentiometers. Force-stress relation in buckling direction is displayed in Fig. 5 where double dash-dot line represents principal stress which is increased by the effect of the bending moment and single dash-dot line represents principal stress which is decreased by the effect of the bending moment.

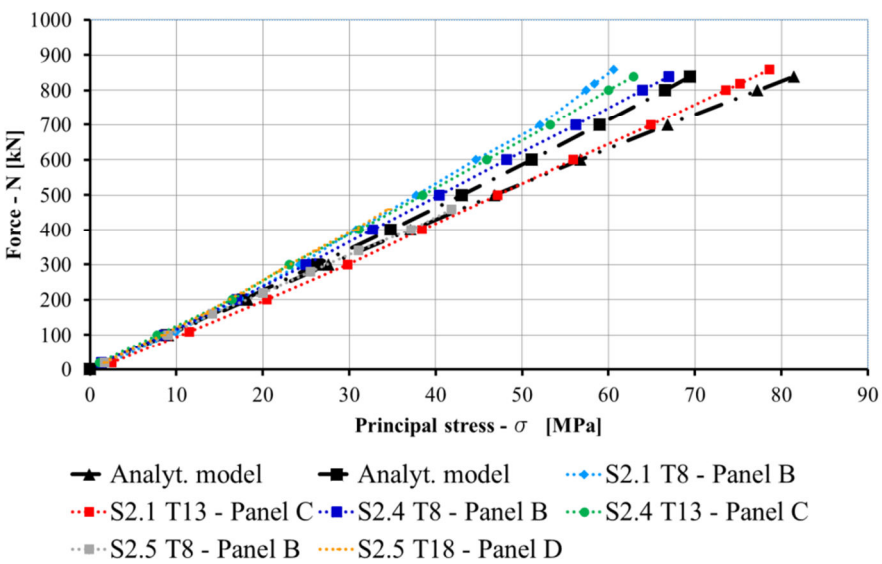


Fig. 5 - Normal principal stress in main direction of column buckling

Force-stress relation in direction perpendicular to the buckling is shown in Fig. 6. Normal stress was determined without the effect of additional bending moment. Results of analytical model fit with the experimental data and can be considered as a safe design with higher stress level with regard to the real stress recorded by strain gauges.

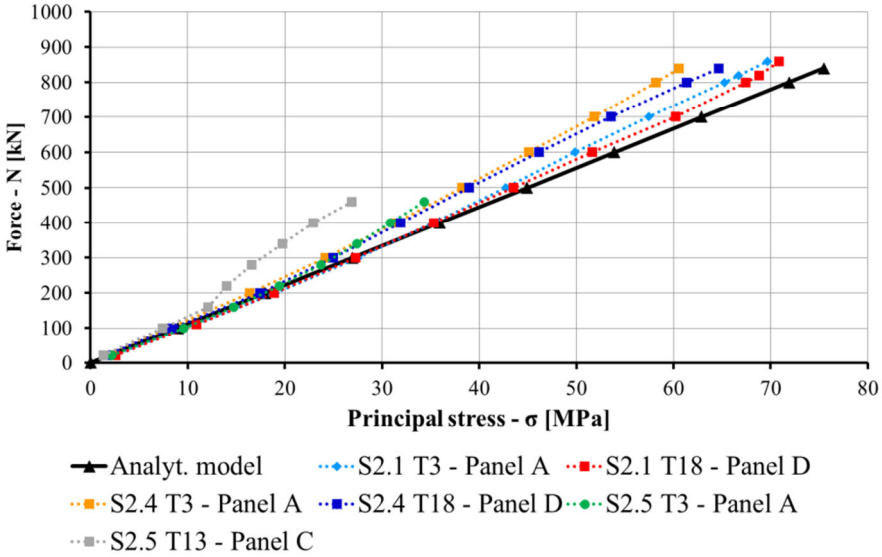


Fig. 6 - Normal principal stress in perpendicular direction to the column buckling

Comparison of measured horizontal deflection in direction of column buckling with analytical results are displayed in Fig. 7. It concerns the mid-span cross-section. Test specimen S2.5 reached the minimal load bearing capacity when the first crack was detected as well as the lowest force at collapse due to the unsufficient material properties of plastic pad. Test specimen showed greater horizontal deflection at the same time.

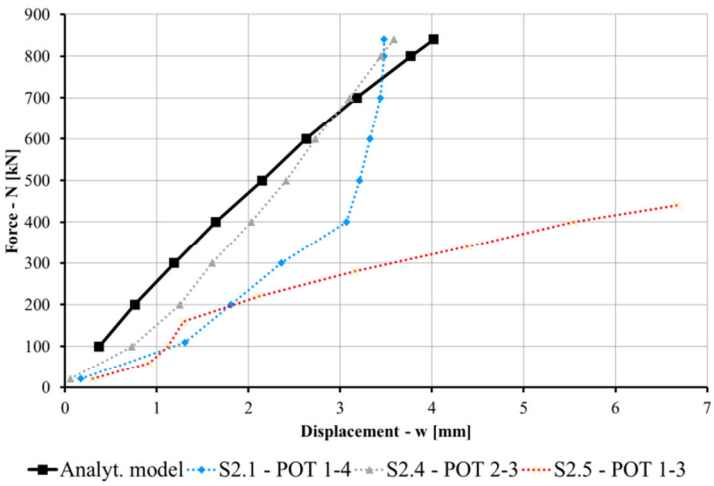


Fig. 7 - Normal principal stress in perpendicular direction to the column buckling

Discussion

The analytical model above mentioned fits with the experimental data at the mid-span cross-section in both directions and can be used for the preliminary estimation of column behaviour. More accurate model should be improved at the top and bottom part due to the lateral tension

and the local deformation of plastic pad at higher level of loading. The influence of adhesive connection between the glass panes and plastic pad should be also taken into account.

CONCLUSION

In this paper, experimental assessment of the structural performance of glass columns has been presented. The specimens were made from four double layered float glass panels with thickness 2x 10 mm and total length 3000 mm bonded at the edges into the hollow cross-section. Three test specimens were totally tested and experimental results were discussed and compared in order to highlight their overall compressive behaviour and failure mechanism. Specimens were subjected to the axial force continuously increased until the collapse. All specimens had significant load bearing capacity that was established at the moment of the first crack observation. Partially damaged column also showed significant residual load bearing capacity, i.e. additional load transfer before the collapse. It was observed that the first crack occurred at the bottom parts above the steel shoe due to the lateral tension. Technical solution of the top and bottom support affected normal forces transfer from the steel support through the plastic pad into the glass panes and had appreciable influence on the load bearing capacity.

Due to brittleness of the glass it is important to focus on details. Any imperfections can cause local stress peaks which may lead to premature breakage or absolute collapse. The choice of glass type has also the effect. Thermally improved glasses (toughened or heat strengthened glass) increased load bearing capacity but the residual capacity is almost negligible.

ACKNOWLEDGMENTS

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