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Fracture Behaviour of Glass Columns Experimental Study of Axial Loaded Glass Columns

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Abstract. Nowadays supporting structures can be transparent due to the development of glass strengthening procedures. The building glass as a versatile building material enables the efforts of the architects due to its transparency. This paper focuses on glass columns in the topic of load-bearing glasses and also on the design and load bearing capacity of fins and stability issues. Laboratory experiments were carried out at the BME, Department of Building Materials and Engineering Geology on the fracture behaviour of centrally compressed glass columns. More than 120 specimens where loaded until fracture. The load and deformations were measured. Based on the experimental results the critical force was determined and with force-deflection diagrams were illustrated the fracture and stability processes. Authors are going to compare the results of the laboratory experiments and theoretical calculations.

1. Introduction

Glass is called also the material of the third millennium, although glass is a brittle material and for a long time its brittleness was a well-known property besides its transparency [1]. This paper focuses on the buckling behaviour of the load bearing glass elements, especially on the glass columns. Laboratory tests were carried on axially compressed glasses in the BME, Department of Construction Material and Engineering Geology. Previous studies were demonstrated by the Authors of present paper about the topic: effect of non-standardised loads on glass columns which preferred to take into account beside of the standardised loads [2]. Based on the laboratory experimental results were presented e.g. effect of the rate of loading, heat strengthening, effect of the different height of the specimen and the effect of the lamination with total thickness of 12 mm (single layer, and laminated – two, and three layers – glasses) on the behaviour of glass columns. Three different stages were determined and introduced in the buckling behaviour of glass columns [2]. The critical buckling force was studied based on the international theoretical results and the laboratory tests [3]. Continuing the previous laboratory research, additional tests were done to clean earlier issues and to draw attention to the design problems of the glass columns. Present paper introduces the effect of the support on the buckling behaviour of glass columns e.g. influence of the damping material, and the fracture pattern of glass columns were studied as well. The fracture of this structural element can cause stability problems in the whole building, therefore the fracture process of glasses used in load bearing elements, must be extensively studied. The widespread application of glass justifies the economic efficiency of the construction beside of the safety.

2. Phenomenon of flexural buckling

Axial loaded columns start to deform without horizontal displacement at the beginning of the loading process. Damping material (rubber min. SHORE 60) is recommended to apply between the glass and the supporting steel surface. Therefore, the vertical displacement contains the deformation of the glass and the damping material as well. When the compression load reaches a critical value, the buckling of the column begins. This force is called (N_{cr}) critical buckling force. In the first Stage of the buckling process the loaded element can be unloaded without visible residual deformations. Until the loading force is increased up to the critical buckling force it is mainly a stability problem (SLS- Service Limit State of the columns). After reaching the critical buckling force post-critical Stages follow. In the case of further increase of the loading force, the column reaches the Ultimate Limit State (ULS), where the risk of the whole construction failure is significant. Significant displacements can be observed between SLS and ULS which serves as a reserve of the glass column in the post-critical Stages. The critical buckling force calculated with the application of the Euler formula was studied as follows:

$$N_{CR} = \frac{\pi^2 EI}{(\upsilon L)^2} \tag{1}$$

This formula includes physical properties of the glass element. However, the critical buckling force is sensitive of varying in the effective length factor. This factor can have different values depending on the shape of the buckled elements. Figure 1 introduces general buckled shape with the value of the effective length factor.

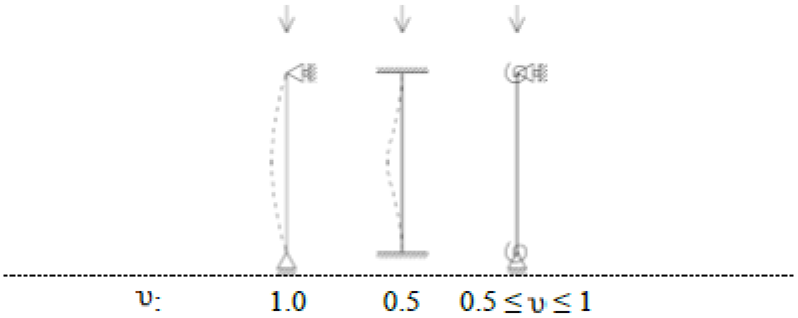

Figure 1. Critical buckling shape and the effective length factor

The effective length factor in the reality of a glass columns is between 0.5 and 1. Although the damping material causes displacement in the supports, - and functions like a spring in the fixings - the real effective length factor cannot be more than the value 1. The displacement of the damping material is not relevant compared to the overall column. The effective length factor varies during the loading process. Until the SLS the effective length factor approaches the value 1 (it functions rather like a pinned support) and after the SLS it reduces. The buckling of the specimen causes more fixed state in the supports (functions rather like a fixed support).

3. Laboratory experiments

3.1. Test parameters

Laboratory experiments were carried out to study the buckling behaviour of single and laminated glass columns. The specimens were tested with use of Instron 5989 testing machine. Single layer float and heat-strengthened glass and laminated glass consisted of both float and heat-strengthened glass layers were tested. The scales of the geometry of specimens (height, thickness, width) were selected on the basis of existing glass columns from international and Hungarian realized projects. Test parameters of glass specimens were the following: Constants: test arrangement, the type of support; width of glass (80 mm); interlayer material (EVA foil with thickness of 0.38 mm); edgework; temperature (+23 ± 5°C). Variables: type of glass layers: HSG/ non heat-treated Float; height of specimens: 1000 mm; 920 mm; 840 mm; number of glass layers and the thickness of specimens: single layer: 8 mm; 12 mm, laminated: 4.4 mm; 6.6 mm; 8.4 mm, laminated: 4.4.4 mm; The rate of loading: 0.5 mm/min; 1 mm/min. Support: Height of fixing: 95 mm; rubber plate (Shore A 80) was used between the steel supports and the glass. Simplified designation is used to distinguish the studied specimens, these are e.g. H_2(4.4)_2_920_0.5: ~ H, F: Type of glass: H – HSG; F – non heat-treated float glass; 2(4.4): Number of glass layers ex.: 4.4 mm laminated glass; 2: The number of specimen; 920: Nominate height of specimen [mm]; 0.5: Rate of loading [mm/min]. Abbreviations are used for the float laminated glass VG and for heat-strengthened laminated glass VSG [2-4].

3.2. *Experimental test set-up*

The load and vertical displacement of the upper cross-head of the Instron 5989 universal testing machine were continuously measured. At three different heights the buckling displacement (horizontal displacement) of all specimens were continuously measured with HBM displacement transducers during the tests. Strains at centre point on the surface of the glass panels were measured with HBM LY11-10/120 strain gauges. The tests were carried out at a room temperature (+23 ± 5°C). At least three specimens were tested at each testing combination. Laminated specimens were loaded until all glass layers were fractured. In total, 120 specimens were tested. The specimens were mounted as shown in figure 2 [2-4].

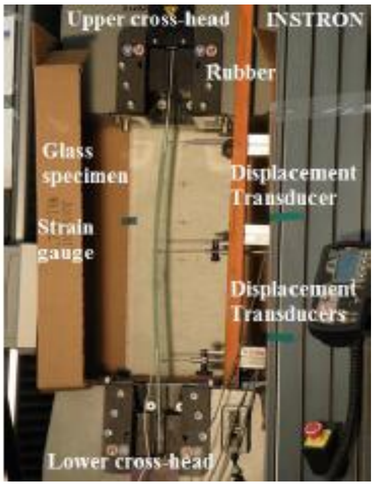

Figure 2. Test-set up

3.3. *New experimental results*

As mentioned in section 1 three different stages can be distinguished (figure 3 where number and arrows demonstrate the stages). In the 1st Stage, the elastic deformation of the damping materials (rubber plates) influences the vertical and horizontal displacements and no buckling occur (first stable stage). The allowed buckling load during structural design calculations is suggested to be the maximal load of the 1st Stage (stable state) reduced with safety factors. The 2nd Stage is a short term stage which indicates a geometrical unstable condition (the direction of horizontal displacement can be shown) and the specimen loses its former stability (bound phenomenon, instability). The 2nd Stage in the buckling behaviour is mainly influenced by the type of the supporting structure (fixed/pinned) and the stiffness of the glass columns. In the 3rd Stage, both the vertical and horizontal displacement increase until fracture of the glass (second stable stage). Considering the experimental results in certain cases the 2nd Stage was absent during the loading procedure. A specific value to the critical buckling load cannot be observed and the beginning of the post-critical Stage is difficult to determine. Strain gauges were placed in the centre of both outer surfaces of the glass columns. The figure 4 indicates the loading force vs. strains on the glass surface. At the beginning both outer surface of the glass column is in compression after that, the compression starts to decrease at one outer glass surface and tensile stresses develop. The buckling process starts during this phenomenon.

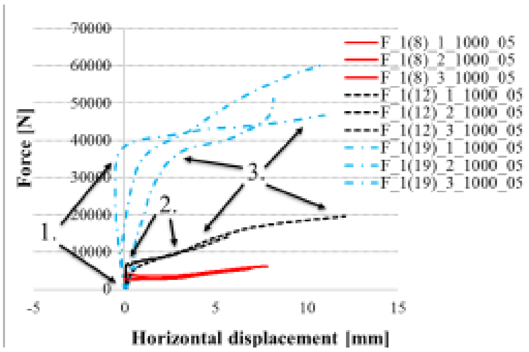

Figure 3. Stages of the bucking behavior

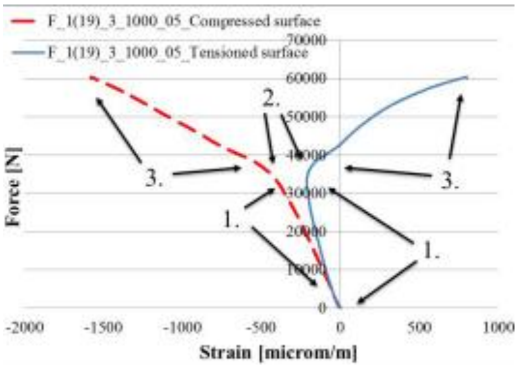

Figure 4. Strain vs. Force

Mean stresses calculated at the moment of buckling are shown in table 1. The stresses increase with the increase of the cross-sectional area of the glass. The stresses increase with the decrease of the height of the specimens in the case of laminated glasses. No significant difference can be observed between the stresses at the moment of buckling of float or HSG glasses with same thicknesses and with the height of 1000 mm, although this difference increases with the decrease of the height.

Table 1. Mean stresses at the moment of buckling

Number of layers	Thickness [mm]	Height [mm]	Stress of float glasses [N/mm^2]	Stress of HSG glasses [N/mm^2]
1	8	1000	6.26	3.99
	8	920	3.79	5.81
	8	840	7.58	5.12
	12	1000	9.33	10.72
	19	1000	25.32	22.57
2	4.4	1000	4.10	3.98
	4.4	920	6.13	4.73
	4.4	840	8.69	5.11
	6.6	1000	7.90	11.13
	8.8	1000	13.29	12.37
	8.4	1000	-	7.36
	10.10	1000	14.95	17.17
3	4.4.4	1000	7.50	8.22

3.4. Fracture pattern

The glass specimen fractures when the tensile strength of glass is exceeded by the stresses developed on the tensile glass surface. Actually the cracks start from the local edge defects (which were initiated e.g. by edgework). Two inflection points develop during the buckling process. The locations of the inflection points are affected by the height of the glass columns, the stiffness and the supporting conditions as well. Dense crack pattern can be observed in the region of the inflections. Two inflection regions developed, which are near to the supports [4].

Local maximal tensile stresses develop in the inflection regions. In the 3rd Stage the maximal tensile stress developed in the mid of the height of the specimen, opposite to the tensile glass layer at the inflection region. The buckling length of the glass column reduces in the case of fixed support compared to pinned, therefore the location of the local and maximal tensile stresses are influenced by the supporting conditions. In float glasses the cracks with critical thickness can propagate in the location of the local stress regions as well. In the case of heat-strengthened glasses the distribution of cracks influences the strength of the glass, therefore the strength of a glass column is mainly influenced by the area of glass layers in tension.

In the case of glasses consisted of glass layers of 4 mm thicknesses, the fracture originates at the mid of the height of the specimens. With the increase of the thickness of glass layers from 4 mm up to 6 mm the local stresses increase in the inflection regions, therefore in these regions cracks develop. In the case of thickness of glass layers the normal stresses increased in the vertical direction and the cracks propagate also in the vertical direction in the glass layers. In the case of unsymmetrical laminated glasses consisted of thicknesses of 8 and 4 mm glass layers the thicker glass layer fractured at first. More cracks were developed in the thicker (8 mm) glass layer than in the thinner (4 mm) glass layer. Vertical cracks formed in the glass layer with thickness of 8 mm as well (Figure 5-6).

Figure 5. Cracks types and crack regions. Float/VG consisted of 6.6 mm

Figure 6. Cracks types and crack regions. HSG/VSG consisted of 8.4 mm

3.4.1. Studies based on the international experiments.

Laboratory experiments were carried out by Italian researches [5] on laminated specimens consisted of glass layers with thicknesses of 4 mm, and with use of PVB interlayer material. They applied constant width of 300 mm and the heights of the specimens were varied (400, 500 and 600 mm). The specimens were loaded with axial compression. All of the glass layers were fractured, and three regions of cracks were observed in the glass layers. The glass layers fractured at the mid of them and near to the supports. The fragmentation pattern is connected with the more rigid behaviour of these specimens compared to that of used in experiments (e.g. VG 4.4 with height of 1000 mm). In our experiments the scales of the specimens were determined based on the size of the realized glass columns in the literature review, which are commonly used in practice. The ratio height/ width (H/B) varied from 1000/80 to 840/ 80 and the ratio width/ thickness varied from 80/12 to 80/4. The Italian researchers applied in their calculations n=0.5 (buckling length factor) value to evaluate the critical buckling load, although rubber as a damping material was used in the supports. Rubber as a damping material allows deformations (e.g. rotations of the glass specimen in the supports) due to its elastic behaviour.

4. Calculation results. Slenderness and the critical buckling force

4.1. Single layer float glasses

To compare the experimental results a common effective length factor must be determined. The theoretical limits of the effective length factors are comparable in the case of single layer glasses and laminated glasses based on the experimental results [2]. Figure 7 indicates the slenderness of the tested glass columns vs. critical buckling force. The mean results of specimens are above of the effective length factor value 1, which means that the supports are rather pinned. Above of the curves are numbers which show the thickness of the specimens.

4.2. Laminated float glasses

In the case of laminated glasses significant difference can be observed in the buckling behaviour. The laboratory experimental results of laminated glasses consisted of two glass layers, - thickness of 4.4; 6.6; 8.8; 10.10 mm - indicated a more fixed supporting state. Although it means the supports are stiffer, the test set-up did not vary. The changes are justified by the effects of the interlayer material. When calculating the border curves of the critical buckling load, the effect of the interlayer material cannot taken into account. In the laboratory experiments short term loading was applied (loading rate of 0.5 mm/min). In the future it is suggested to study the stress sharing effects in the case of long term loading (Figure 8).

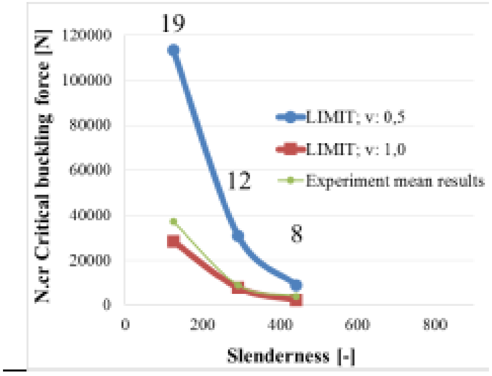

Figure 7. Slenderness vs. Critical buckling force in case of single layer glasses

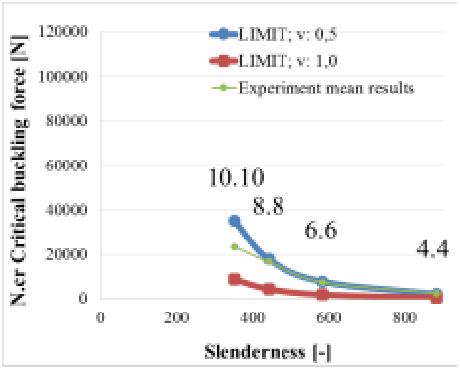

Figure 8. Slenderness vs. Critical buckling force in case of laminated glasses

5. Conclusion

Three different stages can be distinguished in the buckling behaviour of glass columns. However, the 2nd Stage may be missing depending on the initial shape and stiffness of the supporting system. Dense crack pattern can be observed in the region of the inflections. The width of fractured region increases with the increase of thickness of the specimen. The fracture pattern of HSG glasses is denser compared to that of float glasses and contains vertical cracks, as well. No significant difference can be observed between the stresses at the moment of buckling of float or HSG glasses with same thicknesses and with the height of 1000 mm, although this difference increases with the decrease of the height. The range of the effective length factor in the reality of a glass columns varies between 0.5 and 1. Although the damping material causes displacement in the supports, the real effective length factor cannot be more than 1. The supports of single layer glass are rather pinned until the results of laminated glasses are more closed to the fixed supporting condition based on the experiments and calculation.

Acknowledgement

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