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Classification of “I” – Shaped Glass Columns

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Abstract

The application of glass as a modern material in construction field is highly desirable in comparison with other materials such as wood, steel or the reinforced concrete due to aesthetic purposes. Hence there is a high demand of official standards that meet the industry requirements. Glass recommendations which define the function of the materials as a load bearing element are not available as other conventional materials but only some references in the literature. In the last years the properties of glass and the interlayer foil developed at a high rate. This development is not typical if we compare it conventional building materials. However, the glass designing demands are more sensitive in material and safety as well as in comparison with the other materials. Therefore, load bearing capacity, durability and the individual properties of glass must be examined in parallel sequence. More than 120 scaled-size specimens were loaded under compression to study the buckling behavior of glass columns with plane shaped cross-section at the BME, Department of Construction Materials and Technologies. During the tests, loading behavior and properties of the columns were under examination and analysis. The measured and calculated critical buckling forces, maximum forces and strengths were analyzed in function of slenderness. The glass specimens were classified into different groups based on the experimental results because classification is a primary issue at the designing phase. Authors provide aspects to the classification in the present article. Planeness of some specimens were measured to take into account their initial geometric imperfections for the classification. The rollers affect the shape of the glass table during the heat strengthening because waves are formed on the glass at the solidification moment of glass.

Keywords: Buckling; columns; glass; glass planeness; stability

1. Introduction

It is unnecessary to emphasize the role of glass as load bearing elements in buildings. Glass must possess design standards as other construction materials. Although standards cannot cover the glass designing at the international level. Even less information are available for the topic of buckling of glass. Therefore, this subject has to be under investigation in order to ameliorate the safety and reduce the risk of danger. Nowadays several researchers in many countries examine the buckling of glass columns in case of different cross-section. The authors wanted to investigate the base of the buckling phenomenon and the behavior of the glass columns, hence more than 120 plate glass specimens were loaded under compression by concentrated load at the laboratory of Department of Construction Materials and Technologies, BME.

In case of different glass types, the dependency of ULS and SLS of glass columns on the buckling type was investigated in the present article. The own shape distortions influence highly the stability behavior. The different glass processing methods (e.g. heat strengthening, lamination) also have an impact on the own shape. Instead of the existing distortion measurement methods, a new method had to be introduced which was applied in this research. The measured results justified the mentioned effects.

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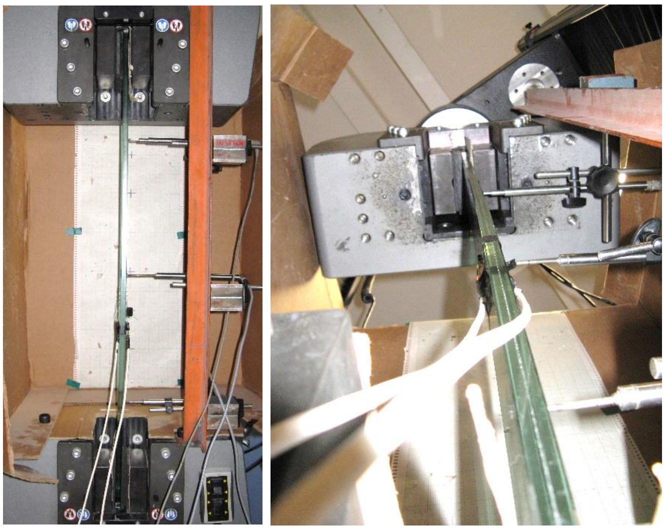
2. Test parameters and test set-up

Laboratory experiments were carried out in order to study the buckling behavior of single and laminated glass columns. Specimens were examined with the application of Instron 5989 testing machine. The scales of the geometry of specimens (height, thickness, width) were selected based on existing glass columns from international and Hungarian realized projects. Test parameters of glass specimens were selected as the following: Constants: test arrangement; support type; glass width (80 mm); interlayer material (EVA foil with thickness of 0.38 mm); edgework with polished edges; temperature (+23 ± 5 °C). Variables: type of glass layers: heat strengthened glass (HSG) / non heat-treated float glass (annealed glass); height of specimens: 1000 mm; 920 mm; 840 mm; number of glass layers and the thickness of specimens: single layer: 8 mm; 12 mm 19 mm, laminated: 4.4 mm; 6.6 mm; 8.4 mm, 8.8 mm, 10.10 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 designations are used to distinguish between 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 were used for the float laminated glass VG and for heat-strengthened laminated glass VSG. Although laminated glass with PVB interlayer foil and fully tempered glass (FTG) were not the part of the test parameters, a few pieces of these were tested as well [1].

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 center point on the surface of the glass panels were measured with HBM LY11-10/120 strain gauges. At least three specimens were tested at each testing combination. Laminated specimens were loaded until all glass layers were fractured (Figure 1-2.)

Figure 1-2. The laboratory test set-up.



3. Experimental results

3.1. *Determined stages in the loading behavior*

Characteristic curves are presented as loading force vs. displacement (vertical, horizontal and deformations) diagrams to study the laboratory experimental results. Curves are categorized in three separate groups according to the numerous experimental results. Variation can be noticed in case of loading force vs. horizontal displacement diagrams. The characterization of the specimens depends on the stages of the loading history of the specimens. The name of stages are [2,3]:

- First stable stage
- Unstable stage
- Second stable stage

3.2. *Grouping of the glass specimens*

The *first group* contains all of the previously mentioned stages and in this group were experienced the highest critical bucking forces when compared to the other groups results. Force reduction can be observed on the vertical displacement diagrams in the buckling moment. Specific buckling point cannot be determined in case of the *second group,* the unstable stage disappears and after a stable section, the buckling is gradual. Only one stable stage can be observed in case of the *third group,* so the ultimate force can be determined, but not the critical buckling force [4].

The results of the specimens had to be distinguished depending on the groups of buckling at the comparison of the influence of the variables. All of three type of buckling can easily occur at one testing combination (one type of glass specimen). Despite the fact that different buckling types and different critical buckling forces are experienced at one testing combination, ultimate forces are equal as shown in Figure 3. The HSG can reach higher horizontal displacements and higher ultimate forces than the annealed glasses. However, the critical buckling forces of annealed and HSG scatter in the same range. The ranges are different for each testing combination. It also demonstrates that the ultimate limit state depends rather on the glass surface defects and on the glass strength, which can be increased by the heat strengthening. Furthermore, the critical buckling force depends rather on the imperfections. These experimental results mean that the type of buckling does not influence significantly the value of the ultimate force.

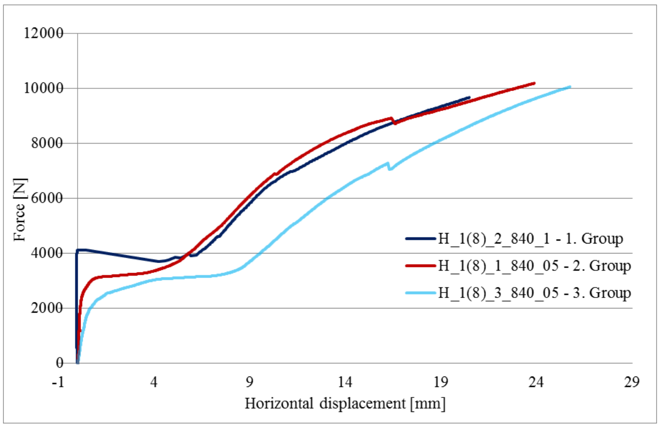


Figure 3. Loading histories of glasses which belong to one testing combination.

The average ultimate force results of the different groups are closely to each other. In Table 1. can be seen the average ultimate force quotients in percentage, which is obtained by the dividing the average ultimate force of a group by another. The standard deviation is below than 10 % in case of ultimate forces, but this value is over than 10 % in case of the critical buckling force due to the different buckling types.

Table 1. The comparison of the average ultimate forces (Fmax) of the groups.

The numbers of compared groups	Quotient [%]	Standard deviation [%]
1 – 2.	101,47	7,94
2 – 3.	97,28	5,66
1 – 3.	97,20	9,07

The difference between the critical buckling and ultimate force is lower in case of the *first group*; it is more significant in case of the *second group* as shown in Table 2. The situation is similar in case of the single layered glass or annealed glass because the difference on average is lower between the critical buckling and ultimate forces than the laminated and HSG.

Table 2. Comparison of the ultimate force (F_{max}) and the critical buckling force (N_{cr}) per groups.

	N_{cr}/F_{max} at the *1. group* [%]		N_{cr}/F_{max} at the *2. group* [%]	
The layering	Single layer	Bilayer	Single layer	Bilayer
Annealed glass	57	94	32	45
HSG	45	77	25	31

4. The distortion measurement

4.1. *Standards and previous measurements*

The distortion of glass influences heavily the stability and load bearing capacity of the load bearing elements. The influencing distortions are the overall bow, roller wave distortion, edge lift or twisted initial imperfection according to the standard EN 1863-1 [5]. This standard does not recommend definitely adequate measurement methodology. For instance, the measurement of roller wave is the following: use a straight edge and place it at right angles to the roller wave and bridging from peak to peak of the wave. However, this measurement does not provide continuous information about the shape of the specimen. This methodology seems simple and inaccurate. The own shape initial imperfections need more information about the shape to take into account at the calculation of buckling. The shape of glass surface was measured by international researchers as well [6]. They applied the previous method and a continuous lineside methodology. The linear error meant the own shape of the auxiliary line structure, hence a displacement transducer was applied perpendicular to the surface, and it was moved along the glass.

4.2. *New measurement methodology*

In our measurement methodology, the glass was fixed and the Wenzel LH 108 3D Coordinate Measuring Machine was moving above of the glass. The glass lied one of its side on the machine. The Metrosoft CM software was applied and micrometer was measured in high accuracy. Reference Point System was the most accurate method for the measurement. The measurement methodology was the following: Three points were chosen from the four corner points on the surface area of the glass. These points were base points of the measurement and they determine a plane. The different distance between the determined plane and the fourth point was divided between the 4 corner points, so a new plane was determined, in which is an average plane according to the four corner points it is called bestfit method. Three additional different base points were added in the two other axis: two points were perpendicular to the longitudinal axis and one parallel to the longitudinal axis. These points were needed to place the glass in three dimension. The machine measured the glass waves perpendicular to the surface. The own shape, twisting and the other distortions were determined with the application of this measurement. The measured points were placed in three different lines, two lines were placed 15 mm from the edges in longitudinal direction. The third line was in the middle of the specimen. The measured points were placed 15 mm from each other in one line. The application of closer measuring point system does not increase the accuracy of the measuring only the measuring time. Three measured lines were applied in case of the 80 mm wide specimens and five in case of 1200 mm long and 360 mm wide specimens.

5. The distortion results

5.1. *Basic notifications of the measurement results*

The twisting of glass was easy to determine in the application of this methodology. However, the difference of the first measured value per lines and the other members of each measurement line have to be analyzed for the overall bow determination. Roller waves are in this methodology the depth between two adjacent waves, which can be also easily determined.

Surface imperfections were measured in vertical direction. It means that the glass specimens lied on side. Hence, the effect of the shoulders, where the glass touched the plane surface of the machine, ought to appear in the measurement. This error does not clearly appear, therefore the measurement data contain them.

The effects of the interlayer foil, the laminating procedure (PVB, EVA) and the tempering were studied on the initial imperfections in case of the 1200 mm long and 360 mm wide specimens. However, the results of these glasses were not suitable to analyze the buckling phenomenon of the glass. Although the 80 mm wide specimens were compressed by centrally load after the distortion measurement. The distortion of the specimens was examined by inspection before the loading. Higher overall bow and roller waves could be determined and in certain cases where the direction of the buckling was predictable. Nevertheless, the distortion, that is noticeable by inspection, means significant imperfections. The latter can influence heavily the critical buckling force of the specimen.

5.2. *Distortion results of the 1200 mm long 360 mm wide specimens*

The maximal measured values of float 12 mm thick single layer glass and laminated glass, consisted of two 6 mm thick glass layers, were below 0,2 mm. The maximal measured value of the other glasses (the laminated float glass consisted of three 4 mm thick glass layers and the other fully tempered single and laminated glasses) were between 0,1-0,6 mm as shown in Table 3. The results of laminated FTG were the largest during the whole testing. The distortion of the annealed glass was even smooth and no visualization of regular curves in the diagrams. The diagrams are rather curved and the roller waves can be observed in case of FTG. The displacements of roller waves are comparable with the distribution of rollers in the heat strengthened furnace where the displacement of the rollers is 125 mm. The value of the overall bow of FTG also stepped to a higher level. Not only small waves were experienced in the results but there were higher waves between more rollers as well. These waves could influence the whole shape of the glass. The highest roller wave depth was 0,077 mm in case of FTG. This value is 0,053 mm was in case of HSG. However, there were smaller waves in case of annealed glass with 0,02 mm depth despite the fact that the float glass was not heat treated. These waves can be formed when the float glass is still not enough solid and already is pulled from the melted tin to the rollers, where it will solidify. These statements must be confirmed by further measurements.

Table 3. Maximal value of the distortion measurement results.

Type of glass	Overall bow [mm]	Roller wave [mm]
Single layer float glass	0,15	0,02
Laminated float glass with PVB foil	0,07	0,002
Laminated float glass with EVA foil	0,2	0,02
Single layer FTG	0,35	0,03
Laminated FTG with EVA foil	0,6	0,077

5.3. *Distortions and own shapes of measured specimens*

In Figure 4. and 5., the distortion measuring results can be seen. Both sides of float and heat strengthened laminated glass, consisted of two 4 mm thick glass layers are drawn. The overall thickness is 8.02 mm and the measured surface is marked with blue color. Normal differences cannot be distinguished from the ideal surface hence the differences were magnified 20 times signed by red color. The surfaces are approximately parallel in case of all type of specimens. Differences can be determined at the end of specimens in case of laminated glasses, where the laminating procedure causes that the surfaces are closing due to the air suction. The detected waves in shorter or longer displacements on one side can be compared with the other side waves. The diagrams clearly illustrate that the convexity of the waves located in the same position (adjacent) are the same except the end waves. The radius of the curves is also similar in same position. Before laminating these glasses had with major probability different own shapes, after the lamination they had definitely one common shape. The overall bow can be seen in case of float glass, which has the major responsibility for the direction of the buckling.

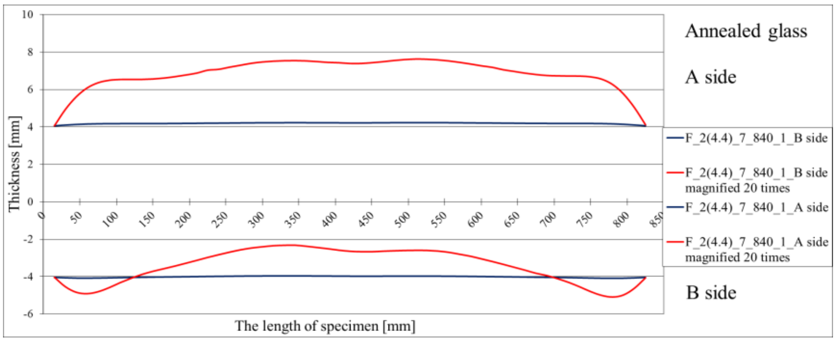


Figure 4. Distortion measurement results in case of annealed laminated glass.

The overall bow was the least in case of the laminated glass consisted PVB interlayer foil, in one case the maximum measured value was less than 8 micrometers which was equal with the sign of the permanent marker. The knowledge of the own shape makes estimable the calculation. The roller waves can increase the critical buckling force in certain cases.

The authors are planning to measure the distortion in case of new specimens with this new methodology and to study the influences of the distortion for the buckling capacity and phenomenon because a lot of new information were determined from this few measurement and it seems much more reliable and accurate than the earlier type of measurement methodology.

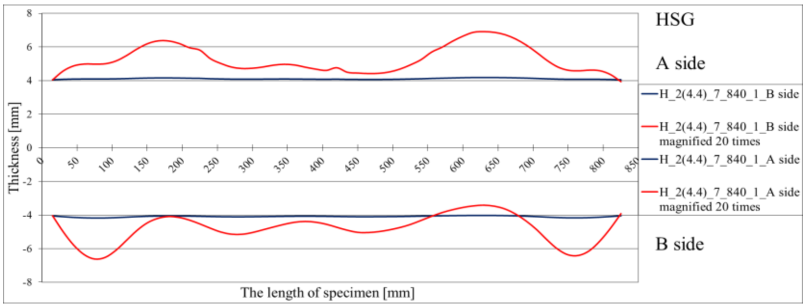


Figure 5. Distortion measurement results in case of heat strengthened laminated glass.

6. Conclusions

In this paper, significant results were demonstrated in the aspect of the "I"-shaped glass columns designing. The type of buckling does not influence significantly the ultimate force. The standard deviation of the critical buckling force is above than 10 %, however it is less than 10 % in case of ultimate force. Therefore, the ultimate force can be calculated independently of the type of buckling. In the future, the authors have to determine and apply designing factors in the calculation formulas of critical buckling force to make the designing more accurate and safe. In case of the first group, the critical buckling forces occurred at higher loading force than the second group depending on the glass types. Concerning the design, the results indicates that the efficiency of the load bearing capacity is better in case of the first group, however designing for the critical bucking forces of second group is safer.

A new distortion measurement methodology was demonstrated. The maximal values of overall bow and the roller wave depth were presented in case of different glass types. It is stated that the lamination method and the heat strengthening can increase mostly the measured values of distortions. The roller wave can increase the buckling resistance in particular case, when the curvature of the local distortion is opposite of the whole buckling direction, the overall bow will decrease the SLS. The measured sinus wave depths were 10 times lower than the overall bow based on the new distortion measurement method. It is necessary to incorporate more realistic own shape of the structural element into the calculation formulas.

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