MŰEGYETEM 1782

BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
DEPARTMENT OF CONSTRUCTION MATERIALS AND TECHNOLOGIES

INTERPRETATION OF THE STABILITY LOSS OF GLASS COLUMNS CAUSED BY SHORT-TERM AXIAL COMPRESSION BASED ON LABORATORY EXPERIMENTS

New Scientific Results

PhD Thesis

András JAKAB
Structural engineer, MSc

Supervisor:
Dr. Salem Georges NEHME, PhD
professor associate

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Contents

1. RESEARCH SIGNIFICANCE AND OBJECTIVES

The analysis of the design of glass columns had become the most investigated research field over the past 10 years. Significant scientific researches were investigated by Swiss (Luible, 2004), Belgian (Belis et al., 2009), Italian (Amadio & Bedon, 2010), Polish (Kalamar et al., 2016) and Chinese (Qiang et al., 2017) engineers, who created the literature of the topic of glass columns design. They investigated small- and large-scaled specimens with rectangle, square (Kalamar et al., 2016), "T" and "X" cross-sections (Aiello et al., 2011).

The answers for the basic questions of the glass columns designing are looked for in my doctoral research, for instance: Which is the best type of glass for glass columns? The influencing factors of the glass columns designing are investigated highlighting the safety aspects. Moreover, the EC 10 Glass design standard is not available for the engineers, therefore the calculation of the vertical diaplacement was applied for the Service Limit State based on the JRC Scientific and Policy Reports (Feldmann & Kasper, 2014)

Ideal pinned support methods were applied by the researchers at the laboratory experiments (Feldmann & Langosch, 2010) (Pesek et al., 2016). The main objective in the PhD research was to investigate the effects of the more realistic conditions of the supports.

Small-scale, simple and plate crossection were tested in the tested specimens. The specimens were loaded by short term axial compression. The load bearing capacity and the factors that influence the loss of stability were analysed. The analysed design factors are applied in case of glass columns that have different cross-sections, therefore present scientific results basically affect the design of glass columns.

The main objectives of the doctoral research are the following:

- Classification of the stability behavior and properties of the glass columns.
- The affects of the glass columns' physical properties on the loss of stability and load bearing capacity.
- More realistic supports were applied, where the lateral stiffness was varied to analyze its effects on the loss of stability and the load bearing capacity
- The analyses of the initial geometrical imperfections and their effects.
- The applicable initial imperfection in the designing.

2. LITERATURE REVIEW

The floating process of the glass production results in perfectly parallel glass surfaces based on the traditional beliefs of the glass industry. The glass can bend due to the small bending stiffnes. The glass can be laminated to increase the bending stiffness and to avoid the deformations. The residual stresses caused by the cutting, modify the glass surface and shape, therefore the float glasses (without heat strengthening) have also geometrical imperfections (EN 1863-1:2012).

The shape of glasses is modified by the heat strengthening procedures. The overall bow values of the glasses increase compared to the float glasses. The modified glass shape develops because the gravity attracts the ductile glass plaine into the ceramic cylinders. To avoid the high deformations, the glass shapes are moved quickly. Although, the glass becomes solid at the softening temperature, the glass shape adopts to a sinus wave shape (EN 1863-1:2012).

The initial geometrical imperfection significanty influences the stability and load bearing behavior of glass columns. The overall bow and the sinus wave of the glasses are measurable according to the EN 1863-1 standard, however the twisted curvature cannot be measured. The recommended measurement methods are not automated, continuous and the measuring accuracy is objectionable. The overall bow (2-1. figure 1) and the sinus wave (2-1. figure 2) depth are limited. The limit of the overall bow is 3,0 mm/m, for the sinus wave it is 0,4 mm. The limit of the overall bow is required, because the increasing of this factor can decrease the force level of the stability loss. Contrary to the overall bow, the increasing of the sinus wave can increase also the force level of the stability loss based on the critical buckling force of Euler, however this theory is still not proved in the practice of glass columns designing.

2-1. Figure a) overall bow (1-size of overal bow; 2-glass specimens) b) sinus wave (3-heat strengthened glass specimens) (EN 1863-1:2012)

In an international research (Belis et al., 2011) overall bow and sinus wave values were analysed on 3 m long glass specimens in case of float glasses (Float), heat strengthened glasses (HSG) and fully tempered glasses (FTG). 120, 150, 200 and 300 mm wide glass specimens were tested. The tests were carried out according to the EN 1863-1, EN 12150 standards and individual tests, where linear variable differential transformers (LVDT) were applied for the continuous and automated tests. Based on the statistical values Jan Belis and the co-authors recommended 0,0025 mm/mm limits for the initial geometrical imperfections of HSG and FTG. The recommended value is 17 % less compared to the recommendation of the maximal overall bow of the EN 1863-1:2012 standard. The authors recommended L/400 limit for initial geometrical imperfections. The imperfection factors that influence the stability loss of the glass columns are summarized in Table 2-1. from the production until the installation.

2-1. Table The imperfection factors that influences the stability loss of the glass columns from the production until the installation

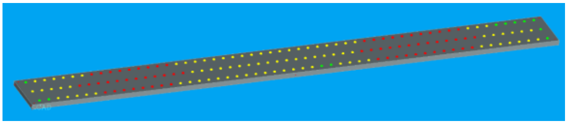
The basic glass product (production)	Glass manufacturing	Installation
- Modification of the material structure due to the liquid tin during the floating - Overall bow and sinus waves - Residual stresses due to the cutting - Size differencies	- Cutting unevenness - Edge works - Heat strengthening - Laminating process: stress sharing, curves, extended edges (inaccuracy)	- Skew position - Lack of damping material or not enough stiffness - Eccentricity at the installation

3. LABORATORY EXPERIMENTS

3.1. Surface measurements

The surface deformation was measured at the Salgglas Ltd with the Wenzel LH 108 3D Coordinate Measuring Machine (3-1. Figure a). The measured data were analysed by the Mestrosoft CM software (3-1. Figure b). Reference Point System was the applied measuring process, and its accuracy is 10^{-3} mm. The specimens were horizontally laid on the machine. 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 machine measured the glass waves perpendicular to the surface. Bestfit point was applied to define a theoretical plaine of glass. The measured results were the distance between the theoretical plaine and the measured surface (the smallest difference between the point and plate).

a)



b)

3-1. Figure a) Wenzel LH 108 3D Coordinate Measuring Machine at the Salgglas Ltd. b) measuring results of a HSG specimen

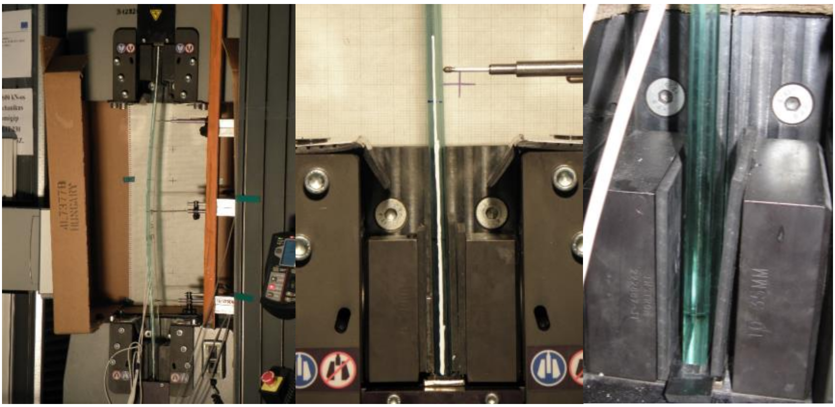
Six base points were applied to determine the position of the glass specimen in the space of the machine. Three points were chosen from the four corner points on the surface area perpendicular to the surface. These points determined a plane, and a last corner was the "bestfit" point, the difference between the last point and the plane was divided between the corner point, this process results the theoretical surface of the glass. Further 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.

The overall bow and sinus wave values of the three different measurement lines were separately determined, therefore the results were absolute values. The analyzis of the twisted figures required the comparison of the three measured lines, therefore it resulted in relative values (future work). The glass shape can be analysed by the pairing of the sides of specimen for instance the effects of the glass producing methods. 68 pcs of surface measurements were carried out on 35 pcs of specimens in the research (at the callibration measurements sometimes only one surface of the specimens was measured).

3.2. Compression by short term axial loading

In order to study the buckling behaviour of glass columns laboratory experiments were carried out in the Laboratory of Department of Construction Materials and Technologies. The small-scaled specimens were tested by the Instron testing machine (3-2. Figure). The scales of the geometry of specimens (height, thickness, width) were selected based on existing glass columns of completedprojects in Hungary: the ratio of the height/width is 12,5. All tested specimens were loaded until fracture by displacement controlled short term axial compression. Constant load was not applied so the deformations of the viscoelasticity materials were not investigated. Float and HSG glasses were tested, which were provided by Rákosy Glass Ltd., therefore the results of the research refer to the glass applied in the factory and to the glass processing methods of the factory.

During the compression tests the horizontal (in three different heights), the vertical displacement, the loading force and the strain of the middle point of the specimens were measured.



a) b) c)

3-2. Figure a) Experimental test set-up b) partly fixed and c) partly pinned support

Experimental constants: *test arrangement; support type; hardness of damping material*: Shore A 80; the type and *the thickness of interlayer foil:* EVA, single layer foil 0,38 mm, the *testing temperature* +23 ± 5 °C, the *polishing* of the glasses; the *rate of loading*: in the calibration period: 0,5 mm/min and the testing period 1,0 mm/min and the *type of glass* ($CaONaSiO_2$).

Experimental variables: the *type of glass*: *float glass* without heat strengthening and *HSG*; *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 glasses consisting of the following layers: 4.4 mm, 6.6 mm, 8.4 mm, 8.8 mm, 10.10 mm, 4.4.4 mm; *glass width*: 80 mm, 100 mm, 120 mm; the *stiffness of support, rather pinned* (only 1-1 layer damping material is applied between the glass and steel, means easily rolling) or *rather fixed* (the space between the glass and steel filled completely with rubber, limited rolling 3-2. Figure), however the elasticity of the rubber cannot be totally fixed; *the setting accuracy*: the normal condition was the perfectly vertical direction of the specimens, at the additional tests the specimens were skewed by 1,0±0,5° degrees.

The experimental program can be seen in Table 3-1. The Table contains 228 pcs of glass specimens and the 12 pcs used for additonal tests. Further tests were carried out on same specimens whichare not included in the Table 3-1. The explanation of the simplified symbol is in Table 3-2.

3-1. Table Experimental program

Layering	Nominal heights [mm]	Width [mm] / Type of glass						Summa-rized
		80		100		120		
		Float	HSG	Float	HSG	Float	HSG	
8	1000	5	10	2	2	3	3	25
	920	3	7	-	-	-	-	10
	840	3	7	-	-	-	-	10
4--4	1000	4	4	-	-	-	-	8
4.4	1000	6	9	2	3	3	3	26
	920	4	8	-	-	-	-	12
	840	4	7	-	-	-	-	11
12	1000	7	4	2	2	3	3	21
6.6	1000	8	6	2	2	3	3	24
4.4.4	1000	5	3	3	2	3	3	19
8.4	1000	-	3	2	2	3	3	13
19	1000	3	3	2	2	3	3	16
8.8	1000	4	3	2	2	3	3	17
10.10	1000	3	3	2	2	3	3	16
Summarized		59	77	19	19	27	27	**228**

3-2. Table Simplified symbols of the specimen F_2(6.6)_2_1000_100_1

Symbol	Explanation
F	Type of glass (Float)
2(6.6)	The number of layeres and a nominal thicknesses of layers e.g: 2×6 mm
2	Serial number of the specimen in case of the similar specimens
1000	The nominal height of specimen: 1000 mm
100	The nominal width of specimen: 100 mm
1,0	The applied rate of loading [mm/min]

4. RESEARCH METHODS

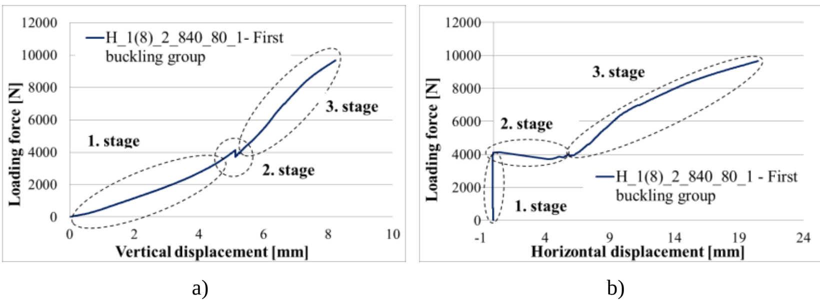
4.1. Surface measurements

The overall bow, sinus wave and the shape of the specimens were measured by the RPS and results were compared in Microsoft Excell. The surface curves were represented along the specimens, where the maximal peak means the maximal overall bow. In case of HSG the sinus waves were measured from the represented length-surface distortion curves and the mean values were calculated for one side of a specimen, which also characterized the specimen. The mean values contained the three measurement lines of the side of specimen. The effects of the glass manufacturing processes were presented on values of the overall bow, sinus wave and the shape of specimen. The measured deformations of the specimens were below of the standardised limits, therefore the conclusions of the measured values are generally applicable.

4.2. Compression by short term axial loading

The diagram of loading force – horizontal displacements provided the most important information about the buckling behavior of the specimens. The glasses with similar properties were compared foremost, then the experimental variables meant the basis for the comparison e.g: the effects of the stiffness support on the type of stability loss and the maximal force and displacement.

The loss of stability is flexural buckling (Timoshenko & Gere, 1961). Three different stages were observed during the loading: 1. stage: stable, 2. stage: bifurcation (snap through) 3. stage: stable (4-1. Figure a) and b)).

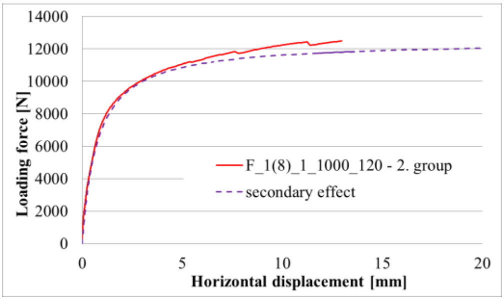


4-1. Figure Characteristic buckling diagrams loading force - a) vertical and b) horizontal displacement in case of the first buckling curves

In case of the first stable stage, the loading force is strictly monotone increasing, while the displacement is monotone increasing. In case of second stable stage the loading force monotone increasing until fracture. Between the two stable stages there is a bifurcation point with a dynamic stage, which can be characterized by a quick snap through phenomenon and the buckling force can characterized by a local peak.

4.3. Calculation of initial geometrical imperfection

The w_0 initial geometric imperfection can be calculated by the secondary effect. The measured Loading force – Horizontal displacement curves were approached by the curve of the displacement of the middlepoint based on the calculation method of the secondary effect, from the safety point of view (4-2. Figure). The method was applied for all of the tested specimens. Based on the experimental variables and the different buckling curves the values of the w_0 initial imperfection were compared and the mean w_0 values were expressed, which were also compared to the designing limits.



4-2. Figure The Loading force – Horizontal displacement diagram of a second buckling group specimen, and the approaching of the horizontal displacement by the calculation of secondary effect

The formula of the horizontal displacement based on the secondary effect can be seen in Formula 4-1. (Feldmann & Kasper, 2014):

$$w(x) = \frac{w_0}{1-\frac{N}{N_{cr}}} \qquad (4\text{-}1)$$

, where:

- w_0 – initial imperfection [mm]
- N – loading force [N]
- N_{cr} – critical buckling force according to Euler [N]

5. NEW SCIENTIFIC RESULTS

Text in bold indicates the new scientific results while italic text provides explanations for the new scientific results.

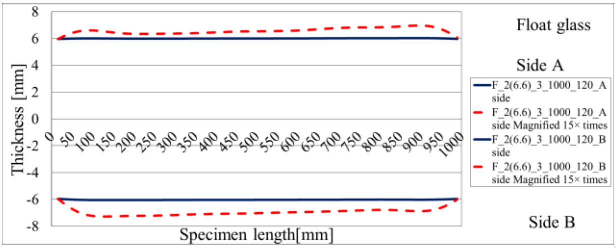
Thesis 1: The comparison results of glass shape, overall bow and sinus wave values measured by the RPS method

Thesis 1.1:

I have developed the measurement of the initial shape, the overall bow and the sinus wave values of glass specimens in accuracy of 10^{-3} mm by the application of the RPS (Reference Point System) method and Coordinate Measuring Machine which isappropriate to determine thedeformations of the glass producing and manufacturing processes.

Publications: [15], [16], [18]

The measured shapes of the float and HSG specimens can be seen in the 5-1. and 5-2. Figures. The overall bow and sinus wave values were determined based on the measurements, these characteristic properties can be seen in the following diagrams.



5-1. Figure The shape and the closing edges of the laminated float specimen

5-2. Figure The shape and the unclosed edges of the laminated HSG specimen

Thesis 1.2:

I experimentally determined based on the RPS measurement results that heat strengthening process increases the overall bow values with one decimal place in case

of single layered glass (from 0,016-0,028 mm to 0,571-1,040 mm). The overall bow values can be increased more than 20 times. The overall bow values of float glass (without heat strengthening) increased 1,5-6,0 times by the lamination process of the EVA interlayer foil (from 0,016-0,028 mm to 0,044-0,258 mm). The sinus wave values of HSG are decreased by the lamination process of the EVA interlayer foil with 40-65 % percentages.

Publication: [18]

The lamination process and the heat strengthening significantly modify the overall bow and the sinus wave values of the glass plates. The increasing of the modification can be observed on the float glass distortion values: in case of the overall bow the single layer glass results are between 0,016-0,028 mm, the laminated float glass values are between 0,044-0,258 mm. The heat strengthening process increases the overall bow (from 0,016-0,028 mm increased until 0,571-1,040 mm) and the sinus wave values (from 0,0044-0,007 mm changed until 0,0332-0,1024 mm) significantly. There is no tendency in the modification of the lamination process at the heat strengthened specimens between the single and double layered glasses.

It can be concluded that the heat strengthening procedure significantly increases the distortion factors, however these can be reduced by the lamination process. The ratio of the modifications due to the heat strengthening and lamination can be seen in the 5-1. Table. An increase by 20 times can be observed in the values of single layer glasses due to the heat strengthening process so the increase is at least one decimal place in the values of overall bow.

The increase of the overall bow was between 1,89-6,36 times due to the lamination process in case of float glasses. The distortion values decrease due to the laminaton process in case of HSG. The distortion values were increased first by the heat strengthening then the values were decreased with 39-67 % by the lamination process.

5-1. Table The effect of manufacturing process on the ratio of overall bow and sinus wave values

			Ratios based on the layering								
Manufacturing process			8	4.4	12	6.6	8.4	4.4.4	19	8.8	10.10
Heat strengthening		Overall bow	**21,91**	1,27	**35,65**	5,80	5,86	5,47	**24,46**	3,59	19,67
		Sinus wave	*8,62*				*3,30*	*3,54*	*12,09*		*5,42*
Laminating process	Float	Overall bow		6,36		2,42	4,82	6,28		4,54	1,89
		Sinus wave									*0,82*
	HSG	Overall bow		0,41		0,47	1,00	1,54		0,97	2,12
		Sinus wave		0,49		0,40	0,42	0,39		0,61	0,33

Thesis 1.3:

I experimentally determined by the RPS measuring method that the not heat strengthened float glass edges close by the lamination process of the EVA interlayer foil. The edge closure influences the stress distribution around the edges and the durability of laminated glasses.

Publication: [18]

The closed edges can be seen in the 5-1. Figure while it cannot be seen in the 5-2. Figure. The autoclave lamination process causes a new common figure for the glass tables. Despite that the shapes of the float laminated glass plates are almost the same its edges are closing in symmetric curves regardless of the shape figures causes same local curves in the plates. Six specimens had closed edges and one was opened in case of laminated float glass, the ratio was reversed in case of HSG (1:7).

Thesis 1.4:

I experimentally verified the experience-based assumption by the RPS measuring method that same sized curvatures are formed at the same position of the specimen in the layers of the symmetrically layered laminated glasses due to the lamination process.

Publication: [18]

The lamination process causes similar curvatures on both sides of the glasses based on the geometrical surface measurement of 16 pcs of laminated glass specimens. 12 specimens had almost the same curvatures on both sides, small differencies could be observed in case of 3 specimens and there was no similatiries in case of assyimetric glass specimens (8.4 layering). In 90 % of the cases, the lamination process caused similar surface distortions / curvatures on glass platese with different shapes and curvatures.

Thesis 1.5:

I experimentally determined that beside the overall bow and sinus wave values, the glass shape also has to be known to predict the buckling direction of the laterally supported plate glass columns about 85 %. .

Publication: [18]

The buckling direction of the glass columns were predicted before the tests based only on the overall bow and the sinus wave, where it was supposed that the higher imperfection values influence more the bucklng direction. The method was successful in 57 % of the cases. When the glass shapes were also taken into account and predicted the buckling direction the successfully predicted buckling direction increased to 86 %. The prediction was right 19 pcs from 22 specimens.

Thesis 2: Theses related to the equilibrium paths of the glass columns

Thesis 2.1:

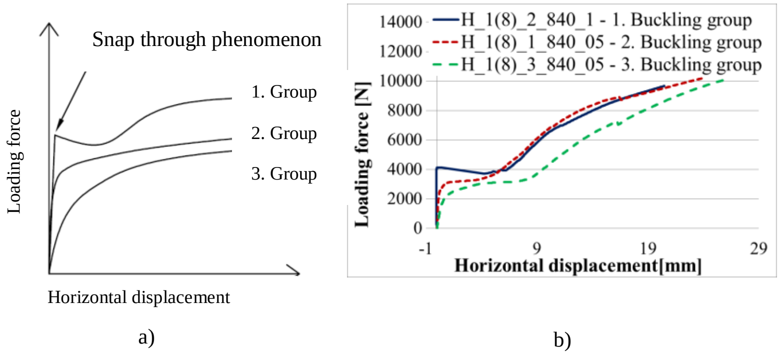
I experimentally determined that the plate glass columns (with slenderness between 0,95-4,45) can be classified into three different buckling groups based on the type of equilibrium path. The buckling starts with snap through phenomenon in case of the 1. buckling group, stable loading stages can be observed before and after the bifurcation. There is no snap through phenomenon in case of the 2. buckling group loading history, however there is an observable limit between the two stable loading stages. Only one stable loading stage can be observed in case of the loading history of the 3. buckling group.

Publications: [1], [2], [4], [6], [9]

The loading histories of the specimens were classified into three different buckling groups based on the properties of stability loss. All of tested specimens could be divided into these groups. The loading histories can be seen in 5-3. Figure a) and b).

In case of the 1. buckling group, the factors that influence the type of stability loss can even increase the force of the stability to such a large extent that it is going to be higher than the maximal load related to the fracture. There is no snap through phenomenon in case of the loading histories of the 2. buckling group members. The limit can be determined between the two stable stages when the buckling phenomenon starts. There is only one stable stage and the buckling starts directly from the beginning of the load in case of the 3. buckling group.

The buckling groups influence the glass columns designing because the w_0 initial imperfections are changed in these groups by the types of the equilibrium path. From 237 experimental tests 30 tests could be classified into the 1. buckling group, 170 tests into the 2. buckling group and 37 tests into the 3. buckling group.



5-3. Figure The Buckling groups in the Loading force-Horizontal displacement diagrams in case of the a) theoretical and b) real measured cases

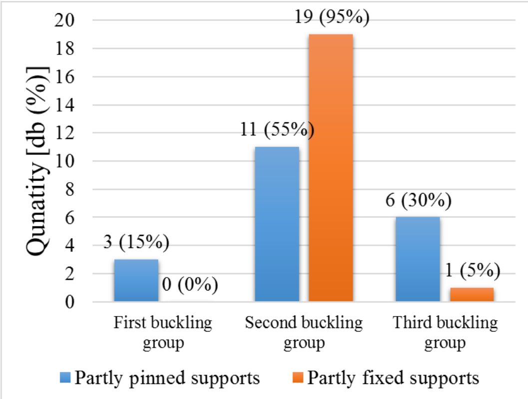
Thesis 2.2:

The type of support significantly inluences the type of equilibrium pathstability loss. Approximately 80% of the specimens, that have partly fixed support, belong to the 2. buckling group. About 20% of specimens belong to the 1. buckling group and 25 % of specimens belong to the 3. buckling group due to the partly pinned support. The partly fixed support increased with 20 % the amount of the 2. buckling group members.

Publication: [15]

The increase of the stiffness of the support (partly fixing) can influence the type of equilibrium path. The specimens can be classified into the 2. buckling group with higher probability by the application of partly fixing than into the 1. or 3. buckling group. Based on all of the tested specimens the effect of the partly pinned to partly fixed changes resulted the following: the amount of 1. buckling group members reduces from 23% (partly pinned support) to 7% (partly fixed support); 2. buckling group members increase from 56% to 81%; 3. buckling group members reduce from 21% to 12%.

The effects of the stiffness were tested on 20 pcs of same specimens as well. The tests were started with the partly pinned support and continued with the party fixed support, the results can be seen in the 5-4. Figure.



5-4. Figure Classification of the specimens according to the type of stability loss if the support is partly pinned at the first test and partly fixed at the second test on the same specimens

Thesis 3: Theses related to the calculated results of the w_0 initial imperfections

Thesis 3.1:

I have experimentally and analytically determined that the w_0 initialimperfection can be reduced by 4 times if partly fixed support (the mean w_0 is between 1,13-1,17 mm) is applied instead of partly pinned (the mean w_0 is between 5,45-8,34 mm).

Publication: [17]

The higher stiffness support (partly fixed) causes the decrease of the w_0 initial geometrical imperfection values, it can be seen in 5-3. Table. The absolute maximal initial geometical imperfection resulted 4,5 mm, its numerical factor is 201 (on 905 mm length) in case of partly fixed support. The lowest mean w_0 value is 1,13 mm, its numerical factor is 798 (on 905 mm length). The maximal mean value is 1,17, its numerical factor 528 (on 905 mm length). The partly pinned w_0 values increase by 4 times compared to the partly fixed support, where the whole length was taken into account at the calculation of numerical factors.

5-2. Table The differencies in the values of the initial geometrical imperfections and its numerical factors due to the effects of the supports

Support	Factors	Based on the mean values		Absolute maximal values
		Lowest value	Maximal value	
Partly fixed	w_0=L/z [mm]	1,13	1,17	4,50
	z=Numerical f.	798	528	201
Partly pinned	w_0=L/z [mm]	5,45	8,34	16,00
	z=Numerical f.	183	120	53

Thesis 3.2:

I experimentally and statistically determined that the w_0 initial imperfections in case of 87% of the tested float glasses were higher than the w_0=L/2000 limit provided by the standards, therefore I recommend w_0=L/500 for the design. The w_0 initial imperfections of the 55% of the tested HSG specimens were higher than the w_0=L/400 limit provided by the standards therefore I recommend w_0=L/300 for the design. I have shown that the type of equilibrium path infeluences the w_0 initial imperfection. The w_0 initial imperfection is recommended to calculate based on the specimen results belonging to the 3. buckling group.

Publication: [17]

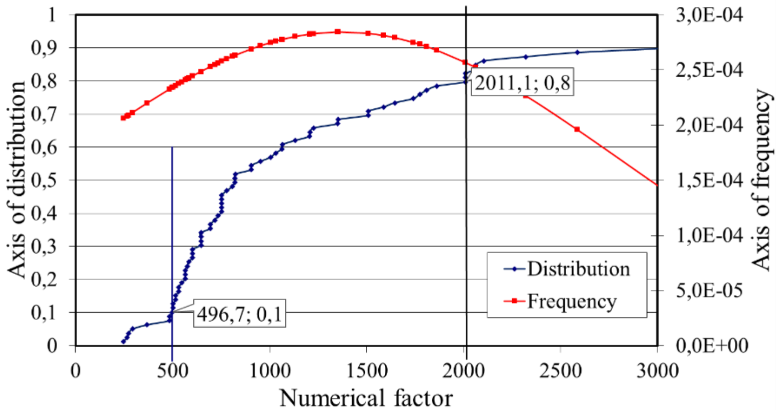
The experimental test results in the 5-4. Table show the amount of the whole partly fixed support specimens, and those amount of specimens that does not comply with the standard. The standards provided limit for the float and HSG glasses: w_0^{float}=L/2000 és a w_0^{HSG}=L/400. It is also important that the recommended limits have to be determined by the 3. buckling groups results, because it has the worse values compared to the other buckling groups.

5-3. Table The quantity of the same glass specimen groups that have higher initial imperfections than the limits of standard with partly fixed support

	1. Group		2. Group		3. Group		Summarized	
	Higher	Sum	Higher	Sum	Higher	Sum	Higher	Sum
Float [db]	4	7	29	32	8	8	41	47
HSG [db]	4	10	12	28	14	17	30	55
Float [%]		57 %		91 %		100 %		87 %
HSG [%]		40 %		43 %		82 %		55 %
Summarized [db]	8	17	41	60	22	25	71	102
Ratio [%]		47 %		68 %		88 %		70 %

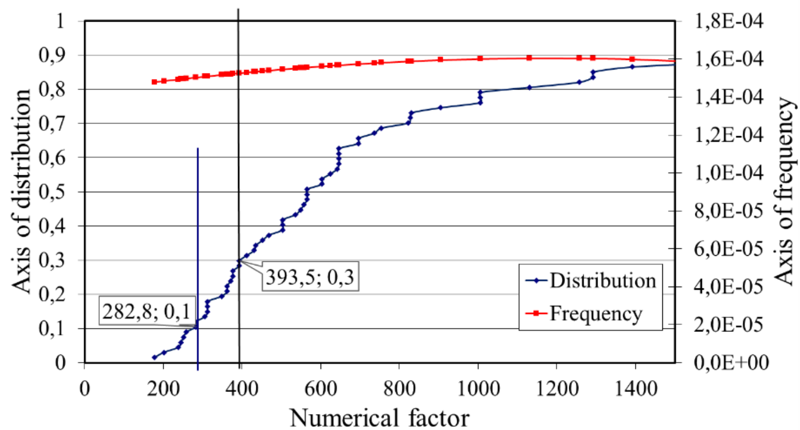
The distribution and the frequency function of the numerical factors of float and HSG specimens can be seen in 5-5. and 5-6. Figures (w_0^{float}= L/14900-L/245 range; w_0^{HSG}= L/1444-L/221 range). I have recommended L/500 limit for float glass and L/300 for heat strengthened glass based on a statistical investigation, where the quantile was 10 % with normal distribution. The application of the 5 % quantile causes over designing and uneconomically large cross-sections.

N = 77 pcs partly fixed float specimens numerical factors distribution and frequency



5-5. Figure The distribution and frequency of the numerical factor related to the w_0 initial imperfection in case of partly fixed float specimens

N = 67 pcs partly fixed HSG specimens numerical factors distribution and frequency



5-6. Figure The distribution and frequency of the numerical factor related to the w_0 initial imperfection in case of partly fixed HSG specimens

6. APPLICATION OF THE NEW SCIENTIFIC RESULTS

The RPS measuring method was successfully applied for the measuring of geometrical imperfections of the plate glasses. New limits were recommended for the initial geometrical imperfections for float glasses and HSG in the calculation method keeping in mind the safety aspects. The differencies between the measured and calculated initial geometrical imperfections were represented. The liquid tin did not influence the glass structures on macroscopic level so the overall bow and the sinus wave values were independent of the type of sides. The type of the support stiffness can influence the type of the equilibrium path, the increase of the support stiffness increases also the probability of the type of equilibrium path of second buckling group so it increases the designing safety and the buckling resistance.

The results of doctoral research facilitates the corresponding layering design in case of the glass columns designing. The initial geometrical imperfection of the float glass is lower than the imperfection of HSG. The maximal horizontal displacements increased by 82,67 % (standard deviation 22 %) due to the heat strengthening effect, the spectacular deformations can be more easily descried in case of the increasing loading force therefore more time remains for the escape from the building. The residual load bearing capacity and the fracture fragments of the float glass are higher than those of the HSG. However the load bearing capacity of the glasses can be further increased by the application of the new generation interlayer foils.

The initial imperfection values are recommended to be determined based on third buckling group results, because that one has the lowest buckling resistance. It is also recommended to eliminate the defects, imperfections and inaccuracies that arise from the glass producing, manufacturing and installation methods by using newer processes e.g. application of continuous support during the heat strengthening, or glass producing instead of ceramics cylinders.

7. PERSPECTIVES

In my recent research the effects of the glass producing, manufacturing and installation were analysed separately on the glass columns design (skewness, shape of glass, heat strengthening, type of support), however the interaction of these factors is going to be my future research work (completed with new factors e.g: point fixing, different stiffnesses of support, different length of support, newer interlayer foils, chemical strengthened glasses).

The applied type of support influences the distribution of the buckling groups members. Therefore it is interesting to analyse the effects of the support for large-scale specimens in ratio 1:1. The initial imperfection can be modelled by the imperfection sensitivity according to the

Catastrophe theory. The importance of the buckling groups can be supported by the application of this theory. The laboratory results ought to be verified with final element softwares in order to apply them in the future in the real structures designing and also to analyse the size effect.

The glass columns designing method contains the $\boldsymbol{\alpha}_0$ material constant and the $\boldsymbol{\alpha}_{imp}$ imperfection factor, the research of these factors ought to be continued. The coupling parameter was analysed on results of small amount specimens, however the factor is sensitive for the changes of the bending stiffness, it requires more laboratory experiments.

The residual capacity is one of the most important research field in the topic of glass designing, and further investigation is planned for the newer interlayer foils, different cross-section and the joints of structural elements and their effect on the stability loss.

The RPS measuring method requires further measurements to investigate the stress sharing between the layers of the laminated glasses at the glass edges.

8. PUBLICATION RELATED TO THE TOPIC OF THE DISSERTATION

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