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Experimental Verification of the Buckling Strength of Structural Glass Columns

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Abstract

This paper deals with experimental research of axially loaded members made of structural (laminated) glass. The purpose of the research is the evaluation of buckling strength and actual behaviour of the columns due to the absence of standards for design of glass load-bearing structures. The experimental research follows the previous one focusing on measuring of initial geometrical imperfections of glass members. Within the frame of the research 15 specimens were tested. All of them were of the same geometry (length 1500 mm, width 150 mm and thickness 12 mm) but had different composition – monolithic glass or laminated double or triple glass made of annealed or fully tempered glass panes bonded together by PVB or EVASAFE foil. Due to rectangular cross section and considered boundary conditions, flexural buckling perpendicular to the weak axis of the cross section occurred. During the testing, lateral deflection and normal stresses at mid-span were measured. Maximum force achieved during the testing has been adopted as buckling strength. Euler's critical loads and equivalent geometrical imperfections were evaluated using a Southwell's method. The results of experiments were statistically evaluated according to the European standard for design of structures EN 1990, appendix D. There are significant differences between the specimens made of annealed glass or fully tempered glass and between the specimens laminated with using PVB or EVASAFE foil – the differences are in the values of buckling strengths and load – deflection, load - stress plots. The next step was to determine the design strength by calculation procedure based on buckling curves approach intended for design of steel columns.

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Keywords: structural glass; laminated glass; flexural buckling; Southwell's method; buckling strength;

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1. Introduction

Glass members and structures are specific for their high slenderness. For this reason, it is necessary to take into account stability problems within static designing. Design models developed for standard structural materials such as steel and timber cannot be directly used for design of glass structures because of some specific aspect of the glass (brittle fracture behaviour, time and temperature dependency of laminated glass and so). Actually European design standards (Eurocodes) are in processing, designers may use draft versions of future final codes - prEN 16612 Glass in building – Determination of the load resistance of glass panes by calculation and testing or prEN 13474-1 Glass in building – Design of glass panes – Part 1: General basis of design. Static design of glass structures including stability problems of glass columns, beams and beam-columns is topic of work of Haldimann et al. [3], Belis et al. [6] or Amadio and Bedon [4].

Nomenclature

ANG	annealed glass
FTG	fully tempered glass
VG	laminated glass (verbundglas)
ESG	fully tempered glass (einscheiben-sicherheitsglas) – without laminating
VSG	laminated safety glass (verbund-sicherheitsglasglas)

2. Experimental evaluation of buckling strength

2.1. Specimens

Within the frame of the research 15 specimens were tested. All of them were of the same geometry (length 1500 mm, width 150 mm and thickness (or sum of glass panes thickness in the case of laminated glass) 12 mm) but had different composition – monolithic glass or laminated double or triple glass made of annealed or fully tempered glass panes bonded together by PVB or EVASAFE foil. The specimens are listed in Table 1. In the table, FTG means fully tempered glass and ANG means annealed glass.

Specimen geometry was chosen so that thin-walled (thin-walled in terms of structural mechanics, not steel structures) rod condition was fulfilled. Vlasov [1] defined a thin-walled rods by condition L : b : t = 100 : 10 : 1, where L is length of the rod, b is characteristic dimension of the cross section, and t is the wall thickness of the cross section.

Table 1. List of specimens.

Specimen	Designation	Description	Glass	Foil	Pieces
T1 – T3	ESG 12	Safety glass	FTG	-	3
T4 – T6	VG 66.2	Laminated glass	ANG	PVB	3
T7 – T12	VSG 66.3	Laminated safety double glass	FTG	EVASAFE	6
T13 – T15	VSG 444.33	Laminated safety triple glass	ANG	EVASAFE	3

2.2. Test set-up

Hinged supports were ensured by steel coulters fitted on both ends of specimen. Coulter was equipped with cutting edge which fits into the conical notch of the bearing plate – see Fig. 1 (b). Timber pads situated between steel coulter and the glass specimen avoided direct contact of the steel and the glass which may cause a failure by local stress concentrations in contacts.

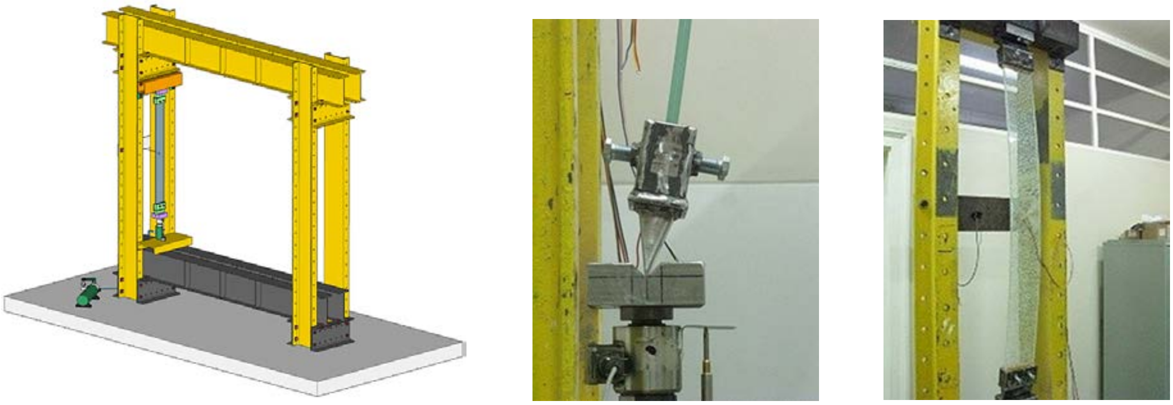

Fig. 1. (a) test set-up; (b) detail of hinged support; (c) destroyed specimen.

The specimen was placed in a steel frame consisting of steel girders and columns. Loading force was generated by manually operated hydraulic press. Test set-up is plotted in Fig. 1(a). Loading force, vertical deflection and horizontal (lateral) deflection at mid-span were measured within testing using force transducer, LVDT and wire sensor respectively. Normal stresses at mid-span were measured at selected specimens using strain-gauges glued to sanded glass. Scheme of measuring devices is plotted in Fig. 2 (a).

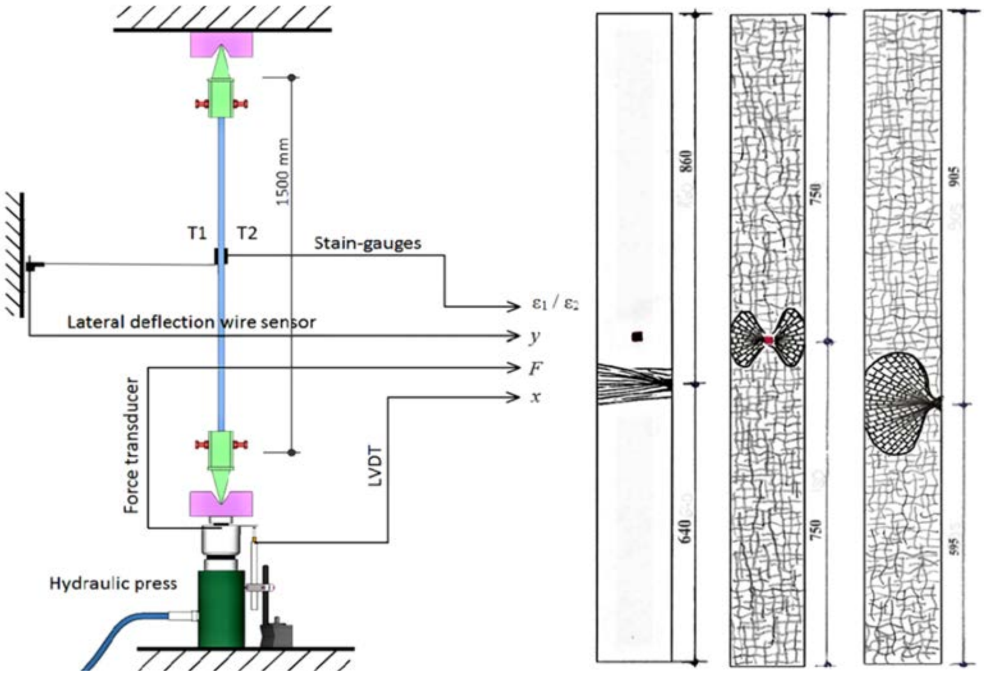

Fig. 2. (a) scheme of measuring devices, (b) typical crack patterns.

Tested specimens were loaded by static force and loading rate was determined by the press cylinder pull (approximately 0,075 mm.s^{-1}).

3. Results

3.1. Failure mechanism

All of the specimens were destroyed by brittle fracture. Typical crack patterns are plotted in Fig. 2 (b) for laminated double glass (VG 66.2), safety laminated double glass (VSG 66.2) and safety laminated triple glass (VSG 444.33).

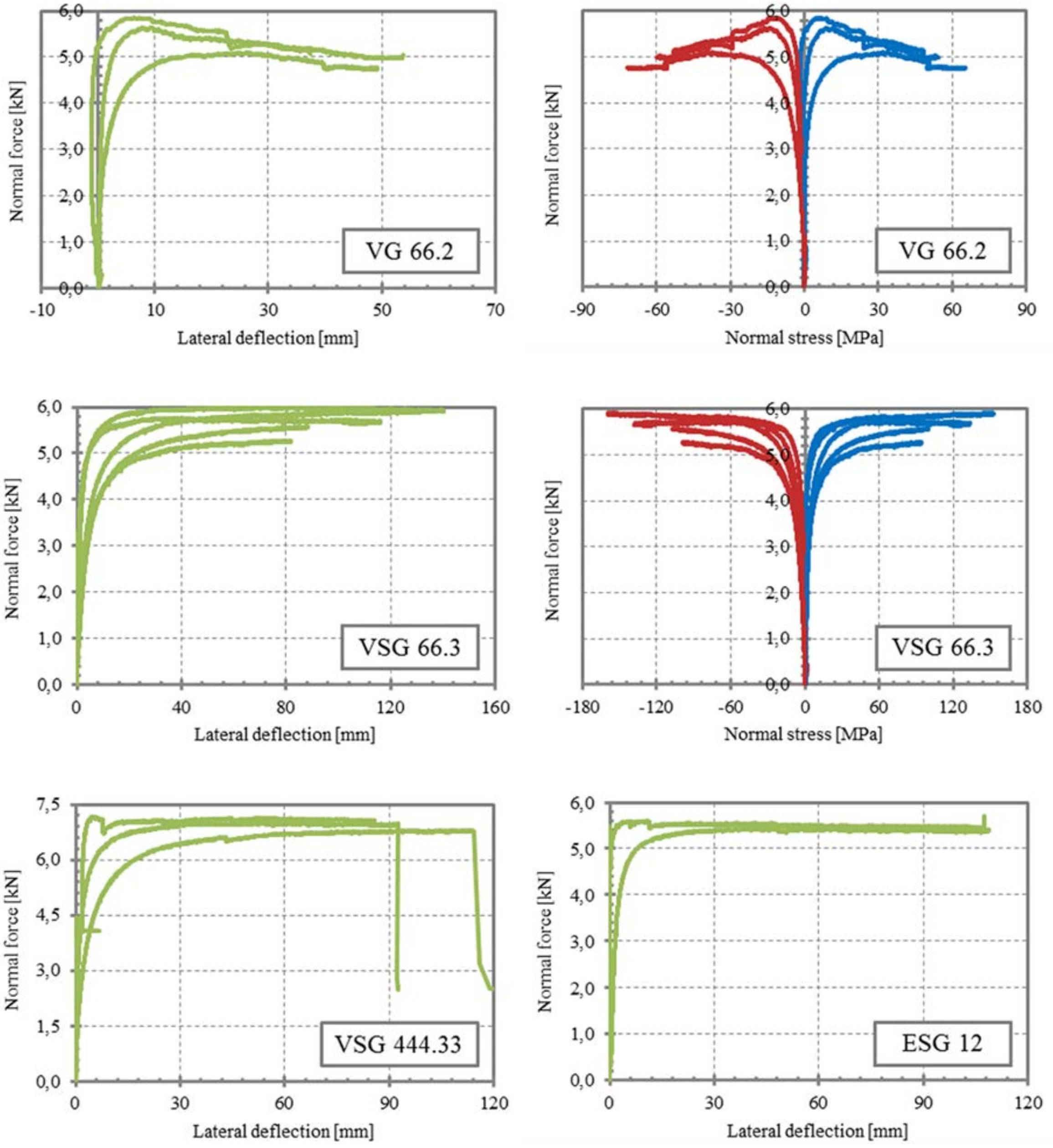

Fig. 3. Force – deflections curves and force – stress curves.

The specimens VG 66.2 were destroyed by fracture of both glass panes, the specimens VSG 66.2 were destroyed by fracture of one glass pane and the specimens VSG 444.33 were destroyed by fracture of one or two glass panes. In Fig. 1 (c) destroyed specimen is plotted.

3.2. Buckling strength and stress

Force-lateral deflection curves and force-normal stress curves are plotted in graphs in Fig. 3. Force-lateral deflection/normal stress curves for all the specimens with the exceptions of laminated double glass with us of PVB foil (VG 66.2) have an increasing tendency from zero up to failure – it means that the tested specimen was some elastic material [2]. The specimen with PVB foil has curves with decreasing tendency from the point of maximal load – it is characteristic for elastic-plastic materials. Plastic behaviour is caused by PVB foil which has low shear modulus at longer load duration.

3.3. Equivalent imperfections and critical forces

In Table 2 equivalent initial geometrical imperfections and critical forces is calculated using Southwell's method.

Table 2. Southwell's method evaluation.

Specimen	$e_{0,ekv}$			$t_{eff,exp,mean}$	$t_{eff,theory}$	$error_{exp}$	$N_{cr,exp,mean}$	$N_{cr,theory}$	$error_{exp}$
	[mm]			[mm]	[mm]	[%]	[kN]	[kN]	[%]
ESG12	1.028	-	0.056	12.14	12.00	1.16	5.53	5.34	3.51
VG 66.2	0.398	0.087	1.243	12.24	12.11	1.09	5.67	5.48	3.36
VSG 66.2	-	0.729	3.667	12.29	12.52	-1.81	5.74	6.06	-5.29
	2.789	0.946	2.368						
VSG 444.33	0.424	0.892	3.156	13.18	13.05	1.04	7.08	6.86	3.15

3.4. Characteristic and design buckling resistance according to the EN 1990

EN 1990, appendix D provides calculating method to determine characteristic value (5% quantile) and design value (0,1% quantile) for normal or lognormal statistical distribution of experimentally determined value. Tab. 3 provides resulting values using this approach.

Table 3. Characteristic and design values of buckling resistances.

Buckling resistance	Method	ESG 12	VG 66.2	VSG 66.3	VSG 444.33
Characteristic value	experiment + EN 1990 – annex D	5.07	4.24	5.15	6.38
	buckling curve	4.59	4.28	5.17	5.82
	second order theory + EN 1990	-	4.36	4.94	6.32
Design value	experiment + EN 1990 – annex D	2.82	2.36	2.86	3.55
	buckling curve	1.98	1.82	2.23	2.51
	second order theory + EN 1990	-	-	3.39	-

3.5. Buckling resistance according to the buckling curves

Calculating method for determining buckling resistance of glass columns was derived from method for metal structures – buckling curves approach. Buckling resistance:

$$N_{b,Rd} = \chi \cdot f_{g,d} \cdot A_{eff} \tag{1}$$

where reduction factor χ and non-dimensional parameter Φ are:

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}} \tag{2}$$

$$\Phi = 0{,}5 \cdot \left[1 + \alpha_{imp} \cdot \left(\bar{\lambda} - \alpha_0\right) + \bar{\lambda}^2\right] \tag{3}$$

where α_{imp} = 0,71 and α_0 = 0,6 proposed by Amadio and Bedon [4] and non-dimensional slenderness:

$$\bar{\lambda} = \sqrt{\frac{\sigma_{Rk} \cdot A_{eff}}{N_{cr}}} \tag{4}$$

Elastic critical force:

$$N_{cr} = \frac{\pi^2 \cdot E \cdot I_{z,eff}}{L_{cr}^{\ 2}} \tag{5}$$

Design value of strength of glass according to the Feldmann, M. and Kasper, R. et al., [5]:

$$f_{g,d} = \frac{k_{\mathrm{mod}} \cdot k_{sp} \cdot f_{g,k}}{\gamma_{M,A}} + \frac{k_v \cdot \left(f_{b,k} - f_{g,k}\right)}{\gamma_{M,v}} \tag{6}$$

Characteristic and design vales of buckling resistance according buckling curves approach are listed in Tab. 3. A comparison of theoretical results and experiments is plotted in Fig. 4.

3.6. Buckling resistance according to the second order theory

This method is based on geometrically non-linear elastic analysis with imperfections (GNIA). Ultimate limit state is attained when normal stress at extreme fibers of cross section reaches to ultimate tensile strength of glass. Normal stress could be calculated according equation (7), where w0 is amplitude of equivalent geometrical initial imperfection (in this case calculated according to the Southwell's method). Results are listed in Tab. 3.

$$\sigma_{\max} = \frac{N}{A} \pm \frac{M}{W} = \frac{N}{A} \pm N\, w_0 \left(\frac{1}{1 - N/N_{cr}}\right) / W \tag{7}$$

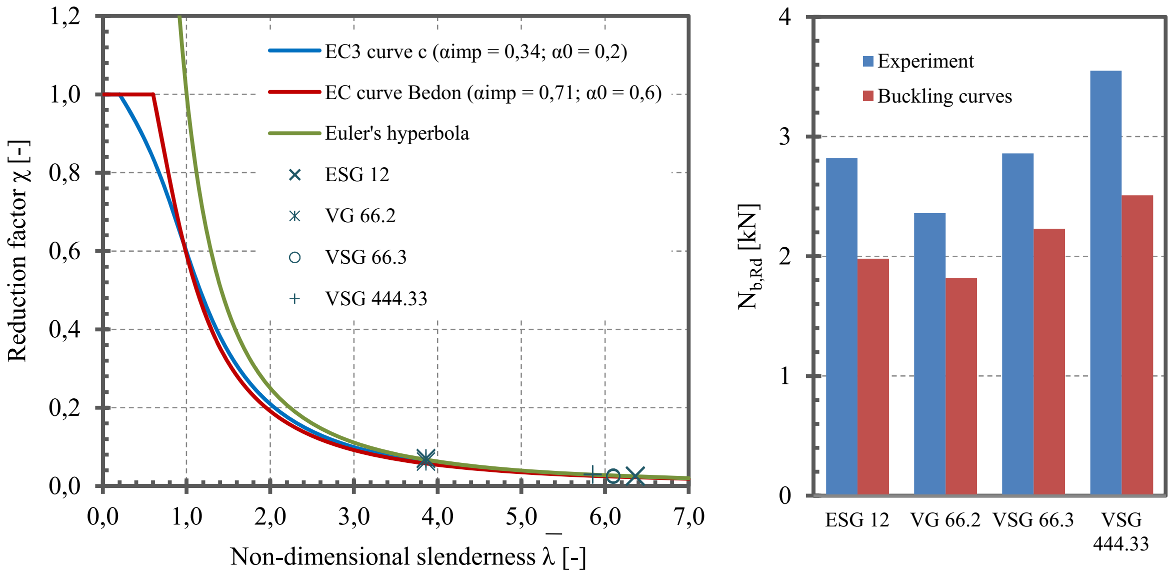

Fig. 4. (a) reduction factor and buckling factor comparison; (b) buckling resistance comparison.

4. Conclusions

This paper summarizes the experimental verification of flexural buckling resistances of structural glass columns. Results ale compared with the calculation of such resistance according to design procedure listed in European standard EN 1993-1-1 using modified buckling curves. The results of the experimental verification show reliable design of glass columns based on the EC buckling curves design procedures.

Acknowledgements

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