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Experimental Verification of the Structural Glass Beam-Columns Strength

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Abstract. This paper deals with experimental research of axially and laterally loaded members made of structural (laminated) glass. The purpose of the research is the evaluation of buckling strength and actual behaviour of the beam-columns due to 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, testing of glass beams and columns. Within the frame of the research 9 specimens were tested. All of them were of the same geometry (length 2000 mm, width 200 mm and thickness 16 mm) but different composition – laminated double glass made of annealed glass or fully tempered glass panes bonded together by PVB or EVASAFE foil. Specimens were at first loaded by axial force and then by constantly increasing bending moment up to failure. During testing lateral deflections, vertical deflection and normal stresses at mid-span were measured. A maximum load achieved during testing has been adopted as flexural-lateral-torsional buckling strength. 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 specimens made of annealed glass or fully tempered glass. Differences between specimens loaded by axial forces 1 kN and 2 kN are negligible. The next step was to determine the design strength by calculation procedure based on buckling curves approach intended for design of steel columns and develop interaction criterion for glass beams-columns.

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 etc.). 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. [1], Belis et al. [2, 3] or Amadio and Bedon [4, 5].

Flexural-lateral-torsional buckling is loss of stability of member subjected to axial force (see Figure 1b) and bending around a rigid axis (see Figure 1a). In the case of laminated glass member, it is necessary to take into account an actual behaviour of the laminated cross section because of additional

degree of freedom for bending and torsion of laminated glass – see Figure 1c. Characteristic load-deflection curve is plotted in Figure 1d.
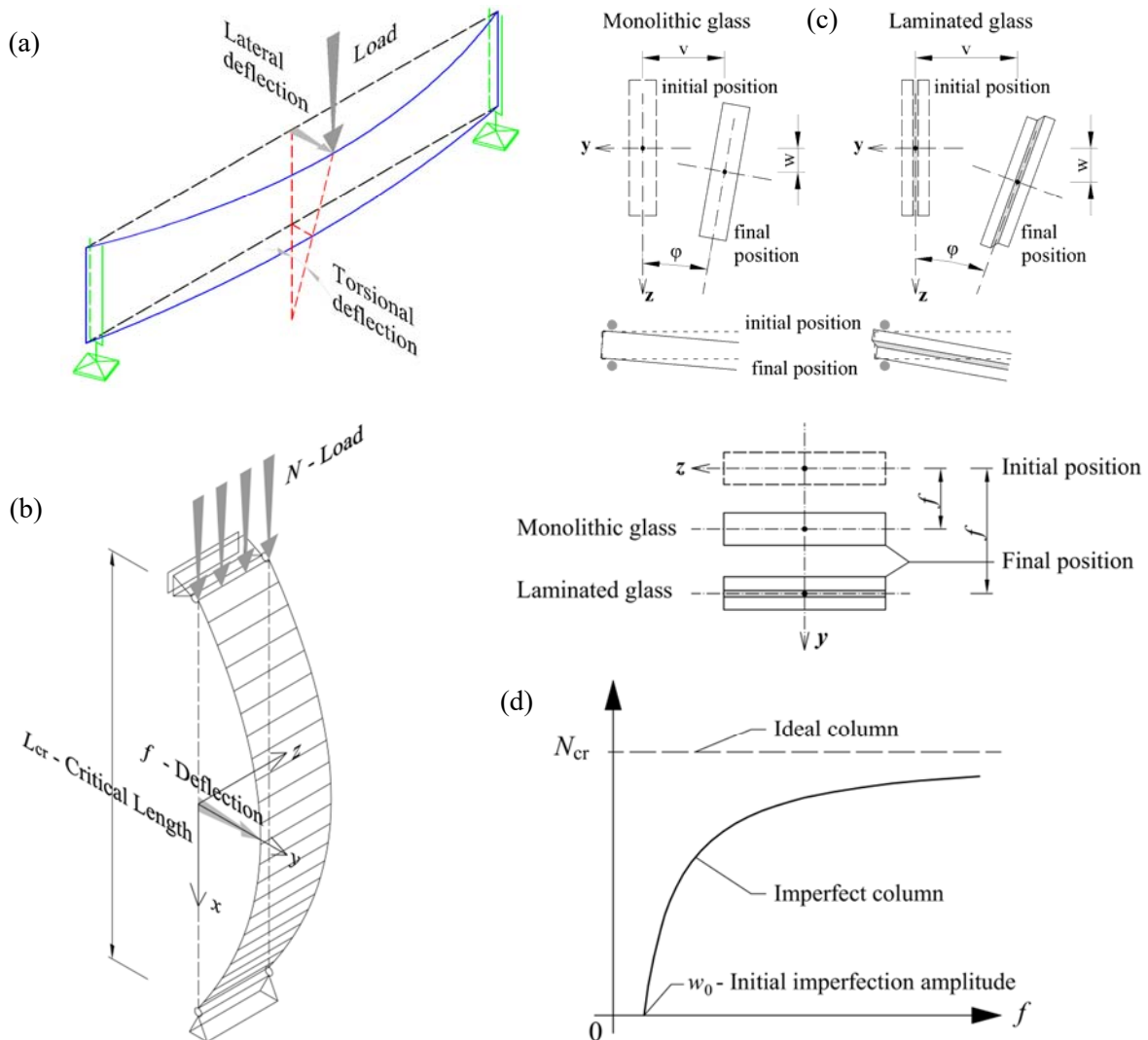
Figure 1. Buckling; (a) lateral torsional buckling; (b) flexural buckling; (c) additional degrees of freedom; (d) load-deflection curve

2. Experimental evaluation of flexural-lateral-torsional buckling resistance

2.1. Specimens

Within the frame of the research 9 specimens were tested. All of them were of the same geometry (length 2000 mm, width 200 mm, laminated double glass made of annealed glass panes or fully tempered glass panes bonded together by PVB or EVASAFE foil). Thicknesses of specimens were 16 mm. The specimens are listed in Table 1.

Specimen geometry was chosen so that thin-walled (thin-walled in terms of structural mechanics, not steel structures) rod condition was fulfilled. Vlasov [6] 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 thickness	Length	Depth	Glass	Foil	Pieces
FLTB1 – FLTB6	VG 88.2	Laminated glass	16 mm	2000 mm	200 mm	ANG	PVB	6
FLTB7 – FLTB9	VSG 88.2	Laminated safety glass	16 mm	2000 mm	200 mm	FTG	EVASAFE	3

2.2. Test set-up

The specimen was placed in a steel frame consisting of steel girder and columns. Loading lateral forces were generated by electrically operated hydraulic press, axial force was generated by man operated hydraulic press. Test set-up is plotted in Fig. 2. Fork support conditions were ensured by steel coulters fitted on both ends of specimen. Coulter was equipped with gusset plate consisting hole for pin – see Figure 5 (b). Timber pads situated between steel parts and the glass specimen avoided direct contact of the steel and the glass which may cause a failure by local stress concentrations in contacts – see detail in Figure 5 (c). Specimen was loaded by two, symmetrically to the mid-span situated, concentrated loads and axial compression force – specimen was subjected by four-point bending and normal force interaction. Lateral loading forces were ensured by one electro hydraulic press and were introduced into specimen by balance arm and loading frames, Figure 5 (a), into two points approximately in third of the length of the beam. Supporting blocks illustrated in figure are plotted only schematically.
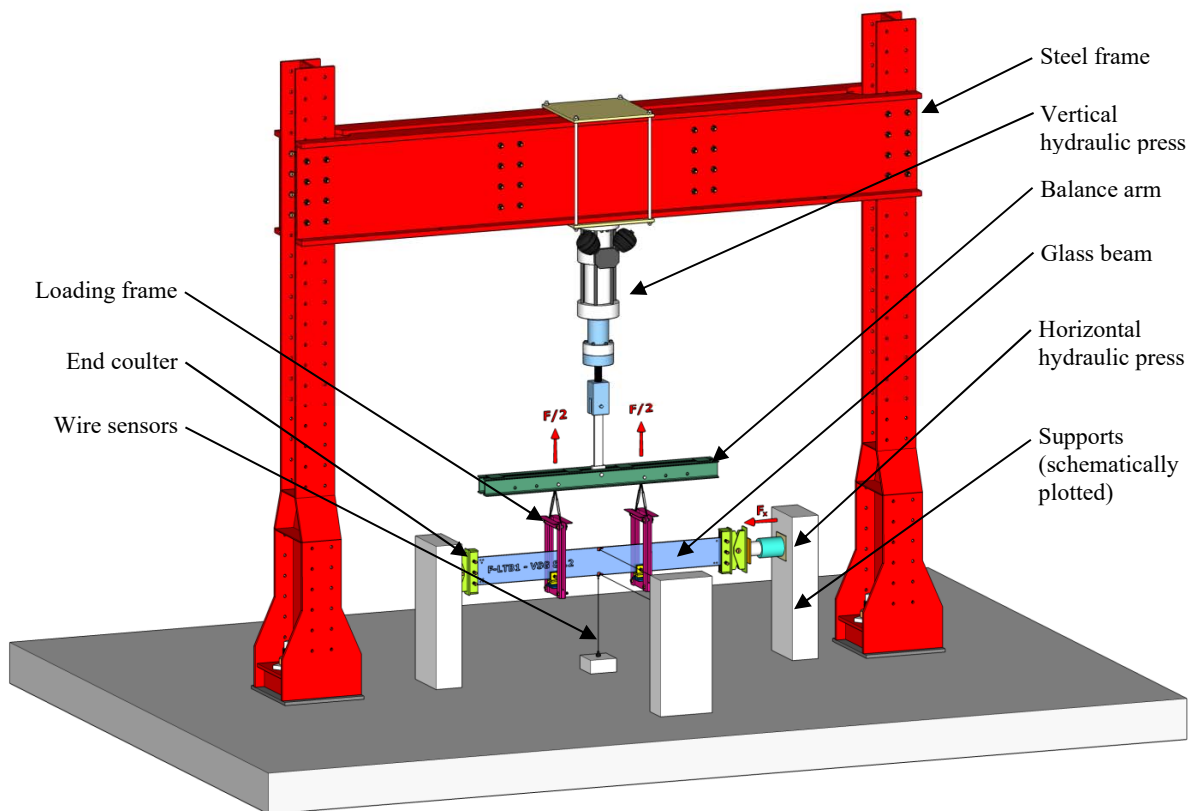

Figure 2. Test set-up – overall view

Figure 3 shows front view of loading scheme. Theoretical length for buckling is between pin axes – 2146 mm.
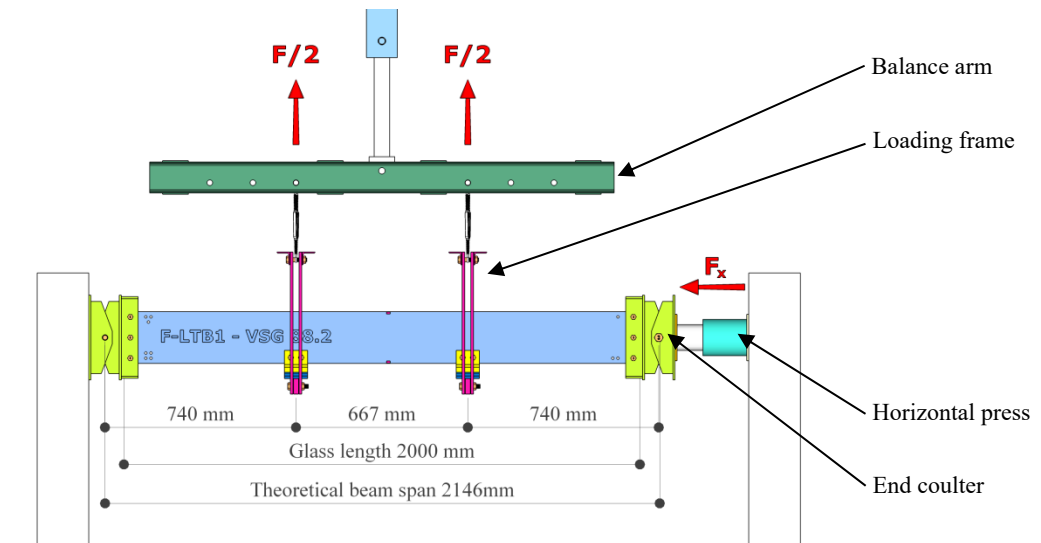
Figure 3. Test set-up – front view

Lateral loading force F, axial force F_x, vertical deflection w_3 and horizontal (lateral) deflections (at bottom v_2 and upper v_1 edges) at mid-span were measured within testing using force transducer and wire sensors respectively. Normal stresses at extreme fibers at concave and convex side of beam at mid-span were measured using strain-gauges $T4$, $T5$, $T6$, $T7$ glued to sanded glass. Scheme of measuring devices is plotted in Figure 4 – cross section view.
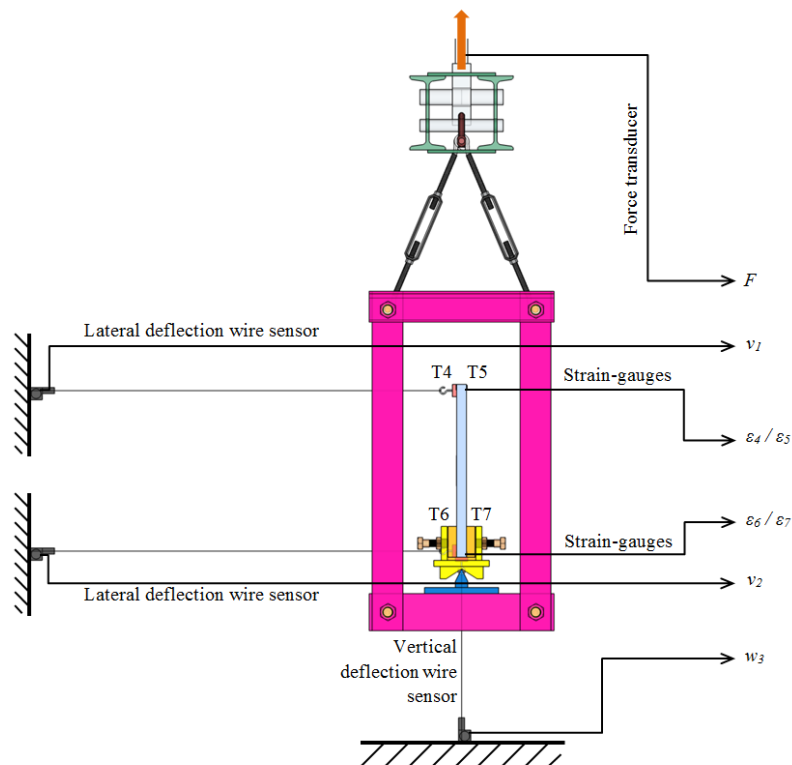
**Figure 4.** Test set-up – cross section detail and measured variables
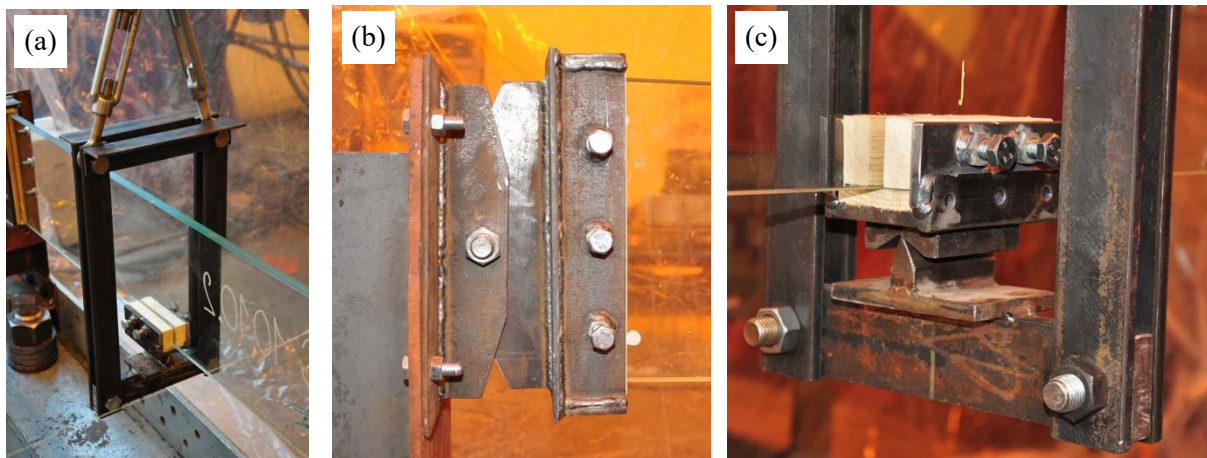
Figure 5. (a) Steel loading frame; (b) End supporting - steel coulters; (c) Load application point detail

At first tested specimen was loaded by axial force – for specimens FLTB1 – FLTB6 by 2 kN and for specimens FLTB7 – FLTB9 by 1 kN that is approximately 50 % and 25 % of Euler's critical forces N_{cr} respectively. Then tested specimen was loaded by static force up to failure of specimen. Loading rate was determined by the press cylinder pull (0.04 mm.s^{-1}).

3. Results and discussions

3.1. Failure mechanism
All of the specimens were destroyed by brittle fracture. In all cases the point of primary failure origin was situated close to the mid-span at tension edge. In Figure 6 characteristic crack patterns for members composed of fully tempered glass (specimen FLTB1) and annealed glass (specimen FLTB4) are plotted.
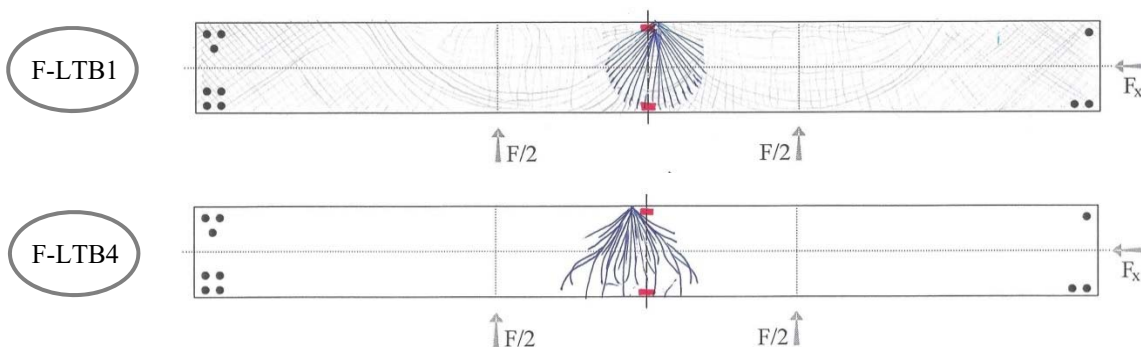
Figure 6. Crack patterns

3.2. Buckling strength and stress
Moment-lateral deflection curves, moment-vertical deflection curves, moment-normal stress curves and moment-angle of torsion curves are plotted in graphs in Figure 7. Lateral deflections are plotted for centroid of cross section; these values were calculated from measured points on bottom and upper edges of glass cross section assuming rigid cross section. Force deformations / normal stress curves for all the specimens have (approximately) an increasing tendency from zero up to failure – it means that the tested specimen was some elastic material [7].
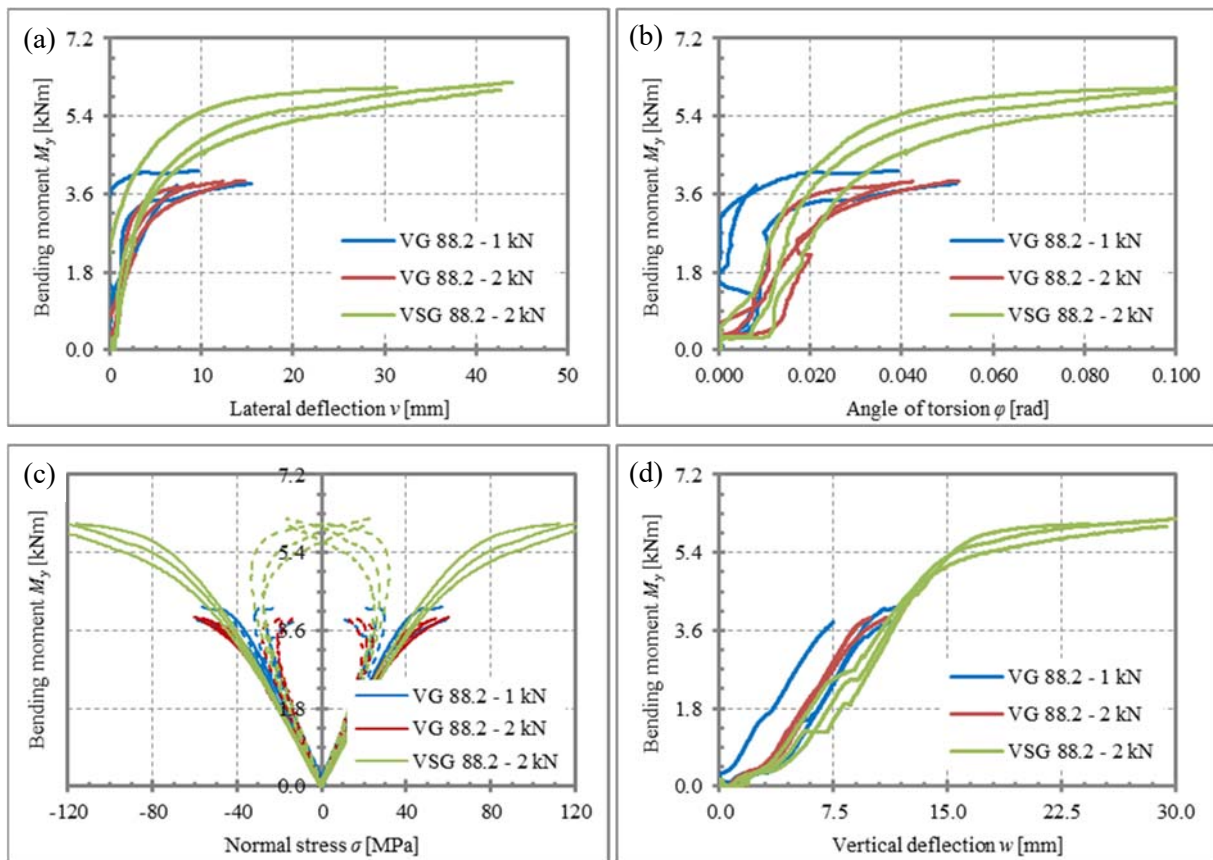
Figure 7. (a) Moment – Lateral deflections curves; (b) Moment – Angle of torsion curves; (c) Moment – Normal stress curves; (d) Moment – Vertical deflections curves for all specimens

In Table 2 there maximal values of deflections, values of normal forces and bending moments at time of failure, maximal value of axial tension stress and test duration are listed.

Table 2. Test results

Specimen	v_{max} [mm]	w_{max} [mm]	φ_{max} [rad]	M_{fail} [kNm]	N_{fail} [kN]	σ_{max+} [MPa]	t_{test} [s]
F-LTB1	31.28	24.33	0.1028	6.07	3.60	112.12	1200
F-LTB2	42.66	29.40	0.1328	6.01	2.62	127.70	1375
F-LTB3	43.94	30.34	0.1315	6.18	2.30	131.15	1377
F-LTB7	12.32	9.90	0.0424	3.88	3.63	54.25	811
F-LTB5	9.06	9.47	0.0390	3.83	3.65	50.62	620
F-LTB6	14.71	11.22	0.0525	3.91	3.38	60.13	757
F-LTB4	15.42	11.74	0.0519	3.84	2.77	58.81	856
F-LTB8	7.34	7.51	0.0080	3.79	2.21	39.81	528
F-LTB9	9.70	11.71	0.0393	4.14	2.87	56.96	764

3.3. Statistical evaluation of test results according to the EN 1990

In graphs in Figure 8 the mean values and standard deviations of bending moment M_{max} and normal stress σ_{max} at the time of failure are plotted. Bending resistance of specimens made of FTG glass is higher than for ANG glass. The bending resistance difference between specimens preloaded by normal force 1 kN (25 % of N_{cr}) and 2 kN (50 % of N_{cr}) is negligible. Normal stresses measured at time of failure corresponding to the characteristic values of glass strength (120 MPa for FTG and 45 MPa for ANG)
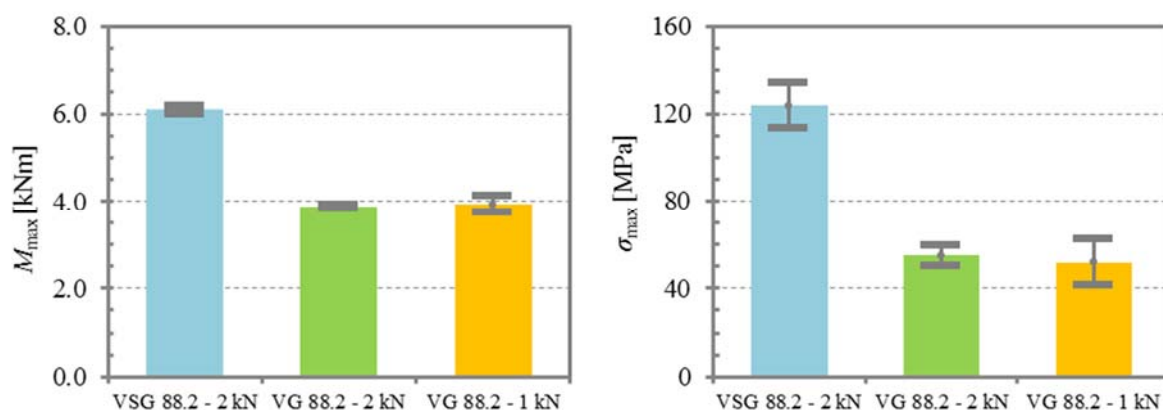

Figure 8. Mean values and standard deviations: a) Maximal bending moment; b) Maximal normal stress

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. Table 3 provides resulting values of bending resistance using this approach. Design values are calculated according to the method b using safety factor of used glass.

Table 3. Statistical evaluation of test results

FLTB resistance	VSG 88.2 – 2 kN	VG 88.2 – 2 kN	VG 88.2 – 1 kN
Characteristic value	5.787	3.738	3.288
Design value – method b	2.676	1.495	1.315
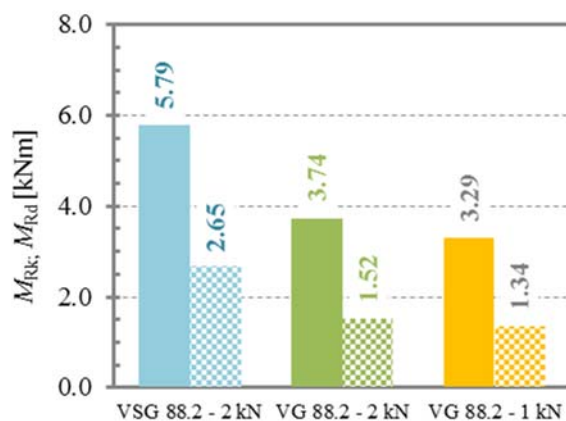
Figure 9. Characteristic and design value of bending resistance with axial loading

4. Buckling resistance according to the buckling curves

4.1. Pure flexural buckling and lateral torsional buckling

Calculating method for determining buckling (both flexural and lateral torsional) resistance of glass members was derived from method for metal structures – buckling curves approach. Flexure buckling resistance is:

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

Lateral torsional buckling resistance is:

$$M_{b,Rd} = \chi_{LT} \cdot f_{g,d} \cdot W_{eff} \tag{2}$$

where $f_{g,d}$ is design value of glass strength calculated according to the Feldmann, M. and Kasper, R. et al., [8]. Effective cross sectional characteristic have to be calculated for laminated glass members using effective glass thickness. Laminated glass effective thickness calculation methods were publidshed by many authors – for example Haldimann [1], Calderone and Bennison [9], Galuppi and Carfagni [10] or Koutsawa and Daya [11].

Reduction factor χ and χ_{LT} for flexural buckling and lateral-tosional buckling is:

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \overline{\lambda}^2}} \tag{3}$$

where non-dimensional parameter Φ and Φ_{LT} is:

$$\Phi = 0{,}5 \cdot \left[1 + \alpha_{imp} \cdot \left(\overline{\lambda} - \alpha_0 \right) + \overline{\lambda}^2 \right] \tag{4}$$

where α_{imp} and α_0 are parameters of EC buckling curves. Several authors proposed values of these parameters - Amadio and Bedon [4, 5] or Haldimann [1].

Non-dimensional slenderness:

$$\overline{\lambda} = \sqrt{\frac{\sigma_{Rk} \cdot A_{eff}}{N_{cr}}} \tag{5}$$

$$\overline{\lambda}_{LT} = \sqrt{\frac{\sigma_{Rk} \cdot W_{eff}}{M_{cr}}} \tag{6}$$

Flexural critical force N_{cr} and moment M_{cr} could be calculated by same way as for metal members according to the EN 1993-1-1 with taking into account effective cross sectional characteristics for laminated glass.

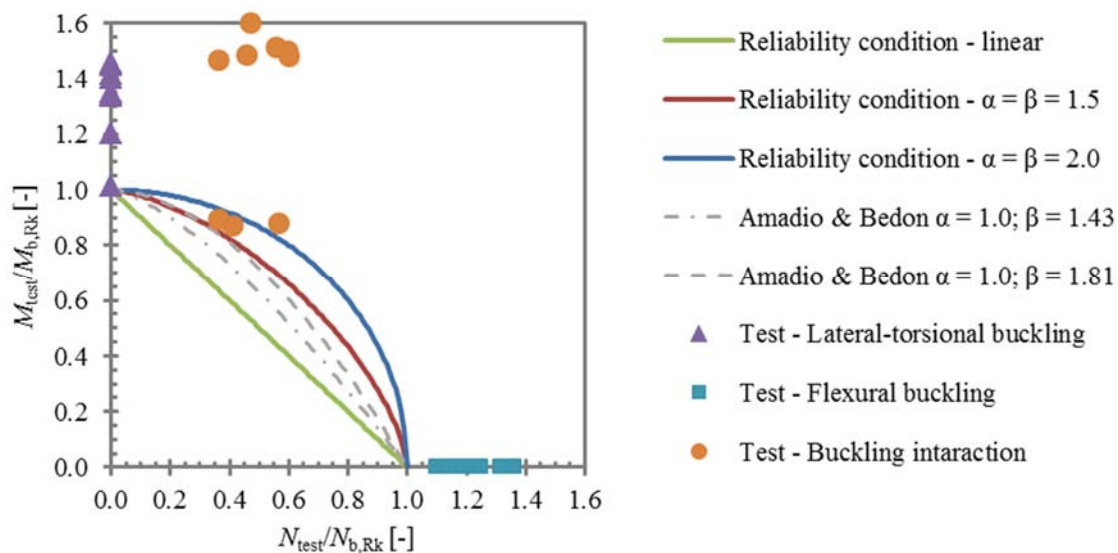### 4.2. Interaction of flexural buckling and lateral torsional buckling

Reliability condition for flexural buckling and lateral-torsional buckling interaction should be determined from wide spectrum of experiments. Linear interaction reliability condition:

$$\frac{N_{Ed}}{N_{b,Rd}} + \frac{M_{Ed}}{M_{b,Rd}} \leq 1,0 \tag{7}$$

Nonlinear interaction should be written with general exponents α and β:

$$\left(\frac{N_{Ed}}{N_{b,Rd}}\right)^{\alpha} + \left(\frac{M_{Ed}}{M_{b,Rd}}\right)^{\beta} \leq 1,0 \tag{8}$$

Presented interaction reliability conditions ale plotted in graph in Figure 10. In the graph are plotted results of testing of glass beams columns and results of previous experimental program of glass beams [12] and glass columns [13]. Plot shows that linear reliability condition is very conservative, for nonlinear condition exponents α and β could be taken by value 1.5.

Figure 10. Flexural and lateral-torsional buckling interaction: reliability conditions and test results

5. Conclusions
This paper summarizes the experimental verification of flexural lateral torsional buckling resistances of structural glass beam-columns. Reliability condition for design of glass beams columns is proposed according to the previous experimental programs.

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