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COMPRESSIVE BEHAVIOR OF LAMINATED GLASS COLUMNS

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Abstract. *This paper examines the behavior in compression of glass columns having tee (T) transverse cross-sections. The work highlights the issues recurring in the design of glass columns in rapid diffusion in the transparent architecture such as: - flexural and torsional buckling; - long-term effects and effects related to the temperature; - glued connections between single panels. In the work expressions are given for the calculation of the load-carrying capacity of columns. The cases of full connection and absence of connection between the panels are analyzed and discussed. The comparison between the analytical and the experimental results highlights that in the case of glass columns with T cross-section failure in the glued section and torsional buckling effects strongly limit the load carrying capacity of members. In these cases the analytical prediction of load carrying capacity with analytical expressions available in the literature allows good prediction and highlights that particular care should be placed on the design of glued section.*

Sommario. *Questo documento esamina il comportamento in compressione di colonne in vetro aventi sezione trasversale a "T". Il lavoro mette in evidenza le problematiche ricorrenti nella progettazione di colonne in vetro quali ad esempio: instabilità flesso-torsionale; effetti a lungo termine dipendenti dalla temperatura; incollaggi tra le lastre. Vengono fornite le equazioni per il calcolo della capacità portante delle colonne. Sono presentati e discussi la condizione di connessione completa e assenza di collegamento tra le lastre. Si osserva che la capacità portante calcolata analiticamente con le relazioni riportate in letteratura è rappresentativa della realtà.*

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1 INTRODUCTION

Several studies were addressed to analyze the effects of the shape and of the dimension of the transverse cross-section of columns often constituted by laminated glass (LG) panels assembled together by two components based glue or epoxy resin [1]. In some other cases [1,3] tee (T) and cruciform (X) cross-sections were utilized to form glass columns to be tested in compression. A cruciform section, which shape is sensitive to torsion, could fail by torsional buckling due to compressive forces. In the case of glass columns a close section cannot be utilized because it does not allows one to clean glass member compromising its transparency (aspect of fundamental importance in the architecture). In these cases (see Fig.1) the better cross-sectional shapes to adopt are T, H and X, while square and double weld cross-sections have to be excluded. Single rectangular glass panels have also to be excluded because of their slenderness that limits the load carrying capacity. For the theoretical design of glass panels against buckling three different approaches are generally followed: - the use of buckling curves based on a slenderness ratio for glass which must be based on the maximum tensile strength [4-7]; - analytical models based on second order theory [6-14].

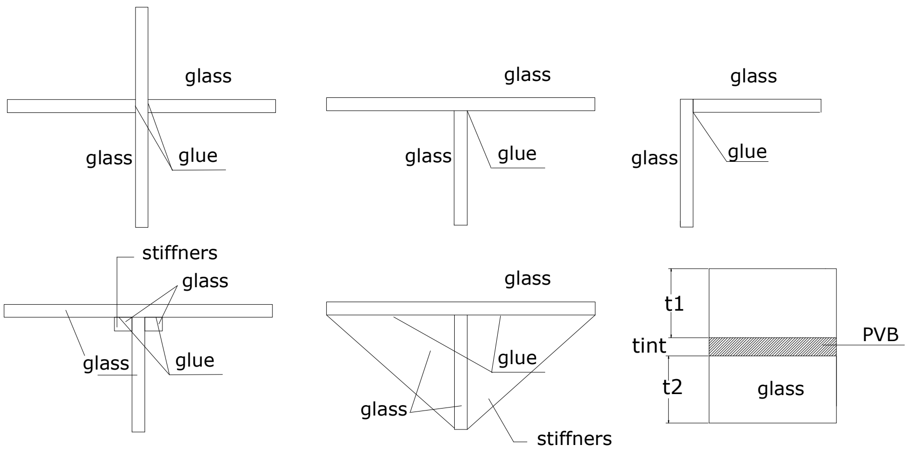

Fig. 1 – Multilayered glass panel and glued connection in different cross-sections.

In these models the maximum tensile stress in the structural glass member can be determined by means of the second order theory; - nonlinear numerical model which allow one to include initial imperfections and specific boundary conditions [7,8]. Other important aspects to take into account in the design of glass columns are the connection between two or more elements. In this case the connections transfer the forces from one element to the other. The material glass behaves elastic; therefore, it is not able to redistribute stresses. A connection in glass members causes stress concentrations, which makes that it should to be designed with great care to prevent brittle failure. Currently techniques and products exist for connecting either glass-to-glass or glass to other materials. Cases here examined refer to glued connections between single panels. Therefore, compression forces are transferred by way of friction. It has to be stressed that the strength of a glued connection not only depends on the intrinsic strength of the bond material, but is based also on: - bond material (i.e. adhesive and cohesive properties); - design of the joint (e.g. geometry of the bond, governing forces to be transferred; - aspects relating to workmanship and curing.

2 CALCULUS OF LOAD CARRYING CAPACITY

In this section it is referred to monolithic and LG panels to form transverse cross-section of glass columns. It has to be stressed that the LG panels are composed of two or more layers of glass with an interlayer in between. The buckling behaviour is therefore dependent on the properties of the interlayer as well. Following the original approach of Newmark et al. [10], Amadio and Bedon [8], for a beam formed by two layers linked by a flexible connection and subjected to an axial compressive load, derive simple expressions for the calculus of the critical load in the form:

$$N_{cr} = \frac{\pi^2 \cdot E \cdot J_{abs} \cdot E \cdot J_{full}}{L^2} \cdot \left(\frac{\alpha^2 \cdot L_o^2 + \pi^2}{\alpha^2 \cdot E \cdot J_{abs} \cdot L^2 + \cdot E \cdot J_{full} \cdot \pi^2} \right) \tag{1}$$

with

$$\alpha^2 = \frac{\dfrac{G_{\text{int}} \cdot b}{t_{\text{int}}}}{\dfrac{E \cdot b \cdot t_1 \cdot t_2}{t_1 + t_2}} \cdot \frac{\dfrac{b^3}{12} \cdot \left(t_1^3 + t_1^3\right) + b \cdot \left[t_1 \cdot \left(\dfrac{t_1}{2} + \dfrac{t_{\text{int}}}{2} \right)^2 + t_2 \cdot \left(\dfrac{t_2}{2} + \dfrac{t_{\text{int}}}{2} \right)^2 \right]}{\dfrac{b^3}{12} \cdot \left(t_1^3 + t_1^3\right)} \tag{2}$$

E being the elastic modulus of glass and L the length of the column; J_{full} and J_{abs} the moment of inertia with full connection and in the absence of connection, G_{int} being the tangent elastic modulus of the interlayer material, which, as is well known from the literature, is strongly dependent on temperature and viscous effects [14,15,16].

To take into account of the initial imperfections and of the initial eccentricity [8] suggest adopting the deformed shape of the multilayer beam.

For buckling analysis of LG panels it is commonly considered the effective thickness, which is the thickness of a monolithic beam with equivalent bending properties in terms of stress and deflection [9]. Following the approach of [14] the equivalent thickness is introduced in the form:

$$t_{eq,w} = \sqrt[3]{2 \cdot t^3 + 6 \cdot \Gamma \cdot t \cdot \left(t + t_{\text{int}}\right)^2} \tag{3}$$

$$t_{eq,\sigma_1} = \sqrt{\frac{t_{eq,w}^3}{t + \Gamma \cdot \left(t + t_{\text{int}}\right)}} \tag{4}$$

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Being $t_{eq,w}$ the equivalent thickness useful for calculation of deformations and $t_{eq,\sigma 1}$ the equivalent thickness useful for strength verification.

With

$$\Gamma = \frac{1}{1 + 9.6 \cdot \beta \cdot \left(\frac{b}{L}\right)^2 \cdot \frac{E \cdot \frac{1}{2} \cdot t \cdot (t + t_{\mathrm{int}})^2 \cdot t_{\mathrm{int}}}{G_{\mathrm{int}} \cdot (t + t_{\mathrm{int}})^2 \cdot [\min(L; b)]^2}} \tag{5}$$

With β=1.09

In this case the critical load can be evaluated as:

$$N_{cr} = \frac{\pi^2 \cdot E \cdot J_{eq}}{L^2} \tag{6}$$

With

$$J_{eq} = \frac{1}{12} \cdot b \cdot t_{eq.w}^3 \tag{7}$$

According to Galuppi and Royer Garfagni [14] particular care has to be placed when equivalent thickness proposed in [12] is utilized. It is because its value is strictly related to the case examined in [12] which is that of a beam simply supported and loaded with uniform load. Therefore, in other cases of interest, such as those of plates with different loading and boundary conditions, Galuppi and Royer Garfagni [14] introduced, on the basis of an energetic approach, an equivalent thickness of more general use.

In the case of utilizing open cross-sections, torsional buckling risk arises and the expressions of resistance N_{oz} of a simply supported column of length L can be found in [15]:

It has to be observed that for angles, tees, and cruciform cross-section the warping section is negligible and therefore the load carrying capacity is limited to:

$$N_{OZ} = \frac{E}{2 \cdot (1 + \upsilon)} \frac{\sum \frac{b \cdot t^3}{3}_w}{\left(\frac{b \cdot t}{2} \cdot \left[(2 \cdot t^2 + b^2) + 2 \cdot (t + b)^2\right] + \frac{1}{12} \cdot b \cdot t \cdot (8 \cdot b^2 + t^2)\right) \cdot \frac{1}{3 \cdot b \cdot t}} \tag{8}$$

According to Stomm and Witte [18] to take into account of the time effects the torsional warping constant of single panel can be calculated as:

$$G \cdot J_i = G \cdot (J_{t1} + J_{t2} + J_{ting}) \tag{9}$$

With

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$$J_{ting} = J_s \cdot \left(1 - \frac{\tanh\left(\frac{\lambda \cdot b}{2}\right)}{\lambda \cdot b} \right) \tag{10}$$

$$J_s = 4 \cdot \left(\frac{t_1 + t_2}{2} + t_{\text{int}} \right)^2 \cdot \frac{t_1 \cdot t_2}{t_1 + t_2} \cdot b \tag{11}$$

And

$$\lambda = \sqrt{\frac{G_{\text{int}}}{G} \cdot \frac{t_1 + t_2}{t_1 \cdot t_2} \cdot \frac{1}{t_{\text{int}}}} \tag{12}$$

As demonstrated in Trahair [15] it results:

$$\frac{\phi_m}{\phi_{om}} = \frac{N/N_{oz}}{1 - N/N_{oz}} \tag{13}$$

Being ϕ_{om} the maximum initial crookedness assumed as

$$\phi_{om} = \frac{w_o}{2 \cdot b} \tag{14}$$

Being w_o the initial imperfection.
From Eq. (13) it results:

$$\frac{N}{N_{oz}} = \frac{1}{1 - \frac{\phi_m}{\phi_{om}}} \tag{15}$$

N_{oz} represents the asymptotic value of critical load for a twisted column without imperfection.

To take into account of the connection between single panels it was supposed that glued connections are utilized. This kind of connection is brittle and under torsion or compression shear stresses arises in the connection. Normal stresses (peeling action) are neglected and shear stresses are supposed uniformly distributed along the glued section of thickness and the entire length of the columns. Two component epoxy resin glued connections can be considered as rigid plastic with viscous time depending effects. Also for temperature up to 50 °C most of the company producing two-component glue based on epoxy resin ensures constant strength values.

From equilibrium of internal forces it results:

$$N = \tau \cdot L \cdot t_g \tag{16}$$

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Also the presence of discontinuous glass stiffeners could increase the torsional resistance and the local buckling resistance. A limit state in the glue connection with two-component glue based on epoxy resin is reached when shear stress reaches the maximum shear stress. Italian Draft [10] for a glass structure suggests values of shear strength in the range between 12 and 18 MPa. Experimental validation of expressions above mentioned can be found in Campione and Rondello (2014) in which experimental researches of [1, 2, 3, 6] were utilised.

Campione et al. [1-2] tested glass panels and also columns with T-shaped cross-section. The columns were assembled with a main panel having a width of 300 mm and one (T-shaped section) orthogonally disposed panels with side 150 mm. Single panels had width 300 mm, thickness 9.52 mm and height equal to 600, 800 and 1000 mm. Fig. 2 shows the strength variation of critical load for columns with T transverse cross-section with the length increases. Flexural buckling, local buckling and torsional buckling strength predictions are given in the same graph. Also strength previsions relative to glue failure are given. Comparison shows that load carrying capacity is that of the connection failure and in the case of T and X cross-section it value is very close to torsional buckling failure. Glue failure was calculated assuming for shear strength both values of 12 and 18 MPa as suggested in Italian DRAFT [9].

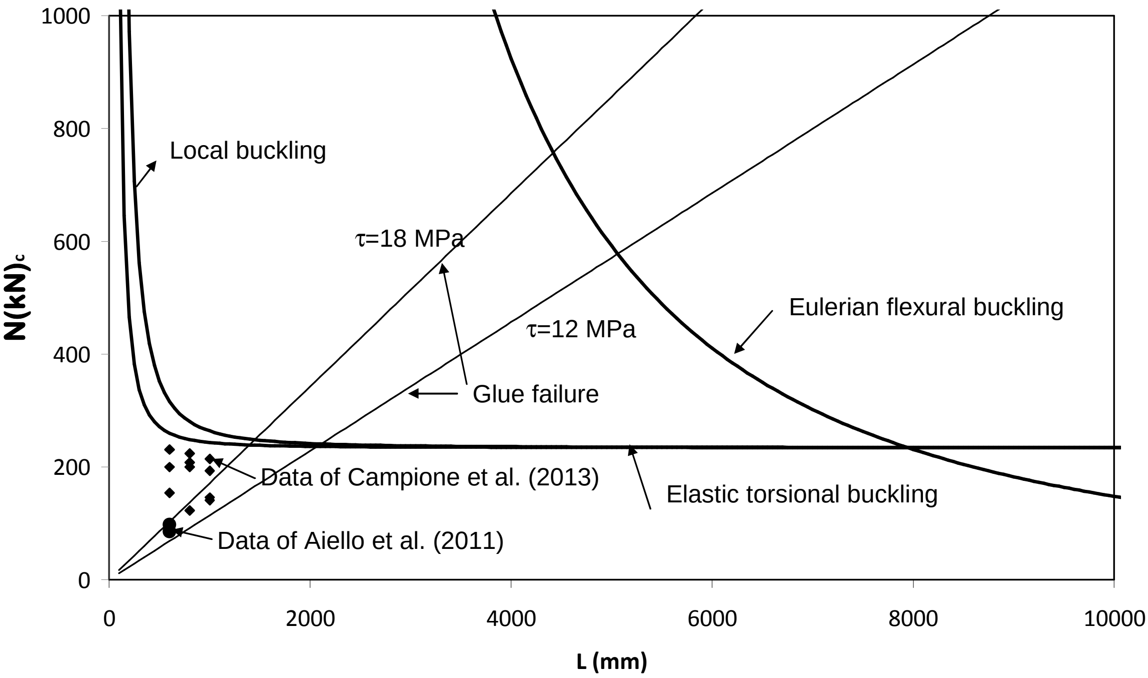

Fig. 2 – Variation of critical flexural load with length variation for T cross-section.

The effective load carrying capacity of glass columns with open cross-section obtained by gluing single panels is strongly affected by the glue resistance and local and torsional buckling; Glued connections result in most of the cases examined the weakest parts of columns.

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