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LATERAL-TORSIONAL BUCKLING OF ALUMINUM MULLION IN CURTAIN WALL

Curtain wall as contemporary facade structures are often preferred by designers on different types of structures. In this paper, they are viewed in a more contemporary, complex and comprehensive way. Wind load was analysed using CFD. The supporting elements of the curtain wall made of aluminium alloys AW 6063.T5 and AW 6082.T5 have been specifically tested for lateral torsional buckling. Recommendations have been made for the use of specific cross-sections, the implementation of which would result in significant savings in the material on the buildings facades.

Keywords: facade, curtain wall, aluminium, steel, lateral torsional buckling

1. INTRODUCTION

Contemporary structures in every respect tend to go beyond the set boundaries, so consequently the contemporary facades have never been so complex. The basic function to protect the users is somehow put aside while only the design striving to the most attractive and challenging facades comes to the fore. Due to their complex function, facade structures are subject to many criteria, which is why they are the subject of constant theoretical and experimental research. “Curtain walls have been around for over a century; however, they still present a challenge for building designers, curtain wall manufacturers and installers” [10]. Curtain walls can be defined as lightweight, skin structure composed of industrially produced elements, most often glass and metal, which assumes all the functions of an outer wall, except the supporting one. They represent a synthesis of aesthetic and technical-technological solutions with practically no limit in formal and structural design. The curtain wall structure, unlike the main load-bearing structure, which receives all the loads of the building, must absorb, transmit and withstand the loads acting on it through carefully designed vertical and horizontal load-bearing elements of the facade. In most cases, problems that occur on facades of this type are a direct consequence of inadequate design, construction and incompatibility with the supporting structure of the building.

Wind is the dominant load for the curtain wall facades and belongs to the stochastic and complex loads and it is a subject of numerous researches [4,11]. Understanding nature and wind behaviour is of key importance for adequate designing of lightweight curtain wall type facade structures and the wind load on the building must be analysed in the earliest stages of designing [8,10].

This type of structures were analyzed in previous research more complexly and comprehensively in particular regarding the effect of wind using computational fluid dynamics as a contemporary method. Based on these results, the sensitivity of the supporting elements of the curtain wall to lateral-torsional buckling has been specifically addressed, and recommendations for the selection of cross-section shapes have been made.

2. MATERIALS & METHODS

2.1 CURTAIN WALL STRUCTURE, MATERIALS AND LOADS

The curtain wall structure consists of vertical bearing elements, mullions and horizontal elements, transoms. Mullions and transoms, placed at proper spacing create frames used to install infill elements, which are prevalently glass, but can be stone, aluminium, copper, composite materials etc. Mullions and transoms can vary, but most often those are tubular, double or mono-symmetrical I sections, T sections etc. These elements can be full and hollow. Some of them are shown in Figure 1. Connections between the elements but also the connections to the bearing structure must be such to ensure displacement due to the effects of external forces, primarily of the wind, to ensure expansion due to temperature and gravity effects, for instance due to the foundation settling.

Figure 1

Characteristic loads for this type of structures, in addition to their own weight, are wind, snow, ice, temperature and earthquake. In some cases, depending on the static system and the shape of the facade, the load that would occur when maintaining the structure should be considered. Wind is the dominant load in light facade structures. What is important and what should be considered is the effect of wind on the corners of buildings and also on the parts of the facades near the roof. Here, due to the formation of the vortex, there is a strong suction effect of the wind and the pressure coefficients are many times higher than in the central parts of the surfaces loaded with wind. Particular attention should also be paid to the effect of temperature since the substructure is often made of aluminium and its thermal expansion coefficient is 3 times higher than that of steel and the dilations that occur in the elements are not small. This problem is usually solved by an adequate choice of the static system or using suitable sliding connections.

Since these are sections with a height much larger than the width of the flange, particular attention has been paid to the stability of the supporting elements of the curtain wall. The area of stability in steel and aluminium is a constant subject of research, and it should be noted that this problem is more complex regarding aluminium alloys than steel for many reasons. The first is that aluminium alloys make a much wider family of materials than is the case with structural steels, not only because of the different alloys and chemical composition, but also because of the considerable changes in mechanical characteristics due to the degree of processing.

Cross sections of the supports used for the load-bearing elements of the curtain wall, mullions and transoms belong to a group of narrow, but deep, cross sections. The reason why such sections are frequently a part of the curtain wall structures lies in several facts. Primarily, the infill elements with a load acting on them should be received from the outside, and on the inside the same elements should be connected to the supporting structure of the structure or to each other so as to allow displacements due to external effects and also the expansion of the elements themselves. What is characteristic of the open cross sections whose height is considerably higher than their width, is that the flexural stiffness about the stronger axis (I_y) is considerably higher than the flexural stiffness about the weaker axis (I_z), while the torsional stiffness (I_t) of these cross-sections is also small. Support elements of such characteristics are sensitive to lateral displacements and rotation about the shear centre. The situation is made additionally complex by the fact that the sections for the curtain wall elements are often symmetrical about one axis only. From all this, it can be concluded that the curtain wall elements need to be checked to lateral torsional buckling, especially those of open cross sections.

2.2 LATERAL TORSIONAL BUCKLING

Lateral torsional buckling of the support element comprises lateral displacement of the element with the simultaneous rotation about the vertical axis of the cross section resulting from the bending around the stronger axis of the cross section when the critical momentum value is reached (Figure 2). This type of element buckling is characteristic of both steel and aluminium supports. However, although there are similarities, the approach to this problem is not the same in the regulations regarding the two materials [5,6].

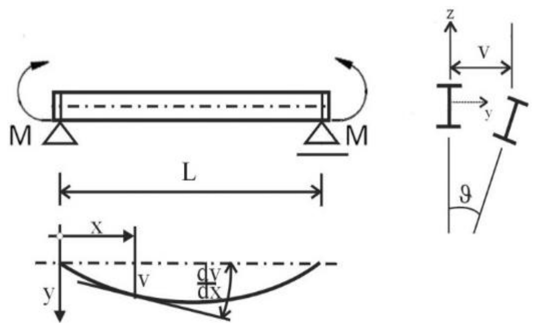

Figure 2. Lateral-torsional buckling

In order to provide a relative lateral torsional slenderness, $\bar{\lambda}_{LT}$ it is necessary to compute the elastic critical momentum for lateral torsional buckling, M_{cr}. However, the standing versions of Eurocode 3 [5] does not provide any recommendations for computation of M_{cr} apart from the note that the computation of the elastic critical moment should be based on the gross cross sections, take into account the support or lateral bracing conditions and the type of load. The reason there is no clearly defined expression for M_{cr} and recommendations for its computation lies in the complexity of this problem, but also in the non-existing consensus of the EU members (Androić 2009). Contrary to the described situation for the calculation of the steel elements resistance to lateral torsional buckling, the regulations regarding the calculation of aluminium supports for lateral torsional bending approach to this problem and the calculation algorithm in Eurocode 9 [6] is clearly defined in Annex I. Stability problems and consequently the lateral torsional buckling problem are much more pronounced in aluminium due to the lower value of the modulus of elasticity comparing to steel.

Equations (1) to (5) present the expression for the elastic critical moment, which when reached causes the loss of stability of the support due to the lateral torsional buckling:

$$M_{cr} = \mu_{cr} \frac{\pi\sqrt{EI_z GI_t}}{L} \tag{1}$$

$$\mu_{cr} = \frac{C_1}{k_z}\left[\sqrt{1 + k_{wt}^2 + \left(C_2\zeta_g - C_3\zeta_j\right)^2} - \left(C_2\zeta_g - C_3\zeta_j\right)\right] \tag{2}$$

$$k_{wt} = \frac{\pi}{k_w L}\sqrt{\frac{EI_w}{GI_t}} \tag{3}$$

$$\zeta_g = \frac{\pi z_g}{k_z L}\sqrt{\frac{EI_z}{GI_t}} \tag{4}$$

$$\zeta_j = \frac{\pi z_j}{k_z L}\sqrt{\frac{EI_z}{GI_t}} \tag{5}$$

Where μ_{cr} is a relative, dimensionless critical moment, G shear modulus, EI_z minor axis flexural rigidity, GI_t torsional rigidity, EI_w warping rigidity, L length between lateral bracings. Coefficients C_1, C_2, C_3, k_z and k_w are defined in EN 1999-1-1:2007 [6].

Expressions (1) to (5) include different support conditions of the load-bearing element, effect of the position of the load application point, but also the cross sections symmetrical around one axis. In case of the cross sections symmetrical around both axes, the gravity and shear centre coincide, while in case of the cross sections symmetrical around one axis it is not true, so the computation equations are more complex. In Figure 3 is presented a mono-symmetrical cross section where G is gravity centre, S shear centre, z_s distance from the shear and gravity centre, z_g distance from S to load application point, z_a distance from G to load application point.

Parameter z_j is of extreme importance for determining the critical moment on the lateral torsional buckling. Equation (6) shows an exact formula for computation of parameter z_j, however, in literature there are numerous propositions for its approximation. When the cross section is symmetrical about the stronger axis (y-y axis) then z_j=0. Equation (7) provides the approximation formula from Eurocode 9, [6].

$$z_j = z_s - \frac{0{,}5}{I_y}\int_A (y^2 + z^2) z\,dA \tag{6}$$

where z_a is the coordinate of the load application point in relation to the gravity; z_s

coordinate of shear centre in relation to the gravity; z_g coordinate of the load application point in relation to the shear centre (Figure 3).

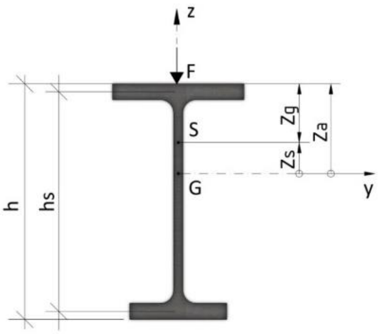

Figure 3

$$z_j = 0{,}45\psi_f h_s \left(1 + \frac{c}{2h_f}\right) \quad (7)$$

$$\psi_f = \frac{I_{fc} - I_{ft}}{I_{fc} + I_{ft}} \quad (8)$$

In the previous equations h_f is the distance between the gravity centre of the top and bottom flange; c height of the flange reinforcing web (see Figure 3); ψ_f factor of cross section mono-symmetry; I_{fc} moment of inertia of the compressed flange about the weaker axis; I_{ft} moment of inertia of the tensioned flange about the weaker axis, h_s distance of the shear center of the top flange and shear center of the bottom flange.

For I cross section, with unequal flanges, without reinforcement, the following stands:

$$I_W = \left(1 - \psi_f^2\right) I_z (h_s/2)^2 \quad (9)$$

In case of the beams loaded the web plane, the position of the load application point has a considerable effect on the value of the critical moment of the lateral torsional buckling, M_{cr}. If the load application point is above or below the shear point *S,* this force causes additional torsional effects. These effects can be stabilizing in case the load is applied below the shear centre, and destabilizing when the load is applied above the shear centre.

In order to determine whether the beam is resistant to lateral torsional buckling, Equation (10) is used, where M_{ed} labels the design bending moment, and with $M_{b,rd}$ design resistance to lateral torsional buckling, provided with Equation (11).

$$\frac{M_{Ed}}{M_{b,rd}} \leq 1.0 \quad (10)$$

$$M_{b,rd} = \kappa_{LT} \frac{\alpha W_{el,y} f_o}{\gamma_{M1}} \quad (11)$$

$$\kappa_{LT} = \frac{1}{\phi_{LT} + \sqrt{\phi_{LT}^2 - \overline{\lambda}_{LT}^2}} \leq 1{,}0 \quad (12)$$

$$\phi_{LT} = \frac{1}{2}\left[1 + \alpha_{LT}\left(\overline{\lambda}_{LT} - \overline{\lambda}_{0,LT}\right) + \overline{\lambda}_{LT}^2\right] \quad (13)$$

In the previous equations κ_{LT} is the reduction factor for lateral torsional buckling; α_{LT} imperfection factor; $\overline{\lambda}_{0,LT}$ horizontal plateau limit.

Relative slenderness of lateral torsional buckling is provided with equation (14):

$$\overline{\lambda}_{LT} = \sqrt{\frac{\alpha W_{el} f_o}{M_{cr}}} \quad (14)$$

where α is the shape factor.

3. ANALYSIS & RESULTS

This research included the resistance analysis of the beams used for vertical load-bearing elements of curtain walls, mullions, to lateral torsional buckling [2]. Aluminium I beams and double as well as mono-symmetrical cross sections are considered. For this purpose, a program (application) was created which enables: input of the selected aluminium alloy, its characteristics and the corresponding buckling class; determining the class for each part of the cross-section (top flange, web, bottom flange) in the case of an evenly distributed load; adopting a cross-sectional class for whole cross-section; calculating the effective thicknesses of the cross-section elements in the case of a class 4 element; calculation of elastic, plastic and effective moments, W_{el}, W_{pl}, W_{eff}; determining the cross section shape coefficient, α depending on the cross section class.

Based on the obtained data, set beam length, *L* and design bending moment, M_{Ed} determination of the elastic critical moment to lateral torsional buckling, M_{cr}, is made possible for the given cross section and the given point of load application on the top flange, shear centre and bottom flange, and all the relevant coefficients and parameters necessary for its computation; determination of z_j according to the exact formula and its comparison with the parameter r_z; determination of the relative lateral torsional slenderness, λ_{LT} for all three positions of the point of load application; determining the reduction factor for the lateral torsion buckling, κ_{LT} and parameters necessary for its determination; determination of design resistance to lateral torsional buckling, $M_{b,Rd}$; determination whether the given beam is resistant to lateral torsional buckling.

It should be emphasized that the application is made for the case when the beams are loaded with evenly distributed load, and in addition to double symmetrical and mono-symmetrical I cross sections, T cross sections are included, too.

Previously described application is used for the analysis of the resistance of an arbitrary I cross section beam to a lateral torsional buckling. Two groups of cross sections are formed. The first group comprises the cross sections having the width of one flange $b_{1,f}$=50 mm and the other group included the cross-sections with the flange width $b_{2,f}$=60 mm. It should be emphasized that the analysis includes T cross-sections too, as special cases of I cross section. The heights of the cross sections of both groups are h= 100, 150, 200 and 250 mm (Figure 4).

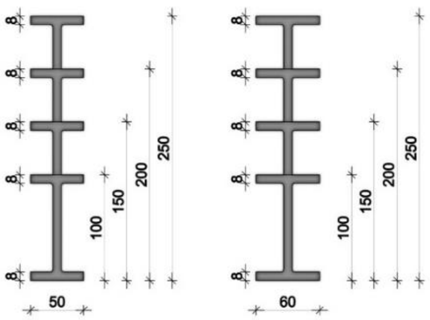

Figure 4. Groups of analysed mullions

Beams with different mono-symmetry factors, ψ_f (Figure 5) were compared using a relative dimensionless critical moment, μ_{cr} [-] provided with equation (2).

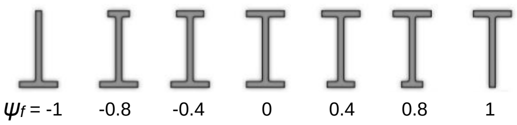

Figure 5. Analysed cross-sections

The load on mullions and transoms mostly acts on the so-called outer flange (flange closer to the exterior) since the infill elements are most often connected in such a way that the load-bearing elements are inside the building. This research, however, included the computation of the critical moment to lateral torsional buckling, even when the load acts in the shear centre and inner flange.

The results are also shown graphically in Figure 6. This diagram shows the resistance to lateral torsional buckling of the examined cross sections (Figure 4 and 5) when the point of load application is on the outer flange (*GN*), shear centre (*CS*) and bottom flange (*DN*) depending on the mono-symmetry parameter ψ_f, for all the examined cross section heights.

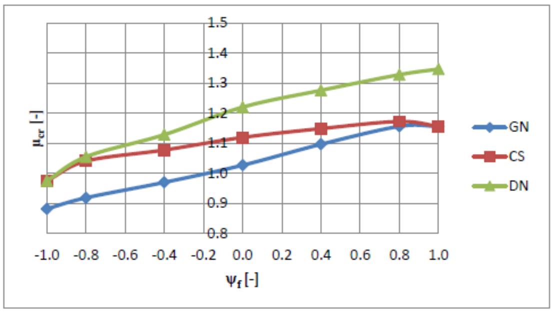

Figure 6. Dependence of μ_{cr} on ψ_f for the cross-section height h= 150 mm

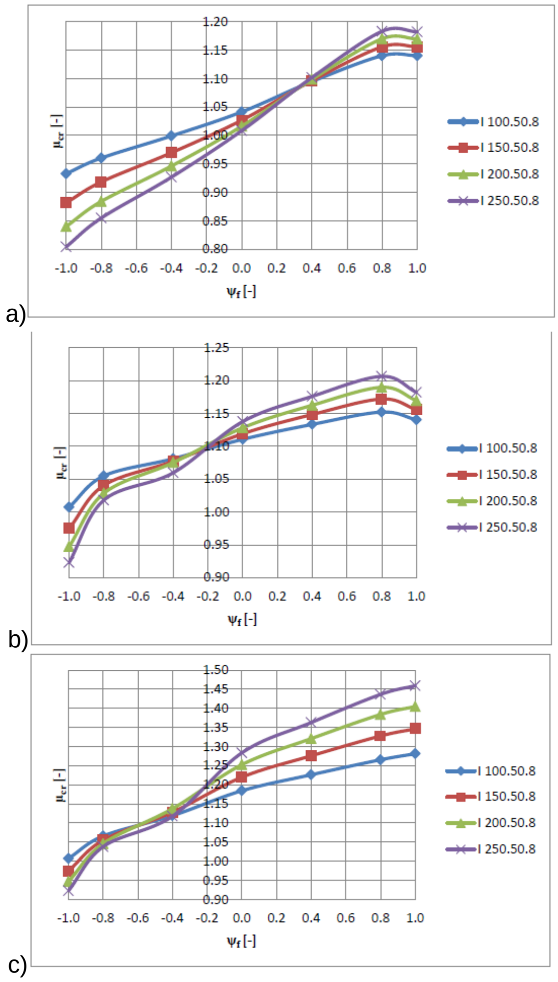

Figure 7. Dependence of μ_{cr} [-] on ψ_f for various cross section heights when the load is applied on GN (a), CS (b) and DN (c)

Figure 7 show dependence diagrams of the dimensionless critical moment μ_{cr} [-] on the mono-symmetry factor ψ_f for the case when the load is applied on the top flange (GN), shear canter (CS) and bottom flange (DN), for the cases of various cross section heights.

4. DISSCUSSION

By incorporating a dynamic analysis of the effect of wind on the facades of tall buildings, a more realistic picture of the loads and stresses generated in the supporting elements of the curtain wall, especially the elements at the corners of the building and at high altitudes, was obtained, given the change in wind speed with height.

A special attention is paid to the mono-symmetry parameter ψ_f and its effect on lateral torsional buckling. The increase of this parameter is followed by the increasing resistance of the tested cross sections to lateral torsional buckling. For the vertical support elements of curtain walls, regarding the lateral torsional buckling, it is convenient to use mono-symmetrical cross sections where the mono-symmetry parameters is $\psi_f > 0$. Cross sections with the values $-1 \leq \psi_f \leq 1$ were examined, and a favourable behaviour was demonstrated by cross sections where $0.2 \leq \psi_f \leq 0.8$. By comparing the resistance of the examined cross sections to lateral torsional buckling, it was determined that the cross sections with the mono-symmetry parameter $\psi_f = 0.8$ are most favourable when the load is applied on the top flange and shear canter (Figure 7 and 8). This research confirmed the fact that, as the position of the point of load application moves from the top flange towards the bottom flange, the resistance of the cross section to lateral torsional buckling increases. Another conclusion is that by increasing the height of the cross section this phenomenon becomes more prominent. Based on the previous facts, it is concluded that the vertical curtain wall elements would be more cost-effective if the infill panels were connected to the mullion shear canter or its lower flange.

5. CONCLUSION

The aim of this scientific research was to do a more complex analysis of the curtain wall as light facade structures. It is obvious that the cross-sectional shape, expressed via the mono-symmetry parameter, has a significant effect on its resistance to lateral-torsional buckling. Since the cross sections of the supporting elements are often curtain wall only symmetrical about one axis, the advantages shown by these cross sections in relation to the resistance to lateral torsional buckling should be exploited. Proper selection of the appropriate cross-sectional shape and the position of the point of load application can increase the resistance to lateral-torsional buckling of the supporting elements of curtain walls. In this way, adopting mono-symmetrical I cross sections would result in significant material savings. This should not be neglected knowing the fact that the cost of the facade makes a considerable share of the total cost of the building.

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