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NUMERICAL ANALYSIS OF LATERAL TORSIONAL BUCKLING OF STEEL I-BEAMS WITH AND WITHOUT WEB-OPENINGS UNDER FIRE

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Abstract

Steel structures are being widely used in construction industry owing to their excellent structural flexibility and to their high ductility to withstand lateral forces. However, for the case of solid and cellular steel beams, high temperature effect may result in different fire response for each case due to a great reduction of yield stress and Young's modulus.
Moreover, when the beams are not restrained, lateral torsional bending phenomenon which are bound to take place is made worse in the case of fire. The aim of this study is to analyse the behaviour of steel beams with and without web openings when taking into account the effect of geometry and material imperfections. The results from the finite element models produced lateral and vertical displacements as well as the buckling moments.

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1. INTRODUCTION

During the last decade, there has been great concern about fire applied loading effect on structural steel frames and their elements, especially when instability phenomenon arises due to high temperatures. In this study, we will highlight at lateral torsional buckling failure of solid and cellular steel beams member at elevated temperature.

Many researchers have studied LTB of solid beams at ambient [1-2] and elevated temperature, [3-4], its knowledge is largely developed recently by investigating the effect of imperfections and residual stresses on the latter's behaviour [5-6], whilst LTB in cellular beams has been less studied at ambient and elevated temperatures.

Recent research works with a focus on the lateral stability of cellular beams consider the effect of combined modes for the elastic behaviour [7-8] and a single mode for inelastic behaviour [9]. The first numerical study incorporates the initial geometric imperfections, residual stresses shows that the combination of web-post buckling and web distortion leads to failure of cellular steel beams. The second numerical study significant reduction in failure loads at fire conditions for different opening shapes.

The investigation conducted by Pattamad et al. [10] is considered by adopting the analytical formulas of the moment gradient factor C_b for the elastic critical moment and the correction factor, k_{LB}, for the calculation of the inelastic lateral resistance.

To achieve adequate fire resistance for cellular steel beams, experimental studies have been carried out to understand the behaviour of the protection especially between and around openings [11].

The objective of this paper is to study the fire behaviour of simply supported steel beams with and without web openings under lateral torsional buckling accounting geometric imperfection and residual stress.

A nonlinear geometric and material analysis, with the Newton-Raphson time step solution, was done using finite element software ANSYS [12]. The analysis investigates the overall displacement and the LTB moment capacity of hot rolled steel section for parent solid beams and their corresponding cellular beams.

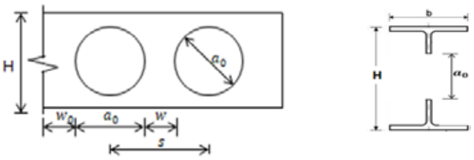
The first part of the numerical simulation results are compared with those obtained by Peter et al. [13]. In the second part where geometrical imperfections and residual stresses are computed for lateral torsional buckling analysis, comparison is made with those calculated according to Eurocode EN 1993-1-2 [14] for solid beams and with analytical formulation from Pattamad.P et al. for cellular beams [10].

2. INPUT PARAMETERS AND VALIDATION

2.1 Model description

The studied floor steel beams are fixed with span L =8 [m], simply supported and made from 610UB101 hot rolled profile and laterally unrestrained to undergo lateral torsional buckling as considered by Peter et al. [13]. The beams were analysed numerically using ANSYS finite element software using SHELL elements.

The openings in the cellular beam are distributed in regular intervals while respecting the following parameters a_0 / h = 0.8, H/h =1.3 and w / a_0 = 0.3 [15]. Where h=602 mm is the initial height of the cross section whose breath b=228 mm and H the final height, a_0 the opening diameter, and w is the web post width, figure 1, table1.



(a) (b)

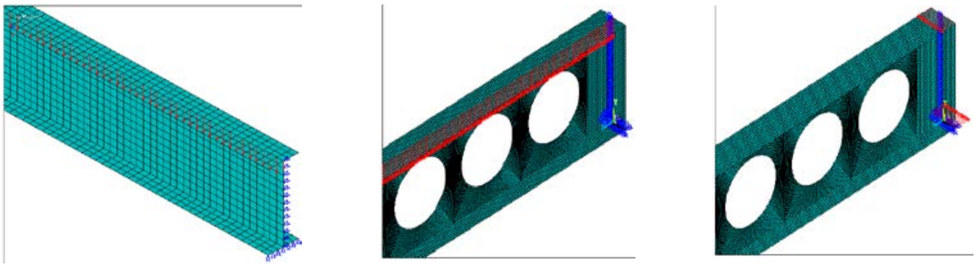
Figure 1: Geometry properties of cellular beam.

Table 1: Properties of the cellular steel section

a_0/h	w/a_0	H/h	w_0/a_0	a_0	w	H	w_0	s	N
				mm	mm	mm	mm	mm	
0.8	0.3	1.3	0.5	481.6	144.48	782.6	240.8	626.08	12

The beams are subjected to constant temperature and an increasing uniform distributed load (U) until the beam collapse. The element steel grade is S430 (f_y = 430 [MPa]) with a typical value of modulus of elasticity of 210 [GPa], and Poisson’s ratio of 0.3.

As a second case the simply supported cellular beams are loaded with end moment (M) modelled by a couple of loads acting on the flanges nodes, as shown in figures 2-c on the right.

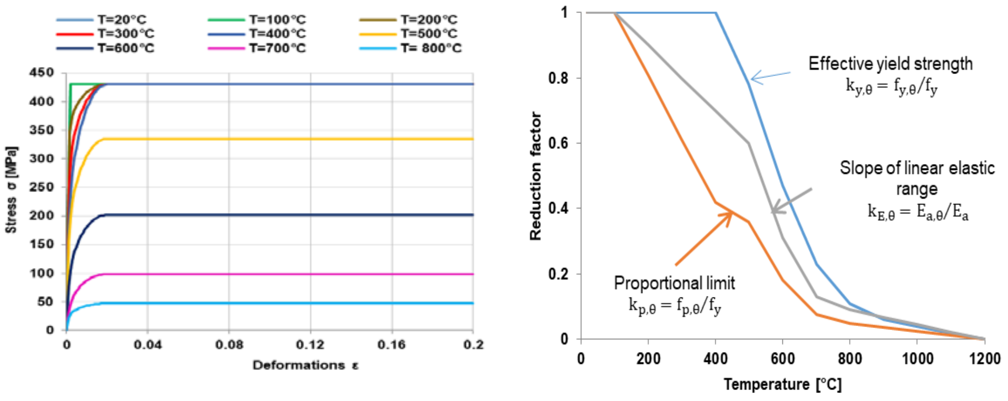


(a) (b) (c)

Figure 2: Finite element models: (a) solid beam with distributed load, (b) cellular beam with distributed load, (c).cellular beam with end moment.

2.2 Mechanical properties at high temperature

The FE models are simulated taking into account material and geometrical nonlinearities. The non-linearity of the material is established according to the stress-strain diagrams for different temperatures of EC3 for S430 steel grade [14] for all simulations. The stress and deformation properties of the steel at elevated temperatures are shown in figure 3.



(a) (b)

Figure 3: Material properties at elevated temperatures: (a) Stress-strain vs. temperature, S430, (b) Reduction factor.

2.3 Validation of the FE model

The reference model of our validation comes out from an investigation by Peter et al. [13] on a bi-articulated steel beams, in fire condition. The simulation account for a constant rise in temperature of 10 °C/min until collapse of the steel beam is reached under the same stress-strain diagram presented above.

The comparative study is made on the basis of the displacement at mid-span and the critical temperature for the two cases, pin-rolled and fixed support conditions. The displacement values (U_y) Vs. time for pin-rolled case is shown in Figure 4, and the displacement, time and corresponding to the critical temperature (θ) for both cases are shown in table 2.

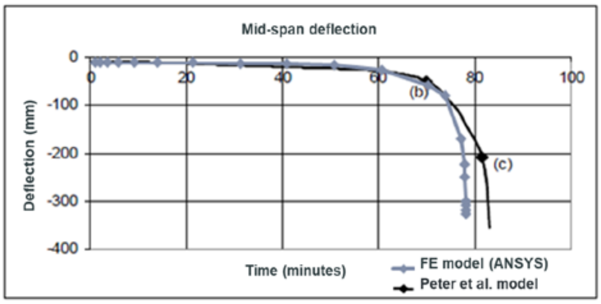


Figure 4: Displacement vs. Time of Pin-rolled steel beam.

Table 2: Comparison of results

	Pin-roller beam			Fixed-fixed beam		
	Time (min)	U_y [mm]	θ_a [°C]	Time (min)	U_y [mm]	θ_a [°C]
Peter et al. model	83	-380.00	830.00	88	-223.00	880.00
FE model (ANSYS)	79.9	-382.30	799.19	89.2	-207.00	892.96

The comparison of displacement-time curves and critical temperatures shows that the numerical model closely represents the mechanical behaviour of beams until collapse, so it can be used as a validated numerical model for this study.

3. NUMERICAL ANALYSIS OF LATERAL TORSIONAL BUCKLING OF SOLID BEAMS AND THEIR CORRESPONDING CELLULAR BEAMS AT HIGH TEMPERATURE

In this part, the previously validated nonlinear FE model is used to investigate the LTB of solid and cellular beams. At elevated temperature the design buckling resistance moment of laterally unrestrained solid beam $M_{b,fi,t,Rd}$ is calculated in compliance with EN 1993-1-2 [14]. For the cellular beam the same equation is used with a correction factor K_{LB} as mentioned by Pattamad et al. [10], for the design of cellular beams with $\lambda_{LT} < 2.5$ as follows:
without shear loads (End moment load):

$$k_{LB} = 1/(-0.01\lambda_{LT} + 1.05) \tag{1}$$

with shear loads (Distributed load):

$$k_{LB} = \min(0.16(A_f / A_w) + 0.66, 1) / \max((-0.1\bar{\lambda}_{LT} + 1.13), 0.9) \tag{2}$$

To account for the geometric imperfections on the FE model, an elastic buckling analysis is performed and the first Eigen buckling mode was introduced with a maximum amplitude value of L/1000 [4]. For residual stresses a maximum compressive and tensile value of 0.3 f_y are applied directly on both web and flange according to the existing literature [6], figure 5. For cellular beams, the residual stresses considered are taken similar to those of the solid beam case.

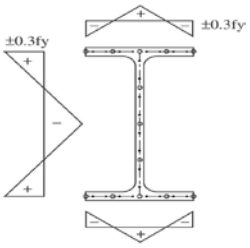


Figure 5: Residual stresses distribution for hot rolled profile [6].

3.1 Elastic buckling analysis

For solid steel member with I-section, the calculation of elastic critical moment M_{cr} for lateral-torsional buckling according to the elastic buckling theory was calculated from the formula given by Kada and Lamri [4], Vila Real et al. [5]. For cellular beam this critical moment was modified with a moment gradient factor C_b as stated in [9], where:

$$C_b = 12.5M_{\max} / (2.5M_{\max} + 3M_2 + 4M_3 + 3M_4) \quad (3)$$

Where: M_{max} is the maximum moment, and M_2, M_3, and M_4 are the values of the moment at $L_b/4$, $L_b/2$ and $3L_b/4$, respectively with absolute values, L_b is the laterally unbraced length of the beam's compression flange, in our case $L_b=L$.

Figure 6, Figure 7 presents respectively the comparison between the critical moment determined from Eurocode for solid beam, from Pattamad et al. [10] for cellular beam and critical moment corresponding to the first buckling mode obtained from results of numerical analysis in function of temperature. The critical moment of Eurocode and Pattamad’s reference model is higher than the critical moment result from numerical simulations for both steel beams loaded uniformly. We also note that the two FE values for both steel beams are somewhat close.

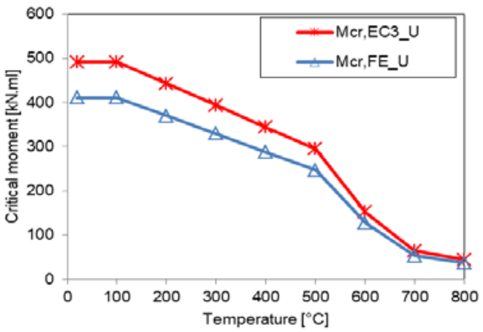


Figure 6 : Comparison of elastic critical moment between EC3 and FE simulation for solid beam

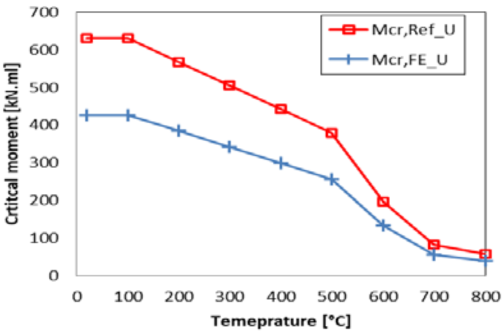
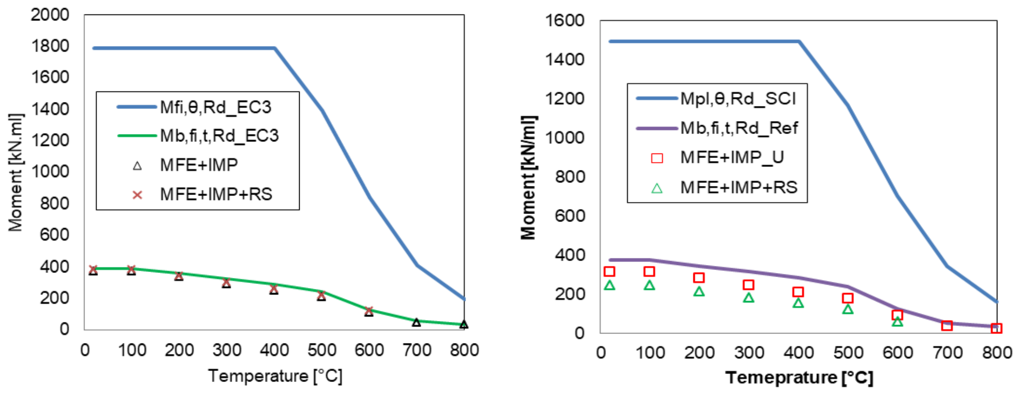


Figure 7 : Comparison of elastic critical moment between Pattamad’s reference and FE simulations for cellular beam

3.2 Inelastic buckling analysis

For the inelastic buckling analysis, the FE models account for the influence of imperfections and residual stresses under elevated temperature to determine the steel beams displacements and fire resistance.

Figure 8a shows the moments M_{FE} obtained by numerical simulations and those calculated analytically by the expression provided in Eurocode 3 Part 1-2 [14], $M_{fi,\theta,Rd}$, $M_{b,fi,t,Rd}$, for solid beams. Figure 8b comparison with Pattamad's [10] results of $M_{b,Rd}$ at ambient temperature and at elevated temperature for $M_{b,fi,t,Rd}$ the design buckling resistance moment is done for cellular beams. For this latter case $M_{b,Rd}$ is multiplied by a reduction factors $k_{y,\theta}$ relative to the value f_y according to EC3-1-2 [14]. The computing of the plastic moment is done for each case with its corresponding critical load.

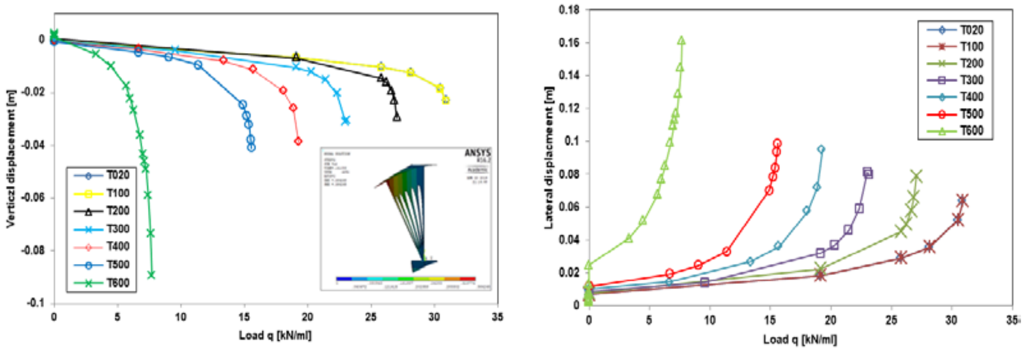


(a) (b)

Figure 8: Bending moment, LTB moment in function of temperature: (a) for solid beam, (b) for cellular beam.

Under a unit uniform load, the first positive buckling mode is considered to include geometric imperfections to the undeformed model which simulates the lateral torsional buckling [10]. In addition, figure 8 shows that the imperfections have great influence on the beam's failure and increase the lateral bending of the flange leading to the LTB of the beam.

Figure 9 shows the obtained vertical and lateral displacement results for cellular beam by numerical simulations in function of applied load. We can see that with the increasing of the applied load over time, from 20 to 500 °C, the beam displacements rising gradually and linearly, after then it's rising quickly with the load.



(a) (b)

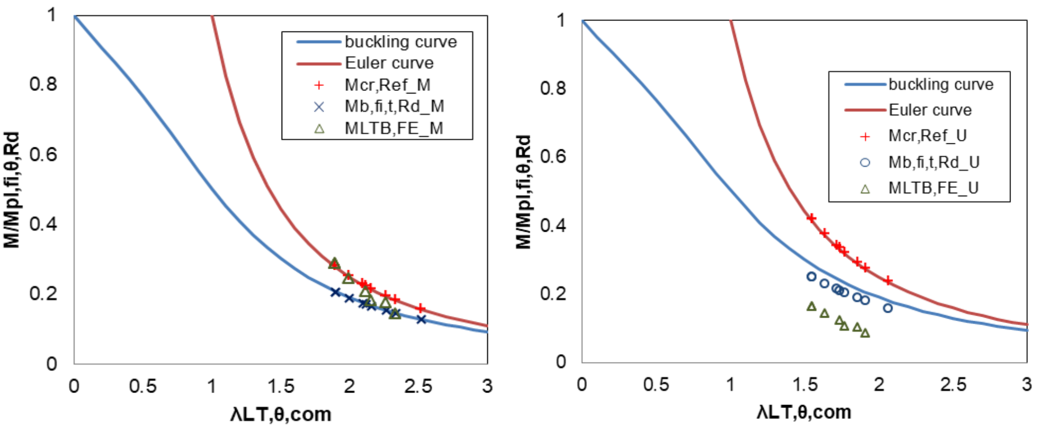
Figure 9: Mid-span vertical displacement (a), lateral displacement (b).

4. PARAMETRIC STUDY OF FACTORS INFLUENCES ON LTB OF CELLULAR BEAMS

4.1 Loading type

In this case we take the same characteristic of the beam as mentioned in 2.1. A comparison is made between two cases of loading, distributed load and end moment load, to determine its impact on lateral torsional buckling resistance of cellular beams at elevated temperatures.

Through the results shown in figure 10, we can observe that for cellular beam the application of load plays a big role to reduce the intensity of lateral torsional buckling. Hence, the load placed on the edge top and bottom of flange makes a beam considerably more stable than a load on the top flange (uniform load).



(a) **(b)**

Figure 10: Influence of IMP and RS in function of no-dimensional slenderness for different loading, (a) with end moment, (b) with distributed load.

4.2 Beam length and their effect on the LTB capacity of steel beams

In this analysis we have applying the load and increasing it to reach the non-equilibrium point with constant temperature (at 20 till 600 °C), lateral imperfections and residual stresses for different lengths. We fixed all the previous conditions of geometric section, support condition and loading (distributed load) with no-dimensional slenderness $\lambda_{LT,com} < 3$.

Figure 11 shows the decrease of the load carrying capacity of solid and cellular beams vs. temperature for different beam lengths (L=5, 8, 9.5 m). At elevated temperature for L=5 m, the load carrying capacity of the solid beam is higher compared to the one of the cellular beams (about 70 %). For the cases with L= 8 and 9.5 m the steel beams capacity are relatively close for all temperature degrees (about 30 %).

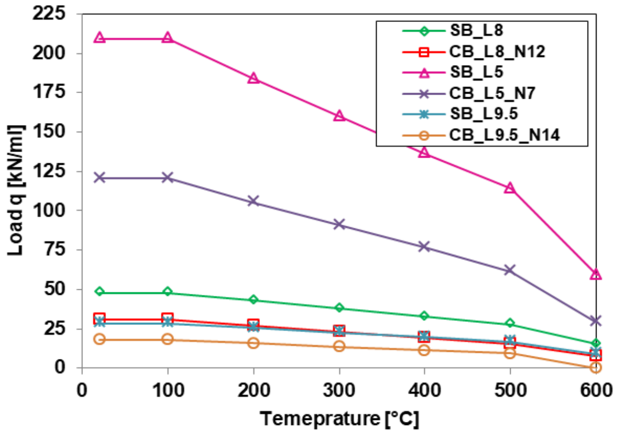


Figure 11: Critical load vs. temperature for different beam length

5. CONCLUSION

The behaviour of solid and cellular beams under fire conditions increases in complexity as the effect of the openings and introduces several pheromones that can only studied by numerical finite element model.

The comparisons show that the imperfections and the residual stresses have a significant effect on the lateral displacements of the beam; it means they are entering in beam resistance to LTB. At elevated temperature, higher than 500 °C the influence of residual stress decreases and the steel beams behaviour is not affected when imperfections and residual stresses are added.

For long beam lengths, the carrying capacity of solid and cellular steel beams is approximately the same. When the unrestrained span of the beam increases the cellular beam load capacity decreases less than for the solid beam. It was also shown that the type of loading affects the LTB intensity of cellular beam.

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