ce/papers The online collection for conference papers in civil engineering
Ernst & Sohn A Wiley Brand
ORIGINAL ARTICLE
eurosteel SHEFFIELD 2021
Ernst & Sohn A Wiley Company

Investigation of residual stresses on the fire resistance of unrestrained cellular beams

Sabrina Benyettou Oribi , Abdelhak Kada[1] , Belkacem Lamri[1], Luis MR Mesquita[2]

Correspondence

Ph.D. S.Benyettou Oribi
Hassiba Benbouali University of Chlef
Faculty of Civil Engineering and Architecture RN19, Ouled Fares, BP. 78C, Chlef 02180-Algeria
Email: s.benyettou@univ-chlef.dz

Affiliations

[1]Hassiba Benbouali University of Chled, Chlef, Algeria.
[2]Polytechnic Institute of Bragança, Brangança, Portugal.

Abstract

It is being a common engineering practice to use steel beams with web openings in buildings requiring long spans, besides giving an important additional advantage of allowing services through instead of underneath the beams. The presence of these openings is penalizing the carrying capacity at ambient temperature and in the case of fire due to large cells and double nonlinearity geometric and material a complex behaviour take place. In this study, numerical models for beams having closely spaced large openings are simulated with ISO834 fire loading including both nonlinearities cited above in the primal investigation. Followed as a second investigation, is the effect of residual imperfections added to the numerical model mentioned above and simulated for different diagrams as presented within updated literature. All simulations were done using the finite element software ANSYS, to analyse the results captured for lateral torsional buckling (LTB) behaviour in terms of vertical and lateral displacement, von Mises stresses for different sections at ambient and fire conditions. For this parametric study, the change in cross-section geometries, opening spacing, beam length on the LTB of cellular beams is analysed.

Keywords

Cellular beam, Residual stress, Fire, Lateral torsional buckling

1 Introduction

The manufacturing method of cellular beams is bases on the use of laminated beams according to a well-defined cut. A double cut is made in the web by flame cutting. The two tees formed are re-welded after shifting by half a wave to get final circular openings in the web [Bitar 2005].

As a result of this procedure, thermal stresses due to uneven cooling of all parts of the section are produced which are called material imperfections or residual stresses. The new distribution of stresses is taking place and is different [Sonck et al. 2014] compared to the ones well known for parent solid sections [Mesquita et al. 2005]. Depending on the section geometric parameters, the loading type, cellular beams may have different resistance at ambient and especially in fire conditions.

The latter has motivated the aim of this work, which is based on the study of the parameters which influence the resistance of an unrestrained steel cellular beam, namely: residual stresses, geometric imperfections, loading and geometry of these beams.

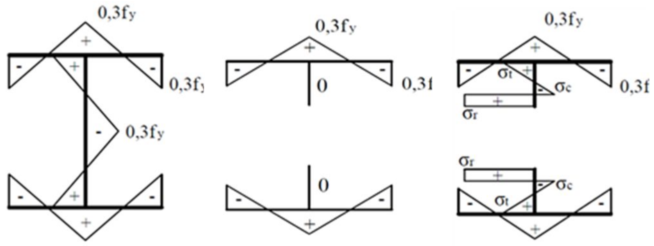
One major aim of the study of structural steel members is to calculate deformations or stresses to determine the behaviour in large displacement up to failure taking into account material non-linearity due to fire.

Given the structural configuration, material and geometric properties of unrestrained solid beams, several studies were carried out on bare sections, to include mainly geometric imperfections in the numerical models [Kada and Lamri 2019], or by performing experimental and numerical analyses for critical temperatures [Mesquita, Piloto, Vaz and Vila Real 2005].

For cellular steel beams without protection, previous numerical studies focused on the presence of openings plus imperfections in the fire situation [Ellobody 2012; Sweedan 2011]. In the same context, the influence of residual stresses on the lateral torsional buckling resistance of the beams was also studied [Sonck and Belis 2015]. Experimental investigations were carried out to compare temperature rates progress in the web post with regard to solid beams and to establish temperature profiles with different values of the thickness for the passive fire protection [Lamri et al. 2017].

The influencing parameters for the residual stresses are mainly related to the geometry, opening properties, type of loading and boundary conditions were included in recent experimental work [Sonck, Van Impe and Belis 2014] to investigate the instability of these beams and which showed, that for lightest section the residual stress distribution has a detrimental effect on the global buckling resistance.

Research work still remains about LTB of cellular beams with influence of initial imperfections at elevated temperature [Benyettou Oribi et al. 2019; Silva et al. 2019]. The numerical study carried out on [Silva, Dalcanal and Mesquita 2019], as part of this work, on the residual stresses proposed new models which takes account of the cutting and welding stages of the plates used for manufacture of steel cellular beams.



(a) (b) (c)

Figure 1 Residual stress distribution models, a) for solid beam, b-c) for cellular beam

The authors conclude that with considering or not the residual stresses on the web, the beam's resistant capacity remains the same, and even their ways of collapse remain the same.

The set of these results makes it possible to define a residual stress model which is then used as incoming data in the following parts which relate to the studies of the lateral torsional buckling.

In this work we will address the lateral torsional buckling (LTB) problems of the cellular beams at elevated temperature due to fire by developing numerical models to identify and analyse their behaviour with regard to failure modes. The numerical simulations account for initial geometrical imperfections and residual stresses as well as geometric and material nonlinearities.

2 Simple calculation methods of bending and LTB resistance of solid and cellular beam at height temperature

2.1 Bending moment resistance

In fire condition the design moment resistance Mfi,θ,Rd of a class 1 or class 2 cross section with a uniform temperature θa according to [CEN-EN-1993-1-2 2005] should be determined by:

$$M_{fi,\theta,Rd} = M_{pl,\theta,Rd} = k_{y,\theta}\left[\gamma_{M,0} / \gamma_{M,fi}\right] M_{Rd} \tag{1}$$

Where:

$K_{y,\theta}$: the reduction factor for the yield strength of steel at the steel temperature θ_a reached at time t; $\gamma_{M,0}$: partial factor for resistance of cross-sections whatever the class is; $\gamma_{M,fi}$: the partial factor for the relevant material property, for the fire situation; M_{Rd} : is the plastic moment resistance.

For solid beam, the design plastic moment resistance of a cross section according to EN 1993-1-1 [CEN-EN-1993-1-1 2005] is given as:

$$M_{pl,Rd} = w_{pl,y} f_y / \gamma_{M0} \tag{2}$$

Where:

$W_{pl,y}$: plastic section modulus; f_y : yield strength of steel.

For cellular beam , the design plastic moment resistance of a cross section according to SCI-P355 [Lawson and Hicks 2011] is given as:

$$M_{pl,Rd} = 2.A_T.Z_c.f_y / \gamma_{M0} \tag{3}$$

A_T: Areas of one T section; Z_c: Centroid of a T section.

2.2 Lateral torsional buckling resistance

Based on the formulations provided in [CEN-EN-1993-1-2 2005; Lawson and Hicks 2011; Panedpojaman et al. 2016] the main analytical formulas for calculating the LTB resistance of a solid and cellular beam sections at elevated temperature are presented below:

$$M_{b,fi,t,Rd} = \chi_{LT,fi}.w_{pl,y}.k_{y,\theta,com}.f_y.\frac{1}{\gamma_{M,fi}} = \chi_{LT,fi}.M_{fi,\theta,Rd} \tag{4}$$

Where $\chi_{LT,fi}$ is the reduction factor for lateral-torsional buckling in the fire design situation; its value for the appropriate non-dimensional slenderness $\bar{\lambda}_{LT}$ should be determined from:

$$\chi_{LT,fi} = \frac{1}{\phi_{LT,\theta,com} + \sqrt{\left[\phi_{LT,\theta,com}\right]^2 - \left[\bar{\lambda}_{LT,\theta,com}\right]^2}} \leq 1.0 \tag{5}$$

With:

$$\phi_{LT,\theta,com} = 0.5\left[1 + \alpha.\bar{\lambda}_{LT,\theta,com} + \left(\bar{\lambda}_{LT,\theta,com}\right)^2\right] \tag{6}$$

And

$$\alpha = 0.65\sqrt{235/f_y} \quad \bar{\lambda}_{LT,\theta,com} = \bar{\lambda}_{LT}\left[k_{y,\theta,com} / k_{E,\theta,com}\right]^{0.5}$$

$K_{E,\theta,com}$ is the reduction factor for the slope of the linear elastic range at the maximum steel temperature in the compression flange $\theta_{a,com}$ reached at time *t;*

$$\bar{\lambda}_{LT} = \sqrt{\frac{w_y f_y}{M_{cr}}} \tag{7}$$

M_{cr} : is the elastic critical moment for lateral-torsional buckling.

For doubly symmetric cross-sections, the elastic critical moment M_{cr} may be calculated from the following formula derived from the buckling theory [Panedpojaman, Sae-Long and Chub-uppakarn 2016]:

$$M_{cr} = C_1 \frac{\pi^2 EI_z}{(L)^2}\left\{\sqrt{\left[\frac{I_w}{I_z} + \frac{(L)^2 GI_t}{\pi^2 EI_z}\right]}\right\} \tag{8}$$

With

For end moment loading C1=1.

E is the Young modulus (E=210000 N/mm²), L: the beam length; I_w represents warping constant; I_z is the second moment of area about the week axis; G: represents shear modulus (G= 80770 N/mm²); I_t: is the torsion constant.

Taking into account the moment distribution between the lateral restraints of members the reduction factor χ_{LT} may be modified as follows [Vila Real et al. 2007]:

$$\chi_{LT,fi,\text{mod}} = \frac{\chi_{LT,fi}}{f} \leq 1 \tag{9}$$

Where:

$$f = 1 - 0.5(1 - k_c) \tag{10}$$

K_c: is a correction factor

3 Description of numerical analysis models

In this section, the numerical model used for the simulations is described. A set of numerical simulations regarding the lateral torsional buckling resistance of laterally unrestrained beams, with and without web openings, is performed. The analysis is carried out with ANSYS software [ANSYS 2016]. A finite element SHELL181 was used. Figure 2 and table 1 show the different characteristics of the studied beams, solid and cellular, where h=450 mm is the initial height of the cross section whose breadth b=190 mm and H the final height, a0 the opening diameter, w is the web post width, S is the spacing between openings. For cellular beams the openings are distributed at regular intervals while respecting the parameters given in [A.C.S and S.A. 2018]. For the final high H=1.3h the cross section class continue to be of class 1, as the original parent section, accordingly to EN1993-1-1 [CEN-EN-1993-1-1 2005].

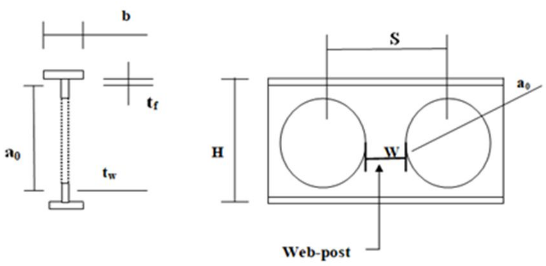


Figure 2 Geometry properties of perforated section

Table 1 Different characteristics of the studied steel beams, solid and cellular

Type	H	a0	S	L [m]	θ [°C]
Solid	1.3 h	-	-	2,3,4,5,6,8,10,12,14	20
Cellular	[1.3,1.4, 1.5]h	[0.8, 1.0, 1.2] h	[1.1, 1.4, 1.7]a0	2,3,4,5,6,8,10,12,14	20, 500, 700

The steel beam grade is S355 (fy = 355[MPa]) with a typical value of modulus of elasticity of 210 [GPa], and Poisson's ratio of 0.3. The stress-strain relationship used for the simulations comes from Eurocode 3 Part 1-2 [CEN-EN-1993-1-2 2005] and is shown schematically in Figure 3.

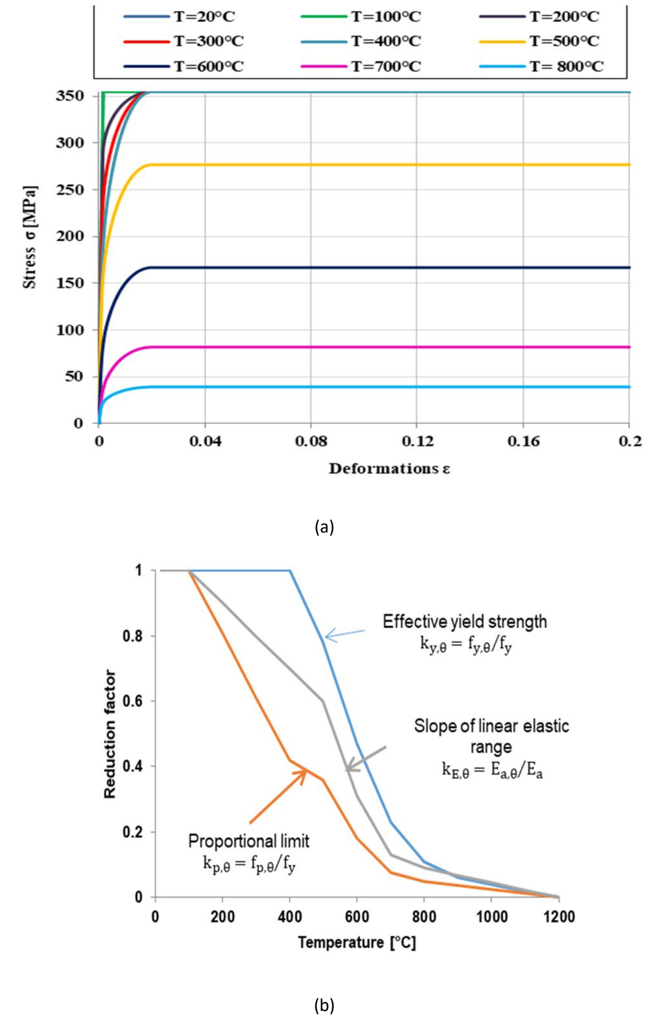
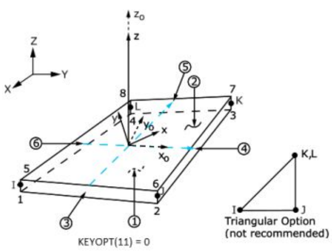
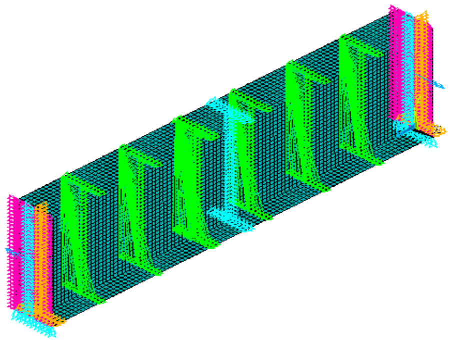


Figure 3 Material properties at elevated temperatures: (a) Stress-strain vs. temperature, S430, (b) Reduction factor

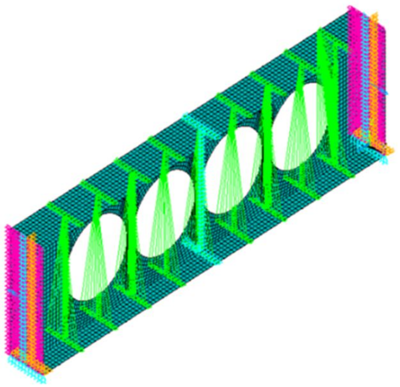
A summary description of the discretization by finite elements as used for numerical simulations is given in Figure 4. The conditions at the ends are designed to create a simple beam with "fork" type supports. It is modelled by blocking the displacements X, Y and the rotation along Z at the two ends, and the displacements Z at mid-span. The rotation ROTX of nodes of ends beam sections are coupled to the chosen master node at the web centre. End plates with thickness two times the flange thickness were also added to the beam ends. To disregard local buckling behaviour, coupling procedure (set for the ROTZ degree of freedom) was applied along the beam span with distance of S/2 and H/2 for cellular and solid beams, respectively. The discretization is based on a quadrilateral mesh with mesh size equal to 0.02 [m]. The collapse uniform moment determined by an incremental and iterative procedure (M=10 000t) by a non-linear geometrically and material analysis, including imperfections based on the linear Eigen buckling mode simulations. The uniform moment is introduced by two couples applied in the beam ends centroid, figure 4.



(a)



(b)

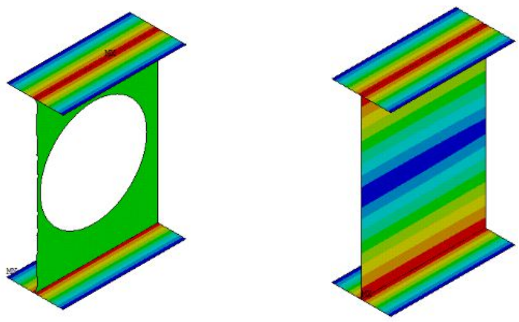


(c)

Figure 4 (a) SHELL181 geometry, (b) Finite element mesh for a solid and cellular beam with L=2 [m].

While Zc is the position of the gravity centre of the Tee section relative to the opening centre, AT is the cross sectional area of the Tee section, Wpl,y is the plastic section modulus, Ky,θ : is the reduction factor for the yield strength of steel at temperature θa.

In solid beam section, simplified model of residual stresses for hot rolled section as proposed [ECCS 1984] was used, figure 5. For the cellular beam, the model proposed by [Silva, Dalcanal and Mesquita 2019], presented in figure (5a), where residual stresses was disregarded on the web was applied. Geometric imperfections are considered with an amplitude value of L / 1000 in accordance with [Vila Real, Lopes, Simões da Silva and Franssen 2007], where L is the beam span.



(a) (b)

Figure 5 Residual stress distributions of rolled sections solid and cellular.

4 Results and discussion

In order to determine the influence of geometric imperfections and residual stress on the LTB resistance of the cellular beam, we have evaluated the spacing between openings, the height of cross section, the opening diameter and beam length at different temperatures. Three different holes' spacing, section heights and opening's diameter are considered for the numerical studies as motioned above in table 1. The numerical lateral torsional buckling resistance is calculated with collapse moment obtained from ANSYS simulations.

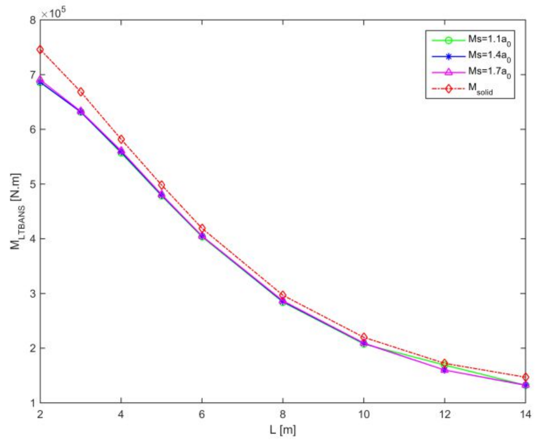
Table 2 comes to identify the comparison between LTB moment resistance of beam lengths L = 2, 6, and 14 [m] with (W/. RS) and without residual stresses (W/O.RS) under different temperature degrees (θ =20, 500, and 700 [°C]) from numerical result.

Table2 LTB moment resistance of cellular beams with and without residual stresses from numerical results

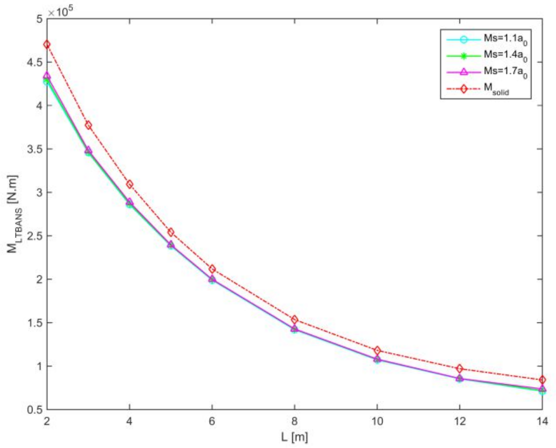
		θ [°C]	20	500	700
MLTB_ANSYS [kN.ml]	L=2 [m]	W/RS	68.56	42.75	12.24
		W/O.RS	69.52	42.98	12.28
		Diff. (%)	1.39%	0.55%	0.39%
	L=6 [m]	W/RS	40.35	19.89	4.31
		W/O.RS	41.02	20.02	4.33
		Diff. (%)	1.66%	0.65%	0.46%
	L=14 [m]	W/RS	13.23	7.11	1.76
		W/O.RS	13.46	7.17	1.77
		Diff. (%)	1.71%	0.84%	0.56%

The numerical results showed that the residual stresses have small effect on LTB moment resistance of cellular beams at ambient temperature. Its effect decreases even more at 500 °C and 700 °C as shown in table 2.

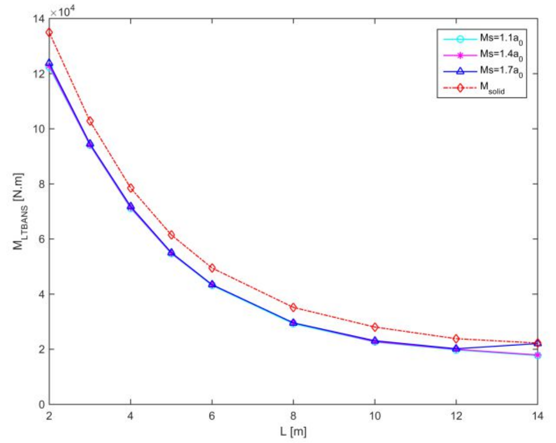
For temperature θ = 20, θ = 500 °C, and θ =700°C, the LTB resistance values for solid and cellular beams with S = [1.1, 1.4, 1.7] a_0 are shown in Figure 6, in function of the beam length. The labels Ms=1.1a0, Ms=1.4a0, Ms=1.7a0, represent the LTB moment resistances of cellular beams with geometric imperfections and residual stress for each spacing S, and M_{solid} the LTB moment resistances of solid beams.



(a)



(b)

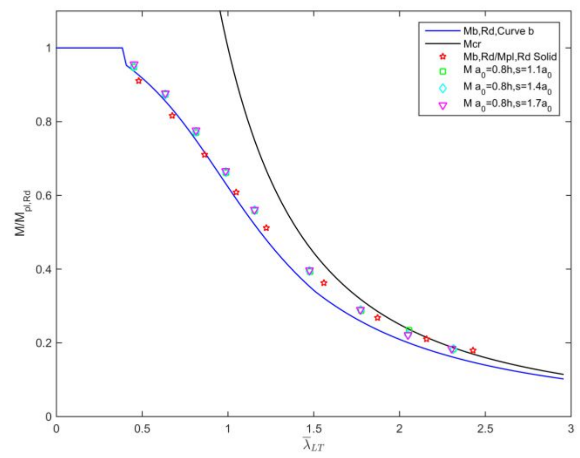


(c)

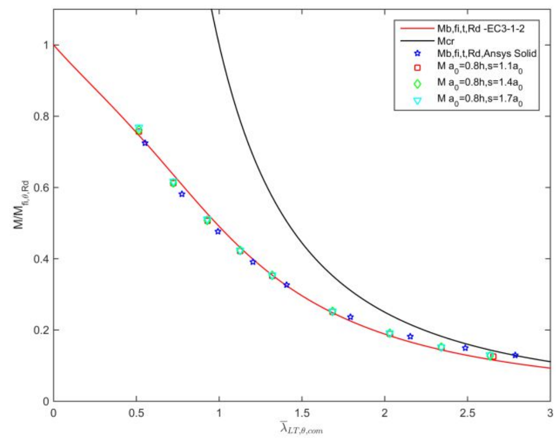
Figure 6 Lateral torsional buckling resistance with different openings spacing, (a) θ=20 [°C], (b) θ=500 [°C], (c) θ=700 [°C].

The LTB resistance decreases with the length increase. The results in Figure 6, show a difference of about 1% in resistance between solid and cellular beam at 20 [°C], about 2 to 9 % at 500, 700 [°C]. It is also observed that for different openings spacing, the results from ANSYS for T=20 [°C] are mostly close. On the other hand, for θ =500 and 700 [°C] the results are approximately the same, for the same beam length.

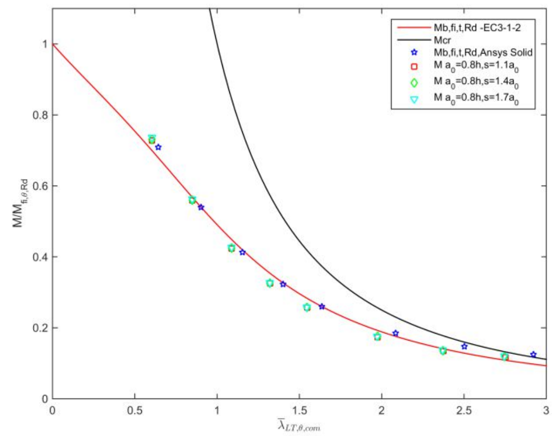
Numerical results of LTB resistance for different cellular beams cross section have been compared with simple formulas from Eurocode 3 Part 1.2. The geometric imperfections and residual stress influence is investigated in terms of the normalized moment (M/Mfi.θ.Rd) where M represents the moment resistance obtained from the FE model (MAnsys) and moment resistance determined from the Eurocode and normalized with plastic bending resistance MRd, according to the no-dimensional slenderness, for solid and cellular beams, figure 7.



(a)



(b)



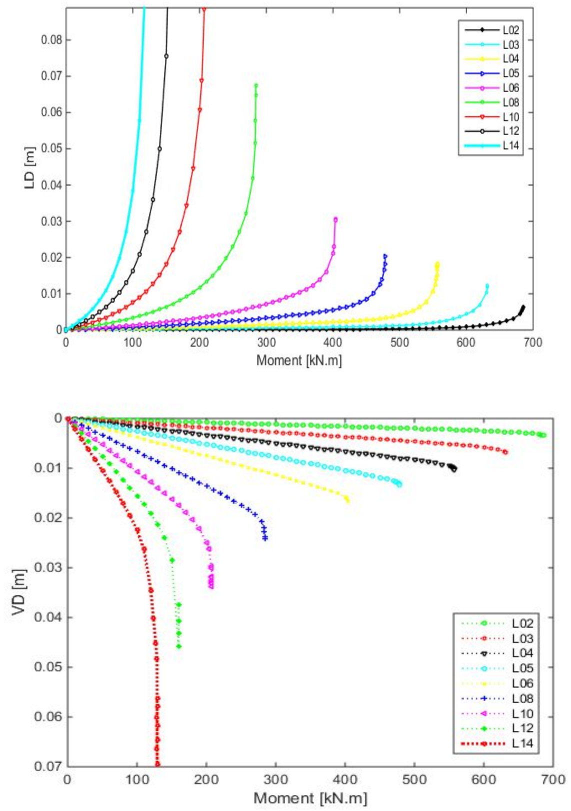
(c)

Figure 7 Influence of openings spacing in function of non-dimensional slenderness, (a) θ=20 [°C], (b) θ=500 [°C], (c) θ=700 [°C].

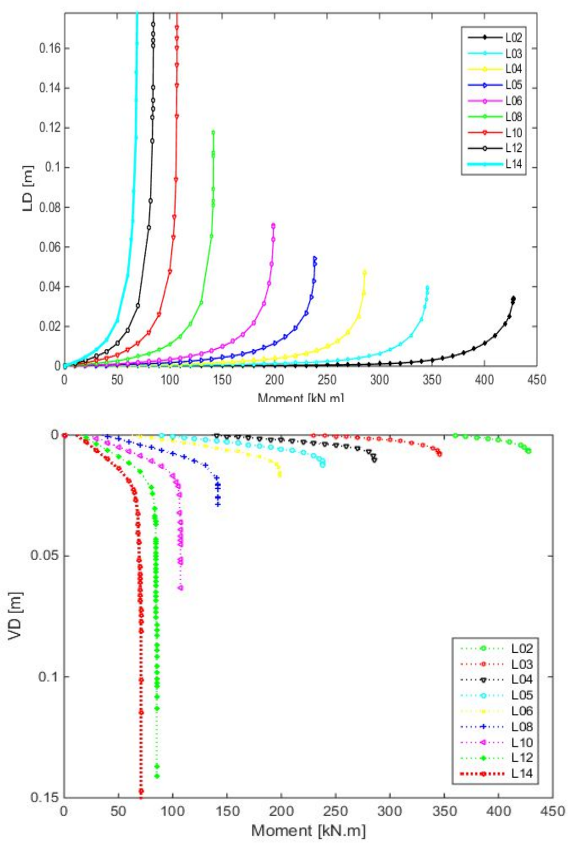
From the results shown in Figure 7, it will be noticed that numerical results follow the Eurocode curve b, giving always higher values compared with the EC3-1-1 [CEN-EN-1993-1-1 2005] design, either for the solid and cellular beams at ambient temperatures. At elevated temperatures, comparisons of evolution curves of resistance moments show a good agreement between analytical and numerical results.

To cover lack of straightness and residual stresses of the steel beam, after introduction of the equivalent deflections, it is necessary to monitor the behaviour of the beam under fire especially when toward to tied other members.

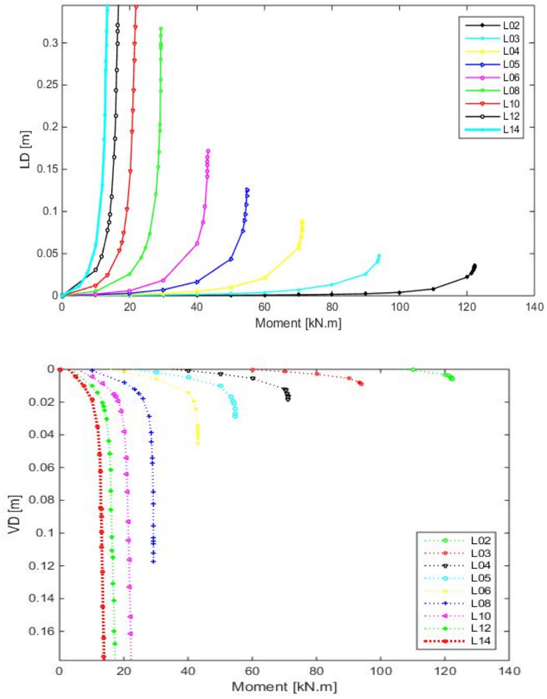
Figure 8 presents the lateral and vertical displacement of different cellular beams with H=1.3h, a0=0.8h, S=1.1a0 in function of the applied load for the different beam lengths values analysed (L=2 to L= 14 [m]).



(a)



(b)

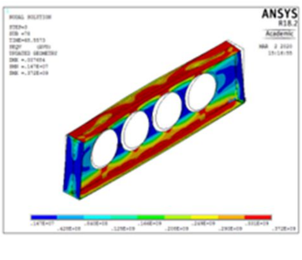


(c)

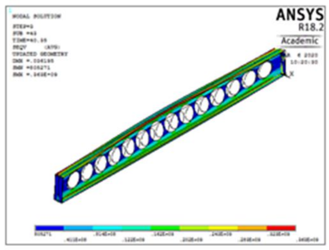
Figure 8 Lateral [LD] and vertical [VD] displacements of cellular beams for (a) θ=20 [°C], (b) θ=500 [°C], (c) θ=700 [°C]

For the all temperature, the beams underwent increasing vertical and lateral displacements close to the collapse moment. The effect of cellular beam length whose boundary conditions are supposed to be simply supported induces a fall in the fire resistance as well as the lateral and vertical displacements.

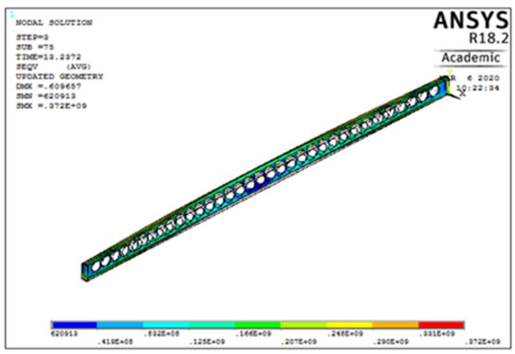
Figure 9 show the distribution of von Mises stress in cross section in cellular beams with 2[m], 6 [m] and 14 [m] of length. The representation of the distribution of Von Mises stress along with the final deformed shape is used to determine the failure mode of the beam. In this case the failure occurs by lateral displacement in the upper side of the perforated section, as is shown in figure 9.



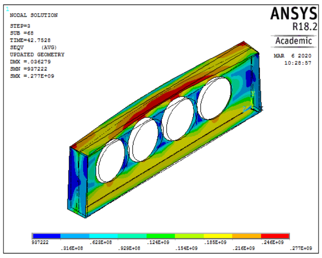
L=2 [m], θ =20 [°C]



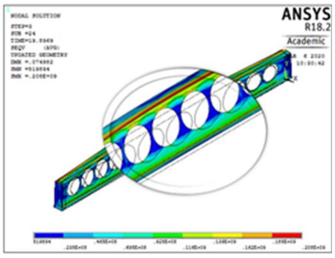
L=6 [m, θ =20 [°C]



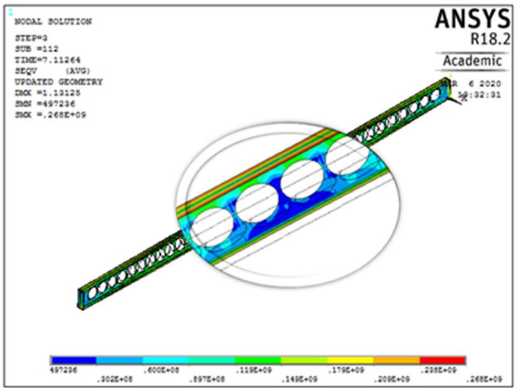
L=14 [m], θ =20 [°C]



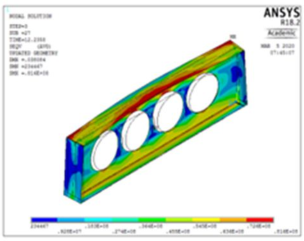
L=2 [m], θ 500 [°C]



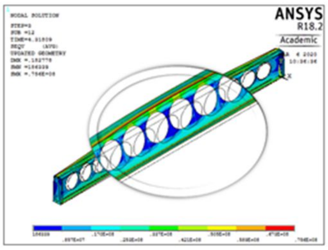
L=6 [m], θ =500 [°C]



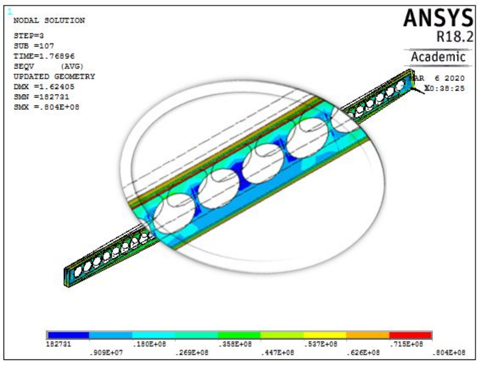
L=14 [m], θ =500 [°C]



L=2 [m], θ =700 [°C]



L=6 [m], θ =700 [°C]

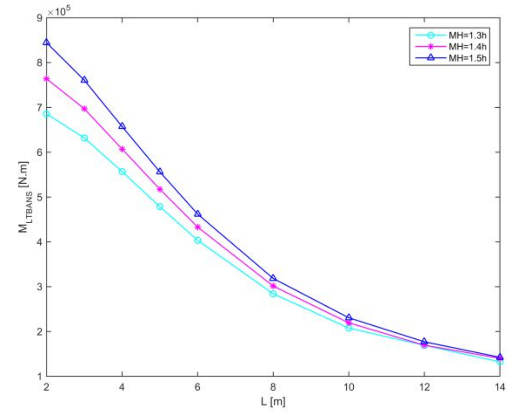


L=14 [m], θ =700 [°C]

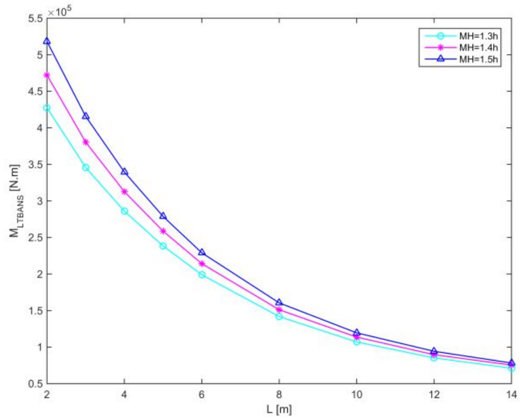
Figure 9 Von Mises stress for cellular beam at different temperature degrees with a_0=0.8h, S=1.1 a_0.

As temperature changes, the stress distribution are affected by the beam length, as the beam length increases, the stresses are concentrated at mid-span.

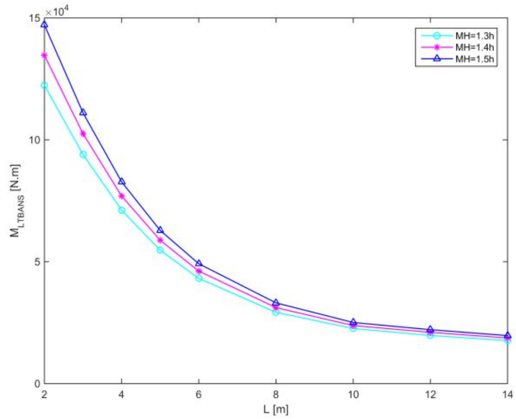
Figure 10 shows results of the LTB moment resistance loss over the beam length for section height variation, H= [1.3, 1.4, 1.5] h, for temperatures θ =20 [°C], θ =500 [°C], and θ =700 [°C].



(a)



(b)

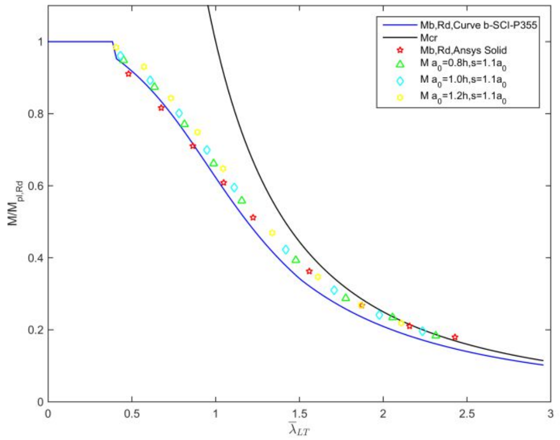


(c)

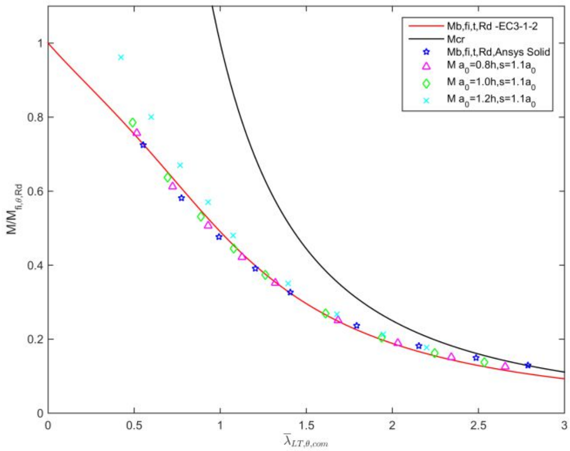
Figure 10 LTB moment resistance of cellular beams varying in height at (a) θ =20 [ºC], (b) θ =500 [°C], (c) θ =700 [°C].

It also shows a clear influence of the variation of the height in the evolution of the beam resistance for lengths spanning from 2 [m] to 8 [m]. However, no change is depicted for the beams resistance at ambient as well as at elevated temperatures beyond 8 [m] span.

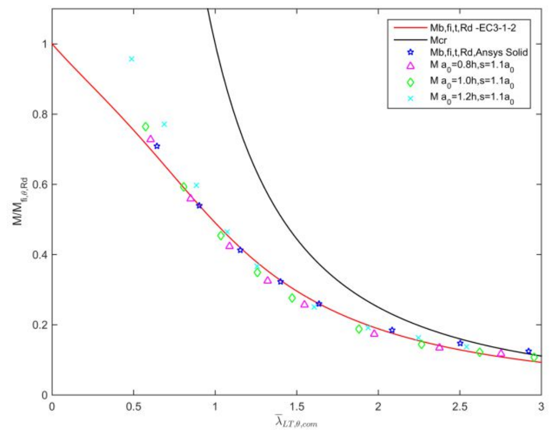
Figure 11 shows plots of numerical results of LTB moment resistance of cellular beam for different opening diameters at θ=20 [ºC], θ=500 [°C], and θ=700 [°C].



(a)



(b)



(c)

Figure 11 LTB moment resistance of cellular beam varying in opening diameter at (a) θ=20 [ºC], (b) θ=500 [°C], (c) θ=700 [°C].

It also highlights a decrease in steel beams resistance with the increase the opening diameter for temperatures θ=20 °C, θ=500, and θ=700 [°C]. The effect depends on beams lengths and is more important for spans exceeding 8 meters.

5 Conclusion

In this work, the study of lateral torsional buckling of cellular beams is exhibited according to a numerical analysis for the investigation of the influence of imperfections, and according to the simple calculation method approach to evaluate the LTB resistance of the beams.

The parametric study using numerical models accounting for imperfections has allowed investigating of the parameters that influence the beam resistance to LTB. The key parameter affecting in this case is the beam length. The spacing between openings when the class of a cross section of cellular beam is the same as the parent section has no influence on the LTB beam resistance at ambient and elevated temperature. It has an effect on the stresses distribution between openings and on the overall beam resistance in function of its length.

For spans less than 8 meters, a clear difference in beams fire resistance is noticed with the increase of the cross section height. However, for lengths spanning over 8 [m], no significant change in fire resistance is obtained.

It is also deduced that as the diameter increases, the buckling resistance of the beam decreases more for beam lengths much than 8 meters.

From the case of study show that the presence of residual stresses in the cellular beam do not have much influence on lateral torsional buckling resistance.

References

[1] A.C.S AND S.A. ACB® and Angelina® beams, A New Generation of Cellular Beams. In ARCELORMITTAL. 2018.

[2] ANSYS. ANSYS Mechanical APDL. [Version for 16.2. 2016.

[3] BENYETTOU ORIBI, S., KADA, A., LAMRI, B. AND MESQUITA, L.M.R. 2019. Numerical analysis of lateral torsional buckling of steel I-beams with and without web-openings under fire. In *Proceedings of the 5th Iberian-Latin-American Congress on Fire Safety _ 5 CILASCI*, Porto, Portugal2019, 10.

[4] BITAR, D. Planchers mixtes à poutrelles ajourées. . In. Paris: Centre Technique Industriel de la Construction Métallique (CTICM) 2005.

[5] CEN-EN-1993-1-1. Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings. In., 2005.

[6] CEN-EN-1993-1-2. Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design. In. Brussels, 2005.

[7] ECCS *Ultimate limit State calculation of sway frames with rigid joints*. Edtion ed. Rotterdam: ECCS, 1984.

[8] ELLOBODY, E. Nonlinear analysis of cellular steel beams under combined buckling modes. Thin-Walled Structures, 2012/03/01/ 2012, vol. 52, p. 66-79.

[9] KADA, A. AND LAMRI, B. Numerical analysis of non-restrained long-span steel beams at high temperatures due to fire. Asian Journal of Civil Engineering, February 01 2019, vol. 20, no. 2, p. 261-267.

[10] LAMRI, B., MESQUITA, L., ABDELHAK, K. AND PILOTO, P. Behavior of cellular beams protected with intumescent coatings. Fire Research, 2017.

[11] LAWSON, R. AND HICKS, S. *Design of composite beams with large web openings: in accordance with Eurocodes and the UK National Annexes*. Edtion ed.: Steel Construction Institute, 2011. ISBN 1859421970.

[12] MESQUITA, L.M.R., PILOTO, P.A.G., VAZ, M.A.P. AND VILA REAL, P.M.M. Experimental and numerical research on the critical temperature of laterally unrestrained steel I beams. Journal of Constructional Steel Research, 2005/10/01/ 2005, vol. 61, no. 10, p. 1435-1446.

[13] PANEDPOJAMAN, P., SAE-LONG, W. AND CHUB-UPPAKARN, T. Cellular beam design for resistance to inelastic lateral–torsional buckling. Thin-Walled Structures, 2016/02/01/ 2016, vol. 99, p. 182-194.

[14] SILVA, J., DALCANAL, P. AND MESQUITA, L. Numerical Analysis of Cellular Steel Beams Failure Modes in Fire Conditions. In *Iberian-Latin-American Congress on Fire Safety.* Springer, 2019, p. 78-92.

[15] SONCK, D. AND BELIS, J. Lateral–torsional buckling resistance of cellular beams. Journal of Constructional Steel Research, 2015/02/01/ 2015, vol. 105, p. 119-128.

[16] SONCK, D., VAN IMPE, R. AND BELIS, J. Experimental investigation of residual stresses in steel cellular and castellated members. Construction and Building Materials, 2014/03/15/ 2014, vol. 54, p. 512-519.

[17] SWEEDAN, A.M.I. Elastic lateral stability of I-shaped cellular steel beams. Journal of Constructional Steel Research, 2011/02/01/ 2011, vol. 67, no. 2, p. 151-163.

[18] VILA REAL, P.M.M., LOPES, N., SIMÕES DA SILVA, L. AND FRANSSEN, J.M. Parametric analysis of the lateral–torsional buckling resistance of steel beams in case of fire. Fire Safety Journal, 2007/09/01/ 2007, vol. 42, no. 6, p. 416-424.