FIRE DESIGN OF STEEL BEAMS WITH WELDED CLASS 4 CROSS-SECTION

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Abstract
The present paper deals with the study of the lateral torsional buckling of steel beams with welded class 4 cross-sections in case of fire. A numerical study of several beams with different class 4 cross-sections submitted to uniform bending moment at elevated temperatures has been performed using the finite element method. The results are compared with existing simplified design rules of Part 1.2 of Eurocode 3 showing that these rules are too conservative. A comparison is also made with the proposed method in the French National Annex. Based on these comparisons a new proposal is presented to check the lateral torsional buckling resistance which is validated against the numerical simulations.

Keywords: lateral torsional buckling (LTB), beams, class 4, fire, residual stresses

INTRODUCTION

The lateral torsional buckling (LTB) of steel members submitted to bending is a phenomena that affects the load carrying capacity of these members, in fact, in beams the compression of the flange may lead to a lateral displacement accompanied by a rotation of the cross-section that prevents the full development of the bending resistance. This phenomenon is influenced by a variety of factors, namely the cross-section shape, the loading pattern, the boundary conditions, among others and needs to be considered in the design. Additionally, slender cross-sections may also buckle under compression stresses before attaining the yield stress in one or more parts of the cross-section. This phenomenon is called local buckling.
In Eurocode 3 (CEN, 2005a), lateral torsional and local buckling are treated in separate ways. LTB is accounted for by reducing the cross-sectional bending resistance of the element by a "reduction" factor that takes this phenomenon into consideration. Local buckling can be accounted for by using the effective width method to make the necessary allowances for reductions of the cross-sectional resistance due to the effects of local buckling. The cross-sections where local buckling may occur are classified as class 4, according to Eurocode 3.
The informative Annex E of the Part 1.2 of the Eurocode 3 (EN1993-1-2) (CEN, 2005b) gives some recommendations for the fire design of steel members with class 4 cross-sections. In this annex, it is suggested to use the simple calculation methods with the design value for the steel yield strength as the 0.2% proof strength instead of the stress at 2% total strain as for the other classes, and that the effective cross-section be determined with the effective width method as for normal temperature, i.e. based on the material properties at normal temperature. This procedure is, however, known to be very conservative (Renaud and Zhao, 2006).
This study focus on the LTB behaviour of steel beams with welded class 4 cross-sections submitted to uniform bending moment in fire situation. The LTB resistance of the steel beams evaluated with the fire design rules prescribed in the EN1993-1-2 and also the French National Annex are compared with numerical results obtained with the software SAFIR (Franssen, 2005), showing that EN1993-1-2 is very conservative as mentioned before and the French National Annex could be improved since it has been developed for hot-rolled profiles. Because of that a new proposal has been developed and validated in this study to check for the

LTB resistance of steel beams with welded class 4 cross-sections submitted to uniform bending moment in fire situation.

1 LTB RESISTANCE OF BEAMS WITH CLASS 4 CROSS-SECTION

The LTB resistance of beam with class 4 cross-section is evaluated in fire situation with the following expression

$$M_{b,fi,t,Rd} = \chi_{LT,fi} W_{eff,y,\min} k_{0.2p,\theta} f_y \gamma_{M,fi} \tag{1}$$

with $W_{eff,y,\min}$ being the section modulus of the effective cross-section calculated with the same rules as for normal temperature, $k_{0.2p,\theta}$ being the reduction factor for the design yield strength of class 4 cross-sections, f_y the design yield strength and its respective partial safety factor for fire situation $\gamma_{M,fi}$. It may be noted that the values given in the Annex E of EN1993-1-2 for the $k_{0.2p,\theta}$ are slightly different from the values obtained with the material law model of EN1993-1-2 for steel at elevated temperatures These values derived from the material law model are given in the French National Annex and are used in this study (see Fig. 1). The reduction factor for LTB in the fire design situation is determined by

$$\chi_{LT,fi} = \frac{1}{\phi_{LT,\theta} + \sqrt{\phi_{LT,\theta}^{\;2} - \overline{\lambda}_{LT,\theta}^{\;2}}} \tag{2}$$

and

$$\phi_{LT,\theta} = 0.5\left[1 + \alpha \overline{\lambda}_{LT,\theta} + \overline{\lambda}_{LT,\theta}^{\;2}\right] \text{ and } \alpha = 0.65\sqrt{235/f_y} \tag{3}$$

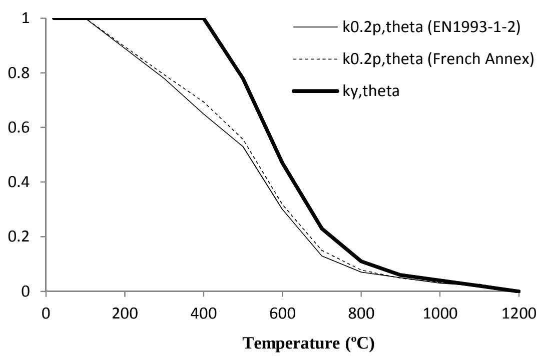
with the non-dimensional slenderness at elevated temperatures given by

$$\overline{\lambda}_{LT,\theta} = \overline{\lambda}_{LT}\sqrt{k_{0.2p,\theta}/k_{E,\theta}} \text{ with } \overline{\lambda}_{LT} = \sqrt{W_{eff,y,\min} f_y / M_{cr}} \tag{4}$$

where $k_{E,\theta}$ is the reduction factor for the *young modulus* at elevated temperature given in EN1993-1-2 and M_{cr} is the elastic critical moment given in the literature.

According to the French National Annex of EN1993-1-2 the LTB resistance of members with class 4 cross-sections should be checked with the same equation (1) but considering

$$\phi_{LT,\theta} = 0.5\left[1 + \alpha_{LT}\left(\overline{\lambda}_{LT,\theta} - 0.2\right) + \overline{\lambda}_{LT,\theta}^{\;2}\right] \text{ with } \alpha_{LT} = 0.34 \tag{5}$$



Temperature (ºC)	k0.2p,theta (EN1993-1-2)	k0.2p,theta (French Annex)	Relative difference (%)
20	1.00	1.00	0.00
100	1.00	1.00	0.00
200	0.89	0.896	0.67
300	0.78	0.793	1.67
400	0.65	0.694	6.77
500	0.53	0.557	5.09
600	0.3	0.318	6.00
700	0.13	0.15	15.38
800	0.07	0.078	11.43
900	0.05	0.048	-4.00
1000	0.03	0.032	6.67
1100	0.02	0.026	30.00

Fig. 1: Variation of the reduction factors with the temperature. *ky,theta* is the reduction factor for the design yield strength of class 1, 2 and 3 cross-sections.

2 NUMERICAL STUDY

2.1 Numerical model

The finite element computer code SAFIR (Franssen, 2005), has been used within this study and the numerical model used is depicted in Fig. 2 and described next.

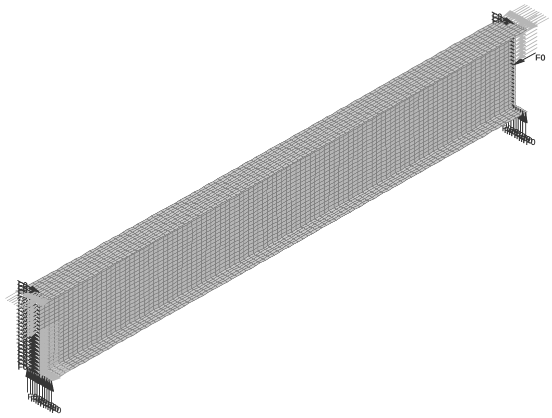


Fig. 2: Numerical model used in this study.

A preliminary study of the density of the mesh has been performed and a total of 10 shell elements for the flange, 22 shell elements for the web and 100 shell elements along the width has been used for the mesh in this study. A uniform bending moment has been applied to the model by means of nodal forces and to prevent numerical problems additional stiff elements along the webs and the flanges have been adopted. The so-called "fork-support" conditions have been considered in the model by restraining vertical displacements of the bottom flange and the out-of-the plane horizontal displacements of the web in the extremities of the beam.
In this study, different temperatures have been considered (350ºC, 450ºC, 550ºC and 700ºC). It was established that the temperature along the beam was constant. The steel grade S355 was used and different beam lengths considered, in a total of 240 different cases.

2.2 Cross-sections analyzed

A total of 5 cross-sections as indicated in Tab. 1 were analysed. In this Tab. the classification for fire design of each cross-section for bending about major axis is shown, and the classification of the flange and of the web is indicated and also the effective width of the flange and of the web as a % of the gross width is shown. It may be noted that, as a simplification EN1993-1-2 allows that cross-section classification be determined as for normal temperature but using a reduced parameter of ε that takes into account the effect of temperature as $\varepsilon = 0.85\sqrt{235 / f_y}$. with f_y being the design yield strength.

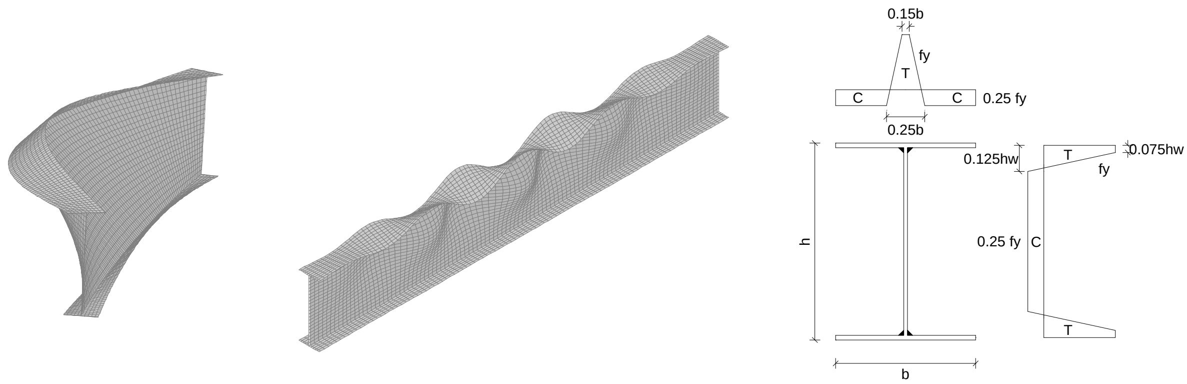
Tab. 1: Summary of the cross-sections analyzed and their classification for bending about major axis for fire design (Steel grade S355)

Cross-section	Dimensions (H x B x tw x tf) (mm)	Class of flange in compression	Class of web in pure bending	Effective width (% of gross width) flange	web	Classification for bending about major axis for fire design
A	460x150x4x5	4	4	84%	86%	4
B	460x150x3x4	4	4	70%	64%	4
C	460x150x5x10	3	4	n.a.	100%	4
D	460x150x4x8	3	4	n.a.	90%	4
E	460x150x4x7	4	4	100%	90%	4

All the cross-sections are classified as class 4 for bending about major axis for fire design. Both cross-sections A and B have reduction of the flange and the web, being section B much less effective than A. For cross-sections C and D only the web is classified as class 4 and for the cross-section C no reduction of the web is needed. For cross-section E, despite the flange being classified as class 4 it has no reduction.

2.3 Geometric imperfections and residual stresses

The geometric imperfections have been introduced in the model by changing the node coordinates to represent the worst scenario for the assessment of lateral torsional buckling resistance of the beams. This has been considered as the shape given by the eigenmodes of a linear buckling analysis (LBA) performed with the software Cast3M (Cast3M, 2012). In accordance with the finite element method of analysis recommendations given in the Annex C of EN1993-1-5 (CEN, 2012) a combination of global and local modes (see Fig. 3) has been used, where the lower mode has been taken as the leading imperfection and the other one reduced to 70%. The amplitude of the imperfections has been chosen as 80% of the fabrication tolerances given in the EN1090-2 (CEN, 2008) as suggested in the same annex, i.e. global mode has been scaled to 80% of L/500 and the local mode to the maximum between 80% of *b/100* or 80% of $h_w/100$, where *b* is the flange width and h_w is the height of the web of the cross-section.



a) b) c)

Fig. 3: Geometric imprefections and residual stresses used in the numerical models. a) Global eigenmode, b) local eigenmode and c) pattern of the residual stresses used in this study (taken from (ECCS, 1984)).

Residual stresses have been introduced in the numerical model with the stress pattern depicted in Fig. 3 c), the values adopted for the residual stresses are in accordance with (ECCS, 1976) as used in a previous study (ECCS, 2000).

3 LTB RESISTANCE OF STEEL BEAMS WITH WELDED CLASS 4 CROSS-SECTIONS AT ELEVATED TEMPERATURES

In Fig. 4, the results obtained for the LTB resistance of several steel beams with different welded class 4 cross-sections at elevated temperatures is shown and compared to actual design provision of EN1993-1-2. In the left chart results are detailed for one cross-section and in the right chart the results of all cross-sections are plotted. The beams are submitted to uniform bending moment.

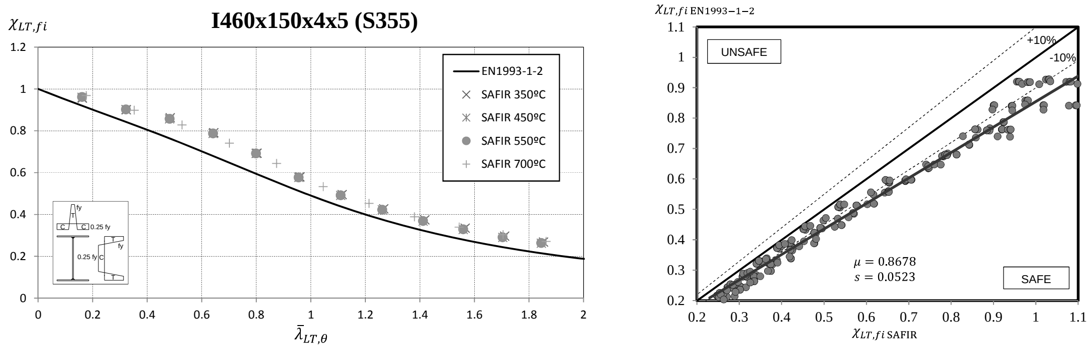


Fig. 4: Comparison between the numerical results calculated with SAFIR and LTB resistance of beams with welded class 4 cross-sections according to EN1993-1-2.

In Fig. 5 the numerical results are again compared with the LTB resistance curve of the French National Annex (see §1). In the left Fig. results are detailed for one cross-section and in the right Fig. the results of all cross-sections are plotted.

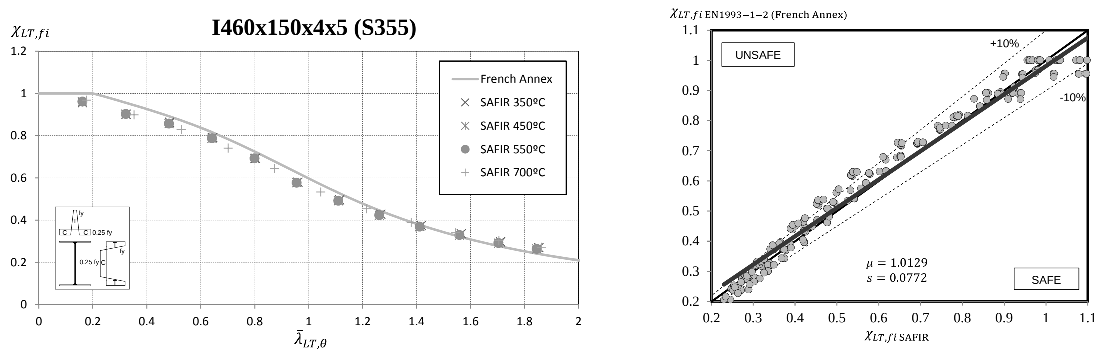


Fig. 5: Comparison between the numerical results calculated with SAFIR and LTB resistance of beams with welded class 4 cross-sections according to French National Annex of EN1993-1-2.

From Fig. 4 it can be seen that the LTB resistance given in the EN1993-1-2 for welded class 4 cross-sections is very conservative. The French National Annex method gives better results as shown in Fig. 5, but it could be improved, mainly because it has been developed for hot-rolled cross-sections. Because of that a new proposal, for the design lateral torsional buckling resistance of beams with welded class 4 cross-sections in fire situation is presented in the next section.

3.1 New proposal for LTB resistance of class 4 welded cross-sections

From the basis of the French National Annex proposal, a new proposal for the LTB resistance of steel beams with welded class 4 cross-sections has been developed by curve-fitting the numerical results obtained with SAFIR. This procedure lead to the use of the same equations for checking the LTB resistance of steel members with class 4 cross-sections given in EN1993-1-2 but considering

$$\phi_{LT,\theta} = 0.5\left[1+\alpha_{LT}\left(\bar{\lambda}_{LT,\theta}-0.2\right)+\bar{\lambda}_{LT,\theta}^{\;2}\right] \text{ and } \alpha_{LT} = 0.49 \qquad (6)$$

In this case, the imperfection factor α_{LT} is chosen as the "curve c" in the Tab. 6.4 of EN1993-1-1. The results obtained with the new proposal are shown in the Fig. 7. In the left chart results are detailed for one cross-section and in the right chart the results of all cross-sections are plotted.

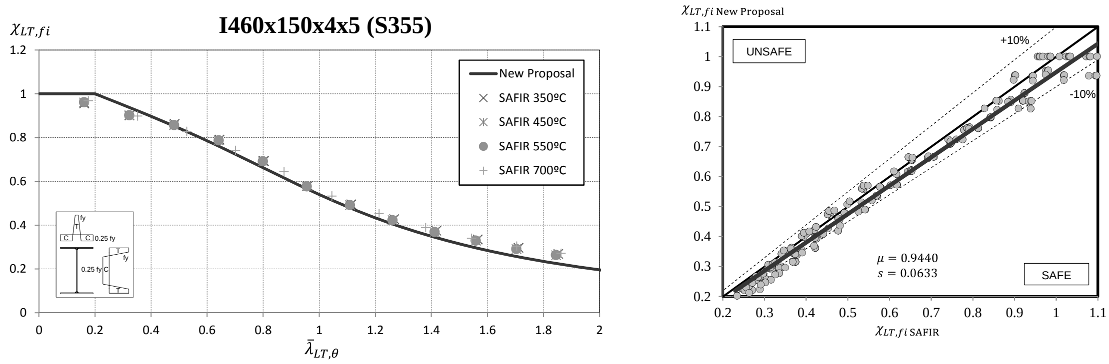


Fig. 6: Comparison between the numerical results calculated with SAFIR and LTB resistance of beams with welded class 4 cross-sections according to the new proposal.

From Fig. 6 it can be seen that this new proposal improves the results and should be used to assess the LTB resistance of steel beams in this case.

4 CONCLUSIONS

In this study the behaviour of beams with welded class 4 cross-section subjected to uniform bending moment was investigated. Using a numerical study with FEM-software SAFIR for different cross-sections, different temperatures and beam lengths, it was possible to observe that the actual fire design rules of EN1993-1-2 for checking the LTB resistance of beams with welded class 4 cross-sections are very conservative. It was also possible to conclude that the French National Annex of the EN1993-1-2, which has been derived for hot rolled profiles, could be improved. For this reason, a new proposal has been developed and validated against numerical results, leading to an improvement of the obtained results.

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