Journal of Constructional Steel Research 122 (2016) 543–556

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Local buckling in laterally restrained steel beam-columns in case of fire

Carlos Couto [a], Paulo Vila Real [a,*], pvreal@ua.pt;, Nuno Lopes [a], Bin Zhao [b]

[a] RISCO — Department of Civil Engineering, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
[b] CTICM — Centre Technique Industriel de la Construction Métallique, Parc Technologique L'Orme des Merisiers, Immeuble Apollo, 91193 Saint Aubin, Paris, France

ARTICLE INFO

Article history:
Received 28 September 2015
Received in revised form 10 April 2016
Accepted 11 April 2016

Keywords:
Fire
Temperature
Class 4
Lateral restraint
Local buckling
Slender
Beam-column
Eurocodes

ABSTRACT

The behaviour of laterally restrained steel beam-columns with slender cross-sections (Class 4) where local buckling occurs under fire situation is numerically investigated. Although recommendations are given in Eurocode to address the local buckling for the case of fire, few studies address its influence at elevated temperatures, and more particularly its influence on the load bearing capacity of laterally restrained beam-columns, which represents an unknown safety level for the Eurocode procedures. As a primary objective of this study, the level of accuracy and safety of simplified methods of Eurocode 3 is studied based on extensive numerical investigation of several member lengths, different bending moment distributions and load ratios for various cross-sections and considering different heating temperatures. Local and global geometrical imperfections as well as residual stresses have been included in the numerical simulations. It is concluded that the Eurocode procedures lack consistency and the capacity of laterally restrained beams-columns is overestimated in many cases due to local buckling. Therefore, modifications to the current design methodology are proposed in this study leading to better estimation of the overall capacity of the laterally restrained beam-columns in case of fire, and finally, improved safety and consistency is achieved.

1. Introduction

The structural elements subjected to axial compression and bending are usually designated as beam-columns. For beam-columns at normal temperature, two methods exist in Part 1.1 of the Eurocode 3 [1] to evaluate their resistance resulting from the work of two different groups in the framework of the European convention for constructional steelwork (ECCS) Technical Committee 8 (TC8 — Stability). The two methods called the "Level 1" and "Level 2" beam-column interaction formulae [2–4] replaced the interaction formulae present in the previous ENV version of the Eurocode 3 Part 1.1 [5] which proved to be very conservative.

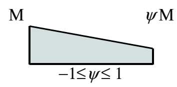
In case of fire, Part 1.2 of the Eurocode 3 [6] adopts the same format as the ENV version with the necessary modifications to account for the reduction of the mechanical properties of steel, namely the yield stress and Young's modulus, as well as the proper reduction factors for flexural and lateral-torsional buckling at elevated temperatures. For beam-columns where lateral restraints prevent the out-of-plane behaviour, the beam-column fails for the in-plane direction and for this case, the corresponding interaction curve that defines the strength of the beam-column under fire situation, is the result of the studies of Talamona et al. [7,8]. Later, numerical studies performed by Vila Real et al. [9,10], Lopes et al. [11] and Knobloch et al. [12] investigated the safety and accuracy of adapting the current methods at room temperature for elevated temperatures and concluded that further modifications were required in order to use them. However, in the referred studies, the local buckling was not covered because the numerical investigations were limited to the use of beam-finite elements that do not capture the plate instability. More recently, Franssen et al. [13] have carried out an experimental programme on eight slender beam-columns in case of fire and validated a numerical model using the software SAFIR [14,15] which is reused in this study to perform the numerical simulations. Apart from that, the behaviour of Class 4 members submitted to combined bending moment and axial compression has not yet been investigated in detail for elevated temperatures, and therefore the safety level and accuracy of the Eurocode procedures have not been checked for the design in case of fire. More precisely, it is not clear how local buckling affects the flexural behaviour of a beam-column and thus the load bearing capacity in case of fire. This paper aims at contributing towards the clarification on this matter.

In this context, several numerical simulations were performed to investigate the behaviour of laterally restrained steel beam-columns with I-shaped Class 4 cross-sections subjected to combined major-axis bending and compression under fire situation. A parametric study using shell finite elements and geometrically and materially nonlinear analyses with imperfections included (GMNIA) was performed at elevated temperatures considering several member lengths, cross-section geometries, different load ratios and bending moment diagrams. Comparison of the numerical results and the interaction curves from Eurocode 3 shows that for Class 4 members the existing formulae overestimates the load-bearing capacity of the beam-columns and it is concluded

* Corresponding author.

http://dx.doi.org/10.1016/j.jcsr.2016.04.012
0143-974X/© 2016 Elsevier Ltd. All rights reserved.

Table 1
Equivalent uniform moment factor for the cases studied.

Moment distribution	Equivalent uniform moment factor β_M
	$\beta_M = 1.8 - 0.7\psi$
	$\beta_M = 1.3$

that the local buckling is not being properly taken into account especially when the member is loaded by a non-uniform bending diagram. It is highlighted that modifications to the current procedure of Eurocode are necessary in order to reduce the number of unsafe results and this paper presents changes to the current formulae that lead to better prediction of the capacity of laterally restrained beam-columns in case of fire enhancing the safety and accuracy of the existing simple design formulae.

2. Eurocode provisions for Class 4 members

2.1. Combined bending and axial compression

According to Part 1–2 of Eurocode 3 [6], the design buckling resistance at time *t* for a member with lateral restraints subject to combined bending and axial compression in fire situation should be verified by complying with Eq. (1) that defines the interaction curve for doubly symmetric Class 4 cross-sections. Class 4 cross-sections are normally submitted to in-plane loading only, and for this reason, Eq. (1) corresponds to Eq. (4.21) from Part 1–2 of Eurocode 3 but adapted for Class 4 sections by considering the effective cross-sectional properties and disregarding the terms relative to out-of-plane bending moments.

$$\frac{N_{fi,Ed}}{\chi_{\min,fi}\ A_{eff}\ k_{0.2p,\theta}\ \dfrac{f_y}{\gamma_{M,fi}}}+\frac{k_y\ M_{y,fi,Ed}}{W_{eff,y,\min}\ k_{0.2p,\theta}\ \dfrac{f_y}{\gamma_{M,fi}}}\le 1 \quad (1)$$

with $N_{fi,Ed}$ and $M_{y,fi,Ed}$ the design axial force and in-plane design bending moment for fire situation. A_{eff} and $W_{eff,y,\min}$ are respectively the effective area of the cross-section and the in-plane effective section modulus, $k_{0.2p,\theta}$ is the reduction factor for the 0.2% proof strength of steel at elevated temperatures, f_y is the steel yield strength and $\gamma_{M,fi}$ is the partial safety factor for fire situation. For the sake of brevity, calculation of effective properties are omitted in the present study but one could refer to Eurocode 3 or, for instance, [16,17] where investigation on the effective cross-sectional properties for assessing local buckling resistance is conducted by the authors under fire situation. Therefore, Eq. (1) can be re-written as

$$\frac{N_{fi,Ed}}{\chi_{\min,fi}\ N_{c,fi,Rd}}+\frac{k_y\ M_{y,fi,Ed}}{M_{y,fi,Rd}}\le 1 \quad (2)$$

whereas $N_{c,fi,Rd}$ is the cross-sectional axial compression resistance and $M_{y,fi,Rd}$ the major-axis bending resistance of the cross-section both for the case of fire. $\chi_{\min,fi}$ is the minimum of the reduction factors for the y-axis ($\chi_{y,fi}$) and *z*-axis ($\chi_{z,fi}$) for flexural buckling in the fire design situation (see Section 2.2). Since in this case only the in-plane failure is considered, one has $\chi_{\min,fi} = \chi_{y,fi}$. The interaction factor is defined according to Eq. (3), as follows

$$k_y = 1-\frac{\mu_y N_{fi,Ed}}{\chi_{y,fi} N_{c,fi,Rd}}\le 3 \quad (3)$$

and

$$\mu_y = (2\beta_{M,y}-5)\bar{\lambda}_{y,\theta}+0.44\beta_{M,y}+0.29\le 0.8 \text{ but } \bar{\lambda}_{y,20^\circ C}\le 1.1 \quad (4)$$

The equivalent uniform moment factors $\beta_{M,y}$ are evaluated using the bending diagram in the major-axis — $M_{y,fi,Ed}$. For the cases considered in this study, the corresponding expressions are given in Table 1 (from Fig. 4.2 of EN 1993-1-2).

In Eq. (4), $\bar{\lambda}_{y,\theta}$ is the column non-dimensional slenderness about y-y axis for flexural buckling at elevated temperature, given by

$$\bar{\lambda}_\theta = \sqrt{\frac{N_{c,fi,Rd}}{k_{E,\theta} N_{cr}}} \quad (5)$$

with $k_{E,\theta}$ is the reduction factor for the Young's modulus at elevated temperature and N_{cr} is the Euler critical load based on gross cross-sectional properties and taking into account the boundary conditions and the buckling direction at normal temperature.

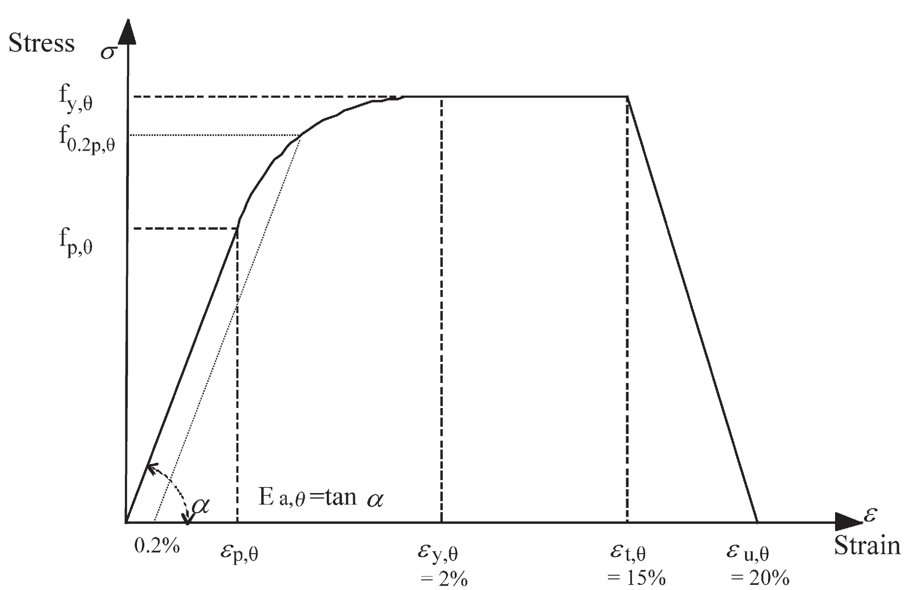


Fig. 1. Stress-strain relationship for carbon steel at elevated temperatures [18].