Engineering Structures 106 (2016) 410–421

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Numerical investigation of the lateral–torsional buckling of beams with slender cross sections for the case of fire

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ARTICLE INFO

Article history:
Received 29 April 2015
Revised 25 October 2015
Accepted 27 October 2015
Available online 11 November 2015

Keywords:
Lateral–torsional buckling (LTB)
Beams
Slender
Fire
Effective section factor
Class 4

ABSTRACT

An extensive numerical study is performed to investigate the lateral–torsional buckling of steel beams with slender cross sections for the case of fire. The influence of local buckling is analysed, and the numerical results are compared to the simplified design methods of Part 1-2 of Eurocode 3 for the case of beams with Class 1 and 2 cross sections. The actual provisions of Eurocode 3 Part 1-2 are demonstrated to be unreliable. A parametric study is carried out to investigate the influence of several parameters on the resistance of laterally unrestrained steel beams with slender cross sections for the case of fire: the effective section factor, temperature, steel grade, depth-to-width ratio (h/b) and residual stresses. Based on the parametric study, a proposal for a new design curve is made for beams with slender cross sections for the case of fire, taking into account the influence of local buckling by grouping the response of beams into different ranges of effective section factors. The capacity predicted by the simplified methods using the proposed design curve leads to an improved yet safe design method compared to the results of the finite element analysis.

1. Introduction

This paper addresses the lateral–torsional buckling (LTB) behaviour of laterally unrestrained steel beams with slender cross sections for the case of fire. Slender cross sections are composed of plates with a high width-to-thickness ratio (slenderness) and, for that reason, are prone to local buckling. Studies about the influence of local buckling in LTB are very scarce for fire situations because LTB has been mainly studied for beams with cross sections without local buckling instability. Bailey et al. [1] numerically investigated the LTB of unrestrained steel beams and concluded that both British code and the Eurocode, at that time, overestimated the limiting temperatures for unrestrained simple beams in fire resistance calculations. Vila Real and Franssen [2] performed a numerical study and proposed a design curve for the LTB of steel beams. This design curve was later adopted in the final version of the Eurocode 3 Part 1-2 (EN 1993-1-2) [3]. The experimental investigation conducted by Vila Real et al. [4], and later by Mesquita et al. [5], carried out on the LTB of steel beams at elevated temperatures was used to validate the proposed method by Vila Real and Franssen [2]. Vila Real et al. [6,7] also studied the influence of the residual stresses in the LTB of steel beams and concluded that for Class 1 members, the residual stresses are negligible, subsequently widening the initial proposal to account for other loading types. An improved proposal for the lateral–torsional buckling of unrestrained steel beams subjected to elevated temperatures was later presented by Vila Real et al. [8]. In this publication, the influence of loading type, steel grade, pattern of the residual stresses (hot-rolled or welded sections) and the h/b ratio, i.e., the depth h and the width b of the cross section, on the resistance of the beam was addressed through an extensive numerical study. Based on this study, a proposal to include a factor to account for other loading cases (the factor "f") as well as a severity factor for the influence of the steel grade in the current design method of Part 1-2 was presented. Dharma and Tan [9] proposed two alternative approaches to the current design method of Eurocode 3 Part 1-2 based on numerical investigation to calculate the lateral–torsional buckling resistance for the case of fire. They proposed an alternative approach to address the discontinuity between the design method at high temperature and at room temperature, an approach based on the Rankine formula that enables the failure temperature to be determined directly, without an iterative procedure, as required in the EN 1993-1-2 design method. In these studies, the beams were considered uniformly heated, and the influence of other temperature distributions was not addressed. On this subject, Yin and Wang [10] have numerically investigated the effects of several design factors

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http://dx.doi.org/10.1016/j.engstruct.2015.10.045
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on the lateral–torsional buckling bending moment resistance of steel I-beams submitted to non-uniform temperature distributions. A proposal was made for a modification to the lateral–torsional buckling slenderness of the beam to account for the non-uniform distribution of the temperature along the cross section; however, only the variation of the temperature in the depth of the cross section was considered. Later, Zhang et al. [11] analysed the LTB behaviour of beams subjected to localised fires and concluded that the failure temperature may be considerably lower than that of uniformly heated beams. Further investigation on the LTB resistance on non-uniformly heated beams should be performed but is outside of the scope of the present study. More recently, a numerical investigation by Lopes and Vila Real [12] on Class 4 stainless steel beams was performed. The influence of the geometrical imperfections (local, global and both) and the residual stresses was analysed at high temperatures, and it was concluded that they are relevant for determining the ultimate load and therefore should be considered according to the expected collapse mode.

Apart from [12], which consists of a study of stainless steel members, none of the remaining studies address slender cross sections prone to local buckling and the influence of local buckling on the LTB resistance of beams. Eurocode 3 [13] classifies these cross sections where local buckling prevents the yield strength from being reached in the compressed parts of the cross sections as Class 4, the highest class. Furthermore, in the establishment of the design rules of Eurocode 3 [3] for the case of fire (Part 1-2), the simple design methods were assumed to be adequate for designing beams with Class 4 cross sections if the recommendations of Annex E of that standard were followed. Annex E of Part 1-2 of the Eurocode 3 suggests the use of an effective cross section determined for normal temperature and the use of 0.2% proof strength ($f_{0.2p,\theta}$, see Fig. 1) for the design yield strength. Thus, the influence of local buckling is accounted for by reducing the cross-sectional capacity, by reducing the effective area, and by considering a reduced value of the yield strength.

The recommendations of Annex E are essentially based on the early work of Ranby [15], who studied Class 4 plates at elevated temperatures. On this matter, the authors [16–18] reached the same conclusions for cross sections that are built up exclusively of plates classified as Class 4 but demonstrated that for Class 4 cross sections with non-Class 4 plates, these recommendations lead to inaccurate results. Local buckling was also shown to prevent the elastic bending resistance being reached even in Class 3 cross sections. Thus, the load bearing capacity of the members with such cross sections is affected and needs to be investigated.

At ambient temperature, investigation on steel members with slender cross sections where failure may occur in a complex local–global interaction has also drawn the attention of different researchers. The "Direct Strength Method" (DSM) developed by Schafer and Pekoz [19] reviewed by Schafer [20] is based on determining the strength of a structural component as an explicit function of its gross cross-sectional properties, elastic critical buckling stresses for all relevant instability modes (i.e., global buckling, local buckling and distortional buckling) and yield strength, without the need to define an effective cross-section. The "Erosion of Critical Buckling Load" (ECBL) approach developed by Dubina [21], of which a review is given by Dubina and Ungureanu in [22], enables the numerical evaluation of the theoretical erosion of critical load into the interactive buckling range. The procedure can be used to calibrate the imperfection factor used to check the buckling strength of members as defined in Eurocode 3. Camotim et al. [23], who used the Generalised Beam Theory (GBT) to analyse the buckling behaviour of steel beams with several loadings and support conditions (including intermediate supports) have presented in [24] their current developments towards an efficient direct approach to estimate the ultimate loading of continuous beams, which may fail in complex modes that combine local, distortional and global features.

In this paper, an extensive numerical investigation is performed by finite element analysis (FEA) to study the influence of local buckling on the LTB resistance of beams with Class 3 and Class 4 cross sections under fire conditions. The effect of temperature, residual stresses, steel grade and the depth-to-width ratio (h/b) on the LTB resistance of beams with slender cross sections are also detailed. Using new methodology to calculate the cross section resistance developed by the authors [16–18] together with the Eurocode 3 Part 1-2 beam design curve leads to an improvement on the results compared to FEA calculations. However, this design curve should be slightly changed for Class 3 and Class 4 cross sections, and a proposal for a new design curve is made. Accordingly, an effective section factor is proposed to group the behaviour of beams with slender cross sections in a way that the interaction between local and lateral–torsional buckling may be accounted

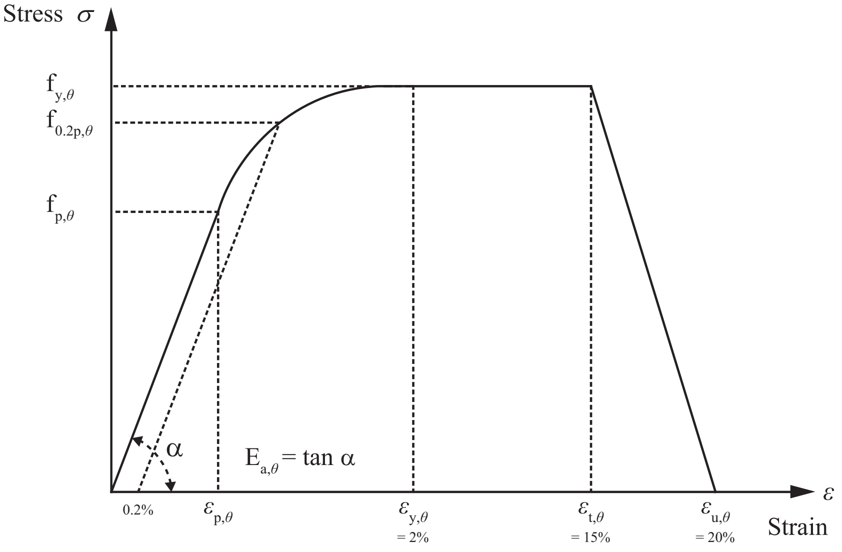

Fig. 1. Stress–strain relationship for carbon steel at elevated temperatures [14].