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The effect of non-uniform bending on the lateral stability of steel beams with slender cross-section at elevated temperatures

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ABSTRACT

In this paper, the effect of non-uniform bending on the lateral torsional buckling (LTB) of steel beams with slender cross-sections subjected to elevated temperatures is numerically investigated. Local buckling is the main failure mode for slender sections whereas the lateral torsional buckling is one of the principal failure modes for beams, thus the interaction between these two failure modes greatly affects the load-bearing capacity of the beams. In the case of fire, recent studies have shown that the design procedures of Part 1–2 of Eurocode 3 are unreliable and too conservative due to the inconsistent treatment of such interaction phenomena. On the other hand, it is known that non-uniform bending has a beneficial effect on the ultimate capacity of beams but there is limited knowledge about its influence on beams with slender cross-sections. This work aims at studying the influence of non-uniform bending on the combined local-global interaction response of beams with slender open I-sections in the case of fire. The inclusion of the factor "" in a recently proposed LTB design procedure that groups the response of the beams into different ranges of effective section factors is analysed and the accuracy of such proposal is demonstrated against around 20,000 GMNIA (Geometrically and Material Non-Linear Analyses with Imperfections) simulations. Finally, the improvements of this proposal on the current Eurocode 3 design procedure are highlighted.

1. Introduction

Steel beams with slender cross-sections are attractive as far as efficiency is concerned. Because the load-bearing capacity is mostly assured by the flanges, the thickness of the web can be reduced and a more ingenious usage of steel can be achieved with this optimization. However, the design rules of the fire part of Eurocode 3 (EN 1993-1-2) [1] for laterally unrestrained beams with slender cross-sections subjected to uniform bending moment, demonstrated to be very conservative and uneconomic [2]. This has been identified to be the result of inconsistent treatment of the coupled interaction between local buckling, which is the main failure mode for the slender cross-sections, and the global behaviour of a laterally unrestrained beam that is mainly governed by lateral torsional buckling (LTB). To solve this inconsistency, the effective section factor concept was developed in [2] to take into account the interaction between local buckling and LTB resulting in a proposal of new design curves. Although the research on LTB of beams in case of fire is a well-established subject that goes back to the first numerical investigations reported in the work of Bailey et al. [3] and the numerical investigations of Vila Real and Franssen [4], that resulted in the LTB design curve adopted in EN1993-1-2 after experimental validation [5,6]. Also, despite the many studies and improvements hitherto, research on the behaviour of steel beams with slender cross-sections and, more specifically, under non-uniform bending is very limited [2,7–10]. For a more comprehensive survey on the subject, see [2].

Furthermore, non-uniform bending is known to have a beneficial effect on the response of laterally unrestrained steel beams [11]. In the case of fire, factor "*f*" was developed for beams with compact ("Class 1 and 2") cross-sections [12,13] leading to better prediction of the capacity of the beams when in the presence of non-uniform bending at elevated temperatures. This factor takes into account the favourable influence on the resistance of beams similarly to the procedure at normal temperature design according to the specific case of Eurocode 3 (EN 1993-1-1) [14].

In this paper, the overall capacity of slender open I-section steel beams subjected to non-uniform bending is numerically investigated at elevated temperatures. The use of factor "*f*" together with the new

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Table 1
Values of the imperfection factors according to the limits of the effective section factor.

Curve	Effective section factor limits	$\alpha_{LT,\text{new}}$
L1	$\frac{W_{\text{eff},y}}{W_{\text{el},y}} > 0.9$	$1.25\varepsilon = 1.25\sqrt{235/f_y}$
L2	$0.8 < \frac{W_{\text{eff},y}}{W_{\text{el},y}} \leqslant 0.9$	$1.00\varepsilon = 1.00\sqrt{235/f_y}$
L3	$\frac{W_{\text{eff},y}}{W_{\text{el},y}} \leqslant 0.8$	$0.75\varepsilon = 0.75\sqrt{235/f_y}$

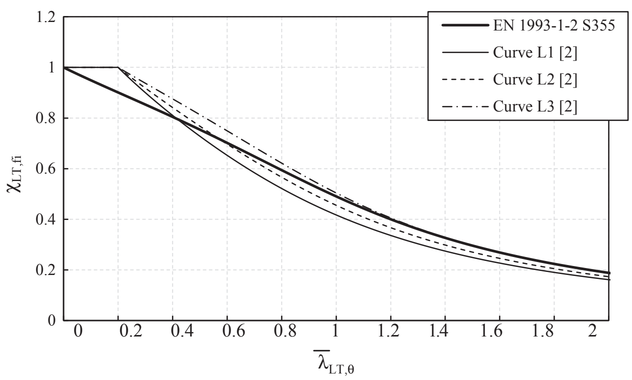

Fig. 1. Comparison of LTB design curves from EN 1993-1-2 and from [2] for the steel grade S355.

design formulae for beams with slender cross-sections [2] is investigated and it is demonstrated that the factor should be limited to $f \geq 0.8$ so that the non-uniform bending are properly accounted for when dealing with beams subjected to bi-triangular bending moments. Finally, an extensive numerical investigation of around 20,000 Geometrically and Material Non-Linear Analyses with Imperfections (GMNIA) simulations is carried out and presented, allowing the comparison of the FEM results with the proposed design procedure and, together with a statistical investigation, demonstrates the validity and accuracy of the proposed approach, also highlighting the improvements on the current design procedure of Eurocode 3.

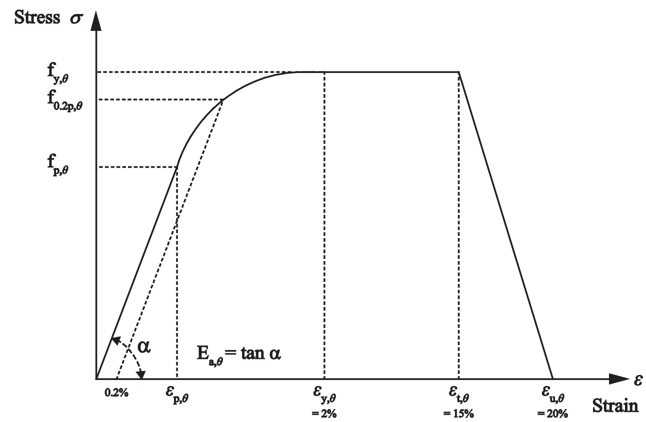

Fig. 3. Stress-strain relationship for carbon steel at elevated temperatures [20].

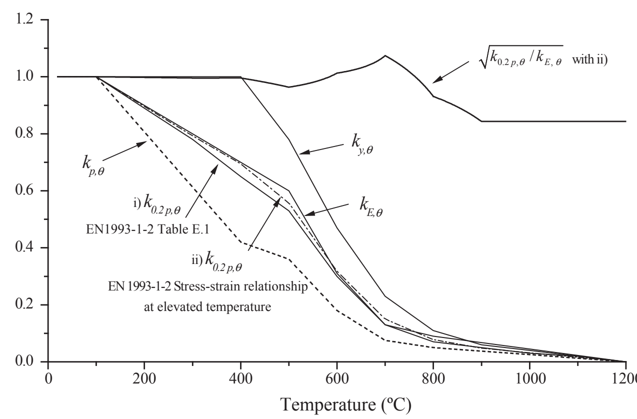

Fig. 4. Reductions factors for the mechanical properties of carbon steel at elevated temperatures according to Part 1.2 of Eurocode 3.

2. Lateral torsional buckling of beams with slender cross sections at elevated temperatures

2.1. Eurocode 3 Part 1–2

In the case of fire, the lateral torsional buckling (LTB) resistance of a beam is determined according to Eurocode 3 Part 1–2 (EN 1993-1-2) by

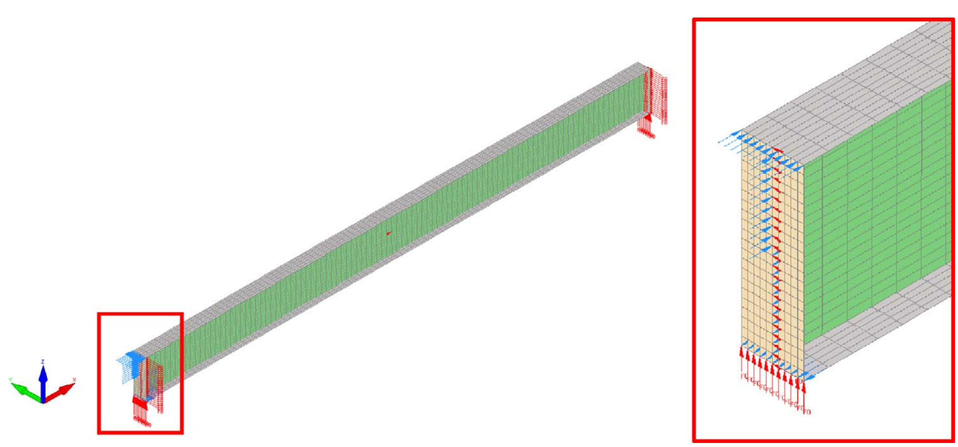

Fig. 2. Numerical model with applied boundary conditions (loads and supports).