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Ultimate capacity of I-sections under combined loading – Part 2: Parametric studies and CSM design

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ABSTRACT

The second part of the study on the ultimate capacity of hot-rolled steel I-sections under combined compression and bending moment, focussing on parametric studies and design, is presented herein. An extensive numerical parametric study was carried out, using the verified finite element (FE) models from the companion paper, to generate further structural performance data for specimens with different steel grades, cross-section slendernesses and loading cases. The numerical results together with the experimental results were then used to assess the accuracy of two codified design methods: the European Standard EN 1993-1-1 (2005) and the American Specification AISC-360-16 (2016). The design strengths predicted by the current design standards were found to be generally rather conservative and scattered when applied to non-slender cross-sections, owing principally to the neglect of material strain hardening and reserve capacities between the classification limits. To improve the accuracy and efficiency of the design rules, the continuous strength method (CSM) – a deformation-based design approach which relates the resistance of a cross-section to its deformation capacity – was extended to cover the design of hot-rolled steel I-sections under combined loading, underpinned by both the experimentally and numerically derived ultimate capacities. Overall, the CSM was shown to offer more accurate and consistent predictions than the current design provisions. Finally, reliability analysis was performed to evaluate the reliability level of the design rules.

1. Introduction

In the design of hot-rolled structural steelwork, cross-section classification is a fundamental feature in most current codes of practice, such as the European Standard EN 1993-1-1 (EC3) [1] and the American Specification AISC-360-16 [2], and determines the extent to which the strength and deformation capacity of a cross-section are limited by the effects of local buckling. Traditionally, classification or slenderness limits have been expressed in terms of width-to-thickness ratios for individual plates of a cross-section, considering boundary conditions – internal (stiffened) or outstand (unstiffened) elements and stress patterns. There has been considerable research on the behaviour and strength of I-sections under combined loading over the past decades, with the aim of assessing and improving the current design rules. Revised slenderness limits for I cross-sections have been proposed by [3, 4], accounting for the effects of web-flange interaction. Dawe and Kulak [5] investigated the local buckling behaviour of beam-columns and proposed web slenderness limits that consider the interaction effects of constituent plate elements and the applied load level. Kettler [6] performed a series of tests to investigate the cross-section resistance of semi-compact (Class 3) I-sections and rectangular hollow sections, and developed a design proposal to describe the transition from plastic to elastic cross-section resistance. Interaction curves for slender I-sections subjected to combined axial load and bending moment were systematically studied by Salem et al. [7] and Hasham and Rasmussen [8, 9], where conservatism in existing codified design provisions was highlighted and improved interaction curves were proposed, resulting in more accurate resistance predictions.

The current codified stepwise approach to the classification of structural steel cross-sections ignores the interaction between the elements, such as the flanges and web, and fails to account for the inherent continuous relationship between the cross-section resistance and its slenderness; additionally, there is limited or no knowledge of the deformations (or strains) required to reach a given capacity, such as the plastic moment capacity in bending, which will vary with cross-section shape, axis of bending, type of steel, and so on. In recent years, a new deformation-based design approach termed the continuous strength method (CSM) has been proposed [10–12] to address these shortcomings. The CSM replaces the concept of cross-section classification with a continuous non-dimensional measure of the cross-section deformation capacity and adopts a simple elastic, linear hardening material model which

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allows for the beneficial influence of strain hardening. Owing to the existence of a yield plateau, the CSM bi-linear material model is less suitable for hot-rolled carbon steels. Thus a more appropriate quad-linear material model [13] has been developed for hot-rolled carbon steels, which exhibits a yield point, followed by a yield plateau and a strain hardening region; this model has been incorporated into the CSM design framework for hot-rolled steel cross-sections under the isolated loading conditions of compression and bending [14, 15]. In this paper, the application of the CSM to the case of hot-rolled steel I-sections under combined loading is explored. The accuracy of different design methods, including EC3 [1], AISC [2] and the proposed CSM, are then assessed based on the test results presented in the companion paper [16] and numerical parametric data derived herein, using the validated finite element (FE) models.

2. Parametric studies

In this section, an extensive numerical parametric study is presented based on the FE models validated in the companion paper [16] to expand the available results over a wider range of I-section geometries, cross-section slendernesses and loading combinations. A detailed description of the FE models and their validation against experimental results, including the ultimate loads, load-deformation curves and failure modes, were reported in the companion paper [16], while the principal aspects relating to the parametric studies are presented herein.

The measured stress-strain curves from the flange tensile coupons for the different material grades (S235 and S355), as reported in the companion paper [16], were adopted in the parametric studies. The length of all FE models was set equal to three times the average cross-section dimensions. For each steel grade, the height (H) and the corner radii (r_i) of the specimens were kept constant at 200 mm and 15 mm, respectively, while four cross-section aspect ratios H/B of 1.0, 1.5, 2.0 and 2.5 were considered by varying the width of the flanges (B) from 200 mm to 80 mm. Maintaining the cross-section outer dimensions, the effect of local cross-section slenderness was investigated by varying the flange and web thicknesses (t_f and t_w), resulting in a range of cross-section slenderness values $\overline{\lambda}_p$ between 0.17 and 0.68. The cross-section slenderness $\overline{\lambda}_p$ is defined as $\overline{\lambda}_p = \sqrt{f_y/\sigma_{cr}}$, where σ_{cr} is the elastic buckling stress of the cross-section under the applied loading conditions, which may be obtained numerically (e.g. using the finite strip software CUFSM, as adopted in the present study) or using approximate expressions [17]. Note that $\overline{\lambda}_p = 0.68$ is the boundary between slender and non-slender cross-sections in the CSM [10], and the present study focuses primarily on non-slender sections where local buckling occurs after yielding. For each cross-section, a combination of 10 different initial loading eccentricities, which varied from 10 to 50 mm in 10 mm intervals and 100 to 500 mm in 100 mm intervals for the loading scenarios of 0, 30, 45 and 60° and from 10 to 100 mm in 10 mm intervals for the loading scenario of 90°, was considered in the parametric studies, leading to a wide range of loading conditions (i.e. ratios of axial force to bending moment). The 0 and 90° cases represent the I-sections under major axis bending plus compression and minor axis bending plus compression, respectively, while the remaining loading scenarios consider I-sections under biaxial bending plus compression. Local geometric imperfections were included in the models and were assumed to be of the form of the lowest elastic buckling mode shape in compression with an odd number buckling half-waves, with an imperfection amplitude of $c/200$, where c is the flat width of the most slender constituent plater element in the cross-section under compression (i.e. that with the highest value of $\sqrt{f_y/\sigma_{cr}}$ under compression). In terms of residual stresses, the ECCS model, as described in the companion paper [16], was incorporated into the FE models. A total of 1500 numerical results were generated, with 750 for each steel grade, including 300 for I-sections under uniaxial bending plus compression and 450 for biaxial bending plus compression. The numerical results, combined with the collected experimental data [16], are analysed in the following sections and used to assess and develop design expressions for hot-rolled steel I-sections under combined loading.

3. Assessment of current design methods and extension of the CSM

In this section, ultimate capacities from the experiments and FE simulations on hot-rolled steel I-sections under combined loading have been used to examine the accuracy of the codified design provisions of EC3 [1] and AISC [2]. Then, extension of the CSM to the case of hot-rolled steel I-sections subjected to the combined actions of compression and bending moment is undertaken. Key numerical comparisons, including the mean and the coefficient of variation (COV), of the axial load ratio, $N_{u,test/FE}/N_{u,pred}$, for each design method are reported in Table 1, where $N_{u,test/FE}$ is the test (or FE) axial load corresponding to the distance from the origin to the test (or FE) data point, and $N_{u,pred}$ is the predicted axial load corresponding to the projection from the origin to the associated intersection with the design interaction curve, as graphically defined in Fig. 1. As shown in Fig. 1, a value of the axial load ratio $N_{u,test/FE}/N_{u,pred}$ greater than unity indicates that the design interaction curve falls short of the corresponding test (or FE) data point and thus results in a safe-sided strength prediction, and vice versa. Note that the comparisons were performed using the measured geometric and material properties of the tested and modelled cross-sections, with all partial safety factors set to unity.

3.1. European code EN 1993-1-1 (EC3)

For hot-rolled steel I-sections subjected to combined compression and bending moment, EN 1993-1-1 [1] employs a linear elastic interaction expression for Class 3 cross-sections, assuming that failure occurs when the maximum stress in the cross-section reaches the yield stress f_y, as given by Eq. (1), in which N_{Ed} is the applied design axial load, M_{Ed} is the applied design bending moment, including the second order bending moment due to the lateral mid-height deflection, N_y is the yield load equal to the product of the gross cross-sectional area A and the yield stress f_y, M_{el} is the elastic moment capacity, and the subscripts 'y' and 'z' refer to the major and minor axis, respectively, and the subscript 'Rd' denotes design resistance.

$$\frac{N_{Ed}}{N_{y,Rd}} + \frac{M_{Ed,y}}{M_{el,y,Rd}} + \frac{M_{Ed,z}}{M_{el,z,Rd}} \leq 1 \tag{1}$$

For Class 1 and 2 cross-sections, the beneficial effect of plastic stress redistribution is allowed for by employing a nonlinear interaction

Table 1
Comparison of combined loading test and FE results with EC3, AISC and CSM capacity predictions.

(a) Major axis bending plus compression No. of tests: 2	$N_{u,test/FE}/N_{u,EC3}$	$N_{u,test/FE}/N_{u,AISC}$	$N_{u,test/FE}/N_{u,csm}$
No. of FE simulations: 300			
Mean	1.07	1.09	1.05
COV	0.11	0.09	0.08
(b) Minor axis bending plus compression No. of tests: 2	$N_{u,test/FE}/N_{u,EC3}$	$N_{u,test/FE}/N_{u,AISC}$	$N_{u,test/FE}/N_{u,csm}$
No. of FE simulations: 300			
Mean	1.45	1.31	1.13
COV	0.31	0.11	0.13
(c) Biaxial bending plus compression No. of tests: 8	$N_{u,test/FE}/N_{u,EC3}$	$N_{u,test/FE}/N_{u,AISC}$	$N_{u,test/FE}/N_{u,csm}$
No. of FE simulations: 900			
Mean	1.46	1.41	1.12
COV	0.32	0.09	0.11