Engineering Structures 157 (2018) 179–191

Contents lists available at ScienceDirect

Engineering Structures

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

The continuous strength method for the design of hot-rolled steel cross-sections

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ARTICLE INFO

Keywords:
Continuous strength method
Finite element modelling
Hot-rolled carbon steel
Reliability analysis
Strain hardening
Yield plateau

ABSTRACT

The continuous strength method (CSM) is a deformation-based structural design approach that enables material strain hardening properties to be exploited, thus resulting in more accurate and consistent capacity predictions. To date, the CSM has featured an elastic, linear hardening material model and has been applied to cold-formed steel, stainless steel and aluminium. However, owing to the existence of a yield plateau in its stress-strain response, this model is not well suited to hot-rolled carbon steel. Thus, a tri-linear material model, which can closely represent the stress-strain response of hot-rolled carbon steel, is introduced and incorporated into the CSM design framework. Maintaining the basic design philosophy of the existing CSM, new cross-section resistance expressions are derived for a range of hot-rolled steel structural section types subjected to compression and bending. The design provisions of EN 1993-1-1 and the proposed CSM are compared with experimental results collected from the literature and numerical simulations performed in this paper. Overall, the CSM is found to offer more accurate and consistent predictions than the current design provisions of EN 1993-1-1. Finally, statistical analyses are carried out to assess the reliability level of the two different design methods according to EN 1990 (2002).

1. Introduction

The section capacities of hot-rolled structural steel members are traditionally determined following the process of cross-section classification, which is based on the assumption of elastic, perfectly plastic material behaviour. Cross-section classification is a key feature of many modern steel design codes, such as EN 1993-1-1 [1], and determines the extent to which the resistance and deformation capacities of a cross-section are limited by the effects of local buckling. The classification of a cross-section is assessed by comparing the width-to-thickness ratios of its constituent plate elements to corresponding slenderness limits, which take account of the edge support conditions and applied loading. The plate elements are typically treated individually, thus neglecting the interaction effects between adjacent elements, i.e. the ability of the less slender elements to provide some assistance in resisting local buckling to the more slender elements, and the classification of the most slender element defines that of the overall cross-section. Furthermore, the maximum stress in the cross-section is generally limited to the material yield stress f_y, neglecting the beneficial effects of strain hardening. Hence, for non-slender cross-sections the compression resistance is limited to the yield load N_y and the cross-section bending resistance to the plastic moment capacity M_{pl} for Class 1 or Class 2 cross-sections and the elastic moment capacity M_{el} for Class 3 cross-sections, which results in a step (or recently proposed linear or parabolic transition [2–4]) from M_{pl} to M_{el} at a particular slenderness limit. Experimental results have shown that the current design rules in EN 1993-1-1 [1] are often conservative in estimating the resistance of stocky hot-rolled steel cross-sections in both compression and bending due primarily to the omission of strain hardening [5–7], and the failure to account accurately for the spread of plasticity in Class 3 cross-sections [8,9].

The importance of plate element interaction effects on the ultimate resistance of structural cross-sections has been examined by a number of researchers. Studies have been conducted on square and rectangular hollow sections (SHS/RHS) [10–13] and I-sections [13–18], while explicit allowance for element interaction through the use of cross-section rather than element elastic buckling stresses in the determination of local and distortional slendernesses is a key feature of the Direct Strength Method (DSM) [19–21]. The beneficial influence of strain hardening has also been observed by a number of researchers [7,22–24], and the exploitation of strain hardening is a key feature of the Continuous Strength Method [25,26].

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https://doi.org/10.1016/j.engstruct.2017.12.009
Received 12 April 2017; Received in revised form 29 October 2017; Accepted 5 December 2017

The CSM is a deformation-based design approach that offers more consistent and continuous resistance predictions than traditional approaches based on cross-section classification, and allows systematically for the beneficial influence of strain hardening. To date, this method has been established for stainless steel [27–29], structural carbon steel [25,30–32] and aluminium alloy design [33,34] utilizing a simple elastic, linear hardening material model, with a strain hardening modulus E_{sh} varying with material grade. This model has been shown to offer a suitably close representation of the stress-strain responses of metallic materials with nonlinear rounded stress-strain behaviour, such as stainless steel, cold-formed carbon steel and aluminium alloys, to enable efficient and accurate designs. However, due to the existence of a yield plateau, this CSM bi-linear material model is less suitable for hot-rolled carbon steels. Thus, a revised CSM material model has been proposed for hot-rolled carbon steels [35] that exhibits a yield point, followed by a yield plateau and a strain hardening region. In this paper, the application of the CSM to hot-rolled steel structural elements, i.e. SHS/RHS and I-sections, focusing primarily on cross-sections in compression and bending, including the development of the material model and the corresponding resistance functions, is outlined. The accuracy of the current design methods in EN 1993-1-1 and the CSM are then assessed based on the results of experiments collected from the literature and numerical simulations performed herein.

2. Numerical modelling

Numerical analyses were carried out using the finite element programme ABAQUS, version 6.13 [36] to simulate the cross-sectional response of hot-rolled steel SHS/RHS and I-sections in both compression and bending. The numerical models were initially validated against existing experimental results on stub columns [5,37–39] and simply-supported beams [7,40], and were subsequently used for parametric studies to expand the numerical data over a wider range of cross-section slendernesses, section geometries and loading conditions. Note that three grade S460 beam tests reported in [40] were discontinued before the maximum bending moment was reached and the results are therefore excluded from the validation study and subsequent assessment. Details of the finite element (FE) modelling approach and the parametric studies performed in the current study are presented in the following subsections.

2.1. Description of the FE models

The reduced integration four-noded doubly curved shell element S4R was employed in all FE models; this element type has been successfully utilised by others in similar applications [10,40,41]. Mesh sensitivity studies were conducted to determine an appropriate mesh density to provide accurate results while minimizing computational time. Hence, an average element size equal to one twentieth of the largest plate width that makes up the cross-section was adopted for the flat parts of the modelled cross-sections, while four elements were employed to model the curved geometry of the corner regions for the SHS/RHS and two elements for each fillet zone of the I-sections. For the I-sections, particular attention was given to ensure that the properties of the fillet zones could be accurately represented. The nodes at each end of the web were shifted by a distance of half the flange thickness to avoid overlapping of the elements at the web-to-flange junction [42], and these nodes were tied to their corresponding nodes at the mid-thickness of the flanges using the "General multi-point constraints (*MPC)"; this ensured that the translational and rotational degrees of freedom were equal for this pair of nodes. The additional area in the fillet zones was allowed for by increasing the thickness of the adjacent web elements (see Fig. 1).

During the validation of the models, measured cross-section dimensions and material properties from the existing tests were incorporated into the FE models to replicate the observed experimental behaviour. In cases where the full stress-strain curves were not reported in the literature, the nonlinear material model for hot-rolled carbon steels proposed in [35] was used. Since the analyses may involve large inelastic strains, the engineering (nominal) stress-strain curves were converted to true stress-logarithmic plastic strain curves as required in ABAQUS for the chosen element type.

Initial geometric imperfections were incorporated into the FE models using the mode shapes obtained from a prior elastic buckling analysis. The lowest buckling mode under the considered loading conditions with an odd number buckling half-waves was used as the imperfection shape, which generally represents the most unfavourable imperfection pattern [43], as shown in Fig. 2. Four different imperfection amplitudes were examined: $a/400$, $a/200$ and $a/100$, where a is the flat width of the most slender constituent plate element in the cross-section (i.e. that with the highest value of $\sqrt{f_y/\sigma_{cr}}$ under the applied loading conditions), and a value obtained from the modified Dawson and Walker predictive model [5,44], as given by Eq. (1), where ω_0 is the magnitude of the local imperfection, t is the plate thickness, f_y is the material yield stress, and σ_{cr} is the elastic buckling stress of the most slender cross-section plate element assuming simply supported conditions between adjacent plates, taking due account of the stress distribution through the buckling factor k_σ [45].

$$\omega_0 = 0.064\left(\frac{f_y}{\sigma_{cr}}\right)t \tag{1}$$

The residual stresses introduced into hot-rolled steel sections are primarily associated with non-uniform cooling rates during the fabrication process, with the more rapidly cooling regions of the sections being left in residual compression and the slower cooling regions in residual tension. The residual stress patterns recommended by the European Convention for Constructional Steelwork (ECCS) [46], as shown in Fig. 3, where compressive residual stresses are designated as positive and tensile residual stresses as negative, were applied to the FE models for the I-sections. The magnitude of the initial stresses depends on whether the height-to-width ratio of the cross-section is less than or equal to 1.2 or greater than 1.2 and is independent of the yield stress, with the nominal stress $f_y^* = 235$ MPa taken as the reference value. For SHS and RHS, a typical pattern of residual stresses, based on DIN recommendations [47], is shown in Fig. 4(a). To simplify the distribution for ease of application in FE modelling, a modified residual stress pattern was proposed by Nseir [37] based on the analysis of measured residual stress magnitudes and distributions, as represented in Fig. 4(b). A constant value of $0.5f_y^*$ was assumed for the compressive residual stresses in the corner regions while the amplitudes of the tensile residual stresses in the flat regions of the web and flanges were determined to achieve self-equilibrium. The simplified residual stress pattern was employed herein for both the validation of the models and the parametric analyses.

The boundary conditions were carefully selected to simulate the experimental setups. For the stub column FE models, each end section was connected to a concentric reference point through rigid body constraints such that the degrees of freedom of all nodes at each end were constrained to the degrees of freedom of its corresponding reference point. All degrees of freedom were then restrained at each end apart from the longitudinal translation at the loaded end to allow for vertical displacement. For the FE models of the simply-supported beams, the reference points were positioned on the lower flange of the section and connected to the nodes within the corresponding end plate region, with boundary conditions applied at each reference point to allow appropriate movement and rotation to simulate simple support conditions. The point loads were applied to the lower part of the web at the web-to-flange junction to prevent web crippling under concentrated loading. Also, for modelling convenience, beam models under pure bending moment were developed and validated against 4-point bending tests and then used in the subsequent parametric studies. The length of