Engineering Structures 175 (2018) 549–564

Contents lists available at ScienceDirect

Engineering Structures

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

The continuous strength method for the design of cold-formed steel non-slender tubular cross-sections

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ARTICLE INFO

Keywords:
Cold-formed steel
Combined loading
Continuous strength method (CSM)
Cross-section resistance
Finite element modelling
Reliability analysis
Simply supported beams
Strain hardening
Stub columns

ABSTRACT

Cold-formed steels typically exhibit a rounded stress-strain response with gradual yielding merging into strain hardening. This form of stress-strain curve is at odds with the elastic, perfectly plastic material model that underpins many of the provisions set out in current structural steel design standards. In particular, the beneficial influence of strain hardening on cross-section capacity is neglected. The continuous strength method (CSM) is a deformation-based design method that enables material strain hardening properties to be exploited, thus resulting in more accurate and consistent capacity predictions. The aim of this study is to extend the CSM to the design of cold-formed steel non-slender tubular cross-sections subjected to compression, bending and combined loading, and to verify the proposals through comparisons with existing test data from the literature and finite element results generated herein. The finite element models were first developed and validated against test results on cold-formed steel cross-sections collected from the literature. An extensive parametric study was then conducted to generate additional data over a wider range of cross-section geometries, slendernesses and loading conditions. The numerical results together with the experimental results were then compared with capacity predictions, calculated according to the current design rules in European Standard EN 1993-1-1 (2005) and American Specification AISC-360-16 (2016) as well as the CSM. The CSM is shown to provide more accurate and consistent design predictions for cold-formed steel cross-sections under different loading conditions than those obtained from existing design methods. The improvements arise from the use of the continuous deformation based design approach, as well the rational exploitation of strain hardening. Finally, the reliability levels of the different design methods were assessed by conducting reliability analyses in accordance with EN 1990 (2002).

1. Introduction

Square and rectangular hollow sections (SHS and RHS, respectively) are generally categorised according to their production route as either hot-finished or cold-formed. Cold-formed steel sections are produced from steel sheet or strip material which is passed through a series of rollers that progressively shape the steel into the required profile at ambient temperature. Significant plastic deformation is typically introduced during the manufacturing process (both during sheet/strip forming and section forming), resulting in changes to the stress-strain characteristics of cold-formed material. Unlike the hot-rolled steel, which generally exhibits an initial elastic response, with a sharply defined yield point, followed by a yield plateau and a subsequent strain hardening region, the material properties of cold-formed steels show a rounded stress-strain response with a moderate degree of strain hardening, but reduced ductility. Non-homogeneity of material properties is also often found in cold-formed sections due to the different levels of cold-working experienced at different locations around the section shape. The corner regions, in particular, of cold-formed cross-sections experience high levels of plastic deformation due to their tight corner radii, resulting in strength enhancements but a corresponding loss in ductility [1–4]. Further information on the properties and behaviour of hot-rolled and cold-formed SHS and RHS can be found in [4,5].

The design approach for cold-formed steel SHS and RHS adopted in steel design specifications [6,7] follows the traditional cross-section classification framework, which is based on the assumption of elastic, perfectly-plastic material behaviour. This design approach limits the maximum stress in cold-formed steel sections to the yield stress (taken as the 0.2% proof stress $\sigma_{0.2}$), thus ignoring the beneficial effect of strain hardening for stocky cross-sections. Experimental results have shown however that the current design methods are often overly-conservative in estimating the resistances of non-slender cold-formed steel SHS and RHS under both isolated loading, i.e. compression [4,8–10] and bending [3,4], and combined loading [8,9]. It is therefore

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https://doi.org/10.1016/j.engstruct.2018.08.070
Received 30 November 2017; Received in revised form 31 July 2018; Accepted 20 August 2018

considered necessary to develop new rational and efficient design techniques that can account for the strain hardening of cold-formed steels at the cross-sectional level.

The continuous strength method (CSM) is a newly developed deformation-based approach for steel design that provides an alternative treatment to cross-section classification and enables the effective exploitation of strain hardening. The CSM was originally developed for stainless steel structural elements [11–13], which exhibit a high degree of strain hardening, and the same concept has since been applied to structural carbon steel [14–19] and aluminium alloy [20,21] design. More recent advancements and developments of the CSM include its extension to circular hollow sections [22,23], cross-sections under combined loading [16,24,25], slender cross-sections [21,25,26], cross-sections at elevated temperatures [27] and composite structures [28,29].

The key objective of the present paper is to investigate the feasibility of applying the CSM to cold-formed steel structural elements, focusing primarily on non-slender SHS and RHS under different loading conditions. A suitable bilinear (elastic-linear hardening) material model is adopted, providing consistency with previous CSM developments and a satisfactory representation of the key stress-strain characteristics of cold-formed steels for design purposes. Geometrically and materially nonlinear finite element (FE) models were developed and verified against existing experimental results to simulate the cross-sectional behaviour of cold-formed steel SHS and RHS subjected to different loading conditions. Upon validation of the FE models, a comprehensive parametric study was conducted to generate results over a wider range of cross-section geometries, slendernesses and loading conditions. The numerically obtained results, together with the collected experimental data, were then used to evaluate the accuracy of existing design provisions [6,7] and the CSM for capacity prediction of cold-formed steel cross-sections. Furthermore, for cross-sections under combined loading, a modified design method which employs similar interaction expressions as given in EN 1993-1-1 [6] but considers the axial and flexural cross-section resistance predictions according to the CSM, was also examined. Finally, reliability analysis was conducted to provide a statistical evaluation of the different design methods.

2. CSM for cold-formed steel cross-section design

The key features of the CSM are (1) a base curve that defines the maximum level of strain ε_{csm} that a cross-section can endure prior to failure by (inelastic) local buckling as a function of the cross-section slenderness and (2) the adoption of a material model that allows for the beneficial influence of strain hardening. This section of the paper describes the extension of the CSM to the design of cold-formed steel cross-sections, including verification of the previously developed base curve and development of a suitable material model, and summarizes the CSM design approach for cross-sections under different loading conditions.

2.1. CSM design base curve

The CSM design base curve provides a continuous relationship between the strain ratio $\varepsilon_{csm}/\varepsilon_y$ and the cross-section slenderness $\bar{\lambda}_p$, where ε_y is the material yield strain equal to f_y/E, with f_y being the yield (0.2% proof) strength and E being the Young's modulus. The definition of the cross-section slenderness $\bar{\lambda}_p$ is given by Eq. (1), where σ_{cr} is the elastic buckling stress. The elastic buckling stress σ_{cr} should preferably be determined for the full cross-section either using numerical methods, such as the finite strip software CUFSM [30], or approximate analytical methods [31]. Alternatively, σ_{cr} may be conservatively taken as the elastic buckling stress of the most slender individual plate element in the cross-section using the classical plate buckling expression [32]. The former approaches take into account the effects of plate element interaction within the cross-section, as used in the direct strength method [33], whereas the latter approach assumes simply supported boundary conditions at the edges of the adjoining plates, which neglects element interaction effects and generally results in a conservative prediction for σ_{cr}. The effect on σ_{cr} of considering element interaction for different cross-section shapes and loading conditions has been discussed by Seif and Schafer [31]. Clearly, more favourable results can be obtained when the effects of plate element interaction are considered, and this is therefore recommended and adopted in the analyses performed herein by calculating σ_{cr} using CUFSM [30]. A detailed description of the definitions of the cross-section slenderness and the strain ratio can be found in [13,16].

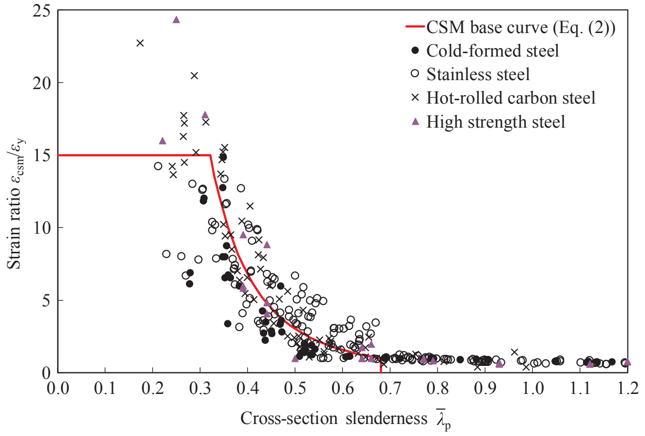

Fig. 1. CSM base curve for non-slender cross-sections.

$$\bar{\lambda}_p = \sqrt{f_y/\sigma_{cr}} \qquad (1)$$

Experimental data from stub column tests and 4-point bending tests on cold-formed steel cross-sections [3,4,8–10] have been collated and plotted in Fig. 1 on a graph of strain ratio $\varepsilon_{csm}/\varepsilon_y$ versus cross-section slenderness $\bar{\lambda}_p$; equivalent test data for high strength steel sections [34], as well as hot-rolled steel and stainless steel sections collected in [13] are also plotted. The CSM base curve, which was originally developed for stainless steel sections, given by Eq. (2), where ε_u is the strain corresponding to the ultimate tensile stress f_u, can be seen to also provide good predictions of normalised deformation capacities for cold-formed steel cross-sections. Two upper bounds have been placed on the predicted CSM strain ratio $\varepsilon_{csm}/\varepsilon_y$; the first limit of 15 is related to the material ductility requirement according to EN 1993-1-1 [6] and prevents excessive deformations and the second limit of $C_1\varepsilon_u$, where C_1 is a coefficient corresponding to the adopted CSM bilinear material model as described in the subsequent section, defines a 'cut-off' strain to avoid over-predictions of material strength. It is noted that the CSM base curve (Eq. (2)) applies to non-slender cross-sections where $\bar{\lambda}_p \leqslant 0.68$, which is identified as the transition point between non-slender and slender sections [13], though extension the base curve to slender cross-sections has also recently been presented [21,25,26].

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{0.25}{\bar{\lambda}_p^{3.6}}, \quad \text{but} \frac{\varepsilon_{csm}}{\varepsilon_y} \leqslant \min\left(15, \frac{C_1\varepsilon_u}{\varepsilon_y}\right) \qquad (2)$$

2.2. CSM material model for cold-formed steels

An elastic, linear hardening material model has been employed throughout the development of the CSM to represent the strain hardening response of metallic materials with rounded stress-strain behaviour, such as stainless steels and aluminium alloys. This model has been verified for austenitic and duplex stainless steels [13], ferritic stainless steels [35] and aluminium alloys [21], and shown to capture the general strain hardening behaviour sufficiently well to enable