Engineering Structures 162 (2018) 177–187

Contents lists available at ScienceDirect

Engineering Structures

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

The continuous strength method for the design of high strength steel tubular sections in compression

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ARTICLE INFO

Keywords:
Continuous strength method
Cross-section resistance
High strength steel
Structural design
Tubular sections

ABSTRACT

This paper aims to extend the deformation-based design method named continuous strength method (CSM) for the design of high strength steel tubular sections in compression. The CSM employs a base curve relating the cross-section resistance to its deformation capacity and adopts an elastic, linear hardening material model. Non-slender and slender circular hollow sections (CHS), elliptical hollow sections (EHS), square hollow sections (SHS) and rectangular hollow sections (RHS) were investigated in this study. Hot-finished, cold-formed and built-up steel tubular sections with yield stresses up to 1405 MPa were covered. An extensive numerical study was carried out to supplement the limited test results of high strength steel stub columns in the literature. The cross-section resistances obtained from the proposed CSM, the direct strength method (DSM), and design methods in EN 1993-1-5, EN 1993-1-6, ANSI/AISC 360-10 and AISI S100 were compared with the experimental and numerical capacities of 742 stub columns. It is shown that the proposed CSM can produce more accurate and less scattered strength predictions than the current DSM and design codes.

1. Introduction

High strength steel (HSS) with a nominal yield stress exceeding 450 MPa has become increasingly popular as an economical and sustainable material. The application of high strength steel can reduce structural self-weight and lower construction costs as well as carbon footprints. Steel tubular sections are widely used due to their aesthetic appearance and advantageous mechanical performance [1]. It is, therefore, imperative to develop design rules for high strength steel tubular sections.

Comprehensive design rules are available for the design of conventional carbon steel cross-sections in design codes and specifications including EN 1993-1-1 [2], EN 1993-1-5 [3], EN 1993-1-6 [4], ANSI/AISC 360-10 [5], AISI S100 [6] and AS/NZS 4600 [7]. The concept of cross-section classification based on the slenderest constituent element within the cross-section and the effective width method are employed for the design of steel cross-section [2,3,5–7], and thus the element interaction within the cross-section cannot be taken into account. EN 1993-1-6 [4] adopts shell buckling theory for the design of shells. An elastic, perfectly-plastic material model without considering the beneficial effect of strain hardening is employed in design codes [2–7]. Consequently, the codified design methods without considering the beneficial effects of the element interaction and strain hardening often produce conservative and scattered predictions of cross-section capacity [8–16]. A deformation-based design method called continuous strength method (CSM) was proposed to overcome the inherent drawbacks of the codified design methods [8]. The CSM adopts an elastic, linear hardening material model to exploit the strength enhancement from strain hardening in non-slender steel cross-sections. Furthermore, the CSM employs a base curve relating deformation capacity of cross-sections to overall cross-section slenderness to consider the element interaction. The CSM has been developed for the design of steel cross-sections using normal strength carbon steel [9–12], stainless steel [12–15] and aluminium alloy [12,16]. It is shown that the CSM yields more accurate and consistent predictions of cross-section capacity with improved design efficiency compared with the codified design methods.

This study extends the scope of the CSM for the design of non-slender and slender high strength steel tubular sections in compression. Current design methods and the CSM for steel cross-sections in compression were described and compared. Finite element (FE) models were developed and validated against test results in the literature. An extensive parametric study on high strength steel tubular sections was then conducted to supplement the limited test results of high strength steel stub columns in the literature. Non-slender and slender circular hollow sections (CHS), elliptical hollow sections (EHS), square hollow sections (SHS) and rectangular hollow sections (RHS) were

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https://doi.org/10.1016/j.engstruct.2018.02.010
Received 20 July 2017; Received in revised form 27 December 2017; Accepted 1 February 2018
0141-0296/

investigated. Hot-finished, cold-formed and built-up steel tubular sections were covered. Cross-section resistances collated from experimental tests in the literature and obtained from the numerical study conducted herein were used to assess the current design methods and proposed CSM for high strength steel tubular sections.

2. Current design methods for carbon steel cross-sections

EN 1993-1-5 [3], ANSI/AISC 360-10 [5], AISI S100 [6] and AS/NZS 4600 [7] employ the concept of cross-section classification and the effective width method for the design of normal strength carbon steel cross-sections. Maximum width-to-thickness ratios namely yield slenderness limits are stipulated for compression parts to classify cross-sections into non-slender and slender cross-sections in design codes [2,3,5–7]. The yield slenderness limits reflect the influence of steel material properties (yield stress and elastic modulus), edge support conditions (stiffened or unstiffened), and the shape of applied stress field (stress ratio) on the level of susceptibility to local buckling of an element within the cross-section. For cross-sections in compression, cross-sections of Class 1–3 or without slender elements are classified if the width-to-thickness ratio of all constitute elements of the cross-section is within the yield slenderness limit. Otherwise, cross-sections shall be considered as cross-sections of Class 4 or with slender elements. The failure of non-slender cross-sections is normally due to material yielding and/or inelastic local buckling. Thus, the corresponding cross-section resistance can exceed the cross-section yield load which equals to gross cross-sectional area times steel yield stress because of strain hardening. However, an elastic, perfectly-plastic material model without considering the beneficial effect of strain hardening is adopted in design codes [3–7]. Class 4 or slender cross-sections fail before the average stress within the cross-sections reaches steel yield stress due to local buckling.

The nominal strength of Class 1–3 and Class 4 cross-sections in compression specified in EN 1993-1-5 [3] is determined by Eq. (1). EN 1993-1-6 [4] employs shell buckling theory to determine the resistance of shells (e.g. CHS members). The corresponding nominal resistance of shells in compression [4] can be obtained from Eq. (2). The nominal compressive strength of cross-sections subjected to yielding or local buckling in ANSI/AISC 360-10 [5] and AISI S100 [6] can be calculated from Eqs. (3) and (4), respectively.

$$N_{\text{EC3-1-5}} = \begin{cases} f_y A & \text{for } \lambda_l \leqslant 0.5 + \sqrt{0.085{-}0.055\psi} \\ f_y A_e & \text{for } \lambda_l > 0.5 + \sqrt{0.085{-}0.055\psi} \end{cases} \quad \text{(EN 1993-1-5 [3])} \tag{1}$$

$$N_{\text{EC3-1-6}} = \chi f_y A \quad \text{(EN 1993-1-6 [4])} \tag{2}$$

$$N_{\text{AISC}} = 0.658^{Qf_y/f_e} Q f_y A \quad \text{(ANSI/AISC360-10 [5])} \tag{3}$$

$$N_{\text{AISI}} = f_n A_e \quad \text{(AISI S100 [6])} \tag{4}$$

where A is the gross cross-sectional area, A_e is the effective cross-sectional area determined by effective width method, f_y is the steel yield stress, λ_l is the plate element slenderness, ψ is the stress ratio, χ is the buckling reduction factor determined by the relative slenderness of the shell, Q is the reduction factor related to the effective cross-sectional area and equals to 1.0 for cross-sections without slender elements, f_e is the elastic buckling stress specified in Section E3 of ANSI/AISC 360-10 [5], f_n is the global column stress determined in accordance with Section E2 of AISI S100 [6]. It is noted that AISI S100 [6] and AS/NZS 4600 [7] adopt the same design equations for cold-formed steel members under compression, and thus the AS/NZS 4600 [7] is not included in the comparison study of Section 8.

The direct strength method (DSM) was proposed by Schafer and Peköz [17,18] for cold-formed structural steel members with flat elements. The strength-based DSM determines the cross-section capacity as a function of overall cross-section slenderness (λ_p) defined by:

$$\lambda_p = \sqrt{f_y/f_{cr}} \tag{5}$$

where f_y is the steel yield stress and f_{cr} is the elastic buckling stress which may be determined using the bespoke software CUFSM [19], suitable numerical tools such as ABAQUS [20], or approximate equations.

The DSM can consider the beneficial effect of element interaction within the cross-section and improve the design efficiency for slender sections with complex geometries or under stress gradients compared with the effective width method. The DSM is currently incorporated in AISI S100 [6]. The DSM nominal compressive strength of cross-sections subjected to local buckling may be obtained from:

$$N_{\text{DSM}} = \begin{cases} f_y A & \text{for } \lambda_p \leqslant 0.776 \\ \left(1-\frac{0.15}{\lambda_p^{0.8}}\right)\frac{1}{\lambda_p^{0.8}} f_y A & \text{for } \lambda_p > 0.776 \end{cases} \quad \text{(Direct Strength Method [6])} \tag{6}$$

where f_y is the steel yield stress, A is the gross cross-sectional area, λ_p is the overall cross-section slenderness. It is noted that the DSM also adopts an elastic, perfectly-plastic material model without considering the beneficial effect of strain hardening.

3. The continuous strength method

3.1. General

The continuous strength method (CSM) was originally proposed by Gardner and Nethercot [8] for the design of non-slender cross-sections using stainless steel. The CSM has been developed for the design of cross-sections using normal strength carbon steel, stainless steel and aluminium alloy [8–16]. The base curve relating cross-section deformation capacity to overall cross-section slenderness and the elastic, linear hardening material model are two key components of the CSM. The CSM, therefore, has two major advantages compared with the current design methods, i.e. rational exploitation of strain-hardening and proper consideration of the element interaction within the cross-section.

3.2. Base curve

The CSM base curve relates the maximum attainable strain (ε_{csm}) to the overall cross-section slenderness (λ_p) as defined by Eq. (5). The base curves proposed for non-slender and slender cross-sections using stainless steel [15] and aluminium alloy [16] in compressions are as follows:

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{\delta_u/L{-}0.002}{\varepsilon_y} = \frac{0.25}{\lambda_p^{3.6}} \leqslant \min\left(15, \frac{C_1\varepsilon_u}{\varepsilon_y}\right) \quad \text{for } \lambda_p \leqslant 0.68 \tag{7}$$

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{N_u}{N_y} = \left(1-\frac{0.222}{\lambda_p^{1.05}}\right)\frac{1}{\lambda_p^{1.05}} \quad \text{for } \lambda_p > 0.68 \tag{8}$$

where ε_{csm} is the CSM limiting strain, ε_y is the yield strain which equals to f_y/E, f_y is the steel yield stress, E is the steel elastic modulus, ε_u is the ultimate strain at ultimate stress, δ_u is the end shortening at the ultimate load, L is the column length, λ_p is the overall cross-section slenderness, C_1 is the coefficient to define a cut-off strain to avoid over-prediction of material stress, N_u is the ultimate load of stub columns, N_y is the yield load which equals to f_yA. It should be noted that the CSM limiting strain (ε_{csm}) is taken as $\varepsilon_{csm} = \delta_u/L$-0.002 for steel materials with a round material response (e.g. stainless steel and aluminium alloy) and $\varepsilon_{csm} = \delta_u/L$ for those with a sharply defined yield point (e.g. hot-rolled steel) in order to be compatible with the adopted elastic, linear hardening material model [12]. Two upper limits ($15\varepsilon_y$ and $C_1\varepsilon_u$)