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Structural response and continuous strength method design of slender stainless steel cross-sections

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ABSTRACT

In current structural stainless steel design codes, local buckling is accounted for through a cross-section classification framework, which is based on an elastic, perfectly-plastic material model, providing consistency with the corresponding treatment of carbon steel cross-sections. Hence, for non-slender cross-sections, the codified design stress is limited to the 0.2% proof stress without considering the pronounced strain hardening exhibited by stainless steels, while for slender cross-sections, the effective width method is employed without considering the beneficial effect of element interaction. Previous comparisons between test results and codified predictions have generally indicated over-conservatism and scatter. This has prompted the development of more efficient design rules, which can reflect better the actual local buckling behaviour and nonlinear material response of stainless steel cross-sections. A deformation-based design approach called the continuous strength method (CSM) has been proposed for the design of stocky cross-sections, which relates the strength of a cross-section to its deformation capacity and employs a bi-linear (elastic, linear hardening) material model to account for strain hardening. In this paper, the scope of the CSM is extended to cover the design of slender stainless steel cross-sections under compression, bending and combined loading, underpinned by and validated against 794 experimental and numerical results. The proposed approach allows for the beneficial effect of element interaction within the cross-section, and is shown to yield a higher level of accuracy and consistency, as well as design efficiency, in the capacity predictions of slender stainless steel cross-sections, compared to the effective width methods employed in the current international design standards. Non-doubly symmetric sections in bending, which may be slender, but still benefit from strain hardening, are also discussed. The reliability of the CSM proposal has been confirmed by means of statistical analyses according to EN 1990, demonstrating its suitability for incorporation into future revisions of international design codes for stainless steel structures.

1. Introduction

Stainless steel is becoming an increasingly attractive choice as a construction material, rather than simply a decorative material, in a range of engineering applications, owing principally to its favourable mechanical properties, good ductility and excellent corrosion and fire resistance. Given the high initial material price of stainless steels, structural design efficiency is of primary concern. For the design of stainless steel plated sections (e.g., square and rectangular hollow sections (SHS and RHS), I-sections, channel sections, angle sections and T-sections) susceptible to local buckling, although a number of design standards exist, the provisions were generally developed in line with the corresponding carbon steel design guidelines, which are based on the idealised elastic, perfectly-plastic material model without accounting for strain hardening, and the traditional cross-section classification and effective width concepts without considering element interaction. Hence, current stainless steel design standards generally ignore these two beneficial effects – strain hardening and element interaction – and have, as a result, been shown to often result in unduly conservative and scattered predictions of cross-section resistances under compression [1–4], bending [3,5–8] and combined loading [9–12].

To address this shortcoming, a deformation-based design approach called the continuous strength method (CSM) has been proposed [13–16]. The CSM replaces the concept of cross-section

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classification, which is defined on the basis of the most slender constituent plate element of the cross-section, with a non-dimensional measure of cross-section deformation capacity, which is presented as a function of the full cross-section slenderness that accounts for the beneficial effect of element interaction within the cross-section. An elastic, linear hardening material model is also adopted, representing better the actual material behaviour of stainless steels, compared to the elastic, perfectly-plastic material model used in current design standards. The CSM [13–15] has previously been developed for the design of non-slender stainless steel plated sections, and shown to yield substantially improved predictions of capacity over the current design standards, due to the consideration of strain hardening and element interaction, while its application to slender plated sections is extended and described herein.

The paper begins with a brief review and comparative analysis of the current design methods for slender stainless steel cross-sections failing by local buckling, including the European codes EN 1993-1-4 [17] and EN 1993-1-5 [18], American specification SEI/ASCE-8 [19], Australian/New Zealand standard AS/NZS 4673 [20], AISC design guide 27 [21] and direct strength method (DSM) [6,22–25]. The continuous strength method (CSM), originally developed to account for strain hardening in the design of non-slender stainless steel plated sections, is firstly described, and then extended to cover the design of slender cross-sections, underpinned by experimental results collected from the literature. A numerical modelling programme is also performed to generate further structural performance data. The present numerical studies focus primarily on tubular SHS and RHS, though a wider study by the authors also includes other open section profiles, such as I-, T-, channel and angle sections. Finally, the combined experimental and numerical data are employed to assess the accuracy and reliability of the proposed CSM for slender stainless steel plated sections.

2. Current design methods for slender stainless steel cross-sections

2.1. Codified design methods

The codified treatment of local buckling in slender stainless steel cross-sections, as given in the current European codes EN 1993-1-4 [17] and EN 1993-1-5 [18], American specification SEI/ASCE-8 [19], Australian/New Zealand standard AS/NZS 4673 [20] and AISC design guide 27 [21], is based on the traditional effective width concept, as adopted in the corresponding carbon steel design standards. The effective width methods treat the cross-section as an assemblage of isolated plate elements without considering element interaction, and account for loss of effectiveness due to local buckling through a reduction in plate element width. The level of the susceptibility of a plate element to local bucking and thus the reduction in plate width and resistance are dependent on its plate element slenderness $\bar{\lambda}_l$, as defined in Eq. (1), where $\bar{b}$ is the flat width of the plate element, t is the plate thickness, $\varepsilon = \sqrt{(235/f_y)(E/210000)}$ is a coefficient related to material properties, in which f_y is the material yield stress, taken as the 0.2% proof stress $\sigma_{0.2}$ for stainless steels, E is the Young's modulus, and k_σ is the plate buckling coefficient, depending on the edge support conditions and the stress ratio across the plate width. Note that the definition of flat width $\bar{b}$ varies between the design codes and the appropriate width has been used for the calculations and comparisons presented.

$$\bar{\lambda}_l = \frac{\bar{b}/t}{28.4\varepsilon\sqrt{k_\sigma}} \quad (1)$$

The reduction factor ρ in plate element width due to local buckling is a function of the plate element slenderness $\bar{\lambda}_l$. The American specification SEI/ASCE-8 [19] and Australian/New Zealand standard AS/NZS 4673 [20] adopt the same reduction factor ($\rho_{ASCE} = \rho_{AS/NZS}$), as shown in Eq. (2) for both internal (stiffened) and outstand (unstiffened) plate elements. The reduction factors used in the European code EN 1993-1-4 [17] and AISC design guide 27 [21] are based on the findings of Gardner and Theofanous [26], as given by Eqs. (3) and (4) for internal ($\rho_{EC3\text{-}1\text{-}4\text{-}I} = \rho_{AISC\text{-}I}$) and outstand ($\rho_{EC3\text{-}1\text{-}4\text{-}O} = \rho_{AISC\text{-}O}$) plate elements, respectively. The European code EN 1993-1-5 [18] for plated carbon steel structural elements considers the effect of stress gradient on the local buckling behaviour of internal plate elements, with the reduction factor shown in Eq. (5), where ψ is the end stress ratio of an internal plate element, but employs the same reduction factor for outstand plate elements as those in EN 1993-1-4 [17] and AISC [21], as given by Eq. (6).

$$\rho_{ASCE} = \rho_{AS/NZS} = \left(\frac{1}{\bar{\lambda}_l} - \frac{0.22}{\bar{\lambda}_l^2}\right) \leqslant 1 \quad (2)$$

$$\rho_{EC3-1-4-I} = \rho_{AISC-I} = \left(\frac{0.772}{\bar{\lambda}_l} - \frac{0.079}{\bar{\lambda}_l^2}\right) \leqslant 1 \quad (3)$$

$$\rho_{EC3-1-4-O} = \rho_{AISC-O} = \left(\frac{1}{\bar{\lambda}_l} - \frac{0.188}{\bar{\lambda}_l^2}\right) \leqslant 1 \quad (4)$$

$$\rho_{EC3-1-5-I} = \left(\frac{1}{\bar{\lambda}_l} - \frac{0.055(3+\psi)}{\bar{\lambda}_l^2}\right) \leqslant 1 \quad (5)$$

$$\rho_{EC3-1-5-O} = \left(\frac{1}{\bar{\lambda}_l} - \frac{0.188}{\bar{\lambda}_l^2}\right) \leqslant 1 \quad (6)$$

On the basis of the effective width of each constituent plate element, the effective cross-section properties, including the effective section area A_{eff} and modulus W_{eff}, can be determined. The effective cross-section resistances under pure compression (N_{eff}) and bending (M_{eff}), are then calculated as the products of the yield stress f_y and the effective section area A_{eff} and modulus W_{eff}, respectively. For slender cross-sections under combined loading, failure is determined based on a linear summation of the utilization ratios under each component of loading, with a limit of unity. The design expression is given by Eq. (7), in which N_{Ed} is the applied axial load, $M_{Ed,y}$ and $M_{Ed,z}$ are the applied bending moments about the two principal axes, N_{eff}, $M_{eff,y}$ and $M_{eff,z}$ are the corresponding design effective cross-section compression and bending resistances.

$$\frac{N_{Ed}}{N_{eff}} + \frac{M_{Ed,y}}{M_{eff,y}} + \frac{M_{Ed,z}}{M_{eff,z}} \leqslant 1 \quad (7)$$

Following comparisons with test and finite element (FE) results, it has been generally found in previous research [27] that the effective width methods result in rather scattered cross-section resistance predictions, especially for sections where the slenderness of the constituent plate elements varies significantly, e.g., RHS with large aspect ratios, owing to the failure to account for the beneficial effect of element interaction in the design. Moreover, application of the effective width method is often cumbersome, due to a shift of neutral axis.

2.2. The direct strength method (DSM)

The direct strength method (DSM) was developed by Schafer and Peköz [22,23] to overcome the cumbersome nature of the effective width method when applied to slender cold-formed car-