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Hot-Rolled Steel and Steel-Concrete Composite Design Incorporating Strain Hardening

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ABSTRACT

Current design codes for steel and steel-concrete composite structures are based on elastic, perfectly plastic material behaviour and can lead to overly conservative strength predictions due to the neglect of the beneficial influence of strain hardening, particularly in the case of stocky, bare steel cross-sections and composite beams under sagging bending moments. 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 capacity predictions. In this paper, a strain hardening material model, which can closely represent the stress-strain response of hot-rolled steel, is introduced and incorporated into the CSM design framework. The CSM cross-section resistance functions, incorporating strain hardening, are derived for hot-rolled steel sections in compression and bending, as well as hot-rolled steel-concrete composite sections where their neutral axes lie within the concrete slab in bending. Comparisons of the capacity predictions with a range of experimental data from the literature and finite element data generated herein demonstrate the applicability and benefits of the proposed approach.

1. Introduction

The concept of cross-section classification is used in current design codes to determine the appropriate structural design resistance of metallic sections. The method limits the maximum stress in the cross-section to the yield stress f_y, neglecting the beneficial effects of strain hardening. Experimental results have shown that the current design methods, based on the idealised elastic, perfectly plastic material behaviour, are often conservative in estimating the resistance of stocky hot-rolled steel cross-sections in both compression and bending [1–3] and composite beams under sagging bending moments [4–6]. The Continuous Strength Method (CSM) is a newly developed deformation based approach to steel design that provides an alternative treatment to cross-section classification, and enables the effective utilization of strain hardening. The method was originally developed for stainless steel structural elements [7–9], which exhibit a high degree of strain hardening, and the same concept has since been applied to structural carbon steel [10–12] and aluminium alloy [13] design.

A bi-linear (elastic-linear hardening) material model has been employed in the CSM to date, providing consistency and a satisfactory representation for design purposes of the observed stress-strain responses of cold-formed steel, stainless steel and aluminium alloys [9, 12,13]. However, due to the existence of a yield plateau, this CSM bi-linear material model is less suitable for hot-rolled carbon steel. Thus, a revised CSM material model is proposed for hot-rolled carbon steel that exhibits a yield point, a yield plateau and a strain hardening region. In this paper, the application of the CSM to bare hot-rolled structural steel elements, focusing primarily on cross-sections in compression and bending, including recent developments and comparisons with test results, is outlined. Extension of the method to composite beams under sagging bending moments is then described.

2. Application of the CSM to hot-rolled steel elements

The key characteristics of the CSM lie in the employment of a base curve that defines the maximum level of strain ε_{csm} ε_{csm}that a cross-section can endure prior to failure by (inelastic) local buckling and the adoption of a material model that allows for strain hardening.

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 $\overline{\lambda}_p$, where ε_y is the yield strain of the material equal to f_y/E, with f_y being the material yield strength and E being the Young's modulus. Within the CSM, the cross-section slenderness $\overline{\lambda}_p$ is defined in non-dimensional form as the square root of the ratio of the yield stress f_y to the elastic buckling stress σ_{cr}, as given by Eq. (1). The elastic buckling stress σ_{cr} should be determined for the full cross-section either using numerical methods, such as the finite strip software CUFSM [14], or approximate analytical methods [15]. As a conservative alternative, the elastic buckling stress of the full cross-section may be taken as that of

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its most slender element using the classical plate buckling expression [16]. The former approach considers plate element interaction effects within the cross-section, as used in the direct strength method [17], whereas the classical plate buckling expression assumes simply supported conditions at the edges of the adjoining plates, which neglects element interaction and generally results in a conservative prediction of σ_{cr}. More favourable results are 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 [14]. The CSM design base curve is given by Eq. (2), where ε_u is the strain corresponding to the ultimate tensile stress f_u. Two upper bounds have been placed on the predicted cross-section deformation capacity $\varepsilon_{csm}/\varepsilon_y$; the first limit of 15 corresponds to the material ductility requirement expressed in EN 1993-1-1 [18] and prevents excessive deformations and the second limit of $C_1\varepsilon_u/\varepsilon_y$, where C_1 is a coefficient corresponding to the adopted CSM material model as described in the next section, defines a 'cut-off' strain to prevent over-predictions of material strength. It is noted that the CSM does not currently apply to cross-sections where $\overline{\lambda}_p>0.68$, which is the boundary between slender and non-slender sections [9], though developments are underway in this area.

$$\overline{\lambda}_p = \sqrt{f_y/\sigma_{cr}} \tag{1}$$

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{0.25}{\overline{\lambda}_p^{\,3.6}} \text{ but } \frac{\varepsilon_{csm}}{\varepsilon_y} \le \min\left(15, \frac{C_1\varepsilon_u}{\varepsilon_y}\right) \tag{2}$$

2.2. Material model

An elastic, linear hardening material model has been adopted in the CSM to represent the strain hardening response of metallic materials, such as cold-formed steel, stainless steel and aluminium alloys. Despite the fact that the actual observed stress-strain response of these materials is rounded, the elastic, linear hardening CSM material model has been shown to capture the general strain hardening behaviour sufficiently well to enable accurate design capacity predictions [9,12,13]. However, this bi-linear material model is less suitable for hot-rolled carbon steel due to the presence of the characteristic yield plateau, with strain hardening not commencing until the attainment of the strain hardening strain ε_{sh}. Thus, a revised quad-linear material model, as illustrated in Fig. 1, is proposed for hot-rolled carbon steel considering both the length of the yield plateau and the strain hardening behaviour.

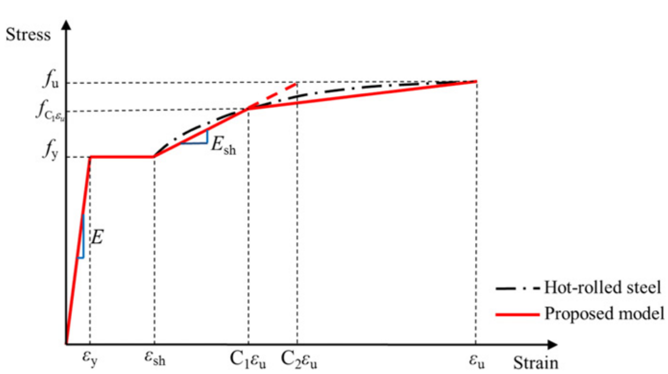

Fig. 1. Typical stress-strain curve for hot-rolled carbon steel and the proposed quad-linear material model.

The adopted stress-strain model consists of four stages and can be written over the full range of tensile strains as:

$$f(\varepsilon) = \begin{cases} E\varepsilon & \text{for } \varepsilon \le \varepsilon_y \\ f_y & \text{for } \varepsilon_y \le \varepsilon \le \varepsilon_{sh} \\ f_y + E_{sh}(\varepsilon - \varepsilon_{sh}) & \text{for } \varepsilon_{sh} \le \varepsilon \le C_1\varepsilon_u \\ f_{C_1\varepsilon_u} + \dfrac{f_u - f_{C_1\varepsilon_u}}{\varepsilon_u - C_1\varepsilon_u}(\varepsilon - C_1\varepsilon_u) & \text{for } C_1\varepsilon_u \le \varepsilon \le \varepsilon_u \end{cases} \tag{3}$$

in which $C_1\varepsilon_u$ represents the strain at the intersection point of the third stage of the model and the actual stress-strain curve, and $f_{C_1\varepsilon_u}$ is the corresponding stress, as shown in Fig. 1. Two material coefficients, C_1 and C_2, are used in the material model. C_1 represents the interaction point discussed previously and effectively defines a 'cut-off' strain to avoid over-predictions of material strength and is included in the base curve (Eq. (2)); C_2 is used in Eq. (4) to define the strain hardening slope E_{sh}.

$$E_{sh} = \frac{f_u - f_y}{C_2\varepsilon_u - \varepsilon_{sh}} \tag{4}$$

Coupon test data on hot-rolled carbon steels from a series of existing experimental programs [1,3,11,19–31] were collected and analyzed to establish predictive expressions for ε_u, ε_{sh} and the material coefficients C_1 and C_2.

For the strain at the ultimate tensile stress ε_u, a comparison between the collected test data and the predictive expression (Eq. (5)) is shown in Fig. 2. For hot-rolled carbon steels, ε_u decreases with increasing f_y/f_u initially, but once f_y/f_u is greater than a value of about 0.9 (normally for high strength steels), ε_u remains almost constant. The expression for ε_u provides good average predictions of the test data, with a mean ratio of the predicted to test values of ε_u being 0.96, and a moderate coefficient of variation (COV) of 0.25. Test data for high strength hot-rolled carbon steel are fairly scarce and more test data are required to further verify Eq. (5).

$$\varepsilon_u = \begin{cases} 0.6\left(1 - \dfrac{f_y}{f_u}\right) & \text{for } \dfrac{f_y}{f_u} \le 0.9 \\ 0.06 & \text{for } 0.9 < \dfrac{f_y}{f_u} \le 1 \end{cases} \tag{5}$$

The collected coupon test data for strain hardening strain ε_{sh} is plotted against the ratio of f_y/f_u in Fig. 3, together with the full cross-section tensile test data reported by Wang et al. [23] and Foster and Gardner

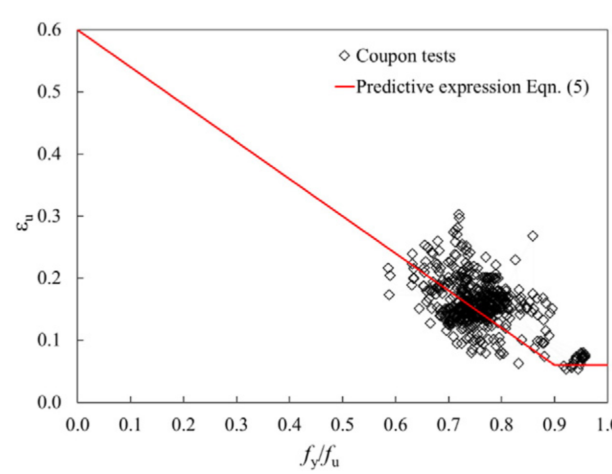

Fig. 2. Predictive expression for ε_u for hot-rolled carbon steels.