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Deformation-based design of stainless steel cross-sections in shear

N.G. Saliba[a], L. Gardner[b,*]

[a] University of Balamand, Lebanon
[b] Imperial College London, UK

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ABSTRACT

The continuous strength method (CSM) is a recently developed deformation-based design method for metallic structures. In this method, cross-section classification is replaced by a normalized deformation capacity, which defines the maximum strain that a cross-section can endure prior to failure. This limiting strain is used in conjunction with an elastic, linear-hardening material stress-strain model to determine cross-section capacity allowing for the influence of strain hardening. To date, the CSM has been developed for the determination of cross-section capacity under normal stresses (i.e. compression, bending and combined loading), where it has been shown to offer more accurate predictions than current codified methods. In this paper, extension of the CSM to the determination of shear resistance is described. The relationship between the normalized shear deformation capacity, referred to as the shear strain ratio, and the web slenderness is first established on the basis of experimental and numerical data. The material model and proposed resistance functions are then described. Comparisons of the developed method with the ultimate shear capacity of a series of tested stainless steel plate girders show that improved resistance predictions of test capacity over current design methods are achieved.

1. Introduction

The current codified approach for the calculation of the compression, bending and shear resistances of stainless steel cross-sections has been observed throughout published studies [1–6] to be conservative in the cases of elements of low slenderness. This may be attributed to: (1) the assignment of cross-sections to discrete behavioural classes and (2) assuming the maximum attainable stress is the 0.2% proof stress f_y (i.e. an elastic, perfectly plastic approximation to the material stress-strain curve and ignoring strain hardening). With initial cost and hence design efficiency being of paramount importance in the selection of stainless steel for main structural components, the application of more sophisticated design methods, exploiting the true material behaviour, such as the continuous strength method (CSM), is considered to be warranted.

Following the successful application of the CSM to stainless steel cross-sections under compression, bending and combined loading [1–6], this paper presents developments of the method towards its extension to the calculation of shear resistance. A review of the key components of the CSM is first presented. Test and numerical data collected from Saliba and Gardner [7] and Saliba et al. [8] have been utilized to establish the preliminary shear base curve and subsequently the CSM shear design equations. The effect of applying the CSM to estimate the shear resistance and bending resistance of plate girders has been evaluated considering two scenarios: (1) the web contribution to the shear resistance calculated according to the EN 1993-1-4 [8,9] design equations but the flange contribution and the bending resistance of the cross-section calculated with allowance for strain hardening according to the CSM and (2) both web and flange contributions to the shear resistance determined using the CSM for shear presented herein and the bending resistance also calculated according to the CSM.

2. Literature review

Initial research into the shear resistance of slender plate girders, carried out by Bleich [10] and later by Basler et al. [11,12], assumed that a theoretical tension field extending over the whole depth of the web is formed once shear buckling occurs. The shear resistance of plate girders was considered accordingly as the sum of the buckling and postbuckling resistances of the web only, ignoring the flange contribution. This approach was found by Calladine [13] and Porter et al. [14] to be conservative, and was developed further by Rockey et al. [15,16] to improve its accuracy, though shortcomings remained for the case of plate girders with widely spaced transverse web stiffeners.

ENV 1993-1-1 (1992) [17] allowed the calculation of shear resistance for carbon steel plate girders using either the tension field method or the simple post critical method [18], though these two methods were replaced [19–21] by improved design equations in the final EN standard. The current design equations for shear buckling for

* Corresponding author.
E-mail address: leroy.gardner@imperial.ac.uk (L. Gardner).

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carbon steel sections, included in EN 1993-1-5 [22], are based on the rotated stress field method developed by Höglund [19,23,24]. The rotated stress field method accounts for the postbuckling shear strength of both unstiffened and stiffened webs and takes into consideration the flange contribution.

In EN 1993-1-5 [22], the ultimate shear resistance $V_{b,Rd}$ is defined as the sum of the web shear buckling resistance $V_{bw,Rd}$ and the flange contribution $V_{bf,Rd}$ as given in Eq. (1).

$$V_{b,Rd} = V_{bw,Rd} + V_{bf,Rd} \leq \frac{\eta f_{yw} h_w t_w}{\sqrt{3}\gamma_{M1}} \tag{1}$$

where the influence of strain hardening is considered through the parameter η, h_w is the web depth, t_w is the web thickness, f_{yw} is the yield strength of the web, and γ_{M1} is a partial safety factor.

The web contribution $V_{bw,Rd}$ is given by Eq. (2):

$$V_{bw,Rd} = \frac{\chi_w f_{yw} h_w t_w}{\sqrt{3}\gamma_{M1}} \tag{2}$$

where χ_w is the web shear buckling reduction factor.

The flange contribution $V_{bf,Rd}$ is defined by Eq. (3):

$$V_{bf,Rd} = \left(\frac{b_f t_f^2 f_{yf}}{c\gamma_{M1}}\right)\left(1-\left(\frac{M_{Ed}}{M_{f,Rd}}\right)^2\right) \tag{3}$$

in which b_f is the overall flange width, t_f is the flange thickness, f_{yf} is the yield strength of the flange, M_{Ed} is the coexistent design bending moment, $M_{f,Rd}$ is the moment resistance of the flanges alone and finally, the longitudinal distance of the plastic hinges that form in the flanges from the transverse stiffeners, c, is given by Eq. (4):

$$c = \left(0.25 + \frac{1.6 b_f t_f^2 f_{yf}}{t_w h_w^2 f_{yw}}\right)a \tag{4}$$

where a is the distance between the transverse stiffeners.

The interaction between shear and bending moment commonly arises in practice and has been the subject of numerous studies [10,11,25–29]. EN 1993-1-5 (2006) [22] prescribes a reduced bending resistance when the coexistent shear force exceed 50% of the shear resistance.

For stainless steel, the first codified shear resistance design equations were presented in the prestandard ENV 1993-1-4 (1996) [30]. The equations were developed on the basis of an experimental study carried out by Carvalho et al. [31] and the simple post critical method of ENV 1993-1-1 (1992) [17], with adjustments to account for the particular nonlinear material characteristics of stainless steel. These equations were later shown by Olsson [32] to be conservative and revised equations were included in the final EN standard, EN 1993-1-4 (2006) [33]. The improved shear design equations were based on the rotated stress field method and are of similar form to those given in EN 1993-1-5 (2006) [22], but with modified functions for the shear buckling reduction factor χ_w, no differentiation between rigid and non-rigid end posts, and an alternative definition of the distance c, as given in Eq. (5).

$$c = \left(0.17 + \frac{3.5 b_f t_f^2 f_{yf}}{t_w h_w^2 f_{yw}}\right)a \text{ with } \frac{c}{a} \leq 0.65 \tag{5}$$

Further improvements to the design rules were proposed in [34–36] and most recently by Saliba et al. [8], who considered an enlarged pool of experimental data and introduced a distinction between web panels with rigid and non-rigid end posts. These proposed equations are presented in Table 1, and, following a recent amendment, are now incorporated into EN 1993-1-4:2006+A1:2015 [9].

Table 1
Web shear buckling reduction factor χ_w.

	χ_w for rigid end post	χ_w for non-rigid end post
$\bar{\lambda}_w \leq 0.65/\eta$	η	η
$0.65/\eta < \bar{\lambda}_w < 0.65$	$0.65/\bar{\lambda}_w$	$0.65/\bar{\lambda}_w$
$\bar{\lambda}_w \geq 0.65$	$1.56/(0.91+\bar{\lambda}_w)$	$1.19/(0.54+\bar{\lambda}_w)$

3. The CSM for the determination of compression and bending resistances

3.1. Overview

The continuous strength method (CSM) [1] is a recently developed method which offers an alternative approach to calculating the resistance of metallic cross-sections. Contrary to the traditional approach which assumes elastic, perfectly plastic material behaviour, the CSM allows exploitation of material strain hardening, such as that exhibited by stainless steel and aluminium. The CSM considers local buckling in the elastic or inelastic range and the associated limiting strain to be the key physical restriction to the exploitation of the spread of plasticity and strain hardening of the material. Hence, the maximum attainable failure stress of a stainless steel cross-section is considered as a continuous function of the material properties, the geometry of the cross-section and the imposed loading, rather than simply a material specific stress (i.e. the yield stress).

The CSM deviates from traditional cross-section classification by adopting a continuous relationship between cross-sectional slenderness and deformation capacity. The deformation capacity of the cross-section is determined from an experimentally derived 'base curve' which links the limiting strain at failure due to local buckling ε_{csm} to the cross-section slenderness [1]. The stress corresponding to this limiting failure strain, is then determined from the material model, which incorporates strain hardening.

A detailed description of the development of the CSM and its successful application to stainless steel, aluminium alloys, high strength steel and carbon steel is presented in [1,38–40], while the most recent developments and improvements to the method are presented in Gardner et al. [3], Afshan and Gardner [6] and Zhao et al. [41].

3.2. Deformation capacity

The local cross-section slenderness is defined in the CSM through Eq. (6):

$$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} \tag{6}$$

where f_y is the material yield (0.2% proof) stress and σ_{cr} is the elastic buckling stress of the full cross-section as used in the direct strength method (DSM) [42], or conservatively, of the most slender constituent plate element.

The deformation capacity $\varepsilon_{csm}/\varepsilon_y$, according to the CSM, is defined by the base curve, given by Eqs. (7) and (8) for non-slender ($\bar{\lambda}_p \leq 0.68$) and slender ($\bar{\lambda}_p > 0.68$) cross-sections, respectively [6,41]:

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{0.25}{\bar{\lambda}_p^{3.6}} \text{ but } \frac{\varepsilon_{csm}}{\varepsilon_y} \leq \min\left(15, \frac{C_1\varepsilon_u}{\varepsilon_y}\right) \text{ for } \bar{\lambda}_p \leq 0.68 \tag{7}$$

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \left(1 - \frac{0.222}{\bar{\lambda}_p^{1.050}}\right)\left(\frac{1}{\bar{\lambda}_p^{1.050}}\right) \text{ for } \bar{\lambda}_p > 0.68 \tag{8}$$

where $\varepsilon_y = f_y/E$ is the yield strain of the material, E is the Young's modulus, ε_{csm} is the CSM limiting strain for the cross-section, and ε_u is the strain at the ultimate tensile stress, which can be approximated from $\varepsilon_u = C_3(1 - f_y/f_u)$; C_1 and C_3 are material parameters taken as C_1