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COMPRESSION CAPACITY OF SLENDER STAINLESS STEEL CROSS-SECTIONS

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The Continuous Strength Method (CSM) is a new strain based design approach developed for nonlinear metallic materials, and has recently been successfully used for stocky stainless steel sections for which the benefit of strain hardening is more pronounced. Typically available stainless steel cross-sections are quite slender, and their failure is dominated by local plate buckling before yielding showing significant post buckling, which does not allow the definition of cross-section deformation capacity currently adopted in CSM. In this paper, a concept of equivalent elastic deformation capacity is introduced for slender sections, and the scope of CSM is extended to predict capacities for slender cross-sections under compression. Design guidelines are proposed to calculate equivalent elastic deformation capacities for various cross-section types using the current knowledge of CSM, which is used to predict the ultimate section capacity when subjected to compression. The proposed rules are verified against all available test results, and are found to in good agreement with experimental evidence.

Keywords: Continuous strength method, Cross-section slenderness, Cross-section capacity, Deformation capacity, Equivalent elastic deformation capacity, Local buckling.

1 INTRODUCTION

Stainless steel sections have been increasingly used for its superior material properties such as corrosion resistance, higher strength, significantly lower maintenance and attractive appearance. Despite its obvious advantages over its traditional counterpart ordinary carbon steel, its usage in structures has been limited primarily due to the lack of appropriate design guidance making optimum utilization of its beneficial properties. Effective width method similar to carbon steel design is the current codified approach to deal with the local buckling of stainless steel cross-sections although there is obvious difference in their material response. SEI/ASCE-8 (2002) and AS/NZS 4673 (2001) have set a limiting cross-section slenderness value of 0.673 below which effective cross-section has to be considered. Eurocode (EN 1993-1-4, 2006) classifies stainless steel cross-sections into four distinct classes with Class 4 being slender. A series of limits for the width-to-thickness ratios (b/t), in terms of the material properties, edge support conditions (i.e., internal or outstand) and the form of the applied stress field, are provided. This kind of discrete classification is suitable for carbon steel as its stress-strain behavior is elastic, perfectly-plastic with clearly defined yield point beyond which instability is triggered by sudden drop of material stiffness. On the other hand stainless steel shows continuous rounded stress-strain response with no definite yield point, which demands a continuous approach to treat its local buckling phenomenon.

The Continuous Strength Method (CSM) is a strain based design approach where local buckling of nonlinear metallic cross-sections is treated as a continuous function, and can explore the benefits of stain hardening. Primary components of CSM are a base curve which relates the deformation capacity of the section and a material model that explicitly recognizes strain hardening. Gardner and Nethercot (2004) first proposed an explicit relationship between cross-sectional slenderness and cross-sectional deformation capacity as a design base curve for stainless steel hollow sections. Ashraf *et al.* (2006) extended the concept to include open sections and proposed a generalized technique for all typical cross-section types, which was late modified by Gardner and Theofanous (2008). In all previous techniques, a two stage Ramberg–Osgood equation, in a number of different formats, were used to find the local buckling stress from the obtained deformation capacity. Recently Afshan and Gardner (2013) proposed CSM guidelines for stocky cross-sections with a simple elastic, linear hardening material model, which produce accurate and consistent predictions at the cross-section level for stocky sections. Simplified material model also makes CSM more practical by avoiding tedious iterations.

However, it is worth mentioning that most of the available cross-sections are quite slender and the recent simplification of CSM is not valid for slender sections. This paper attempts to extend the scope of CSM for slender cross-sections. Hollow sections (RHS and SHS) and open sections (Channel, Lipped Channel and I-section) are considered in this study. A new parameter called Equivalent elastic deformation capacity $\varepsilon_{e,ev}$ is introduced to characterize the deformation capacity for slender sections. All available stub column test results are used to establish relationships between the cross-section deformation capacity of CSM ε_{csm} and the proposed equivalent elastic deformation capacity $\varepsilon_{e,ev}$. The simplified material model proposed by Afshan and Gardner (2013) is used to calculate the cross-section resistance. Overall, the proposed technique produces accurate and consistent predictions for compression resistance of slender sections.

2 CSM FOR STOCKY SECTIONS

Afshan and Gardner (2013) recently proposed a new set of CSM formulation for stocky sections, which is defined by a limit of 0.68 for cross-section slenderness $\bar{\boldsymbol{\lambda}}_{\mathbf{p}}$. CSM is a strain based design approach where a design base curve defines the continuous relationship between the cross-section deformation capacity (i.e., buckling strain at ultimate load) and $\bar{\boldsymbol{\lambda}}_{\mathbf{p}}$. For a given section, the elastic buckling capacity of the full cross-section ($\sigma_{cr,cs}$) is used to calculate $\bar{\boldsymbol{\lambda}}_{\mathbf{p}}$, as shown in Eq. (1) where $\sigma_{0.2}$ is the 0.2% proof stress. $\sigma_{cr,cs}$ may be determined using existing numerical (CUFSM) or approximate analytical methods (Seif and Schafer, 2010).

$$\bar{\lambda}_{\mathrm{p}}=\sqrt{\frac{\sigma_{0.2}}{\sigma_{cr,cs}}} \tag{1}$$

Afshan and Gardner's (2013) proposed elastic, linear hardening material model has its origin at (0.002, 0), and the yield point is defined at (f_y, ε_y) where f_y is equivalent to 0.2% proof stress ($\sigma_{0.2}$) and ε_y is the corresponding elastic strain. The slope of the strain hardening curve is taken as the slope of the line passing through the yield point and a specified point (ε_{max}, f_{max}) where ε_{max} is taken as $0.16\varepsilon_u$ and f_{max} is taken as the ultimate tensile stress σ_u. To be compatible with the adopted material model, the deformation capacity ε_{csm} is obtained by subtracting the plastic strain at $\sigma_{0.2}$ from the actual local buckling strain. The normalized deformation capacity is expressed as a function $\bar{\lambda}_p$ up to the limiting slenderness 0.68 with two upper boundaries as expressed in Eq. (2).

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{0.25}{\bar{\lambda}_p^{3.6}} \quad \text{but} \quad \frac{\varepsilon_{csm}}{\varepsilon_y} \leq 15, \frac{0.1\varepsilon_u}{\varepsilon_y} \tag{2}$$

Once the normalized deformation capacity $\varepsilon_{csm}/\varepsilon_y$ is obtained from the design base curve, the limiting buckling stress f_{csm} for the cross-section with $\bar{\lambda}_p \leq 0.68$ can be calculated using Eq. (3). Hence the cross-section capacity in compression may be estimated using Eq. (4) where A_g is the gross cross-section area and γ_{M0} is the material partial safety factor as recommended in the code.

$$f_{csm} = f_y + E_{sh}\varepsilon_y\left(\frac{\varepsilon_{csm}}{\varepsilon_y} - 1\right), \text{where} \quad E_{sh} = \frac{\sigma_u - \sigma_y}{0.16\varepsilon_u - \varepsilon_y} \quad \text{and} \quad \varepsilon_u = 1 - \frac{\sigma_y}{\sigma_u} \tag{3}$$

$$N_{c,Rd} = \frac{f_{csm}A_g}{\gamma_{M0}} \tag{4}$$

3 CSM FOR SLENDER SECTIONS

Failure of slender sections is typically dominated by elastic local buckling, which takes place before material yielding but significant post buckling behavior is observed, which produces erroneous results if the current definition of ε_{csm} is directly applied for slender sections. Hence, the concept of using an Equivalent elastic deformation capacity $\varepsilon_{e,ev}$ is introduced in this paper. Equivalent elastic deformation capacity is defined by the elastic strain at ultimate load as shown in Figure 1 and can be calculated by Eq. (5) where N_u is the ultimate load of a stub column, E is the Young's modulus and A_g is the gross cross-sectional area.

$$\varepsilon_{e,ev} = \frac{N_u}{EA_g} \tag{5}$$

Relationship between the $\varepsilon_{e,ev}$ and ε_{csm} is established through Eq. (6) where C is a constant that depends on cross-section slenderness of the section $\bar{\lambda}_p$ but varies for section types. Eq. (7) shows the proposed expression to predict C for a given cross-section, where a and b are two constants that depends on cross-section types.

$$\varepsilon_{e,ev} = C\varepsilon_{csm} \quad \text{for} \quad \bar{\lambda}_p > 0.68 \tag{6}$$

$$C = a\bar{\lambda}_p^{\,b} \tag{7}$$

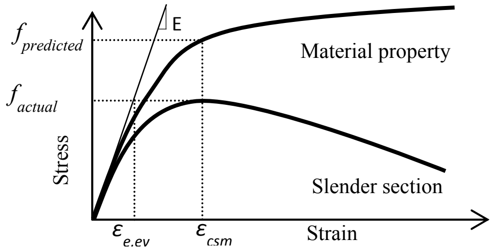

Figure 1. Typical post buckling behavior observed for slender sections.

Test results on 109 slender stub columns with different cross-section types i.e., channel, lipped channel, I-section, RHS and SHS as obtained from available literatures (Rasmussen and Hancock 1993, Talja and Salmi 1995, Stangenberg 2000, Kuwamura 2003, Liu and Young 2003, Young and Liu 2003, Gardner and Nethercot 2004, Young and Lui 2005, Gardner *et al*. 2006, Lecce and Rasmussen 2006, Becque and Rasmussen 2009, Theofanous and Gardner 2009, Saliba and Gardner 2013, Yuan *et al*. 2014) have been used in this study. Five different sets of values for *a* and *b* are proposed for different cross-section types as shown in Table 1. In addition, all cross-section types were considered together to obtain a common set of values for *a* and *b*. Observed typical variation of *C* with respect to $\bar{\lambda}_p$ are shown in Figure 2.

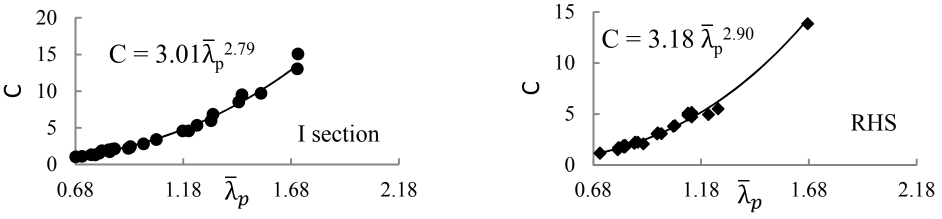

Figure 2. Variation of C with cross-section slenderness ratio $\bar{\lambda}_p$.

Table 1. Values of the coefficient *a* and *b* for different types of cross-sections.

Section Types	***a***	***b***
Channel Section	2.75	2.83
Lipped Channel Section	3.04	3.15
I Section	3.01	2.79
Square Hollow Section (SHS)	2.85	2.50
Rectangular Hollow Section (RHS)	3.18	2.90
All Cross-section types	3.03	2.83

The current base curve and material model proposed by Afshan and Gardner (2013) are adopted herein for the full range of cross-section slenderness. Having determined $\varepsilon_{e,ev}$, the buckling stress f_{csm} for slender sections with $\bar{\lambda}_p > 0.68$ can be calculated by multiplying the $\varepsilon_{e,ev}$ with young's modulus E as given by Eq. (8) and the cross-section compression resistance $N_{c,Rd}$ may be estimated by Eq. (4). This approach clearly eliminates the need for going through the lengthy process of calculating effective cross-sectional properties for slender cross-sections.

$$f_{csm} = \varepsilon_{e,ev} E = C \varepsilon_{csm} E \text{ for } \bar{\lambda}_p > 0.6 \tag{8}$$

4 PERFORMANCE OF THE PROPOSED DESIGN TECHNIQUE

The performance of the proposed method is compared against the considered 109 stainless steel stub column test results, which essentially demonstrated good agreement as shown in Table 2. Compression resistances are also predicted using the current Eurocode design rules and the comparisons for I sections and RHS are shown in Figure 3. It is observed that the proposed CSM technique for slender sections offers slightly improved mean resistance with reduced scatter but more importantly this make CSM applicable for full range of cross-sections.

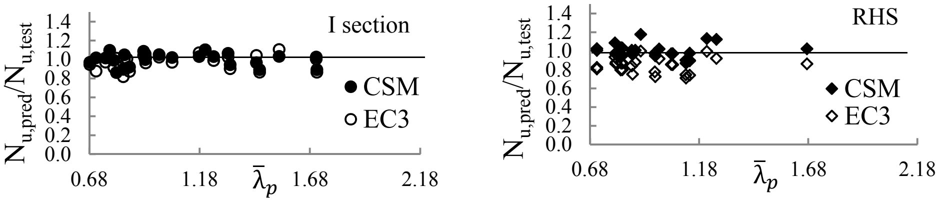

Figure 3. Comparison of the stub column tests with the CSM and Eurocode predictions.

Table 2. Comparison of CSM and Eurocode predictions of section capacity with stub column test results.

Section Type	C according to section types		Single C for all section types		EC3	
	Average N_{csm}/N_{test}	COV	Average N_{csm}/N_{test}	COV	Average N_{EC}/N_{test}	COV
Channel	1.001	0.040	1.098	0.041	1.135	0.071
Lipped C	1.000	0.048	0.997	0.074	0.963	0.066
I Section	0.999	0.070	0.996	0.070	0.978	0.076
SHS	1.002	0.115	1.016	0.137	0.793	0.149
RHS	1.000	0.073	0.948	0.075	0.845	0.092
All Sections	-	-	0.995	0.094	0.896	0.129

5 CONCLUSION

The Continuous Strength Method (CSM) is a rational strain based approach, and has recently been simplified for stocky stainless steel sections. Typically available stainless steel sections are quite slender, and hence the current paper extends the scope of the proposed CSM technique for slender stainless steel sections with $\bar{\lambda}_p$>0.68. A new parameter, Equivalent elastic deformation capacity $\varepsilon_{e,ev}$, is introduced to include significant post-buckling effects demonstrated by slender sections. All available stub column tests on various cross-section types are used to propose simple yet accurate relationships to obtain the ultimate strain for slender sections, which is later used to determine the corresponding failure stress using a simplified material model. The performance of the proposed technique is compared against those obtained in tests as well as those predicted by Eurocode. Overall, the predictions show good agreement with test results, and are marginally more accurate and consistent than Eurocode predictions. The proposed design technique paves the way for turning CSM into a complete design tool for stainless steel without lending itself to the lengthy traditional process of calculating effective cross-sectional properties for slender sections.

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