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Numerical investigation on buckling resistance of stainless steel hollow members

Shameem Ahmed, Mahmud Ashraf*

School of Engineering and Information Technology, The University of New South Wales, Canberra, Australia

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ABSTRACT

Structural stainless steel requires appropriate recognition of its beneficial properties such as material nonlinearity and significant strain hardening. The Continuous Strength Method (CSM) exploits those benefits through a strain based approach for both stocky and slender cross-sections. In this paper, a new design method is proposed that combines the CSM design principles with Perry type buckling curves for stainless steel square and rectangular hollow sections (SHS and RHS) subjected to compression. Numerical models were developed to investigate effects of various parameters on column strength and to develop complete column curves for hollow members. It was observed that cross-section slenderness λ_p and material properties such as non-dimensional proof stress e and strain hardening exponent n significantly influence column resistances. Effects of e and n were appropriately incorporated through introduction of correction factors to modify non-dimensional member slenderness. It was observed that the shapes of column curves were mostly affected by λ_p, and hence imperfection parameter η, as used in Perry formulations, was expressed as a function of λ_p; this technique yielded separate column curves for different λ_p values. The proposed method includes the strain hardening benefits for stocky sections, and abolished the necessity of calculating effective cross-sectional properties for slender sections. Performance of the proposed technique is compared against those obtained by using the European guidelines.

1. Introduction

The structural response of stainless steel is considerably different from ordinary carbon steel as its stress-strain response has characteristic nonlinearity with significant stain hardening, which also varies significantly between grades. Despite the absence of any yield point, current design codes [1–3] treat stainless steel as an elastic, perfectly-plastic material like carbon steel, and the effective width approach with cross-section classification is mostly adopted to account for local buckling. Without appropriate incorporation of its material nonlinearity as well as strain hardening benefits, an efficient design technique for stainless steel design cannot be achieved. The Continuous Strength Method (CSM) [4–9] was developed to exploit these unique properties through a strain based design method that can appropriately include element interactions in predicting cross-sectional resistances. Primary components of CSM are a base curve which relates the deformation capacity of the section to cross-section slenderness, and a material model that explicitly recognises strain hardening. With the recent development of CSM [8,9], cross-section resistances for both stocky and slender sections can be predicted using simple formulations. With its demonstrated accuracy at the cross-section level, the current paper extends this design concept in predicting the buckling capacity of stainless steel columns.

Two fundamentally different approaches i.e. tangent stiffness method and Perry formulations are typically used for obtaining the buckling resistance of stainless steel columns. The tangent stiffness method [2,3] involves simple equations and takes account of material nonlinearity, but the process is iterative and does not consider the inevitable imperfections of the member. Perry curves that are currently adopted in Eurocode [1], use a direct method involving separate curves for different cross-section types, and explicitly address the imperfection of members but do not include material nonlinearity. Rasmussen and Rondal [10] showed that material nonlinearity and non-dimensional proof stress significantly influence column strength, and a single column curve cannot be used to accurately predict the column strength of different grades of stainless steel. Hradil et al. [11] suggested techniques to include material nonlinearity in Perry curves by defining transformed slenderness but the procedure was iterative as they used tangent modulus. Shu et al. [12] recently proposed two base curves and a number of transfer equations which could be used to develop multiple

* Corresponding author.
E-mail addresses: Shameem.Ahmed@student.adfa.edu.au (S. Ahmed), Mahmud.Ashraf@unsw.edu.au (M. Ashraf).

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Notations

A, B, W	coefficients of sigmoidal function
A_{eff}	effective cross-section area
A_g	gross cross section area
C_e	correction factor for e
C_n	correction factor for n
E	initial young's modulus
E_{sh}	slope of the linear hardening section of the bi-linear material model
L	effective length of a column
N_{cr}	elastic buckling load of the column based on gross cross-section area
N_u	ultimate capacity of a column
e	non-dimensional proof stress
f_y, $\sigma_{0.2}$	material yield stress
f_{csm}, σ_{LB}	buckling stress
n	material strain hardening exponent
α, λ_0, β, λ_1	imperfection factors
ε_{csm}	deformation capacity of a cross-section
$\varepsilon_{e,ev}$	equivalent elastic strain at ultimate load
ε_u	material total strain at ultimate strength
ε_y	material elastic strain at yield stress
η	imperfection parameter
λ	member slenderness based of yield stress
λ^*	transformed member slenderness
λ_{csm}	member slenderness based on buckling stress
λ_m	modified member slenderness
λ_p	cross-section slenderness
$\sigma_{cr.cs}$	elastic buckling stress of full cross-section
χ	buckling reduction factor

curves to cover all grades of stainless steel but the suggested formulations are too complicated to be used in practice. Importantly, all of the aforementioned techniques use effective area for slender cross-sections. Huang and Young [13] suggested obtaining material properties measured by using stub column tests instead of coupons so that gross cross sectional area could be used to predict the column capacity; this approach should produce better predictions but stub column results are not always available to be readily used for design purposes.

The objective of this study was to develop a simple design method to calculate the buckling resistance of stainless steel hollow sections i.e. square hollow section (SHS) and rectangular hollow section (RHS) that can appropriately reflect the characteristics of stainless steel. Nonlinear Finite Element (FE) models were developed and verified using available test results as part of the current study. A comprehensive parametric study was carried out to identify the parameters that affect buckling resistance. Generated numerical results were used to develop Perry type column curves based on CSM design principles so that material nonlinearity and strain hardening properties could be incorporated without changing the basic forms of the currently used equations. Multiple curves were proposed that integrate all influential parameters to cover a wide range of stainless steel grades, and finally, the accuracy of the proposed method was verified.

2. Current design methods for predicting buckling resistance

Tangent stiffness method and Perry-Robertson formulations are widely used to determine the buckling resistance of steel columns. Similar to carbon steel, Eurocode (EC3) [1] adopted the Perry type equations for stainless steel columns. Buckling equations currently used in EC3 are presented in Eqs. (1)–(5), where A_g is the gross cross-sectional area, f_y is the 0.2% proof stress ($\sigma_{0.2}$), χ is the buckling reduction factor, A_{eff} is the effective cross-sectional area, λ is the non-dimensional slenderness of the column and N_{cr} is the elastic buckling load of the column based on gross area. A number of column curves were proposed for different cross-section and loading types such as major and minor axis buckling of closed and open sections. Suggested imperfection parameter η is expressed using a linear relationship, $\eta = \alpha(\lambda - \lambda_0)$ where α and λ_0 factors vary depending on cross-section types. Stainless steel is a highly nonlinear material and its nonlinearity significantly varies from grade to grade, which is not recognised in current EC3 guidelines for column resistance. American and Australian codes [2,3], on the other hand, follows tangential stiffness approach which is based on the Euler formula. This method involves a simple equation but the process is iterative as it uses the instantaneous tangent modulus (E_t), which considers material nonlinearity but member imperfection is not considered in the whole process. To overcome the shortcomings of the codes, Rasmussen and Rondal [10], Hradil et al. [11] and Shu et al. [12] tried to incorporate material nonlinearity in the column curves, which are discussed below.

$$N_u = \chi A_g f_y \quad \text{for Class 1, 2 and 3 cross-sections} \tag{1}$$

$$N_u = \chi A_{eff} f_y \quad \text{for Class 4 cross-sections} \tag{2}$$

$$\lambda = \sqrt{\frac{A_g f_y}{N_{cr}}} \quad \text{for Class 1, 2 and 3 cross-sections} \tag{3}$$

$$\lambda = \sqrt{\frac{A_{eff} f_y}{N_{cr}}} \quad \text{for Class 4 cross-sections} \tag{4}$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} \le 1.0$$
$$\text{where,} \phi = 0.5[1 + \eta + \lambda^2] \tag{5}$$

Rasmussen and Rondal [10] numerically investigated the buckling behaviour of nonlinear metallic columns, and showed that proof stress and material nonlinearity have significant effects on column curves. Considering these effects, Rasmussen and Rondal [10] modified the imperfection parameter η into a nonlinear function as shown in Eq. (6), and parameters α, β, λ_1 and λ_0 were expressed as functions of non-dimensional proof stress e ($= \sigma_{0.2}/E$) and strain hardening exponent n. This modification allowed incorporating the material parameters as well as geometric imperfections in column curves. The performance of their proposed formula was very good but too complex to be used in design practice. Australian code [3] adopted this method as an alternative approach by proposing values of α, β, λ_1 and λ_0 for some selective grades of stainless steel.

$$\eta = \alpha((\lambda - \lambda_1)^{\beta} - \lambda_0) \tag{6}$$

Hradil et al. [11] observed that traditional tangent stiffness method and Perry formulations do not appropriately consider geometric imperfections and material nonlinearity. They suggested to incorporate material nonlinearity in Perry formulas by modifying the non-dimensional slenderness λ; a new parameter called transformed slenderness (λ^*) was proposed as shown in Eq. (7) where n is the material strain hardening exponent, E_0 is the initial Young's Modulus and χ is the buckling reduction factor as given in Eq. (5). They recalibrated the imperfection factors α and λ_0 given in EC3 for different sets of material properties. But this method requires iteration as the transformed slenderness and the reduction factor depend on each other.

$$\lambda^* = \lambda\sqrt{1 + .002n\frac{E_0}{\sigma_{0.2}}\chi^{n-1}} \tag{7}$$

Shu et al. [12] observed the effect of non-dimensional proof stress e and strain hardening exponent n on flexural buckling capacity of