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Resistance of stainless steel CHS columns based on cross-section deformation capacity

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Abstract

A conceptually new structural design approach has recently been proposed by the authors to predict the resistance of stainless steel members subjected to various types of loading with cross-sections formed from thin flat plates including angles, channels, lipped channels, I-sections and rectangular hollow sections (RHS). The proposed method does not follow the traditional cross-section classification approach, which primarily relies on the assumption of a bilinear, elastic–perfectly-plastic material model. Instead, deformation capacity of a cross-section is determined directly from the local buckling characteristics of the constituent plate elements. This is then used to obtain the corresponding local buckling stress utilising an appropriate material model. This basic concept is extended herein to predict compression resistance of stainless steel columns with circular hollow sections (CHS). Available test and finite element (FE) results have been used to develop the basic design equation to predict the compression resistance of cross-sections and to propose column curves to determine flexural buckling resistances. The predicted resistances have been compared to those obtained using the current Eurocode; the predictions are significantly more accurate and more consistent than those given by the existing Eurocode.

Keywords: Circular hollow section (CHS); Columns; Compression resistance; Cross-section slenderness; Deformation capacity; Flexural buckling; Stainless steel; Stub column

1. Introduction

Stainless steel has a number of established benefits over carbon steel, but attracts a higher material cost [1]. There is therefore greater incentive for structural design processes to utilise the available strength to the full. Largely due to a lack of data, the custom to date [2,3] has been to adapt procedures for carbon steel with little regard for differences in the behaviour of stainless steel components. Recently, the authors have incorporated several special features of stainless steel – the rounded stress–strain curve and greater strength in the corner regions – in a new approach that provides more accurate and more consistent predictions of performance than do current Codes [4]. To date the procedure has been almost exclusively restricted to cross-sections composed of an assembly of flat plates. However, the method is general in concept and is extended herein, following the proposals of Gardner and Nethercot [5], to deal with the circular hollow sections (CHS). Although the approach is validated only for CHS cross-sections in compression and for axially loaded CHS columns, the general principles are capable of application to more general loading arrangements [4] and to closed sections having more general shapes; the absence of suitable experimental and numerical results currently prevents that generalisation.

2. Tests performed on CHS columns

All available stainless steel CHS column tests have been considered in this paper to devise a basic design curve giving the relationship between deformation capacity and slenderness of cross-sections and to validate subsequent design rules, following the approach proposed by Gardner and Nethercot [5]. A brief overview of each set of tests follows. Rasmussen and Hancock [6] conducted tensile and compressive tests on

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Table 1
Tests available from previous research on stainless steel CHS columns

Reference	No. of specimens		Stainless steel grade	Cross-section slenderness β
	Stub column	Long column		
Rasmussen and Hancock [6]	3	4	EN 1.4306	0.032–0.035
Talja [7]	3	6	EN 1.4435, EN 1.4541	0.026–0.051
Gardner and Nethercot [10]	4	–	EN 1.4301	0.060–0.106
Young and Hartono [8]	3	12	EN 1.4301	0.020–0.034
Bardi and Kyriakides [12]	20	–	EN 1.4410	0.034–0.084
Lam and Roach [13]	2	–	EN 1.4401	0.012–0.056

material coupons and buckling tests on stainless steel SHS and CHS produced from austenitic grade EN 1.4306 material. Talja [7] reported tests performed on welded I-section and CHS beams, columns and beam-columns. Tensile tests were carried out on coupons cut from the specimens, which were produced from austenitic grade EN 1.4435 material. Young and Hartono [8] conducted a series of tests on stainless steel CHS fixed-ended columns produced from austenitic grade EN 1.4301 material. Average results obtained from the supporting tensile tests on material coupons were also reported. Gardner [9] carried on an extensive testing programme involving tubular stainless steel beams and columns. All tested SHS, RHS and CHS sections were produced from austenitic grade EN 1.4301 material. The stress–strain characteristics of the material under both compression and tension were also investigated. All relevant experimental results were reported by Gardner and Nethercot [10,11]. Recently, Bardi and Kyriakides [12] carried out compression tests on stainless steel CHS stub columns with varying diameter-to-thickness ratios. Average material properties for duplex grade EN 1.4410 material obtained from tensile coupon tests were also reported. Lam and Roach [13], as a part of their testing scheme on concrete filled stainless steel tubes, performed compression tests on 2 unfilled stainless steel CHS stub columns. Tensile material tests were conducted on coupons cut from the austenitic grade EN 1.4401 tubes. From the experimental programmes summarised above, a total of 35 fixed-ended stub column test results were collated.

Cross-section slenderness β for each of these 35 test specimens has been determined using Eq. (1), which includes both geometrical and material properties. Table 1 presents a summary of the data showing the variations in material type and also in cross-section slenderness; β varies from 0.012 to 0.106 covering all traditional classes i.e. Class 1–4.

$$\beta = \frac{1}{2}\left(\frac{D}{t} - 1\right)\frac{\sigma_{0.2}}{E_0}, \tag{1}$$

where D and t are the outer diameter of the cross-section and the thickness of the plate, respectively and $\sigma_{0.2}$ and E_0 are the 0.2% proof stress and the initial modulus of the material stress–strain response, respectively.

3. Finite element modelling of the stub column response

All aforementioned stub column test results have been modelled using the finite element (FE) package ABAQUS 6.4 (2003). Stress–strain behaviour has been represented using the modified compound Ramberg–Osgood formulations, proposed by Gardner and Ashraf [14], as given by Eqs. (2) and (3), to accurately predict the pronounced nonlinearity of stainless steel.

$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n \quad \text{for } \sigma \le \sigma_{0.2} \tag{2}$$

$$\begin{aligned}\varepsilon = {} & \frac{(\sigma - \sigma_{0.2})}{E_{0.2}} \\ & + \left(\varepsilon_{t1.0} - \varepsilon_{t0.2} - \frac{\sigma_{1.0} - \sigma_{0.2}}{E_{0.2}}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_{1.0} - \sigma_{0.2}}\right)^{n'_{0.2,1.0}} \\ & + \varepsilon_{t0.2} \quad \text{for } \sigma > \sigma_{0.2},\end{aligned} \tag{3}$$

where E_0 and $E_{0.2}$ are the Young's modulus and the tangent modulus at 0.2% offset strain, respectively, $\sigma_{0.2}$ and $\sigma_{1.0}$ are the proof stresses at 0.2% and 1% offset strains, respectively, $\varepsilon_{t0.2}$ and $\varepsilon_{t1.0}$ are the total strains at $\sigma_{0.2}$ and $\sigma_{1.0}$, respectively and n and $n'_{0.2,1.0}$ are the strain hardening exponents, values of which have been proposed for different grades of stainless steel [15].

The thin-shell element S9R5 has been used to model the stub columns with all the degrees of freedom restrained at both ends except for the vertical displacement at the loaded edge. Constraint equations were used to ensure that all nodes at the loaded end act as a group to move vertically when a concentrated load was applied to one of the nodes. Initial geometric imperfections were introduced using the first eigenmode obtained from the elastic analysis with an appropriate amplitude — $0.02t$ for the stub columns tested by Bardi and Kyriakides [12] as this closely approximates the reported values and $0.2t$ for all other cases (where no specific information is available), which has been proposed as a general guideline for stainless steel CHS stub columns by Gardner and Nethercot [16]. The ultimate load capacity for each of the stub columns obtained from the nonlinear analysis using the Riks method has been compared to the experimental results. For 35 stub columns, the FE predictions were, on average, 96% of the test results with a coefficient of variation (COV) of 0.10. Fig. 1 compares the FE predictions to the corresponding test results. Three of the test results, in particular, were not accurately predicted by the FE models. Two tests reported by Young and Hartono [8] were overpredicted, whilst one test reported by Lam and Roach [13] was underpredicted. The remaining results show better consistency with a COV of only 0.06. Given that the FE models have been developed using predicted [15] stain hardening coefficients n and $n'_{0.2,1.0}$ for