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Structural performance of stainless steel circular hollow sections under combined axial load and bending – Part 2: Parametric studies and design

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ABSTRACT

This paper reports the second part of the study on the structural behaviour of stainless steel circular hollow sections subjected to combined axial load and bending moment. A series of numerical parametric studies is presented, using the validated finite element (FE) models from the companion paper, with the aim of generating further structural performance data over a wider range of stainless steel grades, cross-section slendernesses and combinations of loading. The considered parameters include the outer cross-section diameter, the ratio of outer cross-section diameter to thickness and the initial loading eccentricity. Both the experimentally and numerically derived section capacities were compared with the strength predictions determined from the current European code, the American specification and the Australian/New Zealand standard, allowing the applicability of each codified method to be assessed. The comparisons revealed that the current design standards generally result in unduly conservative and scattered strength predictions for stainless steel circular hollow sections under combined loading, which can be primarily attributed to the neglect of strain hardening in the determination of cross-section resistances and to the use of linear interaction formulae. To overcome these shortcomings, improved design rules are proposed through extension of the deformation-based continuous strength method (CSM) to the case of circular hollow sections subjected to combined loading. Comparisons between the proposals and the test and FE results indicate a high level of accuracy and consistency in the predictions. The reliability of the proposed approach was confirmed by means of statistical analyses according to EN 1990.

1. Introduction

Cold-formed stainless steel structural members are gaining increasing use in a range of construction applications due to their aesthetic appeal, favourable mechanical properties and excellent resistance against corrosion and fire. Given the high initial cost of stainless steels, structural design efficiency is of primary concern. This has prompted research aimed at assessing the accuracy of existing codes and developing new efficient design approaches for stainless steel structures. With regards to cross-section load-carrying capacities, existing design codes [1–3] generally limit the design stress to the 0.2% proof stress without considering the pronounced strain hardening in the strength predictions of stocky cross-sections, and neglect element interaction in the treatment of local buckling. A series of stub column and four-point bending tests have been previously conducted on stainless steel closed sections – square and rectangular hollow sections (SHS and RHS) [4–15] and circular hollow sections (CHS) [16–22], and open sections – I-sections [16,18,23,24], channel sections [18,25–28] and angle sections [18,29]. Comparisons of the test results with codified capacity predictions revealed undue conservatism in the existing standards. To improve the design efficiency, a deformation-based design approach called the continuous strength method (CSM) [30–35], allowing a rational exploitation of strain hardening, has been proposed for stocky cross-sections, and the Direct Strength Method (DSM) [36–38], accounting for the beneficial effect of element interaction, was developed for slender cross-sections, both of which significantly increase the material utilisation in structural design. Revised slenderness limits for the classification of stainless steel cross-sections have also been proposed [39,40]. The structural behaviour of stainless steel SHS and RHS subjected to combined axial load and bending moment has been systematically studied by Zhao et al. [41–43], where the conservatism in existing codified design provisions was highlighted and improved design rules were proposed, offering substantially enhanced capacity predictions.

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The focus of the study in the present paper is on the structural performance of stainless steel CHS under combined loading. Firstly, a series of parametric studies are reported, using the finite element (FE) models validated in the companion paper [44], to expand the available test data pool over a wider range of stainless steel grades, cross-section slendernesses and combinations of loading. All the numerically derived data, together with the experimental results, are then compared with the resistances predicted by EN 1993-1-4 [1], SEI/ASCE-8 [2] and AS/NZS 4673 [3], enabling the accuracy of the existing codified methods to be evaluated. Finally, improved design rules are sought through extension of the continuous strength method to the case of stainless steel CHS under combined loading, and the applicability and reliability of the method are carefully assessed.

2. Parametric studies

In this section, a series of parametric studies is presented, using the FE models validated in the companion paper [44], aiming to extend the available structural performance data over a wider range of stainless steel grades, cross-section slendernesses and loading combinations. A detailed description of the development of the FE models was given in the companion paper [44], so only the key aspects relevant to the parametric studies are presented herein. The parametric studies focus primarily on austenitic stainless steel, though comparative results are also presented for duplex and ferritic grades. The adopted austenitic stainless steel stress–strain curve was obtained from the tensile coupon tests on material cut from the CHS 76.3 × 3 specimens presented in the companion paper [44]. Since only austenitic material was tested, the material properties for the parametric studies on the duplex and ferritic stainless steel circular hollow sections were taken from previous tests on duplex and ferritic stainless steel RHS under combined loading [41,43]. Table 1 reports the employed material properties for each grade, where E is the Young's modulus, $\sigma_{0.2}$ is the 0.2% proof stress, $\sigma_{1.0}$ is the 1.0% proof stress, σ_u is the ultimate tensile strength, ε is a parameter defined as $\varepsilon = \sqrt{(235/\sigma_{0.2})(E/210,000)}$, and n, $n'_{0.2,1.0}$ and $n'_{0.2,u}$ are the strain hardening exponents used in the compound Ramberg–Osgood (R–O) material model [45–49]. Residual stresses were not explicitly incorporated in the numerical models, as discussed in the companion paper [44]. In terms of the geometric dimensions of the modelled circular hollow sections, the outer diameter D was varied between 40 mm and 150 mm, while the cross-section thickness t ranged from 0.7 mm to 10 mm. The resulting $D/t\varepsilon^2$ ratios varied between 15 and 88, covering Classes 1–3 cross-sections, according to the slenderness limits in EN 1993-1-4 [1]. The length of each model was set to be equal to three times the outer cross-section diameter. The end section boundary conditions were applied by coupling all degrees of freedom of the end section to an eccentric reference point, allowing only longitudinal translation and rotation about the axis of buckling. The initial local geometric imperfection pattern along the member length was assumed to be of the form of the lowest elastic buckling mode shape. The adopted local geometric imperfection amplitude was taken as $t/100$, which was shown to lead to the best agreement between the test and FE results in the model sensitivity study [44]. The initial loading eccentricities ranged between 2 mm and 600 mm, leading to a wide range of loading conditions being considered. In total, 472 results were generated [50], including 182 for austenitic stainless steel, 145 for duplex stainless steel and 145 for ferritic stainless steel, all of which are analysed and discussed in the following sections.

Table 1
Summary of key measured material properties for the tensile coupons.

Grade	E (GPa)	$\sigma_{0.2}$ (MPa)	$\sigma_{1.0}$ (MPa)	σ_u (MPa)	ε	R–O coefficient n	$n'_{0.2,1.0}$	$n'_{0.2,u}$
Austenitic	195	302	347	784	0.85	7.3	2.0	1.9
Duplex	199	519	578	728	0.65	5.3	2.8	3.7
Ferritic	190	466	508	515	0.68	6.6	7.6	7.6

3. Assessment of codified design rules and development of new design methods

3.1. General

In this section, the codified design provisions for stainless steel circular hollow sections under combined axial load and bending moment, as given in EN 1993-1-4 [1], SEI/ASCE-8 [2] and AS/NZS 4673 [3], are firstly examined. Then, improved design rules are sought through extension of the deformation-based continuous strength method (CSM) to the case of combined loading, for which the development process is fully described. The accuracy of each method is evaluated through comparisons of the ratios of test (or FE) to predicted capacities under combined loading, calculated in terms of the axial load ratio, $N_u/N_{u,pred}$ [14,43], as reported in Table 2, where N_u is the test (or FE) axial load corresponding to the distance on the N–M interaction curve from the origin to the test (or FE) data point (see Fig. 1), while $N_{u,pred}$ is the predicted axial load corresponding to the distance from the origin to the intersection with the design interaction curve, assuming proportional loading. A value of $N_u/N_{u,pred}$ greater than unity indicates that the test (or FE) data point lies outside the interaction curve and is safely predicted. Note that all the comparisons are made based on the unfactored design strengths.

3.2. European code EN 1993-1-4 (EC3)

The current European code for stainless steel, EN 1993-1-4 [1] adopts the same design provisions for circular hollow sections under combined axial load and bending moment as those given in EN 1993-1-1 [51] for carbon steel, where failure is determined based on a linear summation of the utilisation ratios under each component of loading, with a limit of unity. The design expression is given by Eq. (1), in which N_{Ed} is the design ultimate axial load,

Table 2
Comparisons of combined loading test and FE results with predicted strengths.

(a) Austenitic stainless steel				
No. of tests: 23 No. of FE simulations: 182	$N_u/N_{u,EC3}$	$N_u/N_{u,ASCE}$	$N_u/N_{u,AS/NZS}$	$N_u/N_{u,csm}$
Mean	1.54	1.78	1.54	1.17
COV	0.14	0.19	0.14	0.08
(b) Duplex stainless steel				
No. of tests: 0 No. of FE simulations: 145	$N_u/N_{u,EC3}$	$N_u/N_{u,ASCE}$	$N_u/N_{u,AS/NZS}$	$N_u/N_{u,csm}$
Mean	1.43	1.65	1.43	1.15
COV	0.09	0.11	0.09	0.07
(c) Ferritic stainless steel				
No. of tests: 0 No. of FE simulations: 145	$N_u/N_{u,EC3}$	$N_u/N_{u,ASCE}$	$N_u/N_{u,AS/NZS}$	$N_u/N_{u,csm}$
Mean	1.31	1.51	1.31	1.10
COV	0.09	0.09	0.09	0.07

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