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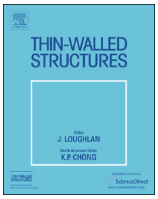

Behaviour and design of stainless steel slender cross-sections subjected to combined loading

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ABSTRACT

The Continuous Strength Method (CSM) is a recently developed strain based design technique that produces accurate predictions for cross-section resistances for stocky sections against individual and combined actions. This paper numerically investigates the behaviour slender stainless steel cross-sections subjected to combined loading i.e. compression plus bending. Generated numerical results and available test results were used to develop CSM formulations to tackle the conservatism shown by the current international codes in predicting resistances of slender sections. Keeping the basic design philosophy in line with the current CSM design technique, interaction equations are re-calibrated herein for slender stainless steel hollow sections.

1. Introduction

Stainless steel is gaining popularity in the construction industry in recognition to its beneficial features such as corrosion resistance, ease of maintenance, higher strength and ductility, and better performance in fire. Stainless steel possesses significantly different material response showing nonlinear rounded stress-strain curve when compared against its traditional counterpart i.e. carbon steel. Capacities of a stainless steel cross-sections are often calculated following the traditional section classification approach, which is based on elastic, perfectly-plastic material model leading to an effective width concept [1–3]. These methods produce conservative results, and the process is tedious when effective width calculation comes into consideration for thin-walled slender sections, whilst, on the other hand, the beneficial effect of strain hardening for stocky sections is neglected in the traditional approach. This prompted researchers to develop new rational design techniques [4,5] that will exploit the beneficial characteristics of the material, and will make the design process simple. Emergence of the Continuous Strength Method (CSM) for stocky sections [6] and the Direct Strength Method (DSM) for slender sections [7] are seen as two significant contributions in the field.

In CSM, the strength of a section is expressed as a continuous function of the section slenderness, and does not rely on the traditional way of cross-section classification. A bilinear elastic, linear strain hardening material curve has recently been introduced to make the design technique simple compared to similar techniques [8,9] proposed previously. Recent developments on CSM include resistance predictions for more general loadings such as compression plus bending [10–13].

It is worth noting that the recent developments of CSM are primarily focussed on stocky sections to exploit the extensive strain hardening of stainless steel. In case of slender sections, prior studies concluded that the used of effective width method can yield reasonable accuracy in predicting section capacities, and hence the lengthy calculation process remained in the design method. Recent research outcomes reported in [14,15] presented simple formulations for predicting section capacities of slender stainless steel cross-sections following the CSM technique, and were shown to produce accurate predictions for cross-section resistances without going into the lengthy process of calculating effective cross-sectional properties.

Current study investigates the behaviour of rectangular and square hollow stainless steel slender sections (RHS and SHS) subjected to simultaneous compression and bending. Available experimental investigations on a variety of relevant loading conditions were used to develop FE models that can simulate the behaviour of stainless steel slender sections subjected to combined loading. Once the modelling technique was validated, a comprehensive parametric study was conducted to generate additional results to understand the behaviour of slender sections representing a wide range of cross-section slenderness. Numerically obtained results were used to evaluate the performance of the

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existing design guidelines [3,16] and the CSM linear interaction equation suggested for slender cross-sections [12] of stainless steel. For combined biaxial bending and compression loading case, currently available interaction formulations for stocky sections were calibrated for slender sections, and a reliability analysis was also carried out following the provisions set out in EN 1990 [17].

2. Numerical modelling

The numerical study conducted as a part of the current research was performed using general purpose commercial FE package ABAQUS [18]. Details of the FE modelling approach adopted in the current study are presented in the following sections. It is, however, worth noting that the key features of the modelling technique are similar to those as reported by earlier researchers in the field; modifications were made where required [13,19,20].

2.1. Developing the FE model: basic principles

FE models were developed using reduced integration shell element S4R, which is reported to perform well in modelling thin-walled metallic cross-sections. A number of recent studies on RHS stub column and beam sections adopted a uniform mesh with element size equal to the section thickness [21,22], which is a convenient option for stocky sections. However, in the case of slender cross-sections, this approach could create too many elements increasing the cost of computation. Table 1 shows details of five different types of mesh that were examined in the current study to obtain an optimum balance between accuracy and computational cost. Obtained results show that the considered ‘Medium-3′ mesh with element size 8 mm × 8 mm in the flat region and with 4 elements in the corner region produced accurate predictions with lower computational cost for both stocky and slender sections. This mesh size was eventually used throughout the numerical study.

ABAQUS requires input of material strength provided as true stress and log plastic strain in its property module. Nonlinear stress-strain behaviour of metals can be represented using the material model proposed by Ramberg and Osgood [23].This technique was modified for stainless steel alloys [24–27], and the current study used the modified Ramberg-Osgood model proposed by Gardner and Ashraf [26] for austenitic and duplex stainless steels. Material model proposed by Rasmussen [25] was also used in cases of ferritic stainless steel grades where failure occurred prior to strains at 1.0% proof stress. The strain hardening component m, where unavailable, was computed using the guidelines proposed in [28]. Other required parameters were obtained from relevant tension coupon test results. Although some differences are observed in the stress-strain response of stainless steel in tension and compression, the current research used tension coupon test data largely due to its easy availability. Compression coupon tests are not very common, and there is little evidence available in the current literature to make any decisive comment on the difference between material's response in tension and compression.

Cold forming process induces plastic hardening and strength enhancement in cold rolled corners as well as in flat portions of SHS and RHS sections. Appropriate material strength was incorporated in the numerical models depending on the position of the elements i.e. flat tension coupon data for elements in the flat region, and enhanced corner strength data for elements in the corner regions. Corner strength enhancement was extended to a length equal to twice the section thickness 2t into the flat portion as suggested in previous research [20,31]. In validation, specimens were selected from sources where tensile material behaviour of both flat and corner area of a section were reported.

Effect of residual stress on the cold formed sections was not considered in the FE models. Prior research [30,32,33] on cold rolled, seam welded SHS and RHS concluded that the magnitudes of membrane residual stresses were negligible, whilst the effect of through-thickness bending residual stress was embedded in test coupons cut from original sections, as the coupons were straightened during the tensile testing. Hence, residual stresses were not incorporated in the developed FE models.

Distribution of initial imperfections was simulated using the deformed shapes obtained from elastic buckling analysis. The lowest buckling mode was used as the imperfection shape. Three different amplitudes, Dawson-Walker model for stainless steel [19], t/100 and t/10, where t is the plate thickness, were used to observe the effect of initial imperfections on compression resistance.

All nonlinear analyses performed on the developed FE models were displacement controlled. For stub columns, the moving end was allowed for axial translation whereas the fixed end was restrained from any translational and rotational movement. Using the rigid body constraint option, each end section was connected to a reference point. Any boundary condition imposed on that reference point was directly replicated on the end sections. During eccentric loading pin ended boundary condition was used, and the reference point was moved to the exact co-ordinates of eccentricity with respect to the centroidal axes of cross-sections. Loading end was free to move along the load direction, and was allowed to rotate in the direction of bending, whereas other end was restrained against all movements except bending. In beam models, the boundary conditions were same as the eccentric loading analysis; the only difference being the reference point was positioned on the lower flange of the section to replicate simply supported boundary condition. In cases where end plates were attached to the test specimens, the reference points were moved to a distance equal to the thickness of the end plates.

Table 1
Mesh density study on the stub column specimen subjected to axial compression.

Section type	Section considered	Mesh name	Flat element size (mm × mm)	Corner element size (mm × mm)	Number of elements	F_u/F_{FE}	Time (s)
Stocky ($\lambda_p = 0.37$)	SHS 150 × 150 × 8 – 5A [29]	Fine-1	2 × 2	2 × 2	65,250	1.075	3233
		Medium-2	6 × 6	6 × 6	7350	1.074	425
		Medium-3	8 × 8	8 × 6	5152	1.072	295
		Course-4	20 × 20	20 × 11.65	748	1.079	35
		Thickness sized	8 × 8	8 × 8	4032	1.051	211
Slender ($\lambda_p = 1.15$)	RHS 160 × 80 × 3 [30]	Fine-1	2 × 2	2 × 2	489,600	0.963	52,922
		Medium-2	6 × 6	6 × 6	14,000	0.934	739
		Medium-3	8 × 8	8 × 6	6300	0.936	288
		Course-4	18.61 × 20	20 × 11.65	960	0.939	36
		Thickness sized	3 × 3	3 × 3	30,400	0.932	1812