Journal of Constructional Steel Research 133 (2017) 156–166

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Full slenderness range DSM approach for stainless steel hollow cross-sections

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ARTICLE INFO

Article history:
Received 23 November 2016
Received in revised form 1 February 2017
Accepted 5 February 2017
Available online xxxx

Keywords:
Combined actions
Cross-sectional resistance
Direct strength method
Enhanced material properties
Stainless steel hollow sections

ABSTRACT

This paper studies the cross-sectional behaviour of austenitic, ferritic and duplex stainless steel hollow sections subjected to several loading conditions and presents a full slenderness range DSM approach for the prediction of cross-sectional strengths. Pure compression, pure bending moment and combined uniaxial bending and compression loading resistances are predicted using the same strength curve, which is based on experimental data gathered from the literature and ultimate strengths generated through parametric studies. The proposed approach is applicable to slender and stocky cross-sections leading to an accurate full slenderness range DSM design approach since the resistance reduction due to local buckling and the effect of strain hardening are taken into account, as is the effect of partial yielding of the cross-section in bending. A new method based on the actual stress distribution of the cross-section is also presented for combined loading conditions, where the cross-sectional behaviour is directly tackled through the same strength curve, providing more accurate results than the methods considering the uncoupled problem. Finally, a statistical analysis is presented to demonstrate the reliability of the proposed DSM approach.

1. Introduction

Slender stainless steel structures are commonly used in construction as cold-formed elements, exhibiting slender cross-sections that are subjected to local and distortional buckling modes. The effective width method is traditionally used to account for the effects of local and distortional buckling in stainless steel standards (e.g. EN1993-1-4 [1], AS/NZS4673 [2], SEI/ASCE 8-02 [3]) leading to tedious and potentially iterative calculations. In contrast, the Direct Strength Method (DSM) is an alternative non-iterative design method developed by Schafer and Pekoz [4] and implemented in the North American Specification AISI-S100-12 [5] for carbon steel structures. The DSM allows the consideration of all instabilities in a consistent manner through the use of strength curves in conjunction with software to determine the elastic buckling modes. All stainless steel grades present a nonlinear stress-strain relationship with pronounced gradual yielding (strain hardening) that makes them different from carbon steel in designing for stability and strength. Although new strength curves have been proposed to adapt the DSM to stainless steel cross-sections in order to account for the different behaviour exhibited by this material (Becque et al. [6], Niu et al. [7], Huang and Young [8,9]), the DSM has not yet been included in stainless steel design standards.

On the other hand, stainless steel standards do not usually take into account the strain hardening effects in the design of stocky cross-sections and overly-conservative capacity predictions are obtained, particularly for austenitic and duplex grades. The Continuous Strength Method (CSM) is a deformation based design method that accounts for the beneficial effect of strain hardening when the resistance of stocky cross-sections is predicted, developed for austenitic and duplex stainless steels by Afshan and Gardner [10] and adapted to ferritics by Bock et al. [11]. Alternatively, Rossi and Rasmussen [12] proposed an alternative design approach that implements strain hardening effects into the DSM formulation, improving the capacity prediction of stocky cross-sections and making it a suitable approach for the full cross-sectional slenderness range. However, these expressions were only evaluated for sections in compression.

This paper presents a comprehensive investigation of the cross-sectional behaviour of stainless steel Rectangular and Square Hollow Sections (RHS and SHS) subjected to different loading conditions, including compression, bending and combined compression and bending. A preliminary study on the behaviour of ferritic stainless steel hollow cross-sections subjected to compression, bending and combined uniaxial bending and compression was conducted by the authors in [13]. In the present paper, an extensive experimental database and additional finite element strengths are presented to extend the study to austenitic and duplex stainless steel grades. The DSM-based approach developed by Rasmussen [14] for beam-columns is also modified and adapted to predict the cross-sectional behaviour under combined compression

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http://dx.doi.org/10.1016/j.jcsr.2017.02.002
0143-974X/

and uniaxial bending loading conditions. The proposed method considers the cross-sectional behaviour directly with a unique strength curve using the local slenderness based on the actual stress distribution instead of considering the uncoupled problem where compression and bending strengths are determined separately.

2. Experimental data and FE ultimate strengths

The analyses and proposals presented in this paper are based on an extensive strength database comprising both experimental and numerical results for different stainless steel grades and loading conditions. This section first presents the collated experimental database and then the relevant information regarding the FE model validation and parametric studies.

2.1. Collected experimental data

Previous research works on stainless steel tubular sections have widely investigated the cross-sectional compression, flexural and combined loading capacities from stub column tests, three and four-point bending tests and stub column tests subjected to combined compression and bending moment conditions, respectively. An extensive experimental database with close to 300 experimental results has been collected through an exhaustive literature review, where tests on RHS and SHS from various stainless steel grades subjected to different loading conditions have been gathered. Table 1 summarizes the available stub column tests, while Table 2 presents the experimental data on tubular stainless steel beams and Table 3 gathers the different tests performed under combined loading conditions.

Table 1
Summary of stub column tests in compression.

Stainless steel	Material grades	References	No. of tests
Austenitic	1.4301, 1.4306, 1.4318	[16–22]	65
Ferritic	1.4003, 1.4509	[23–26]	26
Duplex and lean duplex	1.4462, 1.4162	[19,22,27–30]	32

Table 2
Summary of beam tests.

Stainless steel	Material grades	References	No. of tests
Austenitic	1.4301, 1.4318, 1.4306	[15,21,25,31–35]	47
Ferritic	1.4003, 1.4509	[23,25,26,36]	31
Duplex and lean duplex	1.4462, 1.4162	[8,22,33,37]	23

Table 3
Summary of stub column tests in combined loading.

Stainless steel	Material grades	References	No. of tests
Austenitic	1.4301, 1.4571, 1.4307, 1.4404	[15,22]	21
Ferritic	1.4003, 1.4509	[24,26]	34
Duplex and lean duplex	1.4162	[22]	4

2.2. FE model validation and parametric studies

In addition to the available experimental database, parametric studies based on finite element (FE) modelling have been performed in order to augment the range of cross-section slenderness values investigated experimentally. The FE analyses procured a comprehensive database of ultimate strengths covering the full range of cross-sectional slenderness values by testing virtual specimens with cross-sections not covered by the existing experimental programmes, including slender cross-sections subjected to local buckling. This section presents the validation of the FE models for ferritic stainless steel RHS and SHS subjected to compression, bending and combined axial compression and bending based on the experimental results reported by Arrayago and Real [24,36]. The section also summarizes the conducted parametric studies.

2.2.1. General assumptions and model validation

All FE models were performed by the general purpose software Abaqus. The mid-surface of the cross-section was modelled by the four-node shell element with reduced integration S4R, widely used for cold-formed stainless steel elements. Considering that initial imperfections have an important influence on thin-walled structures, geometric imperfections in the shape of the first elastic buckling mode shape were introduced in all FE models. However, overall imperfections are not relevant for stub columns and beams since cross-section failure is expected, and therefore, only local imperfections with the measured amplitude have been considered in the models. The nonlinear behaviour of stainless steel cross-sections was finally investigated by conducting modified Riks analyses.

For the models representing stub columns subjected to compression and combined loading conditions, the edge elements at the ends of the specimens were kinematically coupled and connected to two reference points where the relevant degrees of freedom were defined. For stub columns subjected to compression all six degrees of freedom were fixed at the lower reference point while only longitudinal displacement was set free at the upper one. For the stub columns subjected to combined loading the rotation around the relevant axis was set free. Loads were introduced as imposed displacements or rotations at the upper reference points in all models. During four-point bending tests, support and loading points were stiffened to prevent web crippling effects, and this stiffening was reproduced with kinematic coupling interaction in the conducted FE models. In these models the bottom faces of the regions corresponding to the support and loading points were coupled and connected to reference points, where boundary conditions and imposed displacements were defined.

Two different material definitions were considered during the validation of the FE models. First, different material definitions based on measured stress-strain properties were assigned to the flat and corner regions of the cross-sections, extending the corner material definition to the adjacent flat parts by a length equal to two times the thickness of the element, as proposed by Theofanous and Gardner [29]. Secondly, weighted average material properties were considered in the FE models, where the same properties were assigned to the entire cross-section as suggested by Hradil and Talja [38], thus allowing the accuracy of this simplification for further FE analyses to be evaluated. The material parameters describing the behaviour of flat parts, corner parts and weighted average behaviour can be found in the original publications by Arrayago and Real [24,36].

Table 4 presents the mean values and coefficients of variation (COV) of the numerical-to-experimental ultimate load and deflection ratios (end-shortenings for compression tests $\delta_{u,FE}/\delta_{u,exp.}$, midspan deflections for bending tests $d_{u,FE}/d_{u,exp.}$ and end rotations for combined loading tests $\theta_{u,FE}/\theta_{u,exp.}$) for the different loading cases analysed. Results corresponding to the two material definitions considered in the FE model validation have been included in Table 4, those corresponding to the measured properties of the flat and corner regions and to the weighted average material properties for the entire cross-section. The results demonstrate that although the most accurate results (smallest COVs) are obtained when the measured stress-strain curves are considered, the adoption of the simplified weighted average material properties still provides excellent results for stainless steel RHS and SHS under different loading conditions.

Experimental curves have been compared to the corresponding FE results considering measured material properties (referred to as FE) and the weighted average material properties (FE, average material)