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Element interaction of cold-formed stainless steel cross-sections subjected to major axis bending

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ABSTRACT

Numerical investigation of cold-formed normal and high strength stainless steel square and rectangular hollow sections subjected to major axis bending is presented in this paper. A non-linear finite element model which includes geometric and material non-linearities was developed and verified against experimental results. The material properties of the flat and corner portions of the specimen sections were carefully incorporated. It was shown that the finite element model closely predicted the failure modes, ultimate moments and deflections of the tested specimens. The model was then used for an extensive parametric study to investigate the interaction effects of constituent plate elements on Class 3 and 2 slenderness limits and cross-section moment capacities of cold-formed stainless steel square and rectangular hollow sections in bending.

The numerical strengths predicted from this study together with the experimental results were compared with the theoretical elastic and plastic bending moments. It was shown that the element interaction surely influences the flexural behavior of cold-formed stainless steel square and rectangular hollow sections especially for slender cross-sections. The design provisions on Class 3 and 2 slenderness limits and effective width equations specified in ASCE Specification, EC3 Code and proposed by Gardner and Theofanous are not suitable for square and rectangular hollow sections in bending since they did not take into consideration interaction effects of constituent plate elements. Hence, the new Class 3 and Class 2 slenderness limits and the cross-section moment capacity design equations are proposed in this study based on the whole cross-section response, which carefully consider the interaction effects of constituent plate elements.

1. Introduction

Cold-formed stainless steel tubular members are being increasingly used in architectural and structural applications due to their desirable features, such as corrosion resistance, easy maintenance, pleasing appearance and favorable mechanical properties. Recently, many researches have been carried out to study the flexural behavior of cold-formed stainless steel. A total of 17 tests were carried out on the cold-formed stainless steel beams by Lin et al. [1] to investigate the effectiveness of compression flanges and webs. Rasmussen and Hancock [2] performed bending tests on cold-formed austenitic stainless steel square and circular hollow sections to determine the bending strength and develop design guidelines. Real and Mirambell [3] investigated the deflection of stainless steel flexural members. Gardner and Nethercot [4] conducted a series of tests on cold-formed austenitic stainless steel square, rectangular and circular hollow sections to assess its structural behavior. Zhou and Young [5] conducted a series of 4-point bending tests on cold-formed stainless steel square and rectangular hollow sections cold-rolled from austenitic stainless steel type 304, high strength austenitic (HSA) and duplex steel sheets. The moment-curvature diagrams for normal and high strength specimens were reported.

Design rules for cold-formed stainless steel structural members are available including the American Specification [6] for the Design of Cold-Formed Stainless Steel Structural Members and the European Code [7] Design of Steel structures, Part 1.4: Supplementary Rules for Stainless Steels. The cross-section classification approach is employed in the EC3 Code as a means of codified treatment for local buckling of cross-sections that are partly or fully in compression. The EC3 Code treats the plate elements in the cross-section individually and classified according to their width-to-thickness ratios as compared to codified slenderness limits. The cross-section response is assumed to the behavior of its most slender plate element in the cross-section. Since the initial cost of structural stainless steel products is approximately four times that of the equivalent carbon steel product [8], hence, the stainless steel structural members must be designed efficiently by considering the interaction of constituent plate elements.

The previous researches show that the interaction effects of constituent plate elements on cross-section response are obvious regarding the slenderness limits and the cross-section ultimate resistances for

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cold-formed stainless steel square and rectangular hollow sections subjected to compression [9,10] and also bending [11,12]. Both Kato [13] and Beg and Hladnik [14] investigated the interaction effects of constituent plate elements on the local buckling for hot-rolled carbon steel H-sections in bending. Seif and Schafer [15] provided analytical expressions for the elastic cross-section local buckling stress considering plate element interaction effects of hot-rolled steel structural shapes in axial compression as well as positive and negative bending about the major and minor geometric axes. Schafer [16] also took into account the interaction effects of constituent plate elements for cold-formed carbon steel sections by using direct strength method.

The purpose of this paper is firstly to develop an accurate and efficient non-linear finite element model to simulate the structural performance of cold-formed normal and high strength stainless steel tubular cross-sections subjected to major axis bending. The initial local imperfection and non-linear material properties of the flat and corner portions of the cross-section have been carefully incorporated into the finite element model (FEM). The finite element analysis program ABAQUS [17] was used for the numerical investigation. The FEM was verified against the bending tests conducted by Zhou and Young [5]. Secondly, an extensive parametric study was performed to investigate the effects of cross-section geometries and material properties on the strength and behavior of cold-formed stainless steel tubular flexural members. Thirdly, the design provisions on Class 3 and Class 2 slenderness limits and effective width formulae specified in the current ASCE Specification [6], EC3 Code [7] and proposed by Gardner and Theofanous [18] were assessed based on the results of the parametric study. The interaction effects of constituent plate elements on cross-section response of cold-formed normal and high strength stainless steel square and rectangular hollow sections subjected to major axis bending were investigated. Lastly, new Class 3 and Class 2 slenderness limits and the section capacity design equations based on the whole cross-section response, which carefully take into account the interaction effects of constituent plate elements, are proposed in this study for cold-formed normal and high strength stainless steel square and rectangular hollow sections subjected to major axis bending.

2. Summary of experimental investigation

The experimental investigation of cold-formed normal and high strength stainless steel tubular flexural members performed by Zhou and Young [5] reported the test ultimate loads, failure modes and moment-curvature diagrams. The specimens were cold-rolled from austenitic stainless steel type 304, high strength austenitic (HSA) and duplex steel sheets. The stainless steel type 304 is considered as normal strength material, whereas the HSA and duplex are considered as high strength material. The specimens consisted of fifteen different section sizes, having nominal thicknesses (t) ranging from 1.5 to 6 mm, nominal overall depth of the webs (d) from 40 to 200 mm, and nominal flange widths (b_f) from 40 to 150 mm. The length of the specimens was chosen such that the section moment capacity could be obtained. Table 1 summarizes the measured test specimen dimensions using the nomenclature defined in Fig. 1. In Table 1, the specimens are labeled according to their steel types and cross-section dimensions. For example, the labeled "N100 × 50 × 2" defines the specimen having normal strength material and nominal overall depth of the web of 100 mm, overall flange width of 50 mm, and thickness of 2 mm.

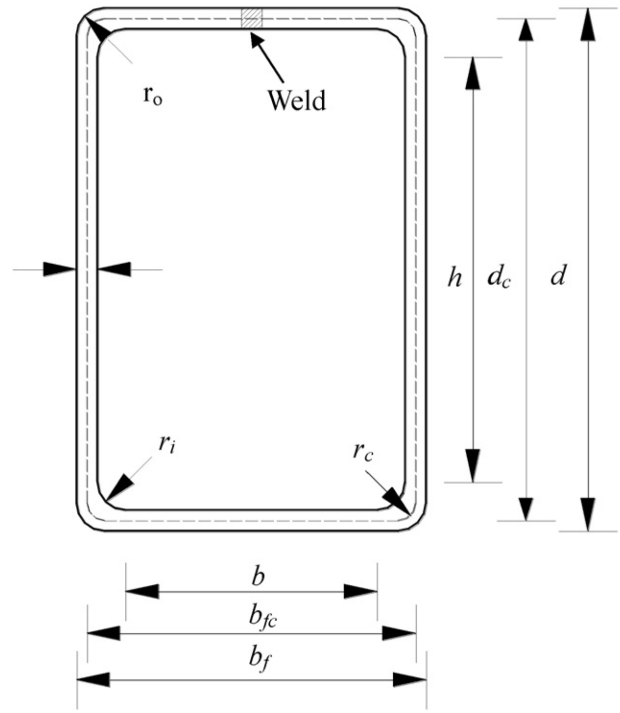

Fig. 1. Definition of symbols.

The material properties of the flat portions of the specimens for each series were determined by tensile coupon tests. The coupons were taken from the center of the face at 90° angle from the weld in the longitudinal direction of the untested specimens. The tensile coupons were prepared and tested according to the American Society for Testing and Materials Standard [19] using 12.5 mm wide coupons of gauge length 50 mm. Furthermore, the material properties of the corner portion of

Table 1
Summary of test specimens [5].

Specimen	Web	Flange	Thickness	Radius	Length	Experimental ultimate moment
	d	b_f	t	r_i	L	M_{Exp}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN.m)
N40 × 40 × 2	40.1	40.1	1.957	2.0	1442	2.35
N40 × 40 × 4	40.1	40.0	3.883	4.0	1441	5.11
N80 × 80 × 2	80.4	80.5	1.908	4.0	1442	6.64
N80 × 80 × 5	79.8	79.9	4.772	7.5	1443	24.78
N100 × 50 × 2	99.9	49.8	1.970	2.0	1440	8.81
N100 × 50 × 4	99.7	49.6	3.881	4.0	1439	21.28
N120 × 60 × 2	120.2	59.9	1.838	2.5	1442	10.25
N120 × 60 × 4	120.0	59.7	3.885	5.5	1442	34.09
H40 × 40 × 2	40.0	40.2	1.937	2.0	1243	3.45
H50 × 50 × 1.5	50.3	50.1	1.541	1.5	1242	3.48
H150 × 150 × 3	150.7	150.6	2.779	4.8	1640	31.68
H150 × 150 × 6	150.5	150.7	5.870	6.0	1650	108.60
H140 × 80 × 3	140.3	80.5	3.094	6.5	1440	33.97
H160 × 80 × 3	160.6	80.9	2.901	6.0	1440	39.36
H200 × 110 × 4	197.7	109.1	3.998	8.5	1644	80.15