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Tests of cold-formed stainless steel tubular flexural members

Feng Zhou, Ben Young*

Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China

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Abstract

A series of tests on cold-formed stainless steel square and rectangular hollow sections subjected to major axis bending is presented in this paper. The tests were performed on sections fabricated by cold-rolling from normal strength material of austenitic stainless steel type 304, and high strength material of duplex and high strength austenitic steel sheets. Tensile coupon tests were conducted to obtain the material properties of the test specimens. The test strengths were compared with the design strengths obtained using the American Specification and Australian/New Zealand Standard for stainless steel structures. The North American Specification for cold-formed carbon steel structural members was also used to predict and compare the bending strengths. In addition, the test strengths were compared with the theoretical elastic and plastic bending moments. It is shown that the design strengths predicted by the three specifications and the theoretical bending moments are generally conservative for the tested specimens. The reliability analysis was performed to evaluate the reliability of the design rules based on the existing resistance factors and load combination specified in the aforementioned specifications. It is shown that the American Specification and North American Specification are reliable for both normal and high strength specimens. The Australian/New Zealand Standard is reliable for normal strength specimens, but slightly unreliable for high strength specimens.

Keywords: Bending; Cold-formed steel; Design strength; Experimental investigation; Flexural members; Square and rectangular hollow sections; Stainless steel; Tubular sections

* Corresponding author. Tel.: +852 2859 2674; fax: +852 2559 5337.
E-mail address: young@hku.hk (B. Young).

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Nomenclature

b_f	overall width of flange
COV	coefficient of variation
d	overall depth of web
E	Young's modulus of elasticity obtained from longitudinal tension coupon test
F_m	mean value of fabrication factor
h	depth of flat portion of web measured along the plane of web
L	actual length of test specimen
M_{ASCE}	nominal flexural strength calculated using ASCE Specification
$M_{AS/NZS}$	nominal flexural strength calculated using AS/NZS Standard
M_e	theoretical elastic bending moment
M_{Exp}	experimental ultimate bending moment
M_m	mean value of material factor
M_{NAS}	nominal flexural strength calculated using NAS Specification
M_p	theoretical plastic bending moment
P_m	mean value of tested-to-predicted load ratio
r_i	inside corner radius
S_x	plastic section modulus bending about the major x-axis
t	web thickness
V_F	coefficient of variation of fabrication factor
V_M	coefficient of variation of material factor
V_p	coefficient of variation of tested-to-predicted load ratio
Z_x	elastic section modulus bending about the major x-axis
β_o	reliability index
ε	elongation (longitudinal tensile strain) after fracture based on gauge length of 50 mm
κ	curvature
σ_p	longitudinal tensile proportional limit
σ_u	longitudinal tensile strength
$\sigma_{0.2}$	longitudinal 0.2% tensile proof stress; and
ϕ	resistance (capacity) factor

1. Introduction

Cold-formed stainless steel members are being increasingly used in architectural and structural application because of the desirable features of the material—corrosion resistance, easy maintenance and pleasing appearance. The use of stainless steel as primary structural components is rather limited due to a lack of research in this area. The current design rules for stainless steel structural members are mainly based on carbon steel, hence, the stainless steel material are not being fully utilized. The mechanical properties of stainless steel are quite different from carbon steel. Annealed stainless steel has the following characteristics as compared with carbon steel: (1) anisotropy; (2) nonlinear stress–strain relationship; (3) low proportional limits and (4) pronounced response to cold work [1]. Cold-formed hollow section is formed by rolling an annealed flat strip into a circular hollow section, which is then welded at the edges. The process is completed by further rolling into a square or rectangular hollow section (SHS or RHS). This process of forming by cold-working produces considerable enhancement to the material properties of the annealed steel. More economical designs can be achieved by taking into account the enhancement of the material properties due to cold-working. In this study, the design strengths and theoretical bending moments were calculated based on the material properties of the finished specimens.

The experimental bases for the cold-formed stainless steel beams were examined by Lin et al. [2], where a total of 17 tests were studied according to the effectiveness of compression flanges and webs. Rasmussen and Hancock [3] conducted an experimental investigation on cold-formed stainless steel square and circular hollow sections subjected to bending. The purpose of the test was to determine the bending strength of stainless steel structural hollow sections and to develop design guidelines for these sections as structural members. In the tests, only the normal strength austenitic stainless steel type 304 was investigated.

Design rules are available for cold-formed stainless steel structural members, including the American Society of Civil Engineers (ASCE) Specification [4] for the design of cold-formed stainless steel structural members and the Australian/New Zealand (AS/NZS) Standard [5] for cold-formed stainless steel structures. The AS/NZS Standard has adopted the design rules of flexural members from the ASCE Specification, except that the AS/NZS Standard has special provisions for square and rectangular hollow sections. The AS/NZS Standard permits plastic design for square and rectangular hollow members with compact sections. The design rules in the ASCE Specification and AS/NZS Standard are identical for the square and rectangular hollow members with non-compact sections.

The purpose of this paper is to present an experimental investigation of cold-formed normal and high strength stainless steel square and rectangular hollow sections subjected to major axis bending. The normal strength test specimens were cold-rolled from austenitic stainless steel type 304, and the high strength test specimens were cold-rolled from high strength austenitic and duplex stainless steel. The test strengths were compared with the design strengths obtained using the ASCE Specification [4] and AS/NZS Standard [5] for cold-formed stainless steel structures. The test strengths were also compared with the design strengths obtained using the North American Specification (NAS) [6] for cold-formed steel structural members. In addition, a comparison between the experimental and theoretical results of the cold-formed stainless steel square and rectangular hollow members subjected to major axis bending is also presented.

2. Experimental investigation

2.1. Test specimens

Bending tests were conducted on cold-formed stainless steel square and rectangular hollow sections. The specimens were cold-rolled from austenitic stainless steel type 304,

Table 1
Measured dimensions and experimental moments for normal strength specimens

Specimen	Web d (mm)	Flange b_f (mm)	Thickness t (mm)	Radius r_i (mm)	Length L (mm)	Test M_{Exp} (kNm)
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

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 15 different section sizes, having nominal thickness (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. Tables 1 and 2 show the measured specimen dimensions for the normal and high strength specimens, respectively, using the nomenclature defined in Fig. 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; the labeled 'H160×80×3' defines the specimen having high strength material and nominal overall depth of the web of 160 mm, overall flange width of 80 mm, and thickness of 3 mm.

2.2. Material properties

The material properties of all specimens were determined by tensile coupon tests. The coupons were taken from the center of the web plate in the longitudinal direction of the untested specimens belonging to the same batches as the bending tests. The coupons were prepared and tested according to the American Society for Testing and Materials Standard

Table 2
Measured dimensions and experimental moments for high strength specimens

Specimen	Web d (mm)	Flange b_f (mm)	Thickness t (mm)	Radius r_i (mm)	Length L (mm)	Test M_{Exp} (kmm)
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

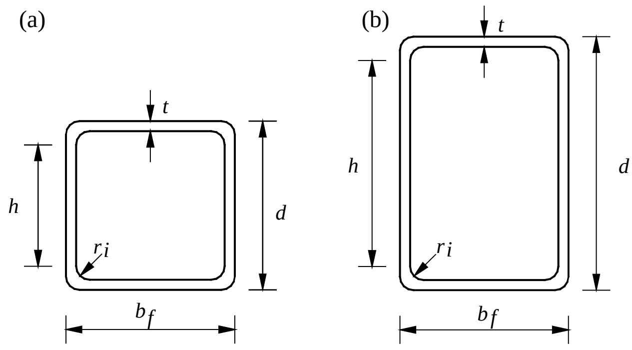

Fig. 1. Definition of symbols: (a) square hollow section; (b) rectangular hollow section.

[7] and the Australian Standard AS 1391 [8] for the tensile testing of metals, using 12.5 mm wide coupons of gauge length 50 mm. The coupons were tested in a 250 kN capacity MTS displacement controlled testing machine using friction grips. Two strain gauges and a calibrated extensometer of 50 mm gauge length were used to measure the longitudinal strain. A data acquisition system was used to record the load and strain at regular intervals during the tests. The static load was obtained by pausing the applied straining for 1.5 min near the 0.2% tensile proof stress and the ultimate tensile strength. This allowed the stress relaxation associated with plastic straining to take place. The material properties obtained from the tensile coupon tests are summarized in Table 3, which includes the type of stainless steel, the measured initial Young's modulus (E), the proportional limit (σ_p), the static 0.2% tensile proof stress ($\sigma_{0.2}$), the static tensile strength (σ_u), and the elongation after fracture (ε) based on a gauge length of 50 mm.

Table 3
Mechanical properties obtained from tensile coupon tests

Specimen	Type	E (GPa)	σ_p (MPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	ε (%)
N40×40×2	304	194	140	447	704	61
N40×40×4	304	196	140	565	725	52
N80×80×2	304	201	120	398	608	59
N80×80×5	304	194	140	448	618	56
N100×50×2	304	198	160	320	635	72
N100×50×4	304	195	140	378	603	60
N120×60×2	304	200	150	361	646	65
N120×60×4	304	200	140	392	696	62
H40×40×2	Duplex	216	164	707	827	29
H50×50×1.5	Duplex	200	182	622	770	37
H150×150×3	HSA	189	155	448	699	52
H150×150×6	HSA	194	147	497	761	52
H140×80×3	Duplex	212	199	486	736	47
H160×80×3	Duplex	208	167	536	766	40
H200×110×4	HSA	200	150	503	961	36

HSA = high strength austenitic.

2.3. Test rig

The schematic views of the test arrangement are shown in Fig. 2a and b, for the elevation and sectional view, respectively. Hinge and roller supports were simulated by half round and round bar. The simply supported specimens were loaded symmetrically at two points through the load transfer plates within the span, using a spreader beam. Half round and round bar were also used at the loading points. In this testing arrangement, pure in-plane bending of the specimens can be obtained between the two loading points without the presence of shear and axial forces. The distance between the two loading points and the distance from the support to the loading point were chosen, such that the section moment capacity could be obtained. Three transducers were used to record the vertical deflections and curvature of the specimens. Two photographs of the test setup for specimens N100×50×2 and H200×110×4 are shown in Fig. 3a and b, respectively.

A 2500 kN capacity DARTEC servo-controlled hydraulic testing machine was used to apply a concentrated compressive force to the spreader beam. Displacement control was used to drive the hydraulic actuator at a constant speed of 1.0 mm/min for all test specimens. A TML data acquisition system was used to record the load and the transducer readings at regular intervals during the tests. The static load was recorded by pausing for

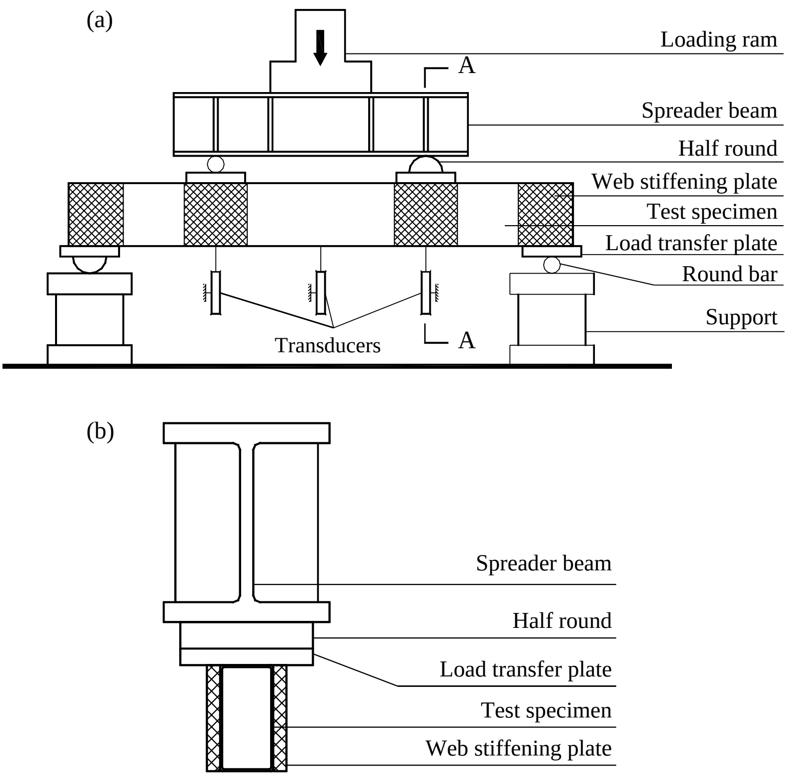

Fig. 2. Schematic views of bending test arrangement: (a) elevation; (b) section A-A.

(a)

(b)

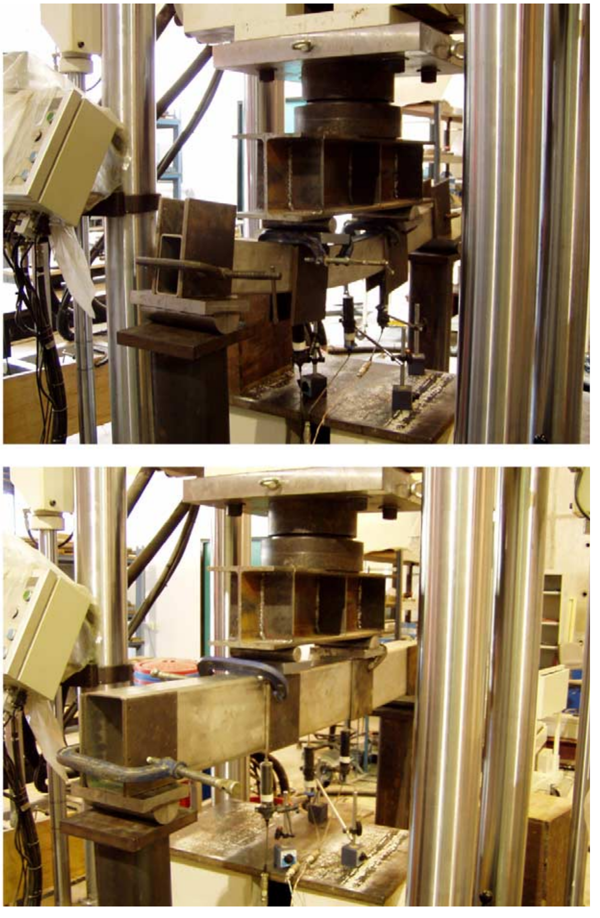

Fig. 3. Test setup: (a) bending test setup of specimen N100×50×2; (b) bending test setup of specimen H200×110×4.

one and half minutes near the ultimate load. This allowed the stress relaxation associated with plastic straining to take place.

2.4. Test results

The experimental ultimate moments (M_{Exp}) of the specimens bending about the major x-axis are given in Tables 1 and 2 for normal strength (type 304) and high strength specimens (high strength austenitic and duplex), respectively. The moments were obtained using half of the ultimate static applied load from the actuator multiplied by the lever arm (distance from the support to the loading point) of the specimens. Out-of-plane bending was not observed in the tests. Fig. 4a and b shows the moment-curvature diagrams fo normal and high strength specimens, respectively. It is expected that the normal strength specimens have a larger curvature than the high strength specimens. This is

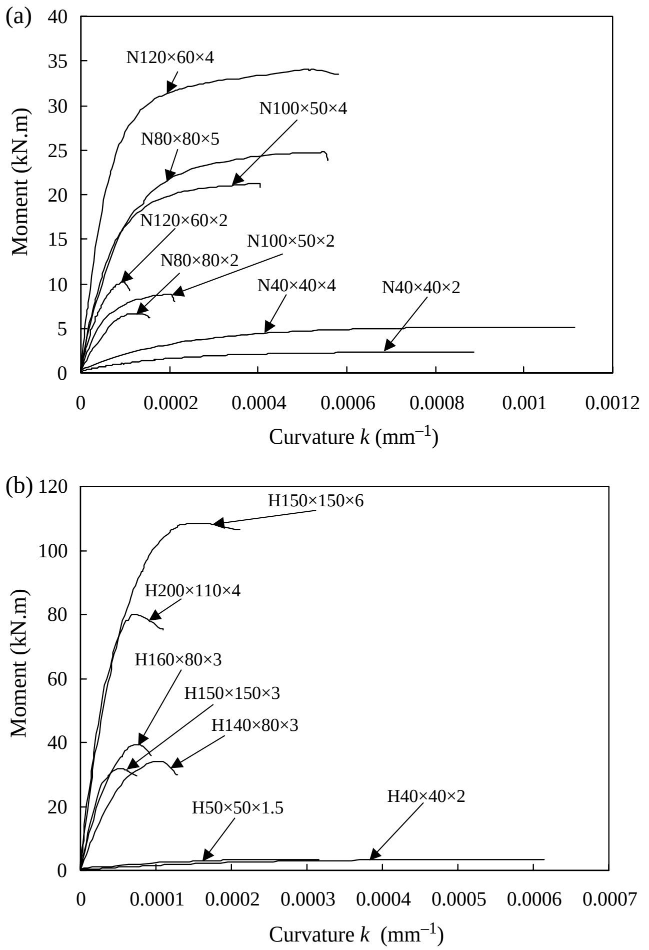

Fig. 4. Moment–curvature diagrams: (a) moment–curvature diagram for normal strength specimens; (b) moment–curvature diagram for high strength specimens

because the normal strength specimens are more ductile than the high strength specimens, as shown in Fig. 4a and b.

3. Comparison of test strengths with theoretical results

The experimental ultimate moments (M_{Exp}) obtained for the normal and high strength specimens were compared with the theoretical elastic (M_{e}) and plastic (M_{p}) bending moments, as shown in Tables 4 and 5. The elastic and plastic bending moments were calculated using the measured 0.2% proof stress ($\sigma_{0.2}$), as listed in Table 3, multiplied by the elastic (Z_x) and plastic (S_x) section moduli of the full sections, respectively, for bending about the major x-axis ($M_{\mathrm{e}}=\sigma_{0.2}Z_x$ and $M_{\mathrm{p}}=\sigma_{0.2}S_x$). The elastic and plastic section moduli were calculated based on the measured cross-section dimensions as detailed in Tables 1 and 2.

Table 4
Comparison of test strengths with theoretical results for normal strength specimens

Specimen	Measured		Test	Theoretical		Comparison	
	E (GPa)	$\sigma_{0.2}$ (MPa)	M_{Exp} (kNm)	Elastic M_e (kNm)	plastic M_p (kNm)	Elastic $\frac{M_{Exp}}{M_e}$	plastic $\frac{M_{Exp}}{M_p}$
N40×40×2	194	447	2.35	1.53	1.82	1.54	1.29
N40×40×4	196	565	5.11	3.06	3.89	1.67	1.31
N80×80×2	201	398	6.64	5.84	6.77	1.14	0.98
N80×80×5	194	448	24.78	13.74	16.66	1.80	1.49
N100×50×2	198	320	8.81	4.71	5.82	1.87	1.51
N100×50×4	195	378	21.28	9.78	12.43	2.18	1.71
N120×60×2	200	361	10.25	7.31	8.97	1.40	1.14
N120×60×4	200	392	34.09	15.04	18.98	2.27	1.80
Mean						1.74	1.40
COV						0.208	0.197

The theoretical elastic and plastic bending moments are conservative for the normal and high strength specimens, except that the plastic bending moment of specimen N80×80×2, with the value of the experimental to theoretical bending moment (M_{Exp}/M_{p}) ratio of 0.98, as shown in Table 4, and the elastic and plastic bending moments of specimen H150×150×3, with the value of M_{Exp}/M_e and M_{Exp}/M_p ratios of 0.90 and 0.78, respectively, as shown in Table 5. The mean value of M_{Exp}/M_e and M_{Exp}/M_p ratios are 1.74 and 1.40 with the coefficients of variation (COV) of 0.208 and 0.197, respectively, for the normal strength specimens. The mean value of M_{Exp}/M_e and M_{Exp}/M_p ratios are 1.35 and 1.09 with the COV of 0.083 and 0.137, respectively, for the high strength specimens.

Table 5
Comparison of test strengths with theoretical results for high strength specimens

Specimen	Measured		Test	Theoretical		Comparison	
	E (GPa)	$\sigma_{0.2}$ (MPa)	M_{Exp} (kNm)	Elastic M_e (kNm)	Plastic M_p (kNm)	Elastic $\frac{M_{Exp}}{M_e}$	Plastic $\frac{M_{Exp}}{M_p}$
H40×40×2	216	707	3.45	2.40	2.86	1.44	1.21
H50×50×1.5	200	622	3.48	2.85	3.32	1.22	1.05
H150×150×3	189	448	31.68	35.19	40.43	0.90	0.78
H150×150×6	194	497	108.60	75.08	88.34	1.45	1.23
H140×80×3	212	486	33.97	23.39	28.65	1.45	1.19
H160×80×3	208	536	39.36	29.84	36.86	1.32	1.07
H200×110×4	200	503	80.15	61.22	75.11	1.31	1.07
Mean						1.35	1.09
COV						0.083	0.137

Table 6
Comparison of test strengths with design strengths for normal strength specimens

Specimen	Measured		Test	Design			Comparison		
	E (GPa)	$\sigma_{0.2}$ (MPa)	M_{Exp} (kNm)	ASCE M_{ASCE} (kNm)	AS/NZS $M_{AS/NZS}$ (kNm)	NAS M_{NAS} (kNm)	ASCE $\frac{M_{Exp}}{M_{ASCE}}$	AS/NZS $\frac{M_{Exp}}{M_{AS/NZS}}$	NAS $\frac{M_{Exp}}{M_{NAS}}$
N40×40×2	194	447	2.35	1.53	1.82	1.53	1.54	1.29	1.54
N40×40×4	196	565	5.11	3.06	3.89	3.06	1.67	1.31	1.67
N80×80×2	201	398	6.64	5.43	5.43	5.43	1.22	1.22	1.22
N80×80×5	194	448	24.78	13.74	16.66	13.74	1.80	1.49	1.80
N100×50×2	198	320	8.81	4.71	5.82	4.71	1.87	1.51	1.87
N100×50×4	195	378	21.28	9.78	12.43	9.78	2.18	1.71	2.18
N120×60×2	200	361	10.25	7.32	7.31	7.31	1.40	1.40	1.40
N120×60×4	200	392	34.09	15.04	18.98	15.04	2.27	1.80	2.27
Mean, P_m							1.74	1.47	1.74
COV, V_p							0.208	0.139	0.208
Reliability index, β_o							3.44	3.30	3.28
Resistance factor, ϕ							0.90	0.90	0.95

4. Reliability analysis

The reliability of the flexural member design rules is evaluated using reliability analysis. The reliability index (β_o) is a relative measure of the safety of the design. A target reliability index of 3.0 for stainless steel structural members is recommended as a lower limit in the ASCE Specification [4]. The design rules are considered to be reliable if the reliability index is greater than 3.0. The resistance (capacity) factor (ϕ) of the flexural strength as recommended by the current ASCE Specification, AS/NZS Standard and NAS Specification, are shown in Tables 6 and 7. The load combinations of 1.2DL+1.6LL and 1.25DL+1.5LL as specified in the American Society of Civil Engineers Standard [9] and the Australian Standard AS 1170.1 [10], respectively, are used in the reliability analysis, where DL is the dead load and LL is the live load. The statistical parameters are obtained from the ASCE Specification [4], where $M_m=1.10$, $F_m=1.00$, $V_M=0.10$, and $V_F=0.05$ are the mean values and coefficients of variation for material properties and fabrication factors. The statistical parameters P_m and V_P are the mean value and coefficient of variation of tested-to-predicted moment ratio, respectively, as shown in Tables 6 and 7. In calculating the reliability index, the correction factor in the ASCE Specification [4] was used. The respective resistance factor (ϕ) and load combinations for the current ASCE Specification, AS/NZS Standard and NAS Specification were used to calculate the corresponding reliability index (β_o). Reliability analysis is detailed in the Commentary of the ASCE Specification [11].

Table 7
Comparison of test strengths with design strengths for high strength specimens

Specimen	Measured		Test	Design			Comparison		
	E (GPa)	$\sigma_{0.2}$ (MPa)	M_{Exp} (kNm)	ASCE M_{ASCE} (kNm)	AS/NZS $M_{AS/NZS}$ (kNm)	NAS M_{NAS} (kNm)	ASCE $\frac{M_{Exp}}{M_{ASCE}}$	AS/NZS $\frac{M_{Exp}}{M_{AS/NZS}}$	NAS $\frac{M_{Exp}}{M_{NAS}}$
H40×40×2	216	707	3.45	2.40	2.86	2.40	1.44	1.21	1.44
H50×50×1.5	200	622	3.48	2.65	2.65	2.65	1.31	1.31	1.31
H150×150×3	189	448	31.68	27.78	27.78	27.78	1.14	1.14	1.14
H150×150×6	194	497	108.60	75.08	88.34	75.08	1.45	1.23	1.45
H140×80×3	212	486	33.97	23.39	28.65	23.39	1.45	1.19	1.45
H160×80×3	208	536	39.36	29.84	29.84	29.84	1.32	1.32	1.32
H200×110×4	200	503	80.15	61.22	75.11	61.22	1.31	1.07	1.31
Mean, P_m							1.35	1.21	1.35
COV, V_p							0.083	0.075	0.083
Reliability index, β_o							3.55	2.98	3.34
Resistance factor, ϕ							0.90	0.90	0.95

5. Comparison of test strengths with design strengths

The experimental ultimate moment (M_{Exp}) obtained from the tests were compared with the nominal flexural strengths predicted using the ASCE Specification [4] and AS/NZS Standard [5]. In addition, the test strengths were also compared with the nominal flexural strengths predicted using the NAS Specification [6] for cold-formed carbon steel structural members. Tables 6 and 7 show the comparison of the test strengths (M_{Exp}) with the unfactored design strengths. In the calculation of the nominal flexural strength, the design rules based on initiation of yielding were used. As mentioned in the Introduction of this paper, the AS/NZS Standard has adopted the design rules of flexural members from the ASCE Specification, except that the AS/NZS Standard has special provisions for square and rectangular hollow sections. The AS/NZS Standard permits plastic design for square and rectangular hollow members with compact sections. The design rules in the ASCE Specification and AS/NZS Standard are identical for the square and rectangular hollow members with non-compact sections. The ASCE Specification and NAS Specification have the same design equations to calculate the strength of the flexural members and using different resistance factors for bending. The design strengths were calculated using the measured cross-section dimensions as shown in Tables 1 and 2 and the measured material properties as summarized in Table 3.

The design strengths predicted by the ASCE Specification are conservative and reliable for normal and high strength tubular sections. The mean values of the tested-to-predicted moment ratio (M_{Exp}/M_{ASCE}) are 1.74 and 1.35, with the corresponding COV of 0.208 and 0.083, and the reliability indices (β_o) of 3.44 and 3.55 for the normal and high strength specimens, respectively, as shown in Tables 6 and 7. For the AS/NZS Standard, the design strengths are conservative and reliable for the normal strength specimens. The value of the reliability index (β_o) is slightly less than the target reliability index of 3.0 for the high strength specimens. The mean values of the tested-to-predicted moment ratio ($M_{Exp}/M_{AS/NZS}$) are 1.47 and 1.21 with the corresponding COV of 0.139 and 0.075, and the reliability indices (β_o) of 3.30 and 2.98 for the normal and high strength specimens, respectively. For the NAS Specification, the design strengths are conservative and reliable for all specimens. The mean values of the M_{Exp}/M_{NAS} ratio and the values of the COV are identical to those predicted by the ASCE Specification, but the reliability indices (β_o) of 3.28 and 3.34 for the normal and high strength specimens, respectively, were obtained when calibrated with the resistance factor of 0.95.

6. Conclusions

An experimental investigation of cold-formed stainless steel square and rectangular hollow sections subjected to major axis bending has been presented in this paper. The test 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 material properties of the test specimens were determined by tensile coupon tests. The experimental results were compared with the theoretical elastic and plastic bending moments. It is shown that the theoretical bending moments are generally conservative for all the test specimens.

The test strengths were also compared with the design strengths obtained using the ASCE Specification, AS/NZS Standard and NAS Specification. The reliability of the design rules has been evaluated using reliability analysis. It is demonstrated that the design strengths predicted by the ASCE Specification and NAS Specification are conservative and reliable for the normal and high strength stainless steel tubular sections. For the AS/NZS Standard, the design strengths are conservative and reliable for the normal strength specimens when calibrated with the existing resistance factor of 0.9. The value of reliability index (β_o) is slightly less than the target reliability index of 3.0 for the high strength specimens.

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