Study on the Bending Capacity of Cold-formed Stainless Steel Hollow Sections

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Abstract

Experimental and numerical studies on the bending capacity of cold-formed stainless steel rectangular and circular hollow sections are reported. Eight four-point bending tests were carried out. Material properties, geometric imperfections, bending capacities, moment-curvature curves were obtained in the tests. Finite element models were developed, and were verified using the test data. Material nonlinearity and geometric imperfections were considered in the modeling. Parameter studies were conducted to expand test data with different material properties and section slenderness. Based on the test results and the finite element analysis results, direct strength formulas were proposed for rectangular and circular hollow sections, respectively. Test data were collected from literatures as references, and compared with predictions of the Eurocode, the American code, the Australian/New Zealand code, the Chinese code, and the continuous strength method (CSM). Comparisons show that the Eurocode, the American code, the Australian/New Zealand code, and the Chinese code are generally conservative. The Chinese code provides most conservative predictions, due to the neglect of strain hardening effect and section plasticity, especially for stocky cross sections. The performance of CSM method is better than the design codes. The proposed formulas show better accuracy in predicting bending capacities of cold-formed stainless steel hollow sections.

Keywords: Cold-formed, Stainless steel, Hollow sections, Bending capacity, tests, Direct strength method

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1 Introduction

Stainless steel has become an attractive material in building constructions due to its durability, favorable mechanical properties, and esthetic appearance. Researches have been carried out on the behaviors of stainless steel members, and design codes have been issued in some countries. Nevertheless, stainless steel contains chromium and nickel, which are more expensive than ferrum in the carbon steel. The high initial cost of the material is the most important issue that restrains its wide application. Using the cross-section with excellent structural behaviors, and improving the accuracy of predictions of design codes are critical points to be considered. In this paper, study was focused on the bending behaviors of cold-formed stainless steel hollow sections.

Johnson and Winter [1] carried out tests on cold-formed stainless steel hat sections and box sections to study the effectiveness of compression flanges and webs. Rasmussen and Hancock [2], Talja and Salmi [3], Real and Mirambell [4], Gardner et al. [5][6], Zhou and Young [7], Theodanous and Gardner [8], Zheng et al. [9], Huang and Young [10], Afshan and Gardner [11], Bock et al.[12], Theofanous et al. [13], Zhao et al. [14][15][16] conducted tests on cold-formed stainless steel rectangular hollow sections in bending. Compared to the number of tests on the rectangular hollow sections, few tests were founded in literature on the circular hollow sections. Rasmussen and Hancock [2], Kiymaz[17], Way[18] performed tests on cold-formed stainless steel circular hollow sections in bending. In these experiments, several grades of stainless steel were considered, including austenitic stainless steel 1.4301(304), 1.4307(304L), 1.4318(301L), 1.4401(316), 1.4404(316L), 1.4435(316L), 1.4541(321), 1.4571(316Ti), ferritic stainless steel 1.4003(3Cr12), 1.4509(441), duplex stainless steel 1.4462(2205), and lean duplex stainless steel 1.4162(32101).

Apart from the experimental studies, design methods were proposed for the predictions of bending capacity of stainless steel hollow sections. The Eurocode 3[19] employs the concept of cross-section classification in the treatment of local buckling, and allows to use section plasticity for stocky cross sections. In the American code[20], section plasticity can be used in the design of rectangular hollow sections, but it is not applicable to the design of circular hollow sections. The provisions in the Australian/New Zealand code[21] are very similar to those in American code, except that partial plasticity design is permitted for the circular hollow section bending members. In the Chinese code[22], plastic design is not allowed for cold formed stainless steel members, and the effective width method is adopted to account for the effectiveness of slender sections. Experimental studies show that these design code are conservative in predicting the bending capacity. To improve the performance of the design codes, Gardner's group [23-26] developed a new method to utilize the strain hardening property of stainless steel, named the continuous strength method (CSM). Huang and Young [10] modified the effective width method in the Eurocode 3[19], and the direct strength method (DSM) formula in the North American Cold-formed Steel Specification[27].

The objective of this paper is to investigate the prediction performance of the Chinese code[22] and to develop the direct strength method (DSM) for stainless steel hollow sections to utilize the strain hardening properties of stainless steel. A series of tests on cold-formed stainless steel hollow sections are firstly presented. Finite element models were developed and validated, and then used to perform parameter analysis. DSM formulas were proposed based on the finite element results. Test data in literatures were collected and compared with the predictions of design codes, the continuous strength method, and the direct strength method.

2 Experimental study

Experimental investigations consist of material tests on cold-formed tubes and the virgin plate, four four-point bending tests on rectangular hollow sections, and four four-point bending tests on circular hollow sections. All the test specimens were cold-rolled from stainless steel plate of austenitic steel S30408 (1.4301)[28]. The steel plate was initially rolled into a circular hollow section and then crushed into a rectangular hollow section. The nominal cross-sections of the rectangular hollow sections are 70mm×3mm and 100mm×3mm. The nominal cross-sections of the circular hollow sections are 89mm×3mm and 127mm×3mm.

2.1 Material tests

A series of material coupon tensile tests were carried out. To obtain the full information of the material properties around the cross section, the cross sections were cut into several strips. The positions of the strips are shown in Fig. 1. The width and the length of the strips are 10mm and 150mm, respectively.

Sixteen coupons from the flat part and two coupons from the corner part were tested for the SHS 70mm×3mm, respectively. For SHS 100mm×3mm, twenty coupons were tested for the flat part, and two coupons were tested for the corner part. Six coupons were tested for each circular hollow section. Besides the coupons from the finished tubes, three coupons were cut from the virgin plate.

Coupon tensile tests were performed in a 100 kN SANS universal testing machine. The tests were

conducted in accordance with the Chinese standard GB/T 228.1-2010[29]. The gauge length of the coupons was 50mm. Load rate was about 0.5 mm/min before the strain reached 0.01, and 5mm/min after that. Prior to testing, a pair of strain gauges were pasted on each face of the coupon to obtain the strain-stress curve. To get rid of introducing moment to the corner coupons, a pair of corner coupons were gripped symmetrically around the steel bar which was located at the end with the same radius as the internal radius of corner in the test specimens. Typical corner coupon is shown in Fig. 2.

Material test results were processed according to the strain-stress model proposed by Gardner[5]. The results of the material test are shown in Table 1 and Table 2 for virgin plates and the tubes, respectively. In these two tables, E_0 is the material Young's modulus, $\sigma_{0.2}$ is the material 0.2% proof stress, n is a strain hardening exponent, $\sigma_{1.0}$ is the material 1.0% proof stress, $n_{0.2,1.0}$ is a strain hardening coefficient representing a curve that passes through 0.2 and 1.0, σ_u is the ultimate tensile stress, δ is the percentage elongation after fracture.

From Table 1 and Table 2, it is concluded that: (1) the nominal yield strength $\sigma_{0.2}$ in the hollow sections are much higher than $\sigma_{0.2}$ of the virgin plates due to the cold working in the production process. The $\sigma_{0.2}$ (489.03 MPa) in the SHS70×3 is over two times of that in the virgin material (243.26 MPa); (2) the ultimate strength is also increased due to cold working, but the degree of increase is not as higher as that of the nominal yield strength; (3) compared to the percentage elongation in the virgin plates, the percentage elongation in the hollow sections was lower. The percentage elongation in the corner part is still higher than 20%, which shows very good ductility.

(4) Because the coupons of virgin plates were curved when taken off from the coil, the elastic Young's modulus is a little bit lower than that of coupons of the hollow sections.

2.2 Beam tests

A total of eight specimens, (two specimens for each section), were tested under four-point bending condition. The dimensions of the specimens were measured, shown in Table 3, using the nomenclatures defined in Fig. 1. Both the local and global geometric imperfections were measured. The global imperfections were measured using a Vernier caliper and one string. The tightened string was used to form a perfect straight line between the two ends, along the longitudinal direction of the specimen. The gap between the string and the edge of the specimen was measured using the Vernier caliper. The maximum value of the gap is regarded as the global imperfection. For the rectangular hollow sections, the local imperfections were examined using an arrangement comprising a dial gauge and a milling machine [5]. For the circular hollow sections, the local imperfections were measured using Vernier caliper. Local imperfections for the circular hollow sections are the average difference between the diameter at the weld and the diameter at the direction 90 degree to the weld.

All specimens with a total length of 1900 mm were simply supported between two steel rollers which allowed axial displacement of the beam's ends. The rollers were located 150 mm inward from the ends of the specimens and, resulting in a span of 1600 mm. The specimens were loaded symmetrically at two points by using a spreader beam. The distance between the two loading point was 600 mm. Two knife-hinge supports were settled between the spreader beam and the loading

points to allow the rotation of the specimens during tests. Loads were applied by using a 300 kN hand hydraulic bottle jack. To avoid the premature failure of the specimens at the loading points due to the concentrated loads, steel plates and steel rings were used to strengthen the cross-section at the loading points for rectangular and circular hollow specimens, respectively. The test configuration is shown in Fig. 3. The steel plate and the steel ring for strengthening are shown in Fig. 4.

A load cell was arranged at the top of the jack, below the bottom of the loading frame to record the total force applied on specimens. At each end of specimens, two displacement transducers (LVDT) were set on the top surface of specimens to measure the rotation of the ends. Another three displacement transducers were placed at the two loading points and the central point of the specimens to measure the vertical displacements. A data acquisition system was used to record the applied loads and the readings of displacement transducers.

Test results are listed in Table 4. In this table, F_t is the maximum load applied using the hydraulic jack, M_t is the ultimate bending moment. For the slender sections, SHS100×3 and CHS127×3, the major failure is the local buckling of the flange in compression. The compression flange buckles inwards with consistent deformation at the web. This type of failure mode is shown in Fig. 5(a) and (b) for rectangular and circular hollow sections, respectively. After reaching ultimate load, the stiffness of the specimen became negative, while the vertical displacement increased very fast. For the stocky sections, SHS70×3 and CHS89×3, no cross-section buckling failure occurred during the tests. For SHS70×3 specimens, at the last stage of the loading, the load reached a plateau, while the vertical displacement increased rapidly. For CHS 89×3 specimens, the circular cross-section

between loading points became elliptical at the ultimate state, while the height of the cross section considerably decreased. Fig. 5(c) shows the failure mode of CHS89×3-1900a.

Fig. 6 shows the relationship between the moment at the central section and the curvature at the pure bending part. In this figure, the vertical axis is the moment at the center of the specimen, while the horizontal axis is the curvature of the specimen at the pure bending part. The curvatures were calculated using Eq. (1) [11]

$$k = \frac{8(D_{\text{midspan}} - D_{\text{average}})}{4(D_{\text{midspan}} - D_{\text{average}})^2 + L_{\text{midspan}}^2} \quad (1)$$

where D_{midspan} is the vertical deflection at mid span, D_{average} is the average vertical displacement at the loading points, and L_{midspan} is the length between the loading points.

3 Finite element modeling and validation

The finite element models of test specimens were developed in ABAQUS[30] using S9R5 element. Two different models (Model 1 and Model 2) for every specimen were built. In Model 1, the full length of test specimens were built with pinned-roller constraint at the bearings shown in Fig. 7. To simulate the enhancement at the loading points and the actual constraint at the bearings, nodes of the cross-sections at the loading points and the supports were coupled with a set of reference points with *rigid body* constraint. Enhanced corner material properties were considered, and the enhanced region is assumed to extend as far as two times the thickness into the adjacent flat parts [5]. In Model 2, only the pure bending part of the test specimen was built. This model was simply-supported, and moments were applied at the two ends. *Rigid body* coupling was applied at the loading points.

In these two models, the geometric imperfections were introduced into model by using the first eigen buckling mode scaled by the measured magnitude of local imperfection to the perfect structural model. For the cold formed sections, the major type of residual stresses is bending residual stress [31]. During tensile coupon tests, the coupons are straightened, which effectively re-introduces the bending residual stresses into the coupons. Therefore, provided the material properties are established using coupons cut from the cross-section, the effects of bending residual stresses are inherently present, and do not need to be defined explicitly in the numerical models[2][5][32].

Analysis results of these two models were compared with test results, shown in Table 5. In this table, M_t is the test bending strength, M_{1u} and M_{2u} are the predicted bending strength of Model 1 and Model 2, respectively. It indicates that bending strength from the test is slightly (about 5%) higher than that predicted by Model 1 on average. That is due to the friction between the knife-hinge and the steel plates (the steel rings for CHS) at the loading points. The test specimen was strengthened by the spreader beam due to the friction force. Although fine sand was used to reduce the friction, it was observed that the friction force pushed the knife-hinge together with the steel plates (the steel rings for CHS) moving towards the supports. Compared the last two columns in Table 5, it indicates that Model 1 and Model 2 provide the same predictions for the test specimens. These two models also provide similar eigen buckling modes, and failure modes. Considering the computation efforts, Model 2 is used in the following analyses.

Fig. 8 shows the failure modes predicted by the finite element results (Model 1). Compared with

Fig. 5, it can be concluded that finite element model can predict failure modes correctly. Fig. 9 shows the moment-curvature curves obtained from tests and finite element models. Over all the moment-curvature curves predicted by finite element model agree well with the test curves. However, at the ultimate strength stage, the test curves are a little bit higher than the curves predicted by finite element models. That is mainly because of the friction force between the knife-hinge and the steel plates

4 Proposed method

4.1 Parameter analysis

The parameter analysis was based on the numerical simulation using Model 2. To expand the data on the bending capacity of cold-formed stainless steel hollow sections, bending members over a wider range of material properties and section slenderness were calculated. Thirty types of material parameters were used. The nominal yield strength considered includes 200MPa, 300MPa, 400MPa, 500MPa, and 600MPa. The strain hardening exponent was set as 3, 4, 5, 6, 7, and 8. Two-stage material model proposed by Gardner [5] was used and material parameters for the second stage of the material model were predicted using approximate formulas [33]. These material properties could represent the commonly used austenitic and duplex stainless steel. Ferritic stainless steel, which has higher strain hardening exponent and lower σ_u/σ_y ratio, was not covered in this paper. The consideration of enhanced corner material properties was simplified as specifying the average value of material properties in the flat and corner regions among the full cross section.

For the rectangular hollow sections, eighteen types of section slenderness were considered, ranging

from 0.25 to 2.0. It should be noted that the section slenderness is calculated using the local buckling stress of the whole cross section and the nominal yield stress. The definition of section slenderness is given in Eq. (2).

$$\lambda = \sqrt{\frac{M_y}{M_{cr}}} \quad (2)$$

where M_y is the nominal yield moment and, M_{cr} is the eigen buckling moment of the whole cross section in bending. The overall profile of the cross-section is 100 mm×100 mm and the thickness varied according to the section slenderness. The outer corner radius is two times of the thickness.

For the circular hollow sections, twenty types of D/t ratio were considered ranging from 10 to 300, corresponding to the section slenderness from 0.1 to 1.5. The outer diameter of the cross-section for all CHS sections is 200 mm, and the thickness varied according to the section slenderness. The length of the members in the calculations was 1000 mm and 2000 mm for rectangular and circular hollow sections, respectively, which is long enough to minimize the influence of the rigid body coupling at the ends to the bending capacity.

Local imperfections were introduced into finite element models using the first eigen buckling mode scaled by the experienced imperfection magnitudes shown in Eq. (3) [5].

$$w/t = \begin{cases} 0.023(\sigma_y/\sigma_{cr}) & \text{for RHS} \\ 0.2 & \text{for CHS} \end{cases} \quad (3)$$

where w is the imperfection magnitude, t is the thickness of cross section, σ_y is the nominal yield stress, and σ_{cr} is the elastic buckling stress. The residual stresses were not considered in the finite element model.

Totally 540 models were analyzed for rectangular hollow sections, and 600 models were analyzed for circular hollow sections. Results of parameter analysis are shown in Figs. 10 and 11 (the black dots in these figures). It indicates that the bending capacity ratio (M_u/M_y) is related to the section slenderness as well as material property. For the members with the same section slenderness, the maximum variation on the bending capacity ratio reaches up to 15% due to the difference of material properties. In order to propose simple and practical design formulas, the influence of material properties on the bearing capacity is neglected and the proposed formulas will be aimed to be applicable to the commonly used stainless steel grades

4.2 DSM formulas

Direct strength method (DSM) is one of the most popular design methods in predicting capacities of thin-walled members. DSM is initially developed to replace the effective width method, which is too complex in predicting the distortional buckling capacity. Recently, DSM has been utilized in the design of stainless steel structural members. In this paper, the DSM method was employed to develop a prediction formula for the local buckling capacity of stainless steel hollow sections.

DSM formulas were obtained by fitting the finite element results shown in Figs.10 and 11. Design formula for rectangular and circular hollow sections are shown in Eqs. (4) and (5), respectively.

$$M_u = \frac{1.1 - 0.17\lambda^{1.82}}{\lambda^{0.32}} M_y \leq \sigma_u W_p \quad (4)$$

$$M_u = \frac{1 - 0.62\lambda}{\lambda^{0.33}} M_y \leq \sigma_u W_p \quad (5)$$

where M_u is the predicted bending capacity, λ is the section slenderness, M_y is the yield moment, σ_u

is the ultimate tensile strength, and W_p is the plastic section modulus. It should be noted that $\sigma_u W_p$ was set as the maximum of the designed bending capacity to avoid mathematic error for compact cross sections.

When using the DSM formulas, section slenderness λ is an important factor. According to the definition of section slenderness (Eq. (2)), critical local buckling moment M_{cr} should be determined in advance. For rectangular hollow sections, critical local buckling moment M_{cr} can be expressed by Eq. (6).

$$M_{cr} = k_f \frac{4\pi^2 E}{12(1-\nu^2)} \left(\frac{t}{b}\right)^2 W \quad (6)$$

where, E is the elastic Young's modulus, ν is the Poisson ratio; t is the thickness, W is the elastic section modulus, b is the width of the flange measured from the mid-thickness ($B-t$), and k_f is the interactive factor, which indicates the contribution of the web stiffness to the local buckling of the flange.

In order to develop an expression for the interactive factor k_f , sixteen rectangular hollow sections with different aspect ratio B/H were analyzed using the finite strip software CUFSM [34][35]. In the CUFSM, a mode identification technique is utilized to obtain the pure local buckling mode. Typical calculation result is shown in Fig. 12.

Fig. 13 shows the analysis results along with the aspect ratio B/H . It indicates that as the ratio of B/H increases, the interactive factor k_f increases as well. The interactive factor is more sensitive to the ratio of B/H as the ratio of B/H is less than 0.5. Based on the calculation results, the interactive

factor k_f is expressed in a two-stage expression, i.e. Eq. (7).

$$k_f = \begin{cases} 3.29 \frac{B}{H} - 0.37 & 0.1 < \frac{B}{H} < 0.5 \\ 0.27 \frac{B}{H} + 1.14 & 1.0 > \frac{B}{H} \geq 0.5 \end{cases} \quad (7)$$

where B is the overall width of the flange, and H is the overall height of the cross section.

Comparisons among the analysis results by CUFSM, the predictions of the Chinese code [22], and Eq. (7) are shown in Fig. 13. The proposed formula provides more accurate predictions than the Chinese design code in calculating the interactive factor. The Chinese code [22] gives unsafe predictions as the ratio of B/H is higher than 0.8.

For circular hollow sections, the critical local buckling moment M_{cr1} can be approximately calculated using Eq. (8) [36].

$$M_{cr1} = \frac{E}{\sqrt{3(1-\nu^2)}} \frac{t}{R} W \quad (8)$$

where M_{cr1} , E , ν , t , W are consistent with those in Eq.(6), and R is the radius of the cross section.

5 Comparisons of the test strengths with the design strengths

5.1 Current design codes

5.1.1 Eurocode (EN 1993-1-4:2006/A1:2015)

In the Eurocode[19], cross sections are classified into four classes according to their plastic behaviors. For Class 1 and Class 2, bending capacity was calculated using the plastic section modulus. For Class 3, the elastic section modulus is used. For Class 4 whose failure is dominated by local buckling, the effective cross section modulus is used. Eq. (9) shows the design formula.

$$M_{c,Rd} = \begin{cases} \frac{W_{pl} f_y}{\gamma_{M0}} & \text{for Class 1 and Class 2} \\ \frac{W_{el,min} f_y}{\gamma_{M0}} & \text{for Class 3} \\ \frac{W_{eff,min} f_y}{\gamma_{M0}} & \text{for Class 4} \end{cases} \quad (9)$$

where $M_{c,Rd}$ is the design bending capacity, W_{pl} is the plastic section modulus, $W_{el,min}$ is the minimum elastic section modulus, $W_{eff,min}$ is the minimum effective section modulus, f_y is the nominal yield stress, and γ_{M0} is the partial factor. Table 6 shows the classification limits. In this table, c is the width of the web or the flange, t is the thickness; d is the diameter of the circular cross section; ε is the material factor, calculated using $(235 \cdot E / f_y / 210000)^{0.5}$.

5.1.2 American code (SEI/ASCE 8-02)

In the American code [20], two design methods are specified for rectangular hollow section. One is based on the initial yielding assumption, while the other one utilizes the inelastic reserve capacity brought about by the spread of plasticity through the section. The second method was employed in this paper. In the second method, the maximum compression strain is defined by $C_y \times f_y / E_0$. C_y is the compression strain factor, calculated by using Eq. (10).

$$C_y = \begin{cases} 3 & w/t \leq \lambda_1 \\ 3 - 2 \left(\frac{w/t - \lambda_1}{\lambda_2 - \lambda_1} \right) & \lambda_1 < w/t < \lambda_2 \\ 1 & w/t \geq \lambda_2 \end{cases} \quad (10)$$

where w is the width of the compression flange, t is the thickness of the flange, λ_1 is calculated using $1.11/(f_y/E)^{0.5}$, and λ_2 is calculated using $1.28/(f_y/E)^{0.5}$. The bending capacity is then calculated by integrating the stress along the cross-section based on the elastic-perfect-plastic material assumption and plane section assumption. The maximum bending capacity should not exceed $1.25M_e$. For

circular hollow sections, plastic design is not allowed, and a linear interpolation is used to account for the effectiveness of the cross-section when the D/t ratio is beyond a certain limit (see Eq. (11)).

$$M_n = \begin{cases} f_y S_f & \frac{D}{t} \leq \frac{0.112E}{f_y} \\ K_c f_y S_f & \frac{0.112E}{f_y} \leq \frac{D}{t} \leq \frac{0.881E}{f_y} \end{cases} \quad (11)$$

where D is the diameter of the circular hollow section, S_f is the elastic section modulus of full, unreduced cross sections, and K_c is the reduction factor calculated by Eq. (12).

$$K_c = \frac{(1-C)(E/f_y)}{(8.93-\lambda_c)(D/t)} + \frac{5.882C}{8.93-\lambda_c} \quad (12)$$

where C is the ratio of the proportionality stress-to-yield stress, and λ_c is equal to $3.048C$.

5.1.3 Australian/New Zealand code(AS/NZS 4673-2001)

In Australian/New Zealand code[21], the design process of the bending capacity is similar to that in the American code. For rectangular hollow sections, the upper limits of bending capacity is the plastic moment ($f_y S_p$) instead of $1.25M_e$ for the stocky cross sections with w/t less than λ_1 . For circular hollow sections, the upper limits of bending capacity is the plastic moment ($f_y S_p$). An interpolation formula is used to consider the effective cross-section properties (see Eq. (14)). Eq. (13) and Eq. (14) show formulas used to calculate bending capacity of circular hollow sections in the Australian/New Zealand codes. The symbols in these equations have the same meanings as those in Eq. (11) and Eq. (12).

$$M_n = \begin{cases} f_y S_p & \frac{D}{t} \leq \frac{0.078E}{f_y} \\ f_y S_f & \frac{0.078E}{f_y} \leq \frac{D}{t} \leq \frac{0.31E}{f_y} \\ K_c f_y S_f & \frac{0.31E}{f_y} \leq \frac{D}{t} \leq \frac{0.881E}{f_y} \end{cases} \quad (13)$$

$$K_c = \frac{(1-C)(E/f_y)}{(3.226-\lambda_c)(D/t)} + \frac{0.178C}{3.226-\lambda_c} \quad (14)$$

5.1.4 Chinese code (CECS 410:2015)

In the Chinese code [22], the plastic design for RHS is not allowed currently. Effective width method is adopted to account for the effectiveness of the slender section. When the b/t ratio is beyond the limits listed in Table 7, the reduction factor should be calculated according to Eq. (15).

$$\frac{b_e}{t} = \begin{cases} \left(2.41 - 1.63\sqrt{\bar{\lambda}_p}\right) \frac{b_c}{t} & \bar{\lambda}_p \leq 1.0 \\ \left(\frac{\bar{\lambda}_p}{3.15\bar{\lambda}_p - 1.86}\right) \frac{b_c}{t} & 1.0 < \bar{\lambda}_p \leq 1.5 \\ \left(\frac{0.092\bar{\lambda}_p + 0.65}{\bar{\lambda}_p}\right) \frac{b_c}{t} & \bar{\lambda}_p > 1.5 \end{cases} \quad (15)$$

where b_c is the width of the plate in compression, b_e is the effective width of the plate, t is the thickness of the plate, $\bar{\lambda}_p$ is the slenderness of the plate, equal to $(\sigma/\sigma_{cr})^{0.5}$, σ is the maximum stress in the plate, and σ_{cr} is the critical buckling stress of the plate, calculated according to Eq.(16).

$$\sigma_{cr} = \frac{kk_1\pi^2 E_0}{12(1-\nu^2)} \left(\frac{t}{b}\right)^2 \quad (16)$$

where b is the total width of the plate, k is the buckling factor (4 for the flange, and 23.87 for the web), and k_1 is the interactive factor between the web and the flange calculated using Eqs. (17) and (18).

$$k_1 = \begin{cases} \frac{1}{\sqrt{\xi}} & \xi \leq 1.1 \\ 0.11 + \frac{0.93}{(\xi - 0.05)^2} & \xi > 1.1 \end{cases} \quad (17)$$

$$\xi = \frac{c}{t_c} \frac{t_b}{b} \sqrt{\frac{k}{k_c}} \quad (18)$$

where c , t_c , and k_c are the width, the thickness, and the buckling factor of the plate next to the plate being calculated. For example, when calculating the interactive factor of the web to the flange, c , t_c , and k_c are the width, the thickness, and the buckling factor of the web, respectively. For the CHS, yield moment is used for sections within the limits given in Table 7.

5.1.5 DSM method

Huang and Young [10] did tests and numerical simulations on the lean duplex stainless steel rectangular cross section and improved the DSM formula in North American Specification for the Design of Cold-formed Steel Structural Members [27], as shown in Eq. (19).

$$M_{DSM} = \begin{cases} 1.1((0.776 - \lambda_l) + 1)M_y & \lambda_l \leq 0.776 \\ \left(1 - 0.15\left(\frac{M_{crl}}{1.1M_y}\right)^{0.4}\right)\left(\frac{M_{crl}}{1.1M_y}\right)^{0.4} 1.1M_y & \lambda_l > 0.776 \end{cases} \quad (19)$$

where M_y is the yield moment of the cross-section, M_{crl} is the critical elastic local buckling moment, and λ_l is the section slenderness.

5.1.6 CSM method

Gardner's group [23-26] developed the continuous strength method (CSM) to utilize the strain hardening property of stainless steel. The CSM method is a strain based design approach featuring two key components: (1) a base curve that defines the level of strain that a cross-section can carry

in a normalized form, and (2) a material model, which allows for strain hardening and, in conjunction with the strain measurement, can be used to determine the cross-section bending resistance. The base curve for rectangular and circular hollow sections is given by Eq. (20)[25] and Eq. (21)[26], while the material model is shown in Eqs. (22), (23) and (24).

$$\frac{\varepsilon_{\text{csm}}}{\varepsilon_y} = \frac{0.25}{\lambda_p^{3.6}} \leq \min \left(15, \frac{C_1 \varepsilon_u}{\varepsilon_y} \right) \quad (20)$$

$$\frac{\varepsilon_{\text{csm}}}{\varepsilon_y} = \begin{cases} \frac{4.44 \times 10^{-3}}{\lambda_c^{4.5}} \leq \left(15, \frac{C_1 \varepsilon_u}{\varepsilon_y} \right) & \lambda \leq 0.3 \\ \left(1 - \frac{0.224}{\lambda_c^{0.342}} \right) \frac{1}{\lambda_c^{0.342}} & 0.3 \leq \lambda < 0.6 \end{cases} \quad (21)$$

$$\sigma = \begin{cases} E\varepsilon & \sigma \leq f_y \\ E\varepsilon + E_{sh}(\varepsilon - \varepsilon_y) & \sigma > f_y \end{cases} \quad (22)$$

$$E_{sh} = \frac{f_u - f_y}{C_2 \varepsilon_u - \varepsilon_y} \quad (23)$$

$$\varepsilon_u = C_3 \left(1 - \frac{f_y}{f_u} \right) + C_4 \quad (24)$$

where, ε_{csm} is the maximum compression strain that the cross section can carry, ε_y is the yield strain (f_y/E), ε_u is the ultimate tensile strain, λ_p is the slenderness of rectangular hollow sections, λ_c is the slenderness of circular hollow sections, E_{sh} is the tangent elastic modulus of the material as the stress is beyond the nominal yield stress, and C_1 , C_2 , C_3 , and C_4 are parameters, related to the types of material. For austenitic and duplex stainless steel, C_1 , C_2 , C_3 , and C_4 are taken as 0.1, 0.16, 1.0, and 0, respectively. For ferritic stainless steel, C_1 , C_2 , C_3 , and C_4 are 0.4, 0.45, 0.6, and 0, respectively.

5.2 Comparisons

Test data on bending capacities of rectangular and circular hollow sections were collected from literatures and compared with current design codes including, the Eurocode, the American code, the

Australian/New Zealand code, and the Chinese code, as well as the CSM method, and the proposed method. Several notes should be made before the comparisons: (1) The partial factors (γ_{M0} and ϕ) were set to 1.0. (2) Tensile material properties from corresponding tests were used in calculations. (3) When using the Eurocode, the corner enhancement of rectangular hollow section was considered in the capacity prediction for Class 1, Class 2, and Class 3 cross-sections. (4) When using the American code, the increase of yield stress in the corner region was ignored for all the cross sections according to the related provisions in the code. (5) When using the Chinese code, corner enhancement was neglected for all the cross sections. (6) When calculating the yield moment M_y for the DSM method proposed by Huang, cold working effect in the corner region was neglected, since the factor 1.1 in Eq.(19) has been used to include the corner enhancement. (7) When calculating the section slenderness for the CSM and DSM methods proposed by this paper, the cold working effect in the corner region was included in the yield moment M_{yc} . ($M_{yc}=\sigma_f \times W_f + \sigma_c \times W_c$, in which, σ_f and σ_c are the nominal yield stress of the flat and corner region, respectively, and W_f and W_c are the elastic section modulus of the flat and corner region, respectively.).

Calculation results are shown in Table 8 and Table 9 for rectangular and circular hollow sections, respectively. In these two tables, M_{en} , M_{asce} , M_{au} , M_{cn} , M_{csm} , M_h , and M_p are the predicted bending capacity by using the Eurocode, the American code, the Australian/New Zealand code, the Chinese code, the CSM method, the DSM formula proposed by Huang, and DSM formula proposed by this paper, respectively.

From Table 8, it can be concluded that: (1) All the seven design methods are conservative in predicting the bending capacity of rectangular hollow sections. (2)The Chinese code gives the

highest ratio of the test results over the predicted values, with the mean value of 1.48 and large scatter of 0.26. The American code, the Australian/New Zealand code, the Eurocode, and the CSM method show good performance in the ascending order. (3) The DSM formula proposed by Huang provides good predictions with the mean value 1.07. The proposed DSM method gives the most accurate predictions. The major difference between these two DSM formulas is the upper limit of the bending capacity. The upper limit of Eq.(19) is $1.85M_y$, while Eq.(3) adopts $\sigma_u W_u$ as the maximum value of bending capacity.

Fig.14 shows the ratios of the test results over the predictions by Eurocode and Chinese code. It indicates that: (1) Chinese code shows good predictions for specimens with slenderness higher than 0.75, which is the limit beyond which the effectiveness of the section should be considered. (2) Chinese code gives more conservative predictions for Class 1 and Class 2 sections. That is because Chinese code uses the yield moment, while the Eurocode adopts the plastic moment for Class 1 and Class 2 sections. (3) For Class 3 and Class 4 sections with slenderness ranging from 0.62 to 0.75, the two codes show similar performance.

Test data collected were also plotted in Fig. 10 together with the finite element results and the proposed strength curve. It can be concluded that: (1) Most of the test data points lie above of the line $M_u/M_{yc}=1.0$ which demonstrates that the strain hardening considerably contributes to the bending capacity of the stainless steel members. (2) Test data points of members of austenitic and duplex stainless steel show the same trend, a little bit above the proposed strength curve, while test data points of ferritic stainless steel members lie below the proposed strength curve. So, the

proposed curve gives unsafe predictions for ferritic stainless steel members. Compared with austenitic stainless steel and duplex stainless steel, ferritic stainless steel has low ratio of σ_u/σ_y , which is the main reason for the different performance of austenitic and duplex stainless steel members to the ferritic stainless steel members. (3) Due to different strengthening methods used in tests to prevent premature local buckling at the loading points, test data points with similar section slenderness scatter in a considerable range.

From Table 9, we can conclude that: (1) the American code provides the most conservative predictions followed by Chinese code, with the ratio of test versus predictions as 1.48 and 1.41, respectively. These two codes do not allow plastic design for circular hollow sections. And the effectiveness of the cross-section is considered when the D/t ratio is beyond certain limits according to the American code. (2) The Eurocode and the Australian/New Zealand code provide the same predictions for all the test specimens. That is because the section slenderness limit for Class 2 and Class 3 in the Eurocode is almost the same with the limit for the plastic /elastic design in the Australian/New Zealand code. (3) CSM method gives good predictions for specimens with section slenderness higher than 0.3, while for the case when the slenderness is less than 0.3, this method shows very conservative predictions. (4) The proposed method provides good predictions on the safe side, with the mean ratio (test over predictions) of 1.11 and the scatter of 0.09.

Test data of circular hollow members are also plotted in Fig. 11 together with finite element analysis results and the proposed strength curve. Due to the strain hardening of stainless steel, the ratios of the test results over yield moments are higher than 1.0 for most of the test specimens. The proposed

curve lies on the lower boundary of the test data. It provides better predictions for the test specimens with section slenderness less than 0.35.

6 Conclusions

A series of tests on the bending capacity of stainless steel rectangular and circular hollow sections were reported. Material properties, geometric imperfections, bending capacities, and moment-curvature curves were obtained. Finite element models were built and validated for the test specimens. Two kinds of finite element models based on full-length members and pure bending segment of members provide almost the same bending capacity, which is about 5% lower than the test results due to the friction between the knife-hinge and the strengthen rig in the test. Parameter analysis were conducted to consider the influence of section slenderness and material properties on bending capacity. DSM formulas were proposed by fitting the finite element results for rectangular and circular hollow sections, respectively. Test data collected from literatures were compared with the predictions of current design codes and the proposed method. Comparisons show that the Eurocode, the American code, the Australian/New Zealand code, and the Chinese code provide conservative predictions for both rectangular and circular hollow sections. CSM method shows better predictions than the design codes. The Chinese code provides very good predictions for slender rectangular sections, but generates the most conservative predictions for stocky cross sections due to the neglect of strain hardening effect and section plasticity. The proposed method provides safe and accurate predictions for the bending capacity of austenitic and duplex stainless steel hollow members. The average ratio and the standard deviation of the test results over the predicted strengths are 1.04 and 0.10 for rectangular hollow members, and 1.11 and 0.09 for circular

hollow members. The behaviors of ferritic stainless steel members are different from that of austenitic and duplex stainless steel members and the proposed formulas were not applicable. More work need to be done on the bending capacity of ferritic stainless steel members.

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Figure

Figure 1 Definitions of symbols and locations of coupons in cross-sections

Figure 2 Corner coupons

Figure 3 Layout of the four-point bending test

(a) Steel plate

(b) Steel ring

Figure 4 Steel plate and steel ring at the loading point

(a) Rectangular hollow section (SHS100×3-1900a)

(b) Circular hollow section (CHS127×3-1900a)

(c) Circular hollow section (CHS89×3-1900b)

Figure 5 Failure modes of test specimens

Figure 6 Moment-Curvature curves of test specimens

Figure 7 Boundary conditions in the finite element models

(a) Rectangular hollow section (SHS100×3-1900a)

(b) Circular hollow section (CHS127×3-1900a)

(c) Circular hollow section (CHS89×3-1900b)

Figure 8 Failure modes predicted using FEM

Figure 9 Comparison of experimental and simulation (Model 1) moment-curvature curves

Figure 10 Comparisons of the test data and the finite element results with the predictions of the proposed DSM formula for rectangular hollow sections

Figure 11 Comparisons of the test data and the finite element results with the predictions of the proposed DSM formula for circular hollow sections

Figure 12 Typical output of the CUFSM for RHS subjected pure bending

Figure 13 Comparisons of the analysis results and the predictions of the design code and the proposed formula for the interactive factor

Figure 14 Comparisons of the Eurocode and the Chinese code with the test data

Table 1 Weighted average tensile material properties of virgin plates

Cross section	E_0	$\sigma_{0.2}$	$\sigma_{1.0}$	σ_u	n	$n_{0.2,1.0}$	δ
SHS70×3	176472	243.26	297.85	636.57	3.77	2.25	0.60
CHS89×3							
SHS100×3	187566	231.78	279.35	627.61	4.97	2.11	0.63
CHS127×3							

Table 2 Weighted average tensile material properties of finished tubes

Cross section	Position	E_0	$\sigma_{0.2}$	$\sigma_{1.0}$	σ_u	n	$n_{0.2,1.0}$	δ
SHS70×3	Flat	196838	489.03	586.71	771.86	3.90	3.94	0.42
	Corner	195303	620.24	781.52	895.98	4.30	4.09	0.25
SHS100×3	Flat	193096	408.27	487.31	712.46	4.17	3.67	0.50
	Corner	194591	560.63	679.45	822.84	4.49	3.73	0.31
CHS89×3		201807	385.35	440.13	678.77	5.44	3.13	0.59
CHS127×3		203186	329.02	375.84	648.44	6.22	2.61	0.60

Table 3 Measured dimensions of test specimens

Specimens	Dimensions					Imperfections/mm	
	H/mm	B/mm	t/mm	r_o/mm	L/mm	Local	Overall
SHS70×3-1900a	71.4	71.8	3.1	6.25	1900	0.086	1.3
SHS70×3-1900b	71.3	71.8	3.1	6.25	1900	0.096	1.6
SHS100×3-1900a	102.2	102.5	3.09	5.88	1900	0.11	2.7
SHS100×3-1900b	102.0	102.8	3.09	5.88	1901	0.11	1.0
CHS89×3-1900a	89.3		3.11		1900	0.12	0
CHS89×3-1900b	89.15		3.11		1900	0.12	0.5
CHS127×3-1900a	127.8		3.04		1900	0.30	0
CHS127×3-1900b	127.8		3.04		1900	0.30	1.3

Table 4 Results of four-point bending tests

Specimens	F_t/kN	$M_t/kN.m$	Failure mode
SHS70×3-1900a	53.84	13.46	Outwards bulge in compression flange adjacent to the steel plate
SHS70×3-1900b	54.82	13.71	Extensive plastic deformation
SHS100×3-1900a	85.53	21.38	Central inwards bulge in compression flange
SHS100×3-1900b	85.83	21.46	Outwards bulge in compression flange adjacent to the steel plate
CHS89×3-1900a	42.96	10.74	Extensive plastic deformation
CHS89×3-1900b	40.73	10.18	Extensive plastic deformation
CHS127×3-1900a	66.86	16.72	Central inwards bulge in compression portion
CHS127×3-1900b	66.56	16.64	Outwards bulge in compression portion adjacent to the steel plate

Table 5 Comparisons of test results and finite element analysis results

Specimens	M_t kN.m	M_{1u} kN.m	M_{2u} kN.m	M_t/M_{1u}	M_t/M_{2u}
SHS70×3-1900a	13.46	13.00	13.01	1.04	1.03
SHS70×3-1900b	13.71	13.00	13.01	1.05	1.05
SHS100×3-1900a	21.38	20.42	20.42	1.05	1.05
SHS100×3-1900b	21.46	20.42	20.42	1.05	1.05
CHS89×3-1900a	10.74	9.84	9.85	1.09	1.09
CHS89×3-1900b	10.18	9.84	9.85	1.03	1.03
CHS127×3-1900a	16.72	16.17	16.25	1.03	1.03
CHS127×3-1900b	16.64	16.17	16.25	1.03	1.02
			AVG.	1.05	1.05
			COV..	0.02	0.02

Table 6 The classification limits for cold-formed stainless steel hollow sections in the Eurocode

Limits	RHS		CHS
	Web	Flange	
Class 1	$c/t \leq 72\epsilon$	$c/t \leq 33\epsilon$	$d/t \leq 50\epsilon^2$
Class 2	$c/t \leq 76\epsilon$	$c/t \leq 35\epsilon$	$d/t \leq 70\epsilon^2$
Class 3	$c/t \leq 90\epsilon$	$c/t \leq 37\epsilon$	$d/t \leq 280\epsilon^2$

Table 7 The classification limits for cold-formed stainless steel hollow sections in the Chinese code

Grades	RHS		CHS
	Web	Flange	
S30403,S31603	121	49	100
S30408,S31608	110	44	90
S22053,S22253	74	30	50

Table 8 Comparisons of test results and predictions of the current design methods and the proposed design method for rectangular hollow sections.

Ref.	Specimens	Grade	λ	$\frac{M_t}{M_{en}}$	$\frac{M_t}{M_{asce}}$	$\frac{M_t}{M_{au}}$	$\frac{M_t}{M_{cn}}$	$\frac{M_t}{M_{csm}}$	$\frac{M_t}{M_h}$	$\frac{M_t}{M_p}$
2	S1B1	304L	0.56	1.28	1.45	1.43	1.68	1.30	1.22	1.19
3	RHS-1 B1	1.4301	0.29	1.23	1.33	1.31	1.62	1.07	0.98	0.94
	RHS-1 B2		0.27	1.20	1.26	1.24	1.52	1.07	0.92	0.95
	RHS-1 B3		0.29	1.24	1.34	1.32	1.62	1.08	0.99	0.95
	RHS-2 B1		0.64	1.26	1.29	1.29	1.48	1.18	1.14	1.07
	RHS-2 B2		0.65	1.26	1.29	1.29	1.49	1.19	1.14	1.07
	RHS-2 B3		0.64	1.26	1.29	1.29	1.48	1.18	1.14	1.07
	RHS-3 B1		0.34	1.24	1.61	1.58	1.92	1.04	1.19	0.98
	RHS-3 B2		0.34	1.23	1.61	1.57	1.92	1.03	1.19	0.98
	RHS-3 B3		0.34	1.23	1.60	1.57	1.92	1.03	1.19	0.97
	RHS-3 B3		0.34	1.23	1.60	1.57	1.92	1.03	1.19	0.97
4†	SHS80×80	304	0.64	1.43	1.39	1.39	1.37	1.07	1.04	0.94
	SHS80×120		0.52	1.00	1.18	1.14	1.38	0.96	0.95	0.85
5	SHS80×80×4B1	1.4301	0.46	1.12	1.27	1.26	1.49	1.06	1.01	0.98
	SHS100×100×2-B1		1.07	1.20	1.12	1.12	1.02	-	1.00	0.95
	SHS100×100×3-B1		0.71	1.39	1.34	1.34	1.30	-	1.07	1.04
	SHS100×100×4-B1		0.57	0.96	1.06	1.05	1.23	0.98	0.91	0.90
	SHS100×100×8-B1		0.25	1.01	1.46	1.44	1.77	0.82	1.02	0.73
	RHS60×40×40-B1		0.24	1.49	1.72	1.68	2.13	1.23	1.24	1.08
	RHS100×50×2-B1		0.59	0.96	1.09	1.07	1.31	1.01	0.98	0.95
	RHS100×50×3-B1		0.39	1.15	1.28	1.25	1.57	1.03	1.02	0.98
	RHS100×50×4-B1		0.30	1.30	1.48	1.45	1.83	1.05	1.12	1.02
	RHS100×50×4-B1		0.30	1.30	1.48	1.45	1.83	1.05	1.12	1.02
6	RHS100×100×3-A	1.4318	0.73	1.42	1.37	1.37	1.32	-	1.11	1.08
	RHS120×80×3-A		0.61	1.11	1.24	1.22	1.47	1.18	1.12	1.09
	RHS140×60×3-A		0.51	1.16	1.32	1.29	1.63	1.14	1.14	1.11
	RHS100×100×3-C850	1.4318-C850	0.83	1.42	1.35	1.35	1.25	-	1.15	1.10
	RHS120×80×3-C850		0.69	1.37	1.35	1.35	1.35	-	1.10	1.09
	RHS140×60×3-C850		0.58	1.12	1.26	1.23	1.55	1.16	1.15	1.12
7	N40×40×2	304	0.43	1.14	1.31	1.29	1.53	1.06	1.01	0.97
	N40×40×4		0.22	1.25	1.34	1.32	1.66	1.11	0.97	0.97
	N80×80×2		0.82	1.28	1.22	1.22	1.14	-	1.05	1.01
	N80×80×5		0.33	1.37	1.51	1.49	1.80	1.16	1.12	1.08
	N100×50×2		0.50	1.30	1.55	1.51	1.87	1.28	1.29	1.20
	N100×50×4	Duplex	0.27	1.47	1.75	1.71	2.17	1.20	1.29	1.11
	N120×60×2		0.67	1.25	1.19	1.19	1.40	1.22	1.11	1.08
	N120×60×4		0.34	1.47	1.83	1.80	2.26	1.21	1.39	1.18
	H40×40×2		0.48	1.22	1.23	1.21	1.44	1.17	1.01	1.09
	H50×50×1.5		0.77	1.37	1.31	1.31	1.22	-	1.10	1.12
	H150×150×3	HSA	1.17	1.22	1.14	1.14	1.05	-	1.07	1.04

	H150×150×6		0.57	1.13	1.25	1.23	1.45	1.15	1.07	1.06
	H140×80×3	Duplex	0.56	1.09	1.21	1.18	1.45	1.12	1.07	1.06
	H160×80×3		0.65	1.01	1.09	1.07	1.32	1.17	1.05	1.06
	H200×110×4	HSA	0.66	0.90	1.09	1.07	1.31	1.03	1.01	0.93
8	100×100×4-B1		0.63	1.25	1.24	1.24	1.41	1.17	1.09	1.05
	100×100×4-B2		0.65	1.19	1.21	1.21	1.35	1.14	1.05	1.02
	80×80×4-B1		0.52	1.14	1.19	1.17	1.39	1.12	1.00	1.05
	80×80×4-B2	1.4162	0.52	1.12	1.17	1.16	1.37	1.10	0.99	1.03
	60×60×3-B1		0.49	1.08	1.17	1.16	1.38	1.05	0.96	0.97
	60×60×3-B2		0.50	1.11	1.20	1.19	1.42	1.08	0.99	1.00
	80×40×4-B1		0.29	1.17	1.30	1.26	1.63	1.13	0.98	1.03
	80×40×4-B2		0.28	1.28	1.43	1.39	1.79	1.24	1.08	1.13
9	SHS-50×2-B1		0.71	1.74	1.69	1.69	1.64	-	1.33	1.24
	SHS-80×3-B3		0.63	1.50	1.35	1.35	1.50	1.26	1.16	1.14
	SHS-80×3-B4		0.63	1.46	1.32	1.32	1.46	1.23	1.13	1.11
	SHS-80×4-B3		0.48	1.29	1.42	1.40	1.66	1.24	1.15	1.15
	SHS-80×4-B4		0.49	1.18	1.30	1.28	1.52	1.14	1.06	1.05
	SHS-100×3-B3		0.79	1.57	1.51	1.51	1.43	-	1.22	1.09
	SHS-100×4-B2		0.60	1.27	1.55	1.55	1.78	1.33	1.32	1.21
	SHS-100×4-B3		0.60	1.24	1.52	1.52	1.74	1.30	1.29	1.18
	RHS-75×45×2-B3	304	0.64	1.39	1.46	1.46	1.71	1.32	1.30	1.20
	RHS-75×45×2-B4		0.63	1.15	1.39	1.39	1.64	1.25	1.23	1.14
	RHS-95×45×2-B3		0.65	1.06	1.31	1.28	1.57	1.19	1.19	1.07
	RHS-95×45×2-B4		0.63	1.02	1.26	1.23	1.51	1.12	1.14	1.02
	RHS-100×50×2-B3		0.75	1.36	1.34	1.34	1.33	-	1.12	1.05
	RHS-100×50×2-B4		0.74	1.45	1.42	1.42	1.41	-	1.19	1.12
	RHS-120×60×3-B3		0.53	1.22	1.32	1.29	1.60	1.23	1.15	1.18
	RHS-120×60×3-B4		0.53	1.26	1.35	1.33	1.64	1.26	1.18	1.21
10	50×30×2.5L900		0.30	1.24	1.38	1.35	1.71	1.20	1.04	1.11
	30×50×2.5L900		0.45	1.11	1.20	1.19	1.41	1.08	0.96	1.00
	50×50×1.5L900		0.81	1.35	1.29	1.29	1.19	-	1.09	1.04
	50×50×2.5L900		0.50	1.21	1.35	1.33	1.58	1.17	1.11	1.09
	70×50×2.5L1100	1.4162	0.51	1.13	1.29	1.27	1.54	1.11	1.08	1.04
	50×70×2.5L1100		0.68	1.42	1.38	1.38	1.34	-	1.08	1.05
	100×50×2.5L1500		0.54	1.10	1.25	1.23	1.52	1.11	1.09	1.06
	50×100×2.5L1500		0.94	1.42	1.30	1.30	1.04	-	1.04	0.99
	150×50×2.5L1500		0.70	1.33	1.06	1.04	1.35	-	1.09	1.09
	50×150×2.5L1500		1.30	1.42	1.26	1.26	0.95	-	0.97	0.97
11	RHS120×80×3-4PB		0.56	1.01	1.10	1.08	1.30	1.04	0.96	0.96
	RHS60×40×3-4PB	1.4003	0.28	1.04	1.18	1.15	1.43	1.01	0.86	0.99
	SHS80×80×3-4PB		0.56	1.02	1.10	1.08	1.27	1.05	0.94	0.99
	SHS60×60×3-4PB	1.4509	0.43	1.05	1.11	1.10	1.30	1.05	0.88	1.02

	RHS120×80×3-3PB		0.57	1.07	1.17	1.15	1.38	1.11	1.02	1.02
	RHS60×40×3-3PB	1.4003	0.29	1.15	1.30	1.27	1.58	1.12	0.96	1.10
	SHS80×80×3-3PB		0.56	1.02	1.10	1.08	1.27	1.05	0.94	0.99
	SHS60×60×3-3PB	1.4509	0.44	1.13	1.20	1.18	1.40	1.13	0.94	1.10
12	60×60×2-3P		0.64	1.04	0.94	0.94	1.03	0.88	0.81	0.80
	80×40×2-3P		0.77	1.23	1.16	1.16	1.04	-	0.91	0.88
	60×60×2-4P		0.65	1.16	1.07	1.07	1.15	1.00	0.91	0.90
	70×50×2-4P		0.57	0.98	1.05	1.05	1.35	1.03	1.00	0.98
	70×50×2-4P	1.4003	0.72	1.21	1.16	1.16	1.10	-	0.93	0.91
	80×40×2-4P		0.47	0.97	1.06	1.06	1.42	0.96	0.96	0.92
	80×40×2-4P		0.77	1.19	1.11	1.11	1.00	-	0.87	0.85
	100×40×2-4P		0.50	0.78	0.84	0.84	1.13	0.79	0.79	0.77
	100×40×2-4P		0.94	1.31	1.20	1.20	0.93	-	0.94	0.90
13	SHS50×50×3		0.42	1.25	1.43	1.41	1.68	1.14	1.11	1.06
	SHS60×60×3	1.4301	0.47	1.22	1.38	1.36	1.61	1.16	1.10	1.07
	SHS100×100×3	1.4307	0.75	1.47	1.42	1.42	1.35	-	1.14	1.07
	RHS60×40×3-MA		0.36	1.27	1.52	1.49	1.84	1.06	1.16	1.04
	RHS60×40×3-MI		0.49	1.24	1.43	1.42	1.66	1.20	1.15	1.10
14	SHS100×100×5	1.4301	0.46	1.30	1.49	1.46	1.73	1.23	1.17	1.12
	SHS120×120×5	1.4571	0.50	1.19	1.42	1.40	1.65	1.17	1.14	1.06
	RHS150×100×6	1.4307	0.36	1.16	1.60	1.57	1.93	1.01	1.19	0.94
	RHS150×100×8	1.4404	0.36	1.07	1.44	1.42	1.68	0.94	1.05	0.87
	SHS150×150×8	1.4162	0.45	1.09	1.43	1.41	1.69	1.02	1.11	0.94
15	SHS40×40×2	1.4509	0.44	1.08	1.23	1.21	1.44	1.05	0.96	1.03
	SHS50×50×2		0.57	0.98	1.11	1.10	1.29	1.02	0.95	0.93
16	SHS60×60×3	1.4003	0.44	1.06	1.17	1.16	1.38	1.04	0.92	1.02
	SHS100×40×2		1.00	1.47	1.33	1.33	1.02	-	1.07	1.03
This paper	SHS70×3-1900a		0.50	1.19	1.33	1.31	1.55	1.16	1.09	1.07
	SHS70×3-1900b	304	0.50	1.22	1.36	1.34	1.58	1.19	1.11	1.09
	SHS100×3-1900a		0.68	1.42	1.39	1.39	1.37	1.24	1.10	1.08
	SHS100×3-1900b		0.68	1.42	1.39	1.39	1.37	-	1.10	1.08
AVG.				1.22	1.31	1.30	1.48	1.12	1.07	1.04
COV.				0.16	0.17	0.17	0.26	0.11	0.11	0.10

Note: † Other two continuous beam tests are not shown in this table, as the bending capacities of the specimens can not be determined directly by the load force. – Section slenderness is higher than 0.68, which is beyond the applicable limit of CSM method.

Table 9 Comparisons of test results and predictions of the current design methods and the proposed design method for circular hollow sections.

Ref.	Specimens	Grade	λ	$\frac{M_t}{M_{en}}$	$\frac{M_t}{M_{asce}}$	$\frac{M_t}{M_{au}}$	$\frac{M_t}{M_{cn}}$	$\frac{M_t}{M_{csm}}$	$\frac{M_t}{M_p}$
2	C1B1	304L	0.24	1.15	1.50	1.15	1.50	1.15	1.10
17	TB01	304	0.37	1.24	1.56	1.24	1.24	1.31	1.16
	TB02		0.47	1.17	1.74	1.17	-	1.29	1.28
	TB03		0.47	1.06	1.48	1.06	-	1.17	1.17
	TB04		0.41	1.25	1.66	1.25	-	1.34	1.24
	TB05		0.33	1.32	1.44	1.32	1.32	1.37	1.15
	TB06	2205	0.33	1.30	1.44	1.30	1.30	1.35	1.14
	TB07		0.42	0.96	1.23	0.96	-	1.04	0.98
	TB08		0.36	1.33	1.59	1.33	-	1.40	1.23
	TB09	1.4541	0.20	1.21	1.59	1.21	1.59	1.14	1.07
18	TB10	1.4435	0.27	1.37	1.37	1.37	1.37	1.14	1.06
	TB11		0.30	1.25	1.25	1.25	1.25	1.28	1.04
This paper	CHS89×3-1900a	304	0.21	1.21	1.59	1.21	1.59	1.14	1.09
	CHS89×3-1900b		0.21	1.15	1.51	1.15	1.51	1.08	1.04
	CHS127×3-1900a		0.23	1.07	1.40	1.07	1.40	1.07	1.02
	CHS127×3-1900b		0.23	1.07	1.39	1.07	1.39	1.06	1.01
	AVG.			1.19	1.48	1.19	1.41	1.21	1.11
	COV.			0.11	0.14	0.11	0.13	0.12	0.09

Note: - D/t ratios of these test specimens are beyond the limit in Chinese code.