Tests on high strength steel hollow sections: A review

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Abstract

Advances in technologies have allowed manufacturers to produce steel plates and sections with strengths of 690 MPa and higher. The use of high strength steel has the potential for significantly reducing the material costs and the self-weight of structures. High strength steel hollow sections can be either welded from steel plates or cold-formed from coils. Tests on different built-up high strength steel hollow sections have been conducted around the globe including Australia, China, Japan and in the United States. The commonly used box-sections were tested, meanwhile the slenderness limits and member capacities against compression were studied. To investigate the performance of cold-formed high strength steel hollow sections, the authors initiated a research programme in Hong Kong, which included both experimental and numerical investigations on cold-formed high strength steel hollow sections. The sections include square, rectangular and circular hollow sections. Based on the results, recommendations on section slenderness limits and expression for determining member capacity are proposed in these studies. This paper summarizes recent research on high strength steel hollow sections and also addresses the design recommendations and limits in codes for both built-up and cold-formed high strength steel hollow sections.

Keywords

High strength steel; Hollow section; Material property; Metal structures; Review; Tubular section.

List of notations

A	gross cross-section area of section
B	overall width of section
D	outer diameter of section
f_y	steel yield stress
H	overall depth of section
i	radius of gyration in bending plane
L	specimen length
M_{AISC}	nominal moment capacities from ANSI/AISC 360-10

M_{DSM} nominal moment capacities using Direct Strength Method from AISI S100-12

M_p plastic moment

M_u ultimate moment

P_{AISC} nominal strength from ANSI/AISC 360-10

P_u ultimate strength of column

P_y yield strength of column

r inner corner radius

R outer corner radius

t wall thickness

$\sigma_{0.2}$ 0.2% proof stress

σ_u ultimate stress

ε_f proportional elongation at fracture

α_b member section constant in AS4100

1. Introduction

High strength steel (HSS) hollow sections have been increasingly used in many structural applications because of their high strength-to-weight ratio and strong resistance against torsional buckling. Their high strength-to-weight ratio can lead to lighter structural components and hence reduce the cost of foundations. The decrease in resources consumption and the reduced transportation time can reduce the carbon footprint and support the sustainability agenda. The definition of high strength steel in this paper is related to those steel materials with nominal steel grade equal to or higher than 690 MPa.

Till now, HSS with strengths higher than 690 MPa has been used most often in bridge engineering. Steels for high performance bridge structures with grade of 500 MPa and 700 MPa were developed in Japan and used in the Tokyo Gate Bridge, which has a span of 440 m, a clearance height of 54.6 m and a total height of 87.8 m. Engineers in Sweden, Germany have also used HSS in bridge engineering especially for members with high stress requirements. The Swedish army even developed a new military bridge using cold-formed and welded S1100 steel, which has a span of 48 m and can resist a 65 tonne tank for 1000 crossings (Collin and Johansson, 2006). Additionally engineers have started using HSS in designated parts of building structures, such as the roof trusses of the Sony Center (Berlin), basement columns and roof truss in Star City (Sydney), the transfer flooring system of Latitude Building (Sydney) (Shi et al., 2014).

The mechanical properties and structural responses of HSS are different from those of ordinary strength steel. In the stress-strain responses measured in material tests, the lower bound of the yield plateau is normally defined as the yield stress for ordinary strength steel. However, there is usually no yield plateau in the stress-strain curves obtained from HSS, thus the 0.2% proof stresses are used as the yield stresses for HSS in design. Additionally, the ductility of HSS material is generally lower than that of ordinary strength steel.

The European Code (EN 1993-1-12, 2007), the American Institute of Steel Construction Specification (ANSI/AISC 360-10, 2010) and the Australian Standard (AS 4100-A1, 2012) have covered the design of HSS with yield strength up to 690 MPa. The corresponding design rules for the European Code and the Australian Standard for ordinary strength steels can be found in EN 1993-1-1 (2005) and AS 4100 (1998), respectively. HSS hollow sections can be either welded or cold-formed from HSS plates and coils. Considerable enhancements inmaterial strength are found for cold-formed high strength steel (CFHSS) due to the cold-working effects, especially for the corner regions of rectangular hollow sections and square hollow sections. More economic design can be achieved by taking the strength enhancements due to cold-working into consideration.

In the past decades, researchers have been investigating the structural performance of built-up high strength steel (BUHSS) hollow sections whereas investigation into structural behaviour of cold-formed high strength steel hollow sections is limited. Compared to BUHSS, cold-formed high strength steel (CFHSS) hollow sections are easier to produce and generally less energy-consuming. This paper aims to review previous and current research on HSS material properties, experimental investigation into high strength steel hollow section structural members, and design rules in current codes for HSS hollow sections. The examined experimental investigation into CFHSS square hollow sections (SHS), rectangular hollow sections (RHS) and circular hollow sections (CHS) were principally conducted by the authors at the University of Hong

Kong. Part of the research findings have been published in international journals and conferences, and references are made to these publications for further details. A set of technical papers investigating the hot-finished high strength steel (HFHSS) tubes was also reviewed.

In the following sections, the manufacturing technologies of high strength steel are firstly reviewed, which are followed by a review of BUHSS, HFHSS and CFHSS steel hollow section structural members.

2. Manufacturing technologies for HSS

The mechanical properties of steel, notably strength and ductility, are influenced by many factors during manufacturing, including the chemical composition, heat treatment and manufacturing processes.

The chemical composition of steel can be changed through adding alloys such as manganese, niobium, nickel and so on. Typical chemical compositions for HSS are extracted from mill certificates and shown in Table 1, in which the nominal grades of steel are shown in the first column. Manganese (Mn) and Nickel (Ni) add tensile strength to steel material. Vanadium (V) and Chromium (Cr) increase the hardness of steel. However, alloying elements like Phosphorus (P), Sulphur (S) and Nitrogen (N) can cause the steel to become brittle, thus the amount of such elements is usually tightly controlled. The carbon equivalent (CEV) is used to describe the weldability of steel and cast iron. The Dearden and O'Neill formula (Equation 1.) calculates the carbon equivalent value and the method was adopted by the International Institute of Welding (IIW, 1967). According to Table 1, the carbon equivalent value rises with the increase in nominal steel strengths, showing that the alloying elements enhance the steel strength but make the material more difficult to weld. Ginzburg and Ballas (2000) assessed the steel weldability as a function of carbon equivalent value as summarized in Table 2. Thus in alloying, a balance between material strength and weldability is usually needed for high strength steel.

$$CEV = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15 \qquad \text{Equation 1.}$$

Heat treatment is another important factor that affects the mechanical properties of steel. Quenching and Tempering (Q&T) and Thermo-Mechanical Controlled Processing (TMCP) are the two main technologies used nowadays to produce HSS. Through quenching, the steel undergoes a rapid cooling process and martensite is usually introduced in this procedure. Martensite is a very hard form of steel crystalline structure and leads to a significant increase in steel strength. The steel is tempered after quenching to improve the toughness and ductility. Compared to the traditional quenching and tempering process, thermo-mechanical controlled processing is now preferred by more steel manufacturers as it provides a finer grained microstructure, reduces CEV value and improves weldability for steel. The thermo-mechanical controlled processing minimizes the use of alloying elements and applies a controlled rolling at a lower temperature than the older quenching and tempering processes. A systematic review of the thermo-mechanical controlled processing technology was conducted by Nishioka and Ichikawa (2012) and it is anticipated that this technology can reduce the resources and energy consumption, and HSS with better quality could be produced in the future using thermo-mechanical controlled processing. Different thermo-mechanically controlled processing methods have been recently described in the literature (Kong and Lan, 2014, Xie et al., 2014, Hu et al., 2014). The efficiency of these methods has been proved by producing various high strength low alloy steel products.

The manufacturing process also decides the mechanical performance of steel products. Welding is mostly used to form HSS heavy sections whereas cold-forming is usually adopted in manufacturing light HSS tubular sections. Therefore, the residual stress distributions and the steel material properties can be different. For ordinary strength steel products, the thickness of commonly used steel sheets or strips for cold-forming ranges from 0.4 mm to 6.4 mm, whereas the steel plates for cold-forming nowadays can be more than 25 mm in thickness (Yu and LaBoube, 2010). Different shapes of cross-sections can be cold-formed, as shown in Figure 1. With the development in technologies, steel manufacturers are now able to cold-form high strength steel coils into different tubular and open sections. The wall thickness of cold-formed high strength steel tubular sections with strength of 690 MPa can now reach 10 mm (SSAB, 2015). Cold-forming usually enhances the material strength of sections, but reduces the ductility and toughness for regions that undergo large plastic deformations. Besides, cast round ingots can be rolled seamlessly and then hollowed out in a piercing mill to form tubular members. The members were then quenched and tempered to S690 tubes, which are hence called hot-finished tubes (Wang et al., 2017). Hot-finished tubes usually possess smaller corner radius and lower residual stress level than their cold-formed counterparts.

3. Built-up high strength steel hollow sections

Manufacturers started producing high strength steel (HSS) plates ($\sigma_{0.2} \geq$ 690MPa) decades ago. From the measured stress-strain curves, the 0.2% proof stresses were usually taken as the yield stresses of steel. As welding technologies developed, HSS plates can be welded into different section shapes, which are called built-up sections in the market. Box-sections are usually preferred among hollow sections by engineers, thus significant research on BUHSS hollow sections are box-sections.

HSS plate buckling behaviour has been investigated through testing of built-up box-section stub columns by Nishino et al. (1967), Nishino and Tall (1970), Usami and Fukumoto (1982), Rasmussen and Hancock (1992), Gao et al. (2009) and Kim et al. (2014). The residual stress distributions of BUHSS box-sections were also investigated and results showed that the residual stress level in those sections is more related to the heat input during welding than the original material strength. Hence, the residual stress-to-yield stress ratios for BUHSS are lower than those of ordinary steel. It was concluded that for the compression strength of columns, the effect of residual stresses is less pronounced than that for ordinary strength steel sections, the reasons are detailed in Rasmussen (2005). Through testing the plate elements in box-sections under compression, Rasmussen and Hancock (1992) suggested using the same yield slenderness limits for both ordinary and high strength steel plates.

The overall buckling behaviour of BUHSS box-section columns was studied in Nishino and Tall (1970), Usami and Fukumoto (1982), Rasmussen and Hancock (1995) and Ban et al. (2013). Comparisons were made from columns made of HSS to those welded from ordinary strength steel. Results showed that, when compared on a non-dimensional basis, the strengths of BUHSS columns exceed those of ordinary strength steel columns. Additionally, the column buckling curves were examined against tested HSS column strengths. Rasmussen and Hancock (1995) recommended the $\alpha_{\mathrm{b}} = -0.5$ curve for BUHSS columns for the Australian Standard. Ban et al. (2013) concluded that the column curves in EN 1993-1-1 (2005) and ANSI/AISC 360-10 (2010) could be used for BUHSS box-section columns although they are conservative. Research on BUHSS box-section beams and beam-columns is still limited nowadays, thus more experimental and numerical investigations in this field are needed.

4. Hot-finished high strength steel hollow sections

Experimental investigations on hot-finished high strength steel (HFHSS) with nominal yield strength of 690 MPa has been conducted by Wang et al. (2016 and 2017) and Wang and Gardner (2017). The hot finished tubes have yield stresses ranging from 759 MPa to 799 MPa with proportional elongations at fracture ranging from 19.3% to 21.7%. The ultimate-to-yield strength ratios are close to unit, which means limited ductility for HFHSS tubular members. The S690 HFHSS tubes has widths and depths ranged from 50 mm to 100 mm and wall thickness ranged from 5 mm to 6.3 mm (Wang et al., 2017). Through stub column tests it was shown that the tested HFHSS sections were very compact hence it is difficult to evaluate the slenderness limit solely for HFHSS products unless further tests or numerical investigations are conducted. Maximum measured residual stresses of HFHSS tubes were around 0.031×yield stress for compression and 0.055×yield stress for tension. Through the experimental and numerical investigations on columns (Wang and Gardner, 2017), results indicated that the design rules in EN 1993-1-1 (2005), ANSI/AISC 360-10 (2010) and AS 4100 (1998) are also applicable to HFHSS square and rectangular hollow section columns. In addition, the bending behaviour of HFHSS square and rectangular hollow sections were investigated in Wang et al. (2016). A set of slenderness limits based on EN 1993-1-1 (2005) was proposed and proved effective for internal compression plate elements of S690 HFHSS tubes.

5. Cold-formed high strength steel hollow sections

Cold-formed high strength steel (CFHSS) hollow sections have great potential in structural engineering due to their ease of fabrication and high strength-to-weight ratios.

A series of experimental investigations on CFHSS circular hollow sections (CHS) was conducted in Australia (Jiao and Zhao, 2001, Jiao and Zhao, 2003, Zhao, 2000, Jiao and Zhao, 2004). The specimens tested in Australia had nominal 0.2% proof stresses of 1350 MPa, the outer-diameter of the sections ranged from 32 mm to 76 mm and the *D*/*t* ratios ranged from 16 to 48. In 2012, a novel research programme on CFHSS square hollow sections (SHS), rectangular hollow sections (RHS) and circular hollow sections (CHS) was initiated by the authors in Hong Kong. The purpose of the research was to investigate the material properties, the members' behaviour against compression, bending and combined loadings for different CFHSS hollow sections. The specimens were cold-formed from high strength steel coils and the nominal 0.2% proof stresses of the specimens were 700 MPa (H-Series), 900 MPa (V-Series) and 1100 MPa (S-Series). The test specimens had nominal thicknesses *t* ranging from 3 mm to 6 mm. For SHS and RHS, the nominal overall depth of the webs *H* ranged from 50 mm to 160 mm and the nominal flange widths *B* ranged from 50 mm to 200 mm (Figure 2). The web slenderness value of the specimens ranged from 8 to 35. For CHS, the nominal overall diameter *D* of the sections ranged from 89 mm to 139 mm and the diameter-to-thickness ratios of the specimens ranged from 22 to 34. In the following sections, the results from these experimental investigations on cold-formed high strength steel SHS, RHS and CHS members are reviewed and discussed.

5.1 Material properties

4.1.1 Tensile coupon tests

This section summarizes the investigation on CFHSS tensile coupon tests conducted by the authors and the results obtained by Jiao and Zhao (2001) are also incorporated for discussion.

To understand the mechanical properties of CFHSS hollow sections, the authors first conducted a series of tensile coupon tests at normal room temperature. The flat coupons, corner coupons and curved coupons were extracted from different positions of sections, as shown in Figure **2**2. The flat coupons were prepared and tested according to the requirements from ISO 6892-1 (2009), AS 1391 (2007) and ASTM E8 (2011). The corner and curved coupons were prepared and tested carefully according to the requirements described in Huang and Young (2014). The chosen gauge lengths for the specimens were 25 mm. The sections were labelled as "Series, width, depth, thickness" and H, V, S stands for nominal steel grades of 700 MPa, 900 MPa, 1100 MPa, respectively. For example, specimen label H200×120×5 stands for a rectangular hollow section with nominal 0.2% proof stress $\sigma_{0.2}$ of 700 MPa. Figure 3 (Ma et al., 2016b) shows six typical CFHSS stress-strain curves obtained from tensile coupon tests. Summarizing all the flat, corner and curved coupon test data, Figure 4 shows the relationship between $\sigma_u/\sigma_{0.2}$ and $\sigma_{0.2}$ Figure 5 shows the trend of decreasing material proportional elongation at fracture with the increase in $\sigma_{0.2}$. The results from Jiao and Zhao (2001) are also included. EN 1993-1-12 (2007) states two requirements for the ductility of high strength steel: $\sigma_u/\sigma_{0.2} \geq 1.05$ and $\varepsilon_f \geq 15\%$. From Figure 4 and Figure 5, it is shown that the tensile coupons tested satisfied the first requirement, whereas the majority of the specimens failed to possess enough proportional elongation at fracture ε_f. The tensile coupon test procedures and proposed constitutive model for CFHSS are detailed in Ma et al. (2015b).

4.1.2 Residual stress measurements

Limited research was found on the residual stresses in CFHSS hollow sections. Therefore, this section mainly describes the investigation of residual stress measurements on three CFHSS hollow sections conducted by the authors. For cold-formed hollow sections, residual stresses can arise from cold-bending, welding and flame cutting. Large residual stresses in sections may cause premature yielding leading to instability in compression members, thus the investigation on residual stresses of CFHSS hollow sections is important. Sectioning method was adopted by the authors to investigate the residual stress distributions in both the longitudinal and transverse directions. A wire-cutting machine with an accuracy of 0.005 mm was used and the setup for cutting is shown in Figure 6. The residual stresses of cold-formed sections can be decomposed into two parts: membrane residual stresses and bending residual stresses. It was found that in the longitudinal direction of specimens, the bending residual stresses of CFHSS sections could be as high as 80% of $\sigma_{0.2}$ whilst the membrane residual stresses are generally smaller than 20% of $\sigma_{0.2}$. The distribution of residual stresses along the sections is detailed in Ma et al. (2015b).

5.2 Stub column tests

Experimental investigation of cold-formed high strength steel stub columns has been presented by Zhao (2000) for CHS, Schillo et al. (2014), Schillo and Feldmann (2015) for SHS and Ma et al. (2016b) for SHS, RHS and CHS. The nominal steel grades of the sections ranged from 700 MPa to 1350 MPa, which are much higher than their ordinary strength steel counterparts. In order to investigate the cross-sectional behaviour against pure compression, the CFHSS columns were designed as stub columns and tested under fixed boundary conditions.

In Ma et al. (2016b), the initial local geometric imperfections of the stub columns were measured before testing. The typical maximum measured local geometric imperfections were 0.162 mm (t/24), 0.394 mm (t/10), 0.174 mm (t/17), and 0.072mm (t/53) for H120×120×4, V120×120×4, V89×3 and S89×4 specimens, respectively. The test setups for typical fixed-ended stub columns are shown in Figure 7. The test results were compared with the predictions calculated from EN 1993-1-1 (2005), ANSI/AISC 360-10 (2010), AS 4100 (1998), AISI S100 (2012) and the Direct Strength Method (DSM, (AISI S100, 2012)). The slenderness limits were first examined and results shown that the relevant yield slenderness limits in codes are applicable for SHS, but conservative for CHS. Chan et al. (2015) proposed an improved CHS yield slenderness parameter $(D/t)(f_y/480)$, instead of $(D/t)(f_y/235)$ for EN 1993-1-1 (2005). Up till now the ultimate strengths P_u of CFHSS CHS stub columns tested all attained the squash load $P_y=Af_y$, thus more investigations on sections with larger section slenderness should be conducted to identify the suitable yield slenderness limit for CHS under compression. The design strengths of stub columns were then compared to the predicted strengths from codes. It is shown that the predictions by the different codes are close and slightly conservative for SHS and RHS. The predictions for CHS were conservative by 12% to 36% on average. The DSM (AISI S100, 2012) gives best prediction for CHS. The current design rules are applicable for CFHSS hollow section stub columns, although they may be rather conservative. The test procedures and results of CFHSS stub columns are detailed in Ma et al. (2016b).

5.3 Beam tests

A series of tests on CFHSS hollow section beams was presented by Jiao and Zhao (2004) and Ma et al. (2016a). In Jiao and Zhao (2004), twelve CHS beam specimens were tested. Both four-point bending tests and pure bending tests were conducted and the codified CHS slenderness limits in bending were examined against the test results. In Ma et al. (2016a), a total number of 25 CFHSS beams in SHS, RHS and CHS were tested. The specimens were cut from the same batch of tubes as the stub column specimens. Four-point-bending was adopted and the test setups are shown in Figure 8. The slenderness limits were first examined. Results showed that the plastic slenderness limit for flanges from EN 1993-1-1 (2005), yield slenderness limit from ANSI/AISC 360-10 (2010) are recommended to be used for SHS and RHS. For CHS, the plastic slenderness limit from EN 1993-1-1 (2005) and the yield slenderness limit from AS 4100 (1998) can be safely adopted although they are conservative.

A comprehensive numerical investigation into CFHSS hollow section beams is needed to generate additional data, which can help researchers suggest more accurate slenderness limits for cold-formed high strength steel SHS, RHS and CHS beams. Comparing the beam strengths to the predicted strength from codes, the authors concluded that the current design methods are generally conservative. The closest prediction for SHS and RHS is given by ANSI/AISC 360-10 (2010), with the corresponding average test to prediction ratio M_u/M_{AISC} equaling to 1.17 (COV=0.047). The best prediction for CHS is from the DSM of AISI S100 (2012), in which the inelastic reserve calculations are conducted and the average M_u/M_{DSM} ratio equals to 1.19 (COV=0.072). The comparison of the test strengths with the design strengths is detailed in Ma et al. (2016a).

5.4 Beam-column tests

An experimental investigation into the behaviour of CFHSS hollow section beam-columns was conducted by Ma et al. (2015a). Three sections, including H80×80×4, H50×100×4 and V89×3, were examined in the study. The pinned boundary conditions were provided by a set of knife edges. The specimen effective lengths were 1655 mm. Combined compression and uniaxial bending were applied through the eccentric loads at both ends of the specimens. For RHS, the specimens were tested for both major and minor axis bending. Eight specimens were prepared for each test series, thus in total 32 specimens were tested in the study. The overall slenderness L/i of the specimens ranged from 47 to 81. The test setup is shown in Figure 9. The overall geometric imperfections were measured before testing on the specimens with a total station machine. The measured maximum overall geometric imperfections were 0.635 mm (L/2331), 0.953 mm (L/1554) and 0.889 mm (L/1665) for the H80×80×4, H50×100×4 and V89×3, respectively.

The measured beam-column strengths were compared to the design strengths from EN 1993-1-1 (2005), ANSI/AISC 360-10 (2010) and AS 4100 (1998). The closest prediction was given by ANSI/AISC 360-10 (2010), in which a two-stage interaction curve is used. The average P_u/P_{AISC} ratio is 1.03 with a corresponding COV value of 0.027. EN 1993-1-1 (2005) adopts different column buckling curves for various types of cross-sections. The CFHSS columns are designated to use the buckling curve 'c', whereas the results shown that the buckling curve 'a' is more suitable. The accuracy of design predictions can be improved by 10% on average if the buckling curve 'a' can be used for CFHSS hollow sections. Typical interaction curves for H80×80×4 are shown in Figure 10. The experimental investigation and comparison to codes for CFHSS hollow section beam-columns are detailed in Ma et al. (2015a).

6. Conclusions

The research on built-up, hot-finished and cold-formed high strength steel hollow sections has been summarized in this paper. The manufacturing technologies of high strength steel have been reviewed. The advantages of thermo-mechanical controlled processing technology were explained. The previous research on residual stresses, plate buckling behaviour and column buckling behaviour for built-up high strength steel box sections were summarized. Design rules from EN 1993-1-1 (2005) and ANSI/AISC 360-10 (2010) can be safely adopted for built-up high strength steel box section columns, while more investigations are required especially for beams and beam-columns. Recent investigations on hot-finished high strength steel hollow sections were also presented and the assessment on the applicability of the current rules in EN 1993-1-1 (2005), ANSI/AISC 360-10 (2010) and AS 4100 (1998) was also discussed.

Research work on cold-formed high strength steel hollow sections in Hong Kong and Australia was also discussed. The mechanical material properties were obtained through tensile coupon tests for flat, corner and curved regions in sections. The local and global geometric imperfections were measured on stub column and beam-column specimens, respectively. The bending and membrane residual stress distributions on sections were obtained using the sectioning method. The structural behaviour of cold-formed high strength steel hollow sections subjected to compression, bending and combined compression and bending were investigated. The corresponding design predictions from codes were examined. Design recommendations on slenderness limits, cross-sectional strengths and member strengths have been explained. Different codified design rules are suggested in this paper depending on the cross-section shapes and loading conditions. The details of the investigations can be found in the publications as referred in this paper.

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Table captions

Table 1 Typical chemical composition for HSS (Ma et al., 2015b)

Table 2 Weldability as a function of carbon equivalent (Ginzburg and Ballas, 2000)

Figure captions

Figure 1 Cold-formed steel sections
Figure 2 Definition of symbols and location of tensile coupons (Ma et al., 2015b)
Figure 3 Six typical stress-strain curves for HSS (Ma et al., 2016b)
Figure 4 $\sigma_u/\sigma_{0.2}$ versus $\sigma_{0.2}$ for tested coupons
Figure 5 ε_f versus $\sigma_{0.2}$ for tested coupons
Figure 6 Residual stress measurements and wire cutting
Figure 7 Typical fixed-ended stub column tests for CFHSS hollow sections
Figure 8 Typical four-point-bending tests for CFHSS hollow sections
Figure 9 Typical beam-column test for CFHSS hollow sections
Figure 10 Typical beam-column interaction curves for H80×80×4

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Table 1 Typical chemical composition for HSS（Ma et al. 2015b）

Grade (MPa)	CEV	C	Si	Mn	P	S	Al	Nb	V	Cu	Cr	N	Ti	Mo	Ni	B
700	.37	.06	.20	1.78	.007	.003	.034	.082	.015	.025	.052	.004	.110	.007	.040	.0003
900	.47	.08	.20	1.05	.010	.002	.037	.002	.012	.017	.899	.005	.030	.142	.078	.0023
1100	.55	.15	.22	1.24	.008	.005	.036	.002	.012	.036	.754	.006	.030	.186	.063	.0024

Cast analysis (%)

Note: Carbon Equivalent Value, CEV = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15

Table 2 Weldability as a function of carbon equivalent (Ginzburg and Ballas, 2000)

Carbon Equivalent (CEV)	Weldability
Up to 0.35	Excellent
from 0.36 to 0.40 incl.	Very good
from 0.41 to 0.45 incl.	Good
from 0.46 to 0.50 incl.	Fair
Over 0.50	Poor

Figure 1 Cold-formed steel sections

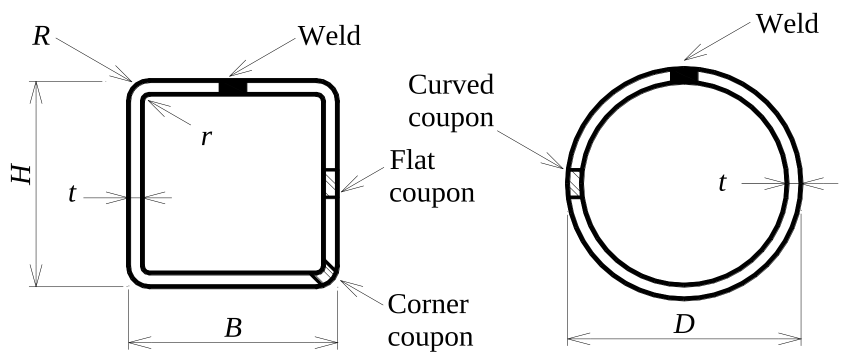


Figure 2 Definition of symbols and location of tensile coupons (Ma et al., 2015b)

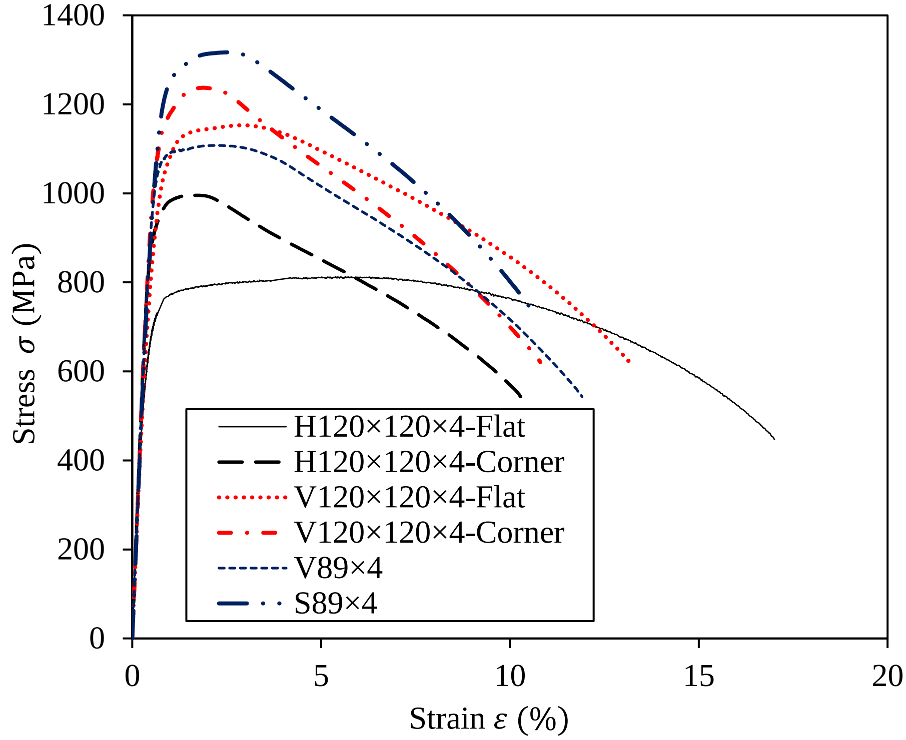


Figure. 3. Six typical stress-strain curves for HSS (Ma et al. 2016b)

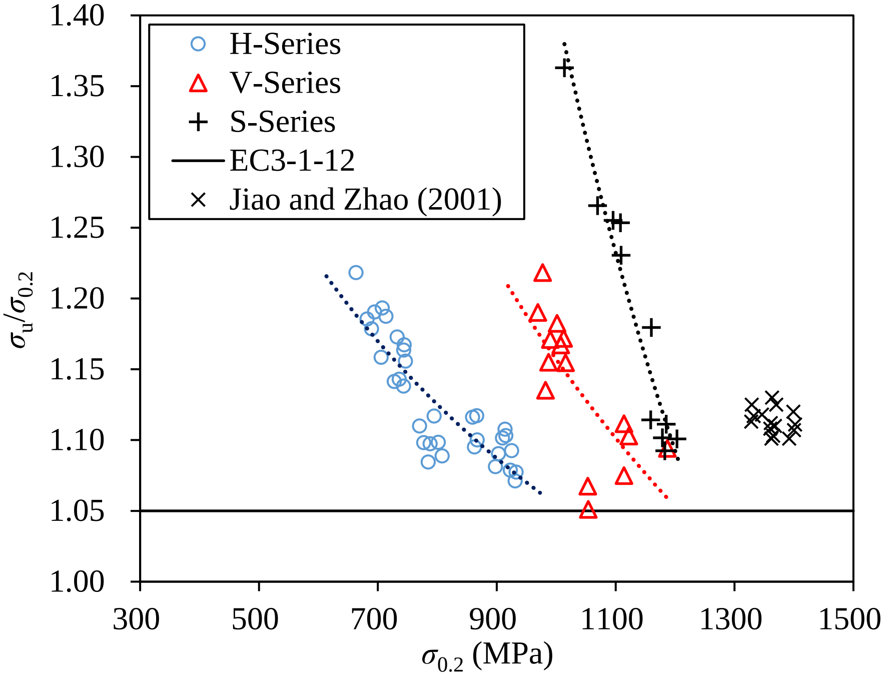


Figure. 4. $\sigma_u/\sigma_{0.2}$ versus $\sigma_{0.2}$ for tested coupons (Ma et al. 2015b)

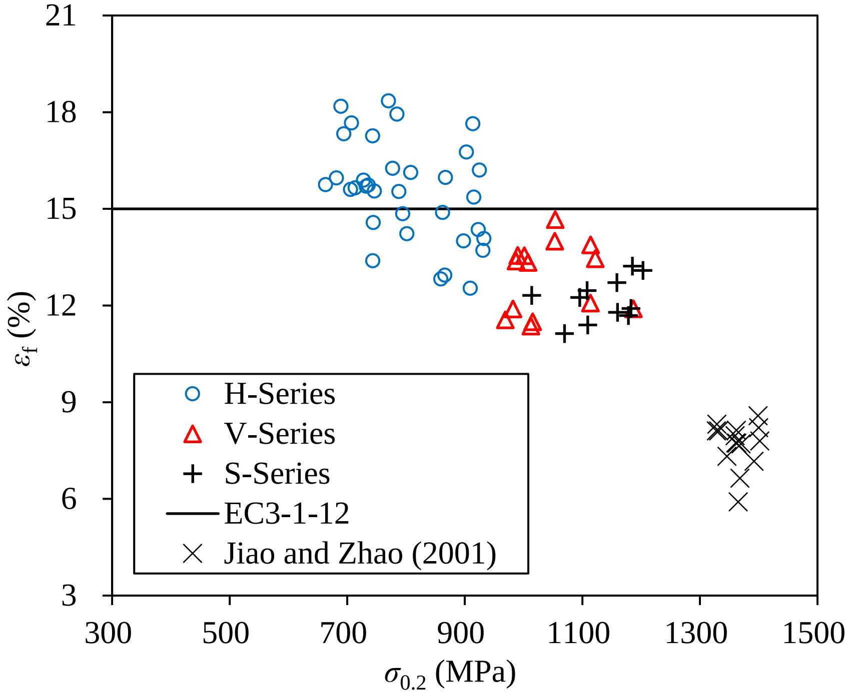
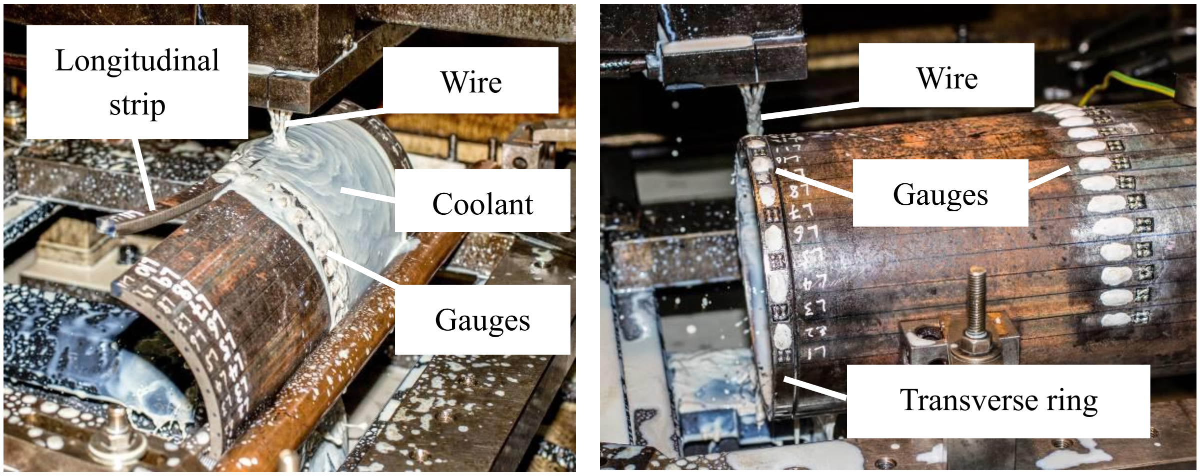


Figure. 5. ε_f versus $\sigma_{0.2}$ for tested coupons (Ma et al. 2015b)



(a) Longitudinal strip cutting (b) Transverse ring cutting

Figure. 6. Residual stress measurements and wire cutting

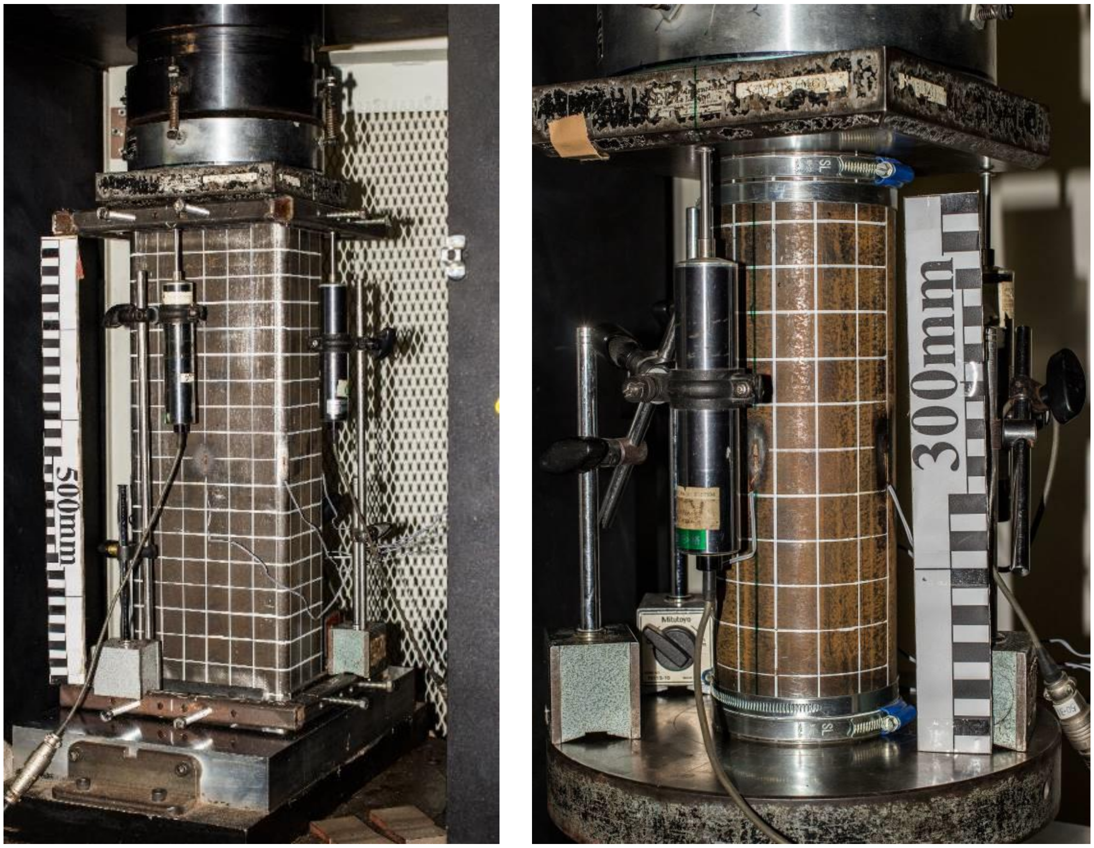


Figure. 7. Typical fixed-ended stub column tests for CFHSS hollow sections

Figure. 8. Typical four-point-bending tests for CFHSS hollow sections

Figure. 9. Typical beam-column test for CFHSS hollow sections

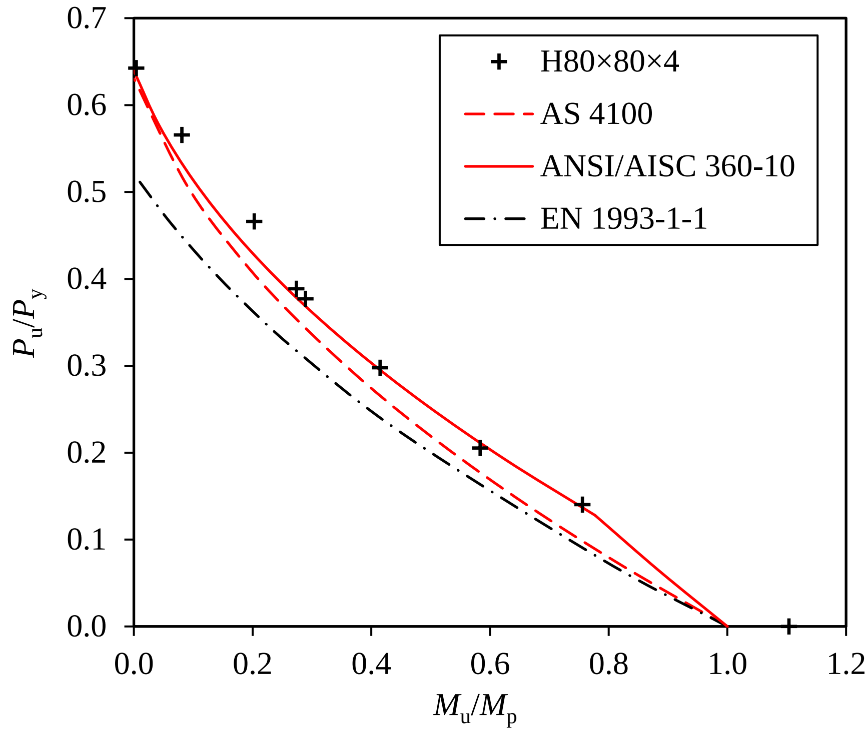


Figure. 10. Typical beam-column interaction curves for H80×80×4 (Ma et al. 2015a)