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Residual stresses in welded flame-cut high strength steel H-sections

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ABSTRACT

The presence of residual stress in members can significantly compromise the stiffness and fatigue life of steel structural components. Researches in this area are well documented for structural members of mild carbon steels. Nevertheless, due to the difference of stress–strain relations and material properties under ambient and high temperatures, the residual stress distribution in a high strength steel member is physically different from those fabricated from mild carbon steel. It is imperative to study the residual stress distribution for structural members fabricated from high strength steel. In this paper, the residual stresses of three welded flame-cut H-section columns with a nominal yield strength of 460 MPa but different cross-section dimensions were investigated. Both sectioning and hole-drilling methods were used in the measurement and the obtained residual stresses were compared between the two methods. The magnitudes and distributions of the measured residual stresses are identical with those of carbon steel, however in relatively smaller residual stress ratios. Finally, based on the measurements, a simplified residual stress distribution for 460 MPa high strength steel members with welded flame-cut H-section is proposed.

1. Introduction

Welded, hot-rolled, flame-cut or flame-straightened structural components are usually not initially stress free. Residual stresses exist in these structural steel members induced by the non-uniform temperature distributions during the manufacture, fabrication or refinement processes. Owing to the sufficiently high ductility of steel material, residual stresses are often not detrimental to the plastic strength of cross sections, but the presence of residual stress may significantly impair the stiffness of compression members and shorten the fatigue life of steel members under periodical load or dynamic load. In order to investigate the effect of residual stresses, the magnitudes and distributions of residual stresses in welded mild carbon steel sections have been extensively investigated [1,2]. Since the stress–strain curves and high-temperature material properties [3] of high strength steel (HSS, yield strength ≥ 460 MPa) are different from the regular strength steel, it is expected that the residual stresses in HSS sections are different from those in mild carbon steel sections. For this reason, the ultimate bearing capacities under compressive load and fatigue life under cyclic load of HSS members will be different from mild carbon steel members. However, the research on residual stresses in HSS welded sections is very limited. HSS members have been applied in many buildings, spatial structures and bridges [4] because of advantages such as reducing structural dead load and dimensions of members, and saving material and space. For the safe and efficient application of HSS members, especially beam-column members, it is important to evaluate the influence of residual stresses in HSS members.

1.1. Previous residual stress researches in HSS H-sections

In 1992, Rasmussen and Hancock [5] fabricated 6 welded H-section stub columns from nominal 6 mm guillotined plates with a yield strength of 670 MPa to study the plate slenderness limits for high strength steel sections. The residual stresses on each side of the component plates were measured for three H-section columns with various cross-sectional dimensions (flange widths from 96 mm to 136 mm) and the distributions were presented. In 1995, Rasmussen and Hancock [6] measured the residual stresses in the welded H-section (flange breadth 140 mm) fabricated from nominal 8 mm flame-cut plates with a yield strength of 660 MPa. The distribution of residual stresses was presented and taken into account for selecting the appropriate design curve for HSS column. In 1996, Beg and Hladnik [7] fabricated 10 beams from nominal 10 mm and 12 mm plates with a nominal yield strength of 700 MPa to investigate the slenderness limit of the class 3 H-section. The residual stresses in flanges of two different H-sections (flange widths of 270 mm and 220 mm) were measured and presented.

Previous research works on residual stress are mainly focused on the effect on local buckling of steel members, therefore the relatively higher width to thickness ratios of flanges are adopted, which are ranging from 7.5 to 10.8. Due to the capacity of the loading equipment, the thicknesses are limited to the range from 6 mm to 12 mm. Nevertheless,

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according to Ref. [5], the same yield slenderness limit formula should be adopted for HSS plates as ordinary strength steel plates. The width to thickness ratio limits decrease with the increase in yield strength. To this end, the residual stresses in sections with width to thickness ratios less than 7.5 should be investigated. In the present paper, the magnitude and distribution of residual stresses in 3 HSS H-sections, which were fabricated from 11 mm and 21 mm HSS plates with flange slenderness ratios varying from 3.4 to 7.1, were investigated by adopting both hole-drilling and sectioning methods.

1.2. Residual stress measurement techniques

Sectioning method, as a destructive method, has been adopted by lots of researchers after it was presented by Kalakoutsky in 1888 and is very popular for measuring residual stresses in structural steel members. Its advantages of adequacy, accuracy and economy have been proven with the condition of careful preparation of the specimen and the measurement procedures [8]. By using a Whittemore gage for the sectioning method, the effect of strip curvature on the determination of membrane residual stresses should be removed if the bending residual stresses are non-negligible. Cruise and Gardner [9] gave an in-depth discussion and a suggestion of the corrections, on aspects of gage hole, surface to neutral axis and chord to arc, which were utilized in the measurement of residual stresses in cold formed stainless steel sections. On the other hand, recently, electrical strain gages were selected for the sectioning method due to better accuracy and applicability to curved steel [9,10]. In addition to the destructive methods, semi-destructive and non-destructive methods had been adopted to the measurement of residual stresses in structure members. A hole-drilling method was used in the measurement of tensile residual stresses near the weld of HSS welded box sections by Clarin and Lagerqvist [11]. They pointed out that the presence of the plastic behavior of specimens should be considered because of the elastic assumption for the measurement of the hole-drilling method. Due to the advantage of direct evaluation of through-thickness residual stresses, X-ray diffraction was also utilized in the measurement of residual stress in cold-rolled stainless steel hollow sections by Jandera and Gardner [12]. Withers and Bhadeshia [13] assessed the capability of a large number of current residual stress measurement techniques (mechanical, diffractive, magnetic, ultrasonic and other methods) from a length scale perspective. Considering the measurement accuracy and cost, the sectioning method was employed in this assessment as most of the previous residual stress experiments on structural steel members. Meanwhile, the hole-drilling method, as a semi-destructive method, was adopted and conducted before the procedure of the sectioning method for comparison purposes.

2. Experimental program

2.1. Material properties

Tension coupons were cut from the same parent plates with nominal thicknesses of 11 mm and 21 mm from which the residual stress specimens are fabricated. The cutting direction was perpendicular to the rolling direction according to GB/T 2975-1998 [14]. An extensometer was fixed on the mid-length of each tension coupon to obtain longitudinal strains for accurate determination of Young's modulus. The linear variable displacement transducer (LVDT) inside the universal testing machine also recorded the displacement between the two clamps after the extensometer was removed when the stress–strain curve turned to drop. The tension coupons were tested in accordance with GB/T 228-2002 [15]. Fig. 1 shows the mean test results of 12 tension coupons, where $Rp_{0.2}$ is the 0.2% proof stress, which is adopted as the yield strength of steel plates, Rm is the ultimate tensile stress, ε_u is the corresponding strain of ultimate stress, E is Young's modulus and $\Delta\%$ is the percentage of elongation after fracture. The stress–strain curve is the combination of the extensometer data and the descending branch data from LVDT. It is shown that the material properties of HSS, not the same as mild carbon steel, have neither a well-defined flat yielding plateau nor such a significant strain hardening. All these different properties will influence the residual stresses in HSS H-sections.

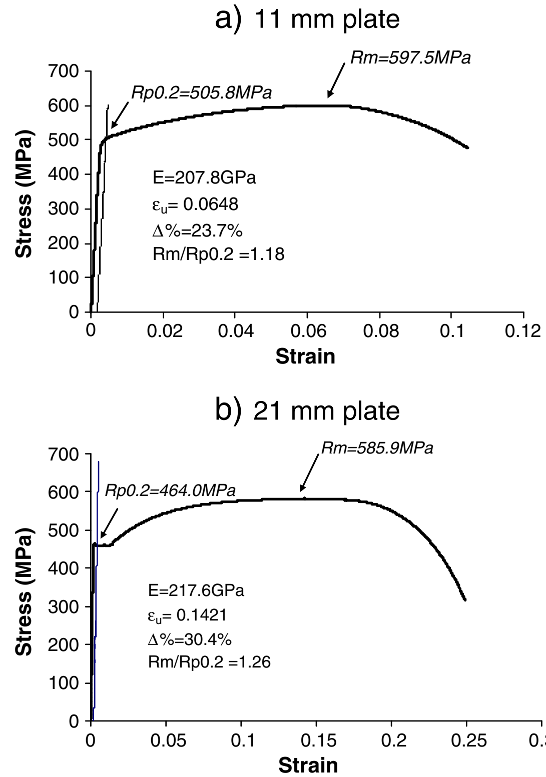

Fig. 1. Stress–strain curve for Q460 steel.

2.2. Fabrication and preparation of specimens

The test specimens were fabricated from Q460 HSS plates with a nominal yield strength of 460 MPa. Q460 steel is a new product of high strength low alloy structural steels in the Chinese constructional steel market. The original plates were flame cut into small component plates. Two flange component plates with a nominal thickness of 21 mm and one web component plate with a nominal thickness of 11 mm were

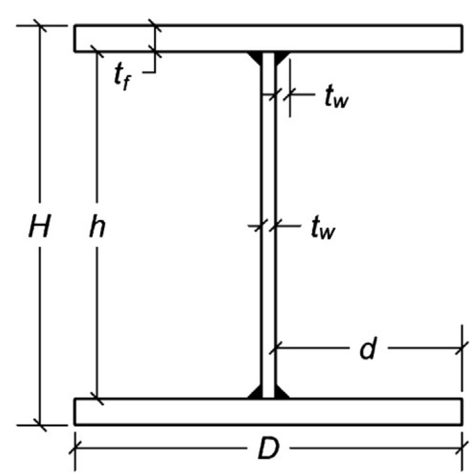

Fig. 2. Definition of symbols.

Table 1
Welding parameters.

Current (amp)	Voltage (volt)	Velocity (mm/s)
190–195	28–30	2.3

welded together to form an H-section, as shown in Fig. 2. The manual gas metal arc welding process using the electrode ER55-D2 with the same nominal yield strength of the Q460 steel was applied. As current practice does not employ complete penetration welding for H-section columns except in the beam-to-column connection region, the component plates were connected by incomplete penetration welding. In order to reduce the shrinkage deformations caused by welding heat, an optimized welding sequence was adopted. The welding parameters used in the fabrication procedures are given in Table 1. The measured geometric dimensions of three test specimens are shown in Table 2. The symbols in Table 2 are illustrated in Fig. 2. In order to eliminate the end effects, the specimens must be long enough to provide a distance of 2 times the lateral dimension from each end to the test region. Hence, the sum of about 4 times D and 400 mm was adopted as the length L of the specimen, as shown in Table 2.

Sectioning will induce significant redistribution and rebalance of the locked-in stresses in the specimens. Thus, as a semi-destructive method, it is reasonable to firstly apply the hole-drilling method to reduce the possible disturbance between the two measurement regions. The holes were drilled in the hole-drilling region which is next to the sectioning region around the mid-length of the specimens, as shown in Fig. 3. The effect of the drilled hole on the stress state of the surrounding area weakens rapidly with the increase in the distance away from the hole center. Generally, the safe distance between two geometric centers of strain gage rosettes is 15 times the diameter of the hole [16]. In this experiment, the diameter of the drilled holes was 1.5 mm, and the safe distance was 22.5 mm. The arrangement of the hole site and sectioning line is shown in Fig. 4. It can be observed that marked holes in the hole-drilling region are far enough from each other and from the sectioning region that will not disturb the equilibrium of the stress for each other or the sectioning region. Therefore, the sectioning method should be conducted after the hole-drilling method under the guaranteed initial state of residual stresses.

2.3. Hole-drilling method

Measure points for the hole-drilling method were marked at the locations under consideration on each surface of hole-drilling regions, as shown in Fig. 5. Surface areas adjacent to the measure points were polished by gauze rounds. After a thorough cleaning and degreasing by an acetone solvent, the strain gage rosettes were attached according to the marked points. Strain rosette TJ120-1.5-φ1.5 made by Zhengzhou Research Institute of Mechanical Engineering (ZRIME) was adopted in this experiment. It is the same as the type A rosette in E837-08e1 but with a different grid size. The recommended diameter and depth of the drilled hole were 1.5 mm and 2 mm respectively. A typical hole-drilling apparatus was applied in finding and fixing the location of the hole. When the centers of the hole and strain gage circle coincided with each other, the hole was drilled by an electric hand-drill. Removing materials from the surface of the specimen caused a redistribution of encased residual stresses. The strains before and after hole drilling were recorded by the strain gage rosettes, as illustrated in Fig. 5. The mean value of machining-induced residual strain, which was measured from annealed coupons, is $-23.7\mu\varepsilon$. This machining-induced residual strain was subtracted from the relieved strain recorded by a strain gage to get the purely relieved strain.

Then the purely relieved strains in the X–Y plane were translated into residual stresses by Eqs. (1) and (2):

$$\sigma_{rx} = E\cdot\frac{B\left(\varepsilon_x+\varepsilon_y\right)+A\left(\varepsilon_x-\varepsilon_y\right)}{4AB}-\sigma_d \tag{1}$$

$$\sigma_{ry} = E\cdot\frac{B\left(\varepsilon_x+\varepsilon_y\right)-A\left(\varepsilon_x-\varepsilon_y\right)}{4AB}-\sigma_d \tag{2}$$

where σ_{rx} is the longitudinal residual stress, σ_{ry} is the transversal residual stress, ε_x and ε_y are the purely released longitudinal strain and transversal strain respectively, A and B are the calibration constants which indicate the relieved strains due to unit stresses within the hole depth, and σ_d is the residual stresses induced by mechanical abrasion. The stress level related calibration constants A and B for the rosette TJ120-1.5-φ1.5 type presented in Ref. [17] were employed here. The residual surface stress σ_d induced by polishing procedures has been measured by ZRIME by using the hole-drilling method and the mean value of −18.9 MPa was suggested.

2.4. Sectioning method

Fig. 4 shows the cutting lines and centers of gage holes marked on the sectioning regions. The gage holes were centrally located using a punch in order to reduce variations in gage length. Corresponding to the center markers, through-thickness holes were drilled on the drilling machine. In this method, strain measurements were taken over a 200 mm gage length using the Whittemore strain gage. The measure sensitivity was $5\mu\varepsilon$. The original gage lengths were measured and recorded before the sectioning process. Three sets of measurements for each gage length were taken if the variation did not exceed 0.005 mm. Temperature changes during the reading processes were

Table 2
Actual dimensions.

Specimen	D (mm)	H (mm)	t_f (mm)	t_w (mm)	d/t_f	h/t_w	L (mm)
R-H-3	156.00	168.00	21.39	11.49	3.4	10.9	1550
R-H-5	225.25	243.75	21.23	11.33	5.0	17.8	1300
R-H-7	314.00	319.50	21.20	11.63	7.1	23.8	1060

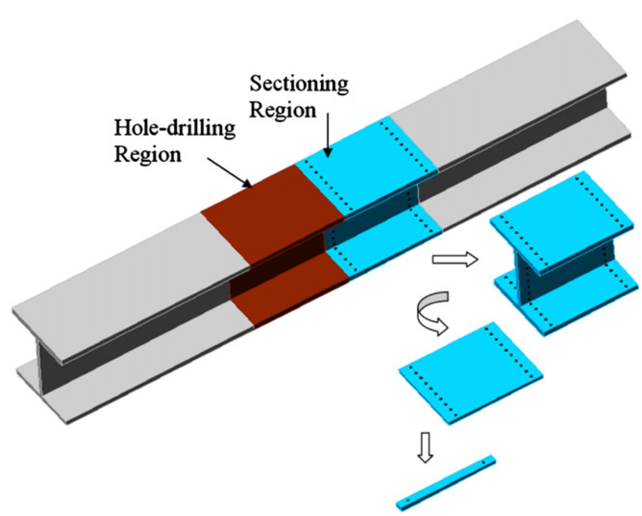

Fig. 3. Measurement regions for the sectioning method and the hole-drilling method.

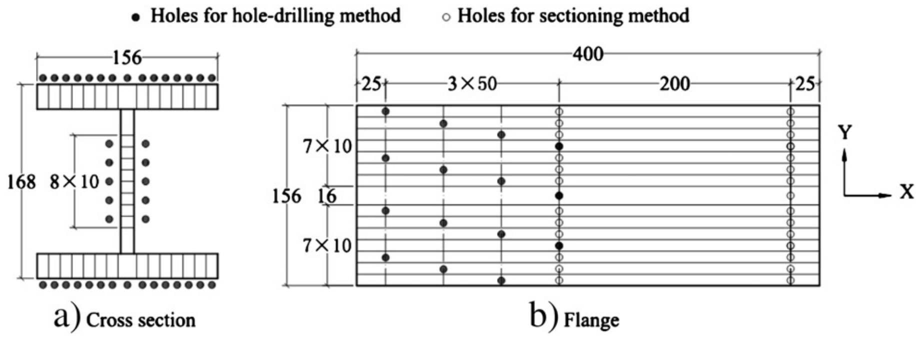

Fig. 4. Distribution of hole drilling and sectioning for R-H-3.

practically eliminated by using a reference bar at the beginning and the end of each measurement set. After the pre-sectioning measure, the sectioning regions were cut out with an electric band saw. Then the procedures of partial and complete sectioning were performed on a milling machine, as shown in Fig. 3. The influence of heat release from mechanical milling was suppressed by supplying a fluid coolant.

The width of each strip was about 10 mm before it was released from the specimen except the middle strips of flanges, the width of which was about 12 mm to 16 mm. Strips sectioned from the same specimen were put together and arranged according to the marked numbers. Iron filings and grease were cleaned from the sectioned strips, especially around and inside the gage holes. Three sets of gage length were measured again following the procedure recommended by Tebedge [8]. The released strains were computed from the measured strains and temperature compensations.

3. Experimental results

3.1. Residual stress measured by sectioning method

Based on the difference in the length of each strip measured before and after sectioning, the residual stresses were calculated by multiplying the released strains by Young's modulus (Fig. 1). Figs. 6–8 show the residual stress distributions of the sections R-H-3, R-H-5 and R-H-7. The solid dots in Figs. 6–8 represent the residual stresses in the outside surface of flange plates or in the right surface of web plates, while the hollow dots represent residual stresses in the inside surface of flange plates or in the left surface of web plates. Because of the inappropriate preparation of gage holes in some strips of the section R-H-7, the original gage lengths exceeded the full scale value of the Whittemore strain gage. The linear interpolation results of neighbor strips are shown in Fig. 8 as gray dots instead of invalid values.

3.2. Residual stresses measured by hole-drilling method

The residual stress distributions obtained by hole-drilling method are shown in Figs. 9–11 for the top flange, bottom flange and web of R-H-3. For comparison, residual stresses obtained by sectioning method are also illustrated in Figs. 9–11. The measured result shows that the gradients of residual stress distributions obtained by hole-drilling method are much steeper than those obtained by sectioning method. Moreover, the maximum residual stress values obtained by hole-drilling method are higher than those obtained by sectioning method. The explanation for these differences is that the measurement through hole-drilling method indicates the surface residual stresses within the boundaries of the drilled hole while the residual stresses obtained through sectioning method represent the mean value of the whole width (about 10 mm) of each strip. Tabulated mean values of compressive residual stress for R-H-3 are shown in Table 3. It can be observed from Table 3 that the mean values of compressive residual stresses obtained by the two methods agree well with each other. It can also be seen that the residual stress distributions obtained by sectioning method is more convenient to be introduced in the numerical analysis.

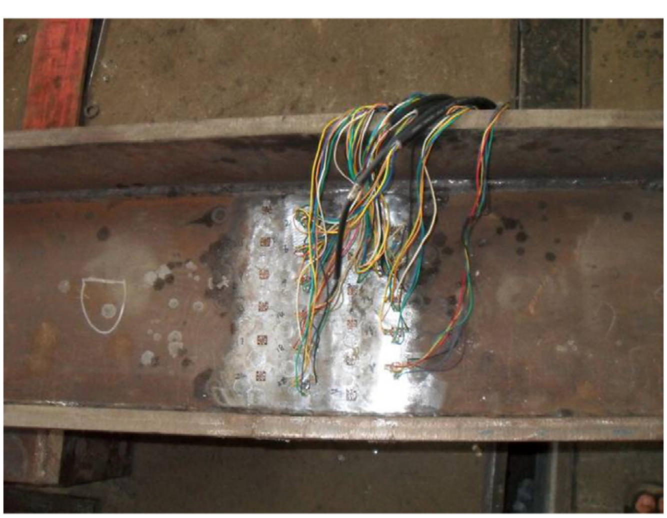

Fig. 5. Test setup of the hole-drilling method.

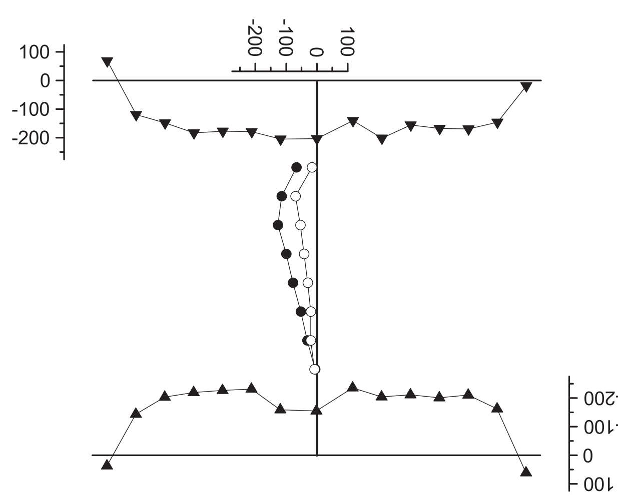

Fig. 6. Residual stress distribution in R-H-3 by sectioning method.

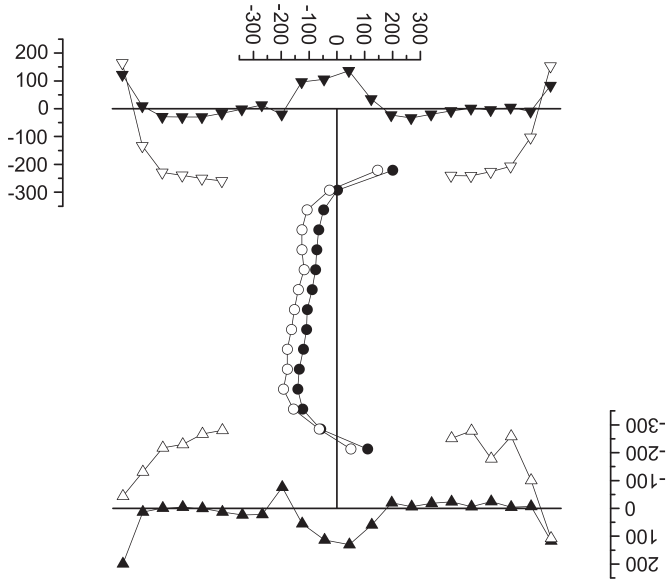

Fig. 7. Residual stress distribution in R-H-5 by sectioning method.

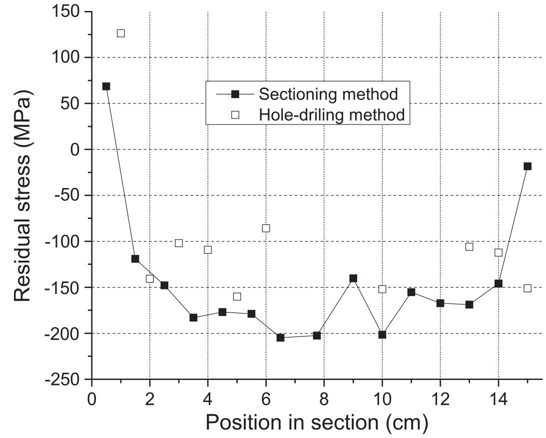

Fig. 9. Comparison of the hole-drilling method and the sectioning method for the R-H-3 top flange.

4. Simplified residual stress pattern

Unlike the compressive residual stresses presented in the flange tips of H-sections fabricated from guillotined plates, H-sections manufactured from flame-cut plates are characterized by tensile residual stress at the flange tips. This favorable residual stress distribution could result in a higher ultimate capacity for welded H-section columns, especially for those under bending about the weak axis. The measured residual stresses by sectioning method shown in Figs. 6–8 have the same pattern as the typical residual stress pattern of flame-cut welded H-sections. The large differences in residual stresses between the outside (right) and inside (left) surfaces of the flanges (webs) indicate that the sectioned strips were bent in the longitudinal direction. These bending stresses are usually induced by the sectioning procedures [9]. In order to obtain the membrane stresses, residual strains on opposite sides were averaged to calculate the effective residual stress, based on the assumption that the residual stresses are uniformly distributed through thickness. If the thicknesses of all component plates are less than 25 mm, the variation of residual stresses across thickness is recognized as negligible [18]. Therefore, the assumption is applicable.

The mean values of residual stresses are shown in Table 4 and a corresponding simplified residual stress pattern for H-sections fabricated from flame-cut plates is proposed based on the results of the sectioning method as shown in Fig. 12. In Table 4 and Fig. 12, α_i and β_i are the ratios of tensile and compressive residual stresses over the yield strength of the base metal, respectively, and the subscripted letter "i" indicates the location of the residual stress block. Since the measurement in blocks (α_1) was not available, the tensile residual stress ratios (α_1) were obtained by applying an equilibrium condition in the measured residual stress distributions. It is founded by Young and Robinson [19] that the rectangular shape of the tension block will result in more conservative column strength than the triangular and trapezoidal shapes. In addition, for the convenience of introducing residual stresses in numerical models, the rectangular shape was adopted in this simplified residual stress pattern.

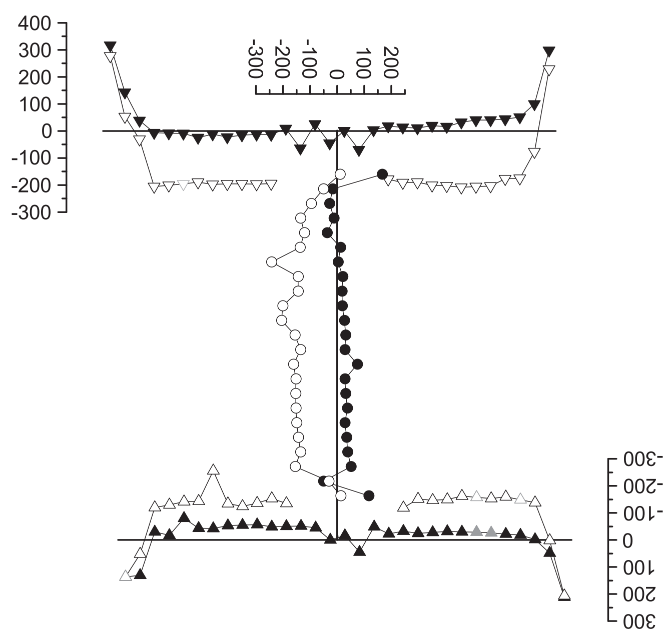

Fig. 8. Residual stress distribution in R-H-7 by sectioning method.

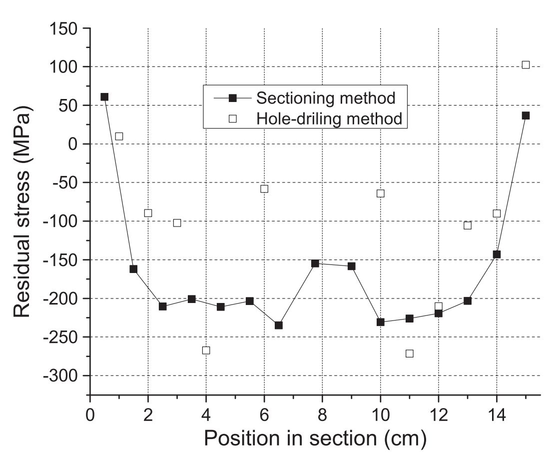

Fig. 10. Comparison of the hole-drilling method and the sectioning method for the R-H-3 bottom flange.

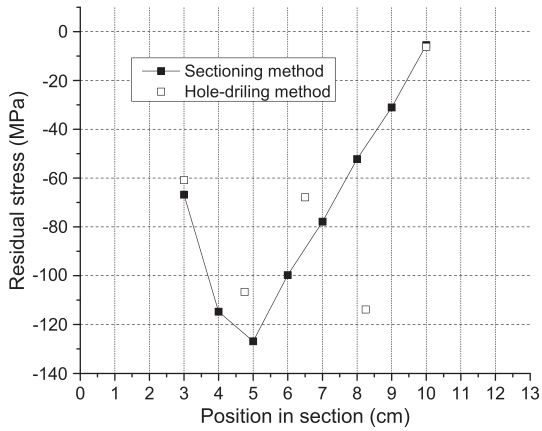

Fig. 11. Comparison of the hole-drilling method and the sectioning method for the R-H-3 web.

5. Discussion

5.1. Compare residual stresses with varying d/t_f

The magnitude and distribution of residual stresses within flanges are of significant effect on the overall buckling behavior of H-section members. Therefore, the variation of the residual stresses induced by changing the width to thickness ratio of outstanding flanges should be emphasized. The measured residual stresses with different d/t_f (Fig. 2) are compared in Table 4. The actual d/t_f of R-H-3, R-H-5, and R-H-7 are 3.4, 5.0, and 7.1, respectively. Accordingly, the compressive residual stress ratios of the specimens are −0.408, −0.271, and −0.195 for the flanges and the tensile residual stress ratios of the flange tips are 0.080, 0.243, and 0.488. The findings show that the increase in d/t_f will result in decreasing of compressive residual stresses within flanges and increasing of tensile residual stresses at flange tips. Consequently, the smaller width to thickness ratio of the member is the more detrimental influence of residual stresses on the local and overall stability expected.

In order to make full use of the materials, flanges are usually designed with a large d/t_f. According to Ref. [5], the same d/t_f limit formula should be applied to HSS and conventional steel plates. This means that the practical width to thickness ratios of outstanding flanges will be relatively lower than those of the ordinary steel. The d/t_f limits of different countries [18–21] are summarized in Table 5, where λ is the member slenderness, and k_c is the coefficient for slender unstiffened elements. If the yield strength f_y is assumed to be 460 MPa for the Q460 steel, the d/t_f limits will range from 8.4 to 14.2. In view of the presented d/t_f limits, R-H-7 with the width to thickness ratio of 7.1 will be the commonly used section for Q460 HSS. R-H-5 with the width to thickness ratio of 5.0 can be recognized as the lower boundary of industry practice.

5.2. Compare residual stresses of different steels

It is of interest to compare the measured residual stresses with those of carbon steels. McFalls and Tall [20] measured the residual stresses of two A36 steel flame-cut welded H-sections. One of the sections, 12H79, with a yield strength of 253 MPa is of similar dimensions with the Q460 HSS specimen R-H-7. Both flame-cut welded H-sections have the same general pattern, which shows tensile residual stress at the junction of the flange and web and flange tips and compressive residual stress at the rest of the shape. The comparison of the compressive residual stresses between Q460 and A36 steel is shown in Table 6. It is found that, regardless of the significant difference in the yield strength of the base material and the weld metals, the magnitude of compressive residual stresses of the specimen R-H-7 is identical with that of the specimen 12H79. However, with the increase in yield strength of the weldment (253.0 MPa to 505.8 MPa), H-sections fabricated from HSS plates will have the lower compressive residual stress ratios. The compressive residual stress ratio decreased from −0.403 to −0.195 for flanges and from −0.243 to −0.131 for webs. It is known that the ratio of residual stress to yield strength, rather than the absolute value, dominates the effect of residual stress on the overall and local buckling behavior of steel members. Therefore, the member's ultimate strength will benefit from the improvement of steel grades.

Table 3
Mean values of compressive residual stresses of R-H-3.

Method	Top flange (MPa)	Bottom flange (MPa)	Web (MPa)
Sectioning	−166.5	−211.8	−76.7
Hole-drilling	−125.1	−212.8	−84.1

Table 4
Ratios of residual stresses.

Specimen	α_1	α_2	β_1	β_2
R-H-3	1.039	0.080	−0.408	−0.152
R-H-5	0.900	0.243	−0.271	−0.235
R-H-7	0.731	0.488	−0.195	−0.131

5.3. Compare measured residual stresses with previous assumptions

The use of HSS has been considered in the theoretic and experimental basis of Eurocode3 [21]. In the absence of experimental confirmation, the European Convention for Constructional Steelwork (ECCS) adopted a compressive residual stress level of 10% yield strength for flanges and web of a welded H-section with rolled flange and a yield strength of 430 MPa and above. The consideration of residual stresses in HSS flame-cut welded H-sections was based on the knowledge that the tensile residual stress block at the flange tips is beneficial for bending about both principal axes and no residual stress pattern was suggested by ECCS. Since direct comparison with the residual stress pattern for the HSS flame-cut H-section was not available, the measured residual stresses of the specimen R-H-7 were compared with the constant distributed compressive residual stress at the level of 10% yield strength. The comparison shows that

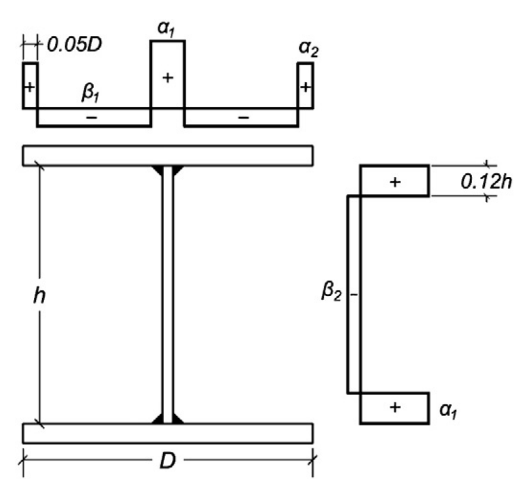

Fig. 12. Simplified residual stress pattern.

Table 5
Section slenderness limits for Q460 steel.

Country	Specification	Limit formula (d/t_f)	Limit value (d/t_f)
Australia	AS4100-1998	$d/t_f \leq 14\sqrt{\frac{250}{f_y}}$	10.3
Europe	Eurocode 3 class 3	$d/t_f \leq 14\sqrt{\frac{235}{f_y}}$	10.0
China	GB 50017-2003	$d/t_f \leq (10+0.1\lambda)\sqrt{\frac{235}{f_y}}$	9.3–14.2
America	AISC-05	$d/t_f \leq 0.64\sqrt{\frac{k_c E}{f_y}}$	8.1–11.9

Table 6
Comparison of residual stresses of different steels.

Specimens	Steel grade	Yield strength (MPa)	Residual stress (MPa)		Residual stress ratio	
			Flange	Web	Flange	Web
R-H-7	Q460	505.8 (flange) 464.0 (web)	−90.5	−66.4	−0.195	−0.131
12H79	A36	253.0	−101.9	−61.5	−0.403	−0.243

adopting the suggested residual stress pattern in [21] may overestimate the column ultimate strength.

6. Conclusion

The residual stress distributions of three different H-sections fabricated from flame-cut Q460 high strength steel plates were presented. The simplified residual stress distributions were proposed. The average compressive residual stresses σ_{rc} in flanges were −19.5%, −27.1% and −40.8% of yield strength according to the width to thickness ratios of outstanding flanges, which were 7.1, 5.0 and 3.4 respectively. The average calculated tensile residual stresses σ_{rt} in each section were 73.1%, 90.0% and 103.9% of yield strength for specimens R-H-7, R-H-5 and R-H-3, respectively. The test results obtained by both sectioning and hole-drilling methods were compared. It is observed that the average values of compressive residual stress obtained by the two methods are similar, but the residual stress distributions obtained by sectioning method is more convenient to be employed in the numerical analysis. By comparing the measured specimens, it is found that the increase in width to thickness ratios of an outstanding flange will result in decreasing of compressive residual stresses within flanges and increasing of tensile residual stresses at flange tips. The comparison of the test result with those of mild carbon steel shows that the residual stress ratios of HSS flame-cut welded H-sections tend to be less detrimental to the column strength than the ordinary steel H-sections.

Acknowledgments

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