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Comparative experimental study of hot-formed, hot-finished and cold-formed rectangular hollow sections

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ABSTRACT

This paper presents a comparative experimental study on the physical, chemical and mechanical properties of indirectly formed hot-formed, hot-finished and cold-formed structural steel rectangular hollow sections. Characteristic geometrical parameters and chemical compositions are examined to investigate the physical and chemical differences. Tensile test and charpy V-notch impact test are employed to evaluate the difference in strength, ductility and toughness. Further, the residual stress distributions in both transverse and longitudinal directions are measured using the sectioning method and hole-drilling technique. It is found out that although the geometrical parameters and chemical composition of the tested hollow sections are similar, the mechanical properties are significantly different, especially for strength, ductility and residual stress distribution. While the hot-finished and hot-formed sections are often treated equally in design, their mechanical properties and residual stresses distribution are actually different.

1. Introduction

Structural Hollow Sections (SHS), especially rectangular hollow sections, are widely used in construction due to the recognition of the inherent aesthetic and structural advantages. Currently, SHSs of steels are classified into two major groups based on the manufacturing methods: cold-formed and hot-finished, in which hot-finished hollow sections consist of another two types, i.e. hollow sections formed hot and formed cold with subsequent heat treatment (hot-formed and hot-finished, respectively) [1,2]. Although these three types of SHSs are manufactured by either direct or indirect forming techniques, the rolling condition/subsequent heat treatment processes lead to significant differences in properties [3]. Through decades of study and practice, the importance of physical, chemical and mechanical properties for designing and analyzing steel structures has been well recognized. Based on the preference on these properties, hot-formed sections are widely favored as the first choices, while cold-formed hollow sections are often misunderstood and treated unfavorably although they are actually easier to manufacture and more economical [4]. As for hot-finished sections, they are often treated the same as

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hot-formed sections in mechanical properties, provided that the sections formed cold are fully annealed in the subsequent heat treatments [5,6].

Among the differences among the three types of SHSs, residual stress is the most frequently concerned, as it is often associated with issues such as brittle fracture, fatigue, stress corrosion, buckling and post-buckling strength reduction [7–9]. In practice, the SHSs produced by hot-forming techniques are considered to be residual stress free and have no change in mechanical properties from base metal [10]. The concerns for locked-in residual stresses are mainly for cold-formed and hot-finished SHSs, as they are formed cold by bending in the beginning. For residual stress contained in cold-formed SHSs, numerous work has been done. Detailed studies of through thickness residual stresses in the longitudinal and transverse directions of square and circular cold-formed thin-walled SHSs can date back to 1980s by stripping method [10]. Later, the through thickness residual stress distribution in cold-formed thin-walled SHSs by panel removal method is also reported [11]. Nowadays, it is well recognized that for cold-formed thin-walled SHSs, the longitudinal residual stresses are in tension at outer surface and in compression at inner surface, and the distribution is assumed to be linear through the thickness [12]. However, studies on the cold-formed thick-walled plate subjected to bending [13,14] show that the through thickness residual stress distribution pattern is not linear. Tong et al. measured the longitudinal residual stress distribution of cold-formed thick-walled SHS and found out the through thickness distribution was different from that of the thin-walled and dependent on the geochemical profile [15]. On the other hand, different from the cold-formed SHS, the concern with the hot-finished SHS is that it is difficult to make sure the sections formed cold are subsequently "properly" heat treated and successfully get rid of the issues associated with cold-forming techniques [16]. Currently, common design standards have taken the effect of residual stresses in consideration implicitly [17–19]. However, there is still few specific guidelines on designing and evaluating the distribution and amount of the residual stress itself in a given SHS, especially for thick-walled cold-formed and hot-finished SHSs.

In this study, the influence of different manufacturing processes on the physical, chemical and mechanical properties of popular thick-walled SHSs including hot-formed and hot-finished square SHSs manufactured to Grade S355J2H of EN 10210 [2] and cold-formed square SHS complying EN10219 [1] Grade S355J2H is investigated experimentally. The aim is to provide useful data for the EN Standards and engineers as reference. This comparative study is carried out in three phases. Firstly, physical and chemical properties are examined to investigate the difference in the geometry and chemical composition. Secondly, tensile test and chapry V-notch impact test are conducted to analyze the difference in the mechanical properties such as yield stress, tensile stress, ductility and impact toughness. Thirdly, sectioning test and hole-drilling test are employed to evaluate the locked-in residual stress in the SHSs qualitatively and quantitatively. By comparing the performance of the tested SHSs in the above three phases, the differences among the tested SHSs are evaluated.

2. Experimental program

2.1. Physical properties test

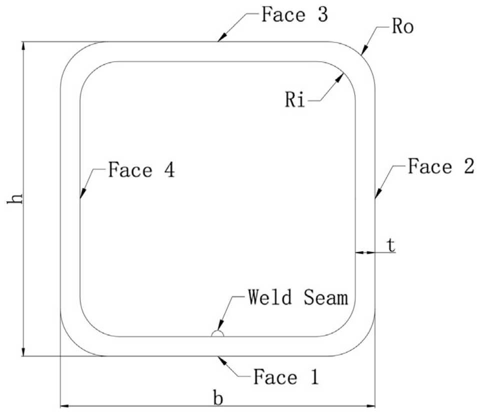
The tested hot-formed and hot-finished hollow sections were of dimensions 180 mm × 180 mm × 12.5 mm, while the cold-formed hollow section was of dimensions 200 mm × 200 mm × 12.5 mm. Surface discontinuities including rolled-in scale and pitting, indentations and roll marks, scratches and grooves, spills and silvers, blisters, sand patches, cracks, shell, and seams were examined. Delivery conditions and dimensional tolerances were checked against EN 10210 [3] and EN 10219 [2] for the hot-formed/hot-finished and the cold-formed SHSs, respectively. The following characteristic geometrical dimensions were measured: width b, height h, wall thickness t at every face, inner corner radii (r_i) and outer corner radii (r_o) for the four corners, as shown in Fig. 1. Based on the mean values of the above dimensions, the main geometrical parameters, including wall slenderness ratio b_m/t_m, mean outer corner radii related to mean wall thickness $r_{o,m}/t_m$ and mean inner corner radii related to mean wall thickness $r_{i,m}/t_m$ were calculated.

Chemical composition analysis was carried out using the Optical Emission Spectroscopy (OES) machine, an universal metal component analyzer widely used in metal producing, processing and recycling industries. The OES machine employed in this study consists of plasma generator, special optics, high performance readout system and ICAL logic system, as shown in Fig. 2. Test specimens were cut from the SHSs from the faces without weld seam and were of the same dimensions: 100 mm long and wide, and 12.5 mm thick (Fig. 2a). For each specimen, three tests were carried out. A complete chemical analysis of the following elements was conducted: C, Mn, Cu, P, S, Al, Ti, Si, Cr, Mo, V, and Ni. Subsequently, the carbon equivalent content was calculated using Eq. (1) provided by AWS [20].

$$CE = \%C + \frac{(\%Mn + \%Si)}{6} + \left(\frac{\%Cr + \%Mo + \%V}{5}\right) + \left(\frac{\%Cu + \%Ni}{15}\right) \quad (1)$$

2.2. Mechanical properties

Standard coupon specimens were cut from the center area of Faces 2, 3 and 4 (Fig. 1) and tested according to EN 10002-1 [21]. The dimensions of the specimens are shown in Fig. 3. Non-proportional gauge length of 80 mm was used as the original gauge length. For conversion of elongation values from non-proportional gauge length to a proportional gauge length $5.65\sqrt{So}$, the conversion tables from BS EN 2566-1 [22] applied. During tests, both strain gauge and extensometer



(a) Definition of the measured geometrical dimensions

(b) the tested cold-formed, hot-formed and hot-finished SHSs (from left to right)

Fig. 1. Definition of the measured geometrical dimensions and the tested SHSs.

were used for stress-strain relationship measurement and record. The loading rate was set as 1 mm/min and stress-strain data points were captured at a frequency of 1 Hz.

Steels having identical material properties when tested in tension at low strain rates can display pronounced differences in their tendency for brittle fracture when tested in impact tests [23]. In this study, charpy v-notch impact test is employed to evaluate the brittle fracture resistance of the cold-formed, hot-formed and hot-finished SHSs. The main measurement from the test is the impact energy absorbed in fracturing the specimens. Standard charpy V-notch specimens were fabricated and tested at −20.0 °C with temperature precision of ±0.1 °C (J2 environment [2,3]). Three samples were cut from each hollow section, as shown in Fig. 4: the first specimen was in the transverse direction (perimeter direction of the SHSs) with V-notch on the outside surface; the second specimen was in the longitudinal direction with V-notch on the outside surface; the third specimen was in the same direction as sample 1 but had V-notch in the normal direction of the SHS. The specimens were of dimensions 10mm × 10mm × 55 mm. A standard V-notch (with angle of 45°, depth of 2 mm, and a root radius of 0.25 mm) was cut in the center of each specimen (Fig. 4).

2.3. *Residual stress measurement*

In this study, the hole-drilling method is employed to quantitatively measure the residual stresses along the perimeter of the SHSs. SHSs with lengths of 1 m were cut from the main tubes, and the hole drilling tests are carried out on the center loops. RS200 milling guide and electric strain gauge FRAS-2-11 are employed to measure the residual stresses released by hole drilling. Test positions are arranged with equal distance (no larger than 50 mm) on all the surfaces, and extra test points are added at corners and welding areas. The arrangement of the drilling points on the cold-formed SHS is shown in Fig. 5a for instance.

During the test, a hole with diameter of 2 mm and depth of 1 mm is drilled at the designated position on the special strain gauge rosette by 8 steps. The released strains at the end of each step are recorded for further analyzing. By comparing the stress at this point before and after hole-drilling, stress relaxation due to hole drilling can be determined. On the assumption

(a) Test Gun

(b) Analyzer

Fig. 2. Chemical test using OES.

that the material is homogeneous and isotropic, and the stress-strain curve is linear, the relieved strain at a point P can be obtained by substituting the stress relaxation into the Hooke's Law [24]:

$$\varepsilon = \frac{1+\nu}{E}\bar{a}\frac{\sigma_\phi + \sigma_\theta}{2} + \frac{1}{E}\bar{b}\frac{\sigma_\phi - \sigma_\theta}{2}cos2\alpha + \frac{1}{E}\bar{b}\tau_{\phi\theta}sin2\alpha \tag{2}$$

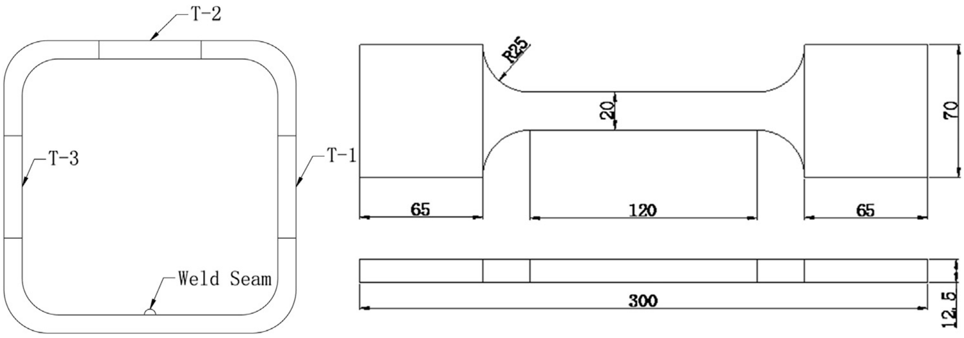


Fig. 3. Sources and dimensions of tensile test specimens.

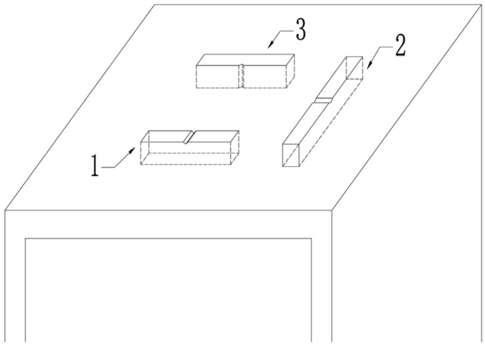


Fig. 4. Souce of the charpy V-notch impact test specimens.

Table 1
Characteristic geometrical dimensions of the tested SHSs.

Hollow sections	b_m (mm)	t_m (mm)	$r_{o,m}$ (mm)	$r_{i,m}$ (mm)	b_m/t_m	$r_{o,m}/t_m$	$r_{i,m}/t_m$
Cold-formed	200.53	12.76	30.00	21.75	15.72	2.35	1.71
EN 10219	200 ± 1.6	12.5 ± 0.5				2.4 to 3	
Hot-formed	180.27	12.72	25.00	12.13	14.17	1.97	0.95
Hot-finished	180.34	12.88	26.75	14.00	14.00	2.08	1.09
EN 10210	180 ± 1.8	−10%				<3	

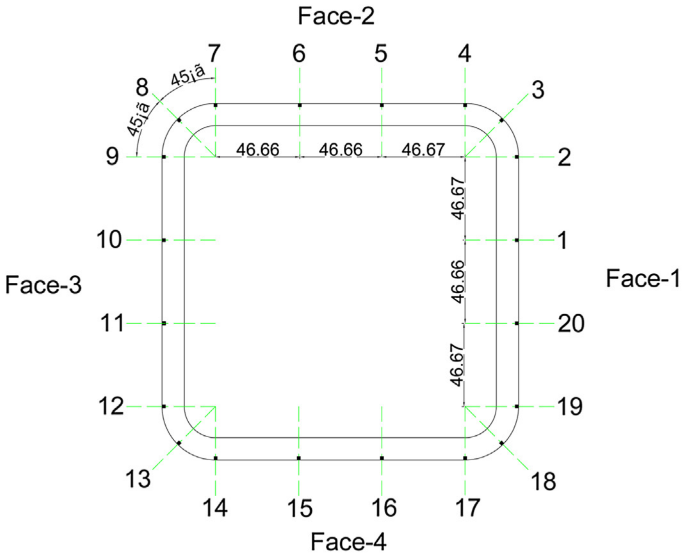
In Eq. (2), E is the Young's modulus, ν is the Poisson's ratio and ε is the relieved strain. σ_ϕ and σ_θ are the stresses in the ϕ and θdirections (Fig. 5b), respectively. α is the angle from the x-axis to the maximum principle stress, and $\bar{a}$ and $\bar{b}$ are almost material-independent calibration constants indicating the relieved strains due to unit stresses within the hole depth. Since the holes are drilled directly on the surface of the tubes (Fig. 5b) and the stress/strain status of the SHS can be treated as plane strain condition, $\sigma_\phi$and σ_θ correspond to the transverse and longitudinal stresses. It should also be noted that the relieved strains are mostly influenced by the near-surface residual stresses. Interior stresses have influences that diminish with their depth from the surface [24]. For the strain rosettes employed in this study (Fig. 5b), the sensitivity diminishes to near zero for stresses beyond 1 mm depth. Therefore, the measurement actually indicates a weighted average of the residual stresses within the near-surface layer, i.e. 1 mm deep from the measured surface.

Besides the hole-drilling method as quantitative measurement, the sectioning test is also employed to qualitatively evaluate the effect of these locked-in residual stresses in the SHSs. The sectioning test is carried out on SHS specimens with length of 200 mm. Three cuts with equal spacing and depth (170 mm) are applied on the flat area of each face, as shown in Fig. 6. By measuring the alteration in the geometry of the sections before/after sectioning, the effect of the locked in residual stress is evaluated.

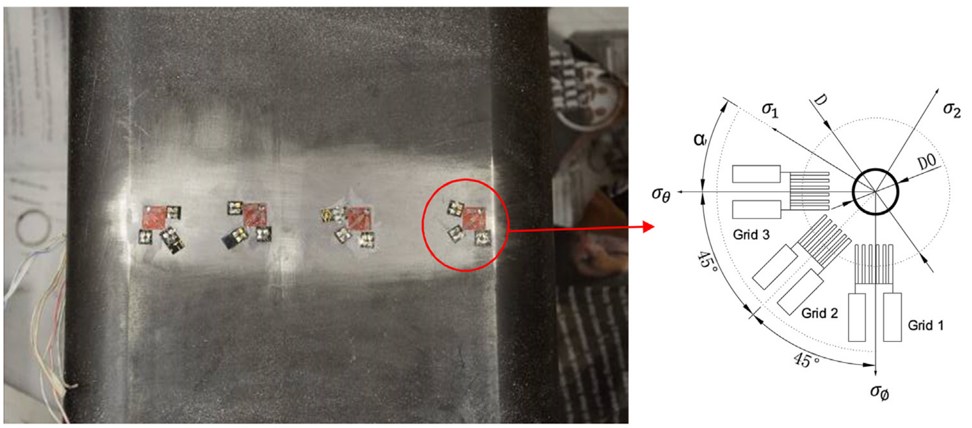
3. Test results

3.1. Geometry and chemical composition

All the surfaces of the investigated hollow sections were elaborately treated by the manufacturers, and no surface discontinuity not allowed in EN 10210 or EN 10219 was found. The measured characteristic geometrical data are listed in Table 1. It can be seen from Table 1 that the global dimensions of the tested sections match the respective specifications excellently.



(a) Hole drilling positions



(b) Strain gauge rosettes for hole drilling

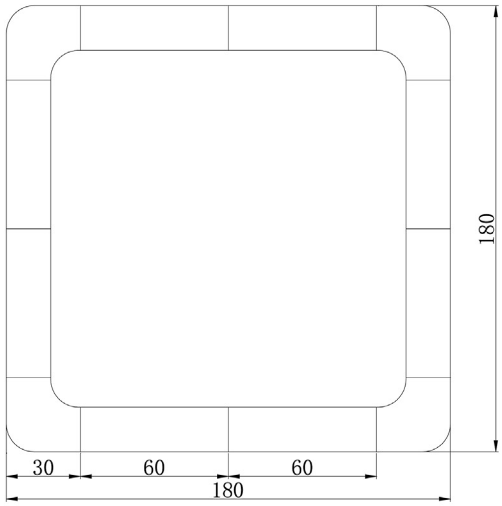
Fig. 5. Drilled holes on the flat area of the cold-formed SHS.

Table 2
Chemical composition (%) of the cold-formed, hot-Finished and hot-formed SHSs.

	C	Mn	Cu	P	S	Al	Ti	Si	Cr	Mo	V	Ni	CE
Cold-formed	0.08	0.97	0.022	0.031	0.005	0.02	<0.001	0.16	0.026	0.008	0.004	0.020	0.281
EN 10219	≤0.2	≤1.6	≤0.35	≤0.04	≤0.04	≥0.02	≤0.05	≤0.6	≤0.3	≤0.2	≤0.05	≤0.8	≤0.45
Hot-formed	0.130	1.330	0.022	0.032	0.009	0.042	<0.001	0.230	0.032	0.006	0.007	0.022	0.400
Hot-finished	0.12	1.300	0.017	0.033	0.006	0.029	<0.001	0.170	0.024	0.010	0.009	0.016	0.360
EN 10210	≤0.2	≤1.6	≤0.35	≤0.04	≤0.04	≥0.02	≤0.03	≤0.6	≤0.3	≤0.1	≤0.2	≤0.8	≤0.45

The biggest difference between the real size and specification is only 0.3% (Table 1, row 4: t_m of the hot-finished section). The major difference among the three sections is in the corner radii. The cold-formed hollow section has the largest corner radii (Table 1, columns 4 and 5), followed by the hot-finished SHS and then the hot-formed SHS. All the measured dimensions (width, thickness, corner radius) comply with the requirements by EN 10210 [3] or EN 10219 [2], except for the external corner radii of the cold-formed SHS which is 2.43T and tightly meets the required value (2.4T to 3.6T) [2].

The chemical compositions of the tested cold-formed, hot-formed and hot-finished square hollow sections are listed in Table 2. It can be seen from Table 2 that all the elements contents are strictly within the limits required by BS EN 10210 or BS



(a) Cutting positions

(b) Sectioning in progress

Fig. 6. Sectioning test.

EN 10219. Although different standards and requirements apply for different SHSs, the chemical compositions of the three sections are similar. Only reasonably small differences can be observed in the contents of C, Mn, Si and Cu, Al. However, the slight differences accumulate to a big difference in CE (Eqn. 1). The cold-formed section turns out to have the lowest CE value, followed by the hot-finished and hot-formed section. It should be mentioned that although the CE values of all the SHSs satisfy the requirements by EN 10210 or EN 10219, the CE of the hot-formed section (Table 2, row 4) tightly meet the 0.4%. As recommended by AWS, for structural steels with CE value above 0.4%, there is potential for cracking in the heat affected zone of flame cut edges and welds [20].

3.2. Mechanical properties

Fig. 7 shows the fractured specimens after the tensile test. It can be seen from Fig. 7 that all the specimens are failed with fracture in the middle of the gauge length. The difference in the elongation of the three series is obvious: cold-formed < hot-finished < hot-formed. As there are nine tested specimens from three kinds of materials, one typical stress-strain curve for each SHS (from face-1, Fig. 4) is picked out and shown in Fig. 8. It can be seen from Fig. 8 that although the hot-formed, hot-finished and cold-formed SHSs consist of similar contents of elements, their mechanical properties differ remarkably. The most distinguishable feature is that the hot-formed and hot-finished show obvious yield plateau but the cold-formed specimens do not. While the cold-formed SHS show the highest strengths followed by the hot-finished and hot-formed sections, the ductility in terms of elongation is the other way around. The characteristic strengths and elongation are further

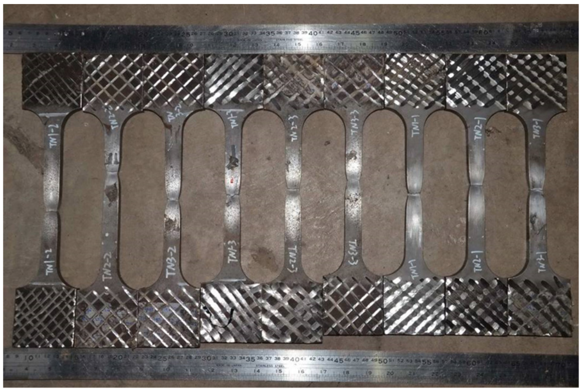


Fig. 7. Tested coupon specimens.

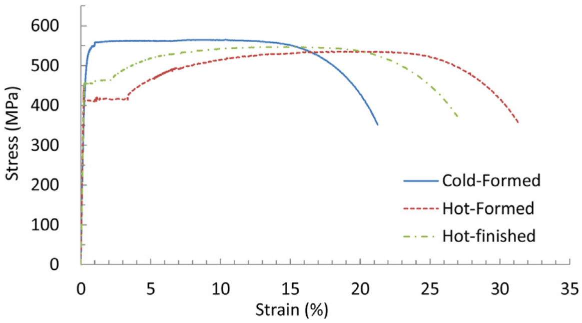


Fig. 8. Typical stress-strain curves of the tesed SHSs (from face-1).

Table 3
Summary of the tensile test results.

Samples (S355J2H)	f_y (MPa)	Average (MPa)	f_u (MPa)	Average (MPa)	Tensile ratio		Elongation (%)
Cold-formed	511.0	521.1	551.6	559.2	1.08	1.07	22
	529.3		562.2		1.06		23
	523.0		563.7		1.08		22
Hot-formed	411.8	410.6	536.1	531.0	1.30	1.29	30
	403.4		521.9		1.29		31
	416.7		535.1		1.28		32
Hot-finished	440.9	474.2	531.2	555.2	1.20	1.17	27
	454.3		546.0		1.20		28
	527.4		588.3		1.12		22
EN 10210	≥355		≥470				Min. 22
EN 10219			≤630				

summarized in Table 3. It can be seen from Table 3 that for the same section, the strengths of different faces are generally comparable except for Face-3 of the hot-finished SHS. This indicates that the cold-formed hollow section can have as homogeneous mechanical properties around the perimeter as the hot-formed and hot-finished SHSs.

Due to the unfavorable concerns on the mechanical properties of cold work hardened steels, cold-formed steels are often downgraded in practice. As can be seen from Table 3, the cold-formed section has average yield strength of 521 MPa, which is 26.9% and 9.9% higher than those of the hot-formed and hot-finished sections, respectively, and is 46.7% higher than the nominal yield strength of grade S355J2H (355 MPa). However, the ductility of the cold-formed section in terms of tensile ratio and elongation is worthy attention. EC3 requires the structural steels to be used in construction must have tensile ratio higher than 1.10 [25]. Since it is commonly difficult for cold-formed steels to meet this criterion, the yield strength has to be downgraded in application. Besides, the elongation at proportional gauge length $5.65\sqrt{So}$ of this cold-formed section also just meet the requirement of 22%. Accordingly, the post-yield performance of the cold-formed section may not be as good as the hot-formed and the hot-finished SHSs.

Table 4 shows the impact toughness of the tested specimens. It can be seen from Table 4 that the toughness values of the three sections are generally comparable and all are much higher than the requirement of 27J. It should be noted that the values are highly dependent on the original position on the SHS and the opening direction of the v-notch (Fig. 4). Specimens

Table 4
Charpy V-notch impact test results.

Samples and Positions		Energy (J)	Average (J)	EN 10210 & EN 10219
Cold-formed	1	168.6	172.8	Min. 27 J
	2	255.4		
	3	94.4		
Hot-formed	1	136.9	154.0	
	2	280.2		
	3	45.0		
Hot-finished	1	143.1	141.8	
	2	210.5		
	3	71.7		

Table 5
Residual stress in the transverse direction.

	Yield Strength (MPa)	Flat area (%)	Corner area (%)	Welding area (%)
Cold-formed	521.1	17.4% to 32.2%	−20.1% to −6.5%	1.1% to 31.3%
Hot-formed	410.6	−11.6% to 16.6%	−14.1% to 12.5%	16.6%
Hot-finished	474.2	9.3% to 13.0%	10.9% to 25.4%	19.6% to 27.7%

Table 6
Residual stress in the longitudinal direction.

	Yield Strength (MPa)	Flat area (%)	Corner area (%)	Welding area (%)
Cold-formed	521.1	54.5% to 60.5%	19.9% to 33.8%	67.7% to 79.8%
Hot-formed	410.6	−32.6% to 18.3%	−30.1% to −7.2%	0.4%
Hot-finished	474.2	20.3% to 20.8%	17.4% to 33.2%	25.6% to 41.7%

from position 2 have the highest toughness values which are much higher than those of position 1 and 3. While the values of specimens from position 3 showed much lower values than the other two, they are still in the safe range.

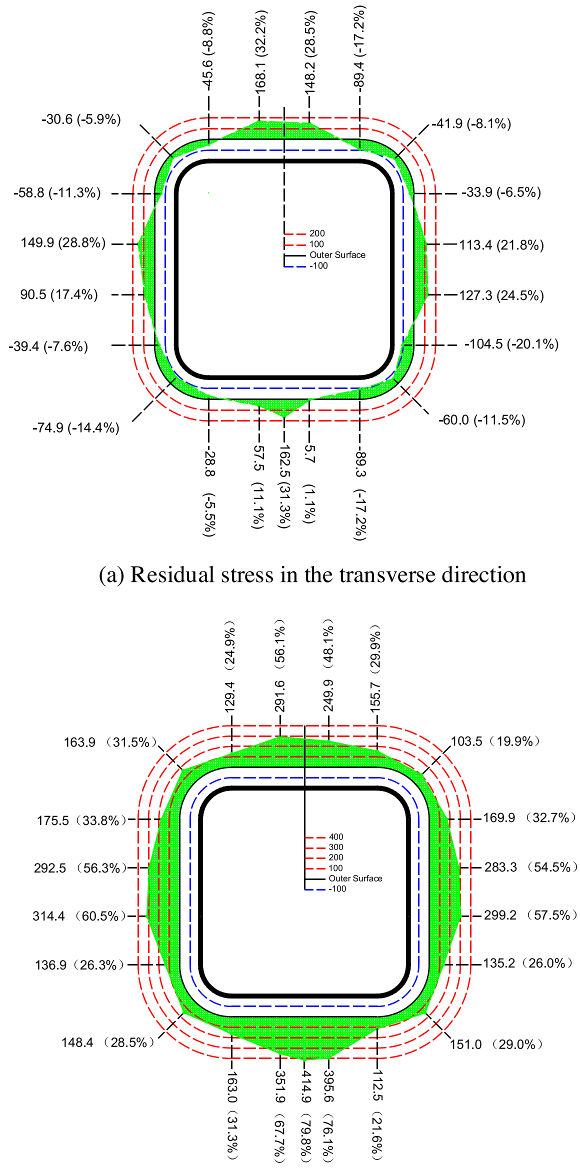
3.3. Residual stresses

3.3.1. Magnitude and distribution of residual stress

The residual stress distributions in both transverse and longitudinal directions of the cold-formed, hot-formed and hot-finished SHSs tested by the holt-drilling method are shown in Figs. 9–11, respectively. The results are also summarized in Tables 5 and 6. In the above figures and tables, residual stresses are evaluated in both absolute value (MPa) and percentage over the yield strength (residual stress/actual yield strength × 100%). It can be seen from Figs. 9–11 that the distribution of the residual stress for all the cases are generally symmetrical about the neutral axes. However, the residual stress patterns and levels in the tested SHSs are remarkably different.

For residual stresses in the transverse direction, the cold-formed SHS clearly contains the highest level, especially at the corner and welding areas. The transverse residual stresses in the corner of the col-formed SHS (Fig. 9a) is compressive stresses while those in the flat and welding area are tensile stresses. The "highest" stress in the corner is −104.5 MPa (−20.1% of actual yield strength) while the highest tensile stresses in the flat and welding area are 168.1 MPa (32.2%) and 162.5 MPa (31.3%), respectively. Compared with cold-formed thin-walled SHSs [10,19], the tested cold-formed thick-walled SHS has similar distribution pattern but remarkably higher residual stress levels. The transverse residual stresses in the hot-formed SHS (Fig. 10a) are mostly low level compressive stresses. The "maximum" (absolute value) value is −58 MPa (−14.1%) in the corner and 68.1 MPa (16.6%) elsewhere. It should be noted that the residual stress level at the welding zone is not much different from the flat areas due to the high temperature heat treatment effects. As for the transverse residual stresses in the hot-finished SHS (Fig. 11a), the stress level is somewhere between the cold-formed and hot-formed SHSs. All the stresses are tensile stresses, which is different from the other two. The stress level in the corner area is lower than the flat area and the welding area and the difference between the latter two is not as significant as the cold-formed SHS.

Compared to the transverse residual stress levels (which are generally below 30% for all the tested SHSs), the residuals stresses in the longitudinal directions are generally higher. The stresses in the hot-formed SHS (Fig. 10b) are all compressive stresses. The "maximum" value is −128.6 MPa (−31.3%) and −125.6 MPa (−30.1%) for the flat and corner areas, respectively. The cold-formed and hot-finished SHSs share similar distribution in residual stresses in this direction, but the cold-formed SHS obviously contains much higher stress level. For this tested thick-walled cold-formed SHS, the residual stress level is lower at the corner area and the maximum value appears at the welding zone. The average stress level in the corner, flat and welding areas are 28%, 56% and 75% of the actual yield strength, respectively. It should be noted that if these percentage values are compared with the nominal yield strength of S355, the stresses are actually higher than the nominal yield strengths. According to Kato et al. [10], the longitudinal residual stress in 203.2 × 203.2 × 4.76 mm cold-formed thin-walled SHS is about −40%, −60% and −70% in the flat, corner and welding areas, respectively. The slightly thicker cold-formed thin-walled



(a) Residual stress in the transverse direction

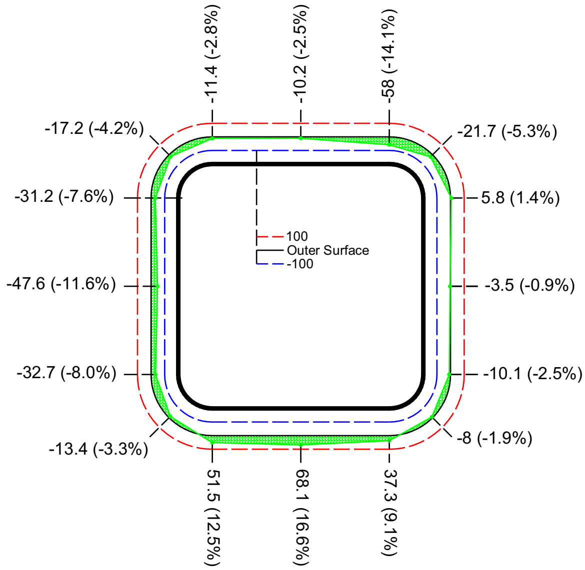
(b) Residual stress in the longitudinal direction

Fig. 9. Residual stress distribution (MPa and%) of the cold-formed SHS.

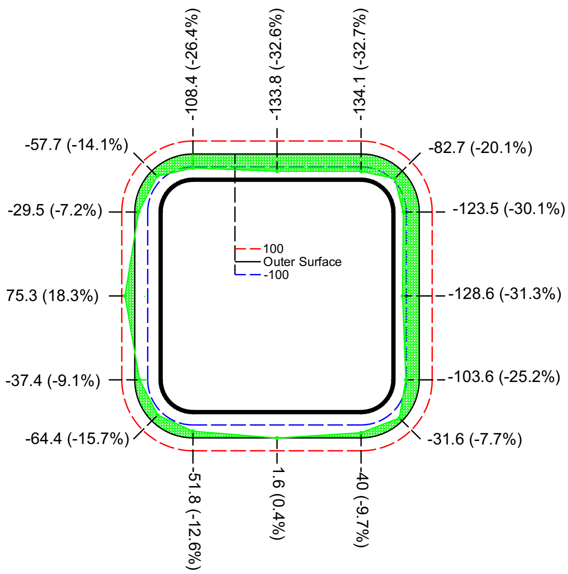
SHS 203 × 203 × 6.3 mm tested by Key and Hancock [11] has longitudinal residual stress about 50% of the yield strength on the surface. The cold-formed thick-walled SHS 300 × 300 × 16 mm tested by Tong et al. [15] has longitudinal residual stresses of about 55% and 18% yield strength in the flat and corner areas, respectively, which are close to the tested cold-formed SHS in this study. Compared to the stress distribution in the cold-formed SHS, that in the hot-finished SHS (Fig. 12b) is much uniform. The highest stress still appears at the welding zone but the maximum level is only 196.7 MPa (41.7%) and the difference between the corner and flat area is much smaller, as shown in Table 6. This should be credited to the stress relieving heat treatment it was subjected to after rolling. Therefore, it seems that the heat treatment this hot-finished SHS subjected to during the final stage of manufacturing relieved considerable level of residual stress in both the transverse and longitudinal directions, although it is still not comparable to that of the hot-formed SHS.

3.3.2. Effect of residual stress

Figs. 12–14 show the specimens after sectioning in comparison with the photos before sectioning, and the dimensional changes are summarized in Table 5. It can be seen from Figs. 9–11 and Table 7 that the cold-formed and hot-finished sections tend to open after sectioning, but the geometry of the hot-formed section remains almost unchanged. The alteration in the



(a) Residual stress in the transverse direction



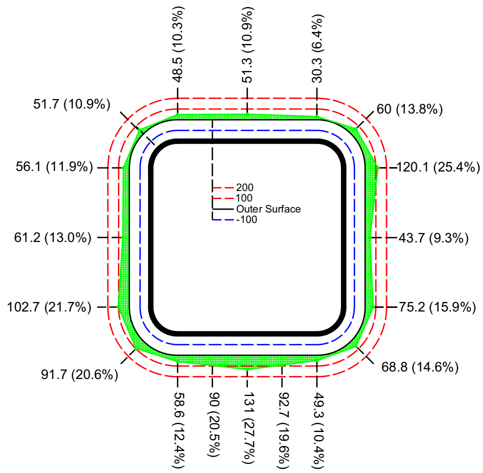
(b) Residual stress in the longitudinal direction

Fig. 10. Residual stress distribution (MPa and%) of the hot-formed SHS.

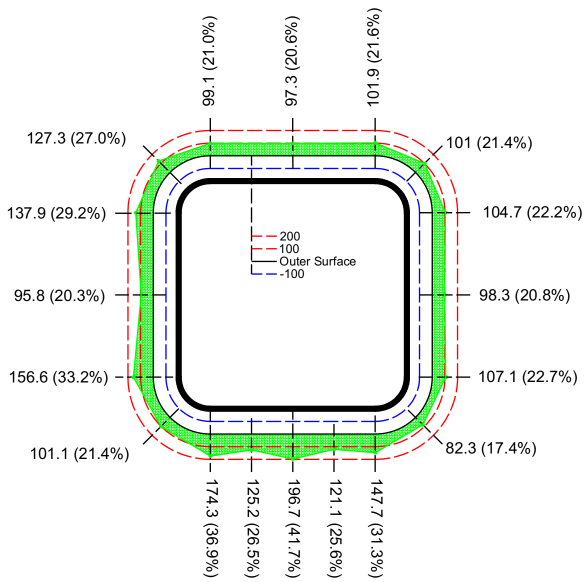
Table 7
Width difference before/after sectioning.

	Before Sectioning (mm)	After Sectioning (mm)	Diff(%)
Cold-formed	200.53	209.5	+4.5%
Hot-formed	180.27	180.0	−0.15%
Hot-finished	180.34	186.5	3.4%

Note: Diff(%) is calculated as After Sectioning/Before Sectioning × 100%.



(a) Residual stress in the transverse direction



(b) Residual stress in the longitudinal direction

Fig. 11. Residual stress distribution (MPa and%) of the hot-finished SHS.

section widths caused by sectioning also imply the amount of locked in elastic residual stresses in the sections. The cold-formed section clearly contains the highest residuals tress amount. Its width increased by 4.5% after sectioning (Table 7, row 2). In accordance with the phenomena shown in Fig. 11, the width of the hot-finished section also increased by 3.4% (Table 7, row 4). In contrast, the residual stress in the hot-formed section is at negligible level, more precisely, slightly compressive. As a result, the width decreased by 0.15% (Table 7, row 3) after sectioning.

3.3.3. Discussion

Theoretically, the hot-formed, hot-finished and cold-formed structural hollow sections studied in this paper are formed by the same manufacturing technique, i.e. continuous rolling method. The residual stresses are the result of plastic bending followed by elastic springback [28], except for the welding area.

Fig. 15 shows a typical roll-forming process for the corner of rectangular hollow sections. During bending, the material between the roller die reactions is expected to undergo certain level of yielding as the stress distribution transits from elastic to plastic. After the plate becomes fully plastic, the engineering strain continues to increase as the rolling radius keeping increasing. When the final bend radius is reached and imposed radial displacement is removed, an elastic springback occurs and elastically unload the corner [26]. At the meantime, certain level of stress is locked-in as residual stress [27]. It should be

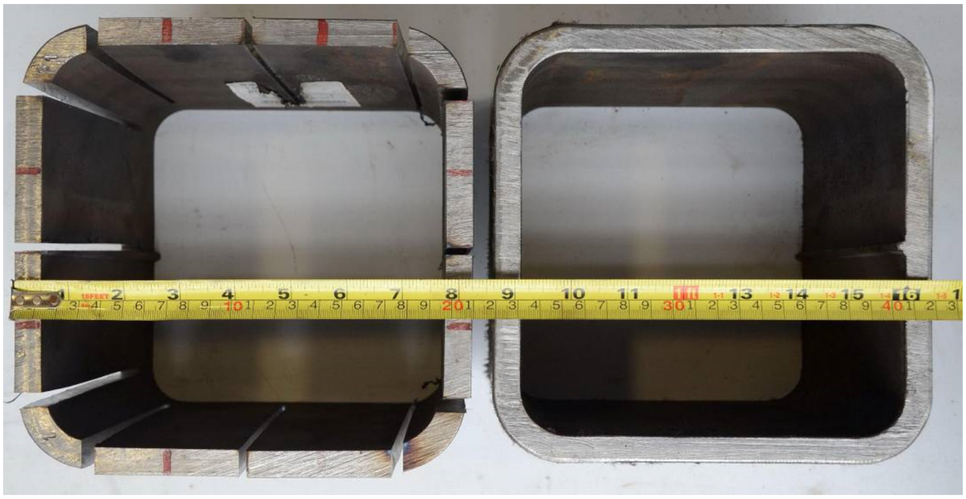


Fig. 12. Sectioning test results of the cold-formed SHS.

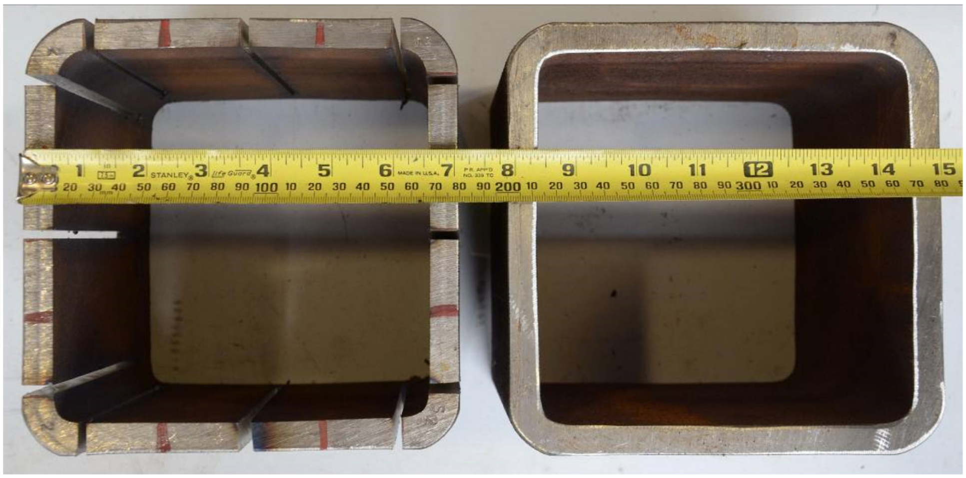


Fig. 13. Sectioning test results of the hot-formed SHS.

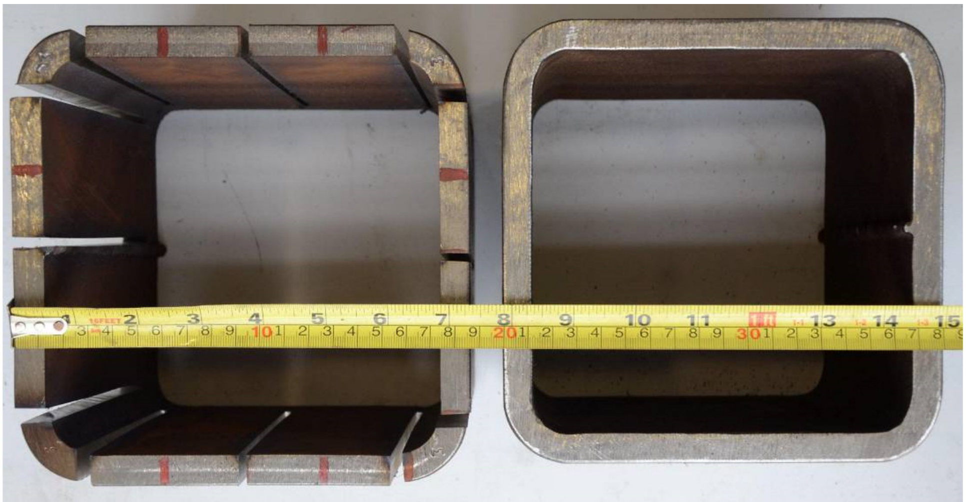


Fig. 14. Sectioning test results of the hot-finished SHS.

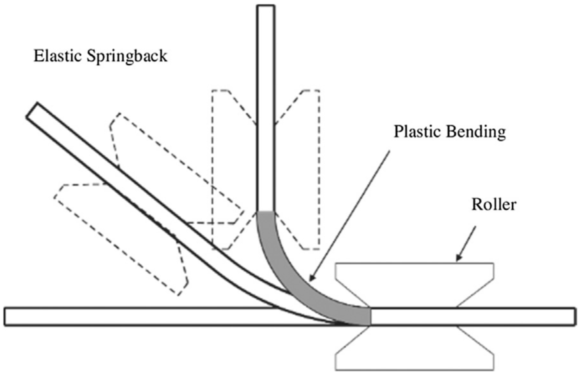


Fig. 15. Definition of the measured geometrical dimensions and the tested SHSs.

pointed out that in the above process, the distribution of residual stress is dependent only on the geometry and mechanical properties including the initial yield strength, f_y and Young's modulus, E [28]. Naturally, the residual stress level in the cold-formed SHS is supposed to be the highest among the three types of SHSs studied in this paper, because of the highest f_y, as shown in Fig. 8. Compared to the cold-formed SHS, the hot-formed SHSs are less concerned regarding the residual stress because the hot-formed SHSs are rolled at high temperature conditions where both the f_y and E are significantly lower than those at room temperature. As for the hot-finished SHSs, they are commonly rolled cold with subsequent heat treatment that is supposed to relieve residual stress by taking advantage of lower f_y and E at elevated temperatures. However, the heat treatment temperature can not be as high as that of hot-forming process and the residual stresses can not be fully released. Accordingly, although the hot-formed and hot-finished hollow sections are treated the same in design, the distribution and amount of residuals stresses contained in the SHSs are totally different, as shown in Figs. 10 and 11. Further, by comparing the distribution patterns of the cold-formed SHS (Fig. 9) and the hot-finished SHS (Fig. 11), it is also noticed that the manufacturing processes, especially the heat treatment processes seem to have larger impact on the distribution of longitudinal residual stresses than that of the transverse direction. The residual stress distribution patterns of the hot-finished and cold-formed SHSs are very similar in the transverse direction but totally different in the longitudinal directions.

4. Conclusions

A three-phase comparative experimental study was carried out to investigate the influence of different manufacturing techniques on the properties of cold-formed, hot-formed and hot-finished thick-walled structural hollow sections (SHSs). Phase-1 investigated the differences in the geometrical profiles and chemical composition. Phase-2 analyzed the difference in the common mechanical properties such as yield stress, tensile stress, ductility and impact toughness. Phase-3 evaluated the distribution and effect of residual stress through sectioning and hole-drilling techniques.

The test results reveal that although the geometry and chemical composition of the tested SHSs are comparable, the mechanical properties are remarkably different. Although the hot-finished SHS shows yield plateau as the hot-formed SHS does, the ductility in terms of elongation and tensile ratio is not as good as that of the hot-formed SHS. While the cold-formed SHS shows much higher strengths, the stress-strain relationship is much worse than the other two SHSs. It is also shown that the residual stresses in the hot-formed SHS is generally compressive and low in stress level in terms of residual stress/yield strength ratio. The cold-formed SHS has lower stress level in the corner areas than that in the flat and welding areas and the distribution pattern is different from that of the well-known cold-formed thin-walled SHSs. Besides, although the hot-finished SHSs are treated equally to the hot-formed SHSs in design, their residual stress distribution pattern is actually similar to that of the cold-formed SHSs but the stress level is much lower than the later due to stress relief heat treatment.

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