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Material properties and residual stresses of octagonal high strength steel hollow sections

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ABSTRACT

This paper presents an experimental investigation to quantify the variation of material properties and residual stresses in the octagonal high strength steel hollow sections from different fabrication routes involving welding or combinations of welding and press-braking. Tensile coupon tests were conducted on the specimens extracted from different locations of the hollow sections with different fabrication routes and static mechanical properties and stress-strain relationship for the specimens were measured. The influence of welding on the material properties was found to be insignificant while strength enhancement was observed for the material at corners formed by press-braking. A stress-strain curve model was proposed for the material across octagonal high strength steel hollow sections. The magnitudes and distributions of longitudinal residual stresses of the octagonal high strength steel hollow sections with different fabrication routes were also measured using the sectioning method and were also found to be dependent on the fabrication route. Based on the measured residual stress results, residual stress models were developed for the hollow sections from different fabrication routes. The obtained variation of material properties and longitudinal residual stresses can be employed to accurately analyse the performance of octagonal high strength steel hollow section structural members for efficient structural designs.

1. Introduction

High strength steel (HSS) tubular members have been increasingly used in structural applications due to their combined advantages of strong buckling resistance, high strength-to-weight ratio, environmental efficiency, aesthetic appearance, and cost efficiency. Extensive experimental and numerical research studies focusing on HSS tubular structures with square, rectangular and circular sections have been conducted to determine the material properties and residual stresses of the hollow sections [1–6] and to investigate the cross-sectional and member behaviour under quasi-static compression, bending and combined loadings [1, 7–25]. In recent years, octagonal steel tubular members have also been used in civil structural applications such as transmission line structures, towers and lattice structures [26–28]. Octagonal hollow sections demonstrate stronger local buckling resistance than that of square and rectangular hollow sections and also provide the flat surfaces for the easier connection construction compared with circular hollow sections. Hence, HSS octagonal cross-section members have attracted the attention from researchers and structural manufacturers to apply the members in long-span truss structures [29, 30]. In order to accurately predict the strength and behaviour of the HSS octagonal tubular members for efficient structural design, the variation of material properties and residual stresses in the HSS octagonal hollow sections which can influence the strength and buckling behaviour of the structures, need to be well understood.

The variation of properties and residual stresses existing in the members without being loaded are primarily induced by the structural fabrication processes [31–33]. Aoki et al. [34] investigated the compressive strength of octagonal steel tubular stub columns which were formed by welding eight steel plates, as depicted in Fig. 1(a). Godat et al. [26] used a different fabrication route by welding two half-sections to form octagonal tubular structures. In their study, each half-section had three cold-bended corners, as shown in Fig. 1(b). Mitiga et al. [35] and Migita and Fukumoto [36] also investigated the compressive strength of octagonal tubular structures produced using another fabrication route for which each half-section had four corners obtained by cold-bending, as shown in Fig. 1(c). In these fabrication routes, welding or combined welding and cold-bending processes were applied. Welding process induces heat-input to the materials around the welding seam and causes heat affected zone (HAZ) in which the material properties can be different from those of the materials outside HAZ [37]. Cold-bending process also affects the material properties due to strain hardening effect at the cold-bending region subject to large plastic deformations [32, 38, 39]. Besides, the welding and cold-bending also lead to non-uniform thermal and plastic strains in the hollow section

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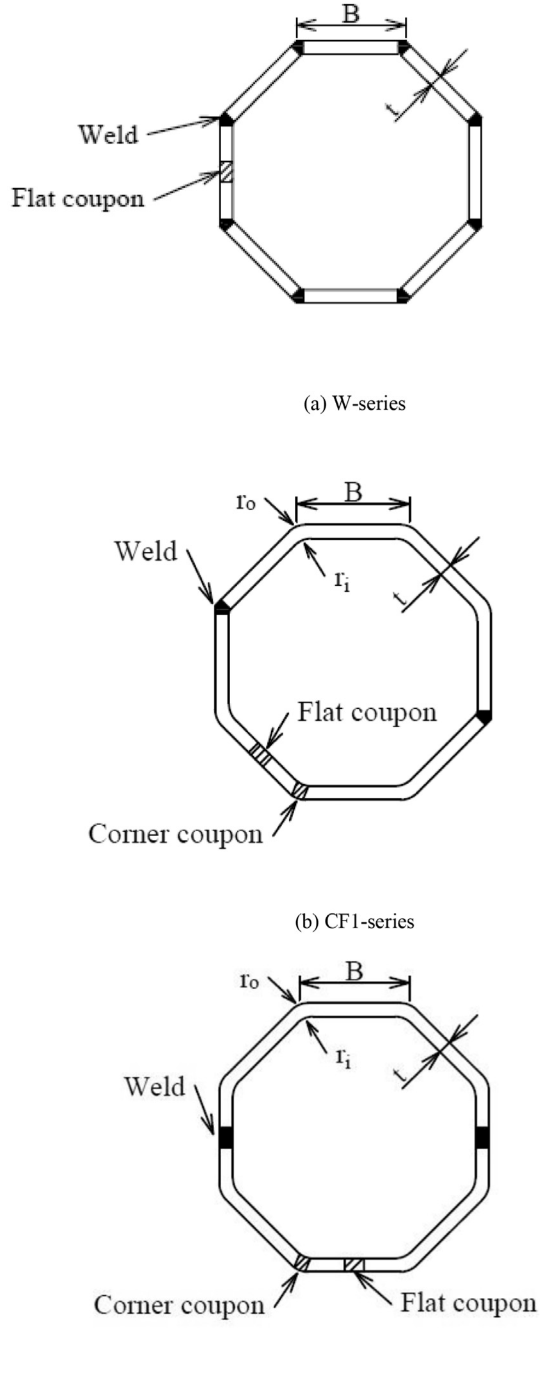

(a) W-series

(b) CF1-series

(c) CF2-series

Fig. 1. Fabrication routes for octagonal steel hollow sections.

structural members and subsequently induce residual stresses. Since the buckling resistance and strength of the structures are dependent on the material properties and residual stresses, ignoring the variation of the properties and residual stresses in octagonal hollow sections can lead to inaccurate estimation of the structural performance. However, to date, no investigations have been performed to determine the variation of material properties and residual stresses in HSS octagonal hollow sections formed using the three different fabrication routes.

Therefore, in this study, the variation of material properties and residual stresses in HSS octagonal hollow sections formed using the aforementioned three fabrication routes are investigated experimentally. Tensile coupon tests were conducted on specimens extracted at different locations in the sections. The measured properties were compared in order to examine the effect of fabrication route on the variation of properties in the HSS octagonal hollow sections. Furthermore, residual stresses in the HSS octagonal hollow sections formed using the three fabrication routes were also measured and compared. The effect of fabrication route on the residual stress distribution in the sections is also discussed.

2. Octagonal hollow section specimens

HSS octagonal hollow section specimens were formed using the three fabrication routes introduced in Section 1. Specimens from the fabrication routes presented in Fig. 1(a)-(c) respectively are named W-Series, CF1-Series and CF2-Series. S690 steel plates with nominal yield strength of 690 N/mm^2 and with thicknesses of 6 and 10 mm were used to form the specimens. The steel plates with each thickness were produced in the same batch, allowing the direct comparison of experimental investigations on the properties and residual stress of the specimens. For each specimen in W-Series, eight steel plates were welded together through gas metal arc welding (GMAW) and full penetration weld was used. The selected electrode wire was 1.2 mm of the category ER110S-G according to the specification AWS A5.28 [40]. Preheating at about 150 °C was applied prior to the start of each welding process. The applied shielding gas was Ar80% + $CO_2$20%. For the welding, the voltage was about 26-29 V while the amperage was about 220-240A. While fabricating the specimens using the CF1 and CF2 routes, the steel plates were longitudinally folded at room temperature through press-braking to form the half octagonal sections. Two half octagonal sections were subsequently welded through GMAW to form each specimen in CF1 or CF2 series. Three cross-sectional dimensions were chosen for specimens with each fabrication route. The measured dimensions for the specimens with different plate thicknesses and plate width-to-thickness ratios between 6.7 and 23.7 are shown in Table 1 using the nomenclature defined in Fig. 1. The specimens are labelled based on the fabrication route and nominal dimensions. For example, the label "CF2-75 × 10" defines the specimen formed using fabrication route CF2 shown in Fig. 1(c) and with the nominal edge length (B) and thickness (t) of 75 and 10 mm respectively.

3. Material properties investigations

3.1. Tensile coupon tests

Tensile coupon tests were conducted to measure the material properties of HSS octagonal hollow sections and to examine the heterogeneity in the material of the hollow sections due to fabrication processes. Longitudinal tensile coupons were taken from both flat and corner regions of the HSS octagonal hollow section specimens. During each tensile coupon test, the loading was paused near yield and ultimate strength for 90 s to obtain the static loads [41]. Static stress-strain curves obtained from the tensile coupon tests were used to determine the static 0.2% proof stress ($\sigma_{0.2}$), static ultimate tensile strength (σ_u), modulus of elasticity (E), static ultimate tensile strain (ε_u) and elongation at fracture (ε_f) of the material.

3.1.1. Flat coupon tests

Flat tensile coupons were extracted from the centre of the faces of HSS octagonal hollow sections, as shown in Fig. 1. The dimensions of the flat coupons conformed to the EN10002-1 [42]. The coupons had 6 mm width along the gauge length. The test set-up of flat coupon is shown in Fig. 2(a). A calibrated mechanical extensometer was mounted onto each coupon specimen to measure the longitudinal strain during the test. Two linear strain gauges were also attached at the midpoint on each of the faces of any coupon specimen. The average strain measured by the two strain gauges was used to determine the modulus of elasticity for each coupon specimen. The strains and elongation at