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

Xing-Zhao Zhang (Exchange PhD Candidate)[a],
Su Liu (Professor of Architecture)[b], Ming-Shan Zhao (Research Fellow)[a,*],
Sing-Ping Chiew (Professor of Civil Engineering)[c]

[a] *School of Civil and Environmental Engineering, Nanyang Technological University, Singapore*
[b] *College of Architecture, Hunan University, China*
[c] *Singapore Institute of Technology, Singapore*

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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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* Corresponding author.
E-mail address: mszhao@ntu.edu.sg (M.-S. Zhao).

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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].

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

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