Journal of Constructional Steel Research 130 (2017) 12–21

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

An experimental study on residual stresses of high strength steel box columns

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ARTICLE INFO

Article history:
Received 1 June 2016
Received in revised form 28 November 2016
Accepted 28 November 2016
Available online xxxx

Keywords:
High strength steel
Built-up box column
Welding residual stresses
Flux-cored arc welding
Submerged arc welding
Post-weld heat treatment

ABSTRACT

As high strength steel (HSS) box columns are often fabricated by welding of steel plates together, welding process during fabrication inevitably introduces residual stresses in the columns and affects their strengths. Hence, a good understanding of the influence of the welding process on the residual stresses of HSS built-up box column is important for the design of such columns. In this study, an experimental investigation to investigate the effects of welding process on the residual stress distributions of HSS built-up box columns was carried out. Two groups of identical specimens fabricated by flux-cored arc welding and submerged arc welding were studied. The influence of different welding methods was investigated by employing the ASTM hole-drilling method to measure the residual stress distributions. Furthermore, a study was also conducted to evaluate the effects of different heat treatment procedures on the magnitude and distributions of the final residual stresses produced.

1. Introduction

Recently, the use of high strength steel (HSS), which generally defined as structural steels that have yield strength larger than 460 MPa, becomes more and more popular in structural engineering for its benefits of high strength to weight ratio and savings in the cost of materials. HSS is currently used in many building and bridge constructions for its advantages in economy, architecture, sustainability and construction safety. In particular, by using HSS, the weight, size, transportation and erection costs of the structural sections could be reduced while the aesthetic and elegance of the structures could be improved.

Different from mild steel which is ready available in forms of rectangular hollow and circular hollow sections, HSS is still mainly available in plate form. Therefore, when HSS is employed to construct tubular structures, welding is almost certainly needed for the construction of box column sections subject to heavy compressive loading which is one of the most common used HSS application areas. Towards this end, the welding method and welding details such as weld pass sequence, preheating temperature, welding speed and heat input adopted during fabrication are important factors that will affect the magnitude and distribution of welding residual stresses. In practice, arc welding is very popular in structural steel construction because of its simplicity and ease to handle in the field. During arc welding, power is supplied to create and maintain an electric arc between the base material and an electrode to melt metals at the welding position. Due to the highly localized heat input during arc welding, microstructure and properties of the base material near the weld are altered. As the cooling rates at different locations of the base material are different, thermal strain and stresses will always be created during the welding process.

In order to investigate the effects of welding residual stresses on built-up sections' performance and behaviors, many experimental studies have been conducted. Nishino et al. [1] carried out an experimental investigation on the buckling of plates with residual stresses. Vila Real et al. [2] studied the effects of residual stresses on the lateral torsional buckling of steel I-beams at elevated temperature. Wang [3] investigated the effects of residual stresses on cold-formed steel column strength. Barsan and Chiorean [4] studied the influence of residual stresses on the load carrying capacity of steel framed structures. In short, most of these studies are focused on the residual stress distributions in steel beams or columns with material yield stress less than 460 MPa. For the investigations of HSS box structures, Yang and Hancock [5] conducted both experimental and numerical studies for HSS box-shaped column. Ban et al. [6] conducted a study of the overall buckling behavior of 960 MPa HSS columns. Recently, in order to obtain a more complete picture on the effects of welding on HSS structures, the authors progressively conducted a few systemic experimental and numerical studies to investigate the mechanical properties of HSS at room and evaluated temperature [7], the effects of welding process on the residual stress distributions and the performance of simply thin-walled plate-to-plate

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http://dx.doi.org/10.1016/j.jcsr.2016.11.025

Table 1
Fabrication scenarios.

Specimen name	Welding method	Preheat condition
A-F-1	FCAW	AW
A-F-2		PH
A-F-3		PWHT
A-S-1	SAW	AW
A-S-2		PH
A-F-3		PWHT

Note: AW: as-welded, PH: pre-heated, PWHT: post weld heat treatment.

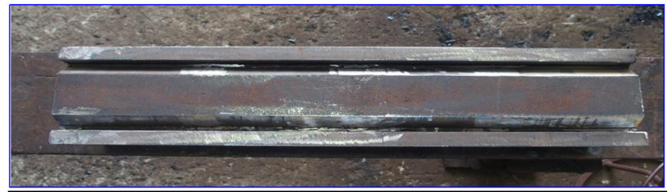

Fig. 1. Weld groove preparation before welding.

joints [8–10], and then similar studies on built-up box T-joints [11–14] as well as developing proper numerical modelling procedures for the prediction of residual stress distributions of HSS built-up box columns [15] and their compressive strengths [16]. In addition, Chiew et al. [17] also conducted numerical modelling for the residual stress distributions of roller bending of steel rectangular hollow sections while Quach et al. [18–20] investigated the residual stresses in press-braked stainless steel sections. However, up to now, there is still a knowledge gap that almost no experimental data can be found for the residual stress distributions of HSS built-up box columns. Furthermore, many previous studies on HSS columns were mainly focused on the structural behavior such as axial compression strength of HSS columns while the impact of the fabrication process on the welding residual stresses was not well studied and understood. Hence, the main objective of the current study is to carry out an experimental investigation on the effects of different welding methods used during fabrication on the magnitude and distribution of residual stresses of HSS built-up box columns. Furthermore, an investigation will also be performed to evaluate the effects of different heat treatment procedures on the final residual stress magnitude and distribution in the HSS built-up box columns tested.

2. Specimen specification

In this study, six identical columns made of RQT701 HSS plate with minimum yield stress of 690 MPa were fabricated by employing different welding processes and then subjected to different heat treatments. The RQT701 [21] HSS plates used in this study is quenched and tempered steel with improved forming and welding performance by substituting some alloying elements with carbon [7]. Its nominal yield strength is 690 MPa and the tensile strength is 790 MPa. In order to assess the influences of different welding processes and heat treatment procedures on the final welding residual stress distributions, two different welding methods, namely the Flux-Cored Arc Welding (FCAW) and the Submerged Arc Welding (SAW) and three different pre and post heat treatment conditions, namely As-Welded (AW) condition without any heat treatment, Preheating (PH) treatment before welding and Post-Weld Heat Treatment (PWHT) were employed during the fabrication of the specimens. Table 1 lists the naming and fabrication scenarios of the six specimens tested in this study.

2.1. Welding procedures used

2.1.1. Flux-core arc welding

FCAW is an arc welding process in which the heat for welding is produced by an arc between a continuously fed tubular electrode and the work piece. It is one of the most commonly used welding processes in structural steel construction. Therefore, it is selected in this study and three specimens were fabricated by using FCAW. The welding penetration profiles for the HSS box built-up columns tested are complied with the AWS D1.1 2008 guideline [22]. Table 2 lists the electrodes and the groove preparation used during the fabrication. It should be noted that the electrode used in the FCAW process is Outershield 690-H with diameter of 1.2 mm, which was specially selected for welding of grade S690 HSS and provided by Lincoln Electric.

Before the fabrication of the HSS built-up box columns, RQT701 HSS strips of size of 110 mm × 110 mm × 500 mm were first prepared. In order to sustain the molten weld during the box column formation, another group of RQT701 HSS backing plates were cut into the size of 31 mm × 16 mm × 500 mm and they were connected to the main HSS plates by spot welding before the main box columns formation welding process. To prevent distortion and shrinkage, two restraining plates were also spot welded to the box column at 30 mm from the ends. After all the preparations were finished, the molten weld was added on the groove by FCAW to form the built-up box columns until full penetration weld was achieved. Fig. 1 shows weld groove preparation before the main welding while Fig. 2 shows the layout and welding sequence of the built-up box columns.

It should be mentioned that during the main welding process, the first four weld passes were sequentially added at the four corners of the box column so that it would be heated evenly to reduce deformation. Similar treatments were applied to weld passes 5 to 8. After that, welding was carried out at each corner in turn until a full penetration weld profile is achieved. Eventually, twenty weld passes were applied in four layers to form the box column. Table 3 lists the main welding parameters including the heat energy input of the welding process and the arch travelling speed. Note that smaller heat input (0.74–0.85 kJ/mm) was applied for weld passes 1–4 (Layer 1 in Fig. 2) so that the heat energy can be more evenly and quickly dissipated and therefore reduces thermal deformation. Higher normal heat input rate (1.27–1.88 kJ/mm) was then applied for the subsequent sixteen weld passes (from Layer 2 to Layer 4 in Fig. 2). Such heat input range was used in the FCAW process because these magnitudes will lead to a reasonable cooling rate and therefore could improve the toughness in the heat-affected zone. Fig. 3 shows the heat input per unit length for each pass used in the main FCAW process. Fig. 4 shows the FCAW process during the box column fabrication which was conducted by a qualified welder.

2.1.2. Submerged arc welding

SAW is selected as the second type of welding process employed in this study since it is also widely used in structural steel fabrication work. It becomes more and more popular recently, especially in projects involving welding of thick steel plates due to its high quality of weld finishing, high welding speed and deposition rate. SAW is a welding process in which the heated molten weld and the welding arc are submerged and protected by a blanket of fusible conductive flux between

Table 2
Electrodes and groove preparation used for FCAW and SAW.

Welding process	Base material		Electrode		Groove preparation		Welding position
	Class	Thickness (T_1)	Class	Diameter (T_2)	Root opening	Groove angle	
FCAW	RQT701	16 mm	Outershield 690-H	1.2 mm	$R = 8$ mm	$\alpha = 36.8°$	Flat
SAW	RQT701	16 mm	LAC-690	3.2 mm	$R = 8$ mm	$\alpha = 36.8°$	Flat