Journal of Constructional Steel Research 151 (2018) 238–252

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Effect of welding and heat treatment on strength of high-strength steel columns

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ARTICLE INFO

Article history:
Received 31 August 2018
Received in revised form 21 September 2018
Accepted 23 September 2018
Available online xxxx

Keywords:
High strength steel
Column strength
Residual stress
Welding
Heat treatment

ABSTRACT

Arc welding is frequently applied to form built-up high strength steel (HSS) box columns from flat plates. Due to the thermal gradients happened in the welding processes, welding residual stresses and geometric imperfections are normally introduced into the columns which can deteriorate the column strength. In the current study, an experimental and finite element analysis study on the strength of built-upHSS box columns under a compressive load was carried out. To evaluate the effect of welding technique and heating treatment on the strength of high strength box columns, two different welding techniques, Flux-Cored Arc Welding (FCAW) and Submerged Arc Welding (SAW), were used in this study. For each welding technique, three different heat treatments including As-Welded condition (AW) without any heat treatment, Preheating (pH) before welding and Post-Weld Heat Treatment (PWHT) were studied. Firstly, the welding residual stresses determined using the hole-drilling method and the initial geometrical imperfections of the columns were carefully measured. After that, the column strength was tested and analysed. Finally, numerical investigations regarding welding residual stress and column strength were conducted to study the effect of welding processes, heat treatment on the strength of built-up high strength steel box columns with different slenderness under compressive load. For both FCAW and SAW fabricated columns, experimental and numerical results show that heating treatment (Preheating and PWHT) could produce a 3%–7% strength improvement depended on the slenderness of the HSS columns. The design approach for HSS columns including the effect of welding technique and different heat treatment was discussed in comparison with existing standards.

1. Introduction

High strength steel (HSS) with yield strength higher than 460 MPa has increasingly been used in buildings and large span structures for its advantages in safety, aesthetics and economy [1–4]. Compared with conventional mild steel, the use of HSS can obtain significant economic benefits by reducing the size of structural components and workloads of welding and transportation. However, most codes and standards related to medium strength steels and in most cases the use of design curves is limited to steels with yield strengths not larger than 460 MPa which is a serious disadvantage for the use of higher strength steels [5]. The mechanical behaviour of HSS is different from mild steel as the ductility of HSS may be not comparable with mild steels. In addition, residual stress due to welding and uneven cooling of HSS plates and shapes could be more significant than that in mild steel and have a negative effect on their structural performances [6–12]. Welded built-upHSS columns are frequently used in high-rise buildings. To provide effective bi-axial column strength and stiffness, welded built-upHSSbox-shaped columns are normally used in the construction of main compressive structural components and steel moment frames. When compared with I-sections, built-up box columns could have better section modulus, which make them advantages for handling complex loading cases. Normally, in the region of the welded area, built-up members could exhibit tensile residual stresses with magnitude higher than the yield stress of the parent material due to the intense heat input [13–15]. The material properties would also be significantly altered in heat-affected zone (HAZ) areas [16]. Therefore, it is significant to understand the impact caused by the intense heat input of the welding process on the mechanical performance of HSS members.

Local and overall buckling of columns has been widely studied for cold-formed columns and some built-up columns made of mild steel. A few experimental and numerical investigations were reported on the local and overall buckling behaviours of built-upHSS columns

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https://doi.org/10.1016/j.jcsr.2018.09.027
0143-974X/

Table 1
Chemical composition of the RQT701 steel plate and electrodes used in FCAW and SAW processes.

CET (%)	C	Si	Mn	S	P	Cr	Mo	V	Ni	Cu	B	Al	Nb	Ti	O
RQT701 Plate	0.14	0.40	1.35	0.003	0.012	0.01	0.12	0.05	0.01	0.01	0.002	0.035	0.035	0.025	/
Outershield 690-H	0.06	0.20	1.5	0.010	0.015	/	0.3	/	2.0	/	/	/	/	/	/
LAC-690	0.08	0.36	1.51	0.007	0.011	0.36	0.44	/	2.59	0.04	/	/	/	/	/

[17,18]. The overall buckling of HSS was also studied [19,20]. Though EN1993-1-12 [21] gives some additional rules and explanation on the use of HSS up to S700 for structural column applications, the impact of the fabrication process for HSS columns on the structural behaviour is still unclear.

Many scholars have shown interest in the column performance made of HSS since the 1980s. Usami and Fukumoto [22] tested twenty-sevenHSS box columns with large width-thickness ratios under centric and eccentric loading conditions. An economical design was proposed based on the test results for stub columns that the local plate buckling was permitted to occur. The early study work [23] did some contribution on the evaluation of residual stress and test study for both slender and stub columns. It was found that the residual stresses are less detrimental to HSS column strength than mild steel column strength. Bjorhovde [24] generated a total of 112 maximum strength column curves and formed the theoretical basis for the American Institute of Steel Construction (AISC) column curves. After that, Rasmussen and Hancock [25] concluded that the overall buckling capacity of HSS columns was higher than those made of mild steel when compared on a non-dimensional basis with investigation work on 11 welded box and I-section columns made of S690 material. Yang and Hancock [26] conducted a series of studies on local and overall buckling and interaction between them for HSS (with a yield stress of 550 MPa) box-shaped columns under compression. The thickness of their specimens ranged from 0.42 mm to 0.60 mm, which means the boxes were very thin, thus they could be formed into a box shape rather than it being built by welding. Welding residual stresses were experimentally and numerically studied for HSS box columns [27,28]. All those studies were mainly focused on the linkage between the geometrical size of the column section and the column strength. Some studies also included determining the initial geometrical imperfections as well as the residual stress pattern. However, few works can be found on investigating the relationship between a fabrication procedure and the column strength.

Martin etal. [29] performed preliminary investigation on the influence of the fabrication process for the plate buckling of thin-walled steel box sections. In this study, since computation cost for the modelling of the welding process is quite expensive, an adaptation of a simplified procedure was used. It was shown that, when welding residual stress is included, the imperfections amplitude has no obvious effect on the buckling strength, stiffness as well as post-buckling behaviour of the box sections. In contrast, when welding residual stress is ignored which means the buckling analysis is purely based on geometric imperfections, the amplitude of these imperfections has a strong impact on the response of the studied box. Ingvarsson [30] investigated the effect of cold-forming residual stresses on the buckling performance of columns. It is found that these residual stresses have a positive effect on the buckling strength of box columns built up by two channel sections welded together in comparison with corner-welded columns. Some recent investigations from China also can be found on the behaviour of axially compressed HSS columns. Welded box columns with a yield stress of 460 MPa were experimentally and numerically studied by Wang etal. [31] with the conclusion that the residual stresses are not detrimental to the plastic resistance for stub columns. However, simplified residual stress patterns were assumed for the cross-sections of the columns and it may not fully show the real case for residual stresses due to the welding process. Ban etal. [32] investigated overall buckling strength of 12 welded box and I-section columns made of S460 HSS.

In summary, most of the published works focus on the performance of HSS structures or structural components without considering the welding effect and heat treatment on the mechanical behaviour of the columns. Only a few studies have investigated on the relationship between the welding techniques and heat treatment and the strength of steel columns fabricated with HSS [33–35]. Hence, the present paper is concerned with an experimental and numerical investigation studying the effect of fabrication procedures including the welding techniques and heat treatment on the strength of box columns made of HSS with a nominal yield stress of 690 MPa. A series of built-upHSS box columns with various welding treatments is analysed.

2. Specimen design

In this paper, six built-upHSS box columns with the same design geometry, made of RQT701 HSS plate with the minimum yield stress of 690 MPa, were fabricated using different welding processes and heat treatment. The RQT701 HSS plates [36] used in the current study have properties close to the European steel specification EN 10025 S690QL [37]. They are made out of quenched and tempered steel with improved forming and welding performance by substituting some alloying elements with carbon. Tables 1 and 2 gives the chemical composition and mechanical properties of the base material and weld electrodes used in Flux-Cored Arc Welding (FCAW) and Submerged Arc Welding (SAW) processes. During the steel delivery process, the RQT701 was heated to a temperature above its upper critical temperature and then very quickly cooled with water. This method of cooling,

Table 2
Mechanical properties of RQT701 steel plate and electrodes used in FCAW and SAW processes.

Items	Minimum yield strength (MPa)	Tensile strength (MPa)	Minimum average impact energy	Minimum elongation (%)
RQT701	690	790–930	27 J@ -45 °C	18
Outershield 690-H	680	760–900	80 J@-40 °C	18
LAC-690	690	760–900	111 J@-60 °C	18

Table 3
Welding conditions and geometry of tested specimens.

Group	Specimen name	Welding method	Preheat condition	Geometry	
				L (mm)	$\overline{\lambda}_y$
A	A-F-1	FCAW	AW	500	0.26
	A-F-2		PH	500	0.26
	A-F-3		PWHT	500	0.26
	A-S-1	SAW	AW	500	0.26
	A-S-2		PH	500	0.26
	A-S-3		PWHT	500	0.26

Note: AW: As-welded, PH: Pre-heated, PWHT: Post weld heat treatment, L: Column length.
For all columns: Outside section width $D = 110$ mm, Steel plate thickness $t = 16$ mm.
$\overline{\lambda}_y$: Non-dimensional slenderness of the section above the y axis (weak axis) shown in Fig.1. It is computed by including the contribution from the backing plates and using the *average* yield stress of 740 MPa.