Journal of Constructional Steel Research 128 (2017) 440–450

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

A numerical study on residual stress of high strength steel box column

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ARTICLE INFO

Article history:
Received 13 July 2016
Received in revised form 21 September 2016
Accepted 22 September 2016
Available online xxxx

Keywords:
High strength steel
Welding residual stress
FCAW
SAW
Preheating
Post-weld heat treatment

ABSTRACT

As high strength steel (HSS) with yield stress of at least 690 MPa is still essentially only available in plate form, HSS box columns have to be "built-up" from plates by welding. During the welding process, residual stress is inevitably generated and could affect the column strength. In this study, a numerical investigation on the welding residual stress distributions of HSS built-up box column is carried out. Two finite element modelling packages, namely the general-purpose package ABAQUS and the welding-function-specific package SYSWELD are employed to simulate the welding and post weld heat treatment process of the column. The predicted results obtained were then validated with test data. In order to investigate the effects of different welding methods, two groups of models corresponding to flux-cored arc welding and submerged arc welding were analyzed. Furthermore, the effects of different heating treatment procedures are also simulated and compared.

1. Introduction

In steel structures fabrication, welding is one of the most commonly used processes to join two or more structural components together. While many different welding processes have been developed, their effects on the micro-structure of the steel components are always controlled by three key parameters, namely (i) the intensity of the heat source which affects the maximum temperature in the welding process, (ii) the heat input rate per unit length which affects the size of the heat affected zone (HAZ) and, (iii) the shielding method employed which affects the quality of the welding and the welding speed. During the welding process, the volume of steel in region near the arc torch expands when the material is heated up. This will cause extrusion effect on the surrounding material and then generates internal stress near the welding regions. The heating and cooling processes will also introduce severe thermal gradients and further increase the magnitude of the internal stress. Eventually, such inhomogeneous volume change and thermal gradients/cycles will generate significant residual stress near the HAZ. The existence of welding residual stress may then affect the strength and ductility of the welded joint.

In order to optimize the welding procedure and understand the magnitude and distribution of welding residual stress, experimental tools such as hole-drilling method, x-ray and neutron diffraction methods are developed. However, such procedures are costly and require many specimens for verification. Hence, the use of numerical modelling technique to study the welding process recently [1] received much attention. Numerical modelling is efficient, flexible and could be cost-saving in practice. It can complement experimental measurement in residual stress study and could be used for designing and optimizing the welding process. Therefore, many numerical modelling procedures are proposed for the prediction of residual stress in different welding processes [1–13].

Currently, two-dimensional (2D) finite element (FE) models with plane strain assumption are still dominating the published works in welding residual stress modelling as the use of more realistic three-dimensional (3D) FE modelling requires much more of computational resource to complete the modelling. When 2D FE model is employed to simulate the welding process, a thin slice of section perpendicular to the motion of the heat source is selected and the longitudinal deformation is ignored. However, with fast advancement in computer hardware, more researchers showed interests on using 3D FE modelling to capture the complex thermal-mechanical processes during welding. 3D FE welding simulation could be employed to study the complicate interactions among many key welding parameters, the evolution of material microstructure, the temperature and residual stress fields [6]. Lindgren and Karlsson's work [7] on using shell elements to model a thin-walled pipe is a pioneer work in the 3D FE residual stress simulation. When compared with 2D FE models, 3D FE models can give more accurate results as it can simulate the 3D thermal heat-exchange process and include all strains and stress components in the analysis. Ueda and Nakacho [8] and Li et al. [9] conducted 3D residual stress analysis for a pipe-plate joint. In order to reduce the computational cost, Ueda et al. [10] firstly studied the multi-pass welding with the lumping technique. The weld passes were lumped into different numbers of blocks which is an effective way to reduce the computational cost while maintaining

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http://dx.doi.org/10.1016/j.jcsr.2016.09.015
0143-974X/© 2016 Published by Elsevier Ltd.

the accuracy of the modelling results. Tahami et al. [11] developed a 3D transient FE model for the residual stresses prediction in butt-welded plates by including the effects of electrode-movement. Kong and Kovacevic [12] used a 3D FE model to study residual stress of lap joint. Lee et al. [13] studied the residual stress distributions near the weld toe of plate-to-plate Y-joints fabricated with HSS plates. Jiang et al. [14,15] studied the impact of different lumping techniques on the residual stress field and compared the effects of welding sequence and starting position on the residual stress distribution. Chiumenti et al. [16] and Dialami et al. [17] studied the numerical modelling technique for friction stir welding processes. Pasternak et al. [18] studied the fabrication of welded plate girders under workshop condition and gave the prediction of imperfections with the aid of simulation tools and simplified engineering models.

The addition of welding filler materials is a complex issue for welding and residual stress modelling. Two existing techniques have been proposed to handle it. The first technique is to include all filler materials in the computational model before welding starts. However, the filler materials that have not been laid yet are first set with reduced material properties to eliminate their influence on other parts of the model. Those reduced strength FE elements are called “quiet elements”. Rybichi et al. [19] and Michaleris [20] used this technique in their models. The second technique is to adjust the model as the welding proceeds on. The FE elements corresponding to the filler materials that have not been added are excluded in the analysis and nominated as “inactive elements”. They are then subsequently added back to the model as the welding proceeds on. This approach was commented as a more accurate method [13] but requires the implementation more advance element controlling features. In many cases it also requires user interactions at each new weld pass.

Recently, the use of HSS in the construction of high strength steel structure received much attention due to its merits in economy, aesthetics and safety [21]. As the stress-strain behavior of HSS is rather different from mild steel especially after exposed to evaluated temperature [22], many studies have been conducted [13,23–27] on the effects of welding on HSS connections. Furthermore, as HSS is still only available in the form of plates, another important issue related to the welding of HSS steel is the fabrication of HSS sections and columns. Obviously, during the fabrication process of HSS sections, extensive amount of welding has to be conducted and the residual stress generated cannot be ignored. In this paper, a numerical investigation on the welding residual stress distributions of HSS built-up box columns was carried out. 3D thermal-mechanical modelling procedures were employed for residual stress analysis for HSS built-up columns. Two FE codes, namely the welding-function-specific SYSWELD [28] and the general-purpose FE package ABAQUS [29], were employed to simulate the welding and the post-weld heat treatment processes. The predicted residual stresses obtained from the FE codes will be validated against actual test results. Furthermore, two groups welding models which are corresponding to the flux-cored arc welding (FCAW) and the submerged arc welding (SAW) are created to complement the actual welding processes performed.

2. Numerical models created

In reference [30], six built-up HSS columns were fabricated by using different welding processes and heat treatments. In this study, numerical models corresponding to these columns were created by using the FE packages SYSWELD and ABAQUS. The welding and heat treatment scenarios modelled in this study are shown in Table 1. These models are corresponding to the six scenarios generated by combining the two welding methods (FCAW and SAW) with the three heat treatment procedures (AW for as-welded condition, pH for preheating treatment before welding, and PWHT for Post-Weld Heat Treatment). The AW models, which are formed by assuming that all fabrication are done under ambient temperature, are benchmark models for the evaluation of the different heat treatment effects. For the PH models, regions near the welding part are assumed to be preheated to a uniform temperature of 100 °C before the welding was started. For the PWHT models, it is assumed that no preheating is applied before the welding while a creep model corresponding to the thermal history of the PWHT process is employed to reproduce the equivalent heat treatment effects. Fig. 1 shows the thermal history of the PWHT process employed in the experimental study.

Table 1
Fabrication and modelling scenarios.

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

AW: As-welded, PH: Pre-heated, PWHT: Post weld heat treatment.

The cross-sectional dimensions of the column modelled, together with the layout and welding sequence of the built-up box column are shown in Fig. 2. Note that the weld passes sequences shown in Fig. 2 for FCAW and SAW are carefully arranged so that the columns will be heated evenly to reduce welding-caused deformation. In all numerical models, the actual welding sequences employed are simplified to two lumps for each corner weld so that the computational cost of the whole modelling process would be reduced to a reasonable level. During the welding modelling, it is assumed that the bottom end of the column is simply supported while the top end of the column is roller supported so that it is free to move in the longitudinal direction during the welding.

3. Modelling procedures

3.1. Modelling in SYEWELD

3.1.1. Overview

SYSWELD is an integrated FE package for modelling the heat effects of welding and heat treatment. In this study, a simplified heat conductivity model is created in SYSWELD to simulate the heat effects of welding on the HSS built-up box columns. In this model, the heat input per unit length of weld will be treated as thermal loading on the column while the major modelling results are the temperature time history during the welding, the deformation field and the residual stress field produced. During the modelling process, the geometry of the box column and the weld profiles are first created using the geometrical modelling pre-processor *Visual-Mesh* in SYSWELD. Secondly, for each HSS built-up column investigated, eight welding trajectories corresponding to the eight weld lumps shown in Fig. 2 are created. Thirdly,

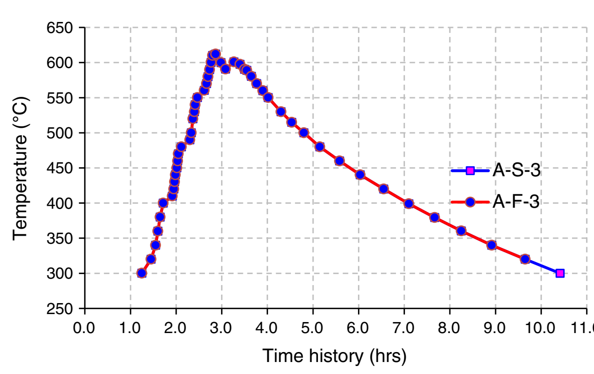

Fig. 1. Thermal history of the actual PWHT process.