Engineering Structures 127 (2016) 18–30

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Proposed modeling approach of welding procedures for heavy steel plates

Omar A. Ibrahim [a], Dimitrios G. Lignos [c,*], Colin A. Rogers [b]

[a] Dept. of Structural Engineering, Alexandria University, Lotfy El-Sied st. off Gamal Abd El-Naser - Alexandria, Alexandria Governorate 11432, Egypt
[b] Dept. of Civil Engineering and Applied Mechanics McGill University, Macdonald Engineering Building, 817 Sherbrooke Street, West Montreal, QC H3A 0C3, Canada
[c] Dept. of Architecture, Civil and Environmental Engineering, Ecole Polytechnique Fédérale de Lausanne (EPFL), EPFL ENAC IIC RESSLab, GC B3 485, Station 18, CH-1015 Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 23 November 2015
Revised 9 August 2016
Accepted 10 August 2016

Keywords:
Steel
Thick plates
Butt welds
Welding simulation
Creep modeling
Heat transfer analysis

ABSTRACT

A numerical modeling approach is proposed to assess the effectiveness of automatic submerged arc welding procedures for steel plates with thickness larger than 50 mm. The scope of study includes partial joint penetration butt welds, their numerical analysis, and the subsequent development of welding recommendations for thick steel plates, with the ultimate objective to reduce the related industrial losses. The proposed approach consists of a heat-transfer numerical model that is integrated with a stress analysis model that was validated with measurements obtained from two heavy steel assemblies that were welded in a fabrication shop. The first consisted of two 75 mm thick plates welded in the flat position, for which temperature measurements were recorded. The proposed model shows good agreement with these measured temperature results. The second consisted of a built-up box column that also utilized 75 mm thick plates. This assembly experienced cracks near the welds after the completion of the welding procedures. Through a comprehensive investigation of the material properties of the steel plates it was confirmed that the material met the specifications in terms of minimum fracture strain elongation and fracture toughness. The model was used to successfully predict the crack initiation due to thermal stresses that were developed near the welds. The proposed model can potentially be employed to assess the defect limits found in current specifications for welded steel assemblies that utilize thick plates.

1. Introduction

Welding is a commonly used method for joining structural steel components. This is attributed to the reliability of the connection, its structural simplicity in terms of load transfer and its cost effectiveness. However, welding can also be problematic; a primary example is that the process is accompanied by residual stresses. These stresses develop in the plates being welded because of the uneven heat expansion and the subsequent contraction upon cooling, both of which are often constrained by the configuration of a structural member's or connection's cross-section. In recent years, the use of thicker built-up members and heavier steel shapes have been preferred for the construction of complicated structural systems having long spans, greater heights and larger loads due to more demanding design and performance requirements [1]. The use of thick plates further exacerbates the development of weld related residual stresses because of the greater constraint to the steel's expansion and contraction; as a result, there is an increased likelihood of crack development originating from discontinuities and imperfections. Design codes and specifications [2–5] provide guidance for the welding processes to ensure the integrity of the welded assembly. However, the available guidelines were developed based on commonly used less than 25 mm thick structural steel plates. The relevant North American design specifications [2–5] account for the aspects introduced by Miller [6] to reduce the intensity of residual stresses induced by the welding procedure; however, these are mostly qualitative recommendations to reduce the restraint placed on the connection and to ensure that minimum material fracture toughness levels are met. Cases of structural failure have been reported due to failure in welded thick steel plates assemblies [7]. Recently, based on feedback from one of the largest steel fabricators in North America; it was required to scrap over 400 tons of thick steel plates that developed unrepairable cracks after welding, with total industry losses exceeding $1M. Given this current situation, the specifications for the welding procedures and the acceptance criteria for cracks and discontinuities for thick steel plates (greater than 25 mm) [2–5] are required to be updated. In order to do so, one of the first requirements is to

* Corresponding author.
E-mail addresses: omar.ibrahim@mail.mcgill.ca (O.A. Ibrahim), dimitrios.lignos@epfl.ch (D.G. Lignos), colin.rogers@mcgill.ca (C.A. Rogers).

http://dx.doi.org/10.1016/j.engstruct.2016.08.022
0141-0296/

develop a practical numerical approach from which one can examine the effect of different welding procedures on thick steel plates and the resulting residual stresses. It is necessary for this tool to comprise the features of the welding procedure, i.e. the welding temperature, the welding travel speed and the preheat/inter-pass temperatures, as well as the steel's time and temperature dependent material properties.

A summary of related laboratory and analytically based studies is provided herein. Bjorhovde et al. [8] conducted an extensive testing program using the sectioning method to measure the residual stresses induced in 50 mm ASTM A36 Gr. 36 [9] plates (f_y = 250 MPa) from rolling, flame cutting and welding. The results of these tests showed that the residual stress post fabrication near the welded area can be as high as the yield stress of the steel. Fisher et al. [10] detected cracks in a W360×1086 ASTM A572 Gr. 50 [11] section (f_y = 345 MPa) spliced with groove welds; the high residual stresses induced by the web groove welds initiated crack instability. The authors recommended using fillet welds instead of butt groove welds to avoid welding near the k-area of jumbo W-sections, which had revealed weak fracture toughness of 35 MPa $\sqrt{m}$ at 0 °C compared to the AWS D1.1 Specification [2] limit of 58 MPa $\sqrt{m}$ at 0 °C. In other research programs the investigation of the effects of the employed welding procedure on steel plates has also been conducted numerically. For example, Brickstad and Josefson [12] developed a numerical simulation for the welding procedure of 40 mm thick stainless steel nuclear piping systems, of 230 MPa yield stress, to investigate the through-thickness variation of axial and hoop stresses and to assess the growth of surface flaws at circumferential butt joints. Acevedo et al. [13] conducted experimental and numerical assessment of residual stresses induced by welding at the region surrounding the toe of a tubular K-shaped joint. The residual stress measurements were conducted through Neutron-diffraction of welded tubes of thicknesses 20 mm and 8 mm. The numerical simulation comprised an uncoupled thermo-mechanical model, which was validated with the experimental data; analytical residual stress distribution equations were also developed. Nikolaidou et al. [14] used an uncoupled thermo-mechanical model to investigate the cause of crack initiation after welding a 25 mm doubler plate to the web of a W360×237 column of high strength A913 Gr. 65 450 MPa steel [15]; the investigation proved that high residual stress induced by the welding procedure resulted in the detected cracks. Further, an uncoupled thermo-mechanical was developed by Lee et al. [16] to produce an assessment of the residual stresses of butt welded 25 mm thick plates and to study the relaxation phenomena accompanied by post-welding cyclic loading. The residual stress outputs from their model were validated by means of the results from a test program [17]. The uncoupled thermo-mechanical model effectively predicted the residual stresses for the 25 mm thick plates.

It is not practical to rely solely on an experimental study of the welding procedure of thick plates in order to improve current welding procedures of heavy assemblies due to the required large-scale weld tests and significant number of parameters to be investigated. Therefore the development and use of a numerical simulation of typical welding procedures for thick plates was justified. This paper describes a numerical uncoupled thermo-mechanical modeling approach which can be used to investigate the effect of the welding procedures on steel assemblies that utilize thick plates (>50 mm) and heavy cross-sections. The simulation was validated with a coordinated experimental program that consisted of three phases; the first phase included the validation of the temperature distribution results from the numerical model with the temperature measurements from the welding procedure of two 75 mm thick ASTM A572 Gr.50 [11] steel plates. The second phase was the validation of the resultant residual stress distribution with experimental results obtained by Chen and Chang [18]. The third phase included the application of the modeling approach to assess the influence of the employed welding procedure for a heavy built-up steel box column, fabricated from the same heat of steel plates studied in the first phase. Cracks were observed in this column after the welding procedure had been completed.

2. Proposed modeling approach for welding procedures

The aim of numerically simulating a welding procedure is to make it possible to use a practical approach to investigate the likelihood of crack propagation, as well as the influence of different welding procedures. A numerical simulation for the welding procedure has to comprise the effects of elevated temperatures on the steel plates and must provide the generated stress from the temperature change. The elevated temperatures change the crystalline structure of the steel material and, correspondingly, its properties (e.g., strength and stiffness). Because our interest is the magnitude of the generated residual stresses from the welding procedure, it is feasible to only include the changes of the mechanical properties of the steel material at elevated temperatures and to disregard the changes in the crystalline structure, since it is inherently incorporated in the strength change; this assumption has been also considered in previous research [12–14,16]. The proposed finite element (FE) approach is demonstrated through detailed Modeling of the welding of a 75 mm thick built-up box column and two 75 mm thick steel plates, using ABAQUS 6.11 [19] for 3-dimensional (3-D) modeling. The FE simulation is divided into two phases. The first phase is a simulation of the heat transfer from the welding procedure through the base metal to obtain the temperature distribution over time. The second phase involves a stress analysis model (or a visco-plastic model to account for potential creep strain effects) to determine the stresses induced by the welding procedure. The two phases were then integrated to simulate the welding procedure.

The element "death and birth" technique, as described by Brickstad and Josefson [12], was incorporated in the FE model. This technique is used to deactivate and reactivate the elements representing the welding beads to simulate the addition of new material to the connection during fabrication. As an example, Fig. 1a and b shows the activation of only the first six passes at each corner of the built-up box column 3-D model shown in Fig. 2a, while the remaining weld passes are deactivated. To achieve this, the "Model Change" interaction in ABAQUS 6.11 [19] was utilized such that prior to the deactivation step the forces/heat-fluxes that the region to be removed exerts on the surrounding nodes are ramped down to zero. Therefore, the effect of the removed region on the rest of the model is completely absent only at the end of the deactivation step. To reactivate a welding pass the same interaction is used with the "strain free" option in ABAQUS 6.11 [19] such that at the start of the weld pass it provides a zero strain contribution to the simulation. The two simulation phases are discussed in detail in Sections 2.1 and 2.2. The mesh sensitivity study and element selection of the FE models in the proposed approach are described in Section 2.3. Additionally, the effect of introducing creep strain properties on the residual stress results is discussed in detail in Section 2.4.

2.1. Heat transfer simulation

The heat transfer simulations for the built-up box column and the two steel plates were generated as illustrated in Fig. 1a and c, respectively. The finite element mesh at the welding area as well as the welding passes for both cases are shown in Fig. 1e and f respectively. To achieve the resulting temperature