EVALUATION OF COMMON WELDING PROCEDURES FOR THICK STEEL PLATES AND HIGH STRENGTH STEEL SECTIONS

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1. ABSTRACT

High strength steel materials and assemblies with thick steel plates (thickness greater than 50mm) are on high demands due to the design complexity and increasing heights of steel frame buildings. Currently employed welding procedures have led to fabrication problems of such assemblies. The welding of thick plates and heavy sections requires more heat input and undergoes higher constraints than common steel plates. To study the residual stresses resulting from the common welding procedures on thick plates, a proposed finite element simulation is established for two case studies that encountered problems due to welding during their fabrication; a welded built-up box column and a high strength steel W-Shape column with welded thick doubler plates. Tensile tests are conducted for both cases as well as Charpy V-Notch tests to determine the material's fracture toughness. The locations of high stress concentrations are identified. The tendency of a crack to propagate due to stresses induced by the welding procedure is determined by comparing the results from the finite element simulation and the material's fracture toughness tests.

2. INTRODUCTION

Welding thick steel plates and heavy sections generates a great deal of concerns in the steel industry due to the accompanied residual stresses and cracks in these sections. This problem was illustrated by researchers since the 1970s; however, in recent years, the same issue became more prudent due to the continuous use of heavy sections and assemblies and high strength steel W-Shape columns; as a result of more demanding design requirements and more complicated structural systems with wider spans and higher altitudes. Despite this increase in the demand of thick plates and heavy sections, the specifications for the welding processes and acceptance criteria for cracks and discontinuities [1-3] are all based on common plate thicknesses of 25mm and offer limited information regarding welding on high strength steel.

Extensive testing to measure the residual stresses induced in 50mm thick plates from rolling, flame cutting and welding was conducted by [4, 5]. The results of these tests showed that the residual stress near the welded area can be as high as the yield stress of the steel. Others [6] detected cracks in a spliced jumbo W-section with groove welds. Advanced finite element (FE) modelling of the welding procedures was employed involving T-joint fillet welds, butt-welded plates and high strength steel plate to plate joints [7] in an effort to better understand and predict the residual stress distribution. The specifications [1-3] considered principles introduced by [8] to reduce the intensity of residual stresses induced by the welding procedure. These are only qualitative recommendations to reduce the restraint and ensure that minimum levels of the material's fracture toughness are met. To the best of our knowledge, there has not been any recent work done to develop an explicit welding procedure for thick plates and heavy sections in North America to reduce the resultant residual stresses and subsequently cracks.

This research aims to study the effect of using common welding procedures on thick plates and heavy sections, from which a new welding procedure can eventually be developed. The study is based on two case studies where the common welding procedure resulted in cracks in the steel components being welded, in which these components were scrapped and the steel fabricator economic losses were estimated in millions of dollars. The first case study is a heavy built-up box column with plates' thickness of 75mm steel A572 Gr. 50, welded in the corners with partial penetration (PJP) groove welds using submerged arc welding process (SAW). The second case study involves a high strength A913 450MPa W360x237 column with two 25mm doubler plates welded to its web as part of a prequalified beam-to-column connection with complete joint penetration (CJP) flare bevel groove welds using a flux core arc welding process with a CO_2 gas shield (FCAW-G). A detailed finite element (FE) simulation of the welding procedure is developed for both cases. A validation of the FE simulation is done by comparing the results with the case study specimen. After validating the FE simulation, the welding parameters can then be studied to reduce the residual stress output and the cracks propagation.

3. FINITE ELEMENT SIMULATION OF THE WELDING PROCEDURE

The finite element simulation is developed in ABAQUS v6.11. The modeling procedure involves two numerical models. The first is a transient heat transfer model to measure the temperature distribution at all times through the welding process. The second is a static model to determine the stresses induced by the welding process. The two models are integrated together to simulate the whole welding procedure. Figure 1 shows dimensions of the case-study-1; a built-up box column and the passes profile at each joint. Figure 2 illustrates the geometry and meshing of the welded column assembly of the case-study-2 consisting of a W360x237 section with two 25mm doubler plates welded to its web [9].

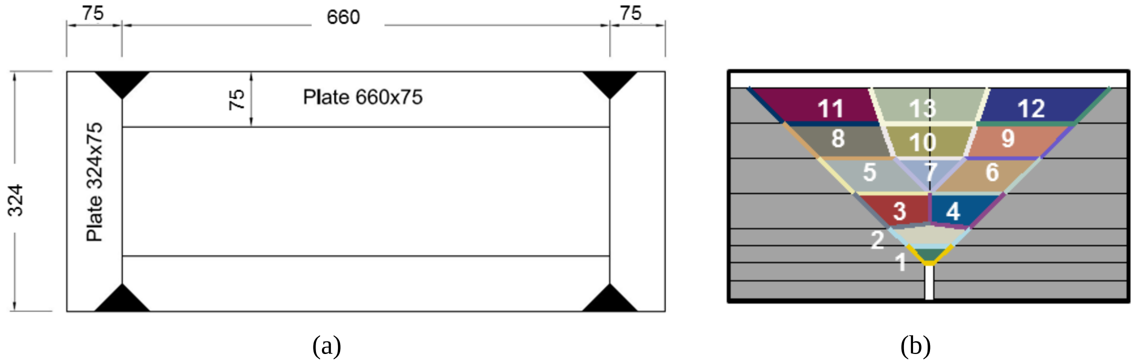

Fig. 1: Case-study-1 a) dimensions (mm) of the built-up box section. b) The weld passes profile at each corner

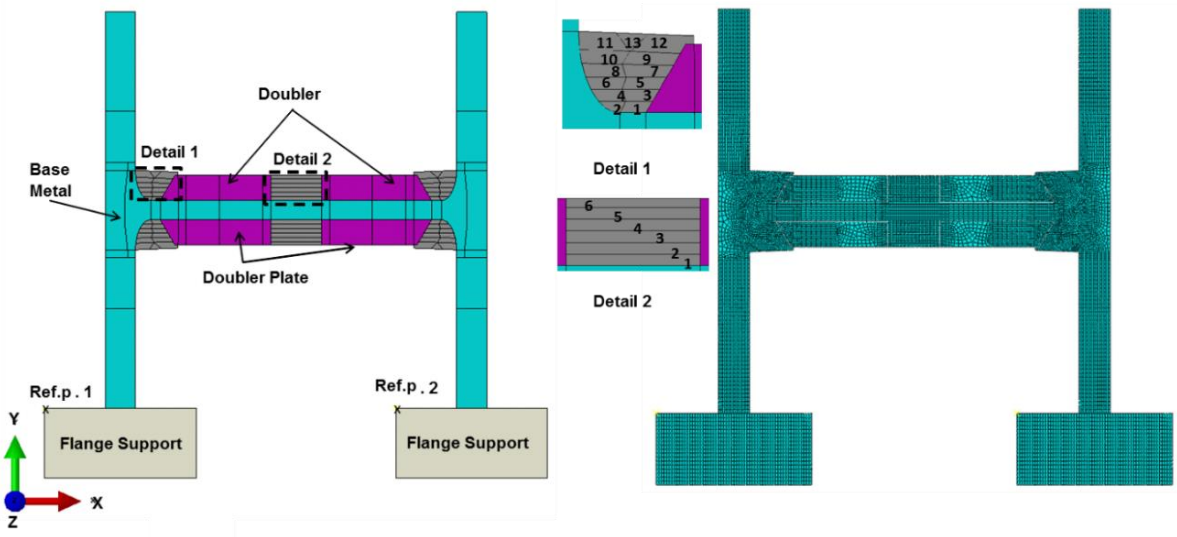

Fig. 2: Case-study-2. 2D model geometry and meshing of the welded column assembly

The output of the heat transfer model is the temperature distribution due to the welding of each pass. The material properties such as the thermal conductivity and the specific heat are defined as temperature dependent; also the heat transfer coefficient and the emissivity are defined. After the welding of each pass, heat convection and radiation boundary conditions are assigned to the surfaces in contact with the atmosphere. The first step of this model is to deactivate all the passes from the model and then reactivate them according to their order in the welding process; this is called the “death and birth” technique [10].

The stress analysis model imports the temperature distributions due to the welding and cooling of each pass from the heat transfer model. These temperature distributions are then translated to strains according to the defined thermal expansion coefficient at different temperatures. Subsequently, these strains are translated to the corresponding stresses according to the defined stress-strain relationship. The modulus of elasticity and yield strength of the steel material are defined as temperature dependent properties.

The proposed modeling approach has been verified in [11]. Both case studies discussed herein were analyzed using this modeling procedure. The first case study (see Fig. 1) is analyzed using a 3-Dimensional model of half of the box-section. The second case study (see Fig. 2) is analyzed using a 2-Dimensional model. The following sections briefly discuss the analysis and the results of the two case studies.

4. CASE STUDY-1: BUILT-UP BOX COLUMN

A number of heavy built-up box columns with plate thicknesses 75mm A572 steel grade 50 were scrapped by one of the largest steel fabricators in North America due to the development of cracks after the welding procedure. Figure 1 shows a schematic representation of the cross section of such column. It is worth mentioning that the fabricator followed the recommendations given by [1-3] for welding thick plates. The welding of each one of the two corners at the same side of the built-up column shown in Figure 1a is completed simultaneously. Each corner consists of 13 weld passes (see Figure 1b). For this thickness, the welding sequence according to the industry partner of this project and AWS D1.1 [1] guidelines involve: (a) Welding of one pass on side-1 of the built-up box column; (b) flipping of the built-up box column and welding of the side-2 to pass number 4; (c) flipping again and welding side-1 to pass number 7; (d) flipping and welding side-2 to pass number 7; (e) flipping and welding side-1 to pass number 13; and finally, flipping and welding side-2 to pass number 13.

In order to investigate the effect of the welding sequence on the induced residual stresses, a finite element model is developed in ABAQUS v6.11. A mesh sensitivity study was conducted for both the 2-D and 3-D welding processes [11]. For the 2-D model, the elements used are linear quadrilateral; the selected mesh was of minimum element size 1mm and the maximum 7mm. For the 3-D model the elements used are linear hexahedral, the selected mesh was minimum element size 2mm the maximum 9mm. Linear elements are selected for the analysis because in ABAQUS time integration in transient problems is done with the backward Euler method, which is unconditionally stable for linear problems.

Different regions of the built-up box column are studied. Figure 4a shows part of the regions that are studied. Figure 4b illustrates the transverse stress distribution along path-1 after the welding of each welding pass; which represent the location of the cracks observed on the case study built-up box columns the stress direction that triggered their propagation. The thick black curves represent the maximum and minimum stress envelopes. The dashed curve represents the final residual stresses in the steel plate at this region.

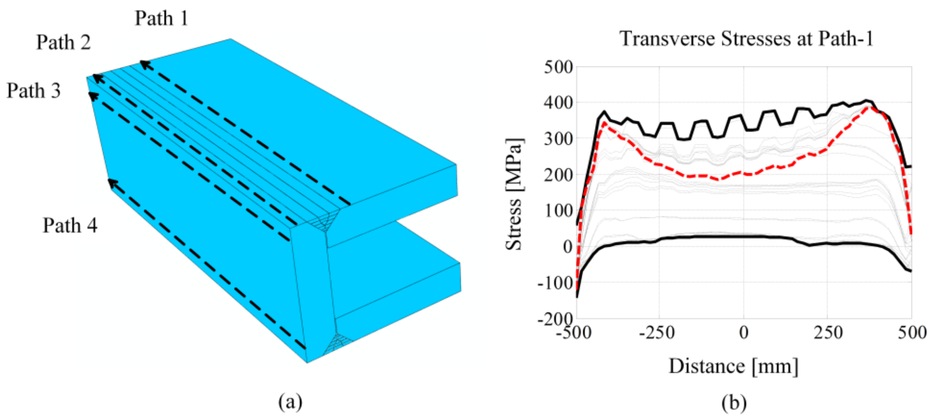

Fig. 3: a) Part of the regions studied for the built-up box column. b) The transverse stress distribution along path-1 after the welding of each pass

From Figure 4b, the stresses at this path can become as high as the yield stress of the steel material through the welding procedure, considering that the yield stress of the material decreases at elevated temperatures. By using linear fracture mechanics [12] and considering the accepted CVN value for A572 steel grade 50 by the specifications [1-3], the acceptable fracture toughness of the material would be 73 MPa.√m. Based on the generated stress at path 1 (about 300 MPa) and considering a discontinuity of 1mm (which is also accepted by the specifications [1-3]), the stress intensity factor would be 500 MPa.√m. Comparing the stress intensity to the fracture toughness indicates that this discontinuity will propagate under the stresses induced by the welding process. These results agree with the case study. The proposed welding simulation technique is currently used by the authors in order to find effective welding procedures in order to improve the acceptance criteria of the AWS specifications.

5. CASE STUDY-2: W-SECTION WITH WELDED DOUBLER-PLATES

Based on available information from the steel industry partner of this research project, cracks (maximum depth of 12.7 mm) occurred in the column flanges near the flange to web junction of high strength W-Shape columns after all welding procedures were completed. For this reason the main focus of case study-2 is on the flange regions of these columns. The cracks were observed in the column flange after misplaced shear tabs at these locations were removed. The crack type is identified to be fracture mode I caused by a tension only stress field applied perpendicular to the crack. In order to explain how the welding process influenced the development of the cracks and to make recommendations as to how best to modify the currently employed procedure such that this type of fabrication related damage could be avoided, a two-dimensional (2D) FE model is developed, which simulates the FCAW-G process of the 25mm thick doubler-plates on the web of the high strength A913 450MPa W360 x237 column shown in figure 2. The column material properties and fracture toughness are evaluated using tensile and Charpy V-Notch testing. The measured material properties are then inserted into the FE model. Results are presented for both measured and expected material properties.

The welding process on each side of the web consists of two 13-pass complete joint penetration (CJP) flare bevel groove welds at the k-areas and two 6-pass plug welds at the middle (see figure 2). The steel column is supported by two rigid bodies at the tip of its flanges to represent the actual supports during welding in the fabrication shop. The numerical model consists of four parts: (1) the W-Shape with the welds; (2) the upper doubler plate; (3) the lower doubler plate; and (4) the flange supports. Between the flange tips and the rigid bodies, surface-to-surface contact interaction is applied and tangential behavior is chosen with a penalty friction formulation and a friction coefficient 0.2. For the FE meshing arrangement of the 2D cross quadrilateral and quadratic elements are selected, with a minimum element size of 2mm. The welding sequence typically used in practice involves completion of all welding passes on the one side of the web of the W-Shape before welding the doubler plate to the opposite side. In particular, the first passes of the CJP welds are performed, followed by the 6 passes of the plug welds and finally the rest of the CJP weld passes. The column is then flipped 180 degrees and the welds on the other side of the web are performed following the same sequence.

After the completion of the final stress analysis the stresses resulting from all welding processes taking place on the web of the column were obtained. In particular, in figure 5 the normal maximum S22 stresses (in the y-y direction) that were observed during the welding process are shown. These stresses represent the stress field in the direction perpendicular to the crack found at the top of the flanges. Figure 5 depicts the maximum S22 stress distribution at two paths, one along the width at the top of the flange and one through the thickness of the flange following approximately the crack path. In figure 5, it is shown that the peak of the S22 stress distribution is at the exact location where the shear tab was welded. Interestingly, this is the location where the crack was detected. Thus, this is a first indication that the residual stresses caused by the welding sequence could have led to the crack initiation at this location. This also confirms that the crack likely existed prior to the welding of the shear tabs. Both FE models (with expected and measured material properties) produce almost the same S22 stress distribution in this step of the analysis with a small difference at the peak values of 6%.

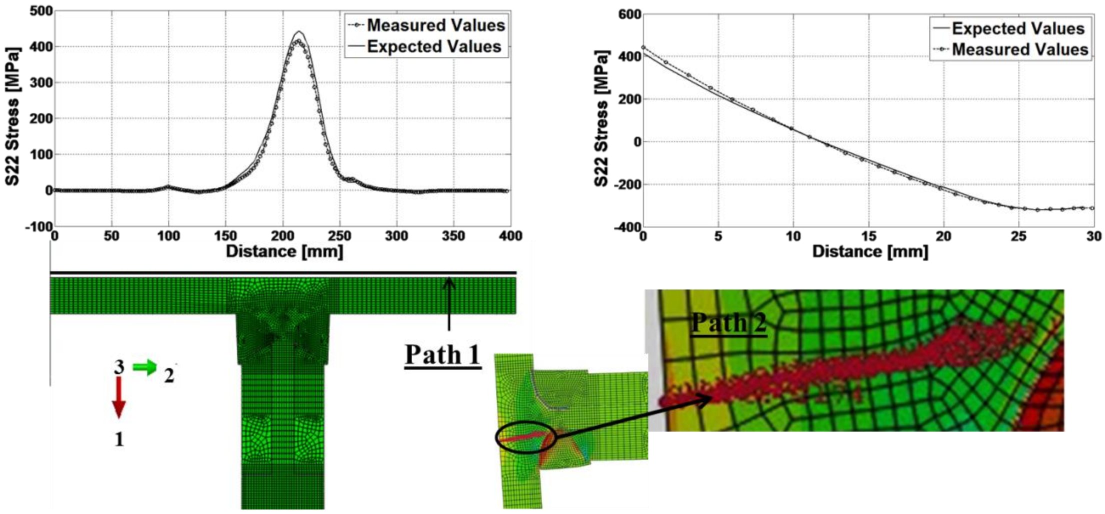

Fig. 4: Maximum S22 stresses in the critical crack region

Having obtained all the information concerning the residual S22 stresses caused by the welding procedure, linear elastic fracture mechanics [12] was employed in order to investigate the possibility of crack initiating in the peak S22 stresses location of the welded column assembly. To this end, for the FE model that employed the expected and measured material properties, the critical crack length a_{cr} was calculated for both cases. The a_{cr} calculated for 0^{o}C was 9mm while for 21^{o}C was 12mm and 13mm, which indicates that a crack found with minimum length of 9mm or 12/13mm, for the two temperatures discussed, can potentially lead to fracture. As mentioned earlier, the depth of the crack found was 12.7mm. Therefore, it was demonstrated that fracture was likely to occur for the welded column assembly investigated (since the temperature in the shop is 15^{o}C) and that the welding sequence was the main cause of the cracking observed.

6. SUMMARY

Currently employed welding procedures in North America don't adequately address welding of heavy plates and assemblies as well as high strength steel materials (i.e., above 450MPa). Reported failures regarding such procedures involve discontinuities and cracking occurring during or right after fabrication due to the residual stresses invoked by the employed welding process. In order to approach the problem, FE modeling of known case studies in collaboration with the North American steel industry is employed. The proposed modeling approach is validated by comparing the FE results with various cases studies. Ongoing research by the authors includes various parametric studies that involve various parameters that affect the welding sequence of such assemblies.

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ΑΞΙΟΛΟΓΗΣΗ ΤΥΠΙΚΩΝ ΜΕΘΟΔΩΝ ΣΥΓΚΟΛΛΗΣΗΣ ΓΙΑ ΜΕΤΑΛΛΙΚΕΣ ΠΛΑΚΕΣ ΜΕΓΑΛΟΥ ΠΑΧΟΥΣ ΚΑΙ ΜΕΤΑΛΛΙΚΕΣ ΔΙΑΤΟΜΕΣ ΥΨΗΛΗΣ ΑΝΤΟΧΗΣ

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ΠΕΡΙΛΗΨΗ

Λόγω της αυξημένης πολυπλοκότητας στον σχεδιασμό μεταλλικών κτιρίων τα τελευταία χρόνια (π.χ. σχεδιασμός για εκρήξεις), οι χάλυβες υψηλής αντοχής διαρροής όπως και οι συνδέσεις με ελάσματα χάλυβα μεγάλου πάχους (πάχη μεγαλύτερα από 50mm) είναι σε υψηλή ζήτηση. Οι υπάρχουσες διαδικασίες συγκόλλησης αυτών των συνδέσεων έχουν οδηγήσει σε διάφορα κατασκευαστικά προβλήματα. Για παράδειγμα, η διαδικασία συγκόλλησης διατομών και ελασμάτων με μεγάλα πάχη συνήθως απαιτεί περισσότερη θερμική ισχύ. Στην περίπτωση αυτή δημιουργούνται μεγαλύτερες παραμένουσες τάσεις σε σχέση με τις αντίστοιχες σε ελάσματα χάλυβα με τυπικά πάχη μικρότερα από 25mm. Μέσω μιας προτεινόμενης διαδικασίας προσομείωσης με πεπερασμένα στοιχεία σε συνδυασμό με μία σειρά πειραμάτων τύπου Charpy, η παρούσα εργασία μελετά την αποφυγή διάδοσης ρωγμών από παραμένουσες τάσεις λόγω συγκόλλησεων σε συγκολλητά υποστυλώματα κιβωτιοειδούς διατομής και σε κομβοελάσματα μεταλλικών υποστυλωμάτων από χάλυβα υψηλής αντοχής διαρροής.