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Chiew, Sing Ping; Jiang, Jin; Lee, Chi King

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Residual stress of high strength steel box T-joints

Part 2: Numerical study

*C. K. Lee, S. P. Chiew and Jin Jiang

School of Civil and Environmental Engineering

Nanyang Technological University

50 Nanyang Avenue, 639798

Singapore

*Email: ccklee@ntu.edu.sg

ABSTRACT

In Part 2 of this study, 3D fully coupled thermal-stress analyses were conducted to simulate the welding process and predict the welding residual stress distributions of the high strength steel box section T-joints. The accuracy of the numerical model is validated by comparing the modeling results with the experimental results. After validating the accuracy of the numerical model, a small scale parametric study was carried out to investigate the influences of joint angle, the starting point of joint welding, the preheating temperature, the brace-to-chord width ratio and the welding speed on the magnitudes and distributions of residual stress along the chord weld toe of the joints.

Key Words: Residual stress, high strength steel box section T-joint, 3D fully coupled thermal-stress analysis

1 INTRODUCTION

Fusion welding is a complex process in which the metal parts are heated until they are melted to join materials. While many experimental tools, including hole-drilling method, x-ray diffraction method and neutron diffraction method could be employed to measure the welding residual stress [1-3], they are costly and many specimens are needed to optimize the fabrication process. This gives much room to numerical modeling it is cost-saving, versatile and able to produce predictions that are beneficial in optimizing the welding process. Many numerical modeling procedures have been suggested for the simulation of the welding process under different complexity [4-5] and for different welding connection types [6-10] as well as failure assessment [11]. Most analyses were performed with sequentially coupled analysis, in which the whole simulation is separated into the thermal analysis step and the stress analysis step. In general, sequentially coupled analysis ignores the effect of heat generation in plastic dissipation and this may affect the accuracy of the model. Hence, the much more computational intensive 3D fully coupled thermal-stress analysis is preferred if the computational time needed is not the main constraint. When a 3D fully coupled analysis is performed, the effect of heat generation in plastic dissipation will be included. In order to balance the accuracy of modeling and computational cost, numerical techniques such as lumping [12-14] and dimensions reduction from 3D to 2D [15] are frequently used. Despite that 2D modeling can effectively reduce the computational cost, it also has some disadvantages. For most 2D models, since the analysis is performed on a single plane, a reasonable fraction of heat sources is chosen according to measurements or assumptions. Therefore, to obtain an accurate heat source model is important but difficult in 2D analysis. Furthermore, 2D models can only give the residual stress at selected cross sections and it cannot fully describe the residual stress distribution in the whole structure, especially along the boundaries of the structures.

In general, the fabrication procedure of welded box section joints is more complicated than that for plate-to-plate joints [15-17]. Firstly, different from traditional rectangular hollow sections, the chord and brace box sections are formed by welding four steel plates together [18]. Secondly, interference of residual stress fields generated during the welding of the chord and brace box sections and that generated during joint welding could complicate the final welding residual stress distribution. Furthermore, many welding and geometrical parameters such as welding speed, preheating temperature and brace to chord width ratio will also affect the welding residual stress distribution. As a result, for the study of welding residual stress of welded box section joints, 3D modeling is deemed to be necessary in order to provide a realistic prediction of the residual stress field.

In Part I of this study [18], the results of an experimental investigation on the residual stress distributions near the weld toe of two RQT701 high strength steel (HSS) box section T-joints were reported. In this paper, a 3D fully coupled thermal-stress analysis procedure for the prediction of residual stress field is presented. Similar to Part I, two numerical models corresponding to the actual fabricated specimens, one fabricated with 100°C preheating and another at ambient temperature, will be created. The numerical modeling results will be first validated by comparing them with the experiential results. After that, a small scale parametric study will be carried out to investigate the impacts of different welding and geometrical parameters on the welding residual stress distributions of the joints.

2 THE NUMERICAL MODELING PROCEDURE

2.1 An overview

As reported in Part I [18], the chord and brace lengths of the specimen are 3m and 2.2m, respectively. However, in order to reduce the computational cost, only 0.9m of the chord box and 0.3m of the brace box of the joint were modeled (Fig. 1). This area was chosen for analysis for the reason that high values of residual stress were found there in the experimental study. The 3D fully coupled thermal-stress analysis was divided in two steps and was conducted by using the finite element package ABAQUS [19]. The first step is to simulate the welding process for the box sections fabrication. In this step, the multi-pass welding along each corner (Section 2.2.2 of [18]) of the box sections was combined into one lump to reduce the computational cost. The second step is to simulate the welding process for the joint fabrication. Since the welding residual stress field in this area is important for the fatigue and fracture performances of the joint, the weld filler was divided into four lumps during modeling. The welding size and the starting position of each welding pass adopted in the numerical model are exactly corresponding to those used in actual fabrication (Fig. 2).

It should be noted that during the 3D fully coupled thermal-stress analysis, while the thermal effects of heat inputs (melting and solidification of welding material and movement of heat source etc) are mainly coupled with the mechanical analysis via temperature depended materials properties and considerations of convection and radiation, the mechanical stress-strain responses of the model (including the effects of large deformations, the addition of welding materials which changed the convection and radiation boundary conditions, please see Section 2.3 for details) were also fully coupled with the thermal analysis. Another point that worth to mention is that in the 3D fully coupled thermal-stress analysis, the impacts of solid-state phase/microstructure transformation (e.g. *martensitic phase transformation)* on the thermal and residual stresses are *indirectly* accounted for by using a set of well accepted temperature dependent latent heat, specific heat, thermal expansion coefficients and other mechanical properties relationships for the welding material and the HSS steel. By carefully defining such temperature dependent properties, the residual stress evolution (generation and relaxation) is modelled as a time and thermal and mechanical dependent mechanical phenomenon. Furthermore, the heat input is directly taken from the weld filler elements and then allowed to propagate to other components. The equivalent heat method was introduced to deal with the latent heat on consolidation front. A full account of the theory and numerical algorithm adopted in the coupling procedure could be found in the ABAQUS theory manual [19].

In order to validate the accuracy of the numerical modeling procedure, two benchmark models, one corresponding to the specimen with preheating and another corresponding to the specimen welded at ambient temperature, were created. For the model corresponding to the preheated specimen, a uniform initial temperature field of 100°C was set for areas within 100m from all weld paths. Note that the use of such uniform preheating temperature fields means that any non-uniform preheating effect was ignored. For the model corresponding to the specimen without preheating, a uniform initial temperature field of 30°C was applied to the whole model.

2.2 Heat source modeling

The accuracy of the heat source model during welding is important for the welding residual stress simulation since the arc torch heat input is the dominant energy source of the welding process. In the past, several generations of the heat source model with increase complexity, from point source model, plane source model to double ellipsoidal model, have been proposed [4,15,20]. In the present study, the double ellipsoidal model [15,17,20] was employed to define the thermal loading. In the double ellipsoidal model (Fig. 3), the front and rear half of the heat source are defined as the quadrant of two different ellipsoids. The fractions f_f and f_r in this thermal model are set equal to 0.6 and 1.4, respectively [20]. Similar to the previous study of HSS plate-to-plate joints [17], the power density distributions inside the front quadrant (q_f) and the rear quadrant (q_r) are defined as:

$$\begin{cases} q_f(x,y,z) = \dfrac{6\sqrt{3} f_f Q}{a \cdot b \cdot c_1 \pi \sqrt{\pi}} e^{\frac{-3x^2}{a^2}} e^{\frac{-3y^2}{b^2}} e^{\frac{-3z^2}{c_1^2}} \\ q_r(x,y,z) = \dfrac{6\sqrt{3} f_r Q}{a \cdot b \cdot c_2 \pi \sqrt{\pi}} e^{\frac{-3x^2}{a^2}} e^{\frac{-3y^2}{b^2}} e^{\frac{-3z^2}{c_2^2}} \end{cases} \quad (1)$$

where, $Q=\eta \cdot U \cdot I$. η=0.8 is the heat source efficiency, U=31V is the voltage of electric arc, I=310A is the current of electric arc (averaged values from Table 2 of Part I [18]) and $a=0.005$, $b=0.010$, c_1=0.010, c_2=0.020 are ellipsoidal parameters [20]. As it is required to define this double ellipsoidal model along all welding paths, a FORTRAN program was written so that the heat source movement was defined automatically during the modeling process.

Note that since the 3D fully coupled thermal-stress analysis does not directly model the change in microstructure transformation near the fusion zone of the welding, in the numerical model, the characteristic length of the fusion zone could only be estimated by recording the peak temperature attended during the simulation. Towards this end, it was found that retrieving and analyzing the temperature history of the 3D joint model was a very complex and computationally expensive task. Hence, in this study, the previous results obtained from a similar plate-to-plate welding model [15, 16] in which the same batch of HSS plates were used but with a much simpler welding geometry were reused.

2.3 Modeling of thermal interactions

During fusion welding when the weld filler is added, heat energy dissipates into the air through convection and radiation on the contact surfaces between the specimen and the air. Obviously, these thermal dissipation contact surfaces changes as welding is going on. However, in 3D modeling, to update all thermal dissipation contact surfaces exactly in every time step and including such updates in every thermal interaction analysis step will make the modeling operation computationally expensive. Hence, in the present study two different approaches for defining the thermal dissipation contact surfaces were employed. When welding simulation was performed for the box sections fabrication, the free surfaces of the boxes were assumed to undergo thermal convection and radiation. The free surfaces in this case include all surfaces from which the heat can dissipate into the air except the front free surface of the existing welding (Fig. 4). Such simplified approach was used as the area of the front free surface of the existing welding is much smaller (less than 1%) than the total free surface area so that the heat loss through it can be ignored. In addition, during the modeling of the box sections fabrication process, the weld length that required to be modeled is rather long (900mm×4 sides + 300mm×4 sides) so that much computational effort could be saved by ignoring the front free surface of the existing welding. On the other hand, during the modeling of the joint fabrication process, a more exact procedure was adopted. Since the weld length for the joint is shorter (200mm×4 sides), the computational cost needed is less but the residual stress results there are more important. Therefore, during the modeling of the joint fabrication process, all thermal dissipation contact surfaces with air, including those front free surfaces of the existing welding, were updated during every thermal interaction analysis step.

2.4 Modeling of arc torch movement

It is mentioned in Part 1 [18], the flux-cored arc welding (FCAW) method was used in the fabrication of both specimens. During welding, the arc torch moving speed was controlled by the welder, which made the welding speed to be slightly non-uniform especially when the arc torch was turning around in the corners of the joint. The welding speed was reduced to obtain full penetration and good weld quality. In another word, the heat input per unit length was not uniform in the joint welding process which consists of four corners and some adjustments of the welding speed are needed in the numerical model. Fig. 5 shows the relationship between the welding speed adopted in the numerical analysis and the location around the joint. The overall average welding speed adopted is 2.8mm/s, which was obtained by dividing the total weld length by the measured welding time for completing one weld pass round the joint. To distinguish the welding speed at different locations, a scale factor ω=1.06 was applied so that the welding speed along the sides of the joint was 1.06×2.8=3.0mm/s. While ω=0.85 was applied at the four corners so that the welding speed at the corners was 0.85×2.8=2.4mm/s. Note that these welding speeds are estimated by using the actual welding times for the sides and corner measured in the experimental study.

2.5 Temperature dependents material properties and finite element mesh

In order to conduct a 3D fully coupled thermal-stress analysis, temperature (*T*) dependents parameters of the RQT701 HSS plate including the thermal properties (the specific heat $c(T)$, the thermal conductivity $k(T)$ and the thermal expansion coefficient $\alpha(T)$) and the material properties (the material mass density $\rho(T)$, the Young's modulus $E(T)$, the Passion ratio $\nu(T)$, the yield strength $f_y(T)$) are essential inputs. In this study, the thermal properties $c(T)$, $k(T)$ and $\alpha(T)$ were obtained from the Eurocode 3 Part 1-2 [15,21] and their detailed plots can be found in Fig. 3 of [15]. For the material properties, measured values obtained from Part I in the experimental study were used (Table 1 of [18]).

Fig. 6 shows the finite element mesh used in the numerical modeling. Note that the size of the finite elements and their grading shown in Fig. 6 are largely deduced based on the previous study related to the residual stress of plate-to-plate joint s [15,16]. In addition, before the final modelling procedure was confirmed and adopted, a few rounds of preliminary modelling trials were conducted in which several different mesh densities and configurations were used in order to access and comparing the accuracy of the modelling and the computational cost incurred. Therefore, the final mesh shown in Fig. 6 in fact, could be considered as a reasonably optimized configuration in the sense that a good balance in accuracy of the model and the computational cost incurred was achieved. The DC3D8 and the DC3D4 elements available in ABAQUS [19] were chosen to obtain a compatible mesh for the whole joint including all welding profiles and the backing plates used in the box sections fabrication. In the actual fabrication process of the box sections, the backing plates were only spot welded to the HSS plates and were not fully attached into them [18]. Fig. 7 shows the modeling details near a corner of the box section. Since only spot welding was used, the areas M_1-M_2 and M_3-M_4 were not fully smeared and there exist a small gap between the adjacent surfaces. While the area M_2-M_3 was completely fused together after welding. However, in order to simplify the model and maintain numerical stability, the areas M_1-M_2, M_2-M_3 and M_3-M_4 were all treated as fully smeared with the HSS plates.

The whole 3D fully coupled thermal-stress analysis procedure for the HSS box section T-joints is summarized in Fig. 8.

3 PURE HEAT TRANSFER ANALYSIS DUE TO NATURAL COOLING

3.1 Natural cooling after preheating

In the previous study on residual stress of preheated HSS plate-to-plate Y-joints [15,16], a uniformly distributed preheating temperature field was assigned to the preheated areas. Such practice is acceptable for the small size HSS plate-to-plate Y-joint with welding length of 150mm only. However, due to the complex joint configuration of the HSS box section T-joint, there always exists a small time gap (up to 2 minutes, depends on the performance of the welder) between the preheating step and the beginning of the joint welding. Hence, by the time when joint welding is started, some natural cooling must be occurred. Therefore, the effects of natural cooling should be evaluated in order to justify the use of a uniform preheating temperature field in the numerical models. As a result, a simple pure heat transfer analysis was carried out to predict the temperature distribution of the preheated specimen by the time joint welding is started. Note that in this natural cooling analysis, no stress analysis was conducted and a uniform preheating temperature field of 100°C was applied to the *whole* joint for the reasons that (i) the preheating temperature is much lower than the maximum temperature attended in welding (≈1800°C) and (ii) the joint is largely unconstrained. As before the welding is started, only spot welds had been conducted to temporarily fix the brace section on the top chord plate. Furthermore, the same mesh shown in Fig. 6 for the 3D fully coupled analysis was again employed for the natural cooling analysis but with all the elements corresponding to the welding profile deactivated.

3.2 Results of natural cooling analysis

The temperature distributions at four selected heat propagation times (1s, 2mins, 5mins and 10mins) after preheating were extracted from the numerical modeling results and shown in Fig. 9. Fig. 9(b) shows that after 2 minutes, the maximum temperature (locate at the corners of the brace box) and the minimum temperature (locate at middle of plate width of the chord box) are 93.4°C and 91.1°C, respectively. After 5 minutes (Fig. 9(c)), the maximum and minimum temperatures were dropped to 82.3°C and 79.0°C, respectively. At 10 minutes (Fig. 9(d)), the maximum and minimum temperatures were further dropped to 69.8°C and 66.4°C, respectively. Fig. 9 shows that the natural cooling rates at different parts of the joint are not constant and the temperatures at the chord weld toe are higher along the two sides parallel to the chord length (sides B1 and B3 in Fig. 5) than the other two sides (sides B2 and B4). Fig. 9 also indicates that if the time gap between the end of preheating to the beginning of joint welding is less than 2 minutes, nature cooling does not have much influence on preheating. However, if the time gap is longer than 5 minutes, then the effect of natural cooling should be included during modeling. As in actual fabrication, the welder was able to start joint welding within 2 minutes after preheating, the effects of natural cooling was ignored and a uniform preheating temperature field was employed during the analysis of the preheated specimen.

4. 3D FULLY COUPLED THERMAL-STRESS ANALYSIS

4.1 Validation of numerical model

In order to validate the accuracy of the 3D fully coupled thermal-stress analysis procedure, the residual stress predicted by the model at the 24 measurement points selected in the experimental study (Fig. 5) around the chord weld toe were extracted and compared with the experimental measurements. Note that in the experimental study, residual stresses were measured at distances of 10mm or 15mm from the chord weld toe and therefore the same locations were chosen from the numerical modeling.

Fig. 10 compares the transverse residual stress (perpendicular to the chord weld toe, Fig. 8 of [18]) obtained from the numerical modeling and from experimental study for the preheated specimen. Note that in Fig. 10, Points 1, 8, 14 and 20 are corresponding to the starting and stopping positions of the actual welding. It can be found that except at Point 10 and Point 22, which are respectively near corners *b* and *d*, most results agreed well between the modeling and the measurements. The differences between the modeling and measurement values at Point 10 (*Corner b*) and Point 22 (*Corner d*) are respectively 71MPa and 149MPa. For other points, the differences between the modeling and measurements are all within 50MPa. Considering the welder's difficulties to maintain a constant welding speed at the four *corners a, b, c,* and *d* and the non-uniform preheating and natural cooling effects, it is believed that such results are acceptable. In general, since a small radius has to be followed for welding at the corners, welding speed must be reduced in order to obtain full penetration weld profile. This means the heat energy input per unit length will be increased at the corners and higher residual stress should be generated there. This fact is shown in Fig. 10 and therefore the numerical model successfully captured the changes of residual stress between the straight sides and the corners. However, since in practice it is more difficult for the welder to maintain a constant welding speed near the corners than along the straight sides, it is reasonable to expect that higher relative error should appear near the corners of the joint. Similar results can also be seen in Fig. 11 that compares the results for the ambient temperature specimen. Good agreements between modeling and experimental results were obtained at most of points, except near Point 10 (*corner b*) and Point 14 (*corner c*), respectively.

4.2 Temperature history of specimens

After some detailed investigations, it is found that while there are some consistent differences in terms of the *magnitudes* of the temperature achieved by the preheated specimen and the ambient temperature specimen, the temperature *distributions* for both specimens are quite similar. This can be explained by the fact that the preheating temperature (100°C) is much lower than the maximum temperature attained during welding (1800°C). Since the temperature distributions for the two specimens are similar at the same propagation time, only the results from the ambient temperature joint are discussed in details (Fig. 12). By following the actual welding procedure, the arc torch was first moved from one end of the chord box to the other end (Fig. 12(a) to Fig. 12(c)). Note that in Fig. 12(a) to 12(c) all the elements belong to the brace section were deactivated, since they were not involved in the chord formation process. After the chord was formed, the welding arc torch was moved to the brace (Fig. 12(d)) and all chord elements were deactivated temporarily. After the brace box section was formed, all chord and brace elements were activated. As the heat source was adding along the joint (Fig. 12(e)), elements along the weld profile were activated progressively. The final temperature field of the whole joint model after cool down is shown in Fig. 12(f).

5 SMALL SCALE PARAMETRIC STUDY

5.1 Ranges of the parametric study

In this section, after the accuracy of the numerical model was validated, a small scale parametric study was carried out to investigate the influence of different welding and geometrical parameters on the residual stress field. A total of 162 3D models were created to investigate the effects of the following parameters:

(*i*) the joint angle α (Fig. 13),

(*ii*) the starting point of joint welding (Fig. 14),

(*iii*) the preheating temperature,

(*iv*) the brace width (D_b) to the chord width (D_c) ratio D_b/D_c (Fig. 2), and

(*v*) the welding speed (Fig. 5).

Note that for the starting point of joint welding, two cases were selected for study. In Case 1, welding was started near corner *a* (Point 1 in Fig. 14) while in Case 2 welding was started at the middle of side B4 (Point 24 in Fig. 14). Case 1 is actually corresponding to the actual welding employed in the experimental study. In both cases, welding was conducted in a clockwise manner. The ranges and values of the parameters selected are listed in Table 1. All models were created and run by using workstations equipped a 3 GHz Intel Core 2 Quad CPU and 8Gb memory. For each model, the computational time needed to complete the whole simulation (from preheating, box sections fabrication to joint welding and cool down) was approximately 30 hours. In order to define all cases of the parametric study in an effective manner, a specially written Python scripting was used (Fig. 8).

5.2 Parametric study results

In order to present the results obtained from the small scale parametric study systemically, the 162 analyses results obtained are divided into six groups. Each group will focus on the variations of the residual stress with respect to two parameters.

5.2.1 Variations of the residual stress with respect to α and the starting point of joint welding

The variations of the residual stress for HSS box joints with D_b/D_c=0.66 that are welded at ambient temperature and a welding speed of 2.8mm/s were studied by varying the joint angle (α=90°,120°,135°) and the starting point of joint welding. Figs. 15 and 16 show the residual stress at the 24 selected monitoring points for the 90° and the 135° joints, respectively. The results for α=120° are found to be in between the 90° and 135° joints and therefore are not shown. It can be observed that, for both joints, when Point 24 (Case 2) is chosen as the starting point of joint welding, a lower residual stress can be found from Point 1 to Point 4 (near the starting point for Case 2). However, for both Cases 1 and 2, there is no obvious difference for the residual stress from Point 5 to Point 24. Furthermore, by comparing Fig. 15 with Fig. 16, it can be observed that the highest residual stress appeared at the 135° joint near corner *b*.

5.2.2 Variations of the residual stress with respective to α and preheating

Fig. 17 compares the transverse residual stress for three joints welded at ambient temperature with different joint angles. It can be observed that for different α the highest residual stress along the chord weld toe (Points 7 to 9) increases as α increases. This phenomenon can be ascribed to the influence of weld size and cooling rate in the welding process [15, 17]. When the joint angle was changed, the weld leg length and the amount of welder filling added from Point 8 to Point 16 (side B2) and Point 20 to Point 4 (side B4) were changed according to the full penetration welding requirements of the American Welding Society welding standard [22]. Fig. 18 compares the transverse residual stress for three joints welded at a preheated temperature of 100°C. Similar to Fig. 17, the residual stress from Point 7 to Point 9 for the 135° joint is higher than that from the 90° and 120° joints. Furthermore, by comparing Figs. 17 and 18, the beneficial effect of preheating can be observed. For joints with different α, the maximum residual stresses of the preheated joints are lower than those of the ambient temperature joints. Furthermore, detailed analyses show that the results obtained from the joints preheated to 200°C are similar to that show in Fig. 18. This implies that any *further* reduction of transverse residual stress by increasing the preheating temperature from 100°C to 200°C is small.

5.2.3 Variations of the residual stress with respect to D_b/D_c and preheating

Fig. 19 compares the transverse residual stress from joints with different D_b/D_c. Fig. 19 shows that when D_b/D_c was reduced from 0.67 to 0.5 and then 0.33, while no obvious change is observed from Point 22 to Point 2 (side B4) and from Point 10 to 14 (side B2), the residual stresses from Point 4 to Point 8 (side B1) and from Point 16 to Point 20 (side B3) are increased significantly. It means that when the distance between the welding along the chord box section and the joint weld toe along sides B1 and B3 is close enough (less than 40mm for the case of D_b/D_c=0.67), interference of the two residual stress fields could be occurred. The net outcome is a reduction of the transverse residual stress along the chord weld toe for sides B1 and B3. This outcome was actually observed in the experimental study (Section 4.2 of Part I [18]) so that despite the same welding conditions, the residual stress along sides B1 and B3 are lower than that along sides B2 and B4. However, such interference disappeared when the difference between the chord and brace width was increased as shown in the curves for D_b/D_c=0.5 and 0.33. Such residual stress interference effect is also demonstrated in Fig. 20 for preheated joints which shows that while there was an overall reduction of residual stress due to preheating, the residual stresses along sides B1 and B3 show a obvious drop for the joint with D_b/D_c=0.67 only.

5.2.4 Variations of the residual stress with respect to D_b/D_c and the starting point of joint welding

Fig. 21 compares the transverse residual stress distributions of joints with D_b/D_c*=0.5* for different starting points of joint welding. It shows that when the starting point is near the middle of the brace, there is a decrease in transverse residual stress from Point 1 to Point 3. However, for the other points there is no obvious difference between the two curves except at Point 9 (corner *b*). Similar conclusion can be drawn from Fig. 22 for joints with $D_b/D_c=0.33$. Furthermore, from Figs. 21 and 22 and other plots obtained for joints with $D_b/D_c=0.67$ and similar study of preheated joints (which are not shown here for simplicity), it can be concluded that the starting point of joint welding only has relatively minor effects on the transverse residual stress distribution.

5.2.5 Variations of the residual stress with respect to welding speed and preheating

Fig. 23 and 24 compares the transverse residual stress around the chord weld toe for joints welded with different welding speeds. It can be observed that higher welding speed can effectively reduce the magnitude of residual stress and this agreed well with the experimental results. When the welding speed was increased from 2.8mm/s to 3.6mm/s, the reductions of residual stress at many points (e.g. Point 9 in Fig. 23) are larger than 100MPa. However, when the welding speed was increased from 3.6mm/s to 4.2mm/s, the reduction of transverse residual stress is marginal. Such beneficial effect of high welding speed could be explained by the fact that under a constant arc voltage and current, increasing the welding speed implies a reduction of heat input which eventually leads to reduction of residual stress. However, a too fast welding speed at the same time may bring in welding defects such as appearance of gas holes, incomplete penetration and insufficient penetration ratio. Thus, how to maintain the quality of welding while increasing the welding speed may post a great challenge to the welding technology development.

5.2.6 Variations of the residual stress with respect to welding speed and D_b/D_c

Fig. 25 compares the transverse residual stress distributions for joints with D_b/D_c=0.5 welded at different welding speeds. Similar to the pervious discussion on welding speed, it is more effective to reduce the residual stress by increasing the welding speed from 2.8m/s to 3.6m/s than from 3.6m/s to 4.2m/s. Fig. 26 compares the transverse residual stress for joint with D_b/D_c=0.33. It can be seen that for the highest welding speed of 4.2m/s, the transverse residual stress distribution around the chord weld toe is smoothened so that while the residual stresses at corners are still higher than that along the four sides, the differences are much reduced when comparing with the case when the welding speed is 2.8 m/s and D_b/D_c=0.67 (Fig. 19). This observation can be explained by the combine effects of heat input and residual stress interference. For a joint with D_b/D_c=0.67 and welded at the slowest speed, the residual stress near the corners are *increased* due to increase in heat input while the residual stress along sides B1 and B3 are *reduced* by residual stress interference (Section 5.2.3) and a highly uneven residual stress distribution is formed. However, for a joint with D_b/D_c=0.33 and welded at the highest speed, the residual stress near the corners are *reduced* while the residual stress along sides B1 and B3 are *increased* due to the absence of stress interference and thus resulted in a more even distribution.

6 CONCLUSIONS

In this paper, a 3D fully coupled thermal-stress modeling procedure for the prediction of residual stress along the chord weld toe of high strength steel box section T-joints is presented. Good agreements were obtained for the two benchmark models which are corresponding to the specimens investigated in the experimental study [18] and the procedure was found to be reliable for predicting the residual stress of the joints.

Besides thermal-stress analysis, pure heat transfer analysis of the preheated joint was also conducted. The analysis results show that cooling rates are not constant at different locations of the joint. After 10 minutes of natural cooling, the temperatures at the chord weld toe are higher along the two sides parallel to the chord length than the tow perpendicular sides. However, if the time gap between the end of preheating to the beginning of joint welding is less than 2 minutes, the natural cooling effect could be ignored.

A small scale parametric study was also carried out to evaluate the effects of the joint angle, the starting point of joint welding, the preheating temperature, the brace-to-chord width ratio and the welding speed on the distributions of welding residual stress. It is found that preheating and faster welding speed can both effectively reduce the magnitude of the residual stress at the weld toe while the starting point of joint welding and the intersection angles only have relatively minor effects. However, it is found that preheat beyond 100° and a welding speed faster than 3.6m/s did not further reduce the welding residual stress significantly. For the brace-to-chord width ratio, if the distance between the chord box section welding and the joint welding is close enough, interference of residual stresses generated could reduce the welding residual stress along the chord weld toe along the sides parallel to the edges of the chord box section.

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