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3D Residual stress modeling of welded high strength steel plate-to-plate joints

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Abstract
A numerical investigation on the residual stress distributions near the weld toe of plate-to-plate Y-joints fabricated by using high strength steel (HSS) plate is carried out in this study. A fully 3D sequentially coupled thermal-mechanical modelling procedure is employed for residual stress analysis for the HSS plate-to-plate joints. Two specimens respectively fabricated by welding at ambient temperature and at a preheating temperature of 100°C are investigated. The 3D numerical models reveal that while high tensile transverse residual stress, which is perpendicular to the weld, is generated near the weld toe of the joint middle section, proper preheating could significantly reduce the magnitude of the residual stress. In addition, it is found that the welding direction between successive weld pass could also affect the maximum residual stress value near the chord weld toe.

Keywords: High strength steel plate-to-plate Y-joints, residual stress, Full 3D fully 3D sequentially coupled thermal-mechanical modelling
1. Introduction

In civil engineering applications, the effects of residual stress distribution are currently not explicitly taken into account in the design of HSS plate-to-plate joint. However, as more and more HSS joints with thicker plate thickness are used in structures with very high loading capacity demand, research in this area recently received much attention. In general, the effect of residual stress on the performance of HSS plate-to-plate joint could be studied either experimentally or numerically. Comparing with experimental investigation, finite element modeling is an alternative powerful tool to investigate the formation process and the distribution of the residual stress with many merits, such as cost and time savings and easy to carry out parametric study. In the past few decades, significant amount of progress on welding residual stress modelling was made. Most successful modelling investigations on the residual stress are based on sequentially-coupled analysis, which is organized in two separate steps. The thermal analysis is performed at the first step so that the temperature field is obtained. After that, the mechanical analysis is performed by importing the temperature field as the thermal loading. Up to now, 2D models are still dominating the published works and this can be ascribed to the fact that 3D modelling needs a lot more amount of computational efforts to obtain the modelling results. Furthermore, most of current 2D models are based on plane strain conditions. It means that a thin slice perpendicular to the motion of the welding heat input source is modelled while the longitudinal deformation is ignored in the analyses.
To capture a more complete view of welding-caused residual stress in structures, some researchers made efforts on 3D numerical modelling. The work explored by Lindgren and Karlsson [1], who used shell elements to model a thin-walled pipe, was a pioneer work in the 3D residual stress simulation. Compared with 2D models, 3D models could give more accurate results of the residual stress field as 3D models can include all strains and stress components. Ueda et al. [2-4] explored the use of the 3D modelling in residual stress analysis for a pipe-plate joint. Wu et al. [5] described the welding modelling procedure for 3D T-joint. They created the 3D model as the reference model and established 2D models to perform parametric studies. One complication of the 3D residual stress modelling is the simulation for multi-pass welding, which is frequently a standard procedure used in the practice. In order to reduce the computational efforts for modelling of multi-pass welding procedure, the lumping technique is frequently used. Ueda et al. [3] firstly studied the multi-pass welding. The weld passes were lumped into different numbers of blocks. It was concluded that the lumping method is an effective way to get an accurate result. In addition, Rybichi et al. [6-7], Free and Porter Goff [8], Brickstad and Josefson [9] and Hong et al. [10] also tried different lumping skills in their models.

The other complication of the residual stress modelling is the addition of filler material. Two methods are commonly employed to handle this problem. The first way is to include the whole structure in the computation model and the weld filler material that has not been laid is also included at the beginning. However, the elements corresponding to the weld filler material that has not been laid yet are set with
reduced material properties to eliminate the influence of those elements on the rest of the model. Those elements corresponding to the weld filler material that has not been laid yet are often called “quite element” [9]. Rybichi et al. [6-7], Brust and Rybichi [11], Michaleris [12] used this approach in their models. The second way to handle is to redefine the model as the welding process was carried on. The elements corresponding to the weld that has not been laid yet are excluded in the analysis at the beginning and they are nominated as “inactive element”. It is commented as a more accurate method but it requires special algorithms to be implemented in the finite element package. Furthermore, in many cases in order to complete the whole modelling procedure, user interactions are required when a new weld pass is added. Jang et al. [13], Lee et al. [14], Acevedo et al. [15], Lee et al. [16-17], Jiang and Zhao [18], Payne and Porter-Goff [19] and Teng et al. [20] have conducted both modelling developments using this approach as well as experimental studies of residual stress distributions in welded joints.

In this paper, in order to obtain a better understanding of the transverse residual stress, which is generated during the welding process and perpendicular to the weld toe, a 3D numerical investigation on the residual stress distributions near the weld toe of Y-joints fabricated by using high strength steel (HSS) with yielding stress of 690MPa plate-to-plate is carried out. A full 3D sequentially coupled thermal-mechanical modelling procedure was employed for residual stress analysis for the HSS plate-to-plate joints. Two specimens, corresponding to welding preformed at ambient temperature and at a preheating temperature of 100°C, are investigated. The results
obtained from the 3D numerical modelling is first verified against experimental results [16, 17] before detailed presentation of the residual stress distributions of the joints are given. It should also be remarked that while the residual stresses in the weld heel could also be important, attention of this paper is only focused on the study of residual stresses at the weld toe. As in general, when subjected to external loadings, the stress concentration factor of the joint in the weld heel is generally lower than that at the weld toe so that the effects of residual stresses in the weld heel are not as critical as those at the weld toe. In addition, due to the limitation of the experimental method used in this study, it is not easily to directly measure the residual stress in the weld heel.

2. Specimen description

Two plate-to-plate Y joints, made of high strength steel with minimum yielding stress of 690MPa, were fabricated by shielded metal arc welding (SMAW). Fig. 1 shows the geometry of the joints. The high strength steel RQT701 plates, which were supplied by the Corus Group, is made of quenched and tempered structural steel with improved forming and welding performance by substituting some alloying element with carbon [16]. In the process of welding, an ultra low hydrogen and moisture resistant type covered LB-70L, which is equivalent to the class ASME/AWS A5.5 E10016-G [21] and supplied by Kobelco of Japan, was employed. The welding procedure was carried out according to the AWS D1.1 2008 standard [22]. In the process of preheating, the
area close to where the weld filler was added (Fig. 2) was heated up to 100 °C. Temperature chalk was employed to ensure the preheating temperature was reached. As the width of both specimens is equal to 150mm, with an average welding speed of 2.6mm/s, the time interval between each weld pass is approximately equal to 58s. As a result, the temperature in the weld filler after finishing a weld pass was still higher than 100°C. Hence, preheating was only conducted before the first weld pass but was not repeated between successive passes.

3. The 3D Modelling procedure

3.1 Overview

In order to obtain in-depth understanding of the residual stress distribution along the joint width direction, full 3D models corresponding to the two joints, one welded at ambient temperature and the other one with preheating, are created. The sequentially thermal-mechanical coupled analysis method is used for the 3D models. A sequentially coupled thermal-stress analysis was conducted [23] by assuming that the stress solutions are dependent on the temperature fields while there is no inverse dependency. Sequentially coupled thermal-stress analysis was performed by first solving the non-linear transient heat transfer problem. The time-dependent temperature data were then fed into the stress analysis model as a predefined field. During the thermal analysis, it was assumed that the stress generated in welding has negligible influence on the temperature field. Furthermore, the heat convection and radiation effects were both considered in the modelling.
3.2 The heat source model

Since the temperature field driven by the weld heat source is the dominant driving force for residual stress formation during the welding procedure, an accurate analysis of the thermal cycle is required to obtain accurate prediction of residual stress. Furthermore, the heating source is also the driving force for phase transformation, thermal strain and stress, and eventually residual stress formation. For the mathematical modelling of thermal cycles, it can be traced back to in the late 1930s when Rosenthal [24] firstly applied the Fourier law into moving heat sources. However, the main shortcoming of this solution is the misfit of temperature field near the fusion and heat-affected zones. To accurately capture the temperature near the arc, Pavelic et al. [25] mentioned that the heat source should be distributed and proposed a Gaussian distribution of heat flux deposited on the surface of the work piece. Considering that the temperature gradient in front of the heat source is different from in the rear, a double ellipsoidal model of power density distribution was introduced by Goldak [26]. In the double ellipsoidal model (Fig. 3), the front half of the source is the quadrant of one ellipsoidal source and the rear half is the quadrant of another ellipsoid. To define the model, the fractions \( f_f \) and \( f_r \) of the heat deposited in the front and rear quadrants are needed such that of \( f_f + f_r = 2 \). It was recommended by Goldak [26] that \( f_f \) and \( f_r \) should be set as 0.6 and 1.4, respectively. The power density distributions inside the front quadrant and the rear quadrant can be expressed as:
\[
\begin{align*}
q_f(x, y, z) &= \frac{6\sqrt{3} f_f Q}{a \cdot b \cdot c_\eta \pi \sqrt{\pi}} e^{-\frac{a^2}{a^2}} e^{-\frac{b^2}{b^2}} e^{-\frac{c_\eta^2}{c_\eta^2}} \\
q_r(x, y, z) &= \frac{6\sqrt{3} f_f Q}{a \cdot b \cdot c_\eta \pi \sqrt{\pi}} e^{-\frac{a^2}{a^2}} e^{-\frac{b^2}{b^2}} e^{-\frac{c_\eta^2}{c_\eta^2}}
\end{align*}
\]

where, \( Q = \eta \cdot U \cdot I \), \( \eta \) is the heat source efficiency, \( U \) is the voltage of electric arc, \( I \) is the current of electric arc and \( a, b, c_1, c_2 \) are ellipsoidal parameters.

In the current analysis, the double ellipsoidal model is employed to predict the thermal and stress field during the welding. In order to automatically renew the weld filler elements as the welding process was carried out, a special FORTRAN program is developed to describe the moving of the heat source. In the absence of better data, experience suggests that it is reasonable to take the distance in front of the heat source equal to one half of the weld width and the distance behind the heat source equal to twice the width [25]. In the current analysis, in order to achieve such conditions, it is assumed that \( a=0.005, b=0.010, c_1=0.010 \) and \( c_2=0.020 \). The arc voltage is assumed to be \( U=26V \) and while the arc current \( I=170A \). The welding speed is 2.6mm/s.

During the coupled modelling process, both the convection and radiation effects are considered in the modelling of the heat loss on the surface of the joints. The convection coefficient \( h \) is defined as 15 W/m²K and emissivity \( \varepsilon \) is set as 0.2. The thermal and mechanical properties used in the study are from references [16-17].

3.3 The weld filler adding process

Fig. 4 shows the welding sequence and directions adopted during actual fabrication of the HSS plate-to-plate joints. Since the lumping technique [16-17] is employed to reduce the computational cost for the 3D modelling, the modelling of the welding
sequence and direction need to be simplified correspondingly. During the fabrication of HSS plate-to-plate joints, a new pass was started from the end position of the previous weld pass and then went in the reverse direction to the previous weld pass (i.e. the weld pass started from the LHS end to the RHS end and then went back from the RHS end to the LHS end). Considering that the second weld passes could have been added in the same direction along joint width (i.e. the weld pass started from the LHS end to the RHS end and then re-started from LHS end again), the effects of welding direction will be studied in this study. In order to predict the residual stress results accurately, the best modelling procedure is to follow exactly the multi-pass welding sequences (i.e. complete modelling of all 14 passes shown in Fig. 4). However, this approach requires the simulation for all the weld passes one by one according to their welding sequences and directions and requires very high computational cost. Hence, in this study, the whole weld process is divided into two lumps only (Fig. 5). In order to analyze the influence of welding direction on the final residual stress field, two cases with different welding directions are studied. The first case (Case 1) is corresponding to a joint in which both weld passes start from the LHS end while the second case (Case 2) is corresponding to a joint in which the first lump starts from the LHS end and the second lump starts from the RHS end, (Fig. 5). It should be mentioned that Case 2 could be considered equivalent to the actual welding direction adopted during the fabrication of the joint.

The meshing and the welding filler adding process is shown in Fig. 6. The element “birth and death” technique [16-17] is used to simulate the weld filler adding process.
During the simulation, the weld filler elements are divided into 5 sets along the plate width for each weld lump and they are reactivated sequentially at the corresponding analysis steps. Hence, for Case 1 and Case 2, the whole weld filler is reactivated in 10 analysis steps. During the welding filler adding process, the convection and radiation surfaces are renewed and updated for each step because when a new set of weld filler is added, the area of the contact surface with air is changed and are updated accordingly.

Fig. 7(a) shows the moment when the first group of weld filler elements is activated. At this moment, the elements corresponding to the weld filler material are activated and the heat source starts to move along the arc torch travelling path. Fig. 7(b) shows the activated elements at the time when the 1st lump of weld is fully added. The centre heat source at this moment moves to the other end of chord plate width. From the temperature contour, it can be observed that as the distance from the heat source centre goes further, the temperature drops quickly. Fig. 7(c) shows the moment when the first group of elements of the 2nd lump of weld is activated. Fig. 7(d) shows the case when all elements that corresponding to the weld filler material are activated.

4. Modelling validation and results

4.1 Model validation

The 3D modelling results are validated in this section by comparing with the testing results and the 2D modelling results that are obtained in the previous study [16-17]. Figs. 8 and 9 compare the 3D modelling results with the 2D modelling results and the
test results. As shown in Fig. 8, for the joint that was welded with preheating, the 3D transverse residual stress at the chord weld toe of the joint middle section corresponding to the welding Case 1 and Case 2 is equal to 243.6MPa and 164MPa, respectively. While from the 2D result modelling results [17], the transverse residual stress at the same location is 229.3MPa. Note that the test results of residual stress are only available at 5mm, 20mm and 35mm positions from the chord weld toe due to the limitation of the measurement procedure [16]. For these three points, the 3D modelling results seem to agree well with test results. In particular the weld direction Case 2 seems to give results closer to the test results while Case 1 generally gives higher residual stress values. It is expected as welding direction Case 2 is corresponding to the actual welding direction adopted in the fabrication. Similar findings can be obtained from Fig. 9 for the joint welded in preheating temperature. It should be mentioned that since the current experimental set up does not allow detailed measurements of residual stress distributions at locations that are very close (<3mm) to the weld toe of the joint, the above validations are based on the limited data available in this study and from references [16] and [17]. However, despite being subjected to these limitations, it is believed that the conclusions and discussions given in the subsequence sections are generally correct.

4.2 3D modelling results for the ambient temperature joint results

The final distribution of the residual stress field for ambient temperature joint is present in this section. Fig. 10(a) shows the transverse residual stress distribution in
the joint when it is fully cooled down to room temperature corresponding to the welding direction Case 1. Note that for the simplicity of presentation, results of welding direction Case 2 is not shown in here. Since it is found that except a slightly lower magnitude of the residual stress is obtained, the resulted residual stress distributions for Case 2 are very similar to that of Case 1. It can be seen that the transverse residual stress is highly localized near the weld and when the distance from the weld is beyond 50mm, the magnitude of the transverse residual stress is close to zero, which agrees with the observation in the testing. It can also be observed that at both the chord width ends (i.e., at the LHS section and the RHS section of Fig. 10a) compressive residual stress appears at the top surface of the chord plate. In contrast, high tensile residual stress turns out in the middle of the chord width.

Fig. 10(c) to Fig. 10(e) gives the transverse residual stress distributions at selected cross sections of the joint. Fig. 10(b) shows the transverse residual stress at the cross section obtained by cutting the joint along the welding path, i.e., along the Section A-A’ of the chord plate at the weld toe. At this cross section, high tensile residual stress exists at the middle section along the width direction while compressive residual stress appears at the LHS and the RHS ends. For the residual stress variation in the depth direction, a layered distribution of residual stress can be found at this cross section. The maximum tensile residual stress appears at the top surface of the chord plate and the residual stress decreases as the depth increase. Fig. 10(c) to Fig. 10(e) show similar distributions of the transverse residual stress in the regions immediately under the weld toe. However, different from the two ends, the part near
the middle section under the weld toe shows high tensile residual stress on the top surface of the chord plate.

Fig. 11 shows the variation of the transverse residual stress variations with the distance from the chord weld toe for the welding direction for Case1. Three cross sections corresponding to the LHS end, the RHS end and the middle section of the joint are selected to show the relationship between the magnitude of residual stress and the distance from the chord weld toe. It can be observed that the magnitude of residual stress within 10mm is much higher than the other parts. With increase of distance, the magnitude of residual stress reduces quickly. When the distance is beyond 40mm, it almost fluctuates near zero. The residual stress variations along the plate depth are shown in Fig. 12. It can be observed that the residual stress on the top surface is much higher than that near the bottom surface.

The transverse residual stress results for the welding direction Case 2 are shown at Fig. 13 and Fig. 14. Similar to Fig. 11 and Fig. 12, inverse relationship between the transverse residual stress and the chord weld toe and plate depth can be found. Finally, by comparing Fig. 11 with Fig. 13 and Fig. 12 and Fig. 14, it can be seen that in general, while the welding directions adopted between different weld passes could affect the final residual stress values and with Case 1 generally gives a higher value of residual stress, its effects on the residual stress distribution are relatively minor.

4.3 3D modelling results for the preheating joint results

Fig. 15 shows the final transverse residual stress distribution, which is perpendicular to the weld, for the preheated joint when welding direction Case 1 was employed.
Again, for simplicity, the distribution corresponding to the welding direction Case 2 is not included due to the similar final distribution. Fig. 15(b) shows the residual stress distribution for the Section $A-A'$ along the welding direction while Fig. 15(c) to Fig. 15(e) show the transverse residual stress at three selected cross sections (the LHS end, the middle section and the RHS end) of the chord plate. Similar to the joint welded at ambient temperature, compressive residual stress appears at the two ends of the plate (Fig. 15(c) for the LHS end and 15(e) for the RHS end). For the middle section of the joint (Fig. 15(d)), a layered distribution of residual stress can again be found at this cross section in the thickness direction. The maximum tensile residual stress appears at the top surface of the chord plate and decreases along the depth of the cross section and eventual compressive stress appear at the bottom.

Fig. 16 shows the variation of transverse residual stress with the distance from the chord weld toe for the welding direction Case 1. Three cross sections corresponding to the two ends and the middle section are selected to show the relationship between the magnitude of residual stress and the distance from the chord weld toe. Similar with joint welded at ambient temperature, inverse relationship between residual stress magnitude and distance can be found. The residual stress variations along plate depth are shown at Fig. 17. It can be observed that the residual stress at the top surface is much higher than that at the bottom surface. Similar conclusion can be also found in Fig. 18 and Fig. 19, which are shown for the transverse residual stress for the welding direction Case 2.
4.4 Comparison between ambient temperature joint and preheated joint results

Fig. 20 and Fig. 21 show the Von Mises residual stress distributions at the middle cross section of the joints fabricated at ambient temperature and preheating, respectively. Again, only results from welding direction Case 1 is shown as the results from Case 2 are similar. From Figs. 20 and 21, it can be seen that for both joints, the regions near the weld toe and weld root are already partially yielded at this position. But in the internal part of weld, the magnitude of Von Mises residual stress is much lower. For the chord plate far away from weld, the Von Mises residual stress is quite low (less than 50MPa). From Fig. 21, it can be seen that, comparing with the ambient temperature joint, the maximum residual stress is lower for the preheating joint. Note that the maximum Von Mises residual stress for preheating joint is 734.2MPa, whereas it is 872.8 MPa for the ambient temperature joint. In addition, the size of area of high stress gradient near the weld toe and root is reduced as a result of preheating.

In order to show the differences between the transverse residual stresses distributions of the two joints, Fig. 22 and Fig. 23 give the distributions of the transverse residual stress at the middle sections of the joints when they are cooled down to room temperature. Despite that similar distributions can be found for the two joints, noticeable residual stress differences can be observed. The maximum transverse residual stress for the ambient temperature joint and the preheated joint is equal to 293.6MPa (42.5% of the yield stress of the HSS used) and 239.3MPa (34.7% of the yield stress of the HSS used), respectively. Hence, preheating can effectively release part of residual stress for the HSS joint. Finally, Fig. 24 compares the differences
between the preheating and the ambient temperature joints for the two welding directions (Case 1 and Case 2). An obvious reduction of residual stress due to preheating can also be found for both Case 1 and Case 2 when compared with ambient temperature joint. Again, it can be seen that while the welding directions adopted between successive weld passes could affect the absolute magnitude of the residual stress, it only slightly affects the final residual stress distributions for both joints.

5. Conclusion

In this paper, a full 3D sequentially coupled thermal-stress analysis procedure for two HSS plate-to-plate welded joints is presented. By comparing with the test results which are obtained by the using hole-drilling technical at locations close to the weld toe of the HSS joints, the following general conclusions can be drawn:

(1) The element ‘birth and death’ is an effective way to simulate the addition of filler in the procedure of welding, the sequential coupled thermo-mechanical is also an acceptable way in the simulation of residual stress.

(2) Comparing with 2D modelling, in general, 3D modelling can give a better understanding of the residual stress distribution in the whole joint, especially at the different cross sections along joint width.

(3) The 3D model reconfirmed the earlier findings in 2D models [16, 17] that the magnitude of residual stress reduces quickly as the distance from the weld toe increases. Furthermore, the 3D modelling results also show that proper preheating
can significantly reduce the magnitude of the principle residual stress at the weld
toe.

(4) Finally, when weld filler is added in different directions between successive weld
passes, the absolute value of the final residual stress could be affected while it has
only a minor effect on the distribution of the residual stress.

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specimens is also appreciated
Reference:


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Figure 1: Geometry of the Y-joint
Figure 2: The preheating area
Figure 3: The double ellipsoidal heat source model and its local coordinate system
Figure 4 Welding direction of the HSS plate-to-plate joint

Note: *LHS*: left hand side, *RHS*: right hand side

- **Vertically outward from the paper** (from RHS to LHS)
- **Vertically inward to the paper** (from RHS to LHS)
Lumping scheme used in numerical modelling of the weld passes

Case 1: Same direction for both lumps

Case 2: Different directions for lumps 1 and 2

Figure 5: Modelling of the welding direction along joint width
Figure 6: Meshing scheme for the HSS plate-to-plate joint

Figure 7: The element “birth and death” technique used in the modelling, welding direction Case 1

(a). Start of adding weld filler elements
(b). The moment when the 1st lump is fully achieved
(c). The moment when the 2nd lump is started
(d). The moment when the final weld profile is obtained
Figure 8: Comparisons of 2D and 3D modelling results with test results at the middle section of the preheating joint (2D and test results are from references [16-17]).

Figure 9: Comparisons of 2D and 3D modelling results with test results at the middle section of the ambient temperature joint (2D and test results are from references [16-17]).
Figure 10: Transverse residual stress distribution for the ambient temperature joint, welding direction Case 1

Note: LHS: left-hand side, RHS: right-hand side, compressive stress is considered as negative
Figure 11: Transverse residual stress variation at different distances from weld toe for the ambient temperature joint, welding direction Case 1

Figure 12: Transverse residual stress variation at different depths for the ambient temperature joint, welding direction Case 1
Figure 13: Transverse residual stress variation at different distances from weld toe for the ambient temperature joint, welding direction Case 2

Figure 14: Transverse residual stress variation at different depths for the ambient temperature joint, welding direction Case 2
Figure 15: Transverse residual stress profile for preheated joint at the chord plate, welding direction Case 1

Note: LHS: left-hand side, RHS: right-hand side, compressive stress is considered as

(a) The transverse residual stress at the final state after cooled down

(b) The transverse residual stress at the weld toe (Section A-A')

(c) The LHS cross section of the chord plate

(d) The middle cross section of the chord plate

(e) The RHS cross section of the chord plate
Figure 16: Transverse residual stress variation at different distances from weld toe for the preheated joint, welding direction Case 1

Figure 17: Transverse residual stress variation at different depths for the preheated joint, welding direction Case 1
Figure 18: Transverse residual stress variation at different distances from weld toe for the preheated joint, welding direction Case 2

Figure 19: Transverse residual stress variation at different depths for the preheated joint, welding direction Case 2
Figure 20: Von Mises residual stress in the middle section of joint for the ambient temperature joint, welding direction Case 1

Figure 21: Von Mises residual stress in the middle section of the preheated joint, welding direction Case 1
Figure 22: Transverse residual stress at the middle section of the ambient temperature joint, welding direction Case 1

Figure 23: Transverse residual stress at the middle section of the preheated joint, welding direction Case 1
Figure 24: Transverse residual stress variation at different distances from weld toe