Finite element analysis of stress and distortion for welding reinforced structure of angular steel

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Abstract. A 3-D finite element model of residual stress and distortion in welded structure with square section for angle steel is developed based on thermal-elastic-plastic theory. The residual stress and deformation for welded structure under different conditions are calculated and their distribution characteristics are comparatively analyzed. Results show that, relatively larger stress is generated in and near the weld zone for the welded joint. With an increase in weld length, both equivalent stress and residual distortion increase accordingly, but the effect of weld length on welding residual stress is limited. Under the conditions of 20 mm, 50 mm and 100 mm long welds, the deformations of the three reinforced structures caused by 15000 Pa external load are 4.80mm, 4.79mm and 4.78mm respectively, indicating they have the similar bearing capacity.

Key words: Residual stress; distribution; structure with square section; numerical simulation.

1. Introduction

Angle steel welded structures with square section are widely used in electric power transmission, bridges construction, and shipbuilding industries. However, the residual stress and distortion generated in the welding process is harmful to joint performance, dimensional accuracy and the bearing capacity of structure, leading to quality problems of the structure [1]. Therefore, it is of great academic and engineering application values to study the stress and distortion in welding structure with square section for angle steel.

As for welding stress, the experimental method is mainly used to detect the stress at the specific position on the surface of weldement currently, but it is difficult to reveal the residual stress distribution in three dimension. In order to compensate for its deficiency, numerical simulation technology has been widely used to investigate the distribution characteristics of stress and distortion for welded components [2]. At present, researchers have conducted a large number of experimental [3] and simulation [4] studies on welding reinforced structure of angle steel. However, few works involves the welded structure with square section. In this paper, a suitable 3-D numerical analysis model is established to study the residual stress and distortion of welded structure with square section for angle steel, along with its bearing capacity under the lateral compressive load condition.
2. Numerical analysis
In this paper, based on thermal-elastic-plastic theory, a sequentially coupled thermo-mechanical FEM was developed to simulate the residual stress and welding deformation distribution in welding structure with square section for angle steel. First, the temperature distribution and its history in the welding model is computed, and then the temperature history is employed as a thermal load in the subsequent mechanical calculation of the residual stress field. In order to simplify the model and reduce the calculation time, in the process of thermal field analysis, the fluid flow in the molten pool is not considered, which means only the solid heat conduction equation is used to calculate the welding temperature field. The influence of the liquid metal in the molten pool on the thermal field was indirectly considered by appropriately improving the thermal conductivity of materials [6].

2.1. The heat source
Considering the calculation efficiency of large angle steel structure, a uniform volume piecewise heat source is used to characterize the welding heat input, which assumes that welding heat is uniformly distributed in a certain heating volume, and the heat flux distribution function is shown as follows:

\[ q = \frac{\eta UI}{V} \]  

Where \( \eta \) is the thermal efficiency; \( U \) is the welding voltage; \( I \) is the welding current; \( V \) is the volume of the heat source; These parameters are set according to the weld length and the cross-sectional area. In addition to heat source, the heat losses due to convection and radiation were also taken into account in thermal analysis, which are simulated using Newton’s law and Stefan-Boltzman law, respectively [5].

2.2. Finite element model
For welding reinforcement structure, the base metal is Q345. It contains two kinds of angle steel, which are L80×7mm, L100×8mm respectively. The whole length of the structure is 2000mm, and the welding conditions with 20mm, 50mm and 100mm weld bead lengths are considered respectively. The specific grid of the model is shown in Fig.1. To reduce the computing time in the case of enough numerical precision, an un-uniform mesh is employed in the calculation. A finer mesh is designed at the weld and its vicinity to obtain more accurate result, while a coarse mesh is applied at the region far away from the weld bead to improve the computational efficiency [6-7]. In the mechanical simulation, the elastic stress-strain relationship of welded material is assumed to obey the isotropic Hooke’s law with temperature-dependent Young’s modulus [8]. Thermal strain is taken into account through thermal expansion coefficient. Regarding the plastic behavior, a rate independent plastic model is applied. The yielding behavior of the welded material satisfies the von Mises principle, and a bi-linear hardening law is employed to simulate the strain hardening. Besides, similar to the thermal analysis, the temperature-dependent mechanical properties of materials are used in the mechanical model.

![Fig. 1](image-url)
3. Results and discussion

3.1. Analysis of stress

Fig. 2 presents the contours of von Mises equivalent stress distribution. It can be seen that the high residual stress is mainly generated in and near the weld zone, which is ascribed to the large temperature gradient along the direction perpendicular to weld bead in the is region. With distance from weld metal, the stress decreases rapidly owing to relatively small temperature gradient. When the weld length is 20mm, 50mm and 100mm, the equivalent stress peaks are 326MPa, 351MPa and 348MPa respectively. The latter two are only slightly higher than the former. But they are all closed to the yield stress of base metal, also demonstrating that the influence of the weld length on welding residual stress is minor. This is due to the fact that weld length cannot affect the temperature filed distribution in and near the weld pool significantly, especially for the case with the weld length greater than 20mm.
Similar to the distribution of residual stress of the component without load, the high residual stress under lateral loading of 15000Pa is also mainly concentrated in and near the weld zone, which can be seen in the contours shown in Fig.3. It is also found that under the action of this external load, the von Mises equivalent stress peaks for the three cases only increases slightly, which are 329Mpa, 352MPa and 355MPa respectively and are still close to the yield stress of base metal. Therefore, it is concluded that the residual stress of welding structures is affected slightly by the 15000Pa external load.

3.2. Analysis of distortion

Fig.4 shows the distortion distribution in welded structure under different welding conditions. It is revealed that, when the weld length takes 20mm, the largest deformation of the welded structure is 3.83mm. While increasing weld length to 50 mm, the biggest distortion of the structure has a minor growth, which is 5.33mm. Under the condition of 100mm long weld bead, the maximum deformation grows significantly, which reaches 11.61mm. The difference of maximum welding residual deformation
for the three cases can be observed more clearly by Fig. 4 (d). Besides, it can also be found in Fig. 4 (d) that the welded structures in the three conditions have the same deformation distribution trend, i.e., the displacement is zero on the restraint side, and it increases gradually from the fixed end to the free end, finally reaching maximum value.

![Fig. 5 Maximum deformations for the three cases under 15000Pa loading](image)

Fig. 5 gives the maximum deformations of the welding reinforcement structures caused by only the lateral loading of 15000Pa under the three conditions, which is irrelevant with the residual deformation. It is observed that for the conditions of 20mm, 50mm and 100mm long welds, the deformations of the welding structures are 4.80mm, 4.79mm and 4.78mm respectively. It shows that the deformation has no obvious difference under the effect to 15000 Pa external load, meaning that the length of weld bead has limited influence on the bearing capacity of welding reinforcement structure. Consequently, from an economic point of view point, the condition of 20mm long weld bead is appropriate for the application of the welded structure.

4. Conclusions
(1) A 3-D finite element model is developed to investigate the residual stress and distortion of square section welding structure, in which an efficient heat source was used to improve the computational efficiency.

(2) The high residual stress appears in the weld zone and its vicinity, and the residual stress decreases sharply with the distance away from the weld zone. The weld bead length has minor influence on the residual stress peak. But, when increasing weld length from 20 mm to 100 mm, the welding residual distortion has large growth.

(3) Under the action of 15000Pa lateral compressive load, the deformation of welded structure in three condition are similar, meaning the distortion resistance of that are close to each other. 20mm long weld bead can be used to the welding structure considering the efficiency and economical requirement.

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