Journal of Constructional Steel Research 102 (2014) 44–58

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

FEA of residual stress in cruciform welded joint of hollow sectional tubes

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ARTICLE INFO

Article history:
Received 20 September 2013
Accepted 27 June 2014
Available online 17 July 2014

Keywords:
Finite element analysis
Cruciform welded joint
Residual stress
X-ray diffraction

ABSTRACT

Welding is a joining process which is most widely used for permanent joining of two or more components. Welding results in a very complex thermal cycle which results in irreversible elastic plastic deformation and residual stresses in and around heat affected zone (HAZ). Residual stresses are produced in weldment due to mismatching and non-uniform distributions of plastic and thermal strains. The existence of residual stresses in structures affects the stress–strain relationship by lowering the proportional limit and thus reduces the buckling strength. The purpose of the present study is to investigate the residual stresses in heat affected zone of cruciform welded joint of hollow sectional tubes. To precisely capture the residual stresses, computational methodology based on three-dimensional finite element model for the simulation of gas metal arc welding in cruciform welded joint is presented. The complex phenomenon of welding is numerically solved by sequentially coupled transient, non-linear thermo-mechanical analysis. X-ray diffraction experimental method is used to validate the finite element model. The study further altered the welding parameters in order to reduce the residual stresses in the joint thereby improving the strength of the joint.

1. Introduction

Welding is a fabrication process in which two or more parts of same or different materials are joined. The process is carried out by melting the work pieces and adding a filler material to form a pool of molten material that cools to become a joint. Fusion welding is a method that involves a heat source, and often a filler material such as a consumable electrode or a wire fed into the weld pool. During the welding processes, residual stresses are produced in a structure as a consequence of local plastic deformations introduced by inhomogeneous temperatures, termed as thermal stresses, consisting of a rapid heating and subsequent cooling phase. During the welding process, the weld area is heated up sharply compared to the surrounding area and fused locally. The material expands as a result of being heated. This expansion is restrained by the surrounding cooler area, which gives rise to thermal stresses. The thermal strains become so high that stresses enter the strain hardening region. Consequently, the weld area is plastically hot-compressed and residual stresses are developed.

Residual stress values can be derived from strain/deformation measurements by different methods, broadly classified as destructive and non-destructive. X-ray diffraction is a non-destructive measurement method for measuring the residual stress in heat affected zone which develops during welding process. In this technique strain is determined directly from measurements of atomic lattice spacing. Stresses are then calculated from these strains.

Researchers have developed many techniques to predict welding residual stresses. Intelligent tools and techniques have been applied to predict residual stresses to meet the demands of automation in industries. Dhas and Kumanan [1] addressed the development of finite element model and neurohybrid models for the prediction of residual stress in butt-welding. Yajiang et al. [2] controlled the weld heat input to minimize the thermal stress to avoid welding cracks. Mochizuki et al. [3] obtained the effect of the welding pass sequence on the residual stress which shows that the residual stress of welds can be substantially reduced with low transformation temperature welding material regardless of the welding pass sequence. The article also described an investigation of welding distortion and residual stress generation by numerical simulations of the temperature, microstructure and thermal stress histories during welding with special consideration of the relationship with phase transformation behavior.

Mousavi and Miresmaeili [4] investigated the effects of fluid flow, plasticity, external constraint, joint design, groove configurations and mechanical constraints on the residual stress distributions and on the distortions produced during the TIG welding process for type 304 austenitic stainless steel using 3D finite element analyses and the results were validated by X-ray diffraction techniques. The results showed that the magnitudes of the transverse residual stresses increased about threefold and the constrained weld structures had less distortion than the non-constrained weld structures. Lee and Chang [5] developed a sequentially coupled three-dimensional thermal–mechanical finite element model to simulate the residual stress states in butt welds of

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http://dx.doi.org/10.1016/j.jcsr.2014.06.011
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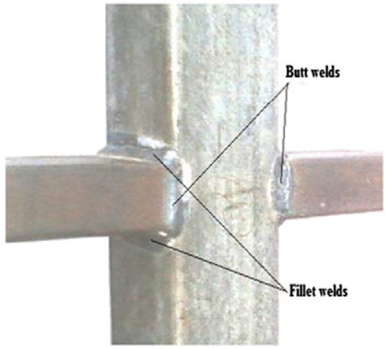

Fig. 1. Cruciform joint.

thin-walled steel plate and the results demonstrated that welding residual stresses severely affected the fatigue crack growth rate in the welds, i.e. the residual stresses could result in a reduction in the fatigue life of the structure compared to that of the cracked body without the residual stresses.

A computational technique based on finite element analysis was developed by Dar et al. [6] for the s subsequent weld-induced residual stress fields and distortion patterns in GTA welded thin-walled cylinders of low carbon steel. A close correlation was developed successfully with the experimental investigations. Along and near the weld line, a high tensile and compressive axial residual stresses occurred on the cylinder inner and outer surfaces, respectively. Huniti et al. [7] investigated the variations of thermal and residual stresses inside a thin mild steel plate during welding processes and presented a theoretical analysis of the thermal and residual stresses inside a thin plate with a moving heat source simulating arc welding. The study found that, as the weld speed decreased, the temperature inside the plate increased and the residual stresses reaching the yield limit were produced in wider areas along the welded area. Zhang et al. [8] presented a validation of the contour method by comparing it with diffraction measurements in a MIG 2024-T351 aluminium alloy welded plate. The potential of the contour method was demonstrated on aluminium alloy welded plate to produce a full two-dimensional map of the longitudinal stress profile across thickness.

Residual stress prediction and measurement was carried out on welded tubular joint structures containing a lack of penetration, with single-U weld groove and no groove, respectively by Barsoum [9]. The lack of penetration size (root error) had a major influence on the fatigue strength assessed from the root side in combination with compressive residual stresses. Brar and Kumar [10] developed a three-dimensional finite element model by making an approximate geometry of the butt welded joint and then the finite element analysis was performed to understand the complete nature of residual stresses in butt welded joint of AISI 304 stainless steel plates by submerged arc welding (SAW), manual metal arc welding (MMAG), gas metal arc welding (GMAW)

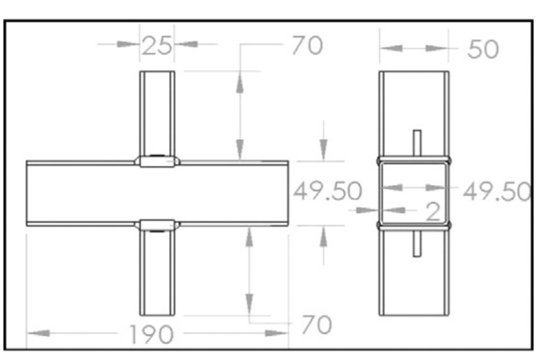

Fig. 2. Detailed geometry of cruciform joint (all dimensions in mm).

Table 1
Chemical composition of mild steel (%wt).

C	Si	Mn	S	P	Ni	Cu	Cr
0.16	0.03	0.32	0.05	0.2	0.01	0.01	0.01

and gas tungsten arc welding (GTAW). It concluded that residual stresses were lowest in case of GMAW and highest in SAW. Teng et al. [11] described the thermal elasto-plastic analysis using finite element techniques to analyze the thermo mechanical behavior and evaluated the residual stresses and angular distortions of the T-joint in fillet welds. With increasing flange thickness, the internal restraints were increased and the tensile residual stress near the fillet weld toe increased. With increasing penetration depth or heat input in fillet welding, the tensile residual stress near the fillet weld toe decreased, and improved the non-penetration defects.

In the present work, GMAW (fusion) welding is used to make the cruciform joint of hollow sectional mild steel tubes and during welding developed residual stresses is measured by X-ray diffraction and finite element method. Cruciform welded joints are widely employed in construction of steel bridges.

2. Joint preparation

A cruciform joint is prepared among three members, with two members located approximately at right angle to third member in the form of a sign + as shown in Fig. 1. IS 4923:1997 Yst 240 mild steel hollow square sectional tube (49.5 mm × 49.5 mm × 2.0 mm) cut into 190 mm long and hollow rectangular sectional tube (50.0 mm × 25.0 mm × 2.0 mm) cut into two pieces of 70 mm long are welded in the form of cruciform joint by gas metal arc welding (as shown in Fig. 2). The chemical composition of mild steel by (%wt) is given in Table 1. The thermal and mechanical properties of IS 4923:1997 Yst 240 mild steel hollow sectional tubes used for the present study are given in Table 2.

During welding process, heat is produced to join the work piece which also raises the temperature in the joint. The raised temperature affects the properties of the work piece. In the present work, the effects of raised temperature on the properties of Yst 240 Mild Steel hollow tubes are taken into account as shown in Fig. 3. As the temperature increases up to the range of 650–750 °C, there is a decrease in the Young's modulus and conductivity values and after that these values becomes constant with the increase in temperature. With the increase in the temperature up to the range of 650–750 °C, the values of Poisson ratio, expansion and specific heat slightly increase and then become constant with further increase in temperature. The value of yield stress slightly decreases with the increase in temperature up to 500 °C and after that rapidly decreases with the increase in temperature up to 750 °C and then becomes constant with further increase in temperature.

In the present work, the cut pieces of hollow tubes are connected together by gas metal arc welding (GMAW), with one tube positioned perpendicular to the other two tubes, thereby forming a cruciform joint connection. The gas metal arc welding parameters (currently in

Table 2
Thermal and mechanical properties of mild steel hollow sectional tubes.

Property	Value	Property	Value
Elastic modulus	2.1×10^{11} N/m^2	Yield strength	2.40×10^{8} N/m^2
Poisson ratio	0.29	Thermal expansion co-efficient	1.3×10^{-5} k^{-1}
Shear modulus	7.6×10^{10} N/m^2	Thermal conductivity	44 w/m-k
Mass density	7860 kg/m^3	Specific heat	620 J/kg/k
Tensile strength	410×10^{6} N/m^2	Elongation	15%