A Study on the Effect of Welding Sequence in Fabrication of Large Stiffened Plate Panels

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Abstract: Welding sequence has a significant effect on distortion pattern of large orthogonally stiffened panels normally used in ships and offshore structures. These deformations adversely affect the subsequent fitup and alignment of the adjacent panels. It may also result in loss of structural integrity. These panels primarily suffer from angular and buckling distortions. The extent of distortion depends on several parameters such as welding speed, plate thickness, welding current, voltage, restraints applied to the job while welding, thermal history as well as sequence of welding. Numerical modeling of welding and experimental validation of the FE model has been carried out for estimation of thermal history and resulting distortions. In the present work an FE model has been developed for studying the effect of welding sequence on the distortion pattern and its magnitude in fabrication of orthogonally stiffened plate panels.

Keywords: elasto-plastic analysis; welding distortion; 3-D finite element analysis; stiffened panel; welding sequence

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1 Introduction

The temperature distributions due to welding play an important role in the resulting distortion of a welded structure. Most of the fusion welding processes are based on local heating of joining surfaces exceeding the melting temperature and then normal cooling to ambient temperature. The temperature distribution is highly non-uniform in nature. This non-uniform heating and cooling leads to incidence of residual stresses and structural deformation or distortion.

Over the years finite element methods have been used by many researchers to predict temperature distribution, residual stresses and distortion. Prominent among them are Friedman (1975), Michaleris and DeBiccari (1997), Bonifaz (2000), and Tekriwal and Mazumdar (1988). Many researchers used the 2-D finite element analysis of Friedman to verify their 3-D computational modeling for the welding process.

Welding deformations are often calculated using analytical approaches (Rao, 1998; Watanbe and Satoh, 1961). Watanbe and Satoh (1961) used analytical methods resulting from the theory of elasticity for prediction of thermal deformations due to welding and line heating. However, since elastic solutions are limited, applications of the method are also limited.

Kamala and Goldak (1993) stated that 2-D approximation of a 3-D problem is not appropriate to predict temperature distribution, residual stresses and distortion patterns. Michaleris and DeBiccari (1997) combined two-dimensional welding simulations with three-dimensional structural analyses in a decoupled approach to evaluate welding induced buckling in panel structures. They had used a kinematic work hardening material model for simulating the plastic behavior of mild steel. Teng et al. (2001) used two-dimensional finite element analysis for predicting residual stresses and distortions in butt and fillet joints.

Depradeux and Jullien (2004) carried out thermomechanical analysis of the TIG process using temperature fields as input for subsequent structural analysis for predicting stress and displacements. Cheng (2005) investigated the effects of in-plane shrinkage strains on welding distortion in thin-wall structures based on three-dimensional axisymmetric modelling. Alberg (2005) developed modeling methodologies using finite element analysis for predicting deformation, residual stresses and material properties such as microstructure during and after welding as well as after heat treatment of fabricated aircraft-engine components.

Generally numerical thermal analysis is highly time consuming. To analyze a test sample with a size of 300mm ×300mm, 25.4mm thick in an SGI work station rated at 200MHz running under OS IRIX 6.2 requires about 12 695 seconds of CPU time (Yu et al., 2001). To minimize computational time and cost axis-symmetry a modeling approach is adopted widely for welding simulation. Recent
investigations have advocated a three-dimensional solid modeling without considering the axis-symmetry for better prediction of distortions and residual stresses (Kamala and Goldak, 1993). Works related to three dimensional finite element analysis without considering the half-symmetry for predicting angular distortions are rarely found in research literature. Fanous et al. used element birth and element movement techniques for three-dimensional axis-symmetric modeling of butt joints.

In this work both finite element methods were used for a simple case of butt welding. To simulate the filler material deposition, the ‘Element Birth’ (Fanous et al., 2003) approach has been used in the numerical model. In this technique the elements are activated or deactivated as the welding heat source moves along the weld line. The temperature distribution patterns were first obtained followed by residual distortions caused by welding.

After verification of the 3-D FE model (Biswas et al., 2006; Biswas et al., 2007; Biswas et al., 2008) the same methodology has been applied to study the distortion behavior of large stiffened panels. Here an FE model has been applied for studying the effect of welding sequence on the distortion pattern and its magnitude in fabrication of orthogonally large stiffened plate panels. The model and the methodology developed in the present work for predicting the effect of welding sequences in residual distortion of orthogonally large stiffened plate panels compared fairly well with experimental results. The model and the methodology developed in the present work can be utilized for choosing the right welding sequence which will yield minimum residual distortion for fabrications of orthogonally large stiffened plate panels.

2 Thermal modeling

A three dimensional finite element thermal model was used in the present work to analyze the heat transfer and temperature distribution in SMA welding. From a literature survey it is clear that the heat transfer mechanism in a molten pool is extremely complex. The various material properties of the metals in the molten state are also not authentically established. In arc welding, except for a small volume of metal, most of the portion of the work piece remain in a solid state. Therefore a three dimensional conduction model was considered to analyze the heat flow and the resulting temperature distribution over the entire plate.

The governing differential equation for heat conduction for a homogenous, isotropic solid without heat generation in the rectangular coordinate system (x, y, z) can be expressed as:

\[
\frac{\partial}{\partial x} \left( K \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( K \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( K \frac{\partial T}{\partial z} \right) = \rho c \frac{\partial T}{\partial t} \tag{1}
\]

where, \(K\) = thermal conductivity, \(T\) = temperature, \(\rho\) = density of the material, \(c\) = specific heat and \(t\) = time.

Eq.(1) can be written as:

\[
\rho c \frac{\partial T}{\partial t} = -L^T q \tag{2}
\]

where

\[
L = \begin{bmatrix}
\frac{\partial}{\partial x} \\
\frac{\partial}{\partial y} \\
\frac{\partial}{\partial z}
\end{bmatrix}
\]

is vector operator and \(q\) is heat flux vector.

\[
L^T q = \nabla q \quad \text{and} \quad LT = \nabla T
\]

where, \(\nabla\) represents grad operator.

Fourier’s law is used to relate the heat flux vector to the thermal gradient

\[
q = -DL \nabla T
\]

where, \(D = \begin{bmatrix} K & 0 & 0 \\ 0 & K & 0 \\ 0 & 0 & K \end{bmatrix}\) is conductivity matrix.

Eq.(2) can be written as:

\[
\rho c \frac{\partial T}{\partial t} = L^T (DLT) \tag{3}
\]

To solve Eq.(3), a set of boundary conditions is needed.

(i) Initial condition

A specified initial temperature for the welding that covers all the elements of the specimen:

\[
T = T_w \quad \text{for} \quad t = 0 \tag{4}
\]

where \(T_w\) is the ambient temperature.

To develop first and second boundary conditions the energy balance has been considered at the work surface as:

Heat supply = Heat loss.

(ii) First boundary condition

A specific heat flows acting over surface of welding region.

\[
q_n = -q_{\text{sup}} \tag{5}
\]

The quantity \(q_n\) represents the component of the conduction heat flux vector normal to the work surface. The quantity \(q_{\text{sup}}\) represents the heat flux supplied to the work surface in \(\text{W m}^{-2}\), from an external welding arc.

\[
q_n = q^T n \quad \text{on the surface weld region for} \quad t > 0 \tag{6}
\]

where, \(n\) is unit outward normal vector.

(iii) Second boundary condition

Considering heat loss (\(q_{\text{conv}}\)) due to convection over the whole surface of a stiffened plate panel (Newton’s law of