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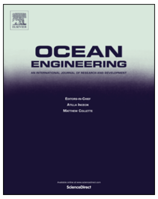

Influence of welding sequence on welding deformation and residual stress of a stiffened plate structure

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ABSTRACT

An important consideration in the safe and efficient manufacture and operation of marine structures is the possible distortion, and consequential induced residual stress, owing to welding. This paper deals with welding simulation of a stiffened plate structure with longitudinal and transverse stiffeners using a thermal elasto-plastic FE method. Shell elements with section integration features are adopted to model the plate and stiffeners and solid elements to model the local detail of weld line region. Linear constraint equations are established between degrees of freedom of the shell and solid elements. Welding parameters of heat input, welding speed and welding sequence are considered in the analysis. A typical fillet-welded joint is studied and the thermal and mechanical results are compared with experimental values. Six welding sequences are simulated. The results demonstrate the specific influences of the different welding parameters on residual distortion and stress in a stiffened plate structure.

1. Introduction

Welding is the principal jointing method in the construction of ship and offshore structures. However, it is inevitable that distortion and stresses are induced during welding due to the non-uniform expansion and shrinkage of material near weld lines (Jang et al., 2002). Welding distortion not only affects the appearance of the structure but also degrades the performance due to the loss of structural integrity and dimensional accuracy (Gannon et al., 2012; Cerik and Cho, 2013). It is therefore essential to predict welding induced distortion at the design stage of ship and offshore structures for the purposes of controlling such distortion in production and minimizing production costs (Conrardy et al., 2006).

Welding induced distortions in structures are influenced by design-related and process-related factors (Tsai et al., 1999). Important design-related factors include material thermal and mechanical properties, plate thickness, structure arrangement, weld joint types and details. The process-related factors include welding method, heat input, welding speed and sequence, assembly strategy and mechanical restraint conditions. Goldak et al. (1984) proposed a double ellipsoid mathematical model for a welding heat source based on a Gaussian distribution of power density. The validity of the theoretical model was verified by the comparison of temperature distribution contours with experimental values. Deng et al. (2013) investigated the welding distortion of a thin plate bead-on joint by a thermal elasto-plastic finite element method (FEM) and discussed the buckling characteristics and deformation modes of the joint. Tsirkas et al. (2003) performed numerical simulation of the laser welding process to study the welding distortion of a butt-joint made of AH36 shipbuilding steel. Temperature dependent material properties and metallurgical transformation were taken into account in the analysis models. Fu et al. (2014) investigated the welding residual stress and distortion of tee joints under various mechanical constraints. FEM analysis and experimental results showed that transverse residual stress, out-of-plane displacement, angular distortion and transverse shrinkage depend significantly on the mechanical boundary conditions. Gannon et al. (2012) studied the influence of welding sequences on the distribution of residual stress and distortion of flat-bar stiffened plates based on FEM simulation. Deng et al. (2007, 2008) used the elastic FEM to study welding induced buckling distortion of large structures. The inherent strains near welding lines were obtained through thermal elasto-plastic FEM analysis of different welded joints. The assembly process of welded structural parts was considered in the methods by means of interface elements. Wang et al. (2013a) applied an elastic FEM based on inherent deformation theory to a car carrier ship's structure. The prediction of the out-of-plane welding distortion for the ship's panel structure was carried out and mitigation measurements using line heating were employed to

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reduce welding distortion. Liang and Murakawa (2012) developed a method based on inverse analysis to obtain the inherent deformations in typical welded joints. A database of inherent deformations in thin plate butt joints was established which was used to predict welding deformation in thin plate welded structures with complex shape or large size.

In summary, current elastic modeling and thermal elasto-plastic methods have drawbacks. The former cannot deal with the welding process because during welding it is likely that strains can be in the post-elastic range. The current thermal elasto-plastic methods are deficient because they are computationally time-intensive and hence expensive, with solid elements being unable to cope with large structures.

This paper focuses on an improved thermal elasto-plastic FEM and examines the influence of welding sequence on distortion and residual stress of a large stiffened plate structure by the method. An approach combining shell and solid elements is proposed to enhance modeling and calculation efficiency. A transient moving heat source is adopted in the numerical analysis to incorporate important design-related and process-related parameters including material properties, welding heat input, speed and direction. Different welding directions and sequences of longitudinal stiffeners are carried out to compare the influence of them for welding distortions.

2. Numerical approach

2.1. Thermal elasto-plastic FEM

Considering the fact that mechanical responses have little influence on the temperature field during the welding process, a sequentially coupled thermal elasto-plastic FEM (Camilleri et al., 2005) is adopted in this study. The solution procedure is separated into two steps. The first one is the heat transfer analysis which produces the transient temperature field of the welding process. In the second step, the temperature results are applied on the mechanical model as external loads. Non-uniform thermal expansion and shrinkage of material will produce stress, plastic strains and distortion responses of the structure.

In the thermal analysis, the FE formulation for transient nonlinear heat transfer analysis is based on the governing equation and boundary conditions listed in Eq. (1).

$$\begin{cases} \rho c\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+\overline{Q} \\ T_s=T_s(x,y,z,t) \\ -\lambda\frac{\partial T}{\partial n}=q_s(x,y,z,t) \\ -\lambda\frac{\partial T}{\partial n}=\alpha(T_s-T_\alpha) \end{cases} \tag{1}$$

where ρ, c ,λ are the density, specific heat capacity and thermal conductivity of material respectively. T is the current temperature; Q is the internal heat generation rate (W/mm^3). T_s is the temperature on the boundary. q_s is the heat flux, T_a is the ambient temperature, and α is the convection heat transfer coefficient.

In the mechanical analysis, the total strain increment (Deng et al., 2013) can be expressed as the sum of components described in Eq. (2).

$$d\varepsilon^{tl}=d\varepsilon^{e}+d\varepsilon^{p}+d\varepsilon^{th}+d\varepsilon^{c}+d\varepsilon^{pt} \tag{2}$$

where $d\varepsilon^{tl}$ represents the total strain increment, and $d\varepsilon^{e}$, $d\varepsilon^{p}$, $d\varepsilon^{th}$, $d\varepsilon^{c}$, $d\varepsilon^{pt}$ represent the increment of elastic, plastic, thermal, creep and phase transformation induced strains respectively. The elastic stress–strain relationship abides by the isotropic Hooke's rule. The Von Misses criterion and linear isotropic hardening law are used to determine the plastic behavior. Thermal strain can be considered using the thermal expansion coefficient. Because the thermal cycles in the welding process are short, creep can be deemed to make an insignificant contribution to the total strain and hence can be ignored. Also, the strain induced by phase transformation is neglected in the current work for the same reason. The geometric nonlinearity of large displacements is accounted for in the mechanical analysis.

2.2. Shell element with section integration

In order to decrease the complexity of geometry modeling, shell elements with section integration (Shen and Chen, 2014) are adopted in thermal analysis of the stiffened plate structure. The shell element can realize three dimensional heat transfer by setting several independent temperature integration points through the shell thickness. Temperature at any position in a shell element can be obtained according to Eq. (3).

$$\theta=\boldsymbol{N}^{\boldsymbol{N}}(\phi_1,\phi_2)\boldsymbol{M}^{\boldsymbol{P}}(\boldsymbol{s}_3)\theta^{\boldsymbol{NP}} \tag{3}$$

where $(\phi_1,\ \phi_2)$ are defined as the local coordinates at the reference surface of shell element; s_3 is the position through thickness; $N^N(\phi_1,\phi_2)$ is an interpolator in the reference surface; $M^P(s_3)$ is the piecewise parabolic interpolator through thickness; and θ^{NP} is nodal temperature values at section integration points.

2.3. Shell/solid model

A characteristic of the welding process is that a significant temperature gradient exists in the region near the heat source. In order to describe the heat transfer near weld line precisely, an FE strategy combining shell and solid elements is used in thermal analysis. The plates are modeled by shell elements at the middle surface of plates and fusion zone modeled by solid elements. Linear constraint equations are used to relate the degrees of freedom at the contact surface of different parts. The details of connection between the solid and shell elements DOF are shown in Fig. 1. The integration points located at the edge of vertical plate are connected with those on the upper surface of horizontal plate. Nodal DOFs of solid element in fusion zone are linked with outer surface integration points of the plates at the corresponding position.

3. Analysis model

3.1. The structure – study object

A stiffened plate structure simulating a ship grillage is selected as the study object in the paper. The structure comprises a plate, five longitudinal stiffeners and two transverse frames. One edge of longitudinal stiffeners is free and another is connected with transverse web frames. The overall dimension of the structure is

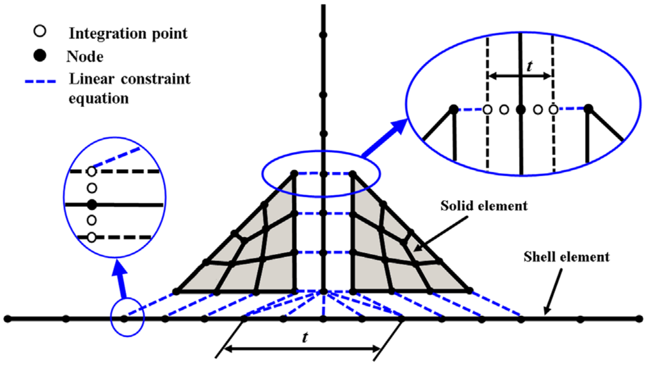

Fig. 1. DOFs connection between solid and shell elements.