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Framework of computational approach based on inherent deformation for welding buckling investigation during fabrication of lightweight ship panel

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ABSTRACT

During the fabrication of lightweight ship panel, thin plates are usually employed and welding induced buckling may be generated, which will significantly influence the manufacturing integrity and performance. Computational approach based on inherent deformation was proposed, and its framework and application were introduced in this study. In detail, typical fillet welded joint was experimentally conducted and its solid elements FE model was numerically examined with experimental validation. Then, welding inherent deformation was evaluated based on computational results; elastic FE analysis with welding inherent deformations as input parameters was implemented to predict out-of-plane welding distortion and critical welding buckling condition. As the practical technique, intermittent welding procedure was employed to decrease the magnitude of welding inherent deformation, and sequentially avoid the occurrence of welding induced buckling. With this holistic investigation, welding induced buckling during thin plate section assembly was represented; critical welding buckling condition and mitigation technique were also demonstrated.

1. Introduction

Welding, as a normal joining method due to its lots of advantages, is commonly employed to assemble steel and its alloy; meanwhile, welding distortion in particular shrinkages, out-of-plane welding distortion, is an essential engineering problem, which is inevitably generated and always influence the final fabrication precision. When thin plate sections are designed and fabricated, not only the conventional welding distortion but also welding induced buckling will be generated. Welding induced buckling will result in loss of dimensional control and structural integrity, and may delay the fabrication schedule and increase the fabrication cost when mitigation is carried out (Wang et al., 2015). During the correction, it is difficult to completely reduce the welding induced buckling due to its features of diversity and instability. Therefore, it is better to avoid welding induced buckling generation whenever it is possible.

Due to the limitation of welding experiment, computational approach in particular FE analysis was widely employed. Tsai et al. (2006) examined the mechanism of welding induced buckling with an integrated experimental and numerical approach as: the bifurcation phenomenon of buckling starts during the cooling cycle and this may continue to grow until the completion of the cooling process. Thermal-elastic-plastic FE analysis considering large deformation with Abaqus was carried out to represent buckling distortion behavior during the thin plates ship panel fabrication. Vanli and Michaleris (2001) employed transient TEP FE analysis to examine the buckling behavior of fillet welded joints with different dimensional size in Abaqus, in which large deformation theory was considered. Predicted welding distortion has a good agreement with measurement; however, the computing process consumes large computer cost and computing time. Deng and Murakawa (2008a) also studied the welding induced buckling with large deformation TEP FE analysis, where butt-welded joint by low carbon steel sheet with 1 mm in thickness was selected. Comparing the simulation results with measurement, there is a good agreement between predictive and measured values. Wang et al. (2012) investigated the welding induced buckling in the fabrication of stiffened welded structure with 6 mm thin plate. Transient TEP FE analysis with solid elements model was carried out, in which large deformation theory was considered. Good agreements between measured and computed out-of-plane distortion are observed.

In order to decrease the computer consumption and practice in actual application, a series of efficient FE analysis with equilibrium welding load such as compressive residual stress, inherent deformation, was proposed. Deng and Murakawa (2008b) developed a welding distortion

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calculation code, which combines TEP FE method and large deformation elastic FE method based on inherent deformation theory. The inherent deformations of typical welded joints used in a large thin plate structure were evaluated using TEP FE analysis. Then, an elastic FE analysis using these inherent deformations was employed to investigate the influence of heat input, welding procedure, welding sequence, plate thickness and spacing between the stiffeners on buckling propensity of examined thin plate welded structure. Later, Wang et al. (2013a, 2014) and Ma et al. (2016) investigated welding induced buckling with an elastic FE analysis based on the inherent deformation. For the stiffened welded structure with thin plates, inherent deformation was evaluated from typical welded joint by means of transient TEP FE analysis and measurement. The buckling behavior not only deformed shape but also magnitude of out-of-plane welding distortion, can be observed from the comparison of computed and measured data. Although the elastic FE analysis with inherent deformation was already used for scientific research and welding mechanical problem solving for several years, these publications almost focus on the prediction accuracy, computational efficiency and mechanism clarification of the welding distortion as well as welding induced buckling. Michaleris and Debiccari (1996) evaluated compressive residual stress parallel to welding line, so-called Applied Weld Load (AWL) by performing local transient TEP FE analysis of the welding process first; and actual ship panel model using coarse shell elements was made to determine the minimum resistance to buckling, so-called Critical Buckling Load (CBL) caused by welding residual stress. Then, they concluded that the compressive residual stress as AWL contributes a loading that eventually results in buckling if this stress exceeds the Critical Buckling Load of the welded structure. Huang et al. (2004, 2007) focused on the fabrication technology of lightweight structures with thin plates. An optical measurement system and advanced computational tools were employed to investigate the generation mechanism of buckling distortion, influential process parameter and effective mitigation techniques, which should not only reduce the buckling driving force but also increase the buckling resistant.

Although the welding induced buckling was examined with experimental and computational approaches in the above mentioned literature, it is still not published that computational framework to completely clarify the prediction and mitigation of welding induced buckling in fabrication of large lightweight welded structure. In this study, experimental measurement and transient non-linear TEP FE analysis on typical fillet welded joint were carried out, and computed results was employed to evaluate inherent deformation after measurement validation. Also, angular distortions obtained by experiment, transient non-linear TEP FE analysis and elastic FE analysis with inherent deformation, of examined fillet welded joint have a good agreement with each other. Later, unit ship panel assembled with previous conducted fillet welding with 6 mm thin plates was examined, in which not only welding induced buckling was represented, but also critical buckling condition was calculated and intermittent zigzag welding procedure was proposed to decrease the magnitude of in-plane inherent deformation for welding buckling mitigation.

2. Theory and method of computation

As summarized before, transient non-linear TEP FE analysis is a classic computational tool for welding mechanics investigation, but with a certain limitation in case of large and complex welded structure. Elastic FE analysis with inherent deformation and interface element is an ideal, practical and potential choice in actual application, where transient non-linear TEP FE analysis was still carried out for inherent deformation evaluation beforehand, and finite strain was employed to consider the contribution of non-linear part to out-of-plane welding distortion. The flow chat of employed TEP FE computation and elastic FE analysis with inherent deformation was presented (Wang et al., 2015), and then, relevant subjects were introduced as follows:

2.1. Thermal-elastic-plastic FE analysis

Thermal process and mechanical process were always considered in a transient non-linear TEP FE analysis, and the uncoupled formulation between them was employed due to the physical interaction during welding process. In detail, transient temperature field caused by moving heat source was computed with considering the influence of non-linear temperature dependent thermal-physical properties. Then, linear thermal expansion behavior is a critical point to consider the contribution of transient temperature field to mechanical response; and the obtained transient temperature distribution was applied as a thermal load to predict the distribution and magnitude of residual stresses, plastic strains and welding distortion.

2.2. Inherent deformation and elastic FE analysis

Generally, the total strain during the welding process can be divided into the strain components given by Eq. (1), namely, elastic strain, plastic strain, thermal strain, creep strain and that induced by phase transformation, respectively. Inherent strain which is a summation of plastic strain, thermal strain, creep strain and that induced by the phase transformation as given by Eq. (2), is usually considered as all total strain components except the elastic strain, Thus, total strain can be rearranged as a summation of the elastic strain and the inherent strain.

$$\varepsilon^{total} = \varepsilon^{elastic} + \varepsilon^{thermal} + \varepsilon^{plastic} + \varepsilon^{phase} + \varepsilon^{creep} \tag{1}$$

$$\varepsilon^{inherent} = \varepsilon^{*} = \varepsilon^{thermal} + \varepsilon^{plastic} + \varepsilon^{phase} + \varepsilon^{creep} \tag{2}$$

From the transient non-linear TEP FE analysis and experimental measurement, Ueda et al. (2007) pointed out that welding distortion and residual stress are generated by inherent strain, which mostly depends on the type of welded joint, material thermal-mechanical properties, plate thickness and welding heat input when the welded joint is large enough. Taking account of an assumed welded joint with large enough size as example, the inherent strain at each location is determined by the highest temperature reached at this location during the welding process, and the constraint supported by the surrounding cold material.

In the actual application, it is much more difficult to apply inherent strain to solid elements model with fine mesh, and elastic FE analysis will still require large computer memory and computing time due to the solid elements model. Concentrating on the welding distortion prediction, shell elements model can be employed to decrease the consumption of computer resource, and inherent deformation was proposed to replace the distribution of inherent strain on each cross section with one value. Since the displacement or deformation is the integration of strain, inherent deformation which is an integration of the inherent strain as given by Eq. (3), can be used to predict welding distortion without a significant loss of accuracy. Moreover, the plastic strain is the dominant component of inherent strain when phase transformation and high temperature creep don't occur and examined specimen cools down to room temperature. Therefore, it can be concluded that inherent deformations generally are the results of plastic strains.

$$\begin{aligned} \delta_x^* &= \frac{1}{h}\iint \varepsilon_x^* dydz \quad \theta_x^* = \frac{12}{h^3}\iint\left(z-\frac{h}{2}\right)\varepsilon_x^* dydz \\ \delta_y^* &= \frac{1}{h}\iint \varepsilon_y^* dydz \quad \theta_y^* = \frac{12}{h^3}\iint\left(z-\frac{h}{2}\right)\varepsilon_y^* dydz \end{aligned} \tag{3}$$

Where, δ_x^* and δ_y^* are the inherent deformation in longitudinal and transverse directions, θ_x^* and θ_y^* are the inherent bending in longitudinal and transverse directions; h is the thickness of welded joint, and x, y, z are the welding direction, transverse direction and thickness direction, respectively.

Based on the definition, inherent deformation mostly depends on the joint parameters such as configuration, material properties, plate thickness and welding heat input comparing with inherent strain. The