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Research paper

Influences of heat input, welding sequence and external restraint on twisting distortion in an asymmetrical curved stiffened panel

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ABSTRACT

Welding distortion not only degrades the fabrication accuracy of ship hull blocks but also decreases the productivity due to correction works. The accurate prediction of welding-induced distortion will help control the dimension accuracy. In this study, a computational approach based on inherent strain theory and interface element method was employed to efficiently and precisely estimate welding-induced deformation for large welded structures generated during assembly process. In the proposed approach, the local shrinkage due to heat input were considered by inherent strain components. On the other hand, the gap as well misalignment between the two parts to be joined, and the change of stiffness during assembly process were taken into account by interface elements. Meanwhile, the geometrical nonlinearity was included in the developed computational approach. In the current study, the features of welding deformation in an asymmetrical curved stiffened panel were numerically investigated by mean of the new computational approach. In addition, the influences of heat input, welding sequence and external restraint on the twisting distortion of the curved stiffened panel were further studied.

1. Introduction

Application of fusion welding technology in fabricating large structures offers several advantages over mechanical joining methods such as improved structural performance, weight reduction, flexibility of design and cost savings etc. In recent years, ship designers have been forced to incorporate lighter, thinner steel structures to reduce topside weight, improve fuel economy, and enhance mission capability [1]. In shipbuilding industry, accuracy management of products is one of the most important problems. Generally, there are two main ways that can be used to realize the goal of accuracy management [2,3]. One way is to manufacture precision control through reducing or minimizing welding deformation produced in the assembling stage. The other is to take the initiative to control the potential welding deformation as much as possible in the production design phase.

From the point of view of materials, design and manufacture, there are many factors that affect welding deformation. Generally, these factors can be categorized into material-related, design-related and manufacturing-related variables. The material-related factors include temperature-dependent thermal physical properties and mechanical properties such as Young's modulus, yield strength and expansion coefficient [4]. Significant design-related variables [5] include type of joint, plate thickness, and location of each joint in a whole welded structure etc. Important manufacturing-related variables [6] mainly contain heat input, welding sequence, groove shape, arrangement of weld passes and external restraint etc.

In shipbuilding, curved structures have widely been used especially in the bow and stern parts. When fusion welding technology is employed to assemble the curved structures significant twisting distortion usually occurs. In order to achieve a high productivity of assembly curved stiffened panel, it is important to accurately predict welding deformation especially twisting distortion and then return the information to both production planning/design stage and manufacturing stage. In this way, effective measures can be taken to control the welding deformation during both the design phase and the manufacturing process. With the development of computational welding mechanics and the progress of computer hardware technology, numerical simulation method is a powerful tool to achieve this goal [7].

In a thin-plate welded joint or structure, welding mechanical behaviors such as residual stress and deformation produced during assembly process have strongly nonlinear characteristics. Multiple nonlinearity occurring in welding process generally includes material

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nonlinearity (thermo-elastic-plastic behavior of weld metal and base metal), geometric nonlinearity (large deformation), and contact nonlinearity (contact relationship between parts to be welded, external restraint, gap and its correction). Therefore, in order to obtain high-precision prediction of welding deformation, these nonlinear problems should be carefully taken into account in a numerical model. In the present work, based on our previous researches [8–11], an attempt was made to develop an effective and useful computational tool to estimate the welding distortion with the consideration of these three kinds of nonlinearity.

The transient thermo-elastic-plastic finite element method (FEM) is useful tool to compute the welding deformation for small-scale and medium-scale welded structures. However, it seems that this method is not a practical approach to calculate the welding deformation for large-scale and complex welded structures because the welding-induced mechanical behavior is a strongly nonlinear problem and a long computing time is usually required. As an alternative, the inherent strain method [12], which deals the residual plastic strains near the weld zone as inherent strains, is a practical and effective approach to predict welding distortion for large-scale welded structures.

When the inherent strain method is employed to estimate welding distortion for a large-scale welded structure, the inherent deformations [13] in each typical joint with specific thickness of plate and welding parameters should be determined beforehand. At present, two feasible and practical methods can be utilized to obtain the inherent deformations for a welded joint. One is the experimental method, and the other is numerical simulation method based on the thermo-elastic-plastic FEM.

Although the numerical simulation method based on finite element method has a relatively long history for the prediction of welding deformation, most numerical models have been mainly used to calculate the welding deformation of flat joints or structures. However, there are few numerical models to study the welding deformation of curved panel structures. In past years, the authors have investigated the influence of initial gap on welding distortion in a curved structure [3], and have measured the deflection in the same curved panel [14]. However, the study on twisting distortion occurring in asymmetric curved structures is still inadequate, and the understanding of the welding deformation and characteristics of curved panels is not comprehensive.

In this study, the main objective is to investigate the features of welding deformation in an asymmetrical curved stiffened panel. Meanwhile, the influences of heat input, welding sequence, and external restraint on the twisting distortion were clarified. The elastic FEM based on inherent strain theory was used to estimate welding deformation for asymmetrical curved stiffened panel. Because the thickness of curved stiffened panel is relatively small, the large deformation (geometrical nonlinearity) was also taken into account in the elastic FEM. Moreover, during the course of assembly, welding sequence, gap/misalignment between parts to be welded should also be carefully modeled. Therefore, the interface element [15], which can model the contact relationship between parts, was introduced into the elastic FEM. In addition, the thermo-elastic-plastic FEM was employed to determine the inherent deformations of each typical joint in curved stiffened panel.

2. Asymmetrical curved stiffened panel and plate stiffened panel models

To investigate the features of welding-induced deformation in an asymmetrical curved stiffened panel, two models were established in current study. One is a flat plate stiffened panel (Model A) as shown in Fig. 1, and the other is an asymmetrical curved stiffened panel (Model B) as shown in Fig. 2. By comparing with the welding deformation of the flat plate stiffened panel model, it is easier to clarify the characteristics of the welding deformation in the asymmetric curved stiffened panel.

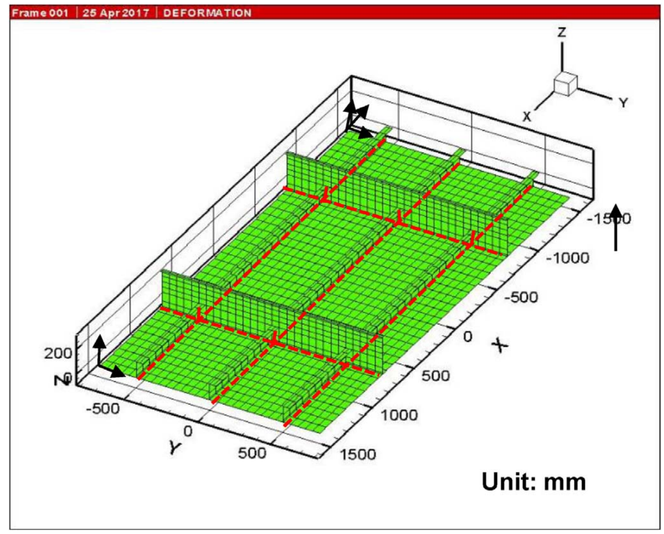

Fig. 1. FE model of plate stiffened panel.

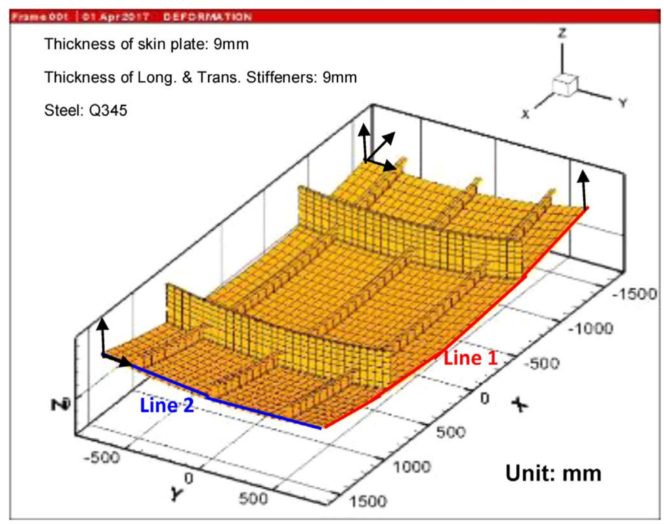

Fig. 2. FE model of curved stiffened panel.

As shown in Figs. 1 and 2, the basic dimensions of these two models are identical. The length and width of the skin plate for these two models are 3000 mm and 1500 mm, respectively. The heights of the longitudinal stiffener and the transverse stiffener are 125 mm and 300 mm, respectively. The span between two transverse stiffeners is 1500 mm, and that between two adjacent longitudinal stiffeners is 500 mm. The thickness of the skin plate, the transverse stiffeners, and longitudinal stiffeners is 9 mm. In curved stiffened panel (Model B), the initial deflection of the skin plate is shown in Fig. 3. The geometrical shape (*Z*-coordinate of the neutral plane) of the skin plate of Model B is defined by the following equation:

$$Z = R_{X'} + R_{Y'} - \sqrt{R_{X'}^2 - X'^2} - \sqrt{R_{Y'}^2 - Y'^2} \quad (1)$$

where, $X' = X\cos\theta + Y\sin\theta$; $Y' = Y\cos\theta - X\sin\theta$; *X*: coordinates along the longitudinal stiffener; *Y*: coordinates along the transverse stiffener; *Z*: coordinates in the vertical direction; *X'*, *Y'*: coordinates in the principal directions; $R_{X'}$: radius of curvature in *X'* direction; $R_{Y'}$: radius of curvature in *Y'* direction.

The skin plate of Model B is a doubly curved plate. In skin plate, the principle orientation angle (θ) from the longitudinal stiffener is 20°. The radii of curvature of the curved stiffened panel in the *X'* principal orientation and the *Y'* principal orientation are 7200 mm and 3600 mm,