Journal of Materials Processing Tech. 256 (2018) 36–50

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

journal homepage: www.elsevier.com/locate/jmatprotec

Efficient welding distortion analysis method for large welded structures

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ARTICLE INFO

Keywords:
Welding distortion
Inherent strain
Simulation
Finite element method
Equivalent force method

ABSTRACT

An efficient approach to predicting the welding angular distortion of large structures by using scalar input variables with no restriction on the mesh size near the welding region is proposed. To transform the input variables according to the mesh size, the explicit form of the force matrix is derived based on finite element theory. The proposed method is easily applied and requires only the measured distortion rate of a unit welded specimen and a user-designed mesh system to conduct the welding distortion analysis. The proposed method was applied to various case studies for verification, and the results show that the proposed method can effectively predict the welding angular distortion.

1. Introduction

When welded, structures receive a cycle of rapid heating and cooling from the welding heat source, and the temperature range changes with the movement of the heat source. This generates a non-uniform temperature distribution in the welded part. This uneven temperature distribution causes weld distortion and residual stress, which are major factors that negatively affect the dimensional accuracy of the assembly, as well as the buckling and fatigue strength of the structure (Masubuchi, 1980). Especially in the case of large welded structures such as shipbuilding blocks, the welding distortion at each assembly stage requires a lot of time and effort to correct. Therefore, predicting the welding distortion that occurs during assembly in the design stage is important. An additional requirement for welding distortion analysis in the shipbuilding industry is that it should be performed as quickly as possible since the analysis results are used for in-process quality controls (Ha, 2008). Although conventional thermal elastoplastic analysis can obtain high-precision results, they are difficult to apply to large welded structures because of the excessive computational time.

In order to reduce the computation time, efficient welding analysis methods based on experimental data have been developed. Most of these simplified methods are based on the inherent strain theory (Ueda and Yuan, 1989). Ueda's group (Ueda et al., 1989) used numerical analysis and experimental observations to show that a source that generates welding deformation and residual stress exists in the weld joint. This source is called the inherent strain and is defined as the permanent deformation that is generated in the heat-affected zone (HAZ) (Ueda and Yuan, 1993). This inherent strain can be calculated by summing the inelastic strain components (Deng et al., 2012). If the inherent strain value in the HAZ is known, the welding distortion and residual stress can be estimated with the elastic finite element method (FEM) (Luo et al., 1997). The estimated inherent strain should be assigned to the FEM model as a nodal load. However, because the strain cannot be directly assigned as a load, the equivalent load or artificial temperature and thermal expansion coefficients (thermal strain) are assigned to the FEM model to generate the welding deformation that occurs due to inherent strain. The equivalent load method based on the inherent strain assigns equivalent loads to the FEM model (Lee, 2002). The loads are converted from the inherent stress remaining at the HAZ (Jang, 2007). For the thermal strain-based method, artificial thermal expansion coefficients with negative values are assigned as a material property to simulate the compressive behavior at the welding line. The nodes at the welding line are assigned with an artificial temperature load to generate the welding distortion (Ha, 2008).

The key difference between the two methods is the input variables. The equivalent load method, based on the inherent strain, uses vector input variables, which are concentrated and distributed forces and moments with directionality. On the other hand, the thermal strain-based method uses scalar input variables, which are artificial temperature and thermal expansion coefficients that only have magnitude. Because the input variables are vectors such as forces and moments, the equivalent load method based on inherent strain needs to decompose the vector values when applied to curved structures, which in turn increases the modeling time (Ha, 2008). The strain as direct boundary (SDB) method uses scalar input variables, so it can reduce the modeling time for the welding distortion analysis of large welded structures (Ha, 2008). Kim et al. (2015) introduced an approach that uses an FEM with

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https://doi.org/10.1016/j.jmatprotec.2018.01.043
Received 29 November 2017; Received in revised form 12 January 2018; Accepted 29 January 2018

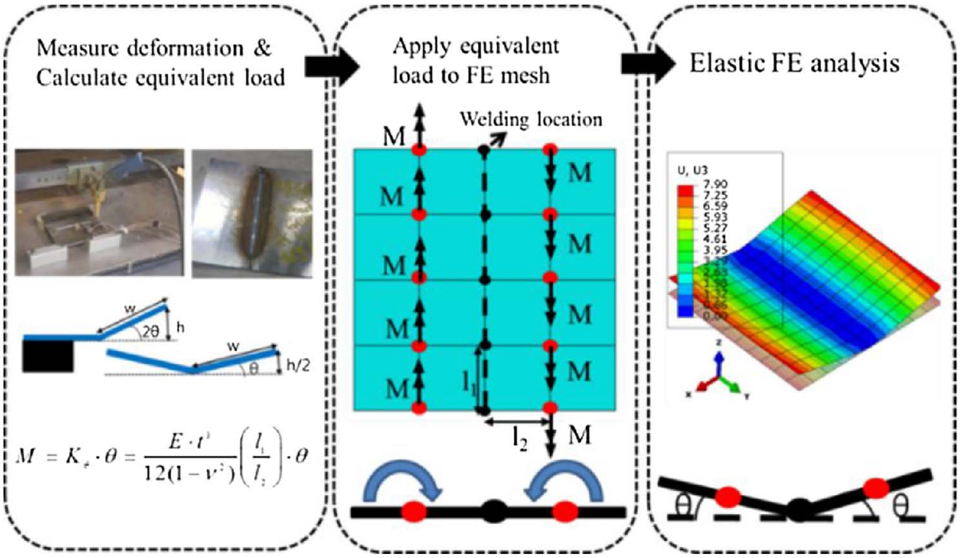

Fig. 1. Procedure for applying the equivalent force method.

layered shell elements. The SDB method and layered shell element-based welding analysis method both use the artificial temperature as a scalar input variable, so there is no need to decompose the input variables for a curved plate or a more complex large welded structure.

For both methods based on the inherent strain, however, the mesh size at the welding region is restricted to the size of the HAZ, so they require a fine mesh and a long modeling time. Strictly speaking, the use of inherent strain does not itself dictate the mesh size. For the SDB method, the mesh size affects the effective application of the inherent strain and modeling of the inherent strain value between the top and bottom of the shell by linear idealization. For the SDB method, the size of the HAZ is generally less than 50 mm (Ha, 2008), which is excessively small for analysis of large welded structures. Moreover, considering that the size of the HAZ varies with the welding joints, the mesh size varies as well. This increases the modeling time, especially for large welded structures.

The key point of inherent strain-based welding analysis is to extract the inherent strain and size of the HAZ. Conventional methods still require time-consuming 3D Thermal Elastic-Plastic Analysis (3D TEPA) or other experimental methods to extract these values (Kim et al., 2015). If only the measurement data of the welded specimen and the concept of using scalar input variables with no restriction of the mesh size near the welding region are used for shell element-based welding distortion analysis, this will be a more efficient solution for large welded structures.

The equivalent force method (Park et al., 2002) predicts the welding distortion by using the equivalent force calculated from the measured deformation of the unit member. This method requires the preparation of a database by conducting a large number of experiments. The procedure of extracting input variables is straightforward and convenient because it only uses the measured distortion rate of the welded specimen. In addition, this method can be used to set the mesh size regardless of the size of the HAZ. When the equivalent force is calculated from the distortion amount, the size of the mesh can be set to that desired by the user because the influence of the mesh size is also considered in the derived equation (Park and An, 2017). However, this method has the same disadvantage as the equivalent load-based inherent strain method because the input variables are vectors. Many experimental studies (Park et al., 2002) have been carried out to reflect the influence of external constraints when applied to a large welded structure. In this study, focus was placed on taking the scalar input variables at the same time as the user-designed mesh size in order to predict the distortion generated from a unit welded specimen.

The objective of this study was to develop an advanced distortion prediction method with a commercial FEM code that can easily be applied to large welded structures. The method only uses the measured distortion rate of a unit welded specimen and scalar input variables with no restriction on the mesh size near the welding region. In this paper, the equivalent force method and SDB method are first explained in detail, then the two methods are compared to derive the proposed method. Various case studies conducted for verification are presented. Finally, a case study on the unit structure is presented. The results show that the proposed method can effectively predict the welding angular distortion using only the measured distortion rate of a unit welded specimen and with no restriction on the mesh size near the welding region.

2. Background

2.1. Equivalent force method

With this method, the equivalent loads can be placed in three categories: longitudinal deformation, transverse deformation, and angular distortion (Park et al., 2002). The welding deformation is predicted in elastic finite element analysis by calculating the equivalent force from the measured welding distortion during the experiment. If only the angular distortion is considered, the relation between the equivalent moment (M) and welding distortion (θ) can be expressed linearly as follows:

$$M = K_\theta \cdot \theta = \frac{E \cdot t^3}{12(1-\nu^2)}\left(\frac{l_1}{l_2}\right)\cdot\theta \tag{1}$$

where M is the equivalent bending moment (N/mm), l_1 is the element length towards the welding line (mm), and l_2 is the element length in the width direction (mm) (Park and An, 2017) (Fig. 1).

This method applies the equivalent force to the nodes adjacent to the weld line regardless of the mesh size in order to simulate the desired angular distortion for a flat plate. With a curved plate, however, the result becomes very sensitive to the location upon which the nodal force acts. When the equivalent force is calculated from the distortion amount, the size of the mesh can be set to that desired by the user because Eq. (1) also considers the influence of the mesh size. With the equivalent force method, welding distortion analysis can be performed at the same time as the general shell model elastic structure analysis. The procedure of extracting the input variables is straightforward and convenient because the method only uses the measured distortion rate of the welded specimen. However, giving the equivalent force, which is the equivalent moment, means that the input variables are vector