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Welding deformation analysis based on improved equivalent strain method to cover external constraint during cooling stage

Tae-Jun Kim[1], Beom-Seon Jang[2] and Sung-Wook Kang[2]

[1]*Hyundai Heavy Industries Co., Ltd., Ulsan, Korea*
[2]*RIMSE, Dept. of Naval Architecture and Ocean Engineering, Seoul National University, Seoul, Korea*

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ABSTRACT: *In the present study, external restraints imposed normal to the plate during the cooling stage were determined to be effective for reduction of the angular distortion of butt-welded or fillet-welded plate. A welding analysis model under external force during the cooling stage was idealized as a prismatic member subjected to pure bending. The external restraint was represented by vertical force on both sides of the work piece and bending stress forms in the transverse direction. The additional bending stress distribution across the plate thickness was reflected in the improved inherent strain model, and a set of inherent strain charts with different levels of bending stress were newly calculated. From an elastic linear FE analysis using the inherent strain values taken from the chart and comparing them with those from a 3D thermal elasto-plastic FE analysis, welding deformation can be calculated.*

KEY WORDS: Welding deformation; Inherent strain; FE analysis; Equivalent strain method; External constraint.

INTRODUCTION

In shipyards, a vessel is constructed by assembling a lot of blocks which are fabricated by assembling respective sub-blocks again. Welding inevitably induces distortion of a block, and this is accumulated during the sequential fabrication process. As the block erection step accounts for about one-third of the whole shipbuilding process, the accuracy of a block in terms of shape and dimension has a critical influence on overall efficiency of production in the shipyard. The welding distortions reduce the fabrication accuracy of ship-hull blocks, and decrease productivity, due to the amount of correction work that is required. To increase the precision of fabrication, the welding distortion and the exact distortion margin at every fabrication stage should be estimated in order to meet the allowable tolerances of ship-hull blocks.

Prediction and control of welding distortions at the design stage, an essential task of shipyards, ensures both high quality and high productivity (Jang, 2007). The most widely utilized method of this type is the thermal Elasto-Plastic Analysis (EPA) method, which delivers relatively accurate results. However, due to the consideration of complicated nonlinearity of material property, it requires long computational time. Thus, the inherent strain method has been developed and improved for an efficient prediction of the welding deformation and welding residual stress (Kim, 2006; Lee, 2002; Kim, 2010).

During welding process, vertical deformation is suppressed vertically on flat work piece in order to reduce the residual welding deformation. This study investigates the effect of the vertical restraints on the residual deformation first and proposes

Corresponding author: *Beom-Seon Jang*, e-mail: *seanjang@snu.ac.kr*

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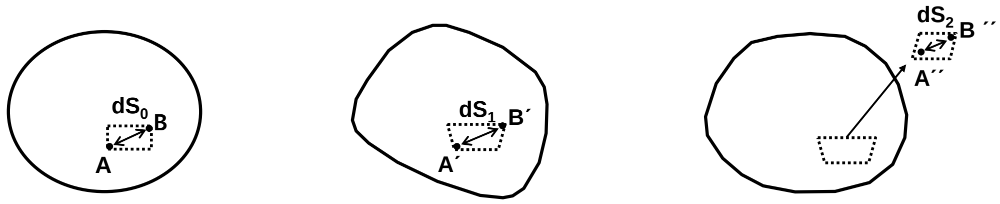
an efficient method for a prediction of welding deformation and residual stress subject to the vertical restraints. This is enabled by incorporating the vertical restraint effect into the inherent strain method as tensile or compressive stress. This proposed method is to be verified in various examples comparing the results with thermal-elasto plastic analysis.

DEFINITION OF INHERENT STRAIN

Inherent strain is defined as follows. Initially, there is a material object that has no stress distribution. When it is under stress, stress acting on a material element is accompanied by strain. Even once the stress is released by cutting out a small piece of material, residual and irrecoverable strain might still exist. This strain is regarded as the inherent strain.

Inherent strain can be further explained by means of the three material states shown in Fig. 1 (Lee, 1999). The initial state has no stress distribution inside (Fig. 1(a)); the material experiences a stressed condition caused by phenomena such as thermal strain (Fig. 1(b)); the stress is partially released by cutting out a small piece of the material (Fig. 1 (c)).



(a) Initial state (stress free). (b) Stressed state. (c) Stress released state.

Fig. 1 Definition of inherent strain.

Based on the above definition, the inherent strain (ε^*) is expressed, by subtracting the elastic strain from the total strain, as

$$\varepsilon^* = \frac{\overline{A"B"} - \overline{AB}}{\overline{AB}} = \frac{dS_2 - dS_0}{dS_0} \tag{1}$$

The total strain can be divided into the thermal (th), plastic (p), and elastic (e) strains,

$$\varepsilon = \varepsilon^{th} + \varepsilon^{p} + \varepsilon^{e} \tag{2}$$

After the welding process, the thermal strain becomes zero, and the inherent strain is the same as the plastic strain (Kim, 2006):

$$\varepsilon^* = \varepsilon - \varepsilon^{e} = \varepsilon^{p} \tag{3}$$

IMPROVED EQUIVALENT STRAIN METHOD CONSIDERING TEMPERATURE DISTRIBUTION

Kim et al. (2014) suggested an Improved Equivalent Strain Method (Improved ESM) considering the temperature distribution. The inherent strain model, a solid-spring model, used for generating inherent strain chart is briefly explained here. When a small element in the middle of entire model expands or shrinks by the temperature difference, its deformation is restrained by elements surrounded along the direction of deformation rather than those perpendicularly attached to the direction as shown in Figs. 2 and 3 shows a 2D biaxial model where springs resisting against the deformation of the center element are relocated to represent the above-mentioned phenomenon. Fig. 4 shows 3D tri-axial restraint model. The process of determining the elastic modulus of the periphery to induce the equivalent restraint is described by Kim et al. (2014). A solid-spring model is considered to be axially symmetric. One of the two faces normal to each axis is fixed, and the other is allowed to move freely along the axis. This boundary condition prevents a rigid body motion, without disturbing the intended structural behavior. The boundary condition adopted in this analysis is depicted in Fig. 5.

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