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곡판의 용접변형 예측을 위한 간이 해석법

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A Simplified Method to Predict the Weld-induced Deformation of Curved Plates

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Abstract

A three-dimensional finite element model has been used to simulate the bead on plate welding of curved steel plates having curvature in the welding direction. By using traditional method such as thermal-elastic-plastic(TEP) finite element analysis. the weld-induced deformation can be accurately predicted. However, three-dimensional finite element analysis is not practical in analyzing the weld-induced deformation of large and complex structures such as ship structures in view of computing time and cost. In this study, used is the equivalent loading method based on inherent strain to illustrate the effect of the longitudinal curvature upon the weld-induced deformation of curved plates.

※Keywords: Curved plate(곡판), Thermal elasto-plastic analysis(열탄소성해석), Weld-induced deformation(용접변형), Curvature(곡률)

1. INTRODUCTION

Welding is a key technology for building metal structures such as ships and bridges. However, welding generally produces the weld-induced distortion due to non-uniform temperature distribution. The weld distortion can be separated into the angular distortion, the transverse shrinkage and longitudinal shrinkage. For this purpose, the transient thermal elasto-plastic analysis by finite element method may be utilized. However, this method is not a practical approach to solve the weld-induced deformation of large and complex structures in view of computing time and cost(Lee 2004). On the other hand, the residual deformation of unit members such as

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bead-on and butt welding can be easily obtained by simple experiments. Thus, if the inherent strain at the weld joint is known, and then the welding deformation of a large structure can be predicted by elastic analysis (Jang et. al 2002, Jang and Lee 2000). In this study, the inherent deformation in both flat and curved plates are defined using the thermo-elastic-plastic analysis and the effect of longitudinal curvature is closely examined.

Several researchers such as Kim(2004), Michaleris and DeBiccari(1997), Wu et al.(2000) and Li et. al(2004) have shown that the transient temperature fields can be computed adequately using finite element methods, given some generic welding trials. The final elastic deformations of the structure, due to the accumulation of individual welds, can be also computed relatively easily, provided that the results from a thermal elasto-plastic stage are available. The challenge, therefore, is to simplify the intractable thermal elasto-plastic stage of the process, starting from a transient temperature field input and leading to outputs of angular deformation and contraction stress field (Mollicone et al. 2006). Several studies were presented about the welding of longitudinal curved plate using inherent strain analysis such as Luo et al.(1999) and Takeda(2002).

2. MODELING FOR NUMERICAL ANALYSIS

A 3-dimensional finite element model of a rectangular butt-joint weld in an mild steel curved plate with dimension L × B = 1000mm × 1000mm, thickness h = 12mm as shown in Fig. 1 with its coordinate system, was tested with the welding conditions given as Table 1. For the sake of symmetric situation in the geometric shape, boundary and loading conditions, one half of the whole plate can be modeled into finite element as in Fig. 2 as usual way. The temperature dependent physical and mechanical properties of mild steel are plotted as in Figs. 3 and 4.

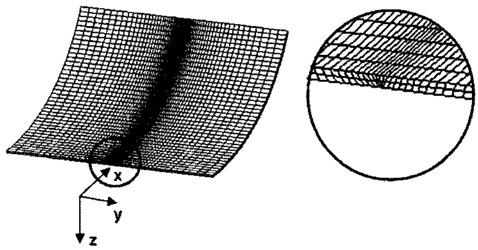
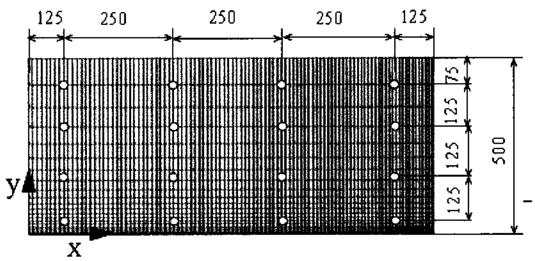


Fig. 1 Coordinates and full FE modeling



○ Fixed Positioning Jig

Fig. 2 Half FE model with fixed positioning jig

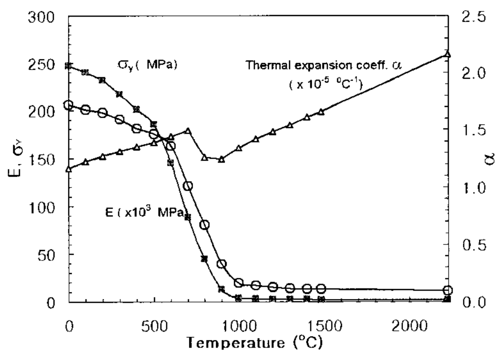


Fig. 3 Temperature-dependent mechanical properties

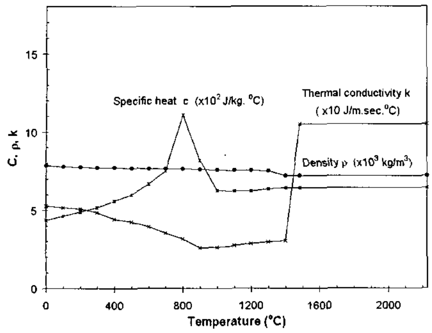


Fig. 4 Temperature-dependent thermal and physical properties

Table 1 Welding conditions

Parameter	Value
Speed (mm/sec)	7.0
Thermal efficiency	0.75
Q (J/mm)	1296.0
Q/h^2 (cal/mm^3)	9.0

As it can be seen in many literatures, weld-induced deformation should be analyzed as the results of moving heat source on the finite body. In this study Gaussian heat flux distribution model is used. Considered is the shell surface's temperature change due to the combined effects of two conditions, namely,

1) conduction within the specimen
2) convection and emission from the specimen surface's temperature to the surrounding air temperature

These two are given as Eqs. (1) and (2). The temperature within the specimen changes from weld pool to the location away from the weld pool due to conduction.

$$q_c = h(T - T_0) \tag{1}$$
$$q_r = \epsilon\sigma(T^4 - T_0^4) \tag{2}$$

where T_0 is the room temperature given as 30 °C; σ is the Stefan-Boltzmann constant given as $\sigma = 5.67 \times 10^{-8}$ W m^{-2} $°C^{-4}$. h and ϵ are convection coefficient and emissivity, respectively(Lienhard(IV) and Lienhard(V) 2004).

With regard to the boundary conditions, horizontal movement is adequately supported at two position jig points. The restraint boundary is more difficult to realize because the vertical transient deformation of the curved plate in welding process should be exactly assessed. The contact points between the plate and the positioning jigs can be modeled as gap elements. Therefore, the problem should be solved by nonlinear analysis but such approach takes much computing time (Takeda 2002). Therefore, this problem is dealt with the following step-by-step elastic analysis in which the deformation due to slipping is neglected:

(1) At the first step, vertical movement is constrained at every fixed positioning jig, by assuming that every poisoning jig is effective to restrict the lateral deformation of the plate as shown in Fig. 2. With such assumption, reaction forces can be easily calculated at positioning points.

(2) At the second step, reaction forces are checked at every jig whether the sign of reaction is positive or negative. As the reaction force is negative, then the constraint at that point should be released.

The total strain due to welding can be written as Eq. (3) and the inherent strain as Eq. (4).

$$\epsilon = \epsilon^e + \epsilon^p + \epsilon^{th} + \epsilon^{tr} \tag{3}$$
$$\epsilon^* = \epsilon^{th} + \epsilon^p + \epsilon^{tr} = \epsilon - \epsilon^e \tag{4}$$

where, ϵ: total strain
ϵ^e: elastic strain
ϵ^p: plastic strain
ϵ^{th}: thermal strain
ϵ^{tr}: phase transformation strain
ϵ^*: inherent strain

In general, the inherent strains caused by welding have six components according to their directions x, y and z. However, in case which the plate has a large length/thickness ratio, only two components, $\epsilon_x^*(x,y,z)$ and $\epsilon_y^*(x,y,z)$ are dominant in x and y direction, respectively. In this study, the transformation strain was neglected. Therefore, the inherent strain is the summation of plastic strain and thermal strain. The equivalent forces and equivalent moments in x and y directions that are shown in Fig. 5 can be computed with Eqs. (5) ~ (8), in which these forces and moments are computed based on inherent strains. Fig. 6 illustrates the inherent strain zone. These forces are to be applied at the mid-plane of plate as plotted in Fig. 7.

The longitudinal equivalent force:

$$F_x = \int_{A_h} E\epsilon_x^* dA = \int_0^h \int_0^{b_w} E\epsilon_x^* dydz \quad (5)$$

The longitudinal moment:

$$M_x = \int_{A_h} E\epsilon_x^* \left(z - \frac{h}{2}\right) dA = \int_0^h \int_0^{b_w} E\epsilon_x^* \left(z - \frac{h}{2}\right) dydz \quad (6)$$

The transverse equivalent force:

$$F_y = \int_{A_h} E\epsilon_y^* dA = \int_0^h \int_0^{b_w} E\epsilon_y^* dydz \quad (7)$$

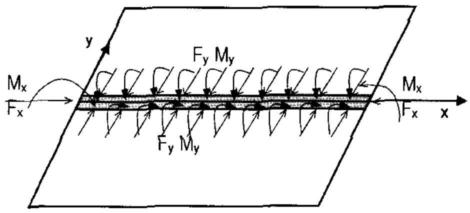


Fig. 5 Equivalent loads along weld line

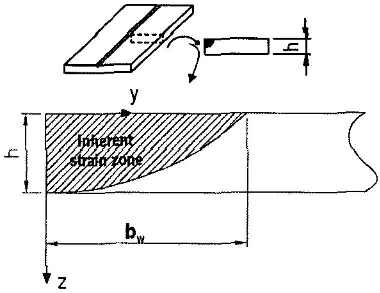


Fig. 6 Inherent strain zone

The transverse moment:

$$M_y = \int_{A_h} E\epsilon_y^* \left(z - \frac{h}{2}\right) dA = \int_0^h \int_0^{b_w} E\epsilon_y^* \left(z - \frac{h}{2}\right) dydz \quad (8)$$

Where A_h: inherent strain region.
b_w: the breadth of inherent strain region.

The temperature distribution at 5 seconds is plotted in Fig. 8 in which the temperature attains to the maximum value at the weld bead and decreases to the other points.

The inherent strain region is estimated by 2-D analysis in which the inherent strain breadth b_w is the distance from weld line to the point that the plastic strain in y direction has value of zero on the top surface (z = 0) as shown in Figs. 6, 9 and 10, respectively.

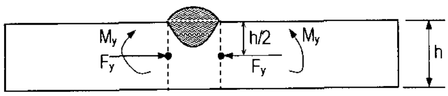


Fig. 7 Mechanical model for transverse bending distortion

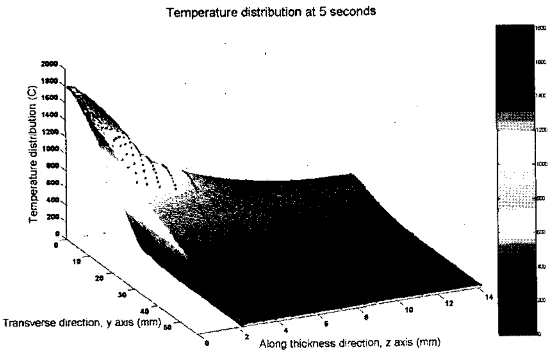


Fig. 8 Temperature distribution at 5 seconds

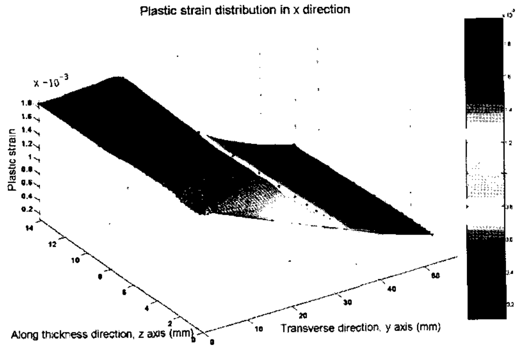


Fig. 9 Plastic strain distribution in x direction

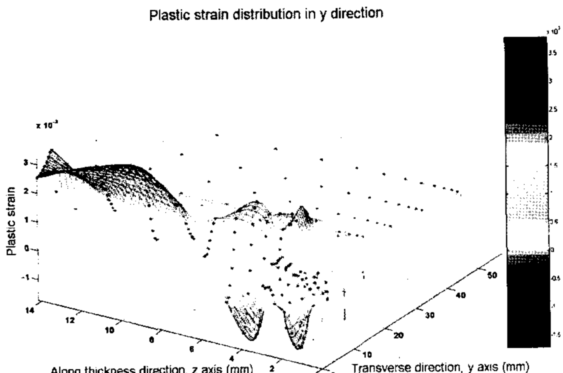


Fig. 10 Plastic strain distribution in y direction

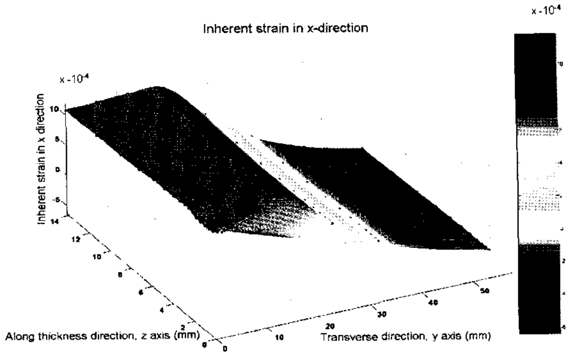


Fig. 11 Inherent strain distribution in x direction

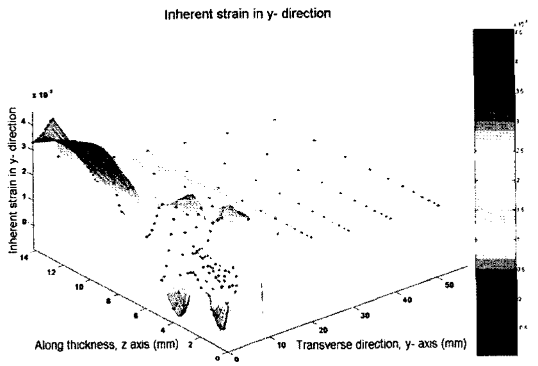


Fig. 12 Inherent strain distribution in y direction

The inherent strain distributions in x and y directions are shown in Figs. 11 and 12, respectively.

Equivalent forces and moments are applied at the nodes on the parallel line to weld line which is apart from weld line by b_w.

3. NUMERICAL RESULTS AND DISCUSSIONS

In order to clarify the effects of curvature on the deformation of the curved plate, four cases with different values of curvature, namely 1/R = 0.001, 0.0005 (welding on the convex side of the plate), 1/R = −0.001, (welding on the concave side of the plate), and 1/R = 0 (flat plate) are analyzed. The results are compared with the results of previous research.

Fig. 13 shows the effect of curvature on vertical distortion along welding line at y = 0 in which the more the curvature increases, the lesser the vertical deformation is for both concave and convex sides. Therefore, the flat plate has maximum value which is around −5.0 mm. Besides, it can be seen that the variation of vertical deformation is not great along the welding line. In a similar manner, the vertical distortion along y-direction at x = 500 mm is plotted in Fig. 14.

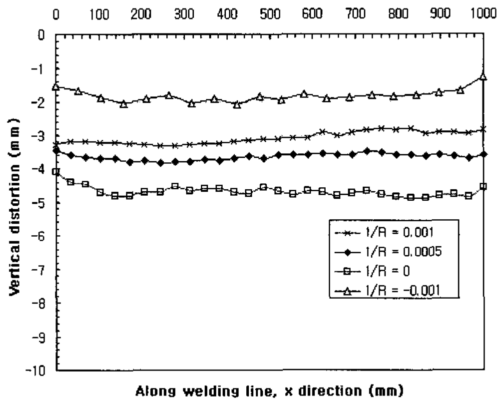


Fig. 13 Vertical distortion along x-direction at y = 0

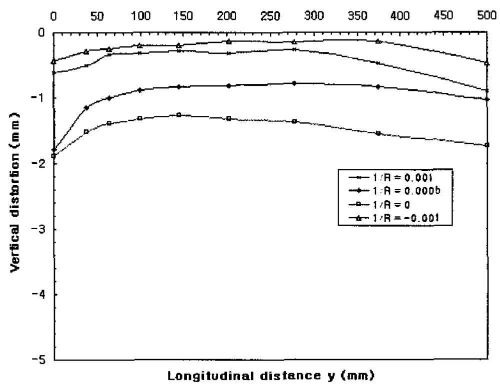


Fig. 14 Vertical distortion along y- direction at x = 500 mm

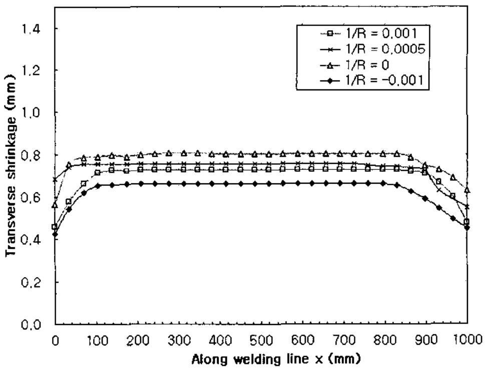


Fig. 15 Transverse shrinkage along x-direction at y = 0

The distribution of transverse inherent shrinkage along the welding line (at y = 0) is shown in Fig. 15 in which the effect of longitudinal curvature on the transverse shrinkage is quite small. As it can be seen that the transverse shrinkage increases at initial time, attains to a constant and decreases at the end of welding process.

Figs. 16 and 17 show the influences of curvature on the longitudinal bending and lateral bending, respectively. The lateral bending and longitudinal bending are the deflections at the center of the plate relative to the line connecting two edge points on the transverse and longitudinal sections, respectively. It can be observed that the longitudinal deflection increases as the curvature increases for both concave and convex sides. Contrarily, the lateral bending decreases with the magnitude of the curvature. The minimum value obtained for the case of flat plate with the value around −2.0 mm for longitudinal bending and around 10.0 mm for lateral bending. The error in the prediction of the elastic analysis is relative small for lateral bending but bigger for longitudinal bending. This big error of elastic analysis comes from neglecting of the differences of the transverse shrinkage forces between the curved plate and flat plate during welding process as shown in Fig. 20. The variation of transverse shrinkage force with curvature is plotted in Fig. 18 in which it decreases from negative curvature to positive curvature. Fig. 19 shows the effect of curvature on transverse shrinkage which the variation of maximum inherent transverse shrinkage due to the change of curvature is not much, therefore it can be treated as constant value in allowable error.

4. CONCLUSIONS

Based on the results from this benchmark analysis and parametric study, the simplified modeling process for simulating welding distortion using a general purpose finiteelement package described here is reliable and instructive. By applying the equivalent loading method based on inherent strain, a three-dimensional thermal elasto-plastic problem can be easily change into elastic analysis. It has been found the results by this simplified method agree well with those of thermo-elasto plastic analysis. Based on the simplified method, the weld-induced

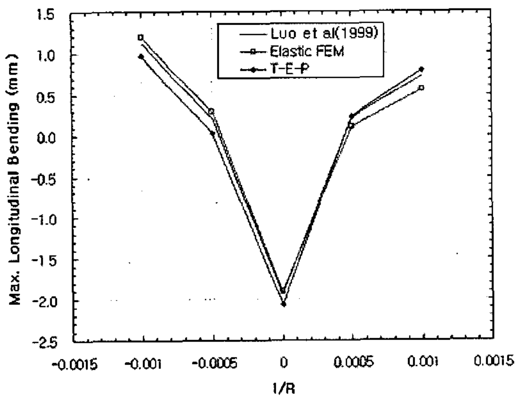


Fig. 16 Effect of curvature on longitudinal bending

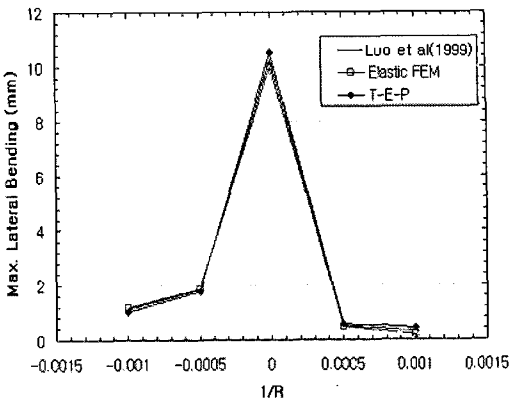


Fig. 17 Effect of curvature on lateral bending

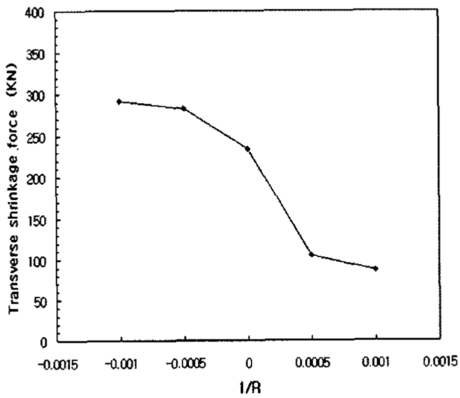


Fig. 18 Effect of curvature on transverse shrinkage force

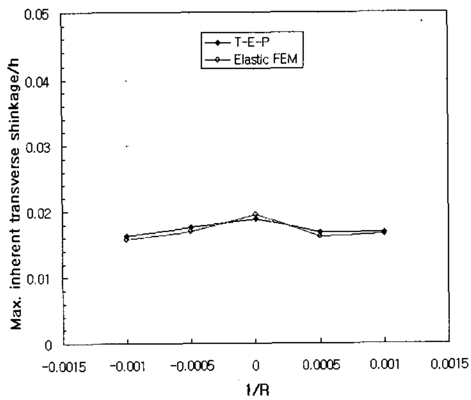


Fig. 19 Effect of curvature on maximum inherent transverse shrinkage

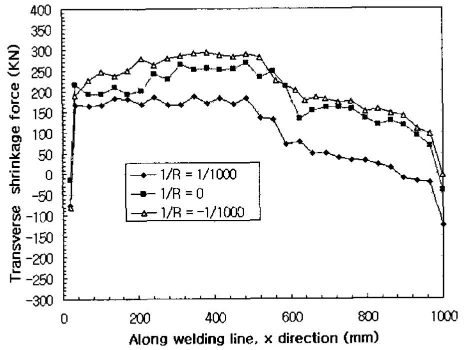


Fig. 20 Effect of curvature on distribution of transverse shrinkage force along welding line

deformation can be predicted easier and faster. The application domain investigated in this study includes the welding and heat forming processes. Therefore, from this study, the prediction of weld-induced deformation of the curved block of ship could be handled more easily than thermo-elasto plastic analysis.

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