PREDICTION AND CONTROL OF ANGULAR DISTORTION IN THICK WELDMENTS

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ABSTRACT

The welding distortion of a hull structure in the shipbuilding industry is inevitable at each assembly stage. The geometric inaccuracy caused by the distortion tends to preclude the introduction of automation and mechanization and needs the additional man-hours for the adjusting work at the following assembly stage. To overcome this problem, a distortion control method should be applied. For this purpose, it is necessary to develop an accurate prediction method which can explicitly account for the influence of various factors on the welding distortion.

In order to minimize the weld-induced angular distortion in thick weldments, this paper proposes the optimum groove design for various plate thicknesses as the distortion control method. The validity of this method has been substantiated by a number of numerical simulations and experiments.

KEYWORDS

Angular distortion, geometric inaccuracy, adjusting work, thick weldments, groove design

1. Introduction

In recent years, the lack of skilled workers in the shipbuilding industry has made it increasingly important to speed up automation and mechanization. At the same time much attention has also been given to the subject of establishing new working processes, only through which the advantages of mechanization can be fully utilized. In order to realize the mechanization of block assembly, it is of great importance to keep a higher accuracy in the previous sub-assembly stages.

The block assembly of ship nowadays consists of cutting, bending, welding, residual stress relaxation and fairing, most of which involve a certain type of heat processes. The residual deformation due to welding among various heat processes is inevitable at each assembly stage. This geometric inaccuracy of each member at the assembly stage precludes the introduction of automation and mechanization and causes the additional man-hours for the adjusting work at the following assembly stage[1].

With the fast development of computers, the numerical analysis method such as thermal elasto-plastic analysis method has become a versatile tool for practical applications in the ship production[2-7]. Using numerical methods such as finite element method and boundary element method, two-dimensional thermal elasto-plastic analysis has been used in solving welding problems. If numerical analysis is proved to be an advantageous tool to predict the residual deformation due to various processes, the optimum methods to minimize the welding deformation can be presented at each assembly stage, which will result in great progress in improving the accuracy of block assembly.

For the purpose of minimizing the angular distortion in thick weldments, this paper proposes the optimum groove design for various plate thicknesses as the distortion control method. The validity of this method has been substantiated by a number of numerical simulations and experiments. Experimental work has been also carried out to clarify the validity of numerical results. It has been found that the numerical results show a good agreement with those of experiments.

In this study, the thermal elasto-plastic analysis varying the welding conditions and plate thicknesses has been performed, and then two-dimensional heat transfer and elastic-plastic problem are solved using the commercial finite element code ABAQUS in transient mode.

2. Numerical modeling of welding process

The welding phenomenon can be categorized as a transient thermal elasto-plastic problem and is a very complex problem. Simulation of thermal elasto-plastic procedures is accompanied by the material and geometric non-linearity, so in spite of the emergence of high-speed personal workstations, the simulation procedure requires a huge amount of computing time and large memory space.

Essentially, the heat transfer and elasto-plastic problem are coupled. Since the welding deformation is expected to be small, the effect of interim deformed shape on heat transfer is negligible. Heat transfer analysis can be, therefore, carried out independently regardless of elasto-plastic analysis. Overall flow of thermal elasto-plastic analysis is shown in Figure 1. Heat transfer analysis considering the effect of weld filler metal is firstly conducted to obtain the time history of the temperature distribution, and then elasto-plastic analysis is performed with the thermal load from the temperature distribution due to heat source.

In order to solve the heat transfer and elasto-plastic problem, the following characteristics must be considered.

(1) Thermal load is the body heat flux.
(2) Heat transfer characteristics is time-dependent.
(3) Physical properties such as thermal conductivity and specific heat are temperature-dependent.
(4) Mechanical properties such as Young's modulus, yield stress and thermal expansion coefficient depend on temperature.
(5) Strain hardening model is needed.

Thermal elasto-plastic analysis requires appropriate constitutive relations. The stress-strain relations are needed to evaluate the plastic strain increment. Residual stresses and strains are produced due to non-uniform temperature distribution and temperature-dependent material properties. The increment of total strain is assumed to be a superposition of increments of elastic strain, plastic strain and thermal strain. The relations are based on the von Mises yield criterion and the Prandtl-Reuss rule.

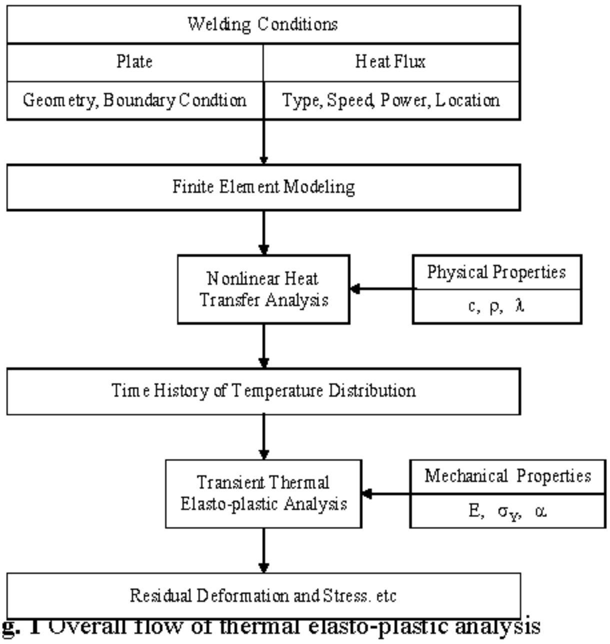


Fig. 1 Overall flow of thermal elasto-plastic analysis

3. Ramp heat input model

Modeling the heat input from the arc is critical task. It directly influences the temperature profile, cooling rate, size of the fusion zone and heat affected zone, and consequently the microstructure and weld metal strength. The loss of energy that occurs from arc to plate is extremely complex in nature and to avoid this complexity a term called arc efficiency is used to quantify the energy made available to the welding plates by the arc. Net heat input from the arc to the weldment is expressed by the following equation :

$$Q = 0.24\eta IV \qquad (1)$$

where, Q : Net heat input or thermal power of the arc(cal/sec)
η : Arc efficiency
I : Arc current(A)
V : Arc voltage(V)

Careful consideration must be exercised in choosing a value of arc efficiency because predicted temperatures are sensitive to change in arc efficiency. Peak temperatures at locations in and around the weld pool change approximately the same as the change in arc efficiency.

The two-dimensional modeling procedure has been used to predict the thermal and mechanical responses of weldments during welding. A cross section of weldment with unit length can be modeled with a ramp heat input function to determine both temperature and deformation histories in a three-dimensional weldment.

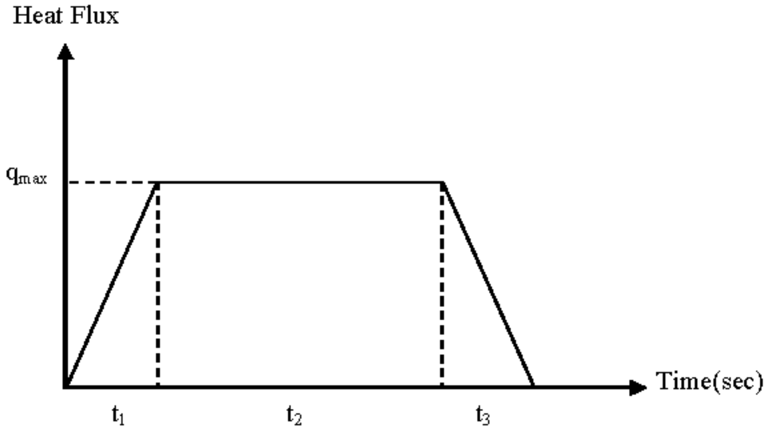
The general amplitude versus time curve for the ramp heat input function is shown in Figure 2. The actual welding time for the arc to travel across the unit thickness of the model is t_1+t_2. The magnitude of 1/v(welding speed) represents actual heat scanning time during welding. The temperature profiles are affected by the ramp time percentage, which is defined to be :

$$\text{Ramp Time Percentage} = [t1/(t1+t2)] \times 100 \tag{2}$$

Heat input energy per unit length and body heat flux were calculated by the following equations :

$$H = 0.24\eta IV/v \tag{3}$$
$$q_b = 0.24\eta IV/V_b \tag{4}$$

where, H : Heat input energy per unit length(cal/mm)
q_b : Body heat flux(cal/mm^3·sec)
v : Welding speed(mm/sec)
V_b : Volume of bead elements(mm^3)



t_1 : Initial ramp time
t_2 : Maximum ramp time
t_3 : Decaying ramp time
t_1+t_2 : Actual heat scanning time during welding
Ramp time percentage = $100t_1/(t_1+t_2)$

Fig. 2 Shape of ramp heat input function

4. Experimental works

The experimental works to show the validity of the present numerical analysis procedure were firstly performed. A submerged arc welding was used as a multi-pass butt welding process and the welding torch is moved by a carriage with a constant speed. Using the digital deformation measurement device, the bending deflection for experimental model is measured after each welding pass. Dimensions of the experimental model are shown in Figure 3, and groove conditions are listed in Table 1. At this time, the welding was first completed on one side, then the specimen was turned over and the other side is welded. Material is AH32 high tensile steel for all models.

Figure 4 illustrates the influence of pass number on the angular distortion. In this figure, it can be seen that a mild increase of angular distortion was observed during front side welding, and then the angular distortion in reverse direction was produced during back side welding. Figure 5 shows the most suitable groove shape to minimize the angular distortion. From this figure, it is found that when $p[=t_1/(t-t_3)]$ is 1/3, 2/5 and 1/2 individually, the angular distortion for each plate thickness(t=66mm, 50mm and 30mm) could be minimized.

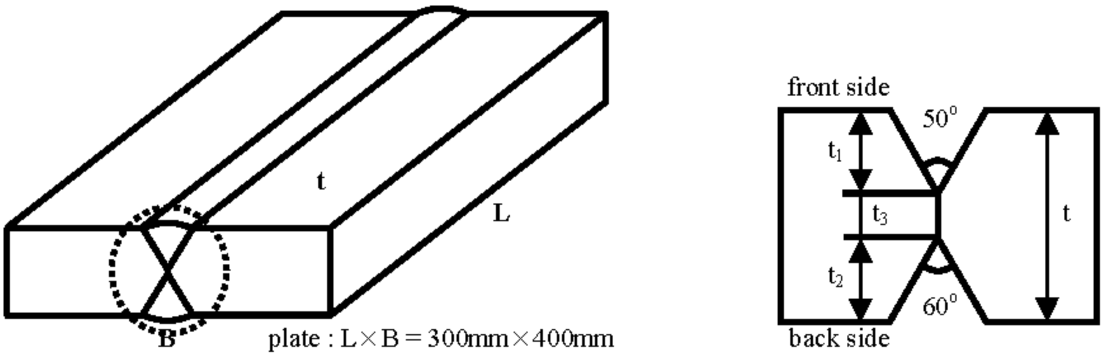
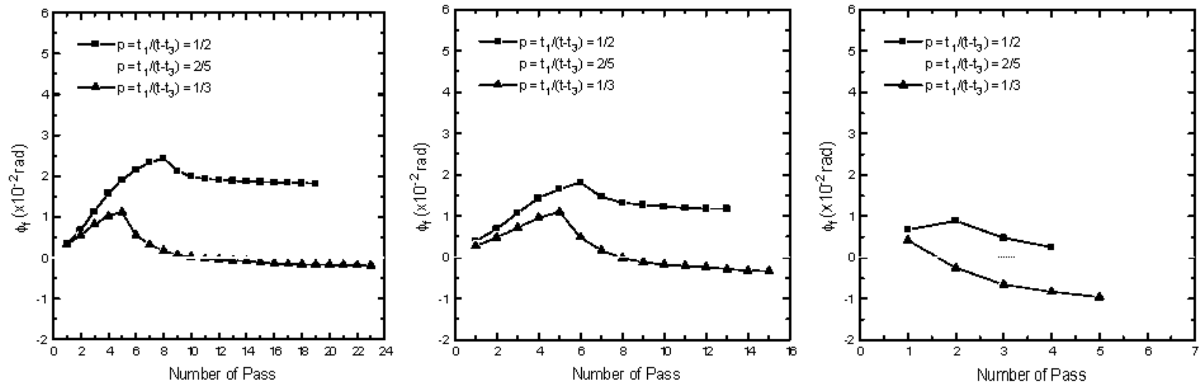


Fig. 3 Dimension of experimental model with X-groove

Table 1 Groove conditions for experimental models

Model	Plate Thickness t (mm)	Root Face t_3 (mm)	t_1 (mm)	t_2 (mm)	Groove Design Parameter $p = t_1/(t-t_3)$
X1	66	4	31.0	31.0	1/2(0.50)
X2			24.8	37.2	2/5(0.40)
X3			20.7	41.3	1/3(0.33)
X4	50	4	23.0	23.0	1/2(0.50)
X5			18.4	27.6	2/5(0.40)
X6			15.3	30.7	1/3(0.33)
X7	30	4	13.0	13.0	1/2(0.50)
X8			10.4	15.6	2/5(0.40)
X9			8.7	17.3	1/3(0.33)



(a) t = 66mm (b) t = 50mm (c) t = 30mm

Fig. 4 Influence of pass number on the angular distortion

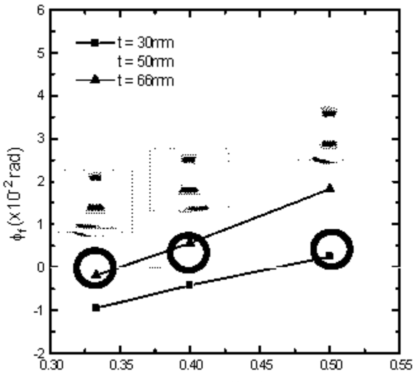


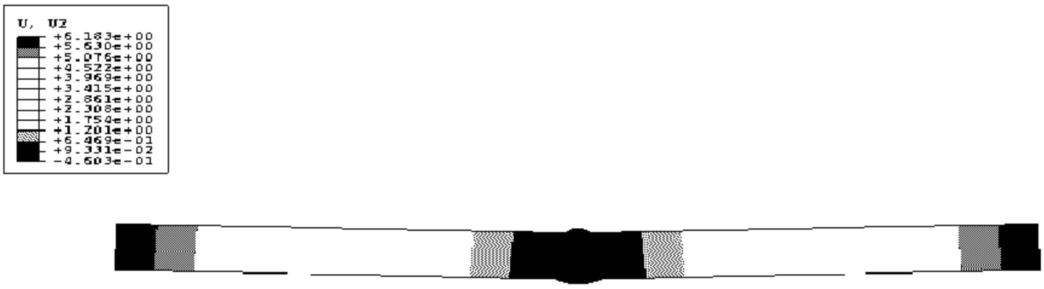
Fig. 5 Most suitable groove shape to minimize the angular distortion

5. Results of numerical analysis

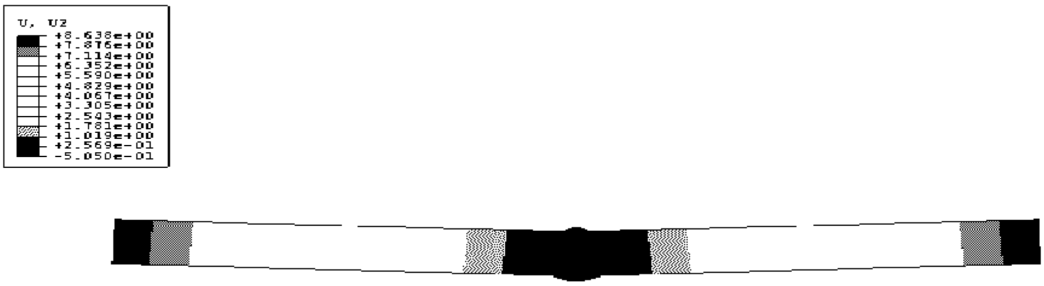
As results of thermal elasto-plastic analysis, those of Model-X3 are presented as the typical example of weld-induced residual deformation. In this section, comparing numerical results with those of experiments, the accuracy of present numerical analysis method was evaluated. The temperature distribution obtained from the heat transfer analysis is applied as a thermal load. Figure 6 illustrates the deformed shape due to X-groove butt welding for Model-X3 and Figure 7 shows the computed welding deflection for Model-X3. From Figure 6 and Figure 7, it can be found that when the groove design parameter, p is 1/3, the angular distortion would be minimized. Experimental and numerical results for angular distortion are compared in Table 2 and Figure 8, from which it can be said that the numerical results show a good agreement with those of experiments.

Table 2 Angular distortions obtained from numerical simulation and experiment

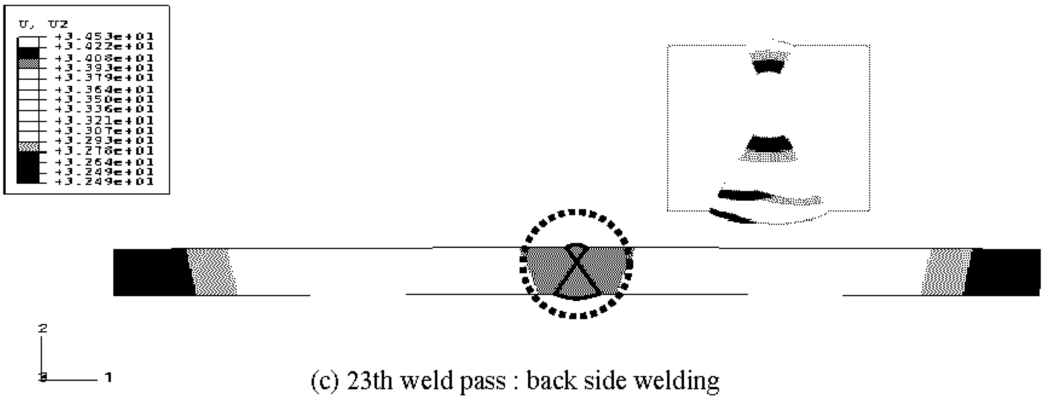
Model	Experimental Results (X10^{-2}rad)	Numerical Results (X10-2rad)	Ratio = Exp./Num.
X1	1.817	1.704	1.066
X2	0.557	0.756	0.737
X3	-0.192	-0.153	1.255



(a) 2nd weld pass



(b) 5th weld pass : front side welding



(c) 23th weld pass : back side welding

Fig. 6 Deformed shape due to X-groove butt welding for Model-X3

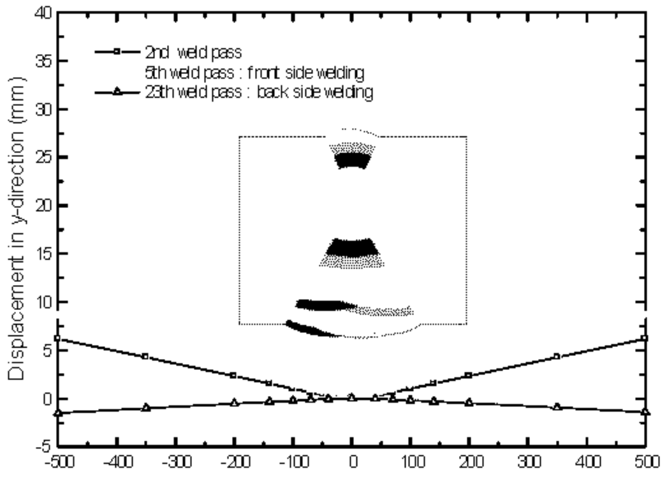


Fig. 7 Computed welding deflection for Model-X3

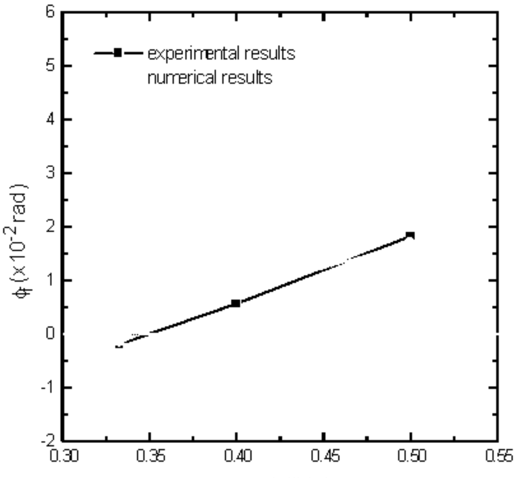


Fig. 8 Comparison of numerical results with experimental results : Model-X1, X2, X3

6. Conclusion

This paper summarizes as follows :

(1) A thermal elasto-plastic analysis method to predict the weld-induced residual deformation was proposed and its validity was confirmed through experiments.
(2) A series of experimental works have been carried out to show the validity of the present numerical analysis procedure, from which it can be said that the proposed simulation method has a good accuracy.
(3) From the experimental and numerical results, it is found that when the groove design parameter, p is 1/3, 2/5 and 1/2 individually, the angular distortion for each plate thickness(t=66mm, 50mm and 30mm) could be minimized.
(4) In order to minimize the weld-induced angular distortion in thick weldments, it is necessary to apply the optimum groove design for each plate thickness.

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