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A Simplified FE Simulation Method with Shell Element for Welding Deformation and Residual Stress Generated by Multi-pass Butt Welding

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Abstract

In order to propose a simplified simulation method using finite element (FE) model for predicting deformation and residual stress generated by multi-pass butt welding, a series of experiments and numerical analyses were carried out. 3-pass butt welding of steel plates was simulated by the thermal elasto-plastic analysis with shell elements and with solid elements respectively. A heat input model for considering the temperature distribution in the thickness direction in shell elements was proposed. The validity of the heat input model was verified by comparing analytical results with experimental results or other analytical results using solid elements. Furthermore, the effectiveness for saving computing time by using shell elements was confirmed from the comparison with the case using solid elements. It was confirmed that the welding out-of-plane deformation and residual stress could be predicted with high accuracy by the proposed method. The computing time was around 14% of that by the precise model with solid elements.

Keywords: welding deformation, residual stress, butt welding, FEM, thermal elasto-plastic analysis

1. Introduction

Welding is widely used for joining and assembling steel structural members in constructing ships, bridges, buildings and so on. Deformation and residual stress are inevitably generated by welding because of expansion and shrinkage of locally heated parts. The welding deformation influences the accuracy of manufacturing structures. When the welding deformation becomes larger than the acceptable value, correction and straightening of it is required (Tamai *et al*., 2002). On the other hand, the welding residual stress reduces the load-carrying capacity and fatigue strength of steel structural members (Martin *et al*., 2002). Sometimes, stress release annealing process is required for constructing important steel structural parts of pressure vessels and line pipe structures (Leggatt, 2008). These processes spend an extra high cost and a long time in manufacturing steel structures. Prediction, control and prevention of welding deformation and residual stress is useful and effective in manufacturing. Then, a method for simulating welding deformation and residual stress with high accuracy and high effectiveness is necessary.

Because FE (Finite Element) analysis is a useful simulation method for prediction of welding deformation and residual stress, a lot of researches related to FE simulation methods of welding process have been reported (Michaleris *et al*., 1999; Zhu *et al*., 2002). Welding is a complicated phenomenon involving non-steady heat transfer due to movement of heat source and temperature dependency of physical constants and mechanical properties of material. Furthermore, three dimensional elasto-plastic problems should be treated for thermal conduction around the weld groove (Lindgren, 2006). Therefore, it takes a long computing time for simulating welding process precisely by FE analysis even though performances of computer currently become higher and higher.

To this problem, the authors proposed an effective simulation method by FE analysis with two dimensional shell elements for predicting the welding deformation and residual stress generated by one-pass butt welding of thin steel plates (Hirohata and Itoh, 2014). It was confirmed that the welding deformation and residual stress could be predicted with high accuracy and the computing time by the proposed method could be largely saved compared with the case using three dimensional solid elements. Although the proposed method by the authors was effective, the application was limited in one-pass butt

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welding of thin steel plates. It is necessary that the application of the proposed simulation method is extended to multi-pass welding because general steel structural members are actually assembled by not only one-pass welding but also multi-pass welding.

In order to propose a simplified simulation method using FE analysis for predicting welding deformation and residual stress generated by multi-pass butt welding, a series of experiments and numerical analyses are carried out in this study. 3-pass butt welding of steel plates are simulated by the thermal elasto-plastic analysis with shell elements and with solid elements respectively. A heat input model for considering the temperature distribution in the thickness direction of the shell elements proposed by the authors (Hirohata and Itoh, 2014) are modified for applying to the multi-pass welding. The validity of heat input model is investigated by comparing the analytical results with the experimental results or the other analytical results using solid elements. Furthermore, the effect for saving computing time by using shell elements is examined from the comparison with the case using solid elements.

2. Multi-pass Butt Welding Experiment

2.1. Specimen and experimental procedure

In order to verify the validity of simulation method proposed in this study, a multi-pass but welding experiment is performed. Figure 1 shows the shapes and dimensions of specimen. The base metal and welding wire are general structural steels specified by JIS (SM400A and YGW11) (Japanese Standards Association, 2008 and 2009). The thickness of base metal is 12 mm. Table 1 shows the mechanical properties and chemical compositions of materials.

For obtaining deformation and residual stress generated by butt welding with high accuracy, a specimen should be made so that a linear misalignment due to tack welding does not occur (Kim *et al*., 2007a). Therefore, the specimen is not assembled by two plates but by only one plate with V-shaped groove in the center of it. The width of plate is 300mm. Although the length of plate is also 300 mm, there are small tabs for the start and end of weld line. The length of weld line is 340 mm including 20 mm length of the start and end of welding on the tabs.

Butt welding is performed on the V-shaped groove by CO_2 semi-automatic arc welding with three passes. Table 2 shows the welding conditions of each pass. After the first welding pass is finished and the temperature at the end of weld line reaches to 200 degrees Celsius, the next pass is started. The third pass is started in the same way after the second pass is finished. There may generally be the influence of time intervals between each pass on the residual stress distribution if the time interval is short. In order to minimize this influence of time interval in the experiment, the time intervals between each pass were taken long enough. When the temperature at the end of

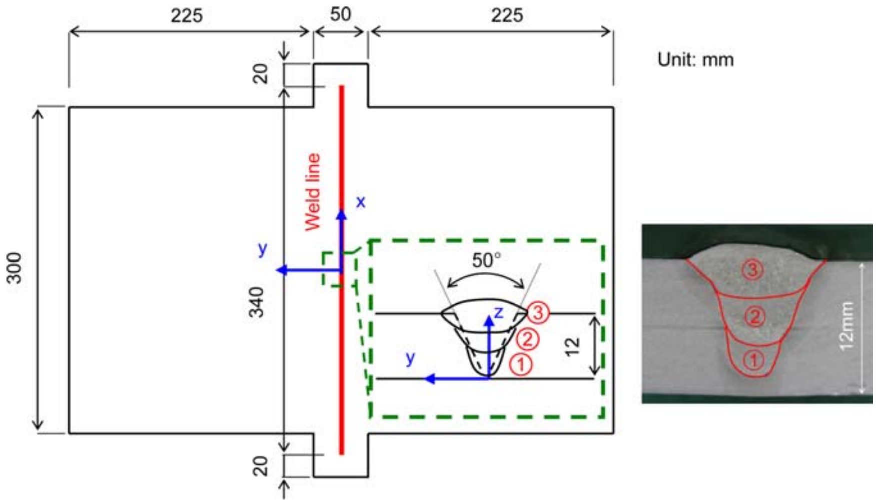


Figure 1. Shape and dimension of specimen.

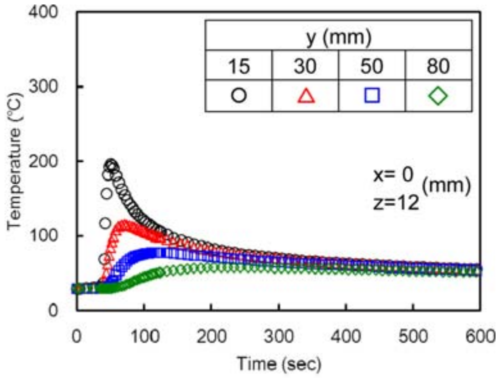
Table 1. Mechanical properties and chemical compositions of materials

	Mechanical properties			Chemical compositions				
	Yield stress	Ultimate strength	Elongation	C	Si	Mn	P	S
	MPa	MPa	%	wt%				
Base metal	304	455	30	0.16	0.20	0.53	0.026	0.005
Welding wire*	490	570	31	0.08	0.51	1.10	0.010	0.010

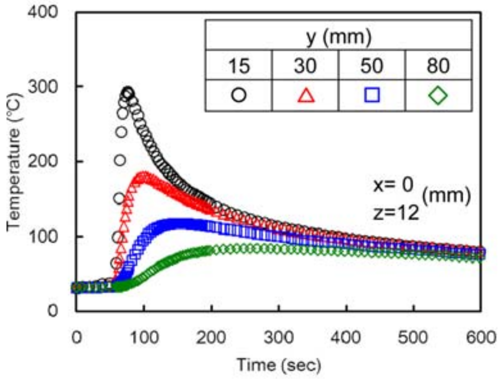
*Catalog value

Table 2. Welding conditions of each pass

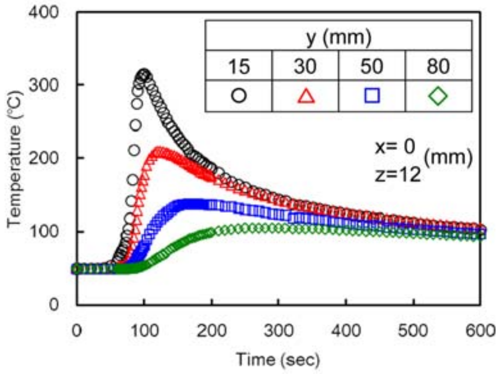
	Current	Voltage	Speed
Pass	A	V	mm/s
1	120	20	5.2
2	115	20	2.8
3	105	20	2.1



(a) Pass 1



(b) Pass 2



(c) Pass 3

Figure 2. Temperature histories obtained by each welding pass.

weld line reached to 200 degrees Celsius, the temperature near the center of specimens became around 60 degrees Celsius. That is, there might be little influence of time intervals between each pass on residual stress distribution in this experiment.

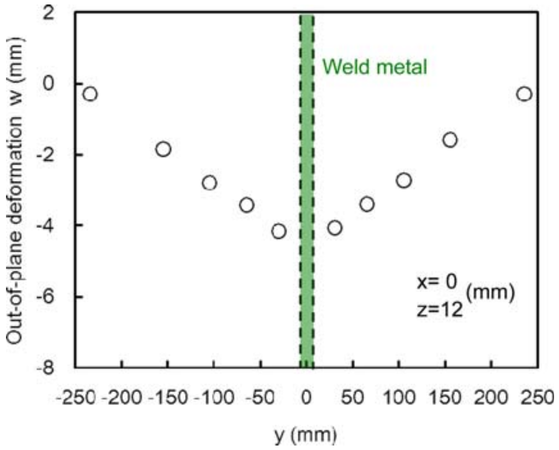


Figure 3. Welding out-of-plane deformation.

The temperature histories in the three passes are measured by thermocouples attached on the surface of plate at the center of weld line (x=0 mm, z=12 mm and y=15, 30, 50, 80 mm). After the three welding passes are finished, the welding out-of-plane deformation is measured by dial gages and the residual stress is measured by the X-ray diffraction (XRD) method (Balasingh and Singh, 2000).

2.2. Experimental results

2.2.1. Temperature histories

Figure 2 shows the temperature histories obtained by each welding pass. The maximum temperature was around 200 degrees Celsius in the first pass at the position of which the distance from the weld line was 15 mm. Those in the second and third passes were around 300 degrees Celsius.

2.2.2. Welding deformation

Figure 3 shows the welding out-of-plane deformation at the center of weld line. The welding out-of-plane deformation is generated due to a difference of temperature between the upper and the lower surfaces of plates in the case of butt welding with V-groove (Japan Welding Society, 2003). In other words, heat energy at the upper surface is larger than that at the lower surface. Therefore, larger shrinkage in cooling process of welding occurs at the upper surface rather than at the lower surface. The V-shaped welding out-of-plane deformation was generated in the specimen. The out-of-plane deformation at the weld metal could not be measured due to the convex shape of weld bead. The magnitude of out-of-plane deformation was around 4.5 mm.

2.2.3. Welding residual stress

Figure 4 shows the welding residual stress around the weld line measured by the XRD method (Balasingh and Singh, 2000). The change of distance of crystal lattice is obtained from the X-ray diffraction angle. The distance

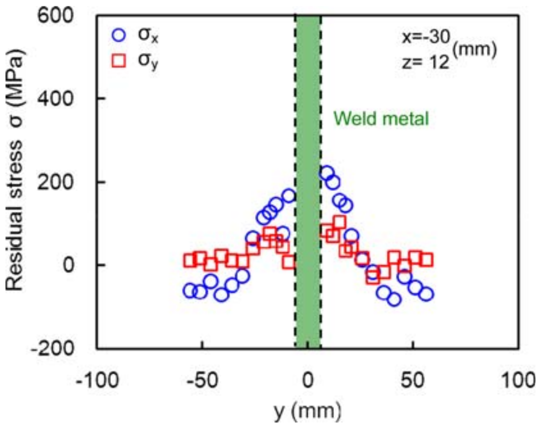


Figure 4. Welding residual stress.

change between the before and the after welding corresponds to the strain generated by welding, that is, the stress generated by welding is measured. However, the XRD method cannot be applied on the weld metal because the crystal lattice distances cannot be measured accurately in the weld metal of which the grain size is coarse. The magnitude of residual stress component in the weld line direction was around 200 MPa at the position of which the distance from the weld line was 10 mm.

3. FE Simulation by Thermal Elasto-plastic Analysis Model

3.1. Precise analysis model with solid elements

It is general that three dimensional solid elements are used for FE simulation of welding process because the three dimensional weld groove shape should be considered. The above welding experiment is simulated by the model with generally used solid elements for investigating its accuracy and computing time. Figure 5 shows the analysis model with solid elements by which precisely simulates the shape of specimen and the welding process, so called, the solid model. A commercial FE program, ABAQUS Ver. 6.13 is used. A half model is adopted by considering symmetric conditions along the weld line. The temperature dependencies of the mechanical properties and physical constants are considered in the analysis (Kim *et al*., 2007b). The shapes of weld metal is modelled by referring the macrograph of welded part as shown in Fig. 5. For modeling the movement of welding heat source, heat input elements are generated step by step in the calculation considering the welding speed. In this model, there are 34 elements in the weld line. The length of each heat input element, L is 10 mm. Therefore, the number of the calculation steps for heat input is 34 per each welding pass. And also, additional calculation step for cooling is required after the heating steps. Of course, each calculation step is divided into many fine time increments.

The heat input of welding, Q (J/mm) is calculated by Eq. (1) (Japan Welding Society, 2003). The heat energy, q_m (J/mm^3) by Eq. (2) is given into the heat input elements as a body heat flux. The heating time per each heat input element is decided by dividing the length of each heat input element, L (mm) by the welding speed, v (mm/s). The sectional area, A (mm^2) is decided by referring the shapes of weld metal of each pass from the macrograph. The heat efficiency, η is selected from 0.65 to 0.8 which are the general values of arc welding (Japan Welding Society, 2003) for simulating the temperature histories obtained by the experiment accurately.

A heat transfer from the surface of model is considered as thermal boundary conditions (Kim *et al*., 2007b). A rigid body displacement is fixed as mechanical boundary conditions.

$$Q = \eta\frac{EI}{v} \tag{1}$$

$$q_m = \frac{Q}{A}\cdot\frac{v}{L} \tag{2}$$

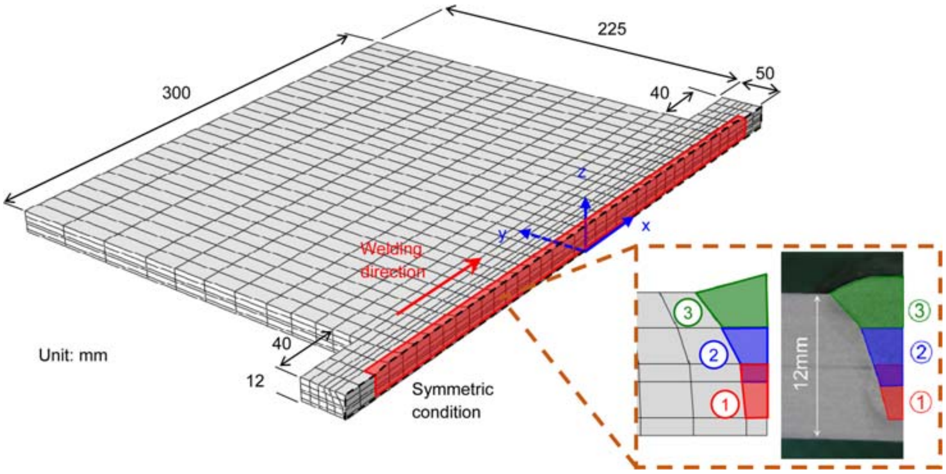


Figure 5. Precise analysis model with solid elements (solid model).

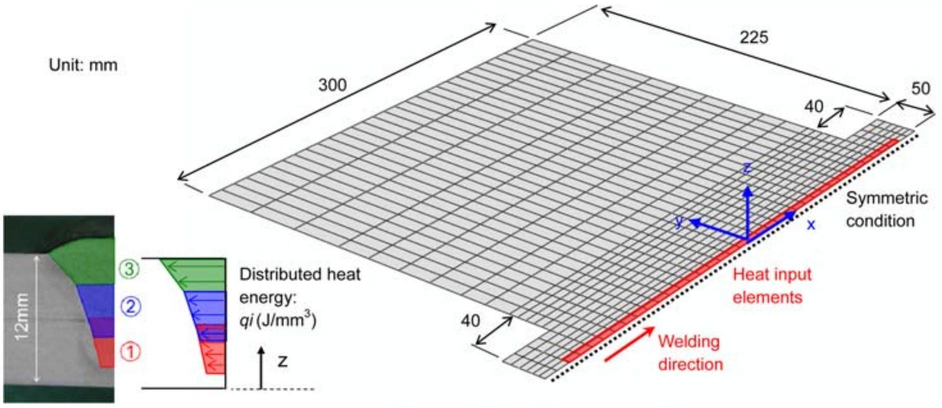


Figure 6. Simplified analysis model with shell elements (shell model).

Here,

Q : Heat input (J/mm)
η : Heat efficiency (65 to 80% in arc welding) (Japan Welding Society, 2003)
E : Welding voltage (V)
I : Welding current (A)
v : Welding speed (mm/s)
A : The sectional area of the heat input elements
q_m : Heat energy (J/mm^3)
L : The length of each heat input element (mm)

3.2. Simplified analysis model with shell elements

The FE simulation of welding generally spends a long computing time because three dimensional solid elements should be used. In order to model the geometric shape of groove and make some layers in the thickness direction, a large number of nodes and elements are required. Therefore, the authors proposed a simplified simulation model using two dimensional shell elements for reducing the number of nodes and elements (Hirohata and Itoh, 2014). Although the previously proposed model was for one-pass butt welding, the applicability of that method is extended to multi-pass welding in this study.

Figure 6 shows the simplified analysis model with 4-nodes shell elements, so called, the shell model. The number of nodes and elements in the thickness direction can be decreased by using the shell elements even though the number of them in the welding direction is the same as that of the solid model. The shape of groove can be simulated by the solid model. Although the shape of groove cannot be considered in the shell model, the sectional area of heat input element is made to be the same as that of the solid model. The movement of heat source is considered in both the solid model and the shell model. And then, the heat energy calculated by Eq. (3) is given into the heat input elements as the concentrated heat flux. The welding out-of-plane deformation occurs due to a difference of temperature between the upper and the lower surfaces of butt welding plates with V-groove (Japan Welding Society, 2003). In order to consider the difference of heat energy in the thickness direction resulting from the groove shape, the heat energy distribution based on the sectional area of each welding pass is assumed. The distributed heat energy is given into each integration point in the heat input elements. There are 9 integration points in the thickness direction of heat input elements of this model (n=9). The concentrated heat flux is applied on the integration points corresponding to the positions in the thickness direction of each welding pass. That is, the heat input distribution in the thickness direction of heat input elements are simulated by changing the position on which the heat energy is given and the magnitude of heat energy according to each welding pass.

$$q_i = \frac{d_i}{d_{ave}} \frac{1}{n} q_m A L \qquad (3)$$

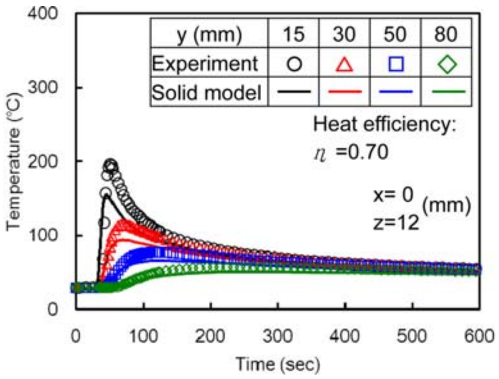
Here,

q_i : The distributed heat energy of i-th integration point (J/mm^3)
d_i : The width of weld metal at the position of each integration point in the thickness direction
d_{ave} : The average width of weld metal
n : The number of integration points inside the heat input element (n is 9 in this case)

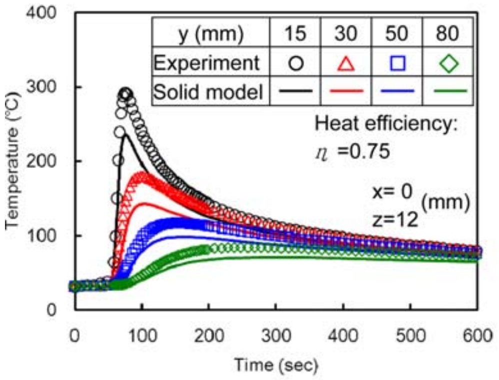
4. FE Analysis Results

4.1. Temperature histories

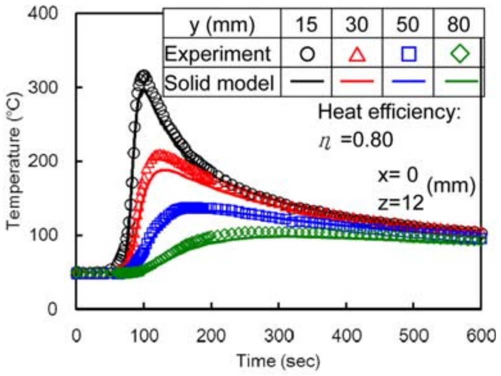
Figures 7 and 8 show the temperature histories obtained by the non-steady thermal conduction analysis with the solid model and the shell model respectively. Figure 9 shows the comparison of analytical results by the solid model and the shell model. It is indispensable that the temperature data are simulated with high accuracy because the temperature data obtained by the non-steady thermal conduction analysis are used as input data for the thermal elasto-plastic stress analysis. In order to simulate the temperature histories obtained by the experiment as accurate as possible, the calculations were tried in some times with



(a) Pass 1

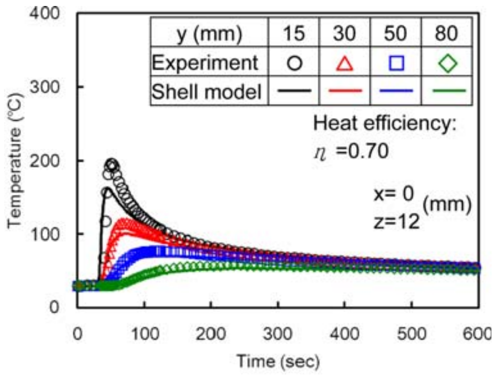


(b) Pass 2

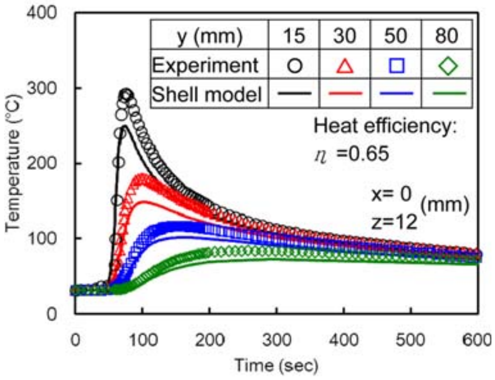


(c) Pass 3

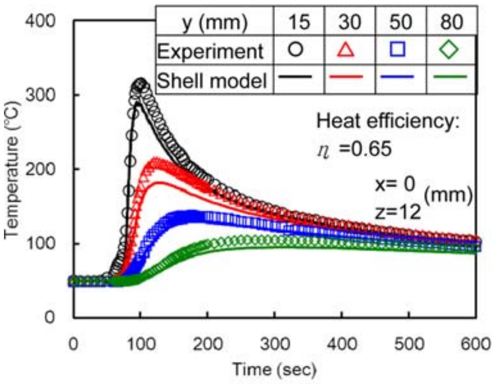
Figure 7. Temperature histories obtained by solid model.



(a) Pass 1



(b) Pass 2



(c) Pass 3

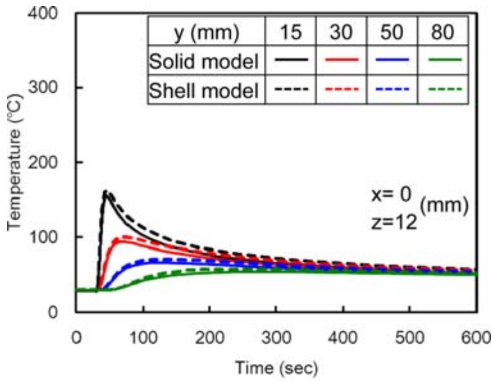
Figure 8. Temperature histories obtained by shell model.

varying the heat efficiency, η. Due to the differences of the heat input element volumes between the solid model and the shell model, the uniform heat efficiency was not suitable for both models from the purpose that the temperature histories be simulated as accurate as possible in each model.

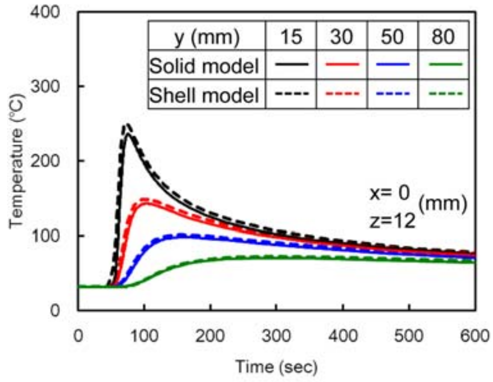
The peak temperatures of analysis models were relatively lower than those of experiments. The differences between them are large in the first and the second passes. Those of the third pass are relatively small. The peak temperatures near the weld line are difficult to be measured because they change drastically around the weld line. It depends on the accuracy of attachment positions of thermocouples. However, the gradients in cooling processes of analysis agreed with those of experiments. Therefore, it can be judged that the analytical results are acceptable from the viewpoints of total welding processes.

4.2. Welding deformation

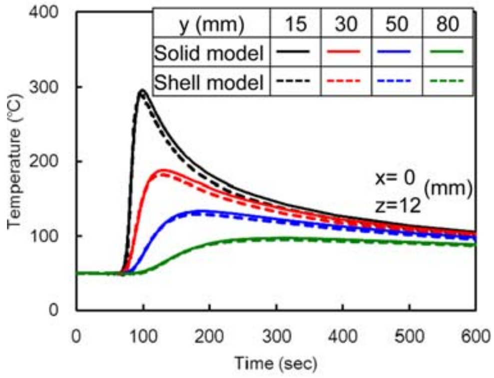
The thermal elasto-plastic stress analysis was carried out by using the obtained temperature data through the thermal conduction analysis. Figure 10 shows the welding out-of-plane deformation. The V-shaped welding out-of-plane deformation obtained by the experiment could be simulated by both of the solid model and the shell model. The results indicated the validity of the proposed simulation



(a) Pass 1



(b) Pass 2



(c) Pass 3

Figure 9. Comparison of temperature histories obtained by solid model and shell model.

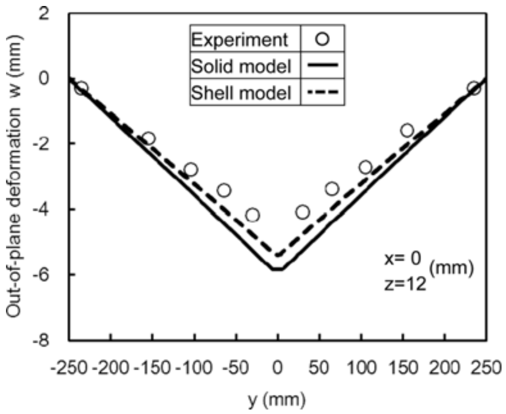


Figure 10. Welding out-of-plane deformation obtained by solid model and shell model.

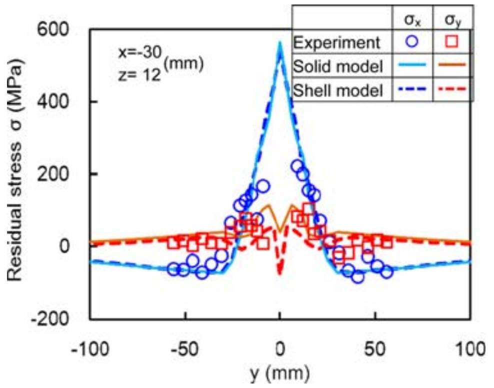


Figure 11. Welding residual stress obtained by solid model and shell model.

Table 3. Computing time comparison of solid model and shell model

	Nodes	Elements	Computing time (s)
Solid model	3870	2940	7292
Shell model	707	648	996

model with shell elements and heat input method for it.

4.3. Welding residual stress

Figure 11 shows the welding residual stress distributions obtained by the thermal elasto-plastic stress analysis. The analytical results by both of the solid model and the shell model were almost the same. They accurately simulated the experimental results obtained by the XRD method. Furthermore, the residual stress distribution in the weld metal could be simulated by the analysis, which could not be measured by the XRD method. Although the magnitude of residual stress component in the welding direction was over the yield stress of material, it was confirmed that the equivalent stress agreed with the yield stress of material.

4.4. Computing time

Table 3 shows the comparison of the number of nodes and elements and the computing time between the solid model and the shell model. When using a general personal computer (CPU 3.40 GHz), the computing time by the shell model was around 14% of that by the solid model. The effectiveness could be confirmed by using the simplified simulation model with shell elements proposed in this study.

5. Conclusions

In order to propose a simplified effective calculation method by FE simulation for predicting deformation and residual stress generated by multi-pass butt welding of steel plates, a series of experiments and numerical analyses were carried out.

The obtained main results are as follows.

(1) A method was proposed for applying two dimensional shell elements instead of generally used three dimensional solid elements in simulating the 3-pass butt welding experiment. In order to consider the difference of heat energy in the plate thickness direction resulting from the groove shape, the heat energy distribution based on the sectional area of each welding pass was assumed.

(2) The non-steady thermal conduction analysis was carried out for simulating the 3-pass butt welding experiment by both of the precise model with solid elements and the simplified model with shell elements respectively. The temperature histories during the welding processes could be simulated by both of the analysis models.

(3) The thermal elasto-plastic stress analysis was carried out by using the obtained temperature data through the thermal conduction analysis. The V-shaped welding out-of-plane deformation obtained by the experiment could be simulated by the simplified simulation model with shell elements. The residual stress distributions by both of the models with solid elements and with shell elements were almost the same. They simulated accurately the experimental results obtained by the XRD method. These results indicated the validity of the proposed simulation model with shell elements and heat input method.

(4) The computing time by the simplified model with shell elements was around 14 % of that by the precise model with solid elements. The effectiveness could be confirmed by using the proposed simplified model with shell elements for simulating the welding deformation and residual stress generated by butt welding.

(5) As a future work, the expansion of this methodology to T-shape or pipe structures is necessary because these structural types are more important and practical from the viewpoint of actual application to actual structures like long-span bridges or large ships.

Acknowledgment

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