NUMERICAL SIMULATION OF WELDING DEFORMATION AND RESIDUAL STRESS BY FEM WITH SHELL ELEMENTS

M. HIROHATA[1*†] and Y. ITOH[1]

[1]*Graduate School of Engineering, Nagoya University, Japan*

ABSTRACT

A series of numerical analyses was carried out for investigating an applicability of shell elements on a simulation of deformation and residual stress generated by a butt welding of thin steel plates. A heat input model for considering the temperature distribution in the thickness direction of the shell elements was proposed. The validity of the heat input model was verified by comparing the analytical results with the experimental results or the other analytical results using the solid elements. Furthermore, it was confirmed that the computing time by using the shell elements was around 8 % of that by the solid elements. These results indicated that simulations of welding deformation and residual stress of large steel structures became considerably easier by using the shell elements.

Keywords: Steel structure, welding deformation, residual stress, FEM, shell element.

1. INTRODUCTION

In constructing steel structures, welding is generally used for joining and assembling members. Then, welding deformation and residual stress are inevitably generated due to expansion and shrinkage of welded parts caused by local heating/cooling. Welding deformation and residual stress influence an accuracy of manufacturing and strengths of members (JSCE 2005). Therefore, it is important that welding deformation and residual stress are predicted and controlled.

For predicting welding deformation and residual stress generated in steel structural members, a thermal elasto-plastic analysis based on FEM is an effective method. In the analysis, three dimensional solid elements are generally used for considering geometric shapes of weld groove. It has been cleared that welding deformation and residual stress are simulated with high accuracy by FEM with solid elements (Kim et al. 2007).

On the other hand, shell elements are more effective than the solid elements from the viewpoints of saving computing time when welding of large structural members is simulated. However, it is not

* Corresponding author: Email: hirohata@civil.nagoya-u.ac.jp

† Presenter: Email: hirohata@civil.nagoya-u.ac.jp

clear how three dimensional shapes of weld groove are modelled by using shell elements. Furthermore, accuracies of simulated results by using shell elements are unknown.

The author has been conducted the several kinds of numerical simulations for predicting the welding deformation and residual stress by FEM (Kim et al. 2012).

In this study, a series of numerical analyses was carried out for investigating an applicability of shell elements on a simulation of welding deformation and residual stress. A butt welding of thin steel plates was simulated by a thermal elasto-plastic analysis with shell elements and with solid elements respectively. By comparing these analytical results with experimental results, an effectiveness of shell elements in simulating welding deformation and residual stress was examined from the viewpoints of an accuracy of analytical results and computing time.

2. ANALYSIS MODEL

Figure 1 shows analysis models in this study. A one pass butt welding of thin steel plates was simulated by a thermal elasto-plastic analysis.

A half model was adopted by considering symmetric conditions along the weld line. A commercial FE program ABAQUS Ver. 6.10 was used for the simulation.

The analysis models were assembled by 8-nodes solid elements and 4-nodes shell elements respectively. They were named the solid model and the shell model. In the case of the solid model, the shape of the heat input elements was determined by considering the geometry of V-groove. In the case of the shell model, the shape of the groove could not be considered. However, the total sectional area of the heat input elements was determined the same as that of the solid model. The heat energy calculated by equations (1) and (2) was gradually given into these heat input elements in the welding direction. The moving of heat source was considered by using an element birth function.

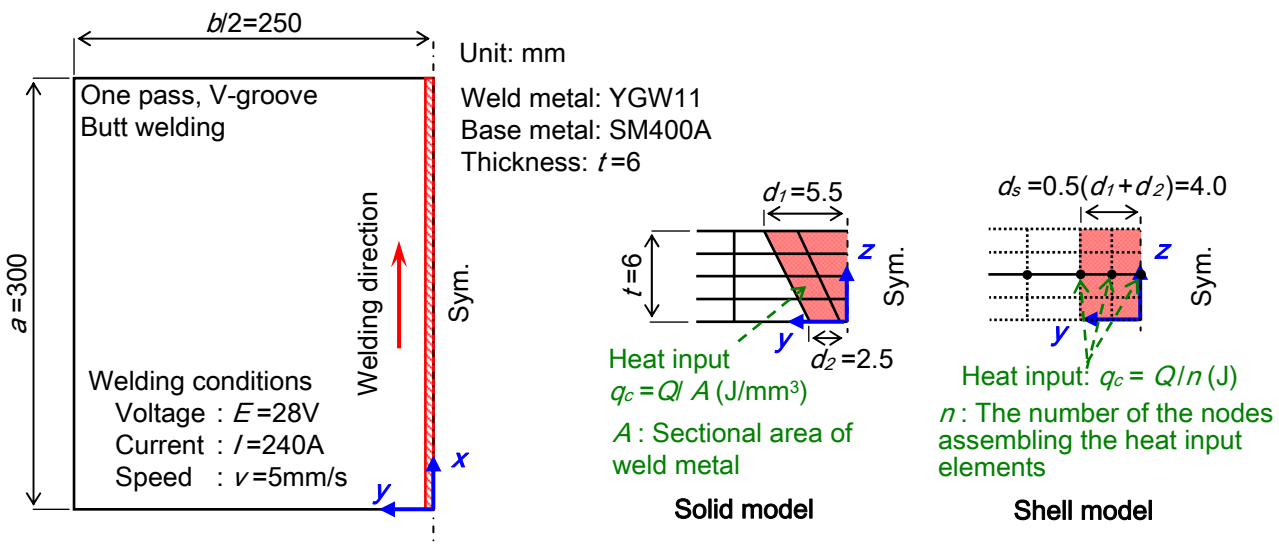


Figure 1: FE models for analysis

$$q_c = \begin{cases} Q/A & \text{(Solid model)} \\ Q/n & \text{(Shell model)} \end{cases} \tag{1}$$

$$Q = \eta \frac{EI}{v} \tag{2}$$

Here, q_c : Heat energy (J/mm^3),

A : The sectional area of the heat input elements,

n : The number of nodes assembling the heat input elements,

Q : Heat input (J/mm),

η : Heat efficiency (from 65 to 80% in arc welding) (JWS 2003),

E : Welding voltage (V),

I : Welding current (A), and

v : Welding speed (mm/sec.).

Mechanical properties and physical constants with temperature dependencies were considered in the thermal elasto-plastic analysis (Kim et al. 2005).

A heat transfer from the surface of model was considered as thermal boundary conditions. A rigid body displacement was fixed as mechanical boundary conditions.

3. ANALYSIS RESULTS

3.1. Temperature histories

Figure 2 shows the temperature histories in the welding. The symbols in the figures represent the experimental results performed by the same welding conditions as that of the analysis model in this study (Kim et al. 2007). Measured positions of the temperature were at the bottom of the plates of the center in the welding direction. The distances from the weld line were 15 mm, 30 mm, 50 mm and 80 mm (y=15, 30, 50 and 80).

Both of the analytical results by the solid model and by the shell model almost agreed with the experimental results. The maximum temperature at the position of y=15 of the shell model was higher than that of the solid model by around 40 degrees Celsius. The reason of it was possibly the difference of the shapes of the heat input elements. That is to say, the width of the heat input elements at the bottom of the shell model was wider than those of the solid model. Therefore, the larger heat energy reached to the temperature measured points in the shell model compared with the solid model.

3.2. Welding residual stress

Figure 3(a) shows distributions of welding residual stress at the cross section of the center in the welding direction. The symbols in the figures represent the experimental results obtained by a

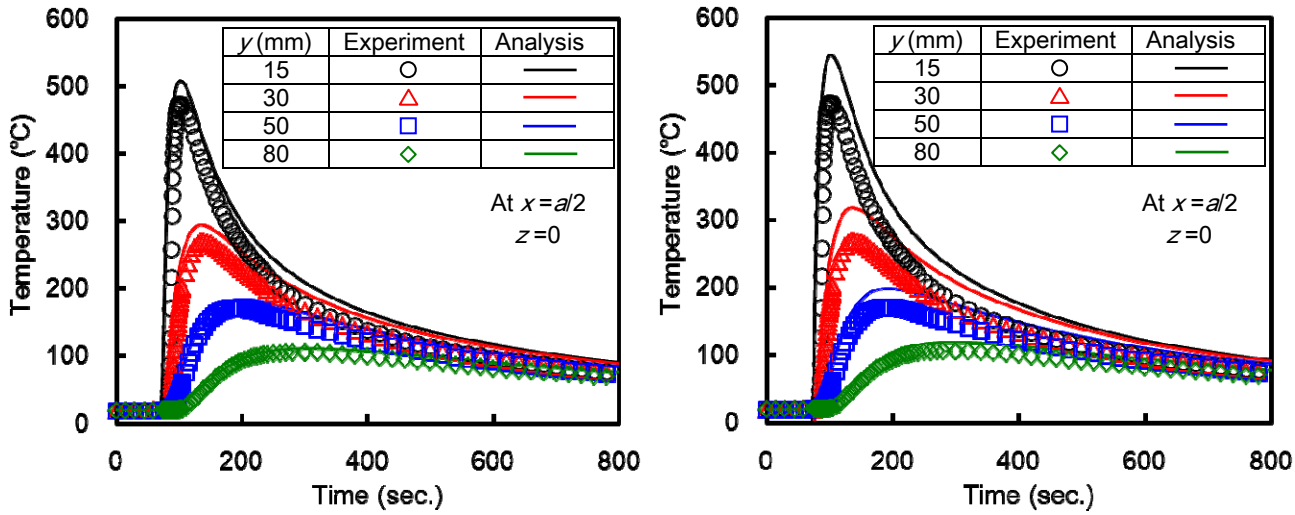
stress relaxation method (Kim et al. 2007). The values of the stress are the average in the thickness direction.

Both of the analytical results by the solid model and by the shell model simulated the experimental result well. Furthermore, these analytical results were almost the same with each other.

3.3. Welding out-of-plane deformation

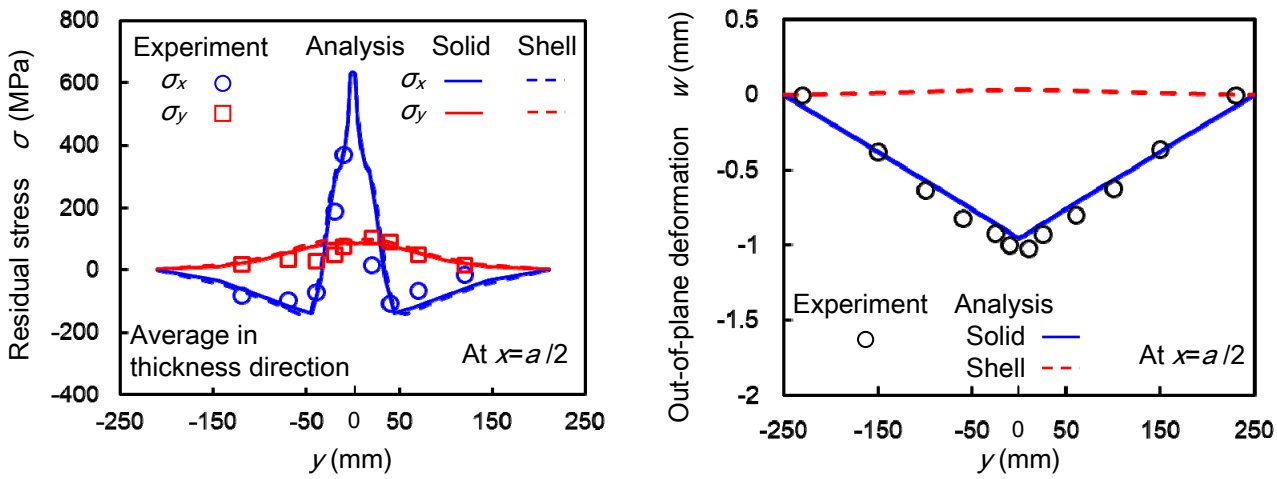
Figure 3(b) shows welding out-of-plane deformations at the center of the welding direction. The symbols in the figures represent the experimental results (Kim et al. 2007).

The analytical result by the solid model agreed with the experimental result. On the other hand, in the case of the analytical result by the shell model, the out-of-plane deformation scarcely occurred.



(a) Solid model (b) Shell model

Figure 2: Temperature histories



(a) Welding residual stress (b) Welding out-of-plane deformation

Figure 3: Welding residual stress and out-of-plane deformation

4. A PROPOSAL OF HEAT INPUT METHOD FOR SHELL MODEL

In the case of one pass butt welding of thin steel plates with V-groove, an out-of-plane deformation occurs due to a difference of temperature between upper and lower surfaces of plates (JWS 2003). In other words, heat energy at upper surface is larger than that at lower surface. Therefore, larger shrinkage in cooling process of welding occurs at upper surface rather than at lower surface.

In the shell model in this study, the difference of the heat energy between the upper and the lower surfaces could not be considered. Therefore, the out-of-plane deformation did not occur.

To solve this problem, a heat input method for the shell model shown in Figure 4 was proposed in this study.

The linear distribution of the heat energy in the thickness direction calculated by equation (3) was considered. The difference of the heat energy between the upper and the lower surfaces was determined by the geometry of V-groove shape. The distributed heat energy was given into each integration point in the heat input elements.

$$q_d = \frac{d(z)}{d_s}\frac{1}{n_i}q_c \tag{3}$$

Here, q_d : The distributed heat energy (J/mm^3),

$d(z)$: The z-coordinate of each integration point,

d_s : The width of heat input elements,

n_i : The number of integration points in the thickness direction, and

q_c : The uniform heat energy calculated by equation (1) (J/mm^3).

Figure 5 shows the temperature histories obtained by the thermal conduction analysis with the proposed heat input method. The maximum temperature at the position of y=15 obtained by the proposed heat input method became lower by 7 degrees Celsius compared with that obtained by the previous shell model without considering the distributed heat energy.

Figure 6 shows the result of the thermal elasto-plastic analysis with the proposed heat input method. By considering the distribution of the heat energy in the thickness direction in the shell model, the welding out-of-plane deformation could be simulated with high accuracy. It could be said that the proposed heat input method was valid. And then, the residual stress distribution was almost the same as that of the solid model although the proposed heat input method was used in the shell model.

5. COMPUTING TIME

When using a general personal computer (CPU 2.93 GHz), the computing time of the solid model was 4462.4 second. On the other hand, the computing time of the shell model was 360.2 second. The computing time of the shell model was around 8 % of that of the solid model.

The obvious effectiveness could be confirmed even in the simple analysis model in this study. The results indicated that the larger analysis models such as actual steel structures are simulated, the higher effectiveness by using the shell elements will be expected.

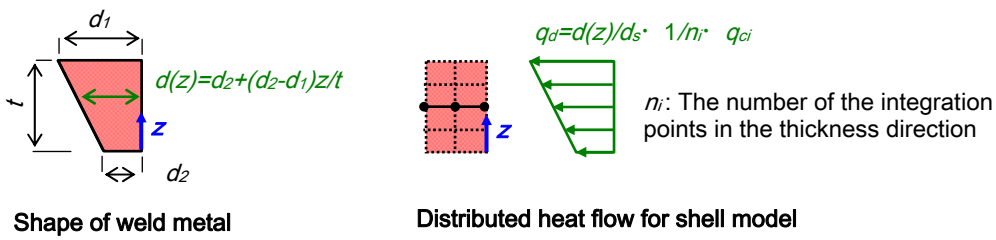


Figure 4: Heat input method considering distributed heat energy in thickness direction

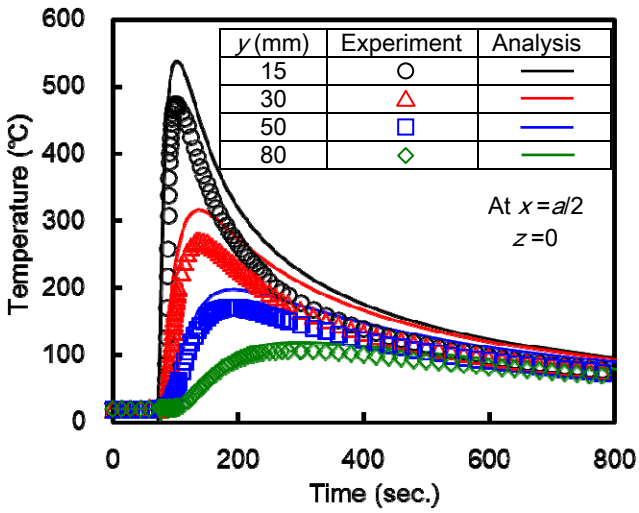
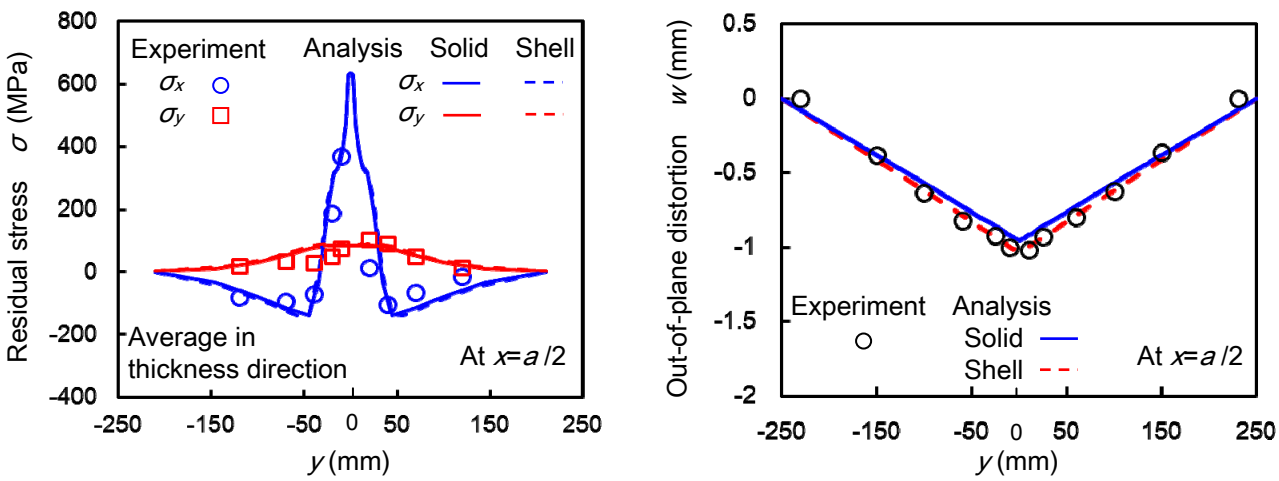


Figure 5: Temperature histories with distributed heat input



(a) Welding residual stress

(b) Welding out-of-plane distortion

Figure 6: Welding residual stress and deformation with distributed heat input

6. CONCLUSIONS

A butt welding of thin steel plates was simulated by FEM with 4-nodes shell elements (the shell model) and with 8-nodes solid elements (the solid model) respectively. By comparing these analytical results with the experimental results, the effectiveness of the shell elements in simulating welding deformation and residual stress was investigated.

The obtained main results are as follows.

(1) Although the temperature by welding of the shell model was higher than that of the solid model, the temperature histories by both models simulated the experimental results.

(2) The residual stress distribution of the shell model and the solid model agreed with the experimental results.

(3) The welding out-of-plane deformation of the solid model simulated the experimental results with high accuracy. However, the out-of-plane deformation scarcely occurred in the shell model without considering the difference of the heat energy between the upper and the lower surfaces.

(4) A heat input method for the shell model was proposed by considering the geometry of weld groove. The welding out-of-plane deformation could be simulated with high accuracy by using this heat input method.

(5) The computing time of the shell model was around 8 % of that of the solid model. The results indicated that the larger analysis models such as actual steel structures are simulated, the higher effectiveness by using the shell elements will be expected.

REFERENCES

Japan Society of Civil Engineers (2005). Guidelines for Stability Design of Steel Structures, MARUZEN Co., Ltd.

Japan Welding Society (2003). A Handbook of Welding and Joining 2nd edition, MARUZEN Co., Ltd.

Kim YC, Lee JY and Inose K (2005). The High Accurate Prediction of Welding Deformation Generated by Fillet Welding, Quarterly Journal of Japan Welding Society, Vol. 23, No. 3, pp. 431–435.

Kim YC, Lee JY, Sawada M and Inose K (2007). Verification of Validity and Generality of Dominant Factors in High Accurate Prediction of Welding Deformation, Quarterly Journal of Japan Welding Society, Vol. 25, No. 3, pp. 450–454.

Kim YC, Hirohata M, and Inose K (2012), Effects of phase transformation on distortion and residual stress generated by LBW of high strength steel, Welding in the World, Vol. 56, 03/04, pp.64-70.