Influence of Various Factors on Welding Distortion of Thin-plate Structures*

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The large deformation including bucking may occur due to welding on thin-plate structures. The prediction of welding distortion on thin-plate structures is difficult since change of deformation mode may occur. In this research, in order to evaluate the welding distortion of thin-plate structures, an analysis method that considers large deformation theory in thermal elastic plastic analysis using Idealized Explicit FEM with solid elements was developed. The developed method was applied to the analysis of stiffened thin-plate structures. The influence of heat input \( Q \) and welding speed \( v \) on large deformation were investigated in the analysis. As a result, it was clear that a buckling-type deformation occurs with larger heat input \( Q \). In addition, it was also found that the bucking-type deformation mode varies with the above factors. It can be assumed that these factors affect the transient deformation behavior on welding and this causes the various generating process of buckling-type deformation. In addition, to discuss the analysis accuracy, the welding distortion of stiffened structure was analyzed and the analyzed results were compared with the experimental measurements. As a result, it was found that both deformations agree with each other. From these results, it was clearly seen that the developed method can stably analyze the welding deformation of stiffened thin-plate structures with large deformation including bucking without introducing initial imperfections.

Key Words: Thermal elastic plastic analysis, Welding Distortion, Thin plate structures, Large deformation analysis, Buckling

1. Introduction

Welding is widely utilized to join the structural members on the production of thin plate structures, such as airplanes, automobiles and ships. On the welding of these thin plate structures, deformation occurs inevitably and it may cause problems. Especially, buckling type deformation occurs due to the geometric nonlinearity of structures and it generates very complex and large deformation. Therefore, to prevent such deformation, it is important to consider buckling strength in the design stage.

To analyze welding deformation including bucking, elastic analysis using inherent strain\(^1\)\(^-\)\(^3\) is widely used. This method can analyze the large deformation problems with saving computing time, but cannot predict the changes of deformation and stress during welding from the beginning of heating to the complete cooling.

On the other hand, thermal elastic-plastic finite element analysis using moving heating source is available to predict the changes of them. However, there are a few previous studies about large deformation analysis by thermal elastic-plastic finite element analysis with using solid elements because of the scale of analysis and the convergence property.

To predict large-scale welding deformation and residual stress problems in realistic computing time, the authors have developed Idealized Explicit FEM (IEFEM\(^3\)). The method is based on dynamic explicit method and it was demonstrated that the IEFEM can simulate the large-scale problem which is difficult to simulate using conventional method. Furthermore, since the IEFEM is based on the dynamic explicit method, it can be considered that the IEFEM can effectively analyze buckling phenomena including snap-through\(^5\) or bifurcation\(^5\) without introducing initial imperfections.

In this study, an analysis method is developed to predict the buckling deformation on welding based on the IEFEM by considering geometric nonlinearity. The developed method is applied to fillet welding of T-joint to investigate the influences of heat input \( Q \) and welding speed \( v \) on the deformation. And the developed method is also applied to the analysis of the stiffened structure to show the validity of the developed method through the comparison with the experimental results.

2. Geometrical nonlinearity

The geometrical nonlinearity is considered in this research to analyze large-deformation phenomena. To consider the geometrical nonlinearity, the following Green–Lagrange strains are employed:

\[
\varepsilon = \frac{1}{2} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_k} \frac{\partial u_k}{\partial x_j} \right]
\] (1)
3. Study on T-joint model

3.1 Analysis model and condition

Figure 1 shows analysis model. The model has a flange on the top of the web and its width is 50 mm. The plate thickness is 2 mm, the length is 1,000 mm, the width is 200 mm and height of the web is 50 mm.

The plate is divided into 4 elements in thickness direction. The number of nodes and elements are 48,379 and 40,600, respectively. The welding is conducted on both sides simultaneously. The heat input \( Q \) is 100 J/mm and welding speed \( v \) is 10 mm/s. To investigate the influence of welding condition on deformation, heat input \( Q \) and welding speed \( v \) are changed. Temperature dependent material constants are shown in Fig. 2. In the figure, the constants are defined as follows;

- \( E \) : Young’s modulus, \( \sigma_y \) : Yield stress, \( \nu \) : Poisson’s ratio, \( \alpha \) : Thermal expansion coeff., \( \epsilon \) : Specific heat, \( \rho \) : Density, \( \lambda \) : Heat conductivity coeff.

![Solid element](image)

Fig. 1 Analysis model of T-joint.

3.2 Influence of heat input

To investigate the influence of the heat input \( Q \), heat input \( Q \) is changed from 75 J/mm to 300 J/mm. Figure 3 shows distributions of displacement in z-direction for the heat input \( Q \) of 75 J/mm, 100 J/mm, 150 J/mm and 200 J/mm. From the figure, it is found that the small deformation less than 1.0 mm is generated on 75 J/mm. On the other hand, in the case of heat input \( Q \) of 100 J/mm, 150 J/mm and 200 J/mm, twisting or wavelike deformation are obtained. And the number of waves found in the panel increases with heat input \( Q \). In the case of heat input \( Q \) of 100 J/mm, the number of half waves in the panel is 3 and that is 5 in the case of 150 J/mm.

Figure 4 shows comparison of distribution of displacement in z-direction along line A-B which is right edge of the panel shown in Fig. 1. From Fig. 4, it can be seen that a small deformation is generated in the heat input \( Q \) of 75 J/mm while large deformation is generated in the larger heat input \( Q \) than 100 J/mm.

![Displacement](image)

Fig. 3 Effect of heat input on distribution of displacement in z-direction. (\( v = 10 \text{ mm/s} \))

![Displacement](image)

Fig. 4 Influence of heat input on distribution of displacement in z-direction along A-B. (\( v = 10 \text{ mm/s} \))
Figure 5 shows the comparison of the maximum displacement in z-direction on the line A-B which is the right edge of the panel. In Fig. 5, filled triangles show displacements for the large deformation analysis and open triangles show those for the small deformation analysis. From the figure, it is found that a small displacement is obtained in the heat input \( Q \) of 75 J/mm and 80 J/mm in both large deformation analysis and small deformation analysis, and the displacements for the both analysis are almost same. In the cases of heat input \( Q \) larger than 90 J/mm, welding distortion along line A-B is about 5 mm and the wavelike buckling are found. From Figs. 3 and 5, it can be seen that buckling type is changed with the heat input \( Q \); in the heat input \( Q \) between 100 J/mm to 150 J/mm, wavelike buckling is generated as shown in Fig. 3 (b) and (c); in the heat input \( Q \) larger than 150 J/mm, wavelike and torsional buckling is generated.

As shown in this section, torsional buckling and wavelike buckling were generated as heat input \( Q \) increases and the larger welding distortions are obtained.

### 3.3 Influence of welding speed

To investigate the influence of the welding speed \( v \), the welding speed \( v \) is changed from 1.0 mm/s to 30 mm/s. The heat input \( Q \) is fixed at 100 J/mm. Figure 6 shows distributions of displacement in z-direction for the welding speed \( v \) of 2.0 mm/s, 5.0 mm/s, 13 mm/s and 20 mm/s in which representative deformation modes are found. In Fig. 6 (a) and (b), in which the small welding speed \( v \) is considered, torsional buckling can be seen and deformation in z-direction at point C defined in Fig. 1 is very large. The deformation of wavelike buckling is not obtained in the welding speed \( v \) of 2.0 mm/s and 5.0 mm/s. From Fig. 6, it is found that the displacement in z-direction at point C in the welding speed \( v \) of 13 mm/s become smaller than that in the welding speed \( v \) of 20 mm/s and wavelike and torsional buckling is obtained. In large welding speed \( v \) at 20 mm/s, large deformation is not obtained (Fig. 6 (d)).

Figure 7 shows the comparison of the displacement in z-direction along the line A-B. From the figure, it is found that welding distortion along line A-B is small in the welding speed \( v \) of 1.0 mm/s and the distortion is large in the welding speed \( v \) of 5.0 mm/s and 13 mm/s. In the welding speed \( v \) of 20 mm/s, no buckling deformation is obtained and its deformation is almost the same as that in the welding speed \( v \) of 1.0 mm/s.

Figure 8 shows the comparison of the maximum welding distortion in z-direction on the right edge of the panel. In Fig. 8, filled triangles show the results for the large deformation analysis.
4. Large deformation analysis of stiffened structure welding

4.1 Analysis model and condition

In this section, the developed method is applied to the prediction of welding deformation of the stiffened structure to show the validity of the developed method. Figure 9 shows analysis model. The plate thickness is 6mm. The model has 2 stiffeners in longitudinal direction and 3 stiffeners in width direction on the base-plate. The analysis model is meshed with hexahedral elements and the number of nodes and elements are 86,987 and 75,920, respectively. Welding speed \( v \), current and voltage are 4.3 mm/s, 180.0 A and 26.0 V, respectively. Welding sequence is also shown in Fig. 9. The material’s temperature dependent material properties are defined as Fig. 2.

4.2 Experimental and Analysis results

Figure 10 shows the experimental results. From this figure, it can be seen that torsional buckling is generated. Figure 11 shows distributions of displacement in z-direction for welding passes 1 to 6. From Figs. 11 (a), (b), (c) and (d), which correspond to the welding of longitudinal members, and Figs. 11 (e) and (f), which correspond to the 1st and 2nd welding of the transverse members,
large deformation is not generated in these welding passes. And figure 12 shows distributions of displacement in z-direction for welding passes 7 to 10. Twisting deformation can be seen after the 7th pass (Fig. 12(a)). In addition, it can be seen that the twisting deformation increases on the subsequence passes after the 7th pass. Comparing Fig. 10 and Fig. 12 (d), it can be seen that the analysis can reproduce the same tendency of the buckling deformation. Figure 13 shows the relationship between displacement in z-direction and pass number. The figure also indicates that the twisting deformation increases after on the 7th pass. Figure 14 shows comparison of the experimental result and computed result for the displacement in z-direction along line A-B defined in Fig. 9. From Fig. 14, it is shown that computed results and experimented results are in good agreement.

From the above results, it can be said that the developed method can accurately analyze large deformation problems for thin-plate welded structures.

Further, in this study, the solutions are obtained stably although the change of deformation modes occurred in the welding. This can be assumed that the effect of dynamic terms in the IEFEM stabilize the analysis.

5. Conclusions

In this research, an thermal elastic plastic finite element analysis method that is based on the Idealized Explicit FEM (IEFEM) by considering geometric nonlinearity was developed to predict welding deformation including buckling in the welding from the beginning of heating to the complete cooling with using moving heat source.

Moreover, the developed method was applied to the analysis of fillet welding of T-joint to investigate the influences of heat input $Q$ and welding speed $v$ on the deformation. In addition, the developed method was also applied to the analysis of the stiffened structure. As a result, the following conclusions were obtained:

1. The developed method was applied to the welding deformation analysis of a fillet welding of T-joint and the variation of deformation modes were numerically investigated. As a result, it was considered that 2 types of buckling, which are torsional buckling and wavelike buckling, were generated. On the smaller heat input $Q$, wavelike buckling was mainly obtained. With the increase of heat input $Q$, twisting deformation became large.

2. The influence of the welding speed $v$ was also investigated. The results in the numerical analysis indicated that torsional buckling type deformation were obtained on smaller welding speed $v$ and buckling type changed torsional buckling to wavelike buckling with the increase of the welding speed $v$. Furthermore, on the larger welding speed $v$, buckling type deformations were not generated.

3. The developed method was applied to the prediction of welding deformation of the stiffened structure. As a result, twisting deformation was found after the 7th pass. In addition, the analyzed results were compared with the experimental measurement. As a result, it was found that computed results and experimented results are in good agreement. In addition, the computation was carried out with no initial imperfection and it is found that the developed method can stably analyze the welding deformation including buckling in the welding from the beginning of heating to the complete cooling.

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