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An Investigation for Introducing Welding Imperfection in Elastic-plastic Large Deformation Analysis[†]

PARK Do-Hyun*, HIROHATA Mikihiro** and KIM You-Chul***

Abstract

When the elastic-plastic finite displacement analysis based on the large deformation theory is carried out for evaluating elastic-plastic mechanical behavior and ultimate strength of a welded steel structural member, the welding imperfection is indispensably considered and introduced as the initial imperfection. However, it is known that the introduced welding imperfection could not be reproduced with fidelity by unbalanced force because the welding imperfection is not legitimate. Therefore, it is anticipated that the welding imperfection can be introduced with fidelity if the legitimate welding imperfection is obtained. In order to investigate the validity of the anticipation, the thermal elastic-plastic analysis for a single-pass butt-welding was carried out and welding distortion and residual stress as the legitimate welding imperfection were obtained in this study. The obtained welding imperfection was introduced into the elastic-plastic finite displacement analysis as the legitimate initial imperfection and it was verified whether the introduced welding imperfection could be reproduced with high accuracy or not. As a result, the introduced welding distortion was changed largely from original value because thin steel plate is easy to bend. Consequently, it was considered that the introduction accuracy of the welding imperfection is dependent on the flexural rigidity of steel plate. Anyway, it is known that there are such case as the introduction accuracy of the welding imperfection falls down when the welding imperfection obtained from the thermal elastic-plastic analysis based on the infinitesimal deformation theory is introduced into the elastic-plastic finite displacement analysis based on the large deformation theory.

KEY WORDS: (Welding imperfection), (Elastic-plastic large deformation analysis), (Thermal elastic-plastic analysis), (Welding distortion), (Residual stress)

1. Introduction

When steel structural members of steel bridges or ships are fabricated and assembled by hot-rolling, flame-cutting, welding, heat-straightening and so on, distortion and residual stress are inevitably generated. They are imperfections of the members. It is well known that they have various influences on the mechanical behavior of steel structural members. Therefore, a lot of researches have been conducted on the influences of the initial imperfections on the mechanical behavior of steel structural members¹⁾. Numerical analysis such as an elastic-plastic finite displacement analysis based on FEM is widely used in these researches. It is necessary that the validity of the initial imperfection is considered in the numerical analysis. However, it is very difficult to obtain the initial imperfection accurately by experiment. Therefore, an idealized initial imperfection is generally used.

For example, the shape of initial deflection of a plate is idealized as a sine wave and its magnitude is idealized to

be proportional to the width of plate. In the case of residual stress, only one stress component along the loading direction is considered. When welding residual stress is noted as a representative thermal process, only the stress component along the welding direction is considered and its distribution is idealized as a rectangular shape^{2), 3)}. Although the distribution of the stress component along the welding direction is variously changed with the width of plate⁴⁾, actually it is neglected. Furthermore, the initial deflection and residual stress should be perfectly correlated and keep the equilibrium of system. However, they are not correlated and do not maintain the equilibrium of the system because the initial deflection and residual stress are considered as independent ones separately^{1), 2), 3), 5)}. Resulting from these problems, it is known that an initial imperfection cannot be introduced with fidelity into an elastic-plastic finite displacement analysis due to unbalanced force^{1), 5)}. Consequently, it is anticipated that the initial imperfection can be introduced with fidelity if a legitimate initial imperfection is obtained.

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Table 1 Dimensions of analysis models

Length L (mm)	300.0	300.0	300.0
Width B (mm)	500.0	320.0	250.0

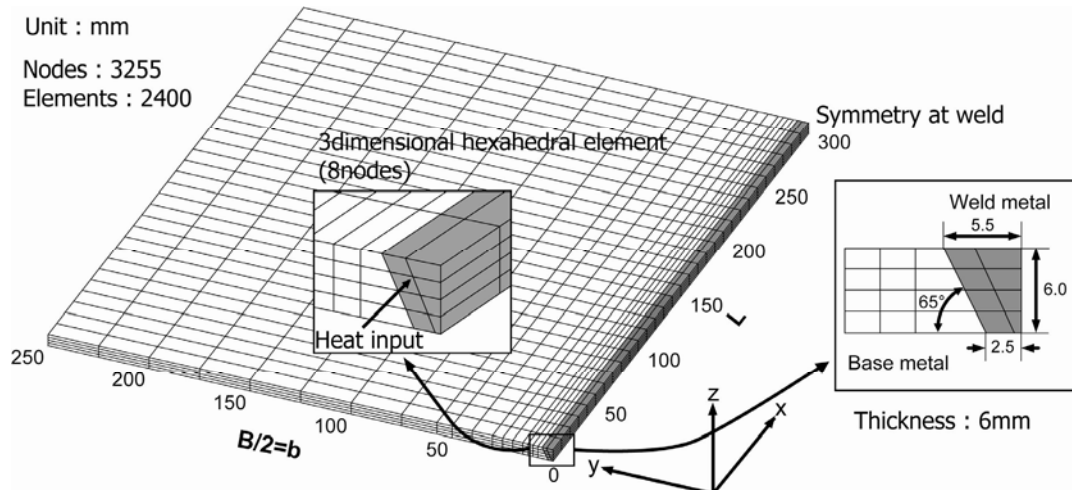


Fig. 1 Analysis model and details

In this study, the imperfection generated by the welding is noted. Therefore, the thermal elastic-plastic analysis^{(6), (7), (8)} for single-pass butt-welding is carried out and welding distortion and residual stress as the legitimate initial imperfection (Hereafter, called as the welding imperfection) are obtained. The self-developed three-dimensional thermal elastic-plastic program^{(6), (7), (8)} based on the infinitesimal deformation theory is used for the thermal elastic-plastic analysis for welding. This program has been verified by many experiments and researches^{(6), (7), (8), (9)}. Finally, the obtained welding imperfection is introduced into the elastic-plastic finite displacement analysis as the legitimate initial imperfection and it is verified whether the introduced welding imperfection could be reproduced with high accuracy or not.

2. Distortion and residual stress generated by butt-welding

In order to obtain distortion and residual stress generated by welding (welding imperfection), the thermal elastic-plastic analysis based on the infinitesimal theory for a single-pass butt-welding of plates is carried out.

Figure 1 shows the model for the thermal elastic-plastic analysis. The length of plate (L) is 300mm and the thickness of plate (t) is 6mm. The widths of plates (B) are 250, 320 and 500mm. Base metal is SM400 and deposit metal is YGW11 provided by JIS Z 3312. As a welding condition, current is 240A, voltage is 28V and welding speed is 5.0mm/sec. **Figure 2** shows the temperature dependencies of mechanical properties. A three-dimensional solid element with 8 nodes is used in the thermal elastic-plastic analysis. The half model with symmetric conditions is used in the analysis. As a

boundary condition, only the rigid body displacement of the system is fixed, that is, displacement (u, v, w) in x, y, z directions are fixed at the point $x=0, y=0, z=0$ and displacement in z direction (w) is fixed at the point $x=a, y=0, z=0$.

In a thermal elastic-plastic problem such as welding, temperature histories correspond to external forces in the general structural mechanical problems. It has been elucidated that welding distortion and residual stress can be simulated high accurately with using the temperature histories simulated with high accuracy and modeling the shape of weld metal with fidelity by the thermal elastic-plastic analysis⁽⁷⁾.

To verify the validity of the temperature histories used in the thermal elastic-plastic analysis, the temperature histories obtained by the non-steady thermal conduction analysis are compared with the experimental results⁽⁷⁾. The measured points are three points ($y=15, 30, 50$ (mm)) on the surface ($z=6$ (mm)) of the specimen whose width is 500mm. **Figure 3** shows that the result of the experiment is well simulated by the analysis and the validity of the temperature histories used in the thermal elastic-plastic analysis is verified.

The thermal elastic-plastic analysis based on the infinitesimal deformation theory is carried out with the temperature histories obtained by the thermal conduction analysis.

Figure 4 shows welding distortion. Here, welding distortion indicates the out-of-plane displacement of the middle plane in the direction of thickness ($z=3$ (mm)). The angular distortion (**Fig. 4 (a)**) appears as V shaped and the absolute value becomes larger as the width of plate becomes larger. The maximum values of the angular distortion correspond to about $B/250$. On the other hand, the longitudinal bending distortion (**Fig. 4**

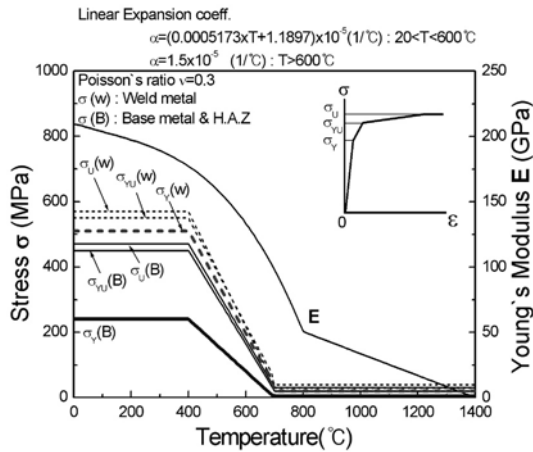


Fig. 2 Temperature dependencies of mechanical properties

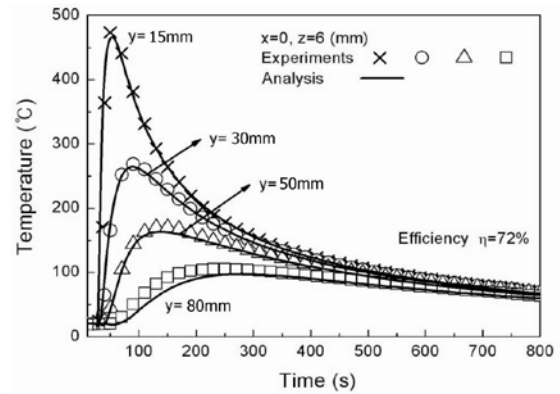
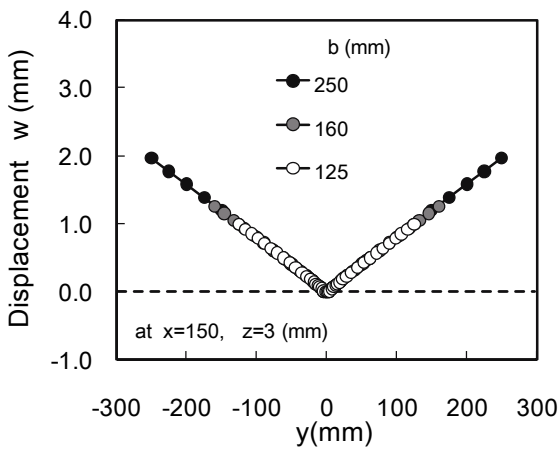
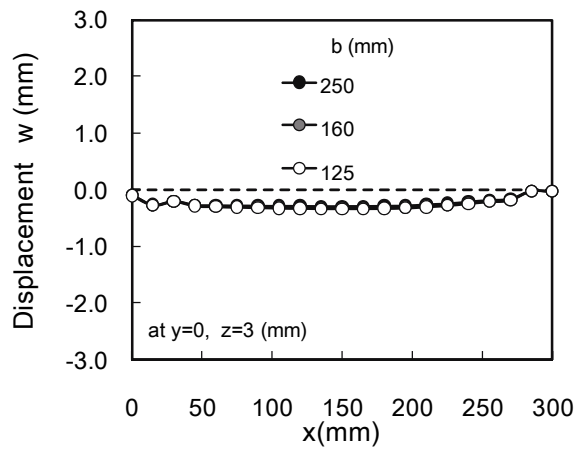


Fig. 3 Temperature histories



(a) Angular distortion



(b) Longitudinal bending distortion

Fig. 4 Welding distortion.

(b) does not depend on the width of plate. The maximum values of the longitudinal bending distortion are about 0.4mm in each model. The longitudinal bending distortion has a tendency to be concave.

Figure 5 shows the welding residual stress. Here, residual stress indicates the average in the direction of thickness because it is confirmed that the values of residual stress in the direction of thickness are approximately the same. Focused on residual stress component along the weld line, σ_x (Fig. 5 (a) and (b)), large tensile stress is generated in the welds ($-3 < y < 3$ (mm)) and the magnitude of the tensile residual stress is larger than the yield stress of the weld metal. However, it is confirmed that the equivalent stress in the welds is equal to the yield stress of the weld metal. The tensile stress field ($-30 < y < 30$ (mm)) is constant regardless of the width of plate. The magnitude and distribution of compressive stress is decided so that the force due to the compressive residual stress balances with that due to the tensile residual stress. Therefore, the magnitude and distribution of compressive stress varies with the width of plate. In the case that the width; b is 125mm, the magnitude of compressive residual stress is approximately equal to the yield stress of the base metal at the

edge of the plate. On the other hand, in the case that the width; b is 250mm, the magnitude of compressive residual stress at the edge of the plate is approximately zero.

It is confirmed that the residual stress component perpendicular to the weld line, σ_y , is largely compressive in both welding start and end. However the other part is a tensile stress field. Residual stress component along the thickness direction (σ_z) and the shear stress components are approximately zero.

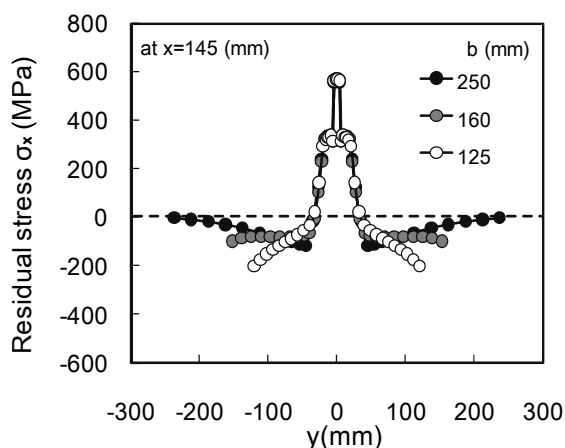
3. Introducing welding imperfection into elastic-plastic finite displacement analysis

Here, the welding imperfection obtained by the thermal elastic-plastic analysis is introduced as initial imperfection into the elastic-plastic finite displacement analysis and the welding imperfection reproduced by the elastic-plastic finite displacement analysis is examined and checked to elucidate whether it converges with the original value or not without any procedures.

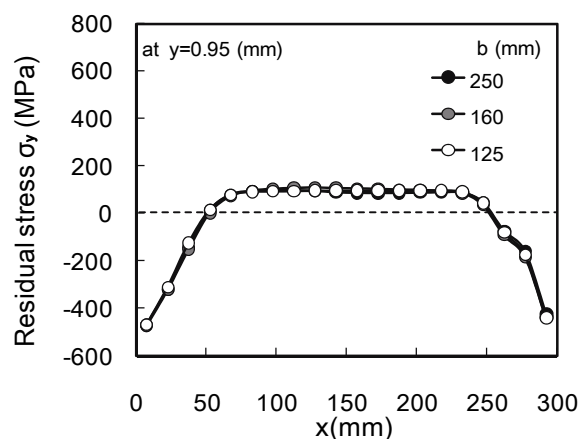
3.1. Model for analysis

Figure 6 shows the model for the elastic-plastic finite

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(a) Distribution of σ_x perpendicular to the weld line



(b) Distribution of σ_y along the weld line

Fig. 5 Residual stress

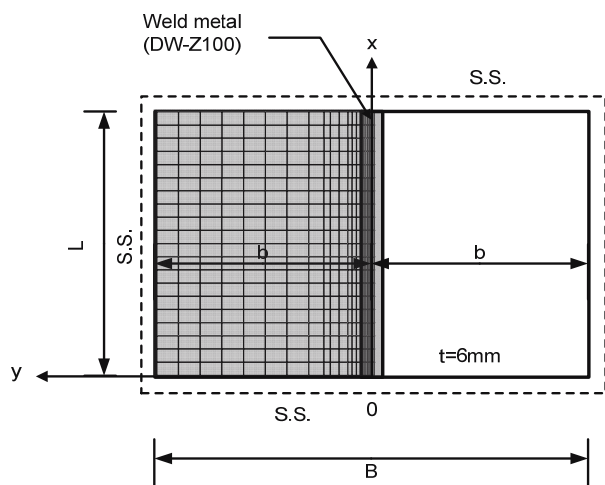


Fig. 6 Model for elastic-plastic finite displacement analysis

displacement analysis. The same three-dimensional solid element with 8 nodes as was used in the thermal elastic-plastic analysis is used. The same coordinate of nodal points as that of the thermal elastic-plastic analysis is used. The stress-strain curves and the mechanical properties of the materials are shown in Fig. 2.

As a boundary condition, the edges of plate ($x=0$ and a , $y=b$, $z=t/2$) are simply supported, that is, the displacement in the out-of-plane direction is fixed at the edges.

The welding distortion obtained by the thermal elastic-plastic analysis is used as initial coordinate of the model and welding residual stress (6 components) is introduced as the initial stress. If the sum of equivalent nodal forces due to residual stress is equal to zero, the introduced welding imperfection will be reproduced perfectly. The welding imperfection reproduced by the elastic-plastic finite displacement analysis should be checked to elucidate whether it converges with the original value or whether it changes from the original value without any procedures.

3.2. Results of analysis

Figure 7, Figure 8 and Figure 9 show the results of introducing welding imperfection in the cases that the half widths (b) are 250mm, 160mm and 125mm. The solid lines (Input) in the figures indicate the introduced welding distortion and residual stress. The symbols (Output) indicate the results after solving the stiffness equation without the external force. The value of welding distortion at the middle plane of the thickness direction and the average value of residual stress of four elements in the thickness direction are shown in the figures.

The shape of out-of-plane displacement is largely changed from the original shape of welding distortion. The component of residual stress σ_x is approximately the same. The component of residual stress σ_y is a little changed from the original value only in the welding start. This tendency is the same in the all models.

Although the welding imperfection simulated with high accuracy by the thermal elastic-plastic analysis was introduced into the elastic-plastic finite displacement analysis, the welding imperfection was not able to be reproduced by the elastic-plastic finite displacement analysis and it changed from the original value without any external force.

In the next section, the reason why the welding imperfection simulated with high accuracy by the thermal elastic-plastic analysis could not be introduced into the elastic-plastic finite displacement analysis is considered.

4. Considerations

It is thought that the sum of the equivalent nodal forces $\{f\}$ due to residual stress $\{\sigma\}$ is not zero when the welding imperfection is introduced. The equivalent nodal force $\{f\}$ due to residual stress is calculated by Eq. (1).

$$\{f\} = \int [B]^T \{\sigma\} dv \quad (1)$$

In the case of the thermal elastic-plastic analysis based on the infinitesimal deformation theory, the initial deflection of the thermal elastic-plastic analysis model is

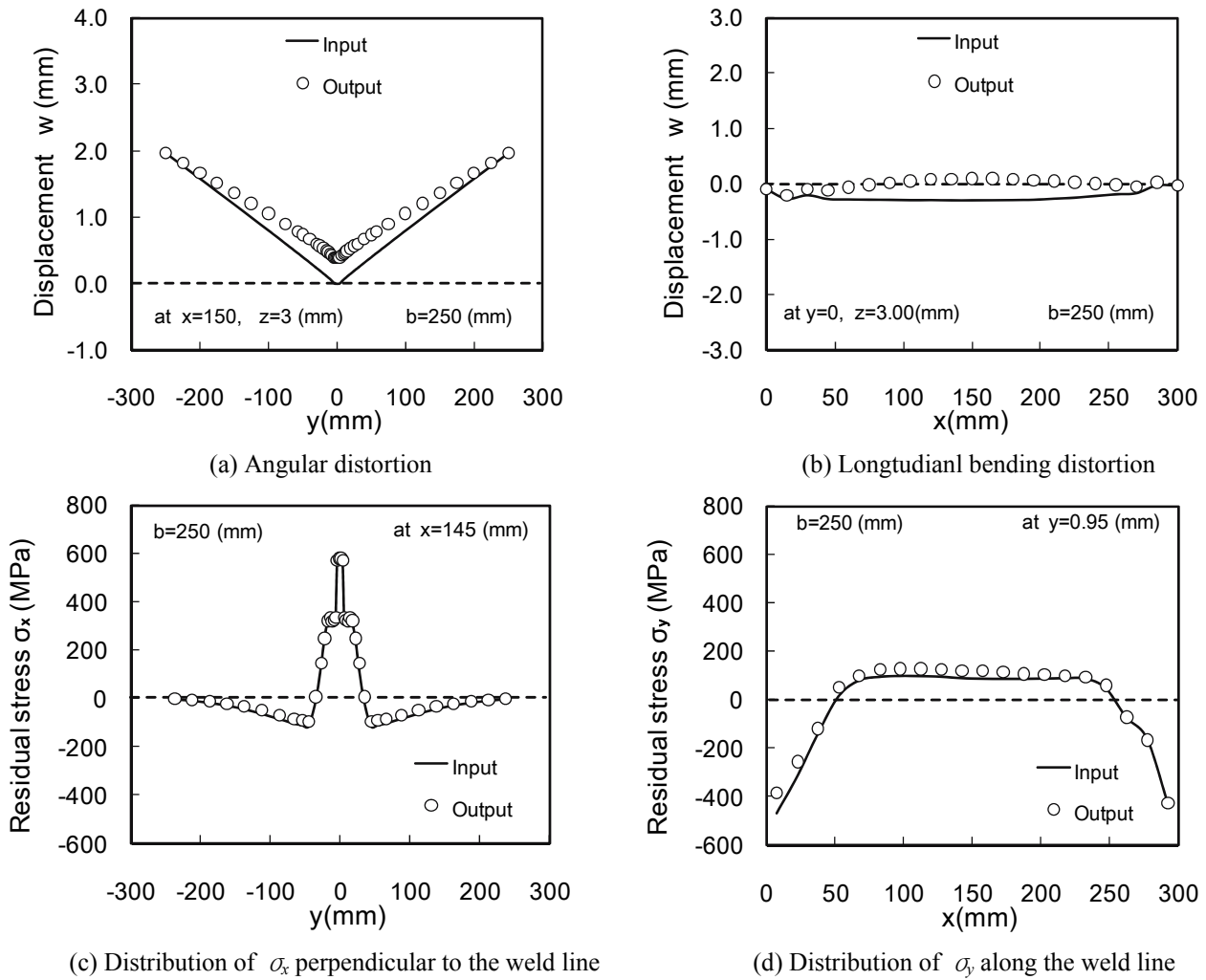


Fig.7 Result of introducing welding imperfection ($b=250\text{mm}$)

not considered and the equivalent nodal force is calculated by using B-matrix decided by the initial coordinates of the analysis model in every calculating step. However, in the case of the elastic-plastic finite displacement analysis, the coordinate of welding distortion, that is, the solution of the thermal elastic-plastic analysis corresponds with the initial coordinate of the elastic-plastic finite displacement analysis model. In other words, both initial coordinates are different from each other. In this case, B-matrix, which is decided by the initial coordinates of the elastic-plastic finite displacement analysis model, is different from that of the thermal elastic-plastic analysis.

Therefore, when the welding imperfection obtained from the thermal elastic-plastic analysis was introduced into the elastic-plastic finite displacement analysis as initial imperfection, an unbalanced force was caused due to the difference between both analysis theories. Moreover, the variation of each direction of the introduced welding distortion was caused by the unbalanced forces of each direction of system in all of nodal points which were not fixed by boundary condition.

The initial coordinates of thickness direction of the introduced welding distortion was largely changed from the original value because the thin steel plate such as analysis model is particularly easy to bend and its flexural rigidity is very small. These results indicated that there is a mechanical relation between the variation of the introduced welding distortion and the flexural rigidity of analysis model. Consequently, it was considered that the introduction accuracy of the welding imperfection is dependent on the flexural rigidity of steel plate.

The results of this study indicated that there is a fundamental problem resulting from the difference between the infinitesimal deformation theory for simulating the welding imperfection and the large deformation theory for introducing the imperfection into the elastic-plastic finite displacement analysis, even though the legitimate welding imperfection simulated by the thermal elastic-plastic analysis with fidelity is introduced into the elastic-plastic finite displacement analysis.

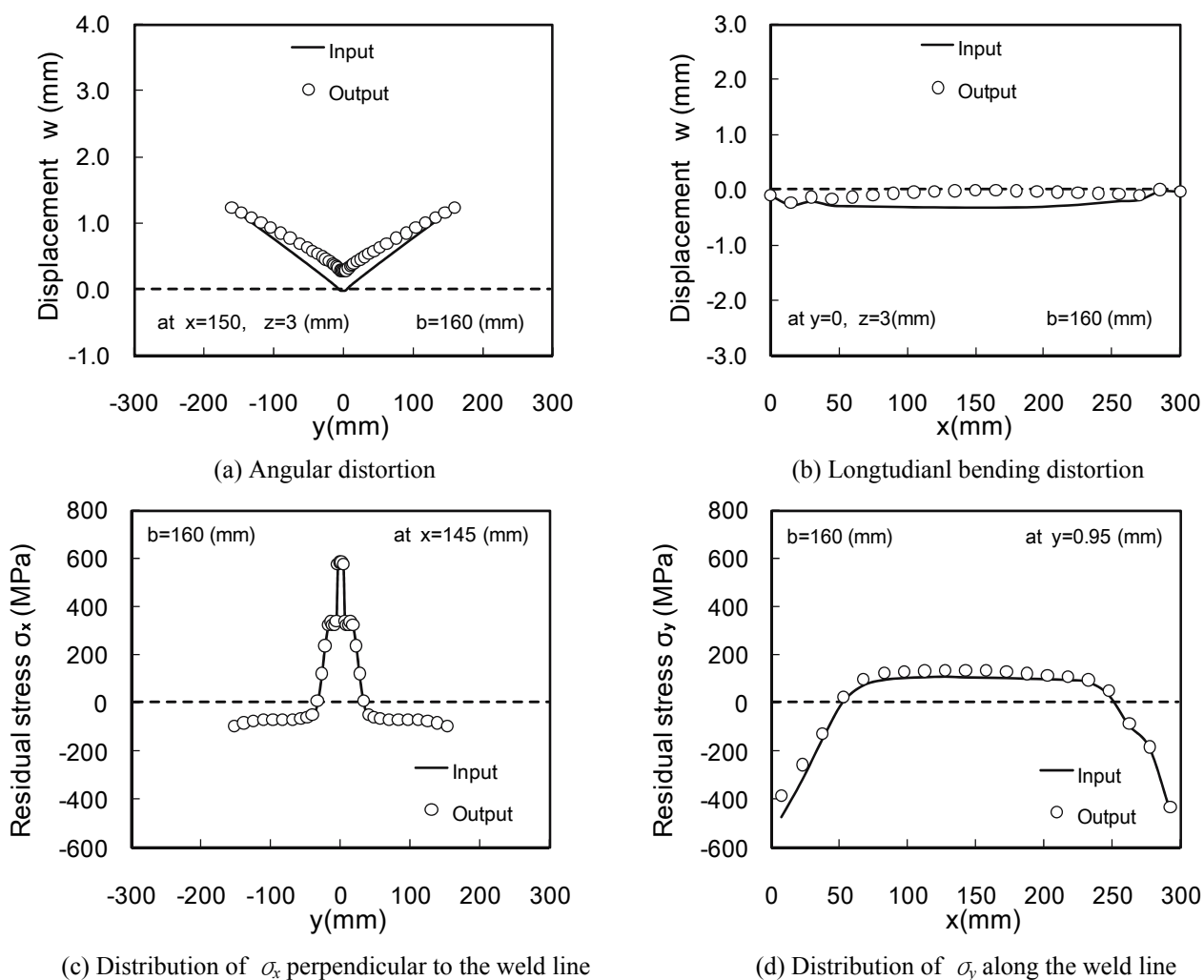


Fig.8 Result of introducing welding imperfection ($b=160\text{mm}$)

5. Conclusions

A series of analyses were carried out to investigate whether the welding imperfection simulated by the thermal elastic-plastic analysis with high accuracy could be reproduced in the elastic-plastic finite displacement analysis with fidelity.

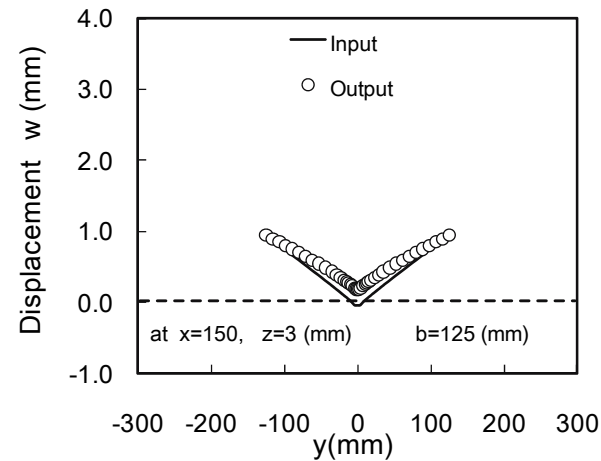
Obtained main results are as follows.

The thermal elastic-plastic analysis based on the infinitesimal deformation theory for a single-pass butt-welding was carried out and the welding imperfection (welding distortion and residual stress) was obtained with high accuracy.

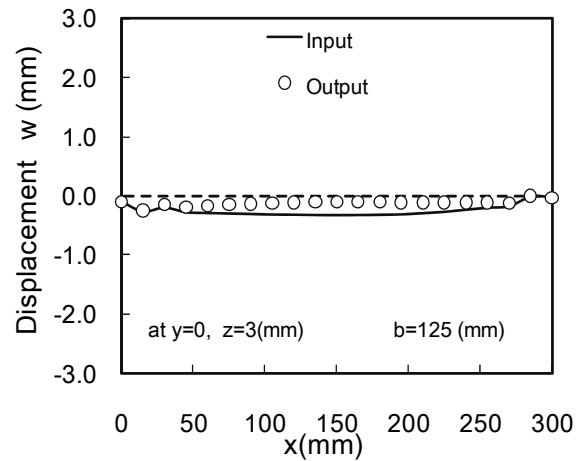
- (1) The angular distortion appeared as V shaped and the absolute value becomes larger as the width of plate becomes larger. The longitudinal bending distortion had a tendency to be concave and the absolute value was constant.
- (2) Attention to the residual stress component along the weld line, its tensile stress field being constant

regardless of the width of plate. However, the magnitude and distribution of its compressive stress varied with the width of plate.

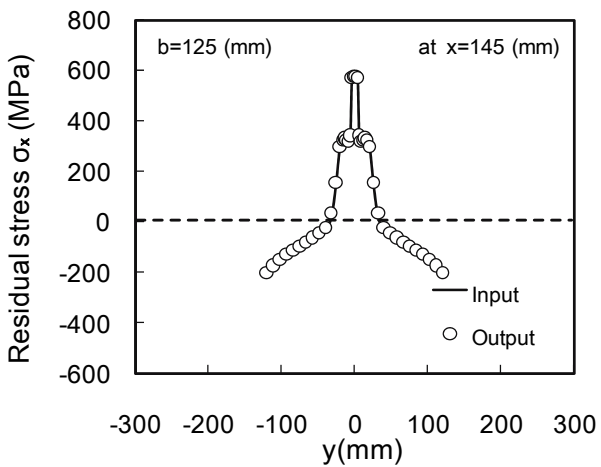
- (3) The obtained welding imperfection was introduced into the elastic-plastic finite displacement analysis as the legitimate initial imperfection and it was verified whether the introduced welding imperfection could be reproduced with high accuracy or not. As a result, the introduced welding distortion was changed largely from original value because thin steel plate is easy to bend. Consequently, it was considered that the introduction accuracy of the welding imperfection is dependent on the flexural rigidity of steel plate.
- (4) It is known that there are cases where the introduction accuracy of the welding imperfection falls down when the welding imperfection obtained from the thermal elastic-plastic analysis based on the infinitesimal deformation theory is introduced into the elastic-plastic finite displacement analysis based on the large deformation theory.



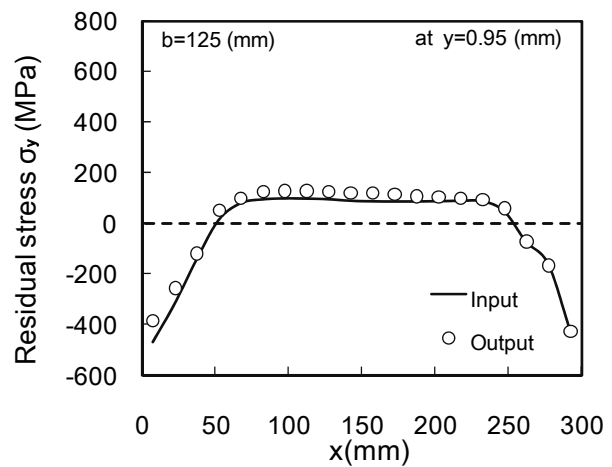
(a) Angular distortion



(b) Longitudinal bending distortion



(c) Distribution of σ_x perpendicular to the weld line



(d) Distribution of σ_y along the weld line

Fig.9 Result of introducing welding imperfection ($b=125\text{mm}$)

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