Effect of Restraint on Residual Stress Generated by Butt-welding for Thin Steel Plates

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Abstract
In repair for fatigue cracks or reinforcement by attaching new members on existing steel bridges, welding is performed under restraint by the surrounding members. It is possible that the tensile residual stress generated by welding under the restraint becomes higher than that under the normal conditions without any restraint. For investigating the effect of the restraint on the residual stress generated by welding, a series of thermo-stress analyses were performed on one-pass butt-welding of thin steel plates (6mm) with changing the degree of restraint of the joints. From the results, the tensile residual stress perpendicular to the weld line was largely affected by the restraint when the in-plane displacement of the edge of the plate was fixed. The tensile residual stress varied from 20% to 80% of the yield stress of the material due to the difference of the degree of the restraint.
Keywords: Welding, Residual stress, Restraint, Thermo-stress analysis

1. INTRODUCTION

A lot of cases that fatigue cracks occur in steel bridges have been reported recently. It becomes a huge problem in maintenance of steel bridges. Therefore, many types of the repair techniques with bolting or welding have been developed [1], [2].
When noting the repair method by welding, the fatigue crack is removed by gouging and then that part is re-welded [2]. However, there were some cases that the fatigue cracks were re-initiated from the repaired part [3]. One of the reasons of them might be defects generated by the repair welding. The other might be high residual stress by the repair welding.
The repair welding is performed under restraint by the existing members surrounding the welded parts. Therefore, it is anticipated that the welding residual stress becomes higher than that under the normal conditions without any restraint.
Although the geometric welding defects can be detected by non-destructive inspections such as PT, MT and UT, it is unknown how residual stress is generated by welding under the restraint.
To these problems, a series of numerical simulation is carried out for investigating the effect of the restraint on the residual stress generated by welding. The thermo-stress analysis is performed on one-pass butt-welding of thin steel plates (6mm) with changing the degree of restraint of the joints. From the results, the features of the residual stress generated by welding under restraint are shown.

2. SIMULATION MODEL OF WELDING BY THERMO-STRESS ANALYSIS

A series of the thermo-stress analyses based on FEM is carried out. For the analyses, a commercial FE program ABAQUS Ver. 6.10 is used.
Fig. 1 shows the model for the analysis. One-pass butt welding on thin steel plates are simulated.
The length of the plate (a) is 300mm. The width (b) is 500mm. The thickness (t) is 6mm.
The base metal is SM400A of which the yield stress is 254.8MPa. The weld metal is a general filler wire matching with the base metal. The yield stress of the weld metal is 509.6MPa. As the welding conditions, the current is 240A. The voltage is 28V. The welding speed is 30cm/min [4]. The physical constants and the mechanical properties used in the analysis are shown in the reference [5].
When noting the fatigue cracks generated at the welded joints, the residual stress component perpendicular to the weld line affects it. Therefore, that stress component is mainly focused on.
It is generally known that the welding residual stress is generated due to restraining the shrinkage of the weld metal by the surrounding base metal in the cooling process of welding. In order to vary the degree of restraint, the slit part in the center of the plate is welded with changing the length of the slit (l). Furthermore, for investigating the effect of the external restraint on the residual stress, the cases that the in-plane displacements at the edge of the plate (y=b/2) are fixed or not are examined.

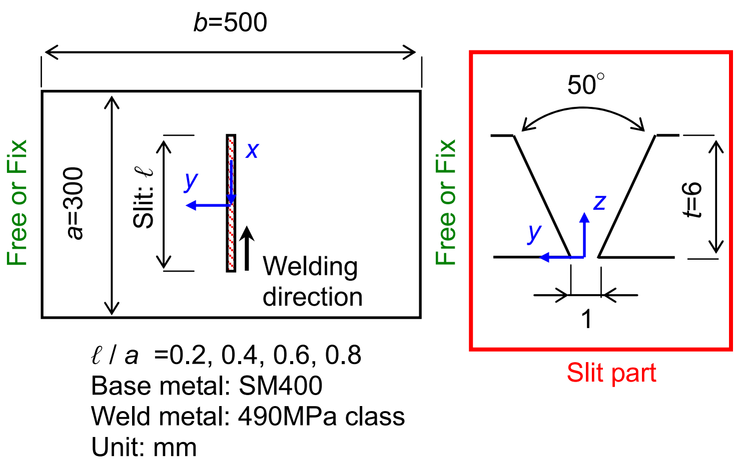


Fig. 1 Model for thermo-stress analysis

These are also considered the situation in repair welding. That is, the repair welding on the fatigue cracks is performed after removing the crack by gouging. It is similar to the welding in the slit. And then, the fix of the in-plane displacements at the edge of the plate corresponds to the restraint by the existing member surrounding the repair-welded parts.

3. RESULTS OF ANALYSIS

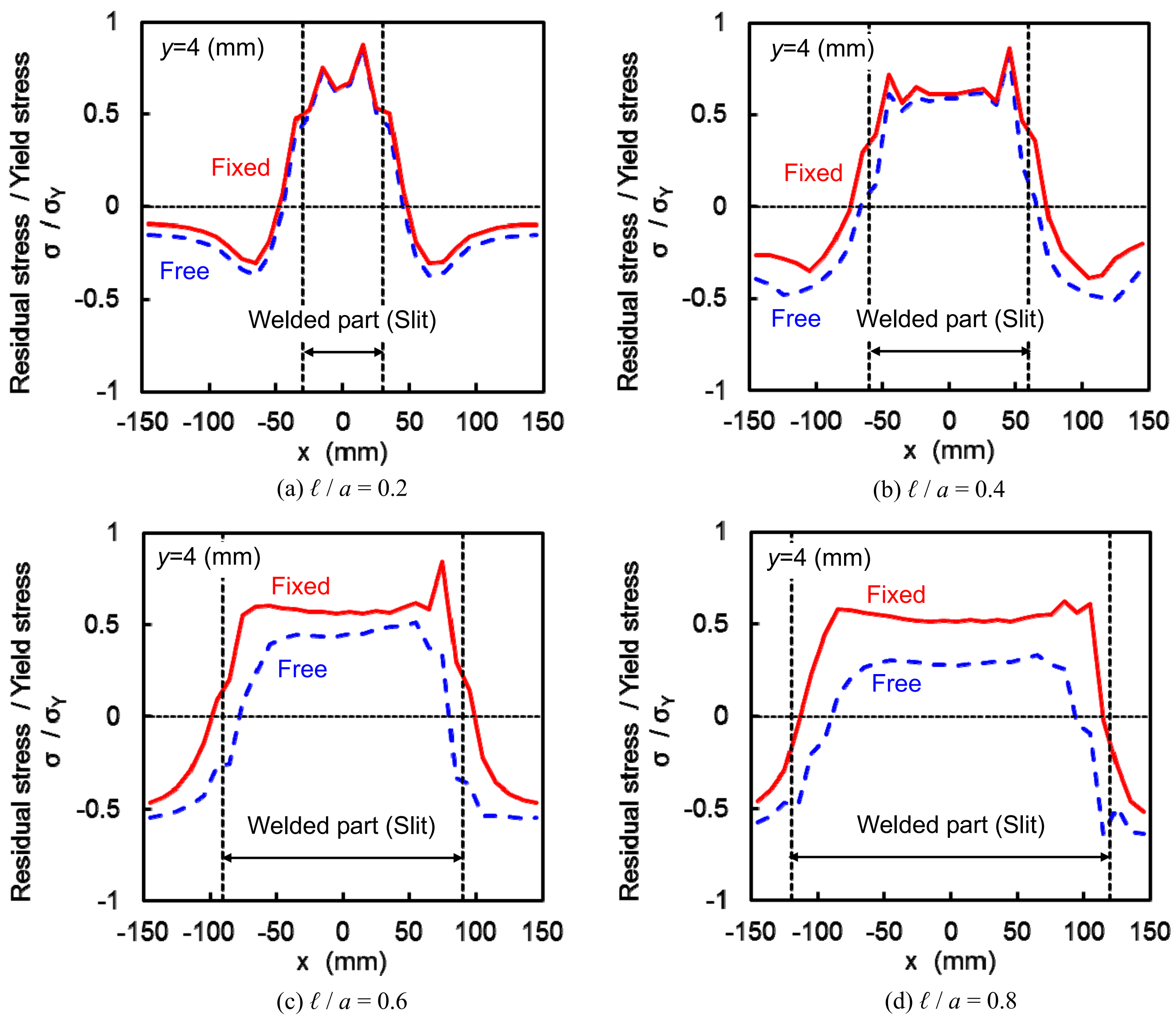
Fig. 2 shows the distributions along the weld line of the residual stress components perpendicular to the weld line. It could be confirmed that the differences of the stress in the thickness direction are small because the thickness of the plate is thin. Therefore, the average stress in the thickness direction is shown in the figures. The stress is divided by the yield stress of the weld metal (σ_Y =509.6MPa).

The broken lines represent the results obtained under the conditions that the in-plane displacements at the edge of the plate (y=b/2) are not fixed, so called "Free". On the other hand, the solid lines represent the results obtained under the conditions that the in-plane displacements at the edge of the plate (y=b/2) are fixed, so called "Fixed".

In both of the Free and Fixed cases, tensile residual stress is naturally generated in the welded parts. Compressive stress is generated in the not welded parts.

Fig. 3 shows the relationships between the slit length and the magnitude of the tensile residual stress at the weld metal. The slit length (l) is divided by the plate length (a). The value of residual stress is that at the center of the weld line. This stress in the Free case is defined as σ_{Free}. In the same way, that in the Fixed case is defined as σ_{Fixed}.

In the Free cases, the tensile residual stress is gradually increased as the slit becomes shorter. When the model of which the l/a is 0.2, the tensile stress is around 80% of the yield stress although it is around 20% of the yield stress in the model of which the l/a is 0.8.



(a) $\ell / a = 0.2$ (b) $\ell / a = 0.4$ (c) $\ell / a = 0.6$ (d) $\ell / a = 0.8$

Fig. 2 Distributions along weld line of residual stress components perpendicular to weld line

In the Fixed cases, the tensile residual stress is also increased as the slit becomes shorter. However, the differences between the Free and the Fixed cases become smaller as the slit becomes shorter. When the models of which the l/a are smaller than 0.4, the magnitudes of tensile stress of them are almost the same.

4. DISCUSSIONS

There are two types of restraint in the analytical models in this study. One is the restraint on the weld metal by the surrounding base metal, so called the self-restraint. The other is the restraint due to fix of the in-plane displacement at the edge of the plate, so called the external restraint.
Here, the effects of these two types of the restraint on the residual stress are investigated.

4.1. Effect of External Restraint on Residual Stress

In order to investigate the effects of the external restraint on the residual stress, the following two parameters are noted. One is the average in-plane shrinkage of the edge of the plate generated in welding of the Free cases, s_a. That is, the average of the in-plane displacements at all nodes of the edge of the plate of each model in the Free cases as shown in Fig. 4 and Eq. (1).

$$s_a = \sum_{i=1}^{n} s_i \Big/ n \qquad (1)$$

Here, s_i is the in-plane shrinkage of i-th nodes at the edge of the plate in the welding direction. n is the number of the nodes at the edge of the plate in the welding direction.
The other is the difference of the tensile residual stress between the Free and the Fixed cases, $\Delta\sigma/\sigma_Y$ obtained by Eq. (2).

$$\Delta\sigma/\sigma_Y = (\sigma_{Fixed} - \sigma_{Free})/\sigma_Y \qquad (2)$$

Here, σ_{Fixed} and σ_{Free} are the tensile residual stress at the center of the weld line shown in Fig. 3. σ_Y is the yield stress of the weld metal.
Fig. 5 shows the relationship between these two parameters.
The average in-plane shrinkage (s_a) becomes larger as the slit length (l/a). This is because the in-plane shrinkage becomes larger as the gross heat input by welding being proportional to the slit length.
When the models of which the l/a are smaller than 0.4, scarcely any in-plane shrinkage occurs. Therefore, the difference between the Free and Fixed models is quite

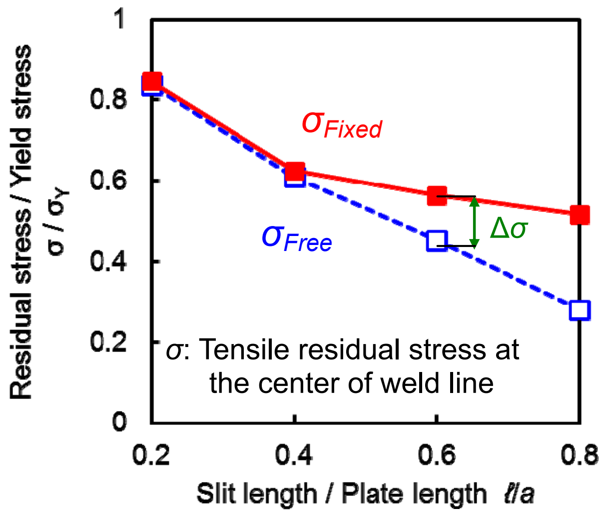


Fig. 3 Relationship between slit length and residual stress

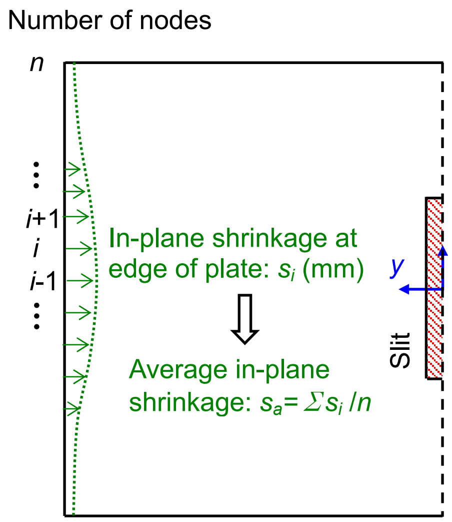


Fig. 4 Definition of average in-plane shrinkage

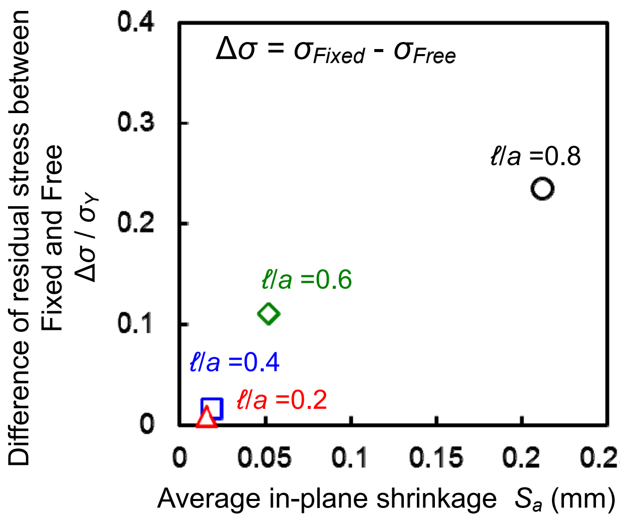


Fig. 5 Relationship between average in-plane shrinkage and difference of residual stress

small. On the other hand, with increase of the in-plane shrinkage, the difference between the Free and Fixed models becomes large.
From these results, it can be confirmed that the effects of the external restraint are caused by fixing the in-plane shrinkage of the edge of the plate due to welding.

4.2. Effect of Self-restraint on Residual Stress
For explaining the degree of the restraint in slit welded joints, the restraint intensity has been proposed [6]. The restraint intensity is defined as the force per unit weld length required for elastically shrinking the gap of the groove by unit length as shown in Fig. 6. The restraint intensity is obtained by performing the elastic analysis on the slit joint model and calculated from the results by Eq. (3).

$$\boldsymbol{R}(\boldsymbol{x}) = \sigma(\boldsymbol{x})\boldsymbol{h}_w / \delta(\boldsymbol{x}) \quad (3)$$

Here, $R(x)$ is the restraint intensity (N/mm·mm). $\sigma(x)$ is the stress applied on the groove (MPa). h_w is the throat thickness (mm). $\delta(x)$ is the displacement of the groove (mm). x is the coordinate along the slit.
Fig. 7 shows the restraint intensities of the Free and the Fixed models obtained by the elastic analyses. In the elastic analyses, forced displacements are applied on the nodes at the slit parts.

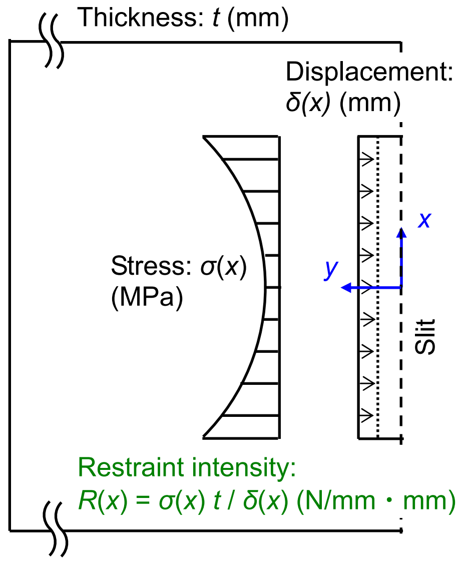
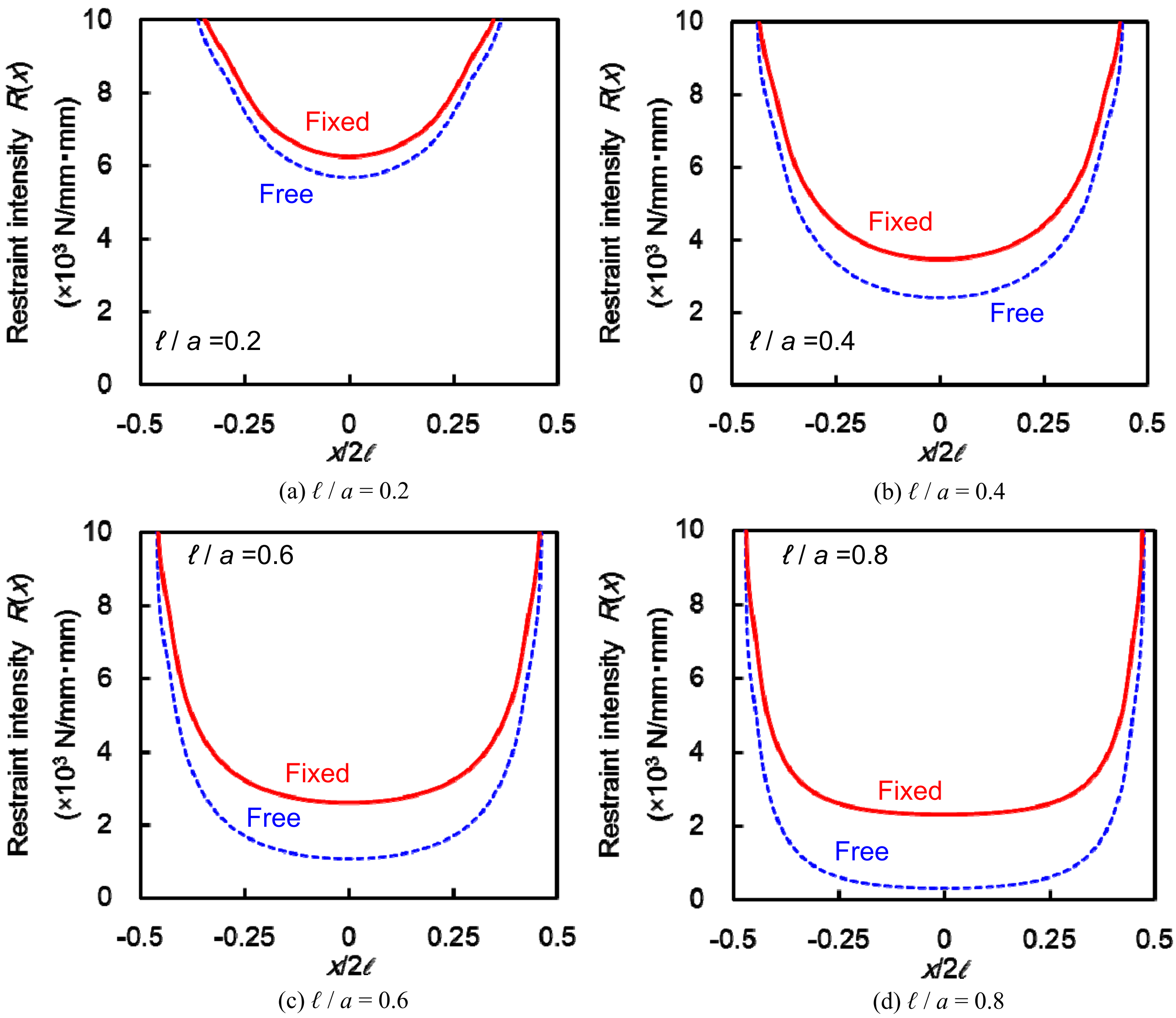


Fig. 6 Definition of restraint intensity



(a) $\ell / a = 0.2$
(b) $\ell / a = 0.4$
(c) $\ell / a = 0.6$
(d) $\ell / a = 0.8$

Fig. 7 Distributions of restraint intensities along slit

In both of the Free and Fixed models, the restraint intensities are the smallest at the center of the slit ($x/2l=0$). They becomes extremely large as being close to the edge of the slit ($x/2l=\pm0.5$). Therefore, the restraint intensity at the center of the slit ($R(0)$) is noted as the representative.

Fig. 8 shows the relationship between the tensile residual stress at the center of the weld line and the restraint intensity at the center of the slit.

The clear relationship between the tensile residual stress and the restraint intensity can be confirmed. Although the restraint intensity has been used for explaining the degree of the restraint in slit welded joints without the fix at the edges of the plate, it can also be used under the condition with the fix at the edges of the plate.

The degree of the restraint of the slit welded joints varies by the length of the slit and the boundary conditions. Although the welding conditions are uniform, the residual stress generated is largely changed with the degree of the restraint. It can be said that the degree of the restraint of the joints should be known with considering the mechanical conditions of the joints in the repair welding on the existing steel structural members.

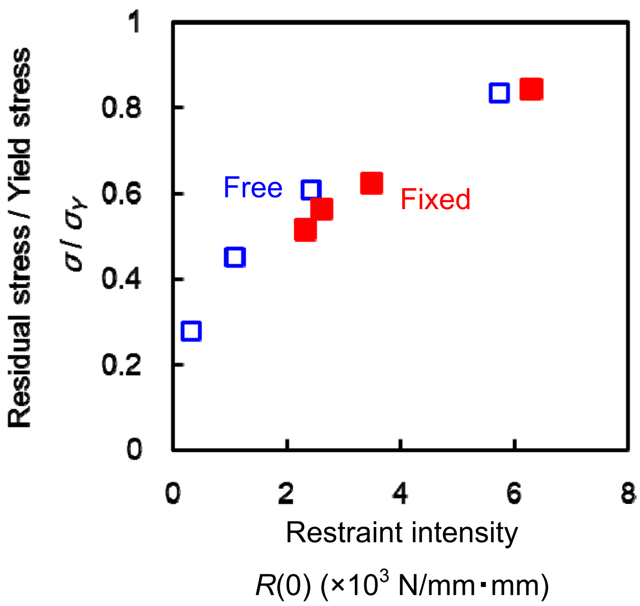


Fig. 8 Relationship between residual stress and restraint intensity

5. CONCLUSIONS

For investigating the effect of the restraint on the residual stress generated by welding, a series of thermo-stress analyses were performed on the one-pass butt-welding on the slit at the center of the steel plates (the length: 300, the width: 500, the thickness: 6 (mm)). The features of the residual stress were compared between the cases with/without fixing the in-plane displacement at the edge of the plates in the breadth direction (so called, the external restraint/the self-restraint). The obtained main results are as follows.

(1) In both conditions under the external restraint/the self-restraint, the tensile residual stress perpendicular to the weld line was increased as the slit length became shorter.

(2) The effects of the external restraint were caused by fixing the in-plane shrinkage of the edge of the plate due to welding. Because the in-plane shrinkage at the edge of the plate became smaller as the slit length became shorter, the difference between the tensile residual stresses under the external restraint/the self-restraint also became smaller.

(3) It could be confirmed that the degree of the restraint was explained by the restraint intensity calculated by the elastic analysis regardless of the difference of the external restraint/the self-restraint conditions.

(4) Although the welding conditions were uniform, the residual stress generated was largely changed with the degree of the restraint. In the models in this study, the tensile residual stress varied from 20% to 80% of the yield stress of the weld metal due to the difference of the degree of the restraint.

(5) It could be said that the degree of the restraint of the joints should be known with considering the mechanical conditions of the joints in the repair welding on the existing steel structural members.

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