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Production Mechanism of Out-of-Plane Deformation in Fillet Welding †

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Abstract

The production mechanism of out-of-plane deformation (longitudinal bending deformation and angular distortion) was investigated. The shape of longitudinal bending deformation was determined by the relative position of the neutral axis for the cross section in fillet welding and the welding heat source. That is, when the neutral axis is above the welding heat source, the shape becomes convex, and when the neutral axis is below the welding heat source, the shape becomes concave. However, even if the position of the neutral axis, which was determined only by the cross section of the object, and the position of the welding heat source coincided, a small longitudinal bending deformation was generated because the central position for expansion and shrinkage did not coincide with the neutral axis of the object. The magnitude of longitudinal bending deformation was influenced by the web height, the distance between the neutral axis and the welding heat source. In angular distortion, the shape of the deformation was determined by the relative position of the neutral axis for the cross section of the flange and the welding heat source. That is, when the welding heat source exists on the flange surface, V-shape angular distortion was generated. The magnitude of deformation was influenced by the flange thickness and the welding speed. The generality of the production mechanism of out-of-plane deformation generated in fillet welding was confirmed.

KEY WORDS: (Fillet welding) (Welding deformation) (Out-of-plane deformation) (Angular distortion) (Longitudinal bending deformation) (Production mechanism) (Modeling) (FEM)

1. Introduction

Fillet welding is performed on steel structures which are constructed by plates and stiffeners. Welding deformation is naturally generated in fillet welding. However, the basic characteristics and the production mechanism of welding deformation, which is largely influenced by welding conditions, sizes, etc., are not yet enough understood.

On the other hand, out-of-plane deformation (longitudinal bending deformation and angular distortion) generated by welding can be corrected by various methods at the manufacturing sites of the welded structures. However, it is well known that these treatments not only harder construction by adding to production time and interrupting automatic manufacturing systems etc., but also influence various strengths of the structure directly or indirectly. Therefore, it is much expected that a system by which deformation generated in welding can be predicted and prevented before welding will be constructed[1]. Such requirements are important problems to be solved soon because the skilled engineers at the manufacturing sites of the steel structures are decreasing.

In this paper, the production mechanism of out-of-plane deformation generated by fillet welding is elucidated by using a model in which the welding heat source is simplified. Then, the generality of the production mechanism is confirmed by the simulation results of actual fillet welding.

2. Production Mechanism of Out-of-Plane Deformation

The production mechanism of out-of-plane deformation is examined by considering the case in

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which the instantaneous heat source (corresponding to the case in which the welding speed is infinitely fast) is assumed ignoring the moving effect of the heat source. On the other hand, the validity of the production mechanism is proved by providing the model changing only the relative position of the neutral axis for the cross section of the object and the welding heat source.

2.1 Model for analysis

Figure 1 shows the object for analysis, the coordinate systems and the sizes. The objects are assumed as three models (Model A, Model B and Model C) in which only the web heights are changed. Each dotted line in the figure expresses the position of the neutral axis for the cross section (yz-section). The neutral axis lies above the weld line (z=23.2(mm)) in Model A, coincides with the weld line (z=18.1(mm)) in Model B and lies below the weld line (z=11.2(mm)) in Model C, respectively.

Fillet welding is performed simultaneously on the left and right sides with a welding heat input (Q=1200(J/mm) (Fig.1). Material is mild steel[2].

As the boundary conditions of the thermal elastic-plastic analysis, only the rigid displacements are restricted and other ones are free.

2.2 Temperature distribution

Figure 2(a) shows an example of the results obtained by three dimensional non-steady heat conduction analysis. This figure expresses the isothermal contours at the time when the welded parts are cooled down to 1500(℃) after the heat is instantaneously put on the whole weld length of the left and right sides for Model A. In the case of the instantaneous heat source, the isothermal contours are parallel to the weld line.

2.3 Production mechanism of out-of-plane deformation

It is considered that the relative position of the neutral axis and the welding heat source (the source of expansion and shrinkage) largely governs the production of out-of-plane deformation. Based on this, the production mechanism of out-of-plane deformation is investigated for Model A below.

2.3.1 Longitudinal bending deformation

Figure 3(a) shows the temperature histories at the middle of the web thickness (y=250(mm)) in the central position (x=300(mm)) of the welding line. **Figure 3(b)** shows the transient out-of-plane displacement, w, at the top (z=135(mm)) and lower edge (z=15.1(mm)) of the web.

Temperature at the lower edge of the web rises owing to the heat conduction from the welded metal (Fig.3(a)) and the lower edge expands. Although it is estimated that the magnitude of the expansion is small, the displacement of the lower edge is larger, that is, concave deformation is largely generated (Fig.3(b)) because the distance from the neutral axis is long and the whole length of the welding line expands at the same

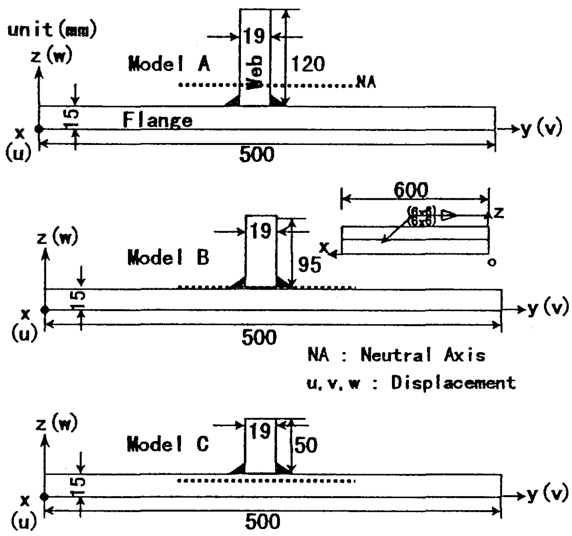
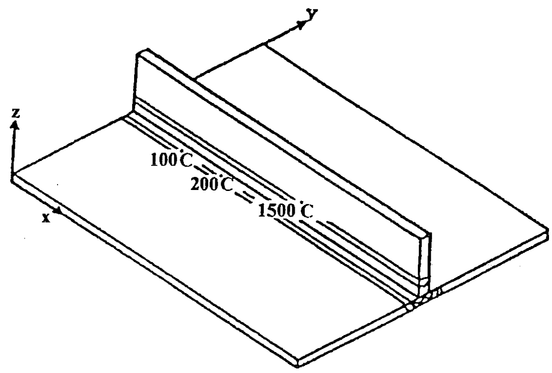
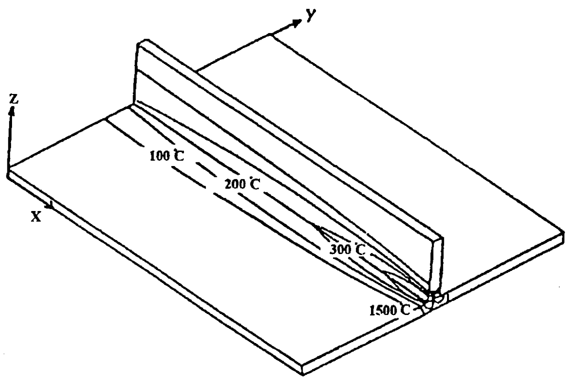


Fig.1 Model of fillet welding.

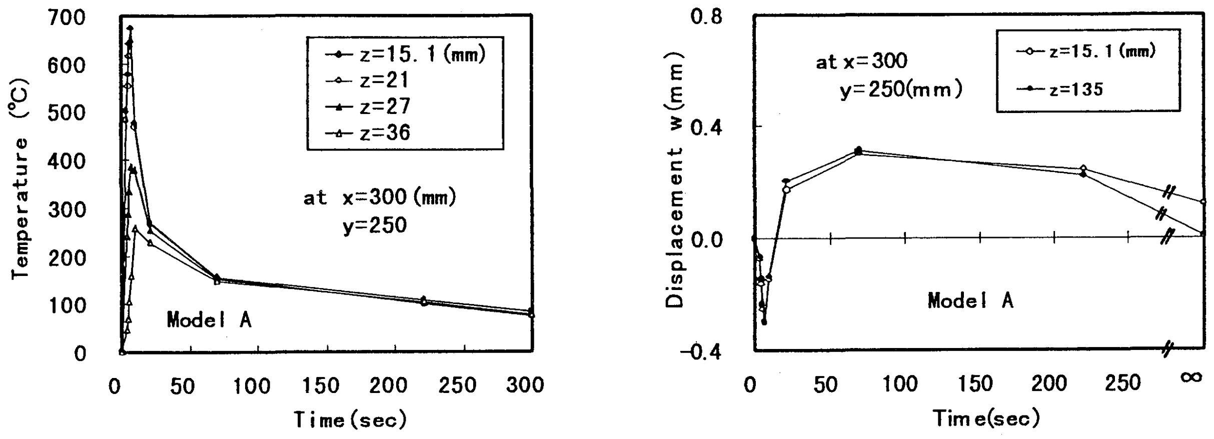


(a) Instantaneous heat source.



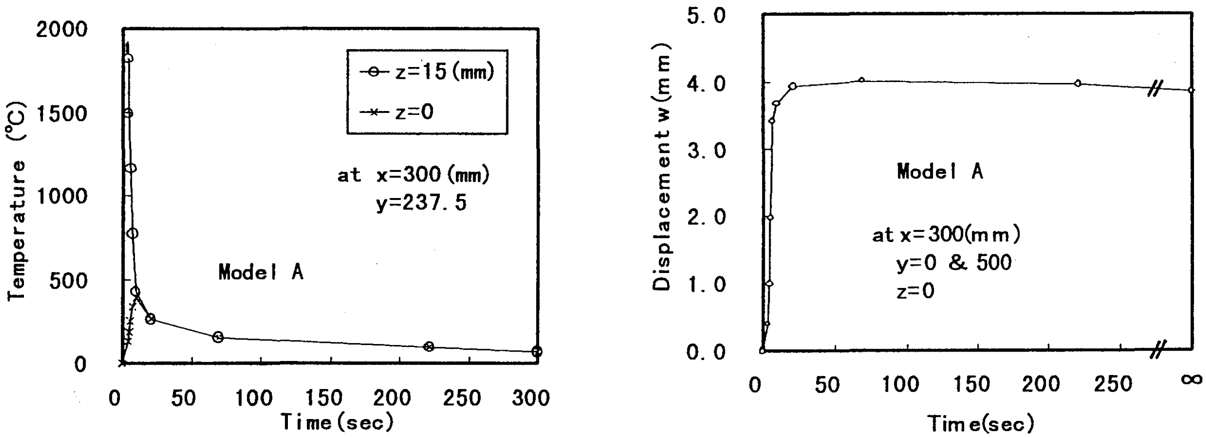
(b) Moving heat source.

Fig.2 Isothermal contours.



(a) Temperature histories. (b) Longitudinal bending displacement.

Fig.3 Temperature history and transient out-of-plane displacement.



(a) Temperature histories. (b) Angular distortion.

Fig.4 Temperature history and transient out-of-plane displacement.

time. After the expansion, the part adjacent to the heat source is only cooled down to room temperature. The lower edge of the web (adjacent to the heat source) largely shrinks in proportion to the cooling and the shape of deformation changes from concave to convex (Fig.3(b)). Then, the temperature of the whole web becomes constant as further cooling occurs (Fig.3(a)). Out-of-plane displacement becomes large until the time when both the lower and the upper contracting regions for the neutral axis become equal (Fig.3(a), (b)). After that, while the upper contracting regions for the neutral axis becomes wider than the lower regions, the temperature of the web cools down to the room temperature. Therefore, out-of-plane deformation is decreasing (Fig.3(b)), and out-of-plane deformation becomes residual deformation.

As the result, it is considered that the shape of the longitudinal bending deformation is determined depending on whether the web expands or contracts to the neutral axis for the cross section. In particular it depends upon whether the lower edge of the web adjacent to the heat source is above or below the neutral axis. That is, the shape of deformation is determined by the relative position of the neutral axis and the welding heat source. It is considered that the magnitude of deformation is largely influenced by the distance between the neutral axis and the welding heat source and by the web height.

2.3.2 Angular distortion

It is known[2)] that the temperature gradient of the flange largely governs the production of angular distortion. Based on this, the production mechanism of angular distortion is investigated below.

Figure 4(a) shows the temperature histories at the surfaces (z=0, 15(mm)), under the weld metal (y=237.5(mm)) and in the central position (x=300(mm)). **Figure 4(b)** shows the transient out-of-plane displacement, w, at the edge (y=0, 500(mm)) of the lower flange surface.

The flange surface adjacent to the weld metal only cools down to room temperature (Fig.4(a)), that is, it only contracts. The neutral axis of the flange lies at the center of the flange thickness. Therefore, angular distortion of a V-shape is generated because the contraction source is above the neutral axis of the flange, that is, the flange edge is raised (Fig.4(b)). In this way, angular distortion is produced while the temperature gradient is disappearing and, after that, angular distortion is not produced.

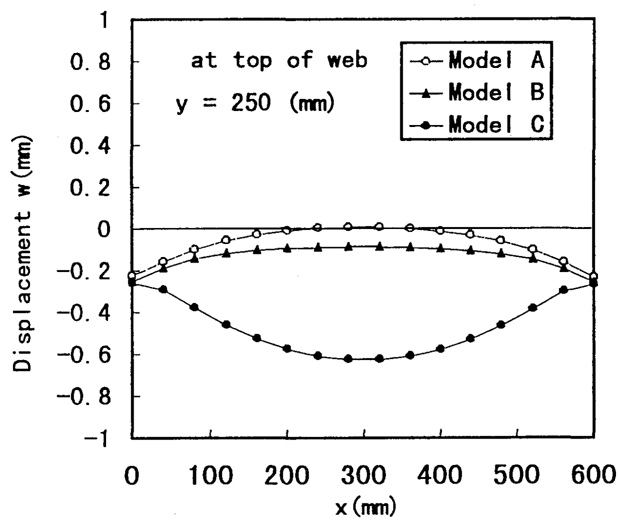
The shape is determined by the relative position of the neutral axis of the flange cross section and the welding heat source. The magnitude is largely influenced by the welding heat input and the flange thickness.

2.4 Validity of production mechanism

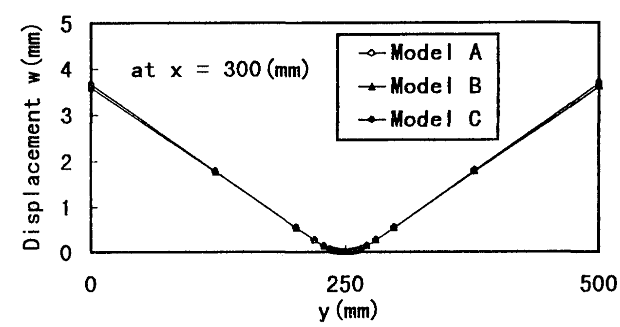
2.4.1 Longitudinal bending deformation

Figure 5(a) shows the longitudinal bending displacement at the top of the web.

As mentioned above, longitudinal bending deformation is determined by the relative position of the neutral axis for the cross section of the object and the welding heat source. In Model A, longitudinal bending deformation is generated in convex form because the neutral axis exists above the welding heat source. In Model C, longitudinal bending deformation is generated in concave form because the neutral axis exists below the welding heat source. It can be easily understood combined with the shrinkage of the weld metal. However, in Model B, small out-of-plane displacement is generated of convex form despite the neutral axis coinciding with the position of the welding heat source. In welding, as the heat diffuses and the thermal expansion and shrinkage are produced in the wide region, a difference between the neutral axis determined by the geometrical and the center of expansion and so shrinkage is generated. Therefore, it is considered that a small out-of-plane deformation is produced.



(a) Longitudinal bending deformation.



(b) Angular distortion.

Fig.5 Out-of-plane deformation generated by Instantaneous heat source.

The above mentioned results supports the validity of the production mechanism.

By the way, noting the magnitude of the shrinkage at the starting and finishing points (x=0, 600(mm)) of welding (Fig.5(a)), the shrinkage is seen to be constant regardless of the web height. This result is indicating that the shrinkage in the z-direction of the web depends on the welding heat input.

2.4.2 Angular distortion

Figure 5(b) shows angular distortion at the central position (x=300(mm)).

The shape is same in all models regardless the web height. That is, the validity of the production mechanism is supported.

On the other hand, angular distortion is the same in all positions and **Fig. 6** shows angular distortion at the starting and finishing points of welding generated in Model A.

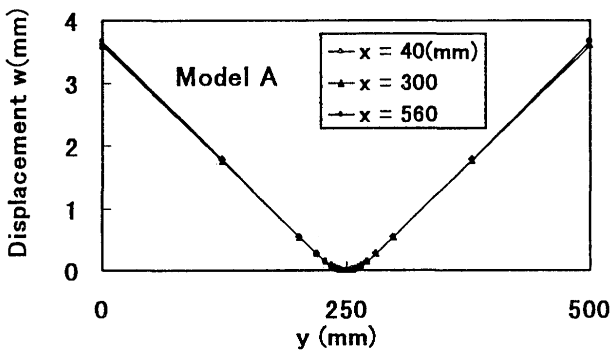


Fig.6 Angular distortion (Instantaneous heat source).

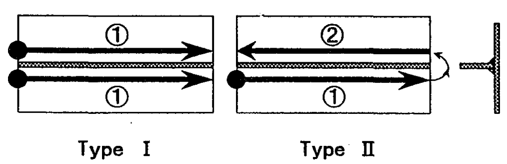
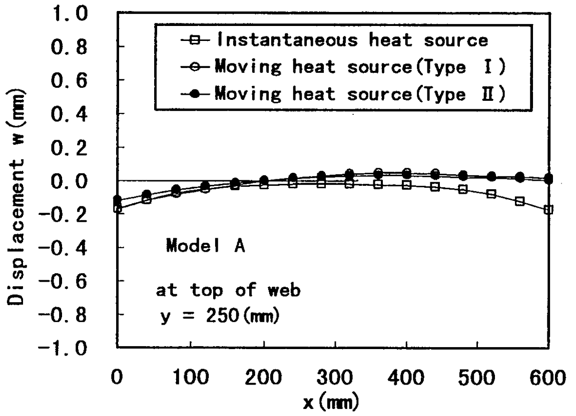
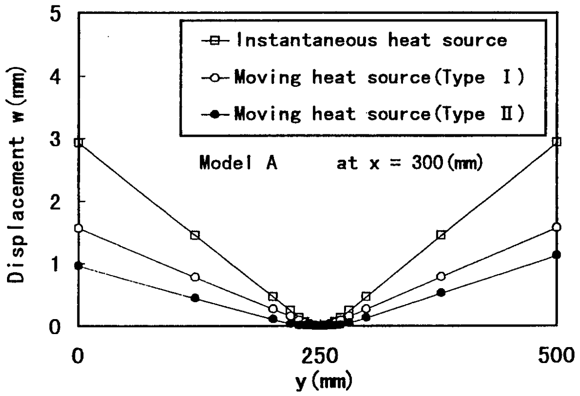


Fig.7 Welding sequence.



(a) Longitudinal bending deformation.



(b) Angular distortion.

Fig.8 Out-of-plane deformation generated by moving heat source.

3. Examination of Generality of Production Mechanism

Using the simplified model, the production mechanism of out-of-plane deformation and its validity were shown. Here, the generality of the production mechanism is variously investigated for the actual fillet welding operation.

3.1 Moving effect of the welding heat source

The welding heat source moves in actual welding. For Model A, keeping the heat input, Q=1200(J/mm), and the welding speed, v=6(mm/s) constant, the cases in which fillet welding is performed on the left and right sides at the same time (Type I) and is continuously performed from the left side to the right side (Type II) are examined (**Fig.7**). Then, the generality of the production mechanism mentioned above is investigated.

Figure 2(b) shows the isothermal contours at the time when welding is finished in Type I as an example of the temperature distribution in actual welding. It is known that the high temperature region is concentrated at the end part of welding different from the instantaneous heat source.

3.1.1 Longitudinal bending deformation

Figure 8(a) shows longitudinal bending displacement at the top of the web.

In each case of Type I and Type II, the neutral axis exists above the welding heat source. So, longitudinal bending displacement is generated in convex form. The validity of the production mechanism is supported. If the size of the model, the welding speed and the total heat input are the same, it is known from Fig.8(a) that longitudinal bending deformation generated in Type I and Type II is almost the same.

On the other hand, comparing the results of the instantaneous heat source and of the moving heat source, there is not so much difference in the magnitude of displacement in the z-direction because the mechanical boundary condition of the instantaneous heat source is similar to that of the moving heat source at the starting point of welding. However, paying attention to the end, the displacement produced by the instantaneous heat source is larger than the displacement produced by the moving heat source.

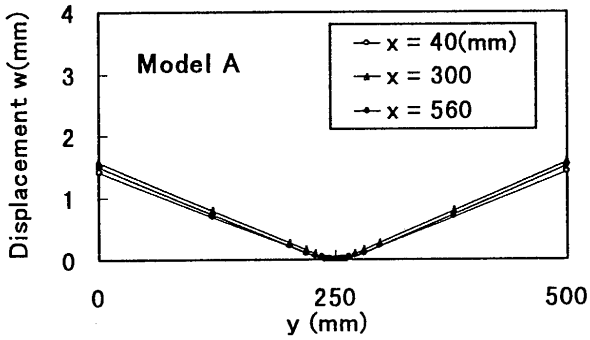


Fig.9 Angular distortion (Moving heat source).

3.1.2 Angular distortion

Figure 8(b) shows angular distortion at the central position (x=300(mm)) of the weld line. The shape of deformation is the same even if the welding speed or the welding sequence are changed. This result supports the validity of the production mechanism.

The magnitude of angular distortion produced by the instantaneous heat source, in which the whole length contracts at the same time, is larger compared with the magnitude of angular distortion produced by the moving heat source. However, the results for the instantaneous heat source do not become the limited value of angular distortion but the limited value that converges within the finite welding speed[2].

The magnitude of angular distortion is smaller in the case when welding is continuously performed from the left side to the right side (Type II) compared to the case when welding is performed on the left and right

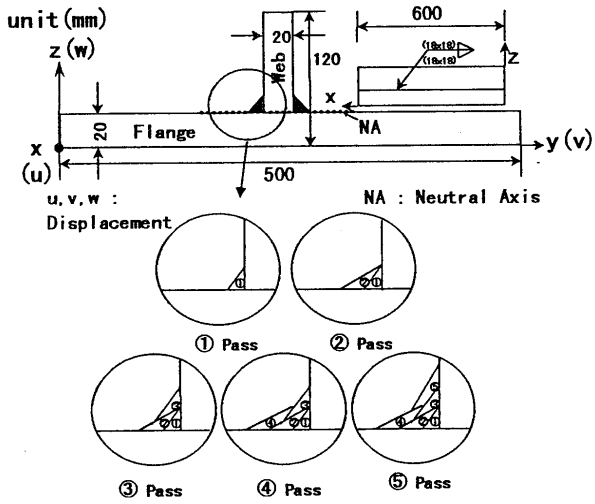


Fig.10 Model of multi-pass fillet welding.

sides at the same time (Type I). It is considered that the heat input is apparently less compared to the case when welding is performed on the left and right sides at the same time because the heat accompanied with welding of left side (the former welding) is diffused when welding of the right side is started after welding of the left side.

On the other hand, the magnitude of angular distortion is different at the starting point (x=40(mm)), at the central position (x=300(mm)) and at the end of welding (x=560(mm)) in the case of the moving heat source (**Fig.**9). However, the difference in absolute value is small.

3.2 Multi-pass welding

Here, the multi-pass fillet welding is assumed because multi-pass welding, in which the neutral axis for the cross section and the position of the welding heat source change, is considered to be proper.

Figure 10 shows the multi-pass model, the coordinate systems and sizes.

The neutral axis for the cross section of the object is on the surface of the flange. As the built-up sequence, five models are provided. Welding is performed on the left and right sides at the same time in all passes and is continuously performed until the final pass in each model is finished.

The heat input, Q, for a pass is 1200 (J/mm) and the welding speed, v, is 6(mm/s).

3.2.1 Longitudinal bending deformation

Figure 11(a) shows longitudinal bending displacement of the top of the web in each pass.

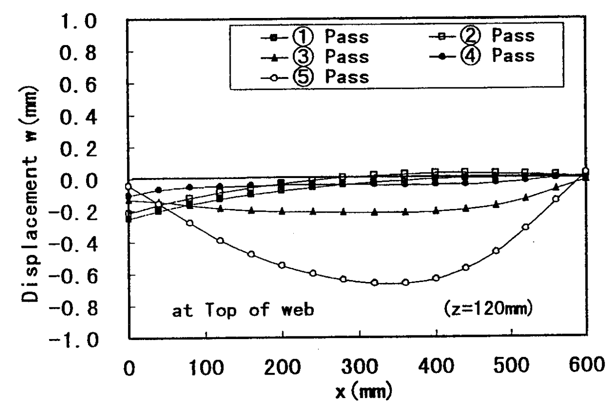
In ① pass welding, small convex longitudinal bending displacement is generated even if the position of the neutral axis coincides with the position of the welding heat source. The reason for this has already been mentioned. In ② pass welding, longitudinal bending displacement is little generated because the positions of the neutral axis and of the welding heat source are same in the case of ① pass welding. Contrary to this, in ③ pass welding, concave longitudinal bending displacement is generated because the position of the welding heat source is above the neutral axis. In ④ pass welding, small convex displacement is generated because the position of the neutral axis coincides with the position of the heat source, as in the case of ② pass welding. In the final ⑤ pass welding, concave longitudinal bending displacement is generated because the position of the welding heat source is above the neutral axis, as in the case of ③ pass welding. Moreover, as the distance between the relative positions are long, large longitudinal bending displacement is generated.

Using the multi-pass model, the validity of the production mechanism is proved.

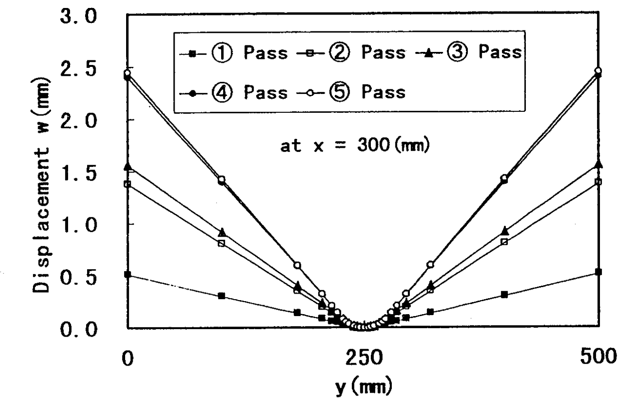
3.2.2 Angular distortion

Figure 11(b) shows angular distortion at the central position (x=300(mm)) of welding.

The shape is the same regardless of the number of passes. By this fact, the validity of the production mechanism is proved.



(a) Longitudinal bending deformation.



(b) Angular distortion.

Fig.11 Out-of-plane deformation generated by multi-pass fillet welding.

The magnitude of angular distortion in the case of ② and ④ pass welding is remarkably large. In the case of ③ and ⑤ pass welding, the increment of the magnitude of angular distortion is small. That is, when the welding heat is directly put on the surface of the flange, angular distortion tends to be remarkably large. It is indicated that angular distortion is largely influenced by the welding sequence.

4. Conclusion

First, using the model in which the welding heat source is simplified to an instantaneous heat source, the production mechanism of out-of-plane deformation generated in fillet welding was elucidated and its validity was examined.

The results can be summarised as follows:

(1) The shape of out-of-plane deformation is determined by the relative position of the neutral axis for the cross section of the object and the welding heat source. That is, when the neutral axis is above the welding heat source, the shape becomes convex, and when the neutral axis is below the welding heat source, the shape becomes concave. However, even if the position of the neutral axis, (which was determined only by the cross section of the object), and the position of the welding heat source coincided, a small longitudinal bending deformation was produced because the central position for expansion and shrinkage did not coincide with the neutral axis of the object.

(2) The shape of angular distortion is determined by the relative position of the neutral axis in the cross section of the flange and the welding heat source. That is, when the welding heat source exists on the flange surface, V-shape angular distortion is generated.

(3) It was confirmed that the direction where out-of-plane deformation is produced does not change even if the heat source moves without changing the relative position of the neutral axis and the welding heat source, or even if the welding sequence is changed.

The validity of the production mechanism was examined by using the multi-pass welding model in which the relative position of the neutral axis and the welding heat source changes in the passes.

(4) The generality of the production mechanism of out-of-plane deformation was confirmed.

(5) The magnitude of longitudinal bending deformation is not so much influenced by the welding sequence or the welding speed but is largely influenced by the distance between the neutral axis and the welding heat source and by the web height.

(6) The magnitude of angular distortion is largely influenced by the welding sequence, the welding speed and the flange thickness.

(7) Angular distortion can be considered to be uniform along the weld line.

(8) When welding is directly on the surface of the flange, the generated angular distortion is remarkably large.

References

1) For example, Y.C. Kim: Estimation of Welding Deformation, J. of Japan Welding Soc., 65-7(1996), 43-47 (in Japanese).

2) Y.C. Kim, K.H. Chang and K. Horikawa: Characteristics of Out-of-Plane Deformation and Residual Stress Generated by Fillet Welding, Trans. of JWRI, 27-1(1998), 69-74.