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FEM Simulation of Welding Distortion in Thin Curved Structures during Assembly Considering Gap and Misalignment †

Dean DENG*, Hisashi SERIZAWA** and Hidekazu MURAKAWA***

Abstract

Ships and automobiles are fabricated from thin curved plates. To assemble parts, welding is commonly used. However, it is impossible to avoid the deformation produced by welding. The deformation causes problems not only in the assembling process but also in the final products. The shrinkage of the weld zone is just one of the reasons for the distortion during assembly. Other factors, such as positioning, fixture and welding sequence must be controlled to achieve the required precision. Since it is influenced by various factors, the quantitative prediction and the control of the welding deformation is difficult. Regardless of the types of structures, the correction or straightening of the deformation, which requires skill and cost, is one of the essential parts of the assembly process. If the welding deformation can be predicted before welding, appropriate measure can be taken to maintain sufficient geometrical accuracy without special skill or large cost.

In this research, a finite element method (FEM) for predicting the welding deformation of three-dimensional curved structures with considering welding sequences is proposed. In this method, the interface element is introduced to model the joining process. The usefulness of the proposed method is demonstrated through the prediction of the welding distortion of the curved plate structures and the influence of the gap correction is investigated.

KEY WORDS: (Interface Element) (Welding Distortion) (Assembly) (Inherent Strain) (Gap) (Misalignment) (Curved Structure) (Twisting)

1. Introduction

Thin plate structures, such as ships and passenger trains, are produced by assembling curved three-dimensional parts by welding. However, the welding deformation caused by local shrinkage is unavoidable. The welding deformation produced in the structure creates gaps between already assembled parts of the structure and the parts to be welded. When gaps or misalignment exceed the tolerable limit, the welding itself becomes impossible or the geometrical accuracy cannot be maintained. Thus, the gaps must be controlled within permissible limit by appropriate correction procedures. The gap and its correction are equally influential to the geometrical accuracy of the welded structure as the local shrinkage produced by welding itself.

In this report, a method to predict the deformation of a structure during assembly by welding is proposed and the influences of the gap and its correction on the geometrical accuracy are examined. As mentioned, the geometrical error in the assembly process by welding is produced by both local deformation due to welding and the gap or the misalignment between the parts. The local deformation can be separated into three, namely the longitudinal shrinkage, the transverse shrinkage and the angular distortion. The influential factors in these local deformations are the heat input and the penetration shape. On the other hand, the gap is influenced by various factors, such as the welding sequence, the positioning, the fixture and the tack welding.

To deal with the local deformation and the gap, an elastic Finite Element code in which the local

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deformation is described by the inherent strain, and the gap is modeled using interface element¹⁾. In the proposed method, the gap and the various joining state between parts, such as the free state, the state in positioning process and the fully joined state after completion of welding can be represented by selecting appropriate values for the parameters (γ :bonding strength, r_0 :scale parameter, δ_G :size of gap) involved in the interface element²⁾. By using the interface element, the welding deformation during assembly process can be precisely predicted by considering the welding sequence and the gap correction.

2. Method of Analysis
2.1 Interface Element

The assembly of the structure can be regarded as the repetition of the positioning of new parts and welding. The parts are physically free before positioning. Through positioning, the relative position of the part, the gap and the misalignment are corrected within tolerable limits. By welding, full bonding between the parts is formed. To model the real assembly process, the change of physical state must be modeled. In particular, the positioning process must be modeled carefully by considering contact, slide and gap between parts. For this purpose, the interface element is introduced. The change of physical state between parts can be described through the bonding stress-relative displacement relation.

Fig. 1 shows the interface element defined between two parts (or two elements belonging to the parts to be joined). The relative displacements between the two parts are normal opening δ_N , transverse opening δ_T , longitudinal sliding δ_L and relative rotation $\delta_{\theta X}$. Similarly, the stresses acting between the parts are denoted as σ_N , σ_T , σ_L and $\sigma_{\theta X}$, respectively.

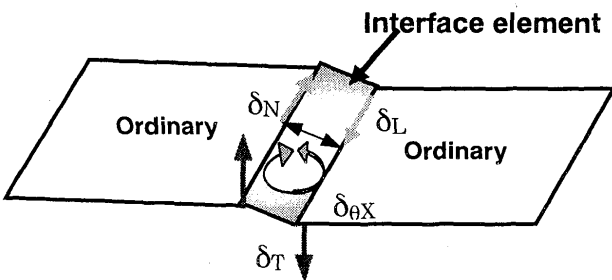


Fig.1 Types of gap described in the interface element.

Normal direction

$$\sigma_N = \begin{cases} \gamma & (\delta_N > r_0) \\ \gamma - \gamma \left(1 - \frac{\delta_N - \delta_{NG}}{r_0}\right)^n & (\delta_N \leq r_0) \end{cases} \quad (1)$$

Shear direction (L: longitudinal, T: transverse)

$$\sigma_L = \begin{cases} \gamma & (\delta_L > r_0) \\ \gamma - \gamma \left(1 - \frac{\delta_L - \delta_{LG}}{r_0}\right)^n & (r_0 \geq \delta_L \geq 0) \\ -\gamma + \gamma \left(1 + \frac{\delta_L - \delta_{LG}}{r_0}\right)^n & (0 > \delta_L > -r_0) \\ -\gamma & (-r_0 \geq \delta_L) \end{cases} \quad (2)$$

Rotational direction

$$\sigma_{\theta X} = \begin{cases} \gamma & (\delta_{\theta X} > r_0) \\ \gamma - \gamma \left(1 - \frac{\delta_{\theta X} - \delta_{\theta G}}{r_0}\right)^n & (r_0 \geq \delta_{\theta X} \geq 0) \\ -\gamma + \gamma \left(1 + \frac{\delta_{\theta X} - \delta_{\theta G}}{r_0}\right)^n & (0 > \delta_{\theta X} > -r_0) \\ -\gamma & (-r_0 \geq \delta_{\theta X}) \end{cases} \quad (3)$$

where, δ represents the opening displacement, in a general sense, between the parts to be joined. As seen from Eqs.(1), (2) and (3), the constants involved in σ , namely γ , n , r_0 and δ_G are parameters defining the relation between the bonding stress σ and the opening displacement δ . The parameter γ represents the maximum bonding force per unit area (interface bonding strength). The parameter n is the shape parameter which determines the shape of the σ - δ curve. The slope increases with n . The parameter r_0 is the scale parameter which gives the precision in positioning. The last parameter δ_G represents the gap remaining at the welding stage. The relationships between the stress σ and the displacement δ are schematically shown in Figs. 2(a) and (b). Due to the symmetry of the shear deformation and rotational deformation, the relation between displacement and stress is symmetric as shown in Fig. 2(b). While that in normal direction is not symmetric as shown in Fig. 2(a).

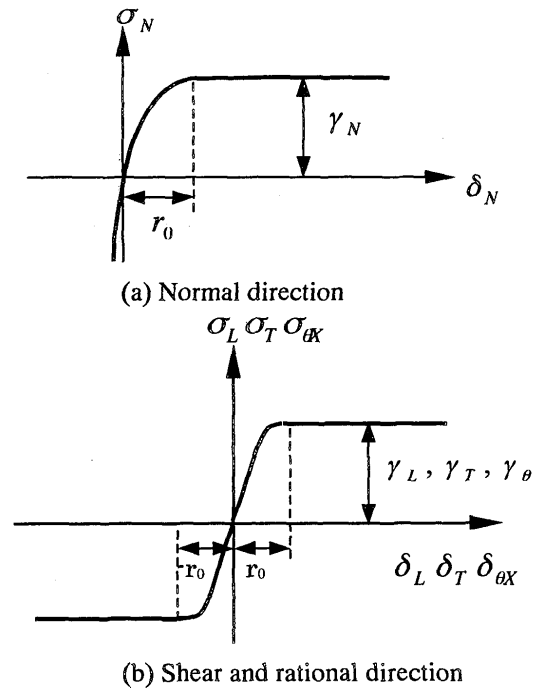


Fig. 2 Relationship between bonding stress and displacement.

The physical relation between parts during the assembly process can be separated into four as shown in Table 1, namely, free, weak positioning, strong positioning and welding. The property of the interface element is mostly defined by the scale parameter r_0 and bonding strength γ . The scale parameter r_0 gives the precision in positioning and a small enough value must be selected to ensure the required precision at the positioning stage. Except for the positioning stage, large value can be used for r_0 . On the other hand, the bonding strength γ must be small when the parts are free. At the positioning stage, a relatively small value such as 10^{-4} MPa corresponds to weak positioning which is not strong enough to close the gap. For the strong positioning which is strong enough to close the gap, a large value such as 10^0 MPa can be given. As shown in Fig. 3, the precision of the positioning can be controlled by adjusting the scale parameter r_0 . When full bonding is formed by welding, 10^{10} MPa can be used. The gap between parts remaining after the positioning stage, δ_G is fixed and introduced into the function describing the state after welding as shown in Fig. 4.

Table 1. Interface element parameters for different stages.

| Stage | r_0 (mm) | γ (N/mm ²) |
|-------------|------------|-------------------------------|
| Free | 10^3 | 10^{-5} |
| Positioning | 10^{-1} | 10^{-4} (weak) |
| | | 10^0 (strong) |
| Welding | 10^2 | 10^{10} |

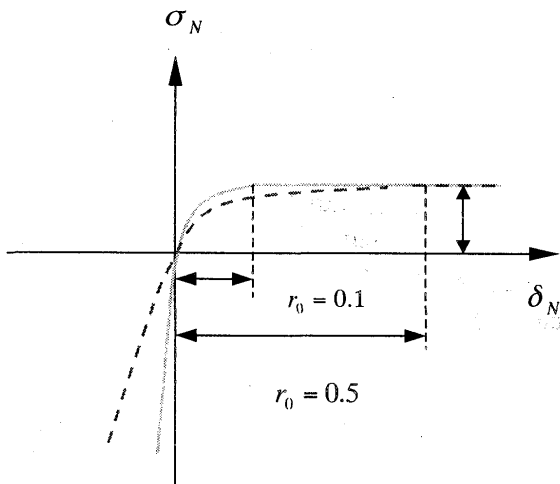


Fig. 3 Relationship between bonding stress and displacement during positioning.

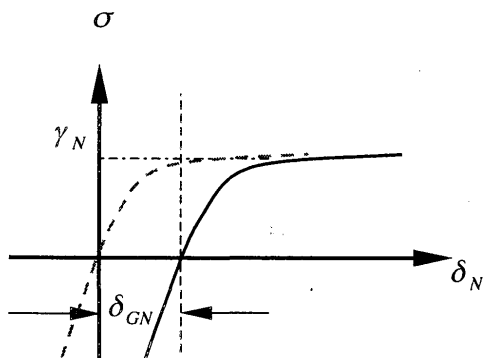


Fig. 4 Relationship between δ and σ for welding joint with gap.

2.2 Procedure of Analysis

The finite element method proposed in this report is developed to predict the distortion of curved thin plate structures by considering the details of the assembly process, such as the positioning, gap correction, tack welding and joining by welding. The parts are subdivided into a finite element mesh using 4-point rectangular plate elements. The state of joining is described by the interface element that is introduced between parts to be joined. The local deformation due to the welding thermal cycle is taken into account through the inherent strain introduced to the elements facing the welding line. Thus, the detailed assembly process can be simulated by controlling the parameters involved in the interface element and the inherent strain according to the assembly stage.

3. Curved Structure Model

The welding deformation of the curved three dimensional structure shown in Fig. 5 consisting of three longitudinal and two transverse stiffeners and a skin plate is analyzed using the proposed method. Both the stiffeners and the skin plate are curved members. The geometrical shape of the skin plate is given by Eq. (4). It is a doubly curved asymmetrical plate. The curvatures of the skin plate in the principal directions are $1/7200 \text{ mm}^{-1}$ in X' and $1/3600 \text{ mm}^{-1}$ in Y' directions as shown in Fig. 6. In case of the standard model, the orientation of the principal direction from the direction of the longitudinal stiffeners θ is 20 degree and the maximum deflection of the skin plate is 305 mm.

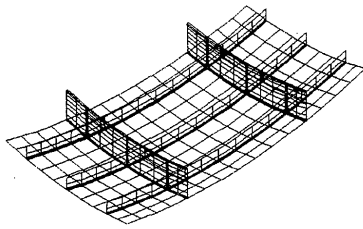


Fig. 5 Asymmetry curved structural model.

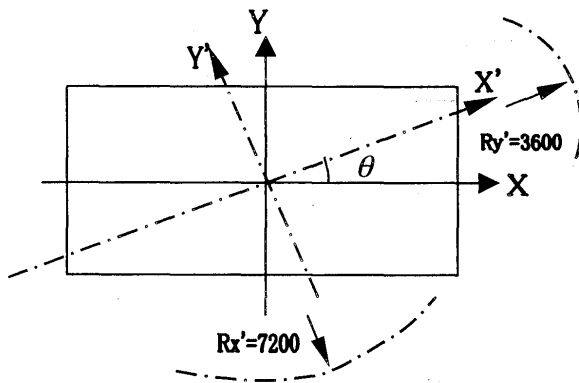


Fig. 6 Principal direction of skin plate.

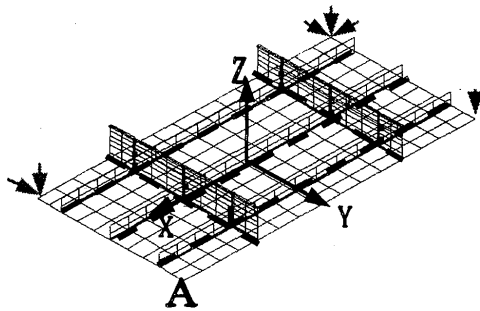


Fig. 7 Boundary condition.

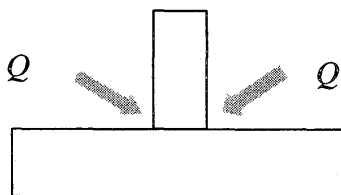


Fig. 8 T joint between skin and stiffener.

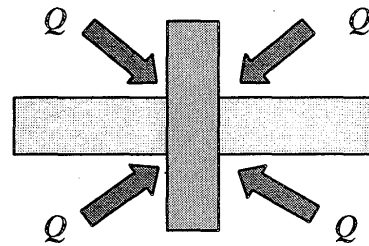


Fig. 9 Cross-shaped joint between L-stiffener and T-stiffener.

$$Z = R_{X'} + R_{Y'} - \sqrt{R_{X'}^2 - X'^2} - \sqrt{R_{Y'}^2 - Y'^2} \quad (4)$$

$$X' = X \cos \theta + Y \sin \theta$$

$$Y' = -X \sin \theta + Y \cos \theta$$

where,

- X, Y : coordinates along stiffeners
- X', Y' : coordinates in principal directions
- $R_{X'}$: radius of curvature in X' direction
- $R_{Y'}$: radius of curvature in Y' direction

3.1 Mesh division and boundary condition

The curved structure model is subdivided into a finite element mesh as shown in Fig. 7. The skin plate, the longitudinal and the transverse stiffeners are divided into $19 \times 16 = 304$, $3 \times 19 \times 3 = 171$, $9 \times 16 \times 2 = 288$ elements, respectively. The number of interface element between welded parts is 125. The total number of elements is 888 and that of the nodes is 1028. The model is fixed at three points as shown in Fig. 7 to prevent rigid body motion. The thick broken lines in the figure show the location of welding lines.

3.2 Welding condition and inherent strain

3.2.1 Heat input

The heat inputs for each welding line are assumed as follows:

- Transverse stiffener/Skin plate : 535 J/mm
- Longitudinal stiffener/Skin plate : 441 J/mm
- Transverse stiffener/Longitudinal stiffener : 441 J/mm

3.2.2 Inherent strain

The structure to be analyzed is assembled by two types of fillet weldings. One is the simple fillet welding joint between the stiffeners and the skin plate as shown in Fig. 8. Another is the cross-shaped fillet joint between the longitudinal and the transverse stiffeners as

shown in Fig. 9. For these joints, the inherent strains for the longitudinal shrinkage, the transverse shrinkage and the angular distortion must be determined from the welding heat input and the thickness of the members. The procedure to determine these is presented in the following using the simple fillet joint as an example.

According to White³⁾, the relationship between tendon force F_{tendon} which produces the longitudinal shrinkage and the welding heat input Q is given by Eq. (5).

$$F_{tendon} = 200 \cdot Q \quad (N) \quad (5)$$

In the case of fillet welding, the welding heat input is given to both the flange and the web. According to the ratio proposed by Cottrell⁴⁾, heats going into the web and the flange are given as,

$$Q_{web} = \frac{h_w}{2h_f + h_w} Q_{total} = \frac{h_w}{2h_f + h_w} 2Q \quad (6)$$

$$Q_{flange} = \frac{2h_f}{2h_f + h_w} Q_{total} = \frac{2h_f}{2h_f + h_w} 2Q \quad (7)$$

where, Q_{total} : total heat input, h_w : thickness of web, h_f : thickness of flange

Fig. 10 shows the elements forming the fillet joint where the inherent strain is introduced. The inherent strain is introduced into these elements. The longitudinal inherent strain for the flange ϵ_{XF} and that for the web ϵ_{XW} are given by,

$$\epsilon_{XF} = -\frac{F_{tendon-f}}{2B \cdot h_f \cdot E} = -\frac{200 \cdot Q_{flange}}{2B \cdot h_f \cdot E} \quad (8)$$

$$\epsilon_{XW} = -\frac{F_{tendon-w}}{H \cdot h_w \cdot E} = -\frac{200 \cdot Q_{web}}{H \cdot h_w \cdot E} \quad (9)$$

where,

E: Young's Modulus

H: width of element on web where inherent strain is given

B: width of element on flange where inherent strain is given.

When the transverse shrinkage on the flange due to the fillet welding is S , the inherent strain in the transverse direction ϵ_Y^* is given as,

$$\epsilon_Y^* = -\frac{S}{B} \quad (10)$$

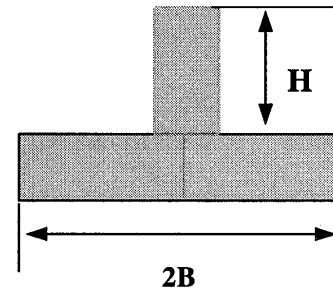


Fig. 10 Elements where inherent strains are introduced.

After correcting the transverse shrinkage produced by tendon force $\nu\epsilon_X$, the final value of the inherent strain in the transverse direction ϵ_Y is given by the following equation.

$$\epsilon_Y = \epsilon_Y^* - \nu\epsilon_X \quad (11)$$

where, ν is Poisson's ratio.

On the other hand, the curvature κ_X to be introduced into the element as the inherent strain is given by the following equation using the angular distortion β produced in fillet welding.

$$\kappa_X = \frac{\beta}{B} \quad (12)$$

4. Simulated Cases

As mentioned in Section 1, the distortion during the assembly process is produced by both the local deformation due to the welding and the correction of the gap and the misalignment between parts. In this section, the influence of the gap correction on the distortion is investigated. To clarify the influence of the gap and its distribution, three cases, namely Cases A, B and C, are analyzed. In Case A, all members are assumed to have no geometrical error. Thus, there is no gap as shown in Fig. 11. In Case B, the longitudinal stiffener is assumed to have larger curvature compared to the designed shape and the gap increases toward its ends as shown in Fig. 12. In contrast, the longitudinal stiffener is assumed to have smaller curvature compared to the designed shape and the maximum gap appears at its center as shown in Fig. 13. The maximum values of the gap are approximately 5 mm in both Cases B and C. These gaps are corrected by pulling the longitudinal stiffeners and the skin plate together using the interface element. The parameter γ , which gives the maximum force per unit area to correct the gap, is assumed to be 0.1 MPa in Cases B and C. After the gap correction, the members are assumed to be tack welded and the final welding is done simultaneously.

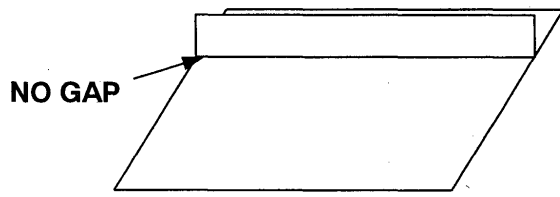


Fig. 11 No initial gap between L-stiffener and skin plate.

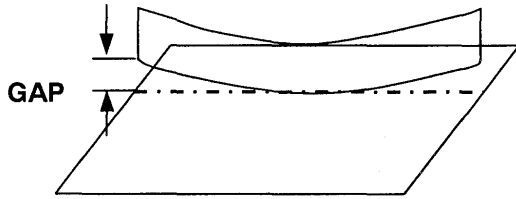


Fig. 12 Edge type initial gap between L-stiffener and skin plate.

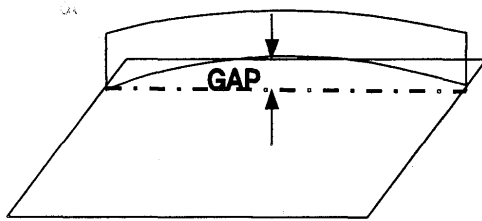


Fig. 13 Middle type initial gap between L-stiffener and skin plate.

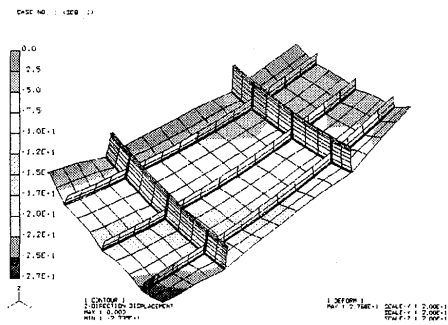


Fig. 14 Deflection in Case A.

5. Computed Results and Discussion

5.1 Computed Results

The distortion in Case A is shown in Fig. 14. As seen from the figure, the twisting distortion can be produced by welding alone when the structure is asymmetric. Figs. 15, 16 and 17, 18 show the deformation after gap correction and the final deformation after welding in Case B and Case C, respectively. As seen

from the comparison between Figs. 15 and 17, the gap correction can produce fairly large twisting distortion and the directions of the twist are opposite to each other. Since the twist in Case B, in which the gap is the end type, is in the same direction as the welding deformation shown in Fig. 14, the final twisting distortion is approximately the sum of them. In Case C, the direction of the twist produced by gap correction is in the opposite direction, the twist by the welding and the gap correction cancel each other as shown in Fig. 18.

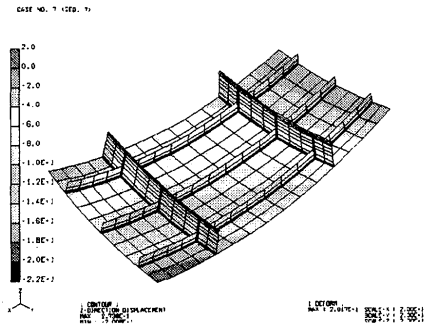


Fig. 15 Deflection after positioning in case.

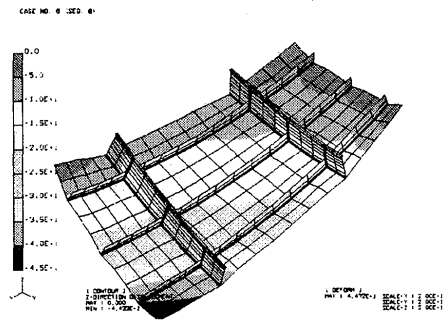


Fig. 16 Final deflection in case B.

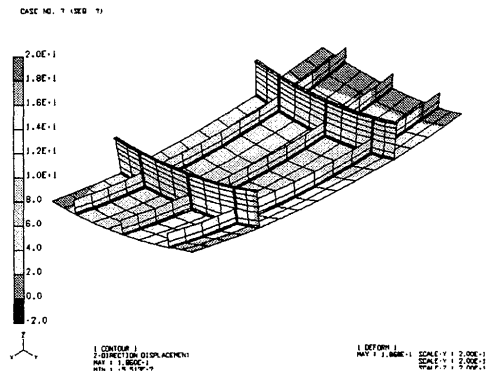


Fig. 17 Deflection after positioning in case C.

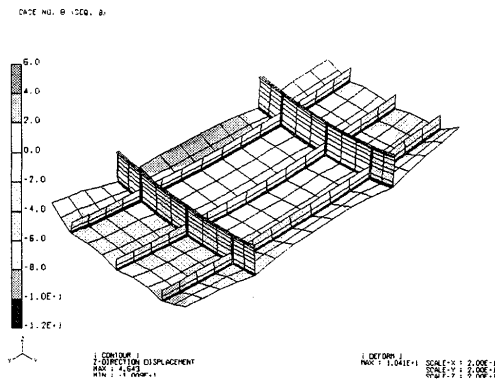


Fig. 18 Final deflection in case C.

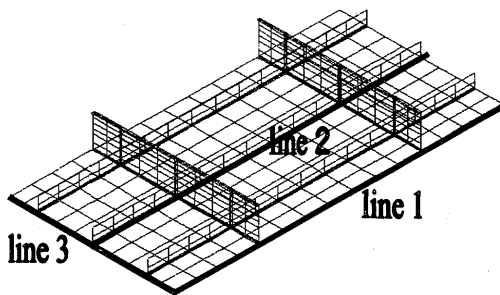


Fig.19 Lines where deflections are compared.

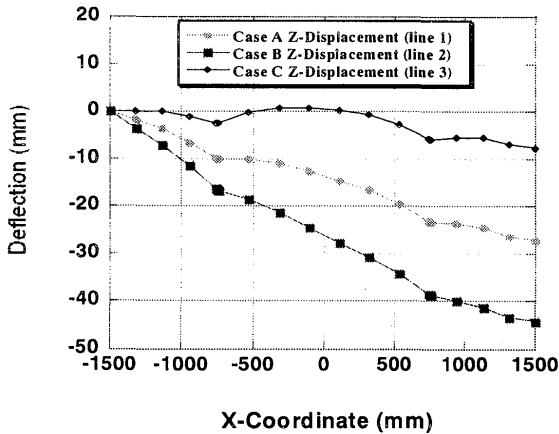


Fig. 20 Deflection along line 1.

5.2 Discussion

To closely examine the distortion in Cases A, B and C, the deformations along the lines shown in Fig. 19 are plotted in Figs. 20, 21 and 22. In Fig. 20, the three cases are compared with respect to the deformation after welding along the edge of the skin plate (line-1). When there is no gap (Case-A), the maximum deflection is 27.3 mm. This deflection is produced by welding alone.

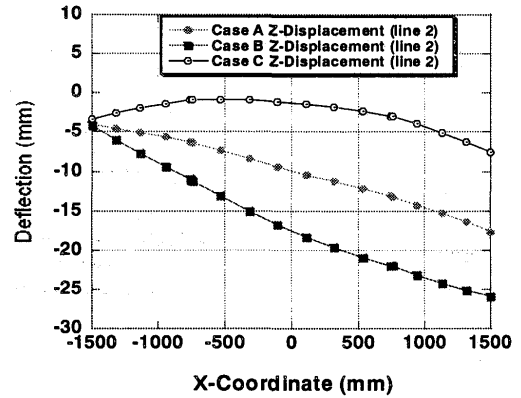


Fig. 21 Deflection along line 2.

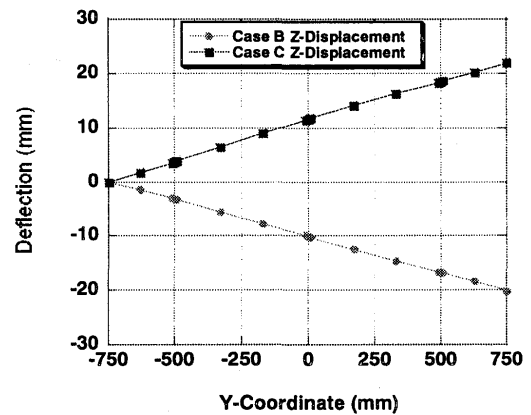


Fig. 22 Deflection along line 3 after positioning.

In case-B, in which end type gap exists and the welding is performed after gap correction, the distortion increases to 43.5 mm. The twisting distortion is enhanced by the gap correction and the distortion due to gap correction is as large as that due to the welding deformation. This means that to reduce the distortion of the structure during assembly, not only the welding deformation, but also the gap must be carefully controlled. When the gap is the center type, the distortion is reduced to 7.8 mm. This tells us that the direction of the twisting distortion changes with the type of the gap.

Similarly, the distortions of the skin plate along the longitudinal stiffener (line-2) are compared in Fig. 21. It is clearly seen that the distortion is strongly controlled by the shape of the gap. It is close to a straight line when there is no gap (Case-A). It is concave and convex curve when the gap is edge type (Case-B) and center type (Case-C), respectively.

The distortions due to the gap correction are compared between Cases-B and C in Fig. 22. The distortions along the end of the skin plate are shown. As already observed in Fig. 22, the direction of the twist is reversed when the type of gap is different and the magnitude of twist is approximately 20 mm.

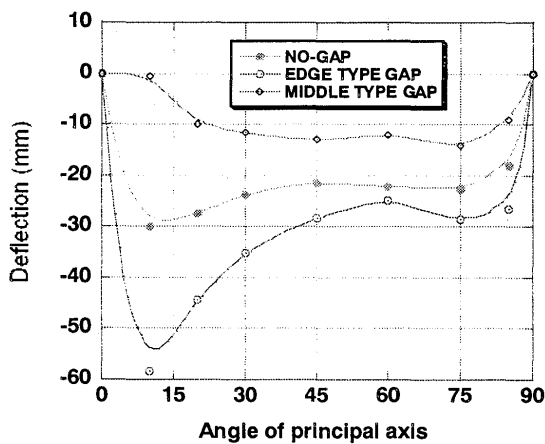


Fig. 23 Relationship between angles of principle and deflection in point A.

6. Influence of Orientation of Principal Axis

In general, the mode of distortion produced during the assembly process becomes symmetric when the structure and welding sequence are symmetric and buckling does not occur. To clarify the relation between the degree of asymmetry and the magnitude of twisting distortion, the orientation of the principal direction of the curvature shown in Fig. 6 is changed from 0 degree to 90 degree and the distortion is analyzed. Fig. 23 summarizes the relation between the orientation of the principal axis and the twisting. The twisting is represented by the deflection at the point A in Fig.7. Three lines in Fig. 23 shows the twisting of the structure without gap, with end type and center type gaps. As it is expected, twisting does not occur when the orientation is 0 degree or 90 degree. In these cases, the structure becomes geometrically symmetric. Excluding these two cases, significantly large twisting distortion is observed and the magnitude of distortion varies with the orientation angle. The magnitude of twisting becomes maximum when the orientation angle is approximately 10 degree. Such tendency is commonly observed both in cases with and without the gap.

7. Conclusions

An elastic finite element method in which the local welding deformation and the gap between parts are

considered through the inherent strain and the interface element is proposed as a method to predict the distortion of the structure during the assembly process. The proposed method is applied to the distortion of an asymmetric curved structure and the following conclusions are drawn.

- (1) By introducing the interface element, it becomes possible to treat the positioning, gap correction process and joining process in a unified fashion.
- (2) When the structure is asymmetric, distortion in twisting mode can be produced by welding local deformation alone.
- (3) When the gap exists between the longitudinal stiffeners and the skin plate, the gap correction process produces twisting of structures in addition to that caused by welding. The direction of the twist changes with the type of the gap.
- (4) In case of the curved structure investigated in this report, the magnitude of the distortion produced by correcting a 5 mm gap is greater than the value of the gap itself and it is equivalent to that produced by welding.
- (5) The orientation of the principal axis of the skin plate has a great influence on the twisting of the structure during assembly.

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