Theoretical Prediction of Welding Distortion Considering Positioning and the Gap between Parts [†]

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Abstract

The welding distortion of a plate structure during the assembly process is influenced not only by the local shrinkage due to the welding thermal cycle but also by the root gap and the misalignment. The former is governed by the heat input. Meanwhile, the latter is strongly affected by the welding procedure, such as the welding sequence and restraint on the joint to be welded. In this research, a method to predict the precision of plate structures during the assembly process considering these factors is developed. The proposed method employs the concept of inherent strain and the interface element to consider both the local shrinkage due to welding and the gap and the misalignment in the weld joint. The proposed method is applied to study the influence of welding sequence on the distortion of the structure during assembly by welding.

KEY WORDS: (Interface Element) (Welding Distortion) (Welding Sequence) (Gap) (Misalignment)

1. Introduction

The assembly process in shipbuilding essentially involves joining of large blocks. Blocks are all-welded thin plate structures. During fabrication of the blocks, distortions occur due to various causes such as the cutting and the welding. Even through it is practically impossible to eliminate distortion completely, it is necessary to produce blocks with a sufficient level of accuracy, so as to avoid problems in the course of assembly.

During welding, local shrinkage is produced as an unavoidable consequence. Even though it is true that the shrinkage induced by welding is the major cause of the geometrical error in the welded structure, there are many other factors, such as initial geometrical error of the parts, root gap of groove, positioning and fixture prior to welding, which cannot be neglected. The sequence of welding is one of the most influential factors on the root gap and the misalignment, and thus to geometrical accuracy.

Generally, there are two factors that result in geometrical error in the welded structure. The first factor is the local shrinkage due to the thermal cycle in the weld zone. The local distortion can be categorized into three, namely, longitudinal shrinkage, transverse shrinkage and angular distortion. These are strongly affected by heat input, shape of penetration, thickness of plate and joint type. The second factor is the gap and the misalignment produced in the joint prior to welding. Influential factors on the gap and the misalignment are welding sequence, positioning and restraint such as tack welding. For a truly reliable prediction of welding distortion during the assembly process, all these factors must be taken into account in addition to the local shrinkage.

In this research, a method to predict the distortion during welding considering all the above factors is proposed. In the proposed method, local shrinkage due to the welding thermal cycle is considered through the inherent strain and the gaps and their corrections are handled by the interface element. The proposed method is applied to the welding distortion of thin plate structures and the influence of welding sequence is investigated.

2. Theoretical Formulation
2.1 Interface Potential

The process of welding between the parts A and B is schematically described in **Fig.1**. The parts A and B are mutually free at the beginning. These parts are pulled
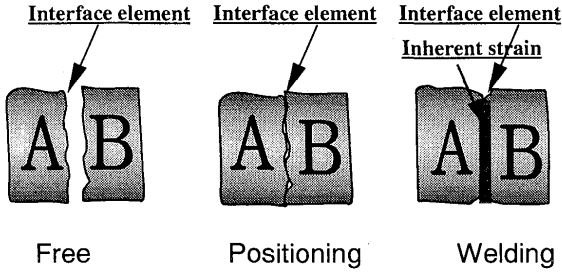
Fig.1 Assembly of joint expressed by interface element

together to the appropriate position and tack welds are made. In this process, the root gap can be different depending on how the root gap and the misalignment are treated. After the positioning, the welding is performed. The three stages, namely free, positioning and welding stages can be modeled using the interface element [1].

The interface element is suitable for describing the interaction between surfaces or parts to be welded. In the free stage, the interaction is extremely weak. On the other hand, the parts are strongly joined after welding. The interaction during the positioning is intermediate but it doses not allow penetration between parts.   Such interaction between the surfaces can be described by the interface potential function ϕ .   In this research, the Lennard-Jones potential function is used. The interface potential per unit area ϕ can be defined by the following equation.

$$\phi(\delta) = 2\gamma \left\{ (\frac{r_0}{r_0 - \delta_G + \delta})^{2n} - 2(\frac{r_0}{r_0 - \delta_G + \delta})^n \right\} \qquad (1)$$

Where, δ is the distance or the displacements between the parts to be welded. δ_G is the root gap of groove produced during the positioning stage. The parameters γ, r_0 and n are the surface energy, the scale parameter and the shape parameter, respectively.   Among them, γ controls the bonding strength and r_0 determines the accuracy in positioning. The shape parameter n changes the shape of the potential and it is chosen to be 4 in our research. The derivative of ϕ with respect to the distance between parts to be welded δ , gives the bonding stress per unit area σ_s , such that

$$\sigma_s = \frac{\partial \phi}{\partial \delta_N} = \frac{4\gamma n}{r_0} \left\{ (\frac{r_0}{r_0 - \delta_G + \delta})^{n+1} - (\frac{r_0}{r_0 - \delta_G + \delta})^{2n+1} \right\} \qquad (2)$$

In case of the three dimensional problem, there are four relative gaps between parts as shown in **Fig.2**, namely opening of groove δ_N , misalignments in the transverse and longitudinal direction δ_T, δ_L and the angular misalignment δ_θ . Then the total potential function ϕ is defined by the following equation.

$$\phi(\delta_L, \delta_N, \delta_T, \theta_X) = \phi_L(\delta_L) + \phi_N(\delta_N) + \phi_T(\delta_T) + \phi_\theta(\theta_X) \qquad (3)$$
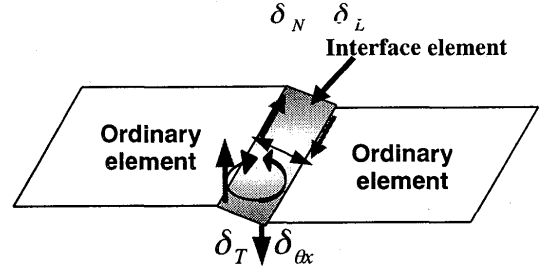

Fig.2   Potential types of interface element

Where:
Potential in the normal direction ϕ_N :

$$\phi_N(\delta_N) = 2\gamma_N \left\{ (\frac{r_0}{r_0 - \delta_{GN} + \delta_N})^{2n} - 2(\frac{r_0}{r_0 - \delta_{GN} + \delta_N})^n \right\} \qquad (4)$$

Potentials in the shear direction ϕ_L and ϕ_N :

$$\phi_L(\delta_L) = 2\gamma_L \left\{ (\frac{r_0}{r_0 - \delta_{GL} + |\delta_L|})^{2n} - 2(\frac{r_0}{r_0 - \delta_{GL} + |\delta_L|})^n \right\} \qquad (5)$$

$$\phi_T(\delta_T) = 2\gamma_T \left\{ (\frac{r_0}{r_0 - \delta_{GT} + |\delta_T|})^{2n} - 2(\frac{r_0}{r_0 - \delta_{GT} + |\delta_T|})^n \right\} \qquad (6)$$

Potential in the rotational direction ϕ_θ :

$$\phi_\theta(\delta_\theta) = 2\gamma_\theta \left\{ (\frac{r_0}{r_0 - \delta_{GA} + |\delta_\theta|})^{2n} - 2(\frac{r_0}{r_0 - \delta_{GA} + |\delta_\theta|})^n \right\} \qquad (7)$$

The relationship between the displacement δ and the stress σ , which are derived as derivatives of ϕ with respect to δ , are schematically shown in **Fig.3**. Due to the symmetry of the shear deformations and rotational deformation, the interface potentials for these modes are assumed as symmetric functions. While that in normal direction is not symmetric.
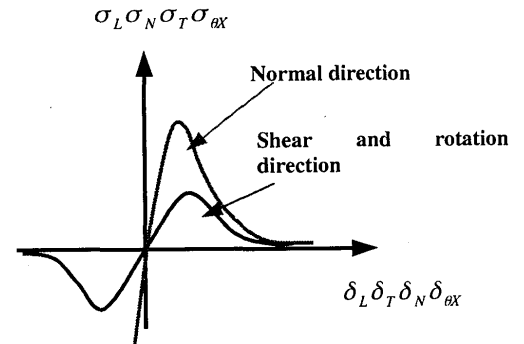
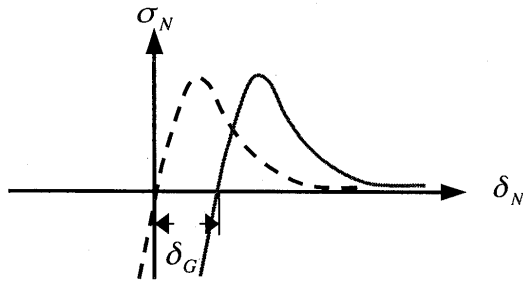Fig.3 $\sigma - \delta$ relationship at interface

90

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

2.2 Simulation method using interface element

The simulation method developed in this research is suitable for thin plate welded structures common in shipbuilding. The welding distortion can be simulated by introducing the interface elements at the weld joints and applying the inherent strain in a step-by-step manner according to the welding sequence. 4-node plate element is used for the parts to be welded.

In the course of simulation, the parameters of the interface element along the welded joint and those for the un-welded joint are different. In other words, since the bonding is strong between the welded parts, the interface energy γ should be large. But in case of the un-welded joint, the bonding is weak. Consequently, the interface energy γ should be small. On the other hand, in the positioning stage, the parameter r_0 should be small in order to describe the contact condition between parts to be welded. The spatial distance between parts produced in the positioning stage will be taken as the root gap. The $\sigma - \delta$ relationship after positioning stage is schematically shown in **Fig.4**. Where δ_G is the root gap in the weld joint.

The important characteristics of the simulation method developed in this research are summarized as follows.

(1) Because an elastic FEM based on inherent theory is employed to predict distortion, it takes a short time to complete the simulation even for large welded structures.

(2) Using the present method, welding distortion in every assembly stage can be predicted.

(3) The influence of welding sequence on welding distortion also can be simulated.

2.3 Equilibrium Equation

When the problem is elastic, the equilibrium equation can be obtained according to the principle of minimum potential energy. In general, the potential energy Π of an elastic body can be expressed as,

$$\Pi = U + U_s + W \tag{8}$$

Where, U is the elastic strain energy of the sturcture, U_s is the interface potential energy, and W is the work done by the external force.

$$\Pi = \Pi(u_0) = U(u_0) + U_s(u_0) + W(u_0) \tag{9}$$

Since the model is an assembly of the ordinary plate elements and the interface elements, the total potential energy $\Pi(u_0)$ is the sum of these for all elements, such that.

$$\Pi(u_0) = \sum \{U^e(u_0^e) + U_s^e(u_0^e) + W^e(u_0^e)\} \tag{10}$$

As shown in Eq.1, the potential of the interface element is a highly nonlinear function, it is necessary to employ an incremental method to solve the problem.

To derive an incremental equation, the total potential energy $\Pi(u_0 + \Delta u_0)$ is expanded into a Taylor series up to the second order with respect to the nodal displacement increment Δu_0, such that

$$\Pi(u_0 + \Delta u_0) = \Pi(u_0) + \delta^1 \Pi(\Delta u_0) + \delta^2 \Pi(\Delta u_0)$$
$$= \Pi(u_0) - \{\Delta u_0\}^T \{f\} + 1/2\{\Delta u_0\}^T[K]\{\Delta u_0\} \tag{11}$$

where, $\delta^1\Pi(\Delta u_0)$ and $\delta^2\Pi(\Delta u_0)$ respectively are the first and the second terms of the nodal displacement increment, and these are related to the force vector $\{f\}$ and the stiffness matrix $[K]$.

$$\delta^1\Pi(\Delta u_0) = -\{\Delta u_0\}^T\{f\}$$
$$\delta^2\Pi(\Delta u_0) = 1/2\{\Delta u_0\}^T[K]\{\Delta u_0\} \tag{12}$$

The equilibrium equation can be obtained as the stationary condition of $\Pi(u_0 + \Delta u_0)$, such that,

$$\partial\Pi(u_0 + \Delta u_0)/\partial\Delta u_0 = -\{f\} + [K]\{\Delta u_0\} = 0 \tag{13}$$

or

$$[K]\{\Delta u_0\} = \{f\} \tag{14}$$

3. Examples of simluation
3.1 I-Section girder model

In order to study the influence of welding sequence and positioning on welding distortion, a simple I-Section girder model as shown in **Fig.5** is selected as an example. The dimensions of two flanges are
L=8000mm, H=1000mm, T=16mm.
Those of the web are
L=8000mm, B=2000mm, T=16mm.
The interface elements are placed along the welding lines between the flange and the web which are indicated with the thick solid line.

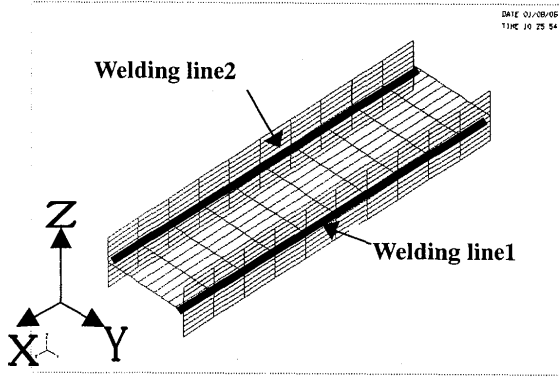**Fig.5** I section girder model

3.2 Welding condition and inherent strain.

3.2.1 *Welding condition*

In the I-section girder model, the type of joint is a fillet and the heat input is assumed as 2400J/mm for all welding passes.

3.2.2 *Estimation of inherent strain*

Generally, there are three types of welding deformations, namely, the longitudinal shrinkage produced by the tendon force, the transverse shrinkage, and the angular distortion. The relationship between the tendon force F_{Tendon} and the net heat input Q_{net} is given by the following equation [2].

$$F_{Tendon} = 0.2Q_{net}(KN) \tag{15}$$

The relationship between the tendon force and the inherent strain in the welding direction is given by the following equation [3].

$$F_{Tendon} = \int E\varepsilon_x dydz \tag{16}$$

where, E is the elastic modulus, and ε_x is the inherent strain in the welding direction.

In the proposed method, the inherent strain is introduced into the elements along the welding line. The magnitude of the inherent strain ε_X in the welding direction can be determined by Eq. (17).

$$\varepsilon_X = F_{Tendon}/(EA) \tag{17}$$

where, A is the cross-sectional area of the element along the welding line. In case of fillet welding, the heat input is given to both the web and the flange. Therefore, the total area A where inherent strain is given is divided into A_w and A_f for the web and the flange, respectively. Following Cottrell [4], A_w and A_f can be determined as follows.

$$A_w = (\frac{h_w}{2h_f + h_w})A \tag{18}$$

$$A_f = (\frac{2h_f}{2h_f + h_w})A \tag{19}$$

where, h_w is the thickness of the web, and h_f is the thickness of the flange and A is the total cross-sectional area.

Meanwhile, the transverse shrinkage and angular distortion are determined according to the experimental data reported by Satoh [5].

3.3 Welding distortion of I-section girder

To study the influence of welding procedure on distortion of the I-section girder, the following three cases are examined.

Case A: simultaneous welding.

Case B: sequential welding with weak alignment between the web and the flange. The left flange is welded first and then the right flange is welded. Case C: sequential welding as case A with strong alignment leaving no gap between the web and the flange.

In case of the simultaneous welding (case A), perfect alignment is assumed and there are neither gap nor slip between the web and the flange.

In case of the sequential welding (Case B and Case C), there is no gap for the first welding between the right flange and the web. But after the first welding, the model bends due to welding distortion. Gaps in normal and shear directions are produced in the groove between the left flange and the web. In order to correct the root gap, two procedures are considered as shown in **Table 1**. One is weak alignment in which the flange is drawn to the web without any deformation. The other is strong alignment that closes the gap with bending in the left flange.
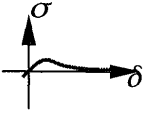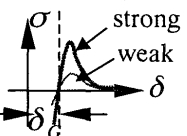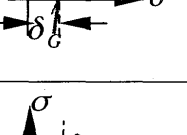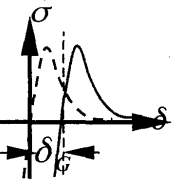
Table1. Welding procedure and gap correction

Case	Welding sequence	Gap correction
A	Simultaneous welding	without gap without slip
B	Sequential welding	Weak gap correction with gap with slip
C	Sequential welding	Strong gap correction without gap with slip

92

The welding distortion after first welding in case B is shown in **Fig.6** and **Fig.7**. Fig.7 is an enlarged view of the root gap produced between the left flange and the web. From this figure, both the gap in the normal direction and the slip in the shear direction can be observed. In case B, the second welding   is performed without correcting either the gap or the slip. The final welding distortion for case B is shown in **Fig.8**. During the above simulations, the parameters of interface element in different stages summarized in **Table 2** are employed.

In the above three cases, the distributions of deflection along the second welding line are shown in **Fig.9**. From this figure, small differences between case A and case C can be seen. In case B, in which   the gap is not corrected, the distribution of deflection is obviously different from   those of case A and case C. The gap has a strong influence on the distribution of deflection,   which may be greater than that of the shrinkage caused by welding itself. The longitudinal shrinkages along the second welding line in the web are shown in **Fig.10**. From this figure, it is seen that the longitudinal shrinkage in case B is almost the same as that of case C, but markedly different from that of case A.   This result shows that the longititudinal shrinkage along the welding line is not afftected by the root gap, but significatntly affected by the slip in the shear direction.

Table2. Interface element parameters for different stages

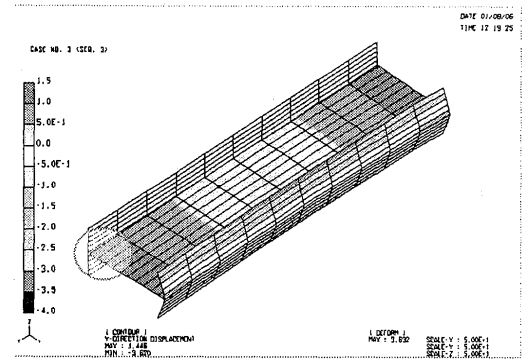| stage	r_0 (mm)	γ (N/mm)	$\sigma - \delta$
Free	10^3	10^{-4}	
Positioning	10^{-2}	10^{-4} (weak)	strong / weak
		10^0 (strong)	
Welding	10^3	10^{10}	

Fig.6 Displacement in Y-direction after positioning (Case B)
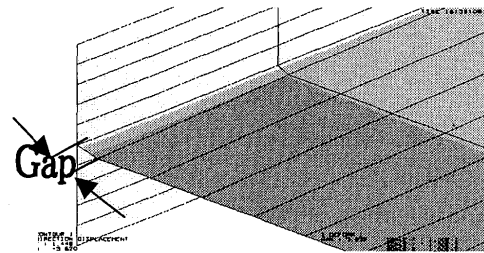

Fig.7 Enlarged view of gap (Case B)
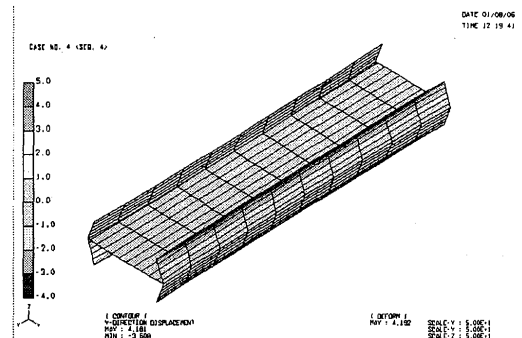

Fig.8 Displacement in Y direction after the 2nd welding (Case B)
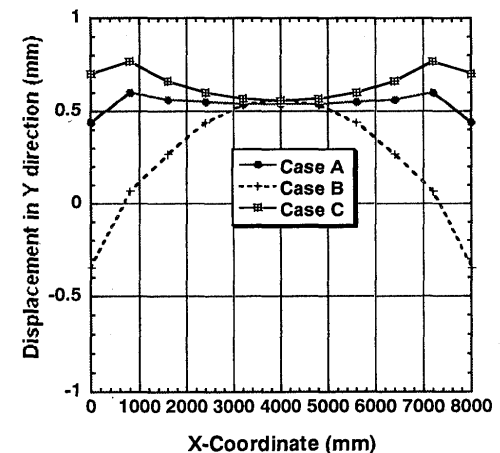

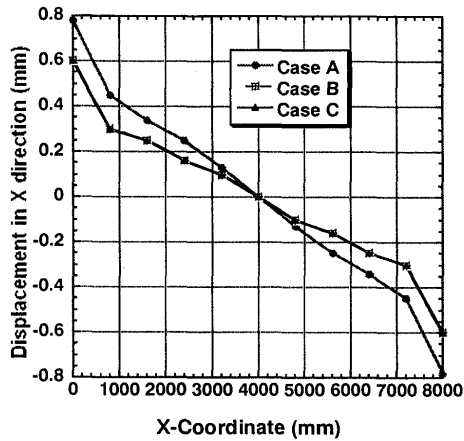**Fig.9** Displacements in Y direction along the second welding line

Fig.10 Displacements in X direction along
the second welding line

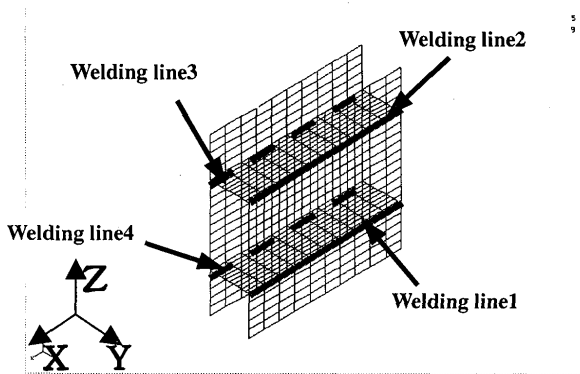## 3.4 Thin plate welded structure

Fig.11 Thin plates welded structure model

In order to study the influence of the welding sequence on welding distortion of thin plate structures, a structure shown in **Fig.11** is selected as an example.
The dimensions of the model are :

Flange: L=8000mm, H=8000mm,T=10mm
Web : L=8000mm, B=2000mm,T=10mm
The webs and the flanges are joined by fillet welding. The heat input is assumed as 2160J/mm for all welding passes.

3.5 Welding distortion of thin structure

In this model, there are four welding lines as shown in Fig.11. Three cases with different welding sequences are analysed to study their influence on welding distortion.

In case A, the four welding lines are welded simultaneously. In case B, the welding lines 1 and 2 are welded first. Then, the welding lines 3 and 4 are welded at the same time. In case C, the four welding passes are welded sequentaly one by one starting from line 1.

The welding distortion in case A is shown in **Fig.12**. The displacement in the Y-direction is shown. In case A,

all members are tack welded. Then the four weldings are performed simultaneously. Because of tack welding , the stiffness of the structure is high and no buckling is obseved.

Similarly, displacement in the Y-direction in case B after welding of the lines 1 and 2 is shown in **Fig.13**. When only two lines on one side are welded at the same time, the stiffness of the structure is relatively low. Consequently, buckling distortion occurs after welding. But when the lines 3 and 4 are welded, the stiffness of the structure becomes higher and buckling distortion does not happen after welding of the remaining two lines.The final welding distortion in case B is shown in **Fig.14**.
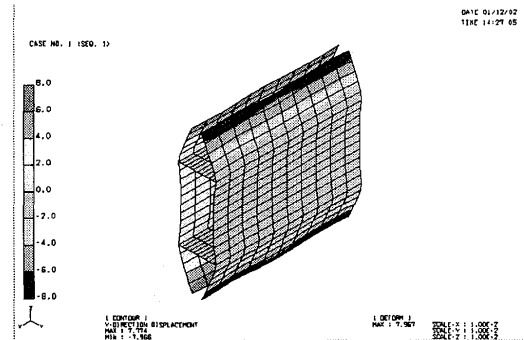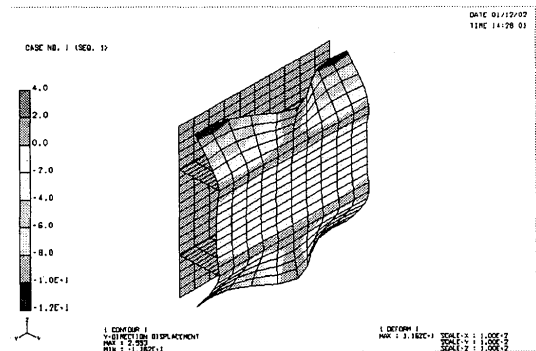

Fig.12 Displacement in Y-direction (Case A)

Fig.13 Displacement in Y-direction after
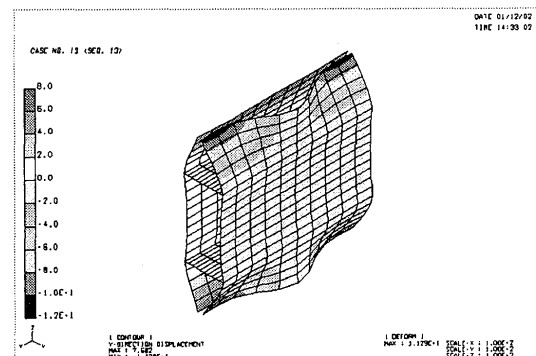1st and 2nd welding (Case B)

Fig.14 Displacement in Y-direction after 3rd and
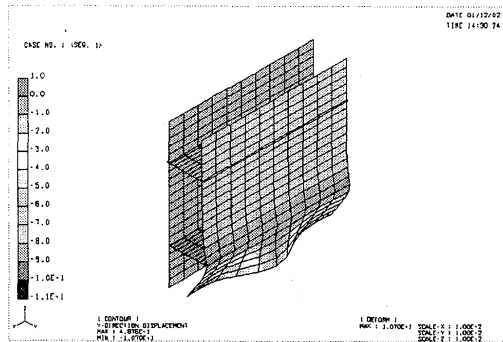4th welding (Case B)

94

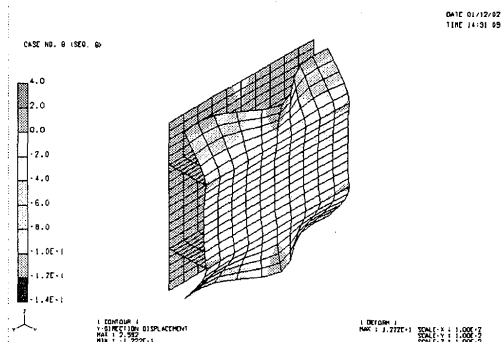**Fig.15** Displacement in Y-direction after
1st welding (Case C)

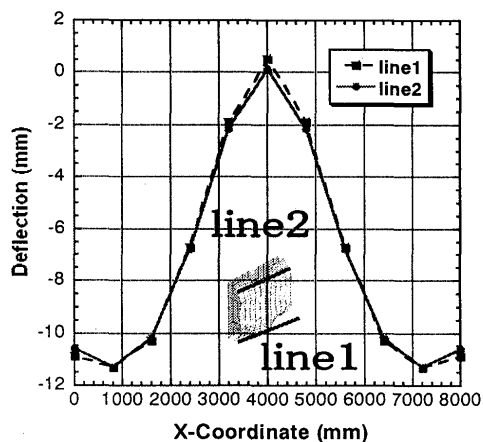**Fig.16** Displacement in Y-direction after
2nd welding (Case C)

Fig.17 Displacements in Y-direction along the line
1 and the line 2 (in case C)

In case C, in which the welding is performed one by one, buckling distortion occurs after welding of the first two lines as shown in **Fig.15** and **Fig.16**. However, as seen from Fig.16, the distribution of the deflection along line 1 is slightly different from that along line 2. Even though the buckling modes after the first welding is the same, the magnitude of the maximum deflection along the line 1 is slightly larger than that along the line 2 as shown in **Fig.17**. The reason is that the stiffness of the structure during the first weld is lower than that in the second weld. The welding distortions after the third welding and the

fourth welding are shown in **Fig.18** and **Fig.19**, respectively. After the welding of lines 3 and 4, buckling distortion does not occur because the stiffness of the structure becomes high.

The distributions of deflection along the line 1 and the line 2 in the three cases are compared in **Figs.20** and **21**. When the four welding passes are simultaneously welded (Case A), the deflection is the smallest. When the four welding lines are welded sequentially one by one (Case C), the deflection is the largest.
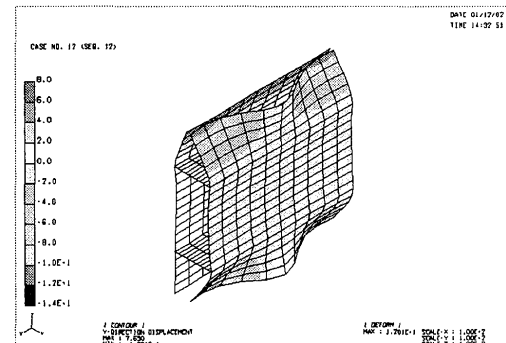

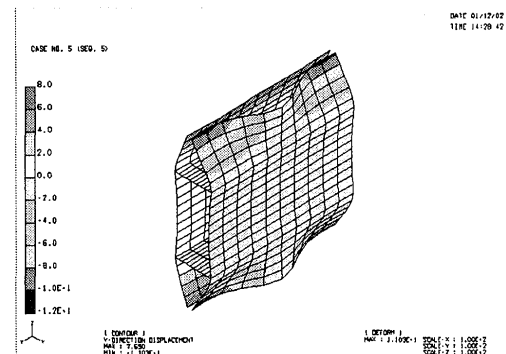**Fig.18** Displacement in Y-direction after
3rd welding (Case C)

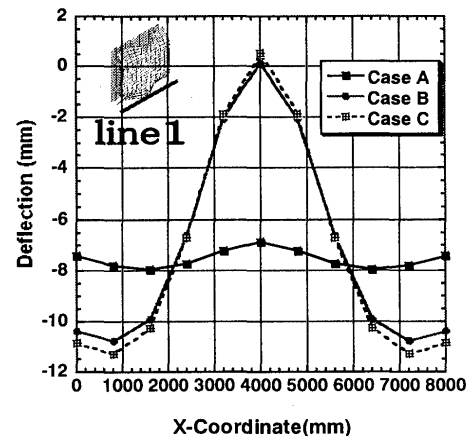**Fig.19** Displacement in Y-direction after
4th welding (Case C)
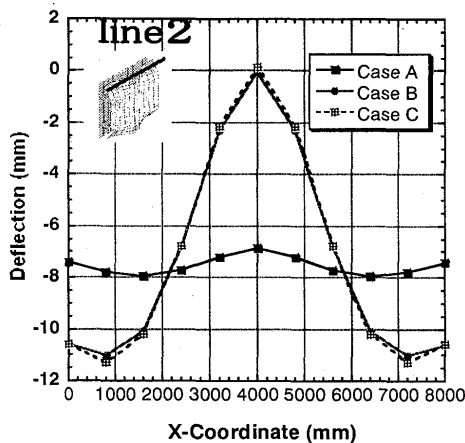

Fig.20 Displacement in Y-direction along line 1

Fig.21 Displacement in Y-direction along line 2
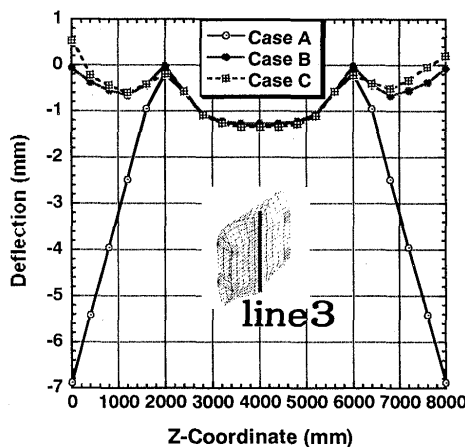
Fig.22 Displacement in Y-direction along line 3

Fig.23 Displacement in Y-direction along line 4

The distributions of deflection in the above three cases along lines 3 and 4 are shown in **Figs.22** and **23**,respectively. The deflections of the panel on the middle section are symmetric in Cases A and B, but un-symmetric in case C, especially in the right panel shown in Fig.22.

4. Conclusions

To predict the distortion of three dimensional thin plate structures during the assembly process by welding, a new finite element method is developed. In this method, the shrinkage due to the welding is taken into account through the inherent strain. The positioning or the correction of the root gap is considered using the interface element. The proposed method is applied to clarify the influence of the welding sequence on the distortion. The conclusions that can be drawn from this investigation are the following.
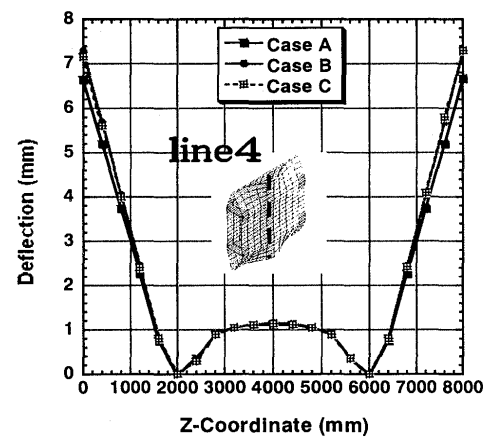
(1) Positioning and the correction of the root gap can be considered in a unified manner by using the interface element.

(2) In I section girder models, the influence of welding sequence and positioning on welding distortion have been clarified.

(3) When thin plate structures are assembled by welding, buckling distortion is prone to occur if an inappropriate welding sequence is selected.

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