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Prediction of Distortion Produced on Welded Structures during Assembly Using Inherent Deformation and Interface Element[†]

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Abstract

The objective of this research is to develop a practically useful finite element method for predicting distortions of structures under welding assembly. In this method, distortions produced by various thermal processes, such as the cutting, the forming, the welding and the straightening can be considered. These distortions are simulated using the inherent strain. On the other hand, the detail of how the gaps and the misalignments are controlled during the fitting process also has significant influence on the distortion. The gaps and the misalignments between parts are modeled using the interface element. The potential capability of the proposed method is demonstrated through simple examples.

KEY WORDS: (Welding distortion), (Assembly sequence), (Inherent strain), (Interface element), (FEM)

1. Introduction

Distortion is an unavoidable problem in the assembly of welded structures. Especially in cases of large structures, such as ships and bridges, as they are assembled sequentially, member by member, or block by block, gaps and misalignments are formed between the structural parts already assembled and the new part due to the welding deformation. The assembly process is the repetition of a cycle which consists of gap correction, tack welding and final welding. In addition to the welding, deformation due to the cutting for which gas, plasma and laser are used as the heat source and that caused by the line heating in the plate forming and the straightening processes must be considered. Thus to predict the distortion in the assembly of welded structures, simulation method which can consider all the processes, such as the cutting, the forming, the fitting, the welding and the straightening need to be developed.

It is often found that the sequence of assembly or welding has a great but unpredictable influence on the distortion and the precision of the welded structures. To clarify the influence of the assembly sequence and those of the cutting, the forming and the straightening processes on the distortion of the welded structures, the authors developed a simulation method which can be easily used by production engineers. For the fast computation of deformation by various thermal processes, the inherent strain method is employed and the interface element is introduced to describe the gap and the

misalignment between the parts and their correction process. The effectiveness of the proposed method is demonstrated through simple examples.

2. Inherent strain, deformation and force

The deformation and the residual stress produced during bead on plate welding or line heating are caused by the irreversible strain or the inherent strain formed in the plastic deformation process^{1, 2, 3)}. Thus, both the deformation and the residual stress produced during various thermal cycles can be predicted by elastic analysis in which the inherent strain is introduced as initial strain. Further, for simple and practical prediction, the inherent deformation, which is the integration of the inherent strain, and the inherent force such as the tendon force can be also introduced. The inherent strain can be employed to deal with the plate forming or the straightening using line heating in which the inherent strain distributes in a broad area⁴⁾, while the inherent deformation and the inherent force can be used for cutting and welding in which the inherent strain distributes in a narrow area.

In general, inherent strain has six components, namely three normal components and three shear components. Noting that the thickness of the plate of the welded structure is thin, the out of plane components can be neglected. When the length of the weld is large enough and the distribution of the inherent strain can be assumed to be uniform, the in-plane shear component can be

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neglected. Thus, the inherent strains need to be considered are ε_x^* in the weld direction and ε_y^* in the transverse direction.

By integrating these according to the following equations, inherent longitudinal shrinkage δ_x^* , inherent transverse shrinkage δ_y^* , inherent longitudinal bending θ_x^* and inherent transverse bending θ_y^* can be defined.

$$\text{Longitudinal shrinkage } \delta_x^* = \frac{1}{h} \int \varepsilon_x^* dy dz \quad (1)$$

$$\text{Transverse shrinkage } \delta_y^* = \frac{1}{h} \int \varepsilon_y^* dy dz \quad (2)$$

$$\text{Longitudinal bending } \theta_x^* = \frac{1}{I} \int \varepsilon_x^* (z - h/2) dy dz \quad (3)$$

$$\text{Transverse bending } \theta_y^* = \frac{1}{I} \int \varepsilon_y^* (z - h/2) dy dz \quad (4)$$

Noting that the stress state in thin plate is plane stress, inherent longitudinal shrinkage force (Tendon Force) F_x^* and inherent longitudinal bending moment M_x^* can be defined and related to the inherent deformation.

$$\text{Inherent longitudinal shrinkage force (Tendon Force)} \\ F_x^* = E \int \varepsilon_x^* dy dz = Eh \delta_x^* \quad (5)$$

$$\text{Inherent transverse shrinkage force} \\ F_y^* = E \int \varepsilon_y^* dy dz = Eh \delta_y^* \quad (6)$$

$$\text{Inherent transverse bending moment} \\ M_x^* = E \int \varepsilon_x^* (z - h/2) dy dz = EI \theta_x^* \quad (7)$$

$$\text{Inherent transverse bending moment} \\ M_y^* = E \int \varepsilon_y^* (z - h/2) dy dz = EI \theta_y^* \quad (8)$$

where, x : coordinate in welding direction
 y : coordinate in transverse direction
 z : coordinate in thickness direction
 h : thickness of plate
 I : moment of inertia
 E : Young's modulus

3. Global and local coordinates

To introduce the inherent strain and the inherent deformation into the scheme of the finite element method, global and local coordinates need to be defined. The global coordinate (x_G, y_G, z_G) is introduced to describe the whole structure. To introduce the shrinkage due to various thermal process, three local coordinates are defined, namely that attached to the heating direction (x_W, y_W, z_W) and those defined for the element (x_E, y_E, z_E)

Table 1 Inherent strain, deformation and inherent force and their reference coordinates

	Thermal process	Coordinate transformation
Inherent strain	Forming and straightening	Heating \leftrightarrow Element Global
Inherent deformation and force	Welding and cutting	Heating \leftrightarrow Element side \leftrightarrow Element Global

and for the side of the element (x_S, y_S, z_S). For the inherent strain given to the element, the element coordinate is used and the element side coordinate is used for the inherent deformation or the inherent force as summarized in **Table.1**.

4. Inherent strain in FEM

As it is discussed, it is not practical to save three dimensional precise distribution of the inherent strain in a database. In this sense, inherent deformation which is the integration of the inherent strain is suitable for reducing the size of the database. However, the information about the distribution is lost through the integration process.

The direct method to obtain three dimensional distribution of the inherent strain is the thermal-elastic-plastic analysis using FEM. The inherent deformation can be obtained in two ways. One is the integration of the computed inherent strain according to **Eqs. (1)-(4)**. Another method is an inverse analysis using the computed displacements as input information^{5, 6}. The inverse analysis can be used to estimate the inherent deformation from the measured displacement.

The inherent strain concentrated as the inherent deformation is regarded as the discontinuity of the deformation. Thus, it is natural to introduce it into the FEM as the discontinuity of the displacement at the node and the concentrated force acting on the node as illustrated in **Fig. 1**. In this method, the inherent transverse shrinkage and the inherent transverse bending are directly related to the deformation and treated as the discontinuity of the nodal displacement. While, the longitudinal inherent strain ε_x^* is transformed into the residual stress. Thus, its integrations, namely the inherent longitudinal shrinkage force (Tendon force) and the inherent longitudinal bending moment M_x^* , are introduced into the FEM as the force and the moment acting at nodes.

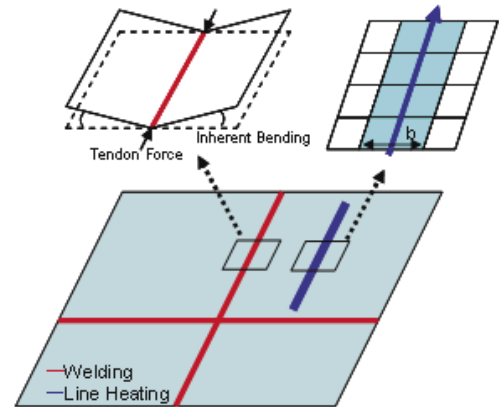


Fig.1 Inherent strain and inherent deformation in FEM

In case of the plate forming and the straightening by line heating, the distribution of the inherent strain is broad. It is natural to introduce such broadly distributed inherent strain directly to the elements as the initial strain. If only the inherent deformation is available from the database, the inherent strain should be given to the element and can be obtained in the following manner. For the simplicity, let's consider the case in which the element is rectangular and its direction is parallel to the heating direction. The inherent strain in the element $\bar{\varepsilon}_x$, $\bar{\varepsilon}_y$ is given by the following equation.

$$\begin{aligned}\bar{\varepsilon}_x &= (\delta_x^* / b) - z(\theta_x^* / b) \\ \bar{\varepsilon}_y &= (\delta_y^* / b) - z(\theta_y^* / b)\end{aligned}\quad (9)$$

Where b is the width of the element.

5. Interface element to control bonding

If all members to be assembled have no geometrical error and they are fully fitted by the tack welding with sufficient stiffness, the welding deformation of the structure is mostly determined by the local shrinkage (inherent deformation) produced by welding. In this case, the sequence of welding has a minor influence on the distortion. However, the assembly process is separated into several stages when the structure is large, such as a ship and a bridge. At each stage, new parts or blocks are fitted to the structure already assembled and welded sequentially. Since, the size and the shape of the structure at the current stage have certain discrepancies from the designed values because of the shrinkage due to the welding, gaps and misalignments are formed as unavoidable consequences. If the gaps exceed the tolerable limit, they are corrected during the fitting process before welding. These gaps and misalignments and their correction in this situation can be regarded as inherent deformation in a broad sense and they are influential in the distortion and the residual stress of the structure as shrinkage due to the welding. The evolution of the mechanical interaction between parts to be assembled from free to fitting, tack welding and fully welded states can be conveniently described by the interface element proposed by the authors⁷⁾. Essentially the interface element is the nonlinear spring arranged between the parts to be welded as shown in Fig. 2. Its mechanical properties can be defined through the opening displacement-bonding force curve ($\delta - F$ curve) shown in Fig. 3. For the opening and closing mode of deformation, stiffness or the resistance against the deformation in the closing direction K_c is set large

enough to prevent the penetration between the parts. Mechanical property for the deformation in the opening direction is defined by stiffness K_o and maximum joining force F_{\max} . The stiffness of the joint K_o is set small when the parts are free and a large value is given after the parts are tack welded and fully welded. The value of the maximum joining force can be selected depending on the maximum capacity of the tool used to control the gap and misalignment. For the shear and the rotational deformation, the $\delta - F$ curve is given as an odd function as shown in Fig. 4. The methodology to choose appropriate values for K_c , K_o representing the stiffness of the joint and F_{\max} representing the maximum value of restraining force must be established as the future research work.

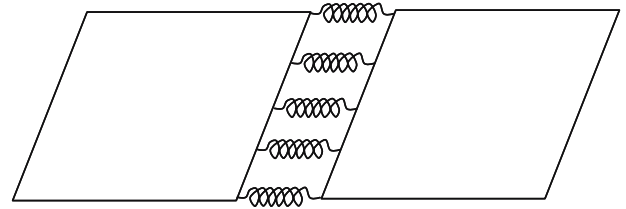


Fig. 2 Interface element

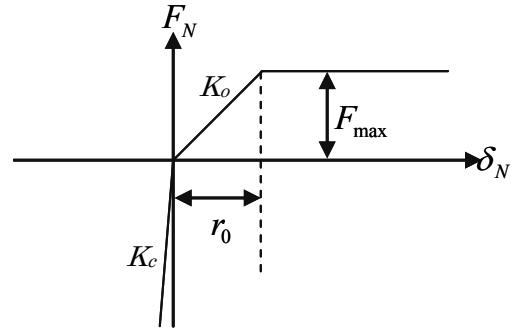


Fig. 3 Relationship between bonding stress and relative displacement (Normal direction)

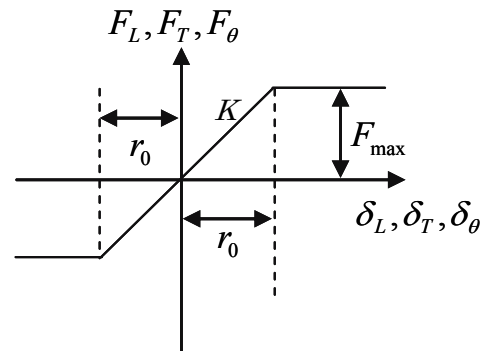
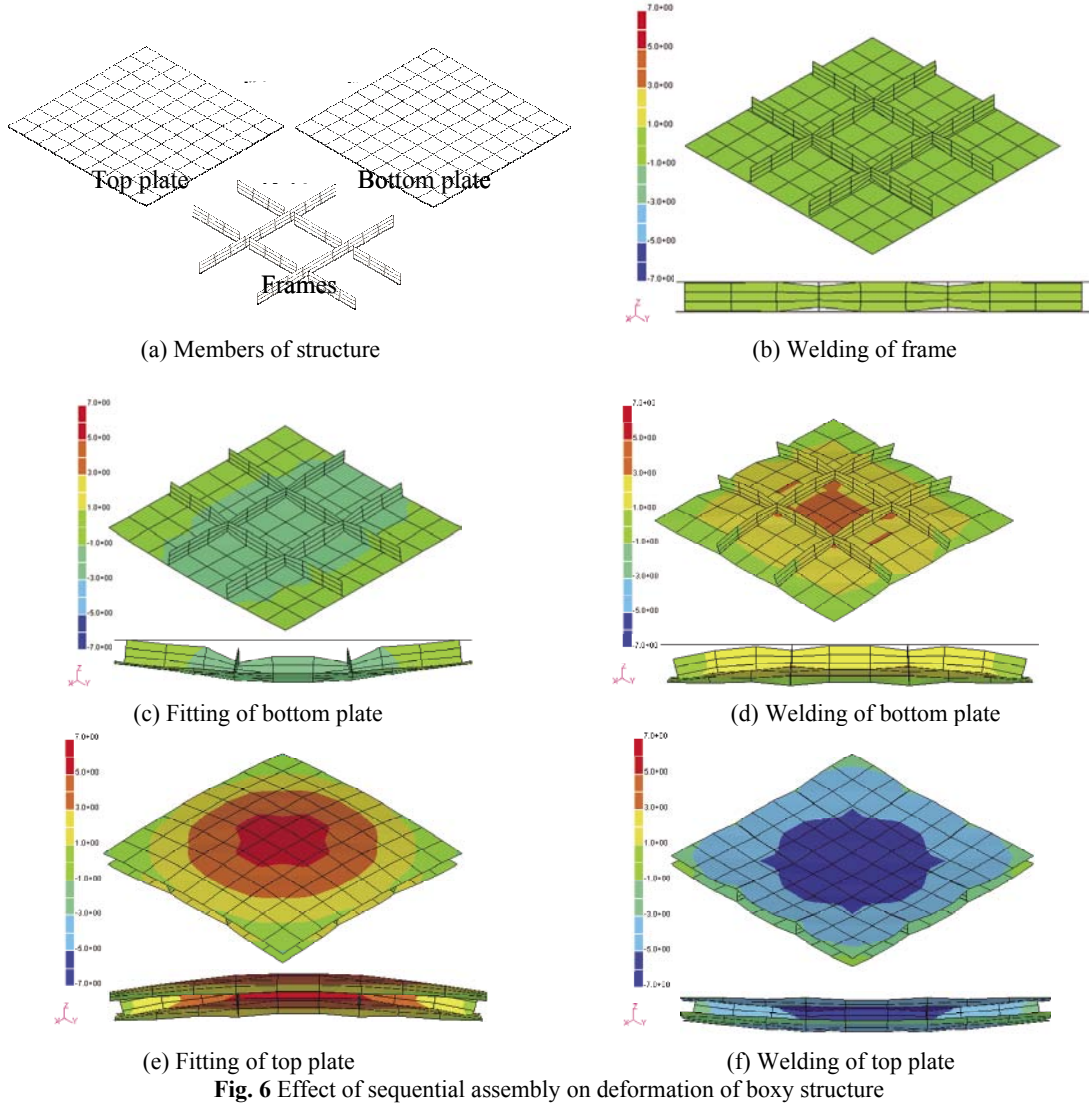
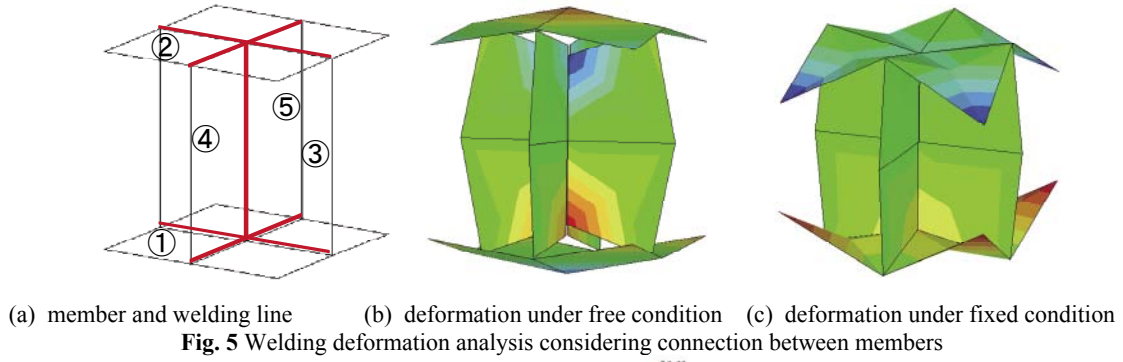


Fig. 4 Relationship between bonding stress and relative Displacement (Shear in x, z directions and rotational direction)



The outline of the proposed concept can be explained using a simple example model shown in **Fig. 5(a)**. The model consists of the top and the bottom plate and the cruciform frames. Both the top and the bottom plates are subdivided into four elements and the frames are subdivided into eight elements in total. The thick lines represent the welding lines and the interface elements which control the mechanical connection between the

members are arranged along these welding lines. The inherent transverse and longitudinal shrinkages and the inherent transverse bending are given to the edge of the element along the welding lines. The values of inherent deformations and forces are determined from the heat input Q and the plate thickness h ⁸⁾. **Figure 5(b)** shows the deformation when the inherent deformation and the inherent force are given when the bonding between the

parts is very weak. Because of the weak bonding, gaps are formed between parts. Bending deformation and the shrinkage are clearly observed in both the top and the bottom plates. The shrinkages in both the transverse and the longitudinal direction are also observed in the frame members. The deformation when the bonding between the members is strong enough is shown in **Fig. 5(c)**. These examples are two extremes in which the bonding is very weak and very strong. For the practical applications, the strength of the bonding must be appropriately defined according to the state of the members whether they are free or fully fixed. By setting the mechanical properties of the interface element separately for each component of deformation, a variety of situations can be simulated. For example, tack weld in the groove which fixes deformations in both opening and shear directions, or a fixture using a strong back which fixes the opening but allows sliding in the shear direction, can be simulated.

6. Influence of assembly sequence

In this report, two simple problems are selected to demonstrate the effectiveness of the proposed method and the mechanism that the assembly sequence influences the distortion of the welded structure. Two simple models chosen here are a stiffened sandwich plate model and a box shaped ship model. The first example is a top and a bottom plates stiffened by a frame grid as shown in **Fig. 6**. Its size is 3000 mm in length and width. The height is 200 mm and the thickness of the plate is 2 mm. Both the longitudinal and the transverse shrinkage given to the plates joined by the fillet welding are assumed to be 0.5 mm. The transverse bending is assumed to be 0.001 Rad. **Figure 6(b)** shows the stage when only the grid form frames are welded. It is shown that the frames become shorter than the top and the bottom plates due to the transverse shrinkage. **Figure 6(c)** shows the deformation after the fitting of the bottom plate to the frame. In the fitting process, the gap between the plate and the frame is closed. Due to this gap correction, the structure bends slightly upward. When the welding of the bottom plate is finished, the structure bends upward as shown in **Fig. 6(d)**. **Figures 6(e)** and **(f)** show the deformation after the fitting and the welding of the top plate, respectively. As shown in **Fig. 6(f)**, the structure bends downward so that the top side which is welded later bends downward. The magnitude of the deflection changing with the sequential assembly process is shown in **Fig. 7**. The dotted line shows the deflection when all the welding is done simultaneously. It is seen that the simultaneous welding is preferable if the situation allows.

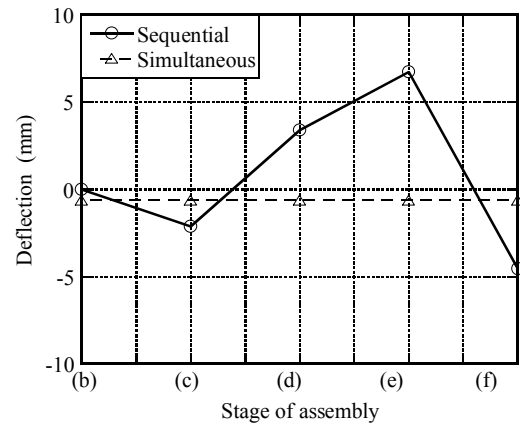


Fig.7 Comparison between sequential and simultaneous welding

Next example is the distortion due to block assembly in ship building. In this example, the influence of sequential assembly of the block is examined to clarify the mechanism of distortion in assembly. The ship is modeled as a box with one deck and one longitudinal bulkhead. The length, the height and the width are 90 m, 21 m and 40 m, respectively. This ship is assumed to be divided into 9 blocks and to be assembled in the sequence shown in **Fig.8**. The distortion for sequential assembly is computed using the proposed method together with the case of simultaneous assembly. In these computation, the transverse and the longitudinal inherent deformation given to the plate edge forming the welding line is assumed to be 0.5 mm. In case of sequential welding, a new block to be assembled is fitted so that it come close enough to touch the blocks already assembled and leave gaps and misalignment produced by the distortion accumulated by previous welding. **Figure 9** shows the distortion of the ship when it is assembled simultaneously and sequentially. As it is shown, the distortion is symmetric when assembled simultaneously, while, the ship bends downward when it is assembled sequentially. The bending deformation along the ship length is compared between the two cases in **Fig. 10**. In case of sequential welding the maximum deflection is about 8 mm, while no deflection is observed for simultaneous assembly. The direction of the deflection is downward in which the top side assembled later becomes concave as shown in the first example. To examine the cause of the deflection in sequential welding, the deformation of the ship is enlarged in **Fig. 11**. It is clearly seen that the gap, in-plane and out-of-plane misalignments are produced and these are accumulated and result in the overall bending of the ship hull.

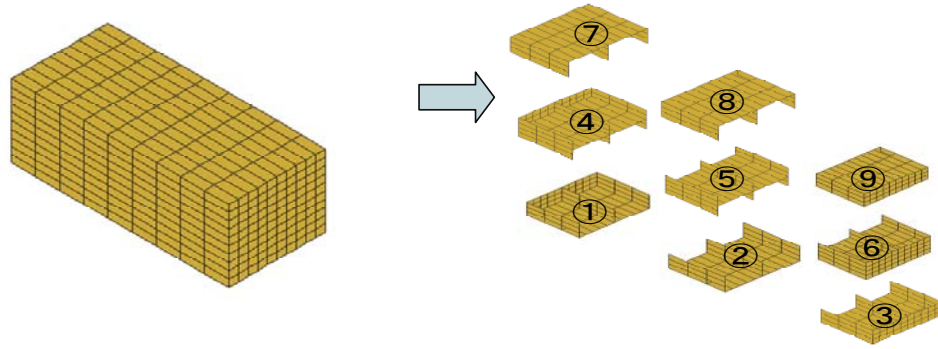


Fig.8 Simple ship and block model

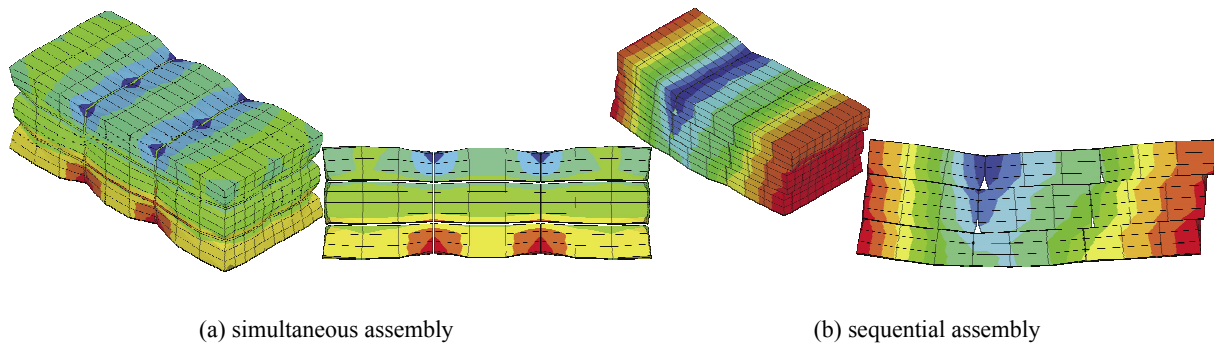


Fig.9 Effect of assembly to simple ship model

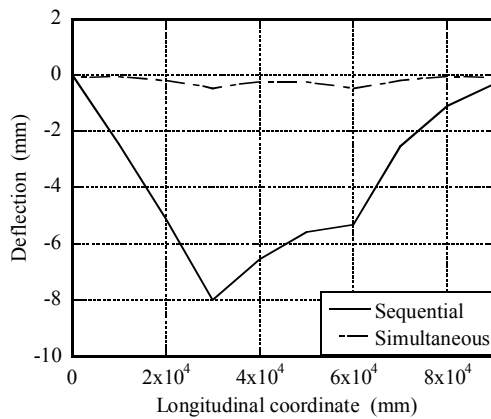


Fig. 10 Comparison between sequential and simultaneous assemblies

7. Conclusions

For the numerical prediction of distortion of structures produced through various thermal processes, such as the cutting, forming, welding and straightening, a method based on the concept of the inherent strain and the interface element is developed. This method is applied to two simple example problems and its capability to simulate the sequential welding process in which gap correction in fitting, tack welding, final welding and straightening if necessary are repeated is demonstrated. Through the comparison between the sequential welding and the ideal simultaneous welding, it is found that the sequence of the assembly greatly influences the distortion of the structure.

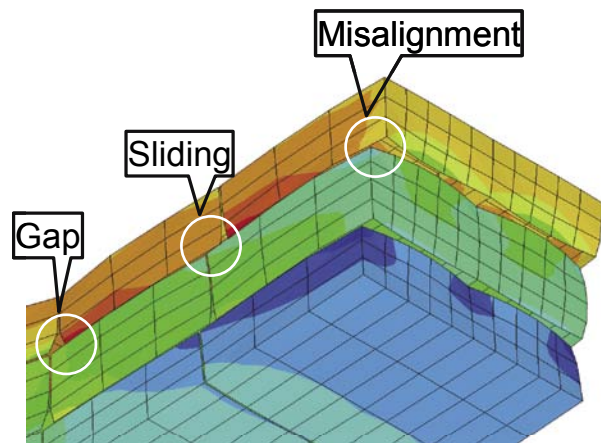


Fig. 11 Causes producing deformation due to sequential assembly

This means that the accumulation of small gap and misalignment through the fitting process has the same influence as the local shrinkage (inherent deformation) produced by thermal processes such as the cutting and the welding.

Though the method developed in this research is rather primitive at present, it has a great potential to become a practical and versatile tool for engineers engaged in assembly of welded structures. By introducing this kind of method, the conventional production system entirely dependent on the skill and the experience of the workers can be transformed to new system based on the theoretical prediction.

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