# Control of Longitudinal Bending Distortion of Built-Up Beams by High-Frequency Induction Heating

*A new practical method was proposed to mitigate longitudinal bending distortion of built-up beams during fabrication processes*

**BY J. U. PARK, S. C. PARK, AND C. H. LEE**


## ABSTRACT

Longitudinal bending distortion is induced by fillet welding during the build-up process of T-section beams. This distortion decreases productivity and the quality of welded structures because it requires additional correction work in the assembly stages of ship construction. Longitudinal bending distortion is caused by the welding moment, which is calculated by multiplying the shrinkage force due to welding by the distance between the welding heat source and a neutral axis on the cross section of built-up beams. However, this distortion can be mitigated by induction heating on the web plate of built-up beams, generating a reverse moment of the same magnitude as the bending moment due to fillet welding. In this study, location and intensity of induction heat input were determined based on experiments and simple equations. The mechanism of longitudinal bending distortion in the build-up process was investigated using three-dimensional thermal elastic-plastic analysis. A new control method of longitudinal bending distortion was proposed using high-frequency induction heating with verification of its validity.


## Introduction

Built-up beams are widely used to improve the longitudinal strength of ship structures. In general, four Very Large Crude-oil Carriers (VLCCs) are built in a year. In this case, about 1050 pieces of built-up beams are to be made in a month. Fillet welding is employed to produce built-up beams, connecting web plates to flange plates. During manufacturing, fillet welding induces built-up beams to deform longitudinally (Ref. 1) because the weld length is relatively long (5~22 m) and weld metals deposited on the joint are located lower than the neutral axis of the built-up beam. Accordingly, various methods have been used to prevent or correct the longitudinal bending distortion in shipyards. The first one is triangular heating on the web plate using a gas burner after welding; the second one is to produce plastic deformation using mechanical presses after welding. But these methods have disadvantages in that distortion has to be corrected in a separate stage of the manufacturing process, which decreases productivity and the quality of hull assembly.

As a result, these problems brought up the necessity of research to estimate and prevent the longitudinal bending distortion, and a series of studies was done by Sasayama (Ref. 2). He estimated the amount of longitudinal bending distortion with a change of leg length of welding using simple beam theory. Okerblom (Ref. 3) presented simple equations to estimate the amount of longitudinal bending distortion through thermal elastic-plastic analysis and verified his theoretical results by comparing against experimental results. Tsuji (Ref. 4) also performed a thermal elastic-plastic analysis to estimate the amount of welding distortion on the cross-sectional part of a strip plate and verified the validity of his results by comparing them with ones obtained from experiments. Masubuchi (Ref. 5) estimated the residual distortion of an aluminum plate with a T-section using one-dimensional thermal elastic-plastic analysis and compared it with results obtained from experiments. Aoki (Ref. 6) classified the factors affecting distortion via numerical analysis and experiments by using the results of the study by Tsuji (Ref. 4) and proposed simple equations. Jang (Refs. 7, 8) estimated the magnitude of longitudinal distortion due to welding and the amount of triangular heating needed to correct the distortion. By the way, all these studies focus on the estimation of the amount of longitudinal bending distortion, except Jang's (Refs. 7, 8). However, his method has the disadvantage that the distortion must be corrected in a separate stage of the manufacturing process after welding.

Therefore, this study focuses on explaining the mechanism of the longitudinal bending distortion in built-up beams using three-dimensional thermal elastic-plastic analysis, and proposing a new control method of this distortion by using induction heating with verification of its validity by comparing the results of numerical analysis and experiments for the large T-section structures.

## Longitudinal Bending Distortion and Its Control Method

During a manufacturing process for built-up beams, fillet welding causes transient and residual longitudinal bending distortion in the built-up beam. The mechanism of the distortion can be explained through three-dimensional thermal elastic-plastic analysis using the finite element method. Major parameters known to have influences on inducing and mitigating longitudinal bending distortion are evaluated by investigating the numerical analysis results.


**KEYWORDS**

Distortion Control
Built-Up Beams
Finite Element Analysis
Induction Heating
Distortion
Longitudinal Bending


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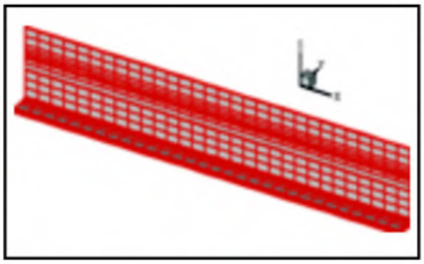

*Fig. 1 — Finite element analysis model for the built-up beam.*

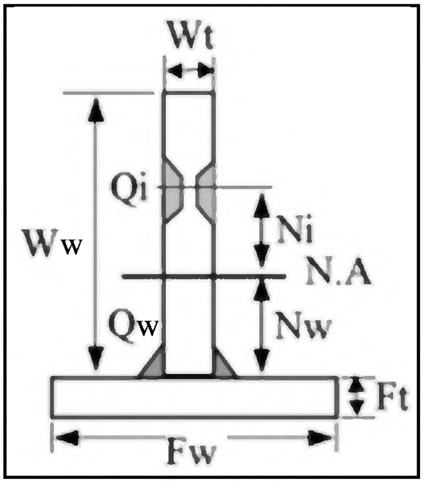


*Fig. 2 — Cross section of the built-up beam with induction heating.*

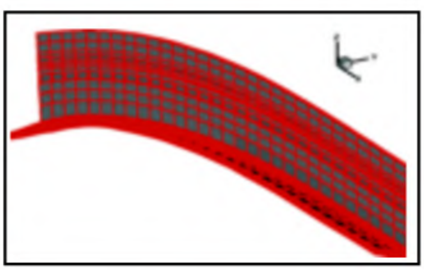

*Fig. 3 — Shape of longitudinal bending distortion of the built-up beam.*

**Table 1 — Dimensions and Heat Input for Finite Element Analysis**

| Model Type | Flange Plate (mm) | | Web Plate (mm) | | Length L (mm) | Heat Input of Ind. Heating ($cal/mm^3 \cdot s$) | Ni (mm) |
|---|---|---|---|---|---|---|---|
| | Width | Thickness | Width | Thickness | | | |
| A1 | 150 | 18 | 250 | 11.5 | 3000 | — | — |
| A2 | 150 | 18 | 250 | 11.5 | 3000 | 0.640 | 95 |
| A3 | 150 | 18 | 250 | 11.5 | 3000 | 0.932 | 95 |
| A4 | 150 | 18 | 250 | 11.5 | 3000 | 0.448 | 95 |
| A5 | 150 | 22 | 300 | 11.5 | 3000 | 0.640 | 122.6 |

## Numerical Modeling and Analysis

Figure 1 shows the finite element analysis model for the built-up beam. A 1:4 model was employed considering the symmetry of the built-up beam with two fillet welds deposited simultaneously on each side of the joint and the huge computational time consumed in analyzing the distortion behavior of T-section joint of 3000 mm in weld length using a moving heat source model. The boundary conditions for the numerical analysis were taken considering the symmetric condition of built-up beams and the prevention of rigid body motion. Under these conditions, welding distortion was generated freely without additional restraints. The verified in-house finite element analysis program was employed and the total numbers of elements and nodes used were 1440 and 2232, respectively. Eight-node isoparametric solid elements and body heat flux model with Gaussian heat distribution were used for numerical analysis.

Also, three-dimensional transient heat transfer analysis was performed for fillet welding with a moving heat source and subsequently three-dimensional thermal elastic-plastic stress analysis was carried out with previously calculated thermal loads, considering temperature-dependent thermal and mechanical properties of the material.

A cross section of fillet welded T-joint with induction heating on both sides of web plate is shown in Fig. 2; Nw is the distance from the neutral axis to the welding heat source, and Ni is the distance from the neutral axis to the induction heat source. Table 1 shows the specimen dimensions and induction heat input conditions used for the finite element analysis.

All the specimens were made of 11.5, 18, and 22 mm thicknesses of AH32 (315 MPa yield strength) steel plates. The submerged arc welding process was used for fillet welding with 720 A, 26 V, 1004 mm/min welding speed, AWS-A5.17 EM13K/L-50 welding wire of 2 mm in diameter, and two fillet welds of leg length of 5 mm were made simultaneously on each side of the web and flange joint. The welding heat input, in the analysis, is 1118 J/mm and the arc efficiency is determined to be 0.9 from a previous study.

### Mechanism and Control Method of Longitudinal Bending Distortion

Figure 3 shows the shape of magnified residual bending distortion obtained from the results of the three-dimensional thermal elastic-plastic stress analysis for Model A1, while Fig. 4 shows the transient and residual longitudinal bending distortion behavior for Model A1 with elapsed times at the top edge of the web plate. During welding, Model A1 deformed downward (–z direction) due to the expansion of the welded joint, but finally deformed upward (+z direction) due to the shrinkage of the welded joint after cooling down to room temperature. For Model A1, the amount of final longitudinal bending distortion was found to be 3.5 mm at the middle of beam length, but a distortion of about 100 mm was observed in a large T-section structure with a length of 20,000 mm of the built-up beam.

The upward convex longitudinal bending distortion is produced by the welding moment (Mw), because the welded joint is located lower than the neutral axis of the cross section of the built-up beam as shown in Fig. 5. The welding moment is represented by multiplying the shrinkage force P(Qw) of the welded joint by the distance (Nw) from the neutral axis of the cross section of the built-up beam to the welding heating source (Qw). The magnitude of longitudinal bending distortion increases with the increase of the shrinkage force and the distance from the neutral axis to the welding heat input (Qw).

The longitudinal bending distortion produced by the welding moment can be mitigated by generating an induction heating moment ($Mi \fallingdotseq Qi \times Ni$) with the same magnitude of the welding moment and orientating it in the direction opposite to the welding moment. In large T-section structures, the welding moment can be obtained with the neutral axis of the cross section of the built-up beam, the location of the welding heating source, and the amount of welding heat input. Also, the induction heating moment can be generated by controlling the amount of induction heat input (Qi) and the distance (Ni) from the neutral axis to the induction heating source. Assuming that the amount of the induction heat input is constant, the distance from the neutral axis to the induction heating source is obtained by $Ni \fallingdotseq Qw \times Nw/Qi$. As a result, the longitudinal bending distortion can be controlled by heating the determined location with the induction heating, simultaneously operating with the welding process.

## Characteristics of Longitudinal Bending Distortion by Induction Heating

The control method of longitudinal bending distortion in the above section is verified by varying the induction heating

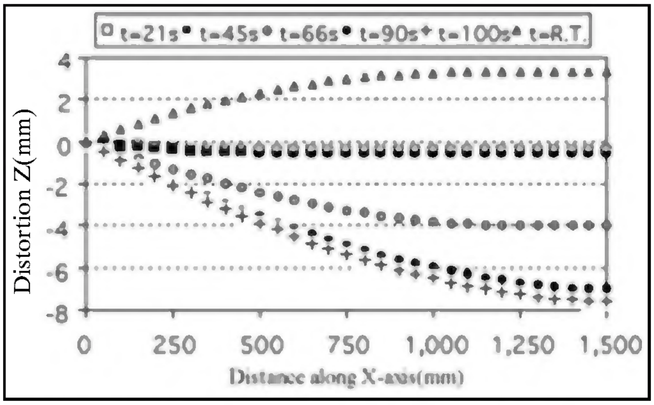


*Fig. 4 — Distribution of longitudinal bending distortion (Model A1).*

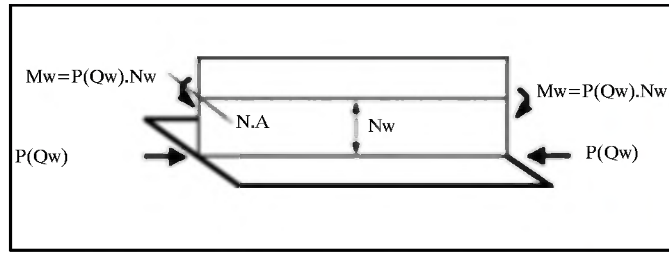


*Fig. 5 — Welding moment for longitudinal bending distortion of the T-joint.*

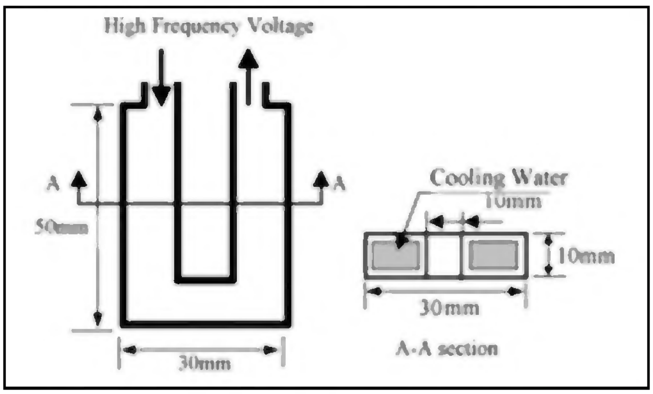


*Fig. 6 — Shape of the induction heating coil.*

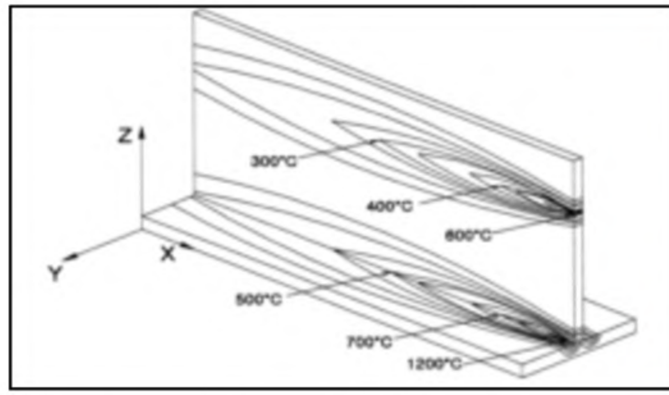


*Fig. 7 — Temperature distribution due to fillet welding and induction heating (Model A2).*

conditions using the three-dimensional thermal elastic-plastic finite element analysis. At first, the effects of intensity of induction heat input on the longitudinal bending distortion are evaluated and subsequently the analysis results are applied to Model A5.

### Numerical Analysis Model

Models A2~A4 in Table 1 were numerically analyzed. The welding conditions were the same as those in the above section. The shape of the induction heating coil is shown in Fig. 6 and two heating coils were placed on each side of the web plates. Induction heating coils were designed to be stationary and built-up beams were forced to move on to the direction of heating coils on the rails with a welding speed. The induction heating rate was equal to the welding speed and the maximum depth of the heat-affected zone (HAZ) by induction heating was about 3 mm with a semielliptical cross section. Though the amount of induction heating has to be calculated by electric and magnetic field analyses for three-dimensional transient heat transfer, the amount of induction heat input was set to 0.64 cal/mm$^3\cdot$ s by performing the three-dimensional transient heat transfer analysis through an iterative process. Also, the location of the induction heating is set to be 95 mm away from the top edge of the web plate.

### Longitudinal Bending Distortion by Induction Heating

Figure 7 shows the temperature distribution (at time = 90 s) produced by induction heating and fillet welding for Model A2. Also, Fig. 8 indicates the transient and residual longitudinal bending distortion based on numerical analysis results. From the analysis results, the maximum transient longitudinal bending distortion by induction heating is reduced to 50% as compared with the one by fillet welding only. From the temperature distribution and thermal history around induction HAZ and weld metal, it was noticed that the transient bending distortion was largely influenced by induction heating, and the residual bending distortion can be controlled by maintaining a balance of shrinkage forces.

The effects of intensity of induction heat input on longitudinal bending distortion were investigated and the analysis results are shown in Fig. 9. In Model A3, the amount of induction heat input was increased by 30% compared to Model A2 and in Model A4, reduced by 30%. From the results of the analysis, the amount of longitudinal bending distortion can be controlled by changing the amount of induction heat input because the magnitude of the longitudinal bending distortion is proportional to the intensity of heat input.

### Investigation of the Validity of Distortion Control Method by Induction Heating

In order to investigate the validity of the control method of longitudinal bending distortion by induction heating, Model A5 was numerically analyzed. The welding and induction heating conditions for finite element analysis were the same as those in Model A2.

The longitudinal bending distortion is generated by the bending moment due to welding, which is the value of the heat input of welding (Qw = 1118 J/mm) multiplied by the distance (Nw = 55 mm) from the neutral axis of the built-up beam to the welded joint. To balance the welding moment, the induction moment must be calculated and applied to in the direction opposite of the welding moment. The amount of induction heat input is calculated as follows:

$$Qw \times Nw \fallingdotseq Qi \times Ni \;\therefore Qi \fallingdotseq (Qw \times Nw)/Ni \quad (1)$$

Because the distance from the neutral axis to the induction heating source was 95 mm, as shown in Table 1, the amount of induction heat input was calculated as

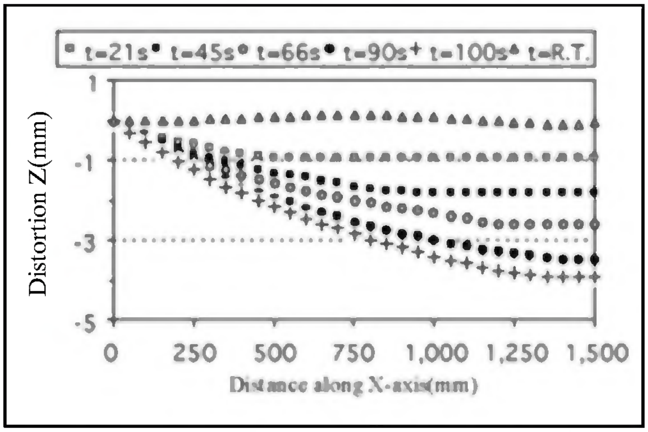


*Fig. 8 — Longitudinal bending distortion by fillet welding and induction heating (Model A2).*

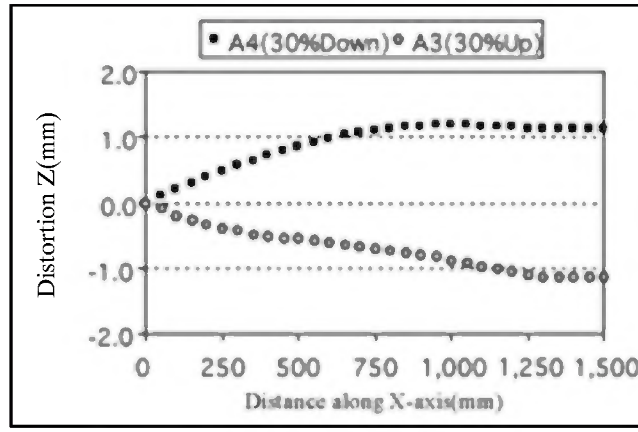


*Fig. 9 — Longitudinal bending distortion by fillet welding and induction heating (Models A3 and A4).*

**Table 2 — Dimensions and Heat Input for Experimental Validation**

| Model Type | Flange Plate (mm) | | Web Plate (mm) | | Length L (mm) | Temperature (°C) | Ni (mm) |
|---|---|---|---|---|---|---|---|
| | Width | Thickness | Width | Thickness | | | |
| E1 | 150 | 18 | 450 | 11.5 | 20,600 | 390 | 200 |
| E2 | 150 | 18 | 450 | 11.5 | 20,600 | 430 | 200 |
| E3 | 150 | 18 | 450 | 11.5 | 20,600 | 470 | 200 |
| E4 | 150 | 18 | 450 | 11.5 | 20,600 | 430 | 145 |
| E5 | 150 | 18 | 300 | 11.5 | 20,600 | 430 | 165 |
| E6 | 150 | 18 | 300 | 11.5 | 20,600 | 430 | 205 |
| E7 | 150 | 18 | 300 | 11.5 | 20,600 | 430 | 225 |
| E8 | 150 | 22 | 500 | 11.5 | 20,200 | 430 | 240 |
| E9 | 150 | 18 | 450 | 11.5 | 20,600 | 430 | 225 |

647 J/mm by Equation 1. The amount of induction heat input and location (Ni) calculated by Equation 1 can be applied to determine the output power of the induction heating instrument with various induction coil shapes. In the case of Model A5, the location (Ni) of induction heating was calculated as 122.6 mm by Equation 1 because the distance (Nw) from the neutral axis of the cross section of the built-up beam to the welded joint was 71 mm, and this value was used in this analysis.

Figure 10 shows the behavior of the transient and residual longitudinal bending distortion by fillet welding only, while Fig. 11 indicates the transient and residual longitudinal bending distortion by induction heating and fillet welding. From the analysis results, the longitudinal bending distortion was measured as about 2.5 mm at the middle of web plate of the built-up beam length by welding only, while the longitudinal bending distortion was produced as almost zero at the middle of length of T-joint by induction heating and fillet welding. Consequently, the validity of distortion control method by induction heating was verified by numerical analysis.

## Experiments for Large T-Section Structures

The control method of longitudinal bending distortion, which was verified by the numerical analysis in the above section, was verified by experiment. In this, effects of the induction heat input and location of induction heating on the longitudinal bending distortion were examined, and finally the control method of longitudinal bending distortion by induction heating was applied to large T-section structures.

### Specimen Dimensions and Experimental Conditions

Table 2 presents the specimen dimensions and heat input for experimental validation. The welding conditions and induction heating coil used for the experiments were the same as those in the above section. However, the conditions of induction heating changed with the experimental conditions. The amount of longitudinal bending distortion was measured, using string and caliper, at the top edge of the web plate when the temperature of both the welded part and the induction-heated part reached room temperature.

### Effects of the Temperature of Induction Heating

To examine the effects of temperature variations due to induction heating on the longitudinal bending distortion, the induction heating coil was set to be located 200 mm upward from the neutral axis throughout the experiment, and the temperature of induction heating changed from 390°C (Model E1) to 470°C (Model E3). These induction temperatures were measured, using an infrared temperature measurement instrument, at a location 100 mm away from the heating coil after induction heating.

Figure 12 shows the longitudinal bending distortion after fillet welding with a change of temperature of induction heating. As the temperature of induction heating becomes higher, longitudinal bending distortion increased in a downward direction (–z direction) because of the increase of the moment by induction heating ($M_i \fallingdotseq Q_i \times N_i$). For Model E3 (470°C), it produced about 50 mm longitudinal bending distortion at the middle of the built-up beam length.

### Effects of Location of Induction Heating

To examine the effects of induction heating location on longitudinal bending distortion, the temperature of induction heating was set to 430°C (the temperature at 100 mm away from heating coil in welding direction) throughout the experiment, and the distance (Ni) from the neutral axis to the induction heating source changed from 145 mm (Model E4) to 225 mm (Model E7).

The amount of longitudinal bending distortion with a change of location of induction heating is shown in Fig. 13, and

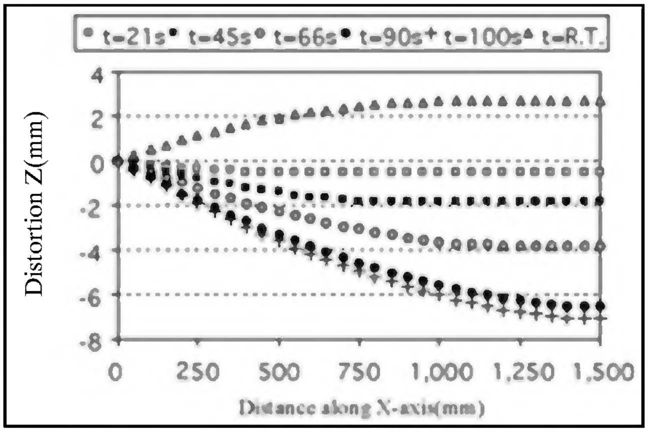


*Fig. 10 — Longitudinal bending distortion by fillet welding (Model A5).*

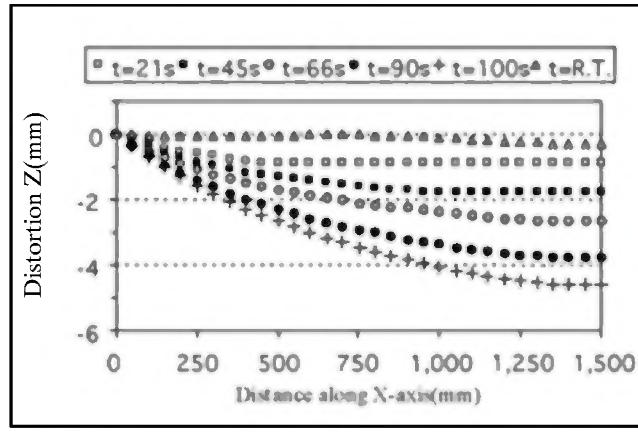


*Fig. 11 — Longitudinal bending distortion by welding and induction heating (Model A5).*

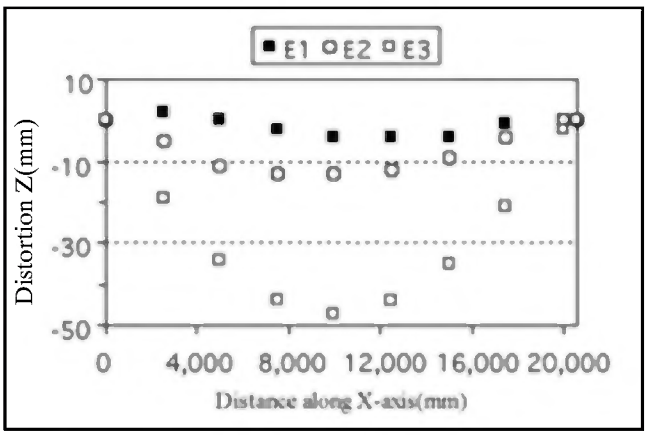


*Fig. 12 — Longitudinal bending distortion with a change of induction heating temperature.*

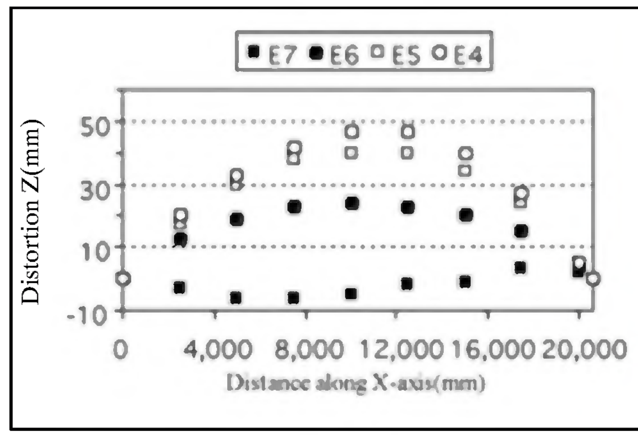


*Fig. 13 — Longitudinal bending distortion with a change of location of induction heating.*

the longitudinal bending distortion was produced to be within ±10 mm in the case of Model E7. However, as the distance from the neutral axis to the induction heating source decreased, upward convex distortion to a maximum of 50 mm occurred. This is because as the distance from the neutral axis to the induction heating source decreased, the bending moment induced by induction heating became less than the bending moment induced by fillet welding.

### Verification of the Validity by Experiments

Based on the results from the numerical analysis in the above section and the experiments in this section, it was found that longitudinal bending distortion can be controlled through physical parameters, namely the temperature and location of induction heating. The validity of this conclusion was investigated by applying the above results to large T-section structures. Models E8 and E9 in Table 2 were used, and the temperature and the location of induction heating were calculated by Equation 1 and the experiment described in this section.

The longitudinal bending distortion of large T-section structures is shown in Fig. 14, which includes the experimental results performed twice with the same experimental conditions for the built-up beam. Based on the results of the experiments, longitudinal bending distortion was found to be within ±10 mm at the middle of length of large T-section structures. These results mean that although the dimensions of the built-up beam change, the longitudinal bending distortion can be controlled by the temperature and location of induction heating calculated from Equation 1.

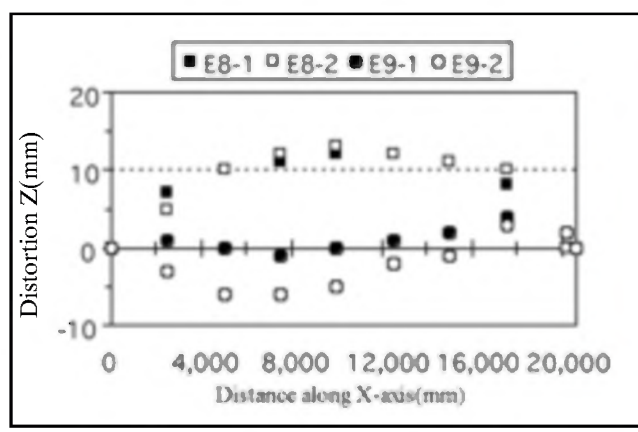


*Fig. 14 — Longitudinal bending distortion for large T-section structures (Models E8 and E9).*

## Conclusions

This study proposes induction heating as a new method to mitigate longitudinal bending distortion due to fillet welding during manufacturing built-up beams. With this method, longitudinal bending distortion can be controlled simultaneously with fillet welding, resulting in improvement of productivity and the quality of block assembly. Also, this study describes the mechanism of the longitudinal bending distortion and the effects of induction heating parameters on longitudinal bending distortion through numerical analysis and experimental results. The following results are obtained.

1. Based on the results from three-dimensional thermal elastic-plastic analysis, the longitudinal bending distortion is produced by the welding moment (Mw), which can be obtained by multiplying the shrinkage force P(Qw) in the welded part by the distance (Nw) from the neutral axis on a cross section of the built-up beam to the welding heat source. Also, the magnitude of the longitudinal bending distortion increases as the shrinkage force and distance from the neutral axis to the welding heat source increase.

2. The longitudinal bending distortion induced by the bending moment due to welding can be mitigated by generating an induction moment (Mi) with the same magnitude as the bending moment, and orientating it in the opposite direction of the bending moment. Then, the induction moment (Mi) is generated by controlling the intensity of induction heat input and the distance (Ni) from the neutral axis to the induction heating source.

3. From the experiments performed to investigate the effects of intensity of induction heat input and its location on the longitudinal bending distortion, it is found that longitudinal bending distortion decreases as the temperature of induction heating becomes higher and the distance from the neutral axis to induction heating source increases. But there is a possibility of providing too much induction moment and in effect ending up with more distortion in the opposite direction.

4. By applying the temperature and location of induction heating obtained from the numerical analysis and experimental results to large T-section structures, it is concluded that longitudinal bending distortion can be controlled by the temperature and the location of induction heating for large T-section structures with dimensional changes.

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