Journal of the Korean Society of Marine Environment & Safety
Research Paper
Vol. 26, No. 3, pp. 254-261, May 31, 2020, ISSN 1229-3431(Print) / ISSN 2287-3341(Online) https://doi.org/10.7837/kosomes.2020.26.3.254

Validation of Efficient Welding Technique to Reduce Welding Displacements of Ships using the Elastic Finite Element Method

Donghan Woo*†

* Ph.D Candidate, Department of Transport and Environmental System, Hiroshima University, Higashi-Hiroshima, Japan

Abstract : *Welding is the most convenient method for fabricating steel materials to build ships and offshore structures. However, welding using high heat processes inevitably produces welding displacements on welded structures. To mitigate these, heavy industries introduce various welding techniques such as back-step welding and skip-step welding. These techniques effect on the change of the distribution of high heat on welded structures, leading to a reduction of welding displacements. In the present study, various cases using different and newly introduced welding techniques are numerically simulated to ascertain the most efficient technique to minimize welding displacements. A numerical simulation using a finite element method based on the inherent strain, interface element and multi-point constraint function is introduced herein. Based on several simulation results, the optimal welding technique for minimizing welding displacements to build a general ship grillage structure is finally proposed.*

Key Words : *Welding technique, Welding displacement, Ship grillage structure, Finite element method, Inherent strain, Interface element*

1. Introduction

To construct ships, which are mainly composed of steel materials, welding is generally employed in heavy industries. However, the large welding temperature range, involving extremely high heating to cooling, inevitably produces local shrinkages, such as longitudinal shrinkage, transverse shrinkage, and angular distortion, as illustrated in Fig. 1 (Woo et al., 2019).

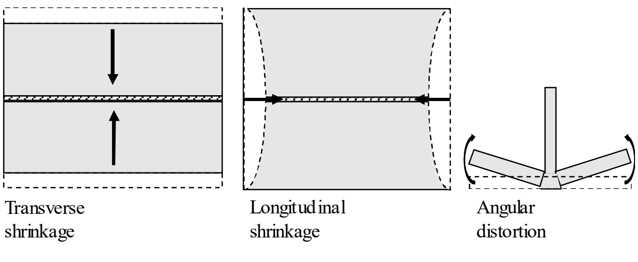

Fig. 1. Classification of welding distortion (Woo et al., 2019).

These local shrinkages result in unexpected misalignments between welded structures and can compromise the structural safety. To constrain these welding displacements, various methods have been employed. In particular, use of specific welding techniques is a basic method used to mitigate welding displacements without additionally introducing constraint tools such as clamps and strongbacks.

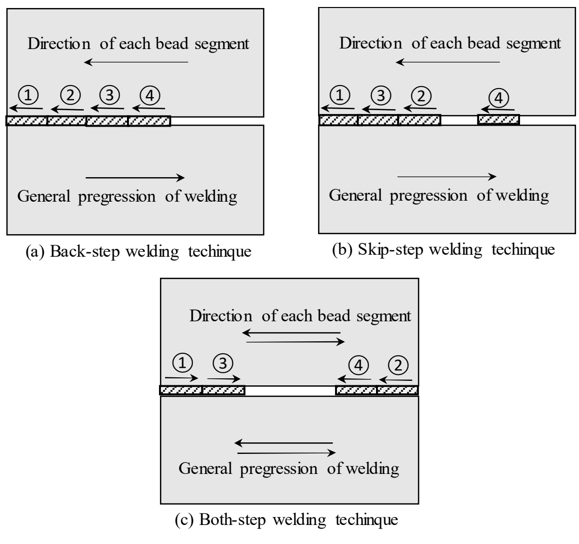

Fig. 2. Back-step, skip-step, and both-step welding techniques.

Back-step welding and skip-step welding are widely used in heavy industries to alter the welding temperature mechanism. In these methods, a welding line is divided into several parts that are differently ordered according to the welder's preference for mitigating welding displacement. In the back-step welding technique, the general progression of welding would be from left

† d184300@hiroshima-u.ac.jp

to right, but each bead segment is deposited from right to left as Fig. 2. To perform skip-step welding, a welder makes a series of intermittent bead segments then finally fills in the gaps between the as Fig. 2. Additionally, a newly introduced welding technique called both-step welding is proposed herein as seen Fig. 2. In the present study, these welding techniques are numerically simulated to validate the most efficient method to mitigate welding displacement.

Previously, most studies of welding displacement using numerical simulations employed the thermal elastic-plastic method (TEPM) to predict welding displacement precisely. However, this numerical method requires long calculation times to simulate even simple welding cases. Consequently, most of the recent studies on welding deformation using numerical simulations employ inherent strain theory in the elastic finite element method (EFEM). Luo et al. (1997) introduced inherent strain theory by considering the initial strain along welding lines to reflect the local shrinkages during progression of the welding process in the EFEM. Liang et al. (2005) validated the application of inherent strain theory in the EFEM to predict welding displacements by comparisons to experiment data. Deng et al. (2007) investigated the reliable applicability of inherent strain theory to the EFEM to analyze the welding process using a comparison with experiments results. Deng et al. (2004) developed the interface element method to reflect the misalignment between welded parts and nonwelded parts during numerical simulations. The Japan Shipbuilding Research Association (2000) proposed equations for predicting inherent strain and deformation of HT50 steel based on a measured experimental database using arc butt welding. As discussed above, inherent strain theory has been sufficiently proved to enable precise and economical analysis of welding displacements.

In the present study, HT50 steel was introduced to structures to be able to apply equations proposed by the Japan Shipbuilding Research Association (2000) to predict inherent strain and displacements. Based on several simulation results, the optimal welding technique for minimizing welding displacements to build a general ship grillage structure is then proposed.

2. Numerical approach for welding simulation

2.1 Inherent deformation and inherent strain

Based on the measured experimental database using arc butt welding (as shown in Table 1), the Japan Shipbuilding Research Association (2000) proposed equations as Eqs 1-3 to be able to calculate the amount of inherent displacements of HT50 steel (Table 2) such as transverse shrinkage S, longitudinal shrinkage F_T and angular distortion θ as Fig. 3. The amount of heat input Q^* decides the magnitude of welding displacement in these equations. Satoh et al. (1976) demonstrated the relationship between the input heat Q^* and the net heat Q_n with the thickness h of the welded steel plate as $Q^* = Q_n/h^2$.

Table 1. Arc butt welding conditions

Current [A]	Voltage [V]	Travel speed [mm/s]	Heat efficiency	Net heat [J/mm^2]
230	23	5	0.77	500

Table 2. Mechanical property of HT50 steel

Density [kg/m^3]	Young's Modulus [MPa]	Specific heat [J/kg/℃]	Yield stress [MPa]	Poisson's ratio
7720	2.0 × 105	659.4	440	0.3

1) Transverse shrinkage

$$S = C_t(L) S_0 \tag{1}$$

$$S_0 = \begin{pmatrix} 1.16 \times 10^{-3} Q_n/h & (Q^* \leq 6.27) \\ h1.44 \times 10^{-4}[(Q^*)^2 - Q^*] + 2.5 \times 10^{-3} & (6.27 < Q^* \leq 20) \\ 2.85 \times 10^{-3} Q_n/h & (20 < Q^*) \end{pmatrix}$$

$$C_t(L) = [4\tan^{-1}(L/200) + (L/100) \times \log(1 + 40000/L^2)]/3.74$$

2) Angular deformation

$$\theta = C_a(L)\theta_0 \tag{2}$$

$$\theta_0 = \begin{pmatrix} 1.44 \times 10^{-3} Q^* & (Q^* \leq 6.27) \\ 1.06 \times 10^{-1} Q^*/(Q^* - 6.16)^2 + 73.6 & (6.27 < Q^*) \end{pmatrix}$$

$$C_a(L) = [8\tan^{-1}(L/120) + (1+v)(L/60) \times \log(1 + 14400/L^2)]/8.84$$

3) Longitudinal shrinkage (Contraction force)

$$F_T = 0.2 Q_n \tag{3}$$

Here,

S: transverse shrinkage [mm]

θ: angular deformation [mm]

S_0: transverse shrinkage at a welding length of 200 mm [mm]

θ_0: angular deformation at a welding length of 200 mm [mm]

$C_t(L)$: welding length compensation coefficient for lateral shrinkage

$C_a(L)$: welding length compensation coefficient for angular deformation

F_t: vertical contraction force [N]

L: welding length [mm]

v: Poisson's ratio

Q_n: net heat input [J/mm]

h: plate thickness [mm]

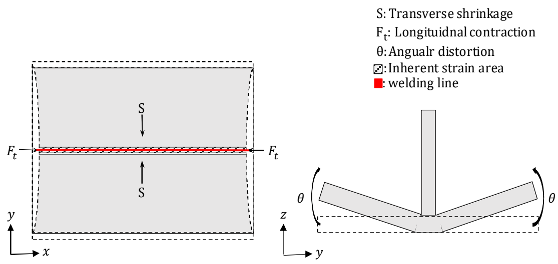

Fig. 3. Inherent deformation along welding line.

Japan Shipbuilding Research Association (2000) derived Eqs 4-7 to calculate inherent strain. In the application of inherent strain in EFEM, the inherent strain is uniformly assigned along the welding lines which have same width at their each side (Ueda et al., 1993).

$$\epsilon_l^* = 0.5(F_T/(Ehb)) \tag{4}$$

$$\epsilon_t^* = 0.5(s/b) \tag{5}$$

$$\epsilon_a^* = -hk \tag{6}$$

$$b = \sqrt{0.117(a/cp)(E/\sigma_y)Q_n} \tag{7}$$

Here,

ϵ_l^*: inherent strain of longitudinal shrinkage

ϵ_t^*: inherent strain of transverse shrinkage

ϵ_a^*: inherent strain of angular distortion

k: magnitude of the curvature of the deformation

a: linear expansion coefficient [1/k]

σ_y: yield stress [MPa]

2.2 Interface element

In the sequential simulation, the definition of the relationship between welded structures and non-welded structures is highly important to analyze welding displacements precisely. To reflect this phenomenon in the numerical simulation, the interface element is assigned along the welding line. Fig. 4 shows that the material properties of the interface element change depending on the stress state of the center of the interface elements prior to processing welding (Woo et al., 2019).

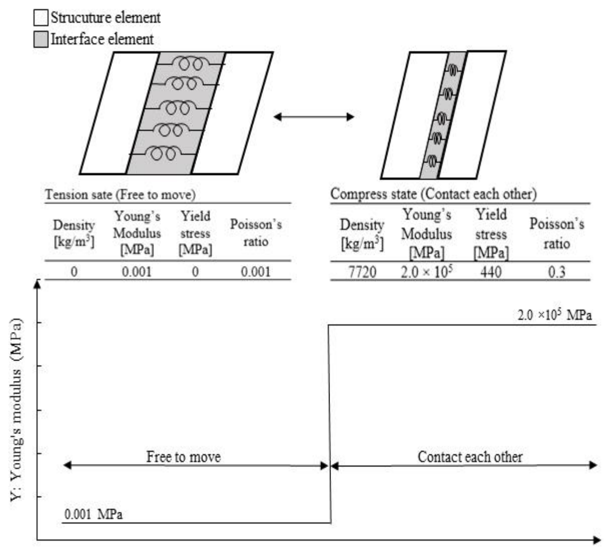

Fig. 4. Mechanical behavior of the material of interface element (Woo et al., 2019).

2.3 Multi-point constraint function

During finite element analysis, the multipoint constraint function (MPC) is applied for connecting different nodes with the same displacement at the same position. Fig. 5 (Woo et al., 2019) shows that, by using the MPC, nodes 1 and 2, which originally were in free movement from each other, are now connected to each other, and they can be defined as attached elements. The MPC can change the state of one node to work as a master or slave. In this study, tack welding (temporarily attaching plates) is employed to model the initial analysis model. As shown in Fig. 5, nodes a and b are initially connected using the MPC as tack welding. In addition, nodes (c, d), (e, f) and (g, h) install the MPC to be activated at an assigned welding order.

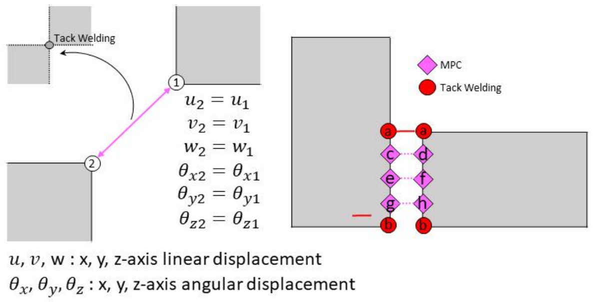

Fig. 5. MPC concept.

3. Analysis model

Two general plane plates (100 × 200 × 10 mm) are selected (see Fig. 6), to validate the efficiency of three welding techniques (back-step, skip-step and both-step welding). HT50 steel was used to the material of the plane plate, and its properties are given in Table 2. The two general plane plates were welded to each other along the red line shown in Fig. 6.

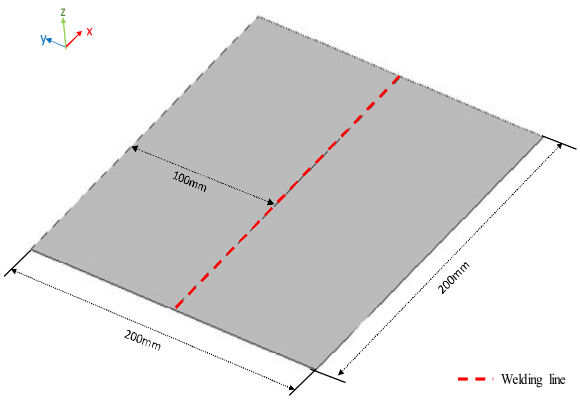

Fig. 6. General plane plate.

To demonstrate the most efficient welding technique to reduce welding displacements in ships, a general ships grillage structure (2000 × 3000 × 10 mm) was introduced (see Fig. 7) (Woo et al., 2019). Table 3 provides the detailed dimensions of the structure. In this model, cross points at both ends of the welding line were tack welded prior to the complete connection. Arc butt weld is employed herein, and the condition of all welding lines is assumed constant, as given in Table 1.

In Fig. 7, the optimal welding sequence of all welding lines is schematically drawn as circled numbers on the general ship grillage structure. Woo et al. (2019) proposed the optimal welding sequence for the structure without the application of a welding technique.

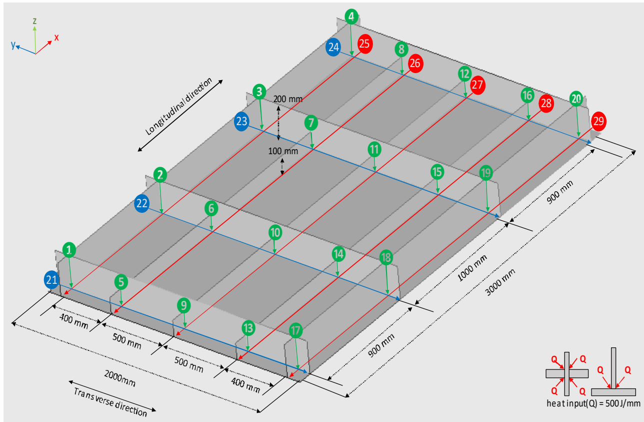

Fig. 7. General ship grillage structure (Woo et al., 2019).

Table 3. Details of the general ship grillage structure

Part	Dimension [mm]
Bottom plate	3000 × 2000 × 10
Longitudinal stiffener (*x*-axis)	3000 × 200 × 10 3000 × 100 × 10
Transverse stiffener (*y*-axis)	2000 × 200 × 10

4. Efficient welding technique

4.1 Results and discussion of the general plane plate

The representative value to discuss with respect to the efficiency of welding techniques to mitigate welding displacements is the average of the z-axis distance of all bottom plate nodes as Eq 8. Additionally, z-axis displacement distribution curves were measured at three lines (M1, M2, and M3) to discuss the magnitude of the angular displacement of the plane plate in Fig. 8.

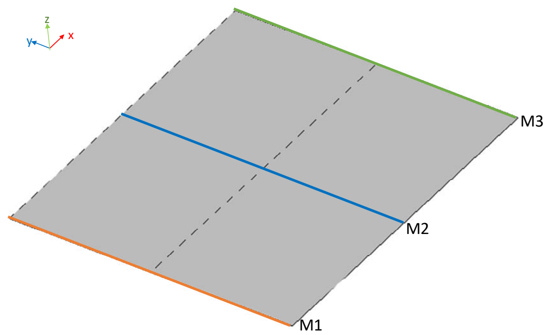

Fig. 8. Measuring line for the z-axis displacement distribution curve of the plane plate structure.

$$A_{displacement} = \frac{\sum_{k=1}^{n} |z_k|}{n} \tag{8}$$

Here,

$A_{displacement}$: z-axis displacement average (mm)

z_k: z-axis displacement of a node of a bottom plate

n: total number of nodes of a bottom plate

Figs. 9 - 12 clearly show the effect on the reduction of welding displacements of the plane plate in comparison to the result of welding displacements without employing an welding technique. In Fig. 9, compared to the value of $A_{displacement}$ without a welding technique, the back-step, skip-step and both-step techniques reduce by 8.1 %, 15.9 %, and 19.5 %, respectively. Hence, these welding techniques undoubtedly affect the mitigation of welding displacements of the total area of the general plane plate. Among these welding techniques, both-step welding is the most efficient method. In Figs. 10 - 12, one can see that the z-axis displacement distributions curves of M1, M2, and M3 of the both-step welding technique closely resemble a flat line. In other words, the welding technique greatly reduces the angular distortion of the welding process.

Compared to the results of the back-step welding technique, the other two welding techniques (skip-step and both-step) exhibit higher efficiency for the reduction of welding distortion. According to these results, the time gap between the next bead segments to be cooled after finishing the previous bead segment is an important factor for mitigating welding displacements.

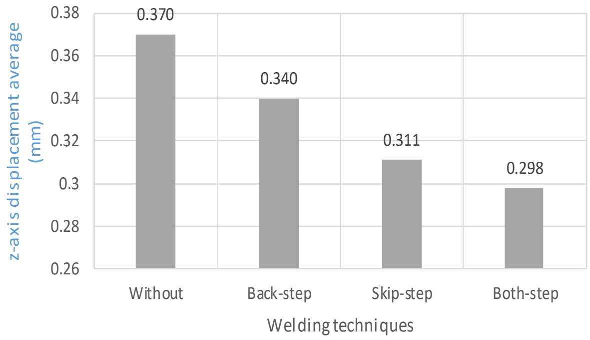

Fig. 9. $A_{displacement}$ of the general plane plate using different welding techniques.

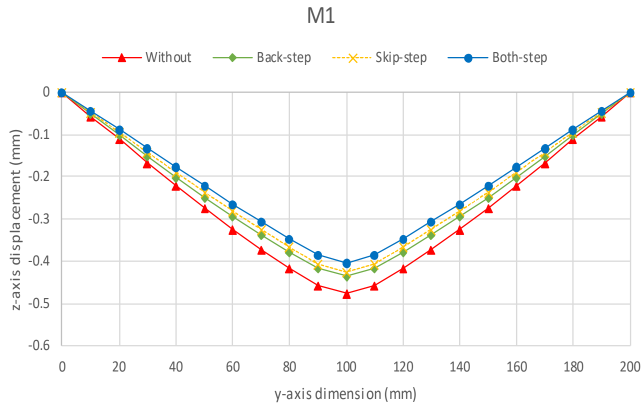

Fig. 10. z-axis displacement distribution curve of the general plane plate (M1).

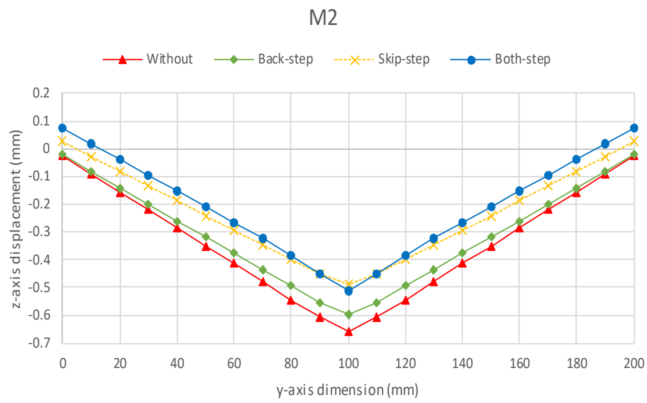

Fig. 11. z-axis displacement distribution curve of the general plane plate (M2).

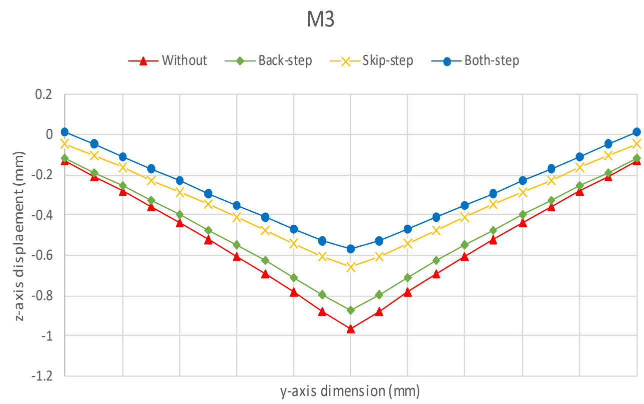

Fig. 12. z-axis displacement distribution curve of the general plane plate (M3).

4.2 Results and discussion of the general ship grillage structure

The z-axis displacement distribution curves were measured at two lines to discuss the magnitude of the angular displacement of the plane plate, as seen Fig. 13.

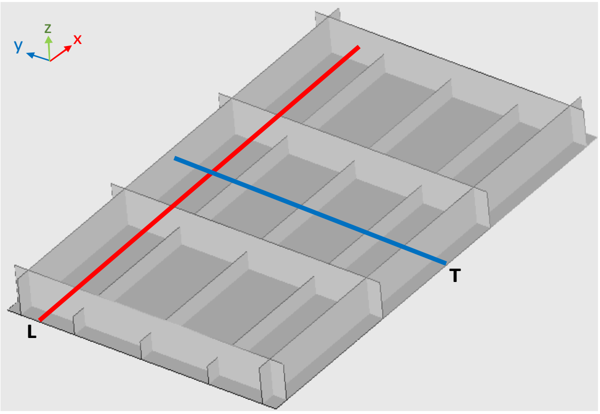

Fig. 13. Measuring line for the z-axis displacement distribution curve of the general ship grillage structure.

Fig. 14 validates the effect of welding techniques during processing the optimal welding sequence on reducing welding displacements of the general ship grillage structure. In the terms of reductions of $A_{displacement}$ from the case without employing a welding technique, the back-step, skip-step, and both-step welding techniques reduce $A_{displacement}$ by 5.8 %, 29.7 %, and 38.9 %, respectively. Compared to $A_{displacement}$ of the skip-step and both-step welding technique, the back-step welding technique is relatively inefficient.

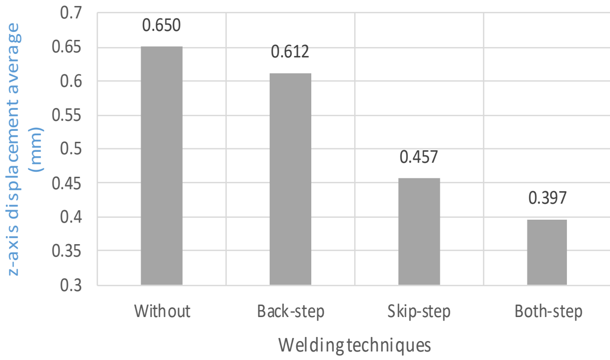

Fig. 14. $A_{displacement}$ of the general ship grillage structure using different welding techniques.

Fig. 15 shows the z-axis displacement distribution of the general ship grillage structure using different welding techniques. In Fig. 15, severely buckled displacement is noted at the center of the general ship grillage structure in the case without using a welding technique. Similarly to what is seen in Fig. 14, Fig. 15 shows that the skip-step and both-step welding techniques highly reduce the buckled displacements of the center of the general ship grillage structure.

The z-axis displacement distribution curves along T and L are plotted in Figs. 16 and 17, respectively. These clearly show the difference in the efficacies of welding techniques. The both-step welding technique exhibits the lowest welding displacements in both z-axis displacement distributions along T and L. In Fig. 16, compared to the z-axis displacement distribution curve without a welding technique, the back-step welding technique successfully mitigates limited sections (100 - 500 mm, 1500 - 1900 mm / y-axis dimension); however, the section of the center (500 - 1500 mm /

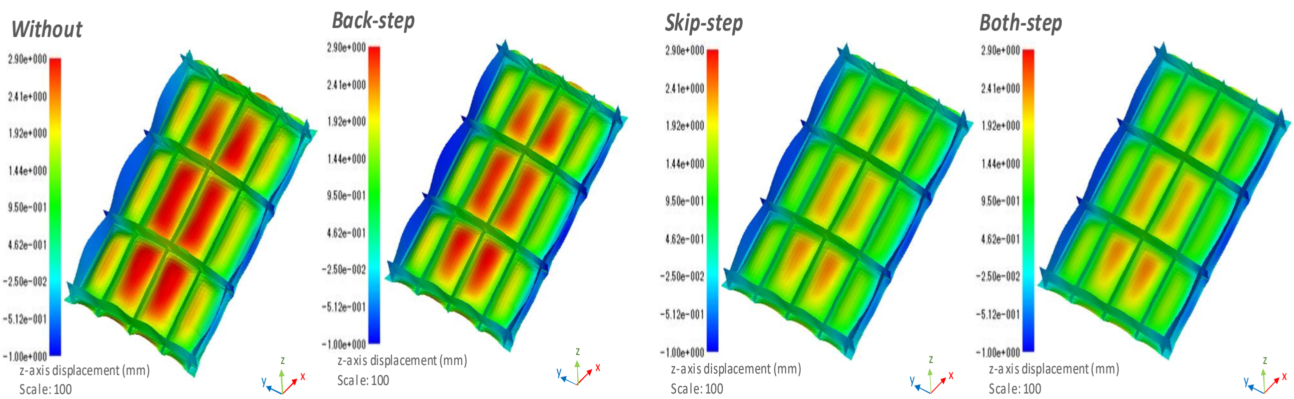

Fig. 15. z-axis displacement distribution of the general ship grillage structure using different welding techniques.

y-axis dimension) shows an the increase of z-axis displacement. In other words, the back-step welding technique is not always helpful for the mitigation of welding displacement of a welded structure. Compared to the result of the application of the back-step welding technique to the general ship grillage structure, the other two welding techniques (skip-step and both-step) offer higher efficiency for the reduction of welding displacements of the welded structure. Hence, the time gap between the next bead segment to be cooled after finishing the previous bead segment is highly crucial for controling the welding heat mechanism, which leads to welding displacements.

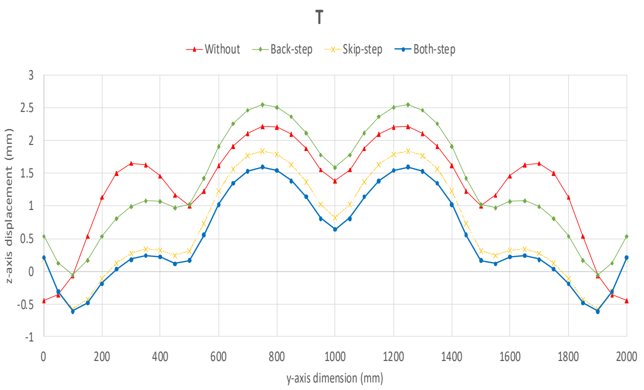

Fig. 16. z-axis displacement distribution curve of the general ship grillage structure (T).

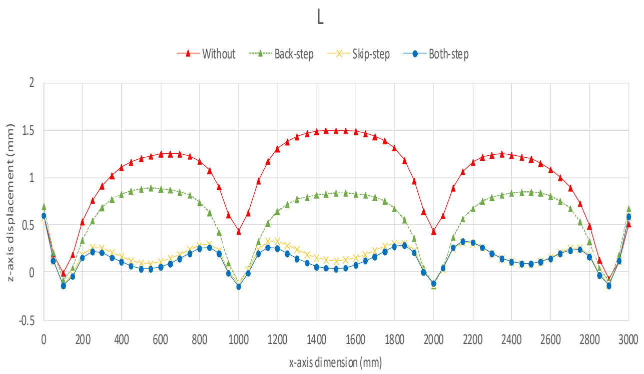

Fig. 17. z-axis displacement distribution curve of the general ship grillage structure (L).

5. Conclusion

In the present study, the most efficient welding technique for minimizing welding displacements in ship constructions was proposed. Several cases were numerically simulated using inherent strain theory, the interface-element method, and the MPC to analyze the effect of three welding techniques (back-step, skip-step, and both-step) on the reduction of welding displacements. This study contributes to understanding of the efficiency of introduced welding techniques on the reduction of welding displacements. The conclusions are as follow:

1. Employing welding techniques obviously reduces $A_{displacement}$ (8.1 ~ 19.5 %) of the plane plate structure. The both-step welding technique is the most efficient method for the reduction of $A_{displacement}$.
2. Compared to the efficiency of the back-step welding technique, the skip-step and both-step welding techniques exhibit much higher efficiency to mitigate welding displacements of the plane plate structure. In other words, the time gap between the next bead segment to be cooled after finishing the previous bead segment is an important factor for mitigating welding displacements.
3. The introduction of welding techniques to welding the general ship grillage structure improves the optimal welding sequence for minimizing welding displacements. In the application of welding techniques, the both-step welding technique leads to the highest reduction in the severely buckled welding displacements of the general ship grillage structure.
4. Although use of the back-step welding technique cam reduce $A_{displacement}$ (5.8 ~ 38.9 %) of the general ship grillage, inspection of the z-axis displacement curve of T shows that it produces an increase of z-axis displacement at some specific sections. Therefore, this method could lead to a negative effect on some parts of welding displacements of the welded structure.
5. To verify the method proposed in this study clearly, an actual experiment on a small-sized mock-up is planned in a future study.

References

[1] Deng, D., H. Murakawa, and W. Liang(2007), Numerical simulation of welding distortion in large structures, Computer Methods in Applied Mechanics and Engineering, 196(45-48), pp. 4613-4627, doi: 10.1016/j.cma.2007.05.023.

[2] Deng, D., H. Murakawa, and Y. Ueda(2004), Theoretical prediction of welding distortion considering positioning and gap between parts, International Journal of Offshore and Polar Engineering, 14(2), pp. 138-144.

[3] Japan Shipbuilding Research Association(2000), Japan Shipbuilding Research Association No. 237 Research Subcommittee (SR237): Research on Advanced Machine Accuracy Management Technology (Total Joint Report), Japan Shipbuilding Research Association, pp. 113-120.
[4] Liang, W., D. Deng, S. Sone, and H. Murakawa(2005), Prediction of welding distortion by elastic finite element analysis using inherent deformation estimated through inverse analysis, Welding in the World, 49(11-12), pp. 30-39, doi: 10.1007/BF03266500.
[5] Luo, Y., H. Murakawa, and Y. Ueda(1997), Prediction of welding deformation and residual stress by elastic FEM based on inherent strain (Report I), Transactions of JWRI, 26(2), pp. 49-57.
[6] Satoh, K. and T. Terasaki(1976), Effect of Welding Conditions on Residual Stresses Distributions in Welded Structures Materials, Journal of the Japan Welding Society, 45(2), pp. 150-156, doi: 10.2207/qjjws1943.45.150.
[7] Ueda, Y., M. Yuan, M. Mochizuki, S. Umezawa, and K. Enomoto(1993), Experimental verification of a method for prediction of welding residual stresses in T joints using inherent strains 4th report: Method for prediction using source of residual stress, Welding International, 7(11), pp. 863-869, doi: 10.1080/09507119309548506.
[8] Woo, D., M. Kitamura, and A. Takezawa(2019), Method to systemically order welding sequence to efficiently mitigate welding displacement of a general ship grillage structure, Ships and Offshore Structures, 19(10), pp. 47-51, doi: 10.1080/17445302.2019.1681865.

Received : 2020. 02. 11.
Revised : 2020. 03. 26. (1st)
: 2020. 04. 13. (2nd)
Accepted : 2020. 05. 28.