Design of Shrinkage Margin for Thin Panel Welded Structure during Manufacturing Process

D. J. Lee and S. B. Shin

Abstract

The purpose of this study is to establish a design tool for the shrinkage margin of a deckhouse caused by welding and flame straightening. In order to do it, the effects of heat intensity and internal/external restraint condition on the shrinkage of the simple weldments were investigated, in order to identify the principal factors controlling shrinkage caused by welding process and flame straightening. Based on the results, predictive equations for longitudinal and transverse shrinkage at the welded structure were formulated as the function of heat intensity and in-plane rigidity. These equations were verified by comparing predicted results with the measured results at a panel structure of deckhouse.

Key Words : Shrinkage, Welding, Flame straightening, Heat intensity, Rigidity, Predictive method, Finite element analysis.

1. Introduction

A major problem during welding is the distortion, which is attributed to incompatible strains caused by uneven temperature distribution during welding and cooling stage. Resultant distortion affects adversely the dimensional accuracy and the structural behavior of welded structure including static and dynamic stability, buckling strength and so on. Many researchers have tried to control welding distortion and thus the dimensional accuracy of the welded structure. As a consequence of these researches[1~6], the effective control methods for angular distortion such as flame straightening, elastic bending and improvement of fit-up joint, have been established and applied to the manufacturing process of actual welded structures. However, the problems related to shrinkage have not yet been cleared and still reported frequently. This is attributed to the fact that the previous shrinkage margin of the welded structure was mainly determined by a trial-and-error method rather than an engineering approach. This approach makes the proactive prediction method of shrinkage margin for individual case very difficult due to the complexity of welded structure. In addition, the efficient method controlling shrinkage at production stage has not yet been established except for the consideration of the pertinent shrinkage margin in design stage. Therefore, it is very important to predict shrinkage during the manufacturing process and to set a proper shrinkage margin in the design stage.

This study has tried to establish a design tool for shrinkage margin of a deckhouse of RIG during manufacturing process. To achieve it, the effects of heat intensity and geometric restraint condition on the shrinkage of the simple weldment were evaluated by conventional finite element analysis and experiment. Based on the results, predictive equations for longitudinal and transverse shrinkage of the welded structure caused by welding and flame straightening were proposed, and verified by comparing predicted results with the experimental results for actual panel structures.

D. J. Lee and *S. B. Shin* : Hyundai Industrial Research Institute, Hyundai Heavy Industries Co. Ltd, Ulsan, Korea
E-mail : str@hhi.co.kr

2. Procedure for FEA and experiment

Finite element analysis (FEA) and experiment were performed in order to investigate the effect of process parameters on shrinkage. FEA was carried out using heat transfer and thermo-mechanical analysis. Table 1 shows the welding and frame straightening condition used in this study.

Table 1 Welding and flame straightening condition used for FEA and experiment

		Heat Intensity [cal/mm]		
Fillet		463~3250		
Butt	1st	346~864		
	2nd	367~864		
		Flow Rate [L/min]		Speed [mm/min]
		Ethylene	O_2	
Flame straightening		11~12	12~14	300~900

Heat transfer analysis was performed using 2-dimensional heat transfer model with a quasi-stationary condition[3]. The heat input models by welding and flame straightening were defined as the volume heat source and the surface heat flux specified by a Gaussian distribution, respectively. Heat loss at all surfaces of the solution domain was governed by natural convection. Thermal properties of the material (A grade steel for shipbuilding) used depend on the temperature and an effective conductivity was used to consider the stirring effect of molten pool. Effect of latent heat at the phase change was considered by modifying the specific heat in the solidification range[4]. Mesh design for thermal-mechanical stress analysis consisted of 8-nodes plane element with general plane strain condition. When the temperature of elements reached the liquid temperature, the plastic strains accumulated by that time were assumed to be relieved. In this region subjected to the temperature above the melting temperature, thermal strain increment was set to zero. For thermo-mechanical analysis, material properties of weldment were postulated to behave as an isotropic, elasto-plastic and strain-hardening continuum and von- Mises criteria was used as an yielding criterion for weld metal and base metal

3. Results and discussion

A panel is the fundamental component of the deck structure, which is constructed by a series of welding procedures; butt welding of individual plate to form a blanket and continuous or intermittent fillet welding of stiffeners to attach to the blanket. And then when the welding distortion exceeds the allowable tolerance, the flame straightening is employed to correct it.

3.1 Shrinkage by butt welding

Shrinkage caused by butt welding was generally classified into transverse shrinkage perpendicular to the welding line and longitudinal shrinkage parallel to the welding line.

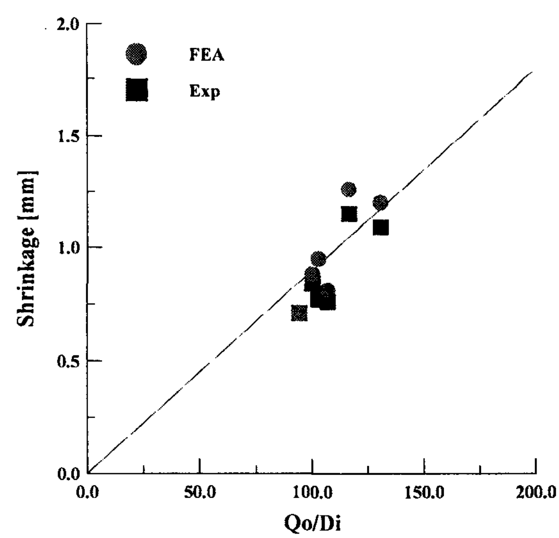


Fig. 1 Relation between transverse shrinkage and Qo/Di at the butt weldment

3.1.1 Transverse shrinkage

Fig. 1 presents the relation between the transverse shrinkage and the ratio of the heat intensity (Qo) to in-plane rigidity (Di) at the both side I-butt weldment. As shown in Fig. 1, the transverse shrinkage is proportional to the ratio of heat intensity to in-plane rigidity along the direction parallel to the welding line.

3.1.2 Longitudinal shrinkage

Longitudinal shrinkage at the weldment is determined by the amount of shrinkage force and internal restraint of the weldment along the direction of welding line. In order to determine the longitudinal shrinkage force, effect of internal restraint condition on the longitudinal shrinkage were investigated. Fig. 2 shows the variation of the effective width of tensile residual stress zone (C) with the ratio of heat intensity and in-plane rigidity at the butt weldment. C represents the width of zone subjected to tensile residual stress when the actual welding residual distribution was modified to rectangular distribution. As shown in Fig. 2, the value of C increases in a linear manner with an increase in Qo/Di value. The longitudinal shrinkage force (SF_B) at the butt weldment could be defined as the function of the heat intensity (Qo) and in-plane rigidity (Di).

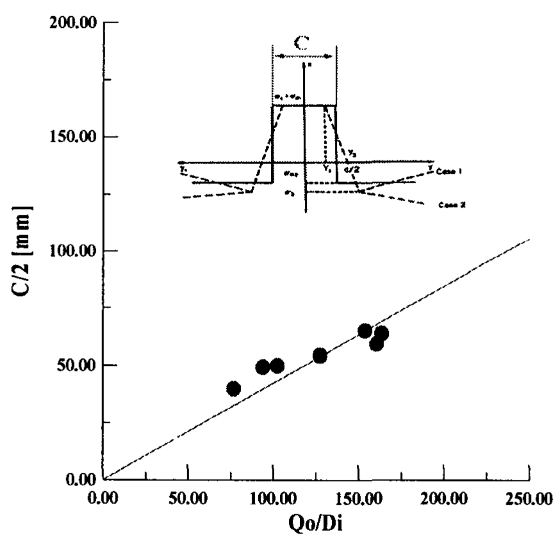


Fig. 2 Relation between effective width of tensile residual stress zone and Qo/Di at the butt weldment

Based on the results, transverse shrinkage (δ_{TB}) and longitudinal shrinkage (δ_{LB}) by butt welding can be formulated as the ratio of heat intensity (Qo) and in-plane rigidity (Di) and function of shrinkage force(SF_B) as following equations, respectively.

$$\delta_{TB} = f\left(\frac{Q_0}{D_i}\right) \tag{1}$$

$$\delta_{LB} = f(SF_B) = f\left(\frac{Q_0}{D_i}\right) \tag{2}$$

3.2 Shrinkage by fillet welding

Fillet welding used for manufacturing the deckhouse is classified into intermittent and continuous welding. The intermittent fillet weld is often used to reduce welding distortion. Therefore, effect of pitch (Ls) between intermittent welds, length (Lw) of each weld, the heat intensity and geometric factors of the fillet weldment on the welding shrinkage have been investigated.

3.2.1 Transverse shrinkage

Fig. 3 shows the variation of shrinkage at the continuous fillet weldment (Ls = Lw) as the ratio of the heat intensity to in-plane rigidity. Welding shrinkage at the continuous fillet weldment increases in a linear manner with an increase in Qo/Di value. Fig. 4 shows the variation of the ratio between transverse shrinkage (δ_{int}) at the intermittent fillet weldment and transverse shrinkage (δ_{con}) at the continuous fillet weldment with the ratio of Lw to Ls. As shown in Fig. 4, transverse shrinkage by intermittent fillet welding is smaller than that by continuous fillet welding. That is, the transverse shrinkage in the intermittent weldment deceases with a decrease the ratio of Lw to Ls. However, when the ratio of Lw to Ls decreases, transverse shrinkage is not linearly reduced.

3.2.2 Longitudinal shrinkage

Fig. 5 shows the relation between longitudinal shrinkage force at the continuous fillet weldment and heat intensity (Qo) for different plate thickness (t). The longitudinal shrinkage force increases with an increase of heat intensity (Qo) and plate thickness (t) as shown in Fig. 5. The increase of the longitudinal shrinkage force with an increase of the plate thickness is associated with the change of plastic zone size by heat input. That is, the plastic zone size of the fillet weldment

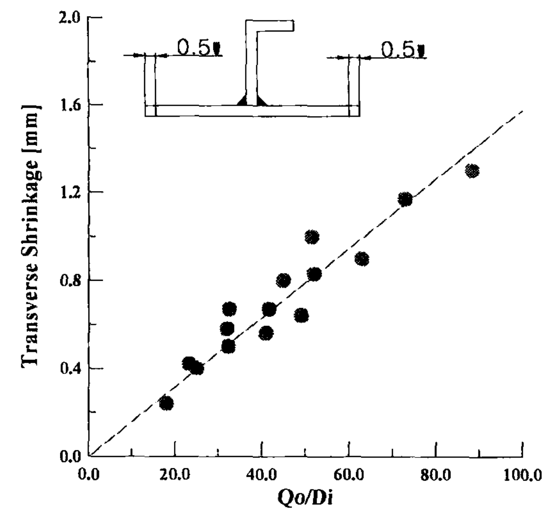


Fig. 3 Variation of the transverse shrinkage at the continuous fillet weldment with the ratio of Qo and Di

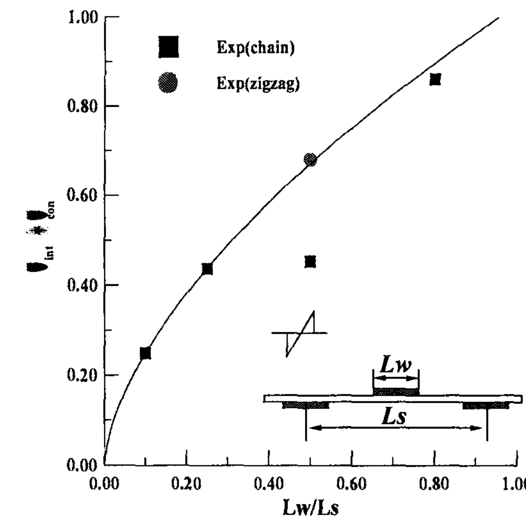


Fig. 4 Variation of the ratio between δ_{int} and δ_{con} with the ratio of Lw to Ls

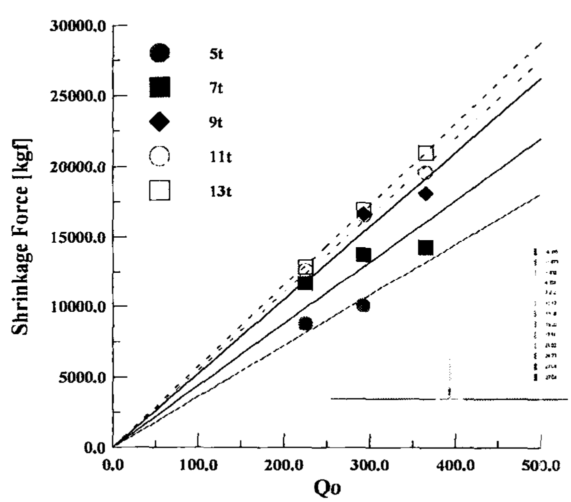


Fig. 5 Variation of the longitudinal shrinkage force in continuous fillet weldment with Qo and t

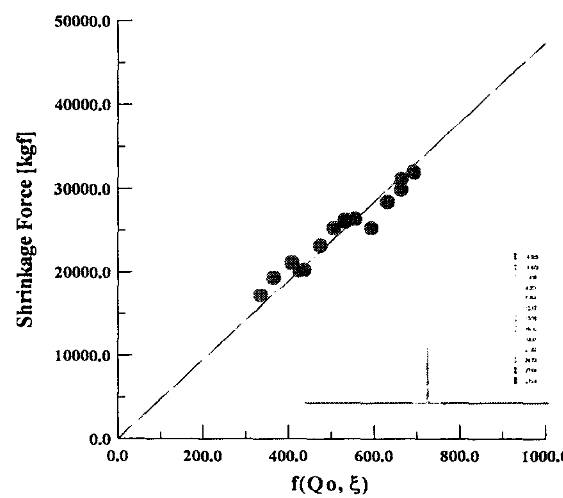


Fig. 6 Variation of the longitudinal shrinkage force in continuous fillet weldment with the function of Qo and ξ

depends on not only welding heat input but also the thickness of base plate. This tendency increases with an increase in the heat intensity and decreases with an increases in the base plate thickness due to the plastic zone size. Therefore, in this study, the effects plate thickness on the shrinkage force was considered by introducing the dimensionless parameter, ξ .

Fig. 6 shows the variation of the longitudinal shrinkage force with a function of heat intensity (Qo) and dimensionless parameter of plate thickness (ξ). As shown in Fig. 6, it is obvious that shrinkage force linearly increases with an increase in the value of f(Qo, ξ).

Based on the results, transverse shrinkage (δ_{TF}) and longitudinal shrinkage (δ_{LF}) by fillet welding can be formulated as followings.

$$\delta_{TF} = f\left(\frac{Q_0}{D_i}, \frac{L_w}{L_S}\right) \tag{3}$$

$$\delta_{LF} = f(SF_F) = f(Q_0, \xi) \tag{4}$$

In order to consider the effect of in-plane rigidity of the fillet weldment, the variation of the longitudinal shrinkage at the fillet weldment with stiffener size was evaluated by FEA under the same welding condition. Fig. 7 shows the variation of the longitudinal shrinkage with the cross-sectional area ratio of stiffener (As) and fillet weldment (Af). δ_b and δ_f are the amount of longitudinal shrinkage at the bead-on-plate weldment and the continuous fillet weldment, respectively. As shown in Fig. 7, the longitudinal shrinkage at the fillet weldment decreases with an increase of the cross-sectional area ratio of stiffener (As) to fillet weldment (Af). This verifies that the in-plane rigidity of the weldment is the principal factor controlling the longitudinal shrinkage of the fillet weldment.

From the above results, the average longitudinal shrinkage of the fillet weldment (δ_f) was defined as equation (5).

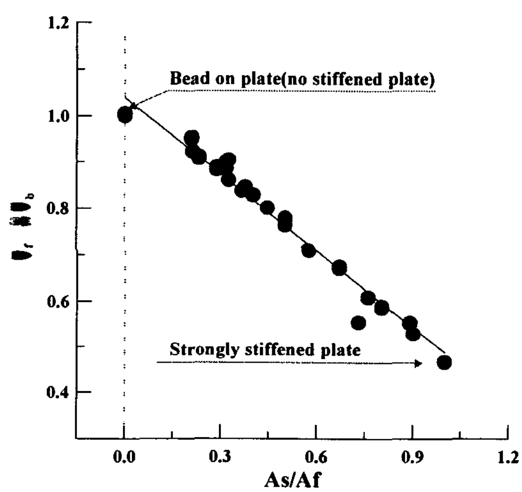


Fig. 7 Variation of the longitudinal shrinkage at the fillet weldment with As/Af

$$\delta_f = \frac{\int \delta\, dW}{W} = \frac{SF_F L}{(A_f)E} f\left(\frac{A_s}{A_f}\right) \quad (5)$$

Here, W is the plate width, and L is the total weld length. In case of the intermittent weldment, the effect of weld length (Lw) should be considered to establish the proper longitudinal shrinkage force because longitudinal residual stress is influenced by weld length. Generally, it is known[5,6] that weld length longer than 457mm is required to produce high tensile residual stress as much as yield stress in the longitudinal direction. Consequently, the predictive equation for the longitudinal shrinkage at fillet weldment can be established as function of the shrinkage force (SF_F), ratio of Lw to Ls, total weld length (L), and ratio of As and Af as shown in equation (6).

$$\delta_{LW} = f\left(SF_F,\ L,\ \frac{A_s}{A_f},\ \frac{L_w}{L_s}\right) \quad (6)$$

3.3 Shrinkage by flame straightening

Flame straightening is used to correct the angular distortion at fillet weldment by applying heat to the back surface of stiffened plate using flame torch. Although flame straightening corrects the angular distortion, it increases the amount of shrinkage due to the additional heat input to the weldment.

3.3.1 Transverse shrinkage

Fig. 8 shows the variation of the transverse shrinkage induced by flame straightening with a ratio of Qo and Di. As shown in Fig. 8, transverse shrinkage increases with an increase of the ratio of the heat intensity to in-plane rigidity. This result indicates that transverse shrinkage can be defined as function of the ratio of the heat intensity and in-plane rigidity of the fillet weldment as shown in equation (3).

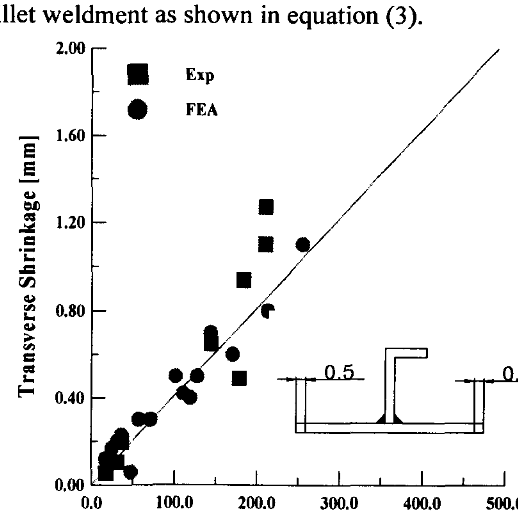


Fig. 8 Variation of the transverse shrinkage at the straightened fillet weldment with the ratio of Qo to Di

3.3.2 Longitudinal shrinkage

The mechanism of longitudinal shrinkage by flame straightening is similar to that of welding. Therefore, a predictive method for longitudinal shrinkage force caused by flame straightening has been established to calculate longitudinal shrinkage. Fig. 9 shows the variation of longitudinal shrinkage force (SF_h) with the function of the heat intensity (Qo) and dimensionless parameter of plate thickness (ξ). As shown in Fig. 9, the shrinkage force has a linear relationship with the function of the heat intensity and dimensionless parameter, ξ .

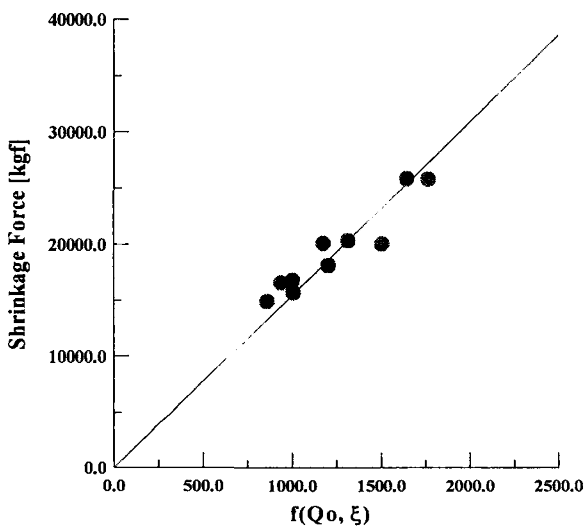


Fig. 9 Variation of the longitudinal shrinkage force in straightened fillet weldment with Qo and ξ

From the results of Fig. 9 and equation (5), the predictive equation for the longitudinal shrinkage by flame straightening can be established as function of the longitudinal shrinkage force, heated length (L_h), and ratio of As and Af as follows.

$$\delta_H = f\left(SF_h,\ L_h,\ \frac{A_s}{A_f}\right) \tag{7}$$

4. Shrinkage margin for welded structure

A predictive method for the shrinkage margin of the welded structure during the manufacturing process including welding and flame straightening can be established using the predictive equations for shrinkage of the simple weldment proposed from the extensive FEA and experiment described in the previous sections. Total shrinkage of a welded structure can be defined by superposing the shrinkages induced during the manufacturing procedures as the following equation.

$$\delta_s = \sum_{i=1}^{l} \delta_F + \sum_{j=1}^{m} \delta_B + \sum_{k=1}^{n} \delta_H \tag{8}$$

Here, l, m, and n are the number of fillet and butt joint, and straightened joint, respectively. δ_F, δ_B, and δ_H are shrinkage caused by fillet welding, butt welding, and flame straightening, respectively.

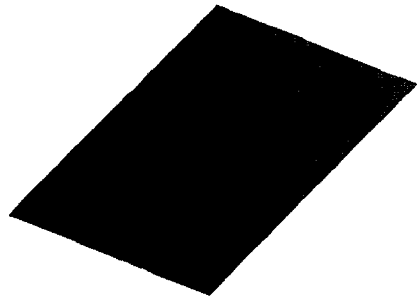
Fig. 10 shows the fabrication sequence of the panel used for the experiment and FEA[7] for verification of the predictive method proposed in this study. As shown in Fig. 10, the panel is constructed by series of welding procedures: butt welding of individual plate to form blanket and continuous fillet welding to attach longitudinal and transverse stiffener to the blanket. Table 2 and 3 shows the dimension of the panel and welding condition, respectively. The change of shrinkage caused by each welding procedure was measured using a 3-dimensional measuring instrument.

Table 2 Dimension of panel used for FEA and experiment

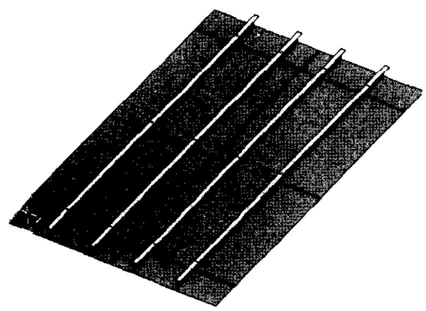
Dimension [L x W x t, mm]		
Base Plate	Longi. Stiffener	Trans. Stiffener
5400x3400x9	100x75x7 UA	300x7 FB

Table 3 Variables used for FEA and experiment

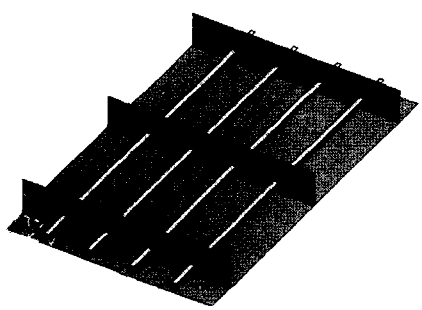
Welding Condition [heat intensity, cal/mm]			
Butt		Fillet	
Backing	Finishing	Longi.	Trans.
467	693	225	269



(a) Butt welding

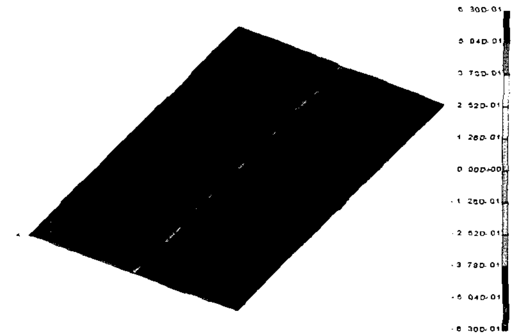


(b) Fillet welding of longitudinal stiffeners

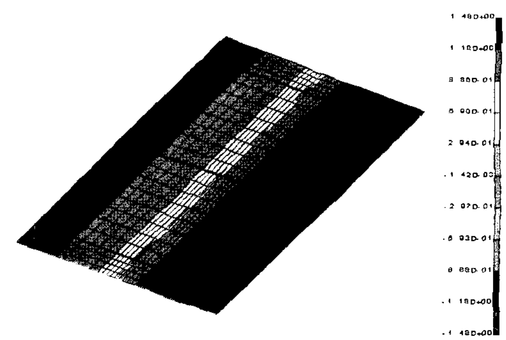


(c) Fillet welding of transverse stiffeners

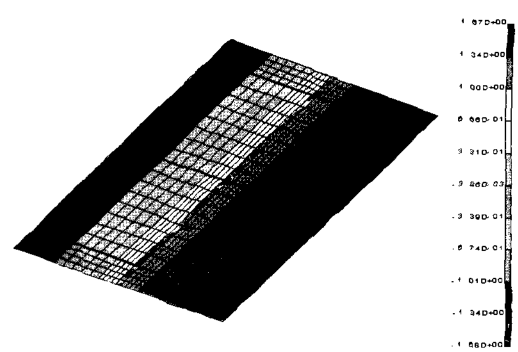
Fig. 10 Unit panel and its fabrication sequence used for the verification



(a) After butt welding



(b) After longi. fillet welding

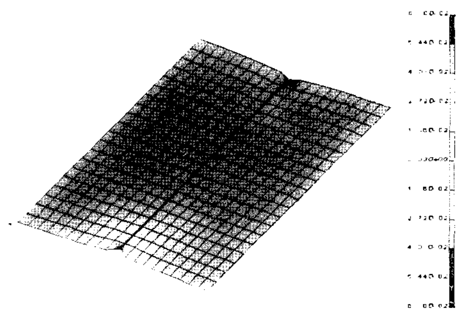


(c) After trans. fillet welding

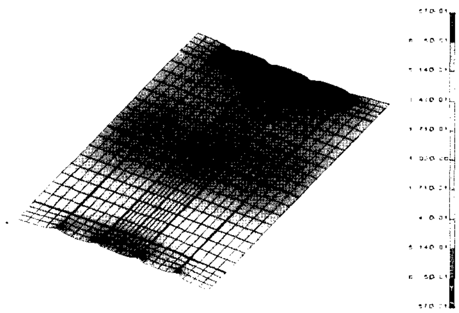
Fig. 11 Contour of shrinkage distribution in the panel width direction after each manufacturing process

Fig. 11 shows the change of transverse shrinkage of the panel obtained by FEA during the manufacturing procedures. The transverse shrinkage of the panel increases with a progress of welding stage. The final transverse shrinkage of the panel after welding process was equal to the sum of transverse shrinkage induced by each manufacturing process.

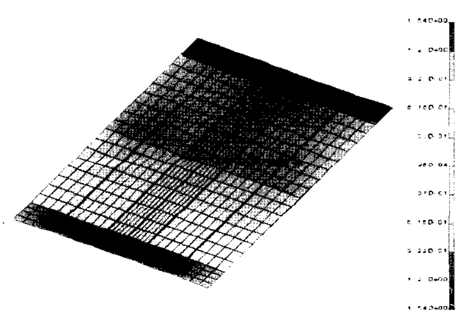
Fig. 12 (a) and (c) show the change of longitudinal shrinkage of the panel obtained by FEA after each manufacturing process. The behavior of longitudinal shrinkage during the manufacturing is coincident with that of transverse shrinkage. These FE results verify the assumption used for predictive method of shrinkage of the welded structure. Table 4 shows the results of transverse and longitudinal shrinkage using the predictive method proposed in this study, FEA and experiment during manufacturing process of the panel. Good agreement among these results can be clearly found.



(a) After butt welding



(b) After longi. fillet welding



(c) After trans. fillet welding

Fig. 12 Contour of shrinkage distribution in the panel length direction after each manufacturing process

5. Conclusion

In order to establish the predictive method of the shrinkage at the actual welded structure such as deckhouse, the extensive finite element analysis (FEA) and experiment have been performed. The main results are summarized as follows.

1. Principal factors controlling shrinkage of the deck structure during the manufacturing process were heat intensity, in-plane rigidity of the weldment and the ratio of Lw to Ls.

Table 4 Changes of shrinkage of the panel during the manufacturing process

	Transverse Shrinkage [mm]		
	After Butt W/D	After Fillet W/D	Sum
Experiment	1.0	2.0	3.0
FEA	1.2	2.2	3.4
Predictive	1.2	1.8	3.0
	Longitudinal Shrinkage [mm]		
Experiment	0.0	2.0	2.0
FEA	0.2	2.2	2.4
Predictive	0.2	2.2	2.2

2. Based on the results, the predictive equations for shrinkage by welding and flame straightening were defined as function of the principal factors.

3. The final shrinkage of the actual welded structure was equal to the sum of the shrinkage induced by each manufacturing process. Based on the results, the design tool for shrinkage margin of the welded structure was proposed and verified by comparing it with results of experiment and FEA

References

1. Y. Iwamura : Reduction of transverse shrinkage in aluminum butt welds, M.S. Thesis, *M.I.T.*, (1974)
2. H. Kihara and K. Masubuchi : Studies on the shrinkage and residual welding stress of constrained fundamental joint, *Reports of transportation technical research institute*, No. 7 (1954) and No. 20 (1956)
3. K. Satoh and S. Matsui : Reaction stress and weld cracking under hindered condition, *Technological Reports of the Osaka Univ*, (1967)
4. E. Friedman : Thermo-mechanical analysis of the welding process using the finite element method, *Trans. of ASME*, Vol. 97 , No. 3 (1975), pp. 209-213
5. E. P. Degramo, J. L. Meriam, and F. Jonassen : The effect of weld length upon the residual stresses of

unstrained butt welds, *Welding journal*, Vol. 25, No. 8 (1946), pp. 485-486
6. K. Masubuchi : Analysis of welded structure, *Pergamon Press*, (1980)
7. S. B. Shin and Y. K. Park : A study on the welding deformation of ship structure using simplified thermo-elastic method, *The 2001 annual autumn meeting of KWS*, (2001), pp. 274-276 (in Korean)