Simulation of Welding Deformation for Precision Ship Assembling (Report I)†

— In-plane Deformation of Butt Welded Plate —

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Abstract

To realize automation and mechanization in shipbuilding industry, it is necessary to clarify the effects of various factors involved in the process and predict welding deformation in advance. As a first step of the studies, the in-plane transverse deformation of one-sided automatic welding is investigated. Numerical simulations have been done on real size plate using the thermal-elastic-plastic FEM method. Good agreement between computed results and measured results is obtained.

The effects of various factors such as, local heating, welding sequence, initial stresses, type of tabs, pitch of tack welds and root gap have been investigated. Local heating affects the shrinkage deformation significantly near the heated region. Welding sequence also has a fairly large effect on the distribution of transverse shrinkage. Some patterns of initial stress in the plate could be an important factor that causes the statistical variation in the measured results.

KEY WORDS :(Butt Welding) (Welding Deformation) (In-plane Shrinkage) (Finite Element Method)

1. Introduction

A lack of skilled workers and a shortage of young labor in the shipbuilding industry have made it increasingly important in resent years to speed up automation and mechanization. At the same time much attention has also been given to the subject of establishing new working processes because only through appropriate working processes can the advantages of mechanization be fully utilized. To realize the mechanized assembly of ship blocks, it is necessary to keep the tolerance of blocks within critical limits. Therefore, a high accuracy in the previous sub-assembly stages are of great importance.

Much work has been done to improve the accuracy of sub-assembly. The sequences of numerical cutting and procedures to control the deformation of each block have been standardized. However, new break through is still needed before mechanization could be effectively used.

The assembly of ship blocks nowadays consists of cutting, bending, welding and removing distortions, most of which involve a certain type of heat processing. With the fast development of computers, thermal-elastic-plastic numerical analysis, mainly used in research during the last few decades, has become a versatile tool for practical industrial applications. If numerical analysis is proved to be an advantageous tool to predict the deformation due to various processes, the experimental and statistical anagement of tolerance now in practice can be replaced by more rational and unified form, which will result in great progress in improving the accuracy of block assembly[1].

To control the geometrical accuracy of manufacturing processes, the mean value and the standard deviation are used as statistical characteristics of the error. It is well known that gas cutting has a large influence on the standard deviation and welding has a great influence on the mean value. In general, welding shrinkage is too large to be ignored, so that spare elongation is considered in advance according to the prediction. This makes welding deformation and its prediction important factors.

The authors, therefore, focus attention on the deformation of welding and method of simulating welding deformation phenomena. As the first step, the shrinkage of plate under one-sided automatic submerged welding which has the features of high density heat input and large shrinkage is investigated. Reported studies on the one-sided automatic welding are mostly experimental works and focused on end cracking[2)-15)]. However systematic and quantitative theoretical works on welding of very large sized plate with considering practical processes such as local heating, different welding sequences and various constraint conditions have rarely been found.

In this paper, the results of welding shrinkage

† Received on Oct.31,1992

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Transactions of JWRI is published by Welding Research Institute, Osaka University, Ibaraki, Osaka 567, Japan

computed by FEM are compared with experimental results. Then the effects of local heating, the influences of welding sequences and constraint conditions on the transverse shrinkage of large sized plate are discussed.

2. Measurements of Welding Deformations

The measurements of welding deformation are made on real ship panels. Table 1 shows the six measured cases. Two are ordinary one-way welding, two are "meeting weldings" and the remaining two are the welding with local heating. Two plate thicknesses of 16mm and 19.5mm are used for each case. Material used is AH32 high tensile steel.

Arrangements of tacks and tabs are shown in Fig.1. To prevent end cracking, short tack welds with long pitch are used for the end part of the seam and long tack welds with long pitch are used for the rest of the seam as shown by Fig.1(a). Also two types of tab plates are considered, one is with slit and the other without slit as shown by Fig.1(b).

It has been known that heating or cooling the position near the end of the welding seam has the effect of preventing end cracking[2]. Thus, cases E3 and E4 are included to investigate the effect of local heating on transverse shrinkage. Two positions of rectangular heating have been shown in Fig. 2. In one case, the rectangular heater is placed parallel to the welding line (E3). In the other case the rectangular heater is placed perpendicular to the welding line (E4) and closer to the end of the plate. The temperature directly under the heater reaches between 220℃ and 290℃ during heating.

The welding sequence used for cases E5 and E6 is the so called "meeting near end" which means the whole weld seam consists of two facing weld beads. The sequence is as follows: the first weld bead is started from one end of the plate and stopped at the point 800mm from the starting end. Then the welding machine is moved to the other end to complete the weld by joining

Table 1 Experiment cases

Cases of experiment	Welding sequence	Heating	Plate size L×W×T (mm×mm×mm)	Tab (Start /End)
E 1	One-way	None	12000×3000×16	Ordinary /Slit
E 2			12000×3000×19.5	
E 3		Local heating 1	12000×3000×19.5	
E 4		Local heating 2		
E 5	End meeting	None	20800×4100×16.5	Ordinary /Odinary
E 6			20800×4100×19	

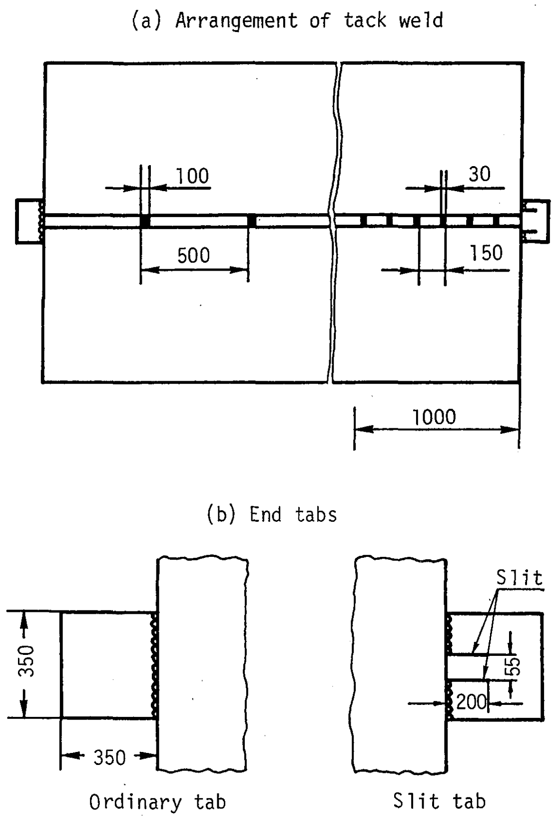


Fig.1 FCB Welding method (case E1~E4)

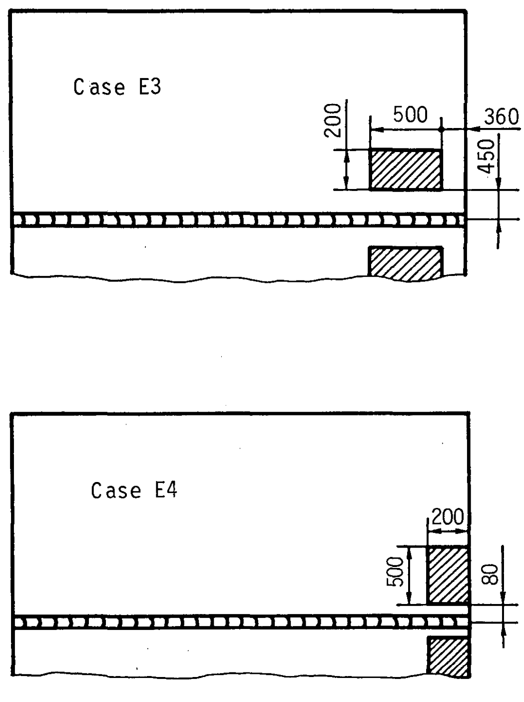


Fig.2 Heated positions of local heating tests

the seam to the former one. In cases E5 and E6, jacks are used to prevent the out-of-plane displacement of plate, whereas such equipment is not used in cases from E1 to E4.

Three-electrode one-sided automatic submerged arc welding is used as a welding method. The shape of the groove is like a capital letter Y with a root of 2-3 mm as shown in Table 2. Also welding conditions are shown in Table 2. To measure the amount of shrinkage, two lines parallel to the welding line are drawn before welding. Transverse shrinkage is obtained by measuring the change in the distance between these lines after welding. Half of the value is used for the comparison with the computed results. The residual deformation of experimental case E2 is illustrated in Fig.3. Figure 3(a) shows the in-plane transverse shrinkage. The distributions of shrinkage show small variation with both x and y coordinates. However, they converge to about 0.8 mm in the middle part of the

Table 2 FCB welding conditions

Thickness (mm)	Electrodes	Current (Amp)	Voltage (Volt)	Speed (mm/min)	Groove shape
16	L	1180	33	680	50°
	T_1	1130	37		
	T_2	830	39		
19.5	L	1230	33	630	
	T_1	1180	37		
	T_2	830	39		

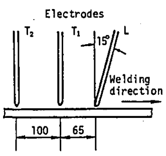


plate 1 meter away from the end. Figure 3(b) shows the longitudinal shrinkage. The maximum value of shrinkage is about 1 mm. Because it happens only near the end of the weld seam, longitudinal shrinkage can be considered as local welding deformation.

Though the plate remains quite flat after tacks were welded, the deformation of the plate becomes concave in shape after the weldings as shown by Fig.3(c). The out-of-plane deflection has a maximum value of 20 mm at the end of the plate and is reduced with the distance from the end of the plate. It becomes almost flat beyond 2 meters. Although this example shows concave deformation, convex deformation may also occur depending on the tack welding and the constraint by jacks. The concave distortion was reduced to half of its original value after a strip of about 100 mm from the end of the plate had been cut off. Figure 4 shows the measured surface temperature distribution in the middle of the plate. It is seen that the temperature gradient in the region within 200mm from the weld line is very large until 10 minutes after welding.

Other measured results will be discussed later together with calculated results. Although both in-plane and out-of-plane welding deformations are large, it is possible to reduce the out-of-plane deformation by constraint using jacks. In the present paper, only the

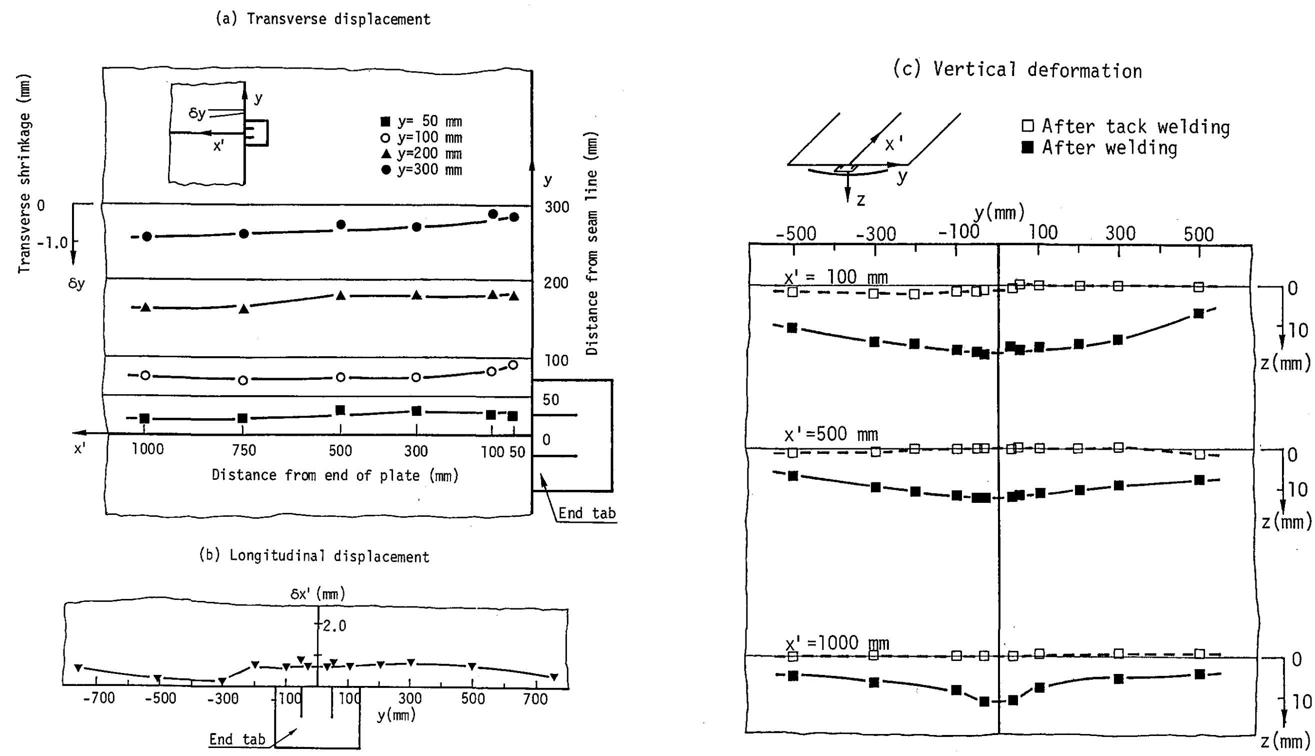


Fig.3 Measured deformation of welded plate

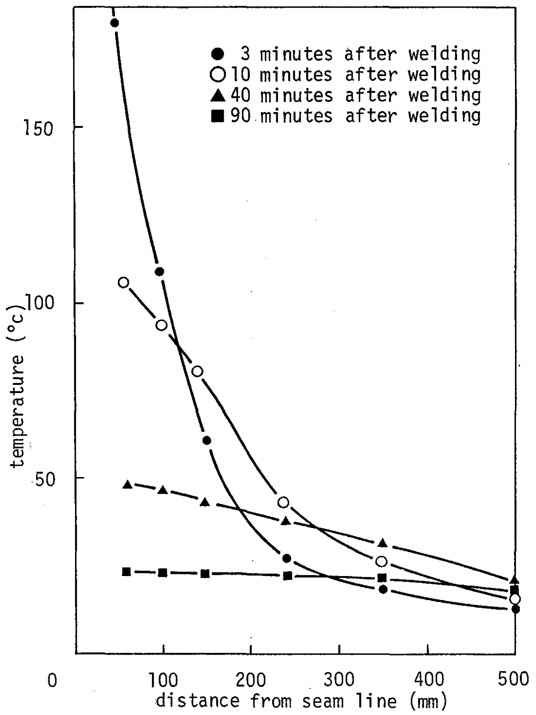


Fig.4 Temperature distribution after welding

transverse shrinkage is discussed and the lateral deflection will be discussed in the next paper.

3. Numerical Analysis

3.1 Method of Analysis

Welding stresses and deformations are highly complicated problems. In fact, it is a coupled thermal mechanical phenomena, accompanying metallurgical processes of melting and solidification. Two dimensional thermal-elastic-plastic FEM using 4-point quadrilateral isoparametric element is employed for the present study[16]. In the finite element simulation, coupling between the thermal and the mechanical processes is considered in the form of thermal expansion and temperature dependence of mechanical properties.

Since the butt welding of two pieces of plates is geometrically symmetrical with respect to the weld seam, half of the model is considered as the finite element model as shown in Fig.5. The starting point of the welding is taken as the origin of the coordinates. Let x axis coincide with the weld seam, and let the positive direction of the y axis coincide with the short edge of the plate. Dummy elements are used to simulate the deposition of weld metal. All the elements on the first line along the x axis, except the elements of tack and tab, are assumed to be dummy elements. These elements hold

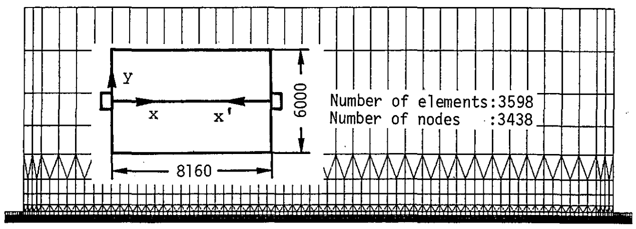


Fig.5 FEM model for analysis

no stiffness before welding and show rigidity as the temperature decreases below the mechanical melting point after the weld metal is filled.

The computations have been done on the workstation (TITAN) and it took about 18 hours for both temperature and stress-strain computations. The temperature field is obtained through solving the transient heat conduction equation by FEM.

Electric current and area where heat input is given are idealized based on the sum of the contributions from the three electrodes. The voltage is chosen as the mean voltage of the electrodes, and the heat efficiency is assumed to be of 85%. The variations of physical and mechanical properties with temperature are shown in Fig.6[17].

3.2 Computed cases

Twelve cases have been computed and they are described in Table 3. When the plate is long enough the influence of plate length on the problem was found to be small through preliminary computations. Thus, the length of the plate is fixed for all cases. Experimental results also show there are no clear differences between the plate thicknesses of 16 mm and 19.5 mm.

Since the transverse shrinkage is expected to vary with the variations of pitches of tacks and shapes of tabs, ordinary one-way welding is used to investigate the influence of tack and tab. Case C2 is the typical welding procedure commonly used in practice. The short and dense tacks are used near the end of the seam. In case C3, uniform tack is assumed for comparison. Case C4 differs from case C3 in the end tab which does not have a slit. In case C5 the pitch of the tacks is assumed to be twice as large as the case C3. Case C1 is bead-on-plate welding which can be considered as the extreme condition in which the tack pitch is zero.

On the other hand if local heating or cooling is applied near the welding seam during the welding, the temperature field and distribution of plastic strains will be changed and result in the changes of residual deformations of the plate. Case C6 and case C7 in Table 3 are used to simulate the local heating as in experimental

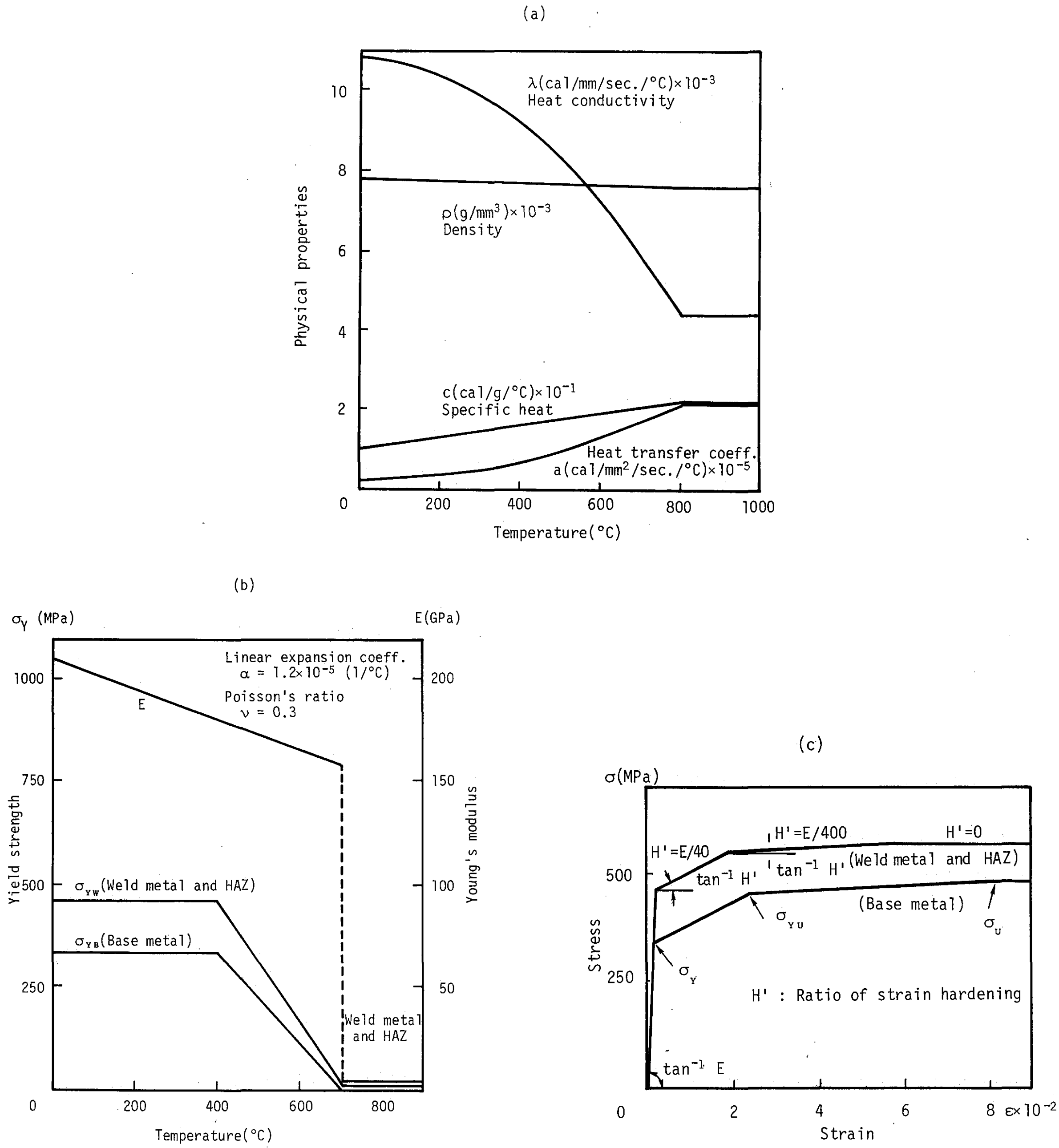


Fig.6 Temperature dependency of physical and mechanical properties

cases E3 and E4. The amount of local heat input q is determined by numerical trial-and-error so that the computed temperature field agree well enough with the measured temperature field. The plate is preheated for one hour prior to the welding as in the experiment. Then the heat input due to the welding is added to the temperature calculation. Both of the heatings are assumed to finish at the same time.

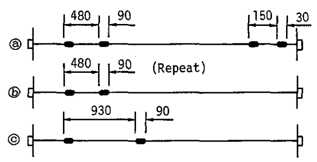
In Fig.7, two kinds of welding sequences are shown and they are corresponding to the cases C8 and C9. Case C8 shows that two weld seams meeting near one end of the plate, which is to simulate the experimental cases E5 and E6. For comparison, case C9 in which welds start from both ends at the same time with the same speed and the two seams meet at the middle of the plate, is also considered.

To clarify the effect of initial stress, case C10 is included. The residual stress is caused by various reasons, such as bending, gas cutting processes and the welding of tacks and tabs. In this report, only the initial stresses

Table 3 Numerical calculation cases

Computed cases	Welding sequence	Heating	Plate size L×W×T (mm×mm×mm)	Tab (Start /End)	Tack	Residual stresses	Gap	Cases of experiment
C1	One-way	None	8160×3000×16	Ordinary /Slit	None	None	None	None
C2	One-way	None	8160×3000×16	Ordinary /Slit	ⓐ	None	None	E1, E2
C3	One-way	None	8160×3000×16	Ordinary /Slit	ⓑ	None	None	None
C4	One-way	None	8160×3000×16	Ordinary /Ordinary	ⓑ	None	None	None
C5	One-way	None	8160×3000×16	Ordinary /Slit	ⓒ	None	None	None
C6	One-way	Local heating 1	8160×3000×16	Ordinary /Slit	ⓐ	None	None	E3
C7	One-way	Local heating 2	8160×3000×16	Ordinary /Slit	ⓐ	None	None	E4
C8	End meeting	None	8160×3000×16	Ordinary /Ordinary	ⓑ	None	None	E5, E6
C9	Center meeting	None	8160×3000×16	Ordinary /Slit	ⓑ	None	None	None
C10	One-way	None	8160×3000×16	Ordinary /Slit	ⓐ	Consider	None	None
C11	One-way	None	8160×3000×16	Ordinary /Slit	ⓐ	None	Consider	None
C12	One-way	None	8160×3000×16	Ordinary /Slit	ⓐ	None	Consider	None

Tack Arrangement



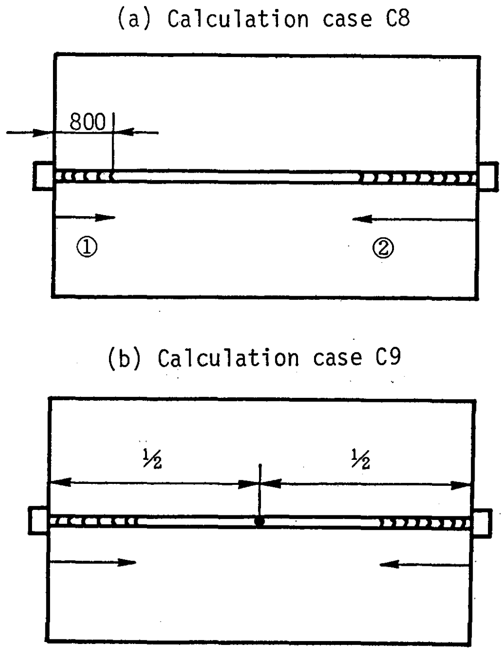


Fig.7 Welding sequence

caused by the welding of the last five tacks and the end tab are considered. Welding conditions for computation are shown in Table 4. No stresses are assumed to be produced during the welding of the start tab and all the tacks except the last five. The effect of other types of initial stress will be discussed in the next report.

In the models for computation, an ideal situation is considered and the root gap is assumed to be zero. However root gap sometimes exists in the groove of the plate due to the error in the gas cutting. When large gaps (3-5mm) occur, local heating and the adjustment of welding sequence of tacks are used to correct or reduce the gaps. Sealing beads and filling metal powder are also employed when the gap is large. To simulate the influence of gap on the transverse deformation of the plate, two gap models are used. In case C11, gap is assumed in the middle part of the plate. In case C12, gap is assumed in two places near the ends of the plate as shown in Fig.8. To simulate welding of such plates with the initial gaps, the heat input per unit length is increase by 20% where the gap exists.

4. Results and Discussions

4.1 One-way welding

Figure 9 shows the computed results of case C2 together with the corresponding experimental results of cases E1 and E2. Residual transverse deformations after welding along the four lines, 50, 100, 600, 1000 mm away

Table 4 Welding conditions for tab and tack

	Current (Amp)	Voltage (Volt)	Speed (mm/min)	Heat efficiency (%)
Tab	650	30	300	85
Tack	500	30	300	85

from the seam, are shown. The coordinates are chosen so that the abscissa x indicates the distance from the starting side of welding, whereas abscissa x' shows the distance from the ending side of welding. Ordinate shows the value of transverse deformation along the line which is parallel to the welding seam.

As seen from Fig.9, deformations at all points are negative due to the shrinkage of the weld seam. The distributions tend to be constant towards the middle of the plate. The magnitude of the shrinkage decreases near the ends of the welding seam. Such difference in the deformation along the line parallel to the seam decreases as the line moves away from the seam. At the outer edge of the plate the shrinkage along the length of plate is almost uniform and it is 0.8 mm as shown in Fig.9(d). Fairly good agreement can be seen between computed results and measured data. Small variation observed in the measured data may be due to the error involved in the measurement by callipers.

Computed results for cases from C1 to C5 along the outer line and the line 50 mm away from the seam are

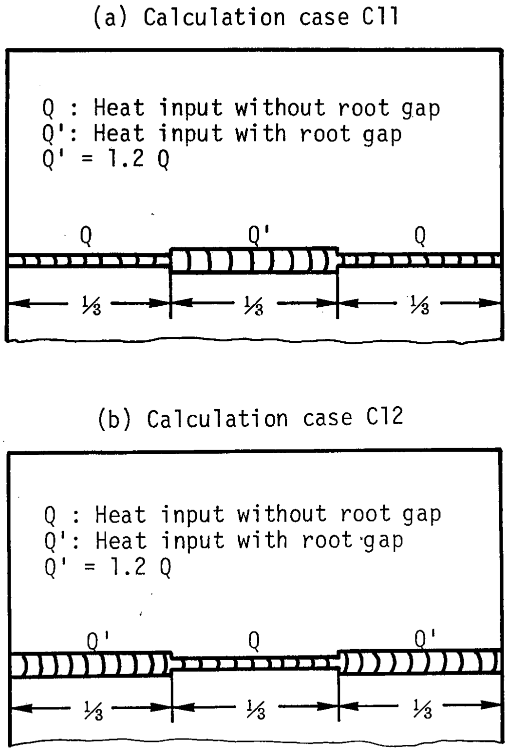


Fig.8 Idealization for analysis of root gap effects

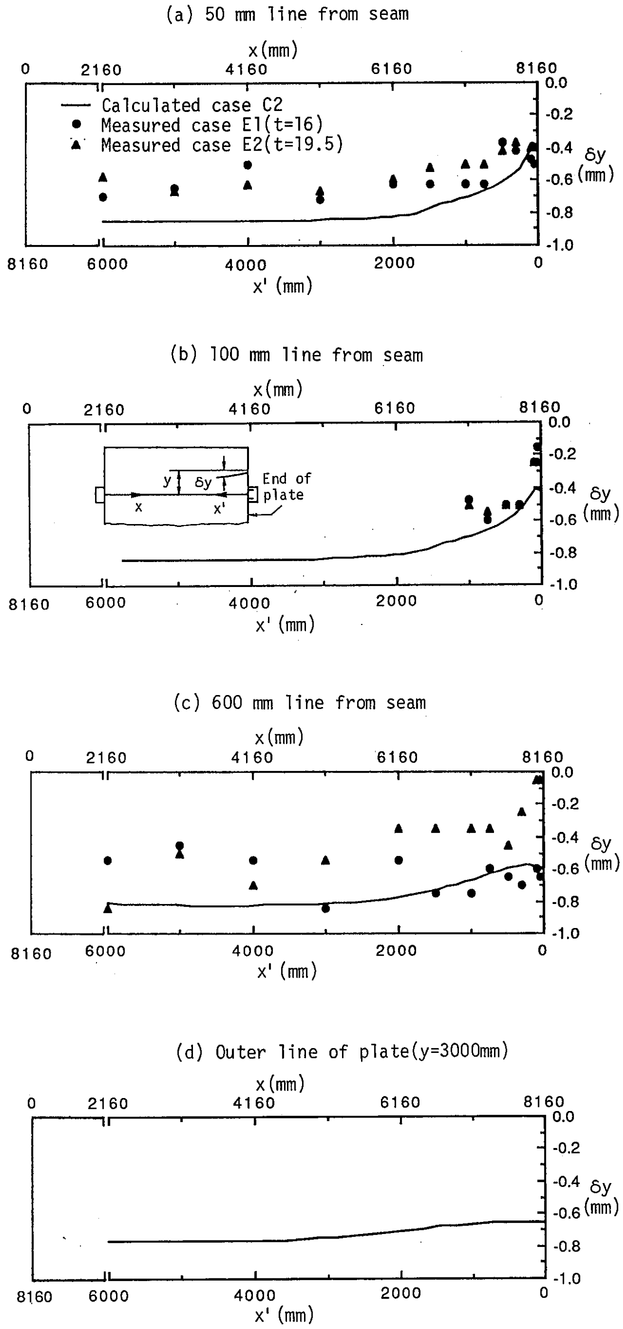


Fig.9 Comparison between calculated and measured shrinkage for cases C2, E1 and E2

shown for comparison in Fig.10. In the central part, the distribution of transverse shrinkage is uniform in longitudinal direction and its value is almost same for the line 50 mm away from the seam and for the outer edge. However, within the ranges of 1 meter from the welding start-point and 2 meters from the welding end-point, the transverse shrinkage near the seam shows a significant decreasing tendency. It is also commonly seen for all cases that the magnitude of shrinkage along the outer edge slightly decreases toward the weld end-point. The U-shape distribution is averaged with the distance from the seam and become almost a straight line along the outer edge.

Case C1 represents the bead-on-plate welding which has the highest resistance against the in-plane rotational deformation. The results of case C1, considered to be a limiting case of extremely strong tack welds, show the least transverse deformation among all the cases. As seen from Table 3, the degree of constraint due to tacks decreases in the order of case C2, case C3, (case C4), and case C5. The amount of shrinkage also decreases in the same order. This means that the stronger the constraint is the smaller the transverse shrinkage becomes. From close observation of the region near x=6000mm in Fig. 10(a), it is found that the point where the shrinkage starts to decrease rapidly moves toward the end of the plate as the constraint becomes stronger. The difference between cases C3 and C4, is the type of end tab plate. The slit tab and the ordinary tab without slit are used for cases C3 and C4 respectively. The distribution of the shrinkage near the end is more uniform in the case C4 than the case C3 due to the stronger constraint.

From the computed results shown in Fig.10, it is concluded that the differences in tack welds and type of tab plates which are commonly used in real practice give

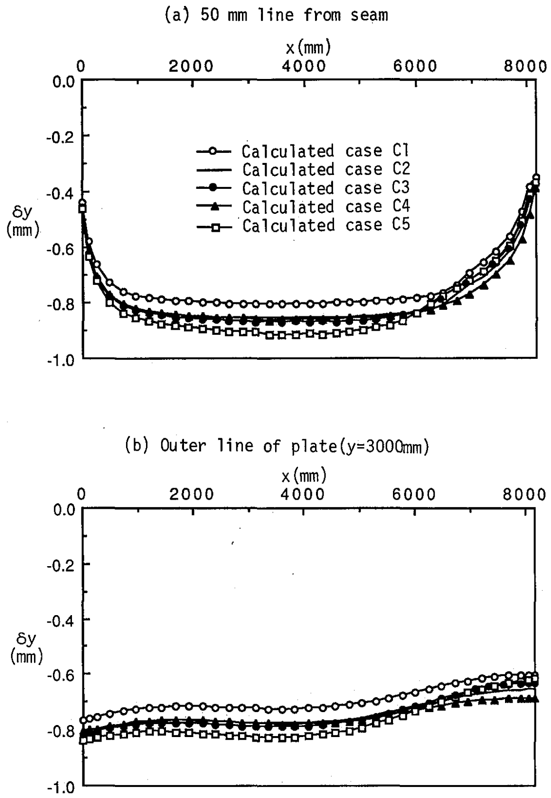


Fig.10 Influence of restraints of groove on the shrikage

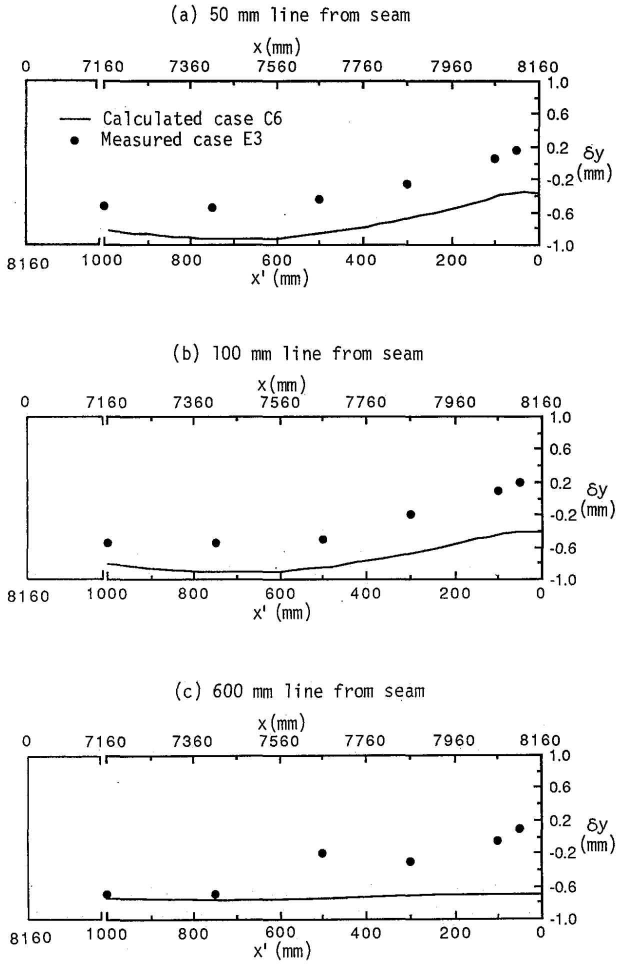


Fig.11 Comparison between calculated and measured shrinkage for local heating 1

small effect on the transverse shrinkage.

4.2 Effect of local heating

Figures 11 and 12 show the calculated results of cases C6 and C7 in which the effect of local heating is considered. The corresponding measured data, cases E3 and E4, are also shown for comparison. The computed and the measured shrinkage distributions along the three lines, 50 mm, 100mm and 600 mm away from the seam, are shown. Though the experimental data have larger values than the computed ones, the experimental and computed results show good agreement in the tendency of their distributions.

Figure 13 shows the computed results of the two local heating cases together with the computed results of case C2 for comparison. As seen from Fig.13, local heating affects the shrinkage deformation significantly near the heated region and position of heating has a big effect as well.

4.3 Effect of welding sequence

The effectiveness of special welding sequences called "meeting near end" and "meeting near center" are examined. In these welding procedures, the weldings start from both ends of the plate and these welds meat at the center or near the end of the plate. Figure 14 shows the distribution of shrinkage along the line 100mm away from the seam. Very good correlation can be seen between the computed results of case C8 and the measured results of cases E5 and E6. Figure 15 shows the transverse deformations of one-way welding and the two "meeting weldings". From Fig.15(a) it is seen that the shrinkage distributions of meeting welding methods deviate from ordinary ones near the meeting points. In the case of "meeting near end" the first welding seam contracts as the temperature decreases and provides stronger constraint to the expansion of the later seam. Thus, the shrinkage near the meeting point becomes maximum. In the case of two simultaneous welds meeting in the middle of the plate, the heat input is doubled near the meeting point. This heat input concentration and the strong constraint in the middle of the plate produce larger compressive plastic strains and larger shrinkage after cooling. From the above reason, the amounts of shrinkage near the seam become biggest at the meeting point for both cases. However, its distribution becomes uniform along the outer side of the

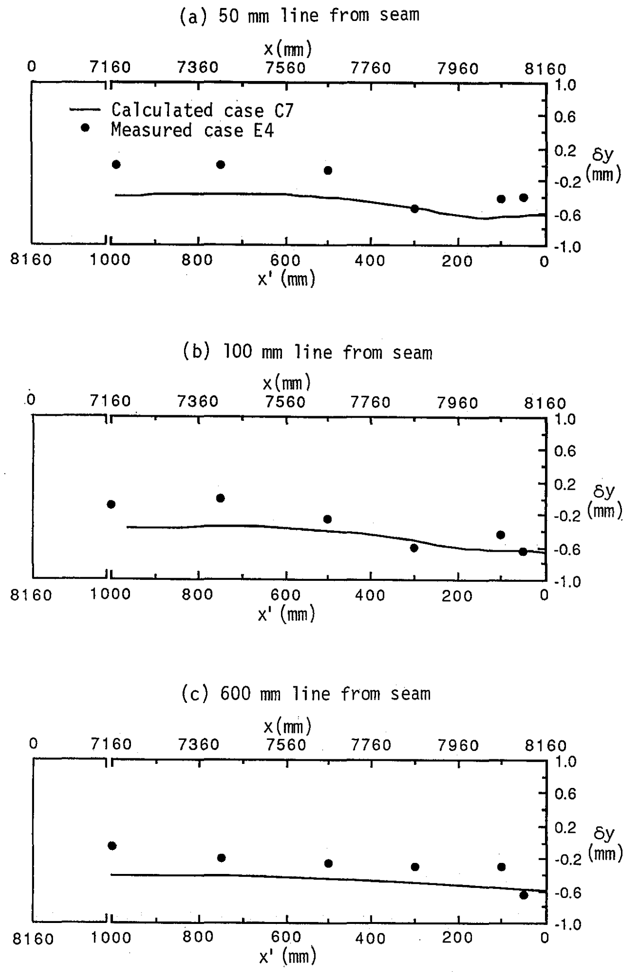


Fig.12 Comparison between calculated and measured shrinkage for local heating 2

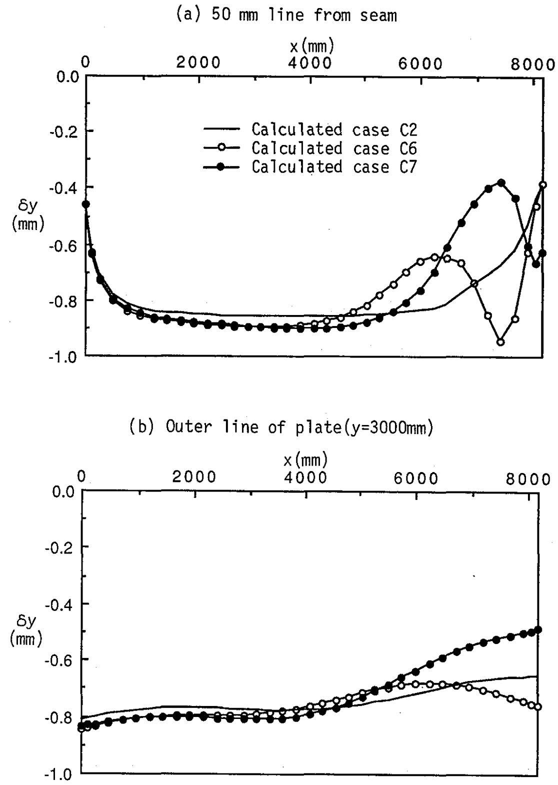


Fig.13 Influence of local heating on the shrinkage

plate.

4.4 Effect of initial stresses

Figure 16 shows the computed results of two cases, one is the case C2 without initial stress and the other is case C10 with initial stress caused by the welding of the last 5 tacks and the end tab. Though these tack and tab weldings involve a length of only 800 mm in total, their influence is observed also in the region 2 meters form the end.This result suggests that some patterns of initial stress may cause significant deviation in shrinkage distribution compared to those without initial stress.

In practical processes, there would be some initial stresses in the plates before welding. In fact, gas cutting, the welding of tacks and tabs, etc, cause residual stress. Initial stresses may be one of the most important reasons for the irregular deviation of transverse shrinkage measured in experiments.

4.5 Effect of gap

The influence of the root gap on the transverse shrinkage is shown in Fig.17. In cases C11 and C12, the root gap is assumed in the center part and the end parts of the plate as shown in Fig.8. Although larger shrinkage near the weld line is found in the region with initial gap, there is almost no difference due to the root gap along the outer edge of plate. In this computation, the heat input 20% more than the standard case is assumed to fill the gap with the weld metal. Such additional heat input results in 10% increase of the shrinkage. It is inferred that this increase of shrinkage by 10% is caused by the additional heat input rather than the initial gap itself. In the real practice, the gap is closed before the welding if it is larger than critical value. To close the gap, various techniques, such as partial heating during tack welds, are employed. However, such processes to close the gap may produce undesirable residual stress and its effect on transverse shrinkage in the final welding may not be ignored. To accomplish highly accurate welding, the effect of such residual stress need to be studied.

5. Conclusion

It is impossible to realize truly effective shipyard

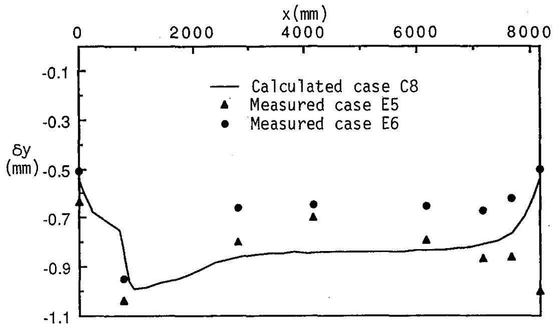


Fig.14 Comparison between calculated and measured shrinkage for C8, E5/E6

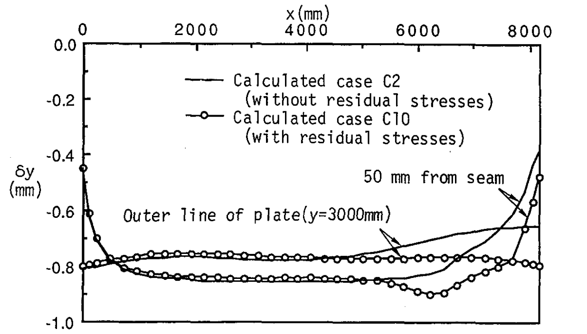


Fig.16 Influence of residual stresses on the shrinkage

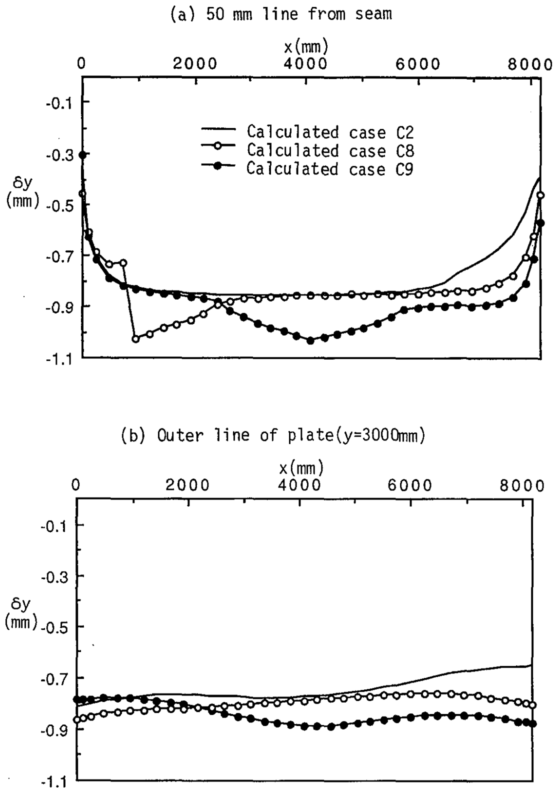


Fig.15 Influence of welding sequence on the shrinkage

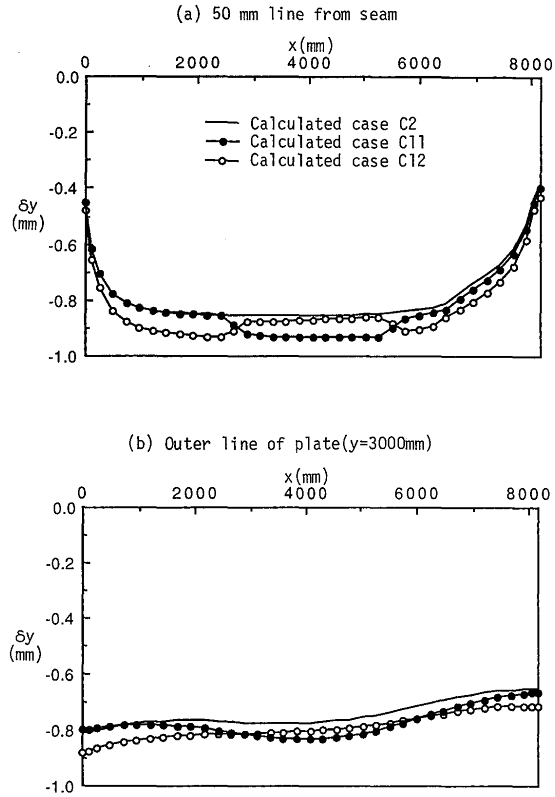


Fig.17 Influence of roof gap on the shrinkage

mechanization and automation unless each part of the ship structure is fabricated with high accuracy. Accuracy in assembling the ship's shell now mainly depends on the accuracy of the gas cutting and welding. As for the degree of deformation, prediction and reduction of welding deformation are of great importance, because welding gives more heat input compared to gas cutting.

For the above reasons, thermal-elastic-plastic FEM is used to simulate the in-plane deformation of one-sided automatic welding with large heat input. The main conclusions drawn from the present study are as follows:

(1) The thermal-elastic-plastic FEM method is used to simulate the effect of various factors on the transverse shrinkage of butt welding. A general correlation between measured results and calculated results is shown. These results suggest the FEM computer simulation is quite reliable and is useful for prediction of deformations in practical processes.

(2) The shrinkage near the seam is larger in the middle section of the plate compared to that at both ends. This gives the U-shape distribution along the length of the plate. This nonuniform distribution is

smoothed as the location is away from the seam.

(3) Stronger constraint of tacks results in less shrinkage and longer uniform deformation range in the middle of the plate. No large differences are apparent, however, within the extent of the real usage of tacks and tabs, and this leads us to the conclusion that the pitch of tacks and type of tabs have little effect on shrinkage distribution.

(4) It has been seen that local heating greatly affects the distribution of transverse shrinkage and the position of heating has a big effect as well.

(5) Considering the fact that the residual stresses caused by the welding of end tab and tacks near the end of the welding have a significant effect on the welding deformation, some patterns of initial stresses must be also taken into account as important factors.

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