Simple Prediction Methods for Welding Deflection and Residual Stress of Stiffened Panels†

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Abstract

In box-girder structures such as hulls of ships and bridges, deck plates play an important role for longitudinal bending strength. There have been a number of reports on the behavior of a stiffened deck plate subjected to in-plane compressive loads until the compressive ultimate strength. The authors also have studied this subject in series. It is known from the results of these researches that welding initial imperfections, such as initial deflection and residual stress, produced in a deck plate largely influence its compressive ultimate strength. Initial deflection and residual stress distribute very complicatedly in an actual deck plate panel. It takes much time to accurately obtain them.

In this research, the production mechanism of initial imperfections is clarified and a new method is developed to estimate average initial imperfections so simply as by hand calculation. The new estimation method is applied to mild steel deck plate panels to show its good accuracy in comparing with actual measured initial deflections of ships. It is also applied to HT steel (high tensile strength steel) deck plate panels to investigate how initial imperfection varies among different kinds of steel.

KEY WORDS: (Simple Prediction Method) (Welding Initial Deflection) (Welding Residual Stress) (Stiffened Panel) (Hull) (Compressive Ultimate Strength)

1. Introduction

In box-girder structures such as hulls and bridges, deck plates play an important role for longitudinal bending strength. There have been a number of reports on the behavior of a plate or a stiffened deck plate subjected to in-plane compressive loads until the compressive ultimate strength. The authors also have studied this subject in series[1)–10)]. As for compressive ultimate strength of a stiffened rectangular plate, they have analyzed the behavior up to failure under the influence of welding initial imperfections such as initial deflection and residual stress, and clarified its characteristics. It is known from the results of these researches that welding initial imperfections produced in a deck plate largely influence its compressive ultimate strength, and that such welding initial imperfections should be considered in the study of compressive ultimate strength of a deck plate. However, initial deflection and residual stresses distribute very complicatedly in an actual deck plate panel. It takes much time to obtain accurate information, since they should be observed either in a real ship or on a specimen of the same size as the actual stiffened deck plate panel which has been furnished under the same welding conditions as actual ones. Moreover, the observation results from a limited number of ships or experimental specimens do not necessarily provide generalized information.

In this research, a theory based on the production mechanism of initial imperfections is developed in order to propose a new method to estimate average initial imperfections so simply as by hand calculation that utilizes a limited information, such as the sizes of a stiffened deck plate panel and the welding conditions of the stiffeners. The new estimation method is applied to mild steel deck plate panels to show its accuracy. It is also applied to HT steel (high tensile strength steel) deck plate panels to investigate how initial imperfection varies among different kinds of steel.

2. Simple Estimation Method for Welding Initial Deflection

To be presented here are the estimating equations for welding initial deflection produced in one of the deck plate panels of a ship, which are stiffened with longitudinal and transverse members. Initial deflection can be simply and accurately calculated by equations which are expressed in terms of the sizes of a panel and stiffeners and the welding conditions. First, angular distortion due to fillet welding of a T-joint without restraint is obtained, and then welding initial deflection in a rectangular plate stiffened on one side is estimated.

2.1 Angular distortion of unrestricted T-joint due to fillet welding

Angular distortion δ_f due to fillet welding of an unrestricted T-joint (see **Fig. 1**) can be calculated by the for-

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mulae presented by Watanabe and Satoh[11] as follows:

(i) In case of one-pass welding

$$\delta_f = c_1 \chi^m e^{-c_2 \chi} \text{ (rad)} \tag{1}$$

where, $\chi = I/(t\sqrt{vt}) \times 10^{-3}$

I: welding current (A), v: welding speed (cm/sec), t: plate thickness (cm), m, c_1, c_2: constants determined by the kind of steel, welding method, etc.

(ii) In case of multi-pass welding

$$\delta_f = (W/W_0) c_1 \chi^m e^{-c_2 \chi} \text{ (rad)} \tag{2}$$

where,

W: weight of total weld metal (per unit weld length)

W_0: weight of weld metal per layer (per unit weld length). When the welding condition is almost the same for each passes and the number of layers is relatively small, $(W/W_0) = n$. n: the number of layers.

The constants, m, c_1 and c_2, appeared in the above equations are determined by the kind of steel, welding method, etc. Their values were shown by Akashi et al. for the cases where SM41, SM50, SM58 and HT80 were welded by shielded metal arc welding or submerged arc welding processes[12]. In this study, auto-con welding process, which is considered to approximate to the gravity welding process widely used in shipyards, is applied to SM41, SM50 and SM53 plates of 6 to 40 mm plate thickness by one-pass welding method. Then angular distortion produced in respective T-joint is analyzed by Eq. (1). As a result, the constants, m, c_1, c_2, are obtained as shown in **Table 1**.

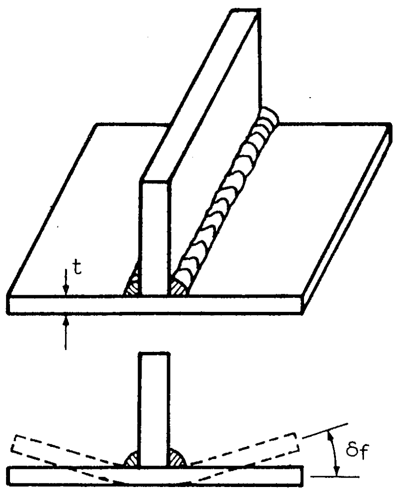


Fig. 1 Angular distortion due to fillet weld of T-joint.

2.2 Angular distortion restraint coefficient K_δ and angular distortion δ_0 due to fillet welding of T-joint under restraint

In this section, angular distortion δ_0 due to fillet welding of a continuously stiffened panel as shown in **Fig. 2** is estimated using δ_f described in Section 2.1. Since the panel is so deformed as to satisfy the symmetry condition at the mid-span between the stiffeners, this welded joint is henceforth called "fillet welded T-joint under restraint".

Table 1 Constants in estimating equation for angular distortion.

Material of Plate	σ_Y (kgf/mm^2)	m	c_1	c_2
SM41	29.	1.6	0.36	2.8
SM50	39.	1.9	0.48	2.8
SM53	41.	1.8	0.35	2.5

- Weld Metal : LB-52
- Thickness of Plate t = 6 ∿ 40 mm
- Condition of Welding : 300A, 37V, 20.9 cm/min, Q = 31,500 J/cm
- Leg Length : 10 mm

Assuming an ideal condition that the stiffeners shown in Fig. 2 are welded simultaneously, a continuously stiffened panel is modelled as a beam as shown in **Fig. 3 (a)** considering the symmetry conditions with respect to the center line of the stiffener and at the mid-span of the panel. The symbols in Fig. 3 (a) denote as follows:

M_1: concentrated bending moment equivalent to one due to transverse shrinkage of weld metal, which causes the same angular distortion as that due to fillet welding.

M_2: bending moment which makes the slope at $x = l$ zero so that the symmetry condition is satisfied.

l_1: acting position of M_1

$2l$: distance between stiffners

θ: slope

This beam model is used to obtain the angular distortion restraint coefficient which will be defined below.

First, in the case where only the equivalent moment M_1 acts at the position $x = l_1$ as in **Fig. 3 (b)**, the slope at the same position, θ_1, is expressed as follows:

$$\theta_1 = \begin{cases} (M_1/EI)\,x & (0 \leqq x \leqq l_1) \\ M_1 l_1/EI & (l_1 \leqq x \leqq l) \end{cases} \tag{3}$$

The slope θ_1 is equivalent to the angular distortion δ_f of T-joint on the unrestricted condition mentioned in Section 2.1. That is,

$$\delta_f = M_1 l_1/EI \tag{4}$$

Next, in the case where only M_2 acts as in **Fig. 3 (c)**, the slope θ_2 is expressed by the following equation.

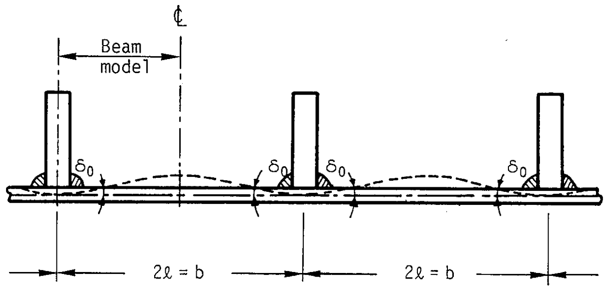


Fig. 2 Deflection of panels due to fillet weld between panel and stiffener.

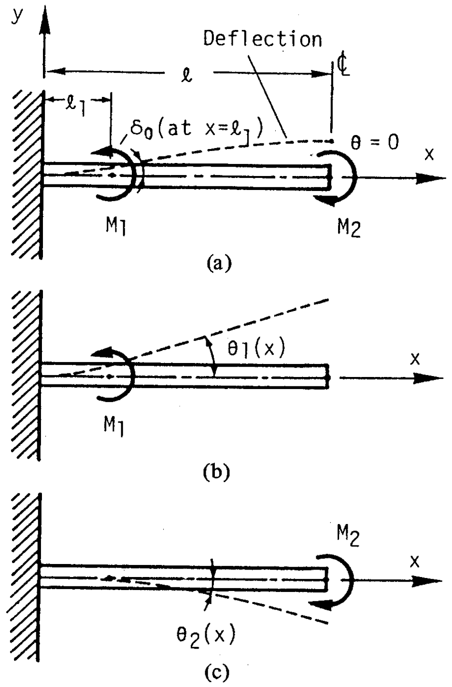


Fig. 3 Deflection of beam by equivalent moment to the shrinkage force near weld metal.

$$\theta_2 = -(M_2/EI)\,x \qquad (0 \leqq x \leqq l) \qquad (5)$$

As $\theta_1 + \theta_2 = 0$ at $x = l$ for the original deflected configuration shown in Fig. 3(a), the relation between M_1 and M_2 may be written as

$$M_2 = (l_1/l)M_1 \qquad (6)$$

Accordingly, θ_2 is as follows:

$$\theta_2 = -(M_1/EI)\,(l_1/l)\,x \qquad (7)$$

For such a case where moments M_1 and M_2 act simultaneously as in Fig. 3(a), an equation is derived from Eqs. (3) and (7) for the slope δ_0 at $x = l_1$, where M_1 acts.

$$\delta_0 = (M_1 l_1/EI)\,(1 - l_1/l) \qquad (8)$$

When equivalent bending moment M_1 which causes the welding angular distortion acts, the slope at $x = l_1$ differs between the following two cases; in one case the end is free and in the other case restraint is imposed to the end so as to satisfy the symmetry condition. They are expressed by Eq. (4) and Eq. (8) respectively. The ratio between these slopes is then defined as the angular distortion restraint coefficient K_δ; that is,

$$K_\delta = \delta_0/\delta_f = (1 - l_1/l) \qquad (9)$$

Equation (9) is a function of l_1 which specifies the acting position of M_1. This l_1 will be estimated next. **Figure 4** depicts the distribution of bending moment of the beam shown in Fig. 3(a). It is seen from Fig. 4 that $x = l_1$ is an inflection point of deflection. Taking this into account, l_1 is estimated based on the result of thermal elastic- plastic analysis. Having analyzed several beams with different beam length l and different welding conditions, the resulting respective deformations are investigated in detail, and it is known that the acting position of M_1, that is l_1, is near the toe of weld metal; that is,

$$l_1 = (t_s/2) + f \qquad (10)$$

where, t_s: plate thickness of a stiffener, f: leg length

Consequently, the angular distortion restraint coefficient K_δ and angular distortion δ_0 at the toe of weld of T-joint under restraint may be expressed as follows:

$$K_\delta = 1 - (t_s + 2f)\,/\,(2l) \qquad (11)$$

$$\delta_0 = K_\delta \cdot \delta_f \ \text{(rad)} \qquad (12)$$

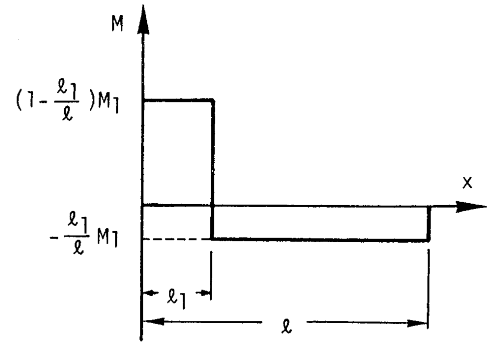


Fig. 4 Distribution of moment in the beam.

2.3 Welding initial deflection of a rectangular plate stiffened on one side

On the basis of angular distortion due to fillet welding of T-joint under restraint mentioned in Section 2.2, initial deflection due to welding angular distortion of a rectangular plate surrounded by one-sided stiffeners is estimated. The estimating formula is derived using the principle of virtual work.

(1) Procedure of analysis

The following procedures are taken to estimate initial deflection due to angular distortion which is produced when longitudinal and transverse stiffeners are welded to a rectangular plate.

(i) A rectangular plate with length a and breadth b as shown in **Fig. 5(a)** is to be analyzed. As the boundary condition, it is assumed that the plate is simply supported and the edges of the plate are kept straight. First, deformation of the plate is considered when the length is long enough in comparison to the breadth (**Fig. 5(b)**). Imposing uniform bending moment M_x along the longer edges, M_{ox} is defined as such M_x that makes the slope at the acting point of moment in the middle of the long edge ($x = a_l/2$, $y = 0, b$) equal to angular distortion δ_{ox} under restraint, which is expressed by Eq. (12). Now, it is considered that this moment M_{ox} is induced along the longer edges of the rectangular plate due to fillet welding of longitudinal stiffeners.

(ii) Similarly, moment M_{oy} due to welding of transverse stiffeners may be calculated.

(iii) Maximum welding initial deflection $w_{o\,max}$ of the plate shown in Fig. 5(a) is calculated, which is produced in the middle of the plate by the actions of moments M_{ox} and M_{oy} obtained in the above procedures (i) and (ii) respectively.

(2) Assumed shape of initial deflection and its maximum initial deflection

When uniform bending moment acts along the long edge of a sufficiently long plate shown in Fig. 5(b), the shape of deflection in y-direction in the middle portion ($x = a_l/2$) becomes parabolic. On the basis of this fact, the shape of initial deflection is assumed as follows:

$$w_o = (\sum_m A_m \sin \frac{m\pi x}{a})(y^2 - by)(-\frac{4}{b^2}) \qquad (13)$$

For this initial deflection, M_{ox}, M_{oy} and $w_{o\,max}$ are calculated consecutively by respective procedures described in (1). In this study, the principle of virtual work (virtual displacements δA_m ($m = 1, 2, 3, ...$)) is applied. Therefore, the maximum initial deflection $w_{o\,max}$ produced in the middle of the rectangular plate may be expressed as follows:

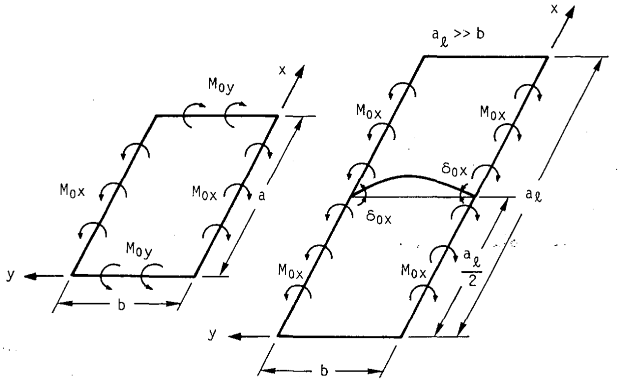


Fig. 5 Prediction of deflection of panel due to welding for long. and trans. stiffeners.

$$w_{o\,max} = \sum_m \left\{ (-1)^{(m-1)/2} \frac{\frac{2b}{\pi m}\delta_{ox} + \frac{2\pi b^4}{15a^3} m\,\delta_{oy}}{\frac{\pi^4 b^4}{60a^4} m^4 + \frac{\pi^2 b^2}{3a^2} m^2 + 2} \right\} \qquad (14)$$

(provided m takes only odd numbers)

where,

$$\delta_{ox} = K_{\delta x} \cdot \delta_f = \{ 1 - (t_s + 2f)/b \} \delta_f$$

$$\delta_{oy} = K_{\delta y} \cdot \delta_f = \{ 1 - (t_s + 2f)/a \} \delta_f$$

If welding condition, the kind of steel and plate size are specified, the maximum deflection $w_{o\,max}$ produced in the rectangular plate can be estimated by substituting δ_f obtained by Eq. (1) (or (2)) into Eq. (14).

Deflection caused by angular distortion due to fillet welding has thus been estimated. Yet, actually, shrinkage of weld metal along the weld line produces additional deflection to it. In cases of deck plates of a ship, however, the additional deflection is usually so small that only the deflection due to angular distortion shown by Eq. (14) may be enough for consideration. The magnitudes of these two kinds of deflections will be compared in Chapter 4, using actual deck plates.

Equation (14) converges well when calculated to the 11th term ($m = 21$), and only about 1% error is observed to the 6th term ($m = 11$).

3. Simple Estimation Method for Welding Residual Stress

When longitudinal compressive ultimate strength of a deck plate panel is evaluated, the influence of residual stress should be taken into account. Longitudinal residual stress is produced by fillet welding of a deck plate and longitudinal stiffeners, and this is considered to influence the strength much more than other components of welding residual stresses. Accordingly, only this longitudinal component σ_w is treated in the following (see **Fig. 6**)[13].

(i) As for longitudinal welding residual stresses distributed in the breadth direction of a panel (in y-direction), it is assumed that the pattern of distribution of both tensile stress near the weld zone and compressive one in the central portion of the panel is rectangular and the residual stresses are self-equilibrating (the result of thermal elastic-plastic analysis considering the effect of stiffeners has proven that this assumption is mostly applicable to deck plates and the like which are constrained greatly against in-plane deformation).

(ii) When multi-pass welding is applied to fillet weld, stresses produced by laying the pass with maximum heat input (ΔQ_{max}) become dominant residual stresses. In reference to some actual distributions, the breadth b_t of tensile residual stress distribution may be given as follows:

$$b_t = (t_s/2) + 6.19 \times 10^{-2} \times \Delta Q_{max}/(t_s + 2t) \quad (15)$$

where,

t_s: plate thickness of longitudinal stiffener (mm), t: plate thickness of a panel (mm), ΔQ_{max}: maximum heat input per pass (J/cm)

(iii) The magnitude of tensile residual stress, $\sigma_{w\ max}$, is equal to the yield stress σ_Y in deck plates of the conventional materials, though it is considered that tensile stress hardly reaches yield stress due to phase transformation expansion at the cooling stage in SM58 and HT80 of the materials mentioned in Section 2.1. Accordingly, the magnitude of tensile residual stress in respective material is assumed as follows on the basis of the study by Satoh et al.[14].

$$\sigma_{w\ max}\ (SM41) = \sigma_Y\ (SM41) \times 1.0$$
$$\sigma_{w\ max}\ (SM50) = \sigma_Y\ (SM50) \times 1.0$$
$$\sigma_{w\ max}\ (SM53) = \sigma_Y\ (SM53) \times 1.0$$
$$\sigma_{w\ max}\ (SM58) = \sigma_Y\ (SM58) \times 0.8$$
$$\sigma_{w\ max}\ (HT80) = \sigma_Y\ (HT80) \times 0.55 \quad (16)$$

(iv) Compressive residual stress directly influences the compressive ultimate strength and its breadth and magnitude can be obtained by so using those of the above mentioned tensile stress as to satisfy an equilibrium condition.

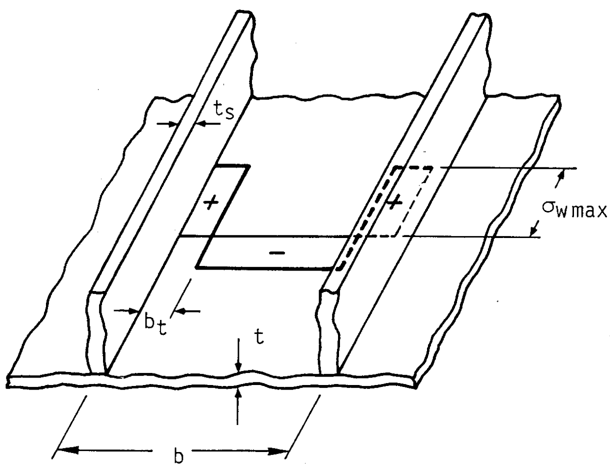


Fig. 6 Distribution of residual stresses due to welding of longitudinal stiffeners.

4. Applicability of the Simple Estimation Method

In the previous chapters, the simple estimation methods for initial imperfections due to fillet weld joining longitudinal and transverse stiffeners to a rectangular plate has been presented based on the result of study on deck plate panels in a ship hull. In this chapter, applicability of the method is discussed. The estimating equations for residual stress are expanded ones from those shown in Ref. 13 so as to apply to HT plates. Then, the accuracy of the equations will not be examined here since they are reliable. Investigation is made into the accuracy of the estimating equations for initial deflection. First, for actual mild steel deck plate panels, initial deflections calculated by the equations are compared with the observed ones. Then, this estimating method is applied to HT deck plate panels, too.

4.1 Applicability to mild steel deck plate panels

First, deck plate panels of mild steel with 28 kgf/mm^2 yield stress will be analyzed.

The authors, formerly, observed initial deflections on 21 panels of 4 kinds in a 60,000 ton Bulk Carrier (hereinafter called B.C.) and 12 panels of 2 kinds in a Pure Car Carrier for 5,500 cars load (hereinafter P.C.C.)[8)–10)]. The plate thicknesses were 15, 19 and 34.5 mm in B.C. and 8 and 11 mm in P.C.C.. Among these, the 8 mm thick panels of P.C.C. seemed to have been subjected to straightening, and therefore are not discussed here. The sizes and welding conditions of the panels treated in this Chapter are indicated in **Table 2.**

Using the estimation method shown in Chapter 2, welding initial deflection of the above mentioned panels of five different sizes are obtained. As is seen from the welding conditions indicated in Table 2, the voltage varies a great deal among respective panels, so that the average values of voltage and current are used for estimation of initial deflection. As for B.C., the welding conditions are corrected in the way that heat input corresponds to the length of legs because the 15 mm thick panel has short legs different from other three kinds of panels. As for the constants in the equations for estimation of angular distortion, those of SM 41 by auto-con welding (similar to gravity welding), indicated in Table 1, are used. As a result, maximum initial deflection $w_{o\ max}$ is obtained for respective five kinds of panels.

Thus estimated are the initial deflection due to angular distortion. When they are compared with the observed values, additional deflection Δw_o by the longitudinal shrinkage of weld metal should be included in them as mentioned in Chapter 2. The additional deflection may be obtained by elastic large-deflection analysis, which proves that Δw_o is extremely small compared with $w_{o\ max}$ due to angular distortion; that is, Δw_o is 0.6% of $w_{o\ max}$ in 34.5 mm thick plates and 4% in 11 mm thin plates. Accordingly, it is needless to consider added deflection due to production of residual stresses, which counts little as far as the similar panel sizes and welding conditions are used. Whereas, the above observed values of maximum

Table 2 Sizes of deck panels and stiffeners, and welding conditions.

Kind of Ship	Sizes of Panels and Stiffeners: Panel a × b × t (mm)	Sizes of Panels and Stiffeners: Long. Stiffener h × t_s (mm)	Number of Deflection-Measured Panels	Conditions of Welding: Current (A)	Conditions of Welding: Voltage (V)	Conditions of Welding: Velocity (cm/min)	Leg Length (mm)
Bulk Carrier	2400×800×34.5	400 × 35	12	290 ∼ 300	24 ∼ 46	15	8
	2100×800×19	300 × 28	3				8
	2800×800×19	300 × 29	3				8
	2800×800×15	250 × 19	3				6
Pure Car Carrier	3440×780×11	200×90×9/14 I.A.	6	200 ∿ 250	24 ∿ 46	15	5

initial deflection scatter more or less, so that their mean values and standard deviation values are put to comparison. The estimates of the maximum initial deflection due to only angular distortion and the observed values are compared as shown in **Fig. 7** which proves that the estimation method is highly accurate.

In accordance with the results of researches done by the authors, the shape of initial deflection is idealized so as to define the standard initial deflection as shown in **Fig. 8**[8)–10)]. This shape along the longitudinal center line, is flat in the middle portion and a half of the half-wave of the buckling mode in the vicinities of the both ends, making the maximum initial deflection $w_{o\,max}$ identical. Moreover, one half-wave of sinusoidal-curve is assumed for the deflection in the breadth direction. Thus presented standard initial deflection may be expressed as follows with respect to the longitudinal center line (y = b/2):

Predicted maximum deflection $w_{0\,max}$ (SM53) (mm)

a × b × t	2400 × 800 × 34.5	2100 × 800 × 19	2800 × 800 × 19	2800 × 800 × 15	3440 × 780 × 11
$w_{0\,max}$	0.69	2.44	2.54	2.80	4.59

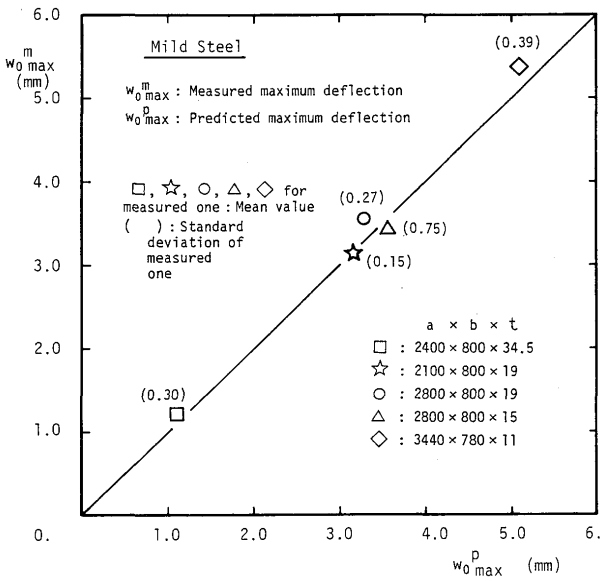
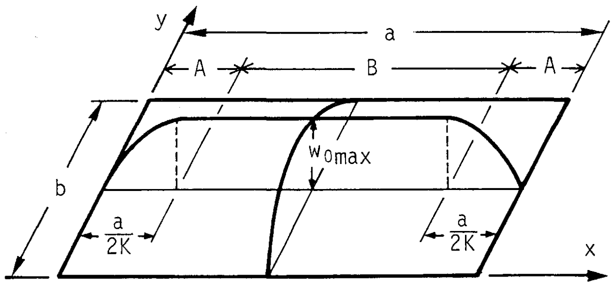


Fig. 7 Comparison between predicted maximum initial deflection and measured ones.

$$w_o = \begin{cases} w_{o\,max}\left|\sin\frac{K\pi x}{a}\right| & (0 \leqq x \leqq \frac{a}{2K},\ \frac{2K-1}{2K}a \leqq x \leqq a) \\ w_{o\,max} & (\frac{a}{2K} \leqq x \leqq \frac{2K-1}{2K}a) \end{cases} \tag{17}$$

where, a: length of panel, $w_{o\,max}$: magnitude of maximum initial deflection, K: the number of half-waves of buckling mode

The initial deflection, which is formed as standard initial deflection and has maximum value $w_{o\,max}$ calculated by the estimation method, is compared with the observed deflection along the longitudinal center line. The result is shown in **Fig. 9**. As for the panels of 11 and 34.5 mm in thickness, initial deflection has been measured on six and twelve panels respectively. Three results are arbitrarily chosen respectively. The estimated deflections show a good coincidence with the observed ones.



Standard initial deflection

$$w_0 = \begin{cases} w_{0max}\left|\sin\frac{K\pi x}{a}\right|\sin\frac{\pi y}{b} & \text{(in A)} \\ w_{0max}\sin\frac{\pi y}{b} & \text{(in B)} \end{cases}$$

Fig. 8 Idealized standard initial deflection.

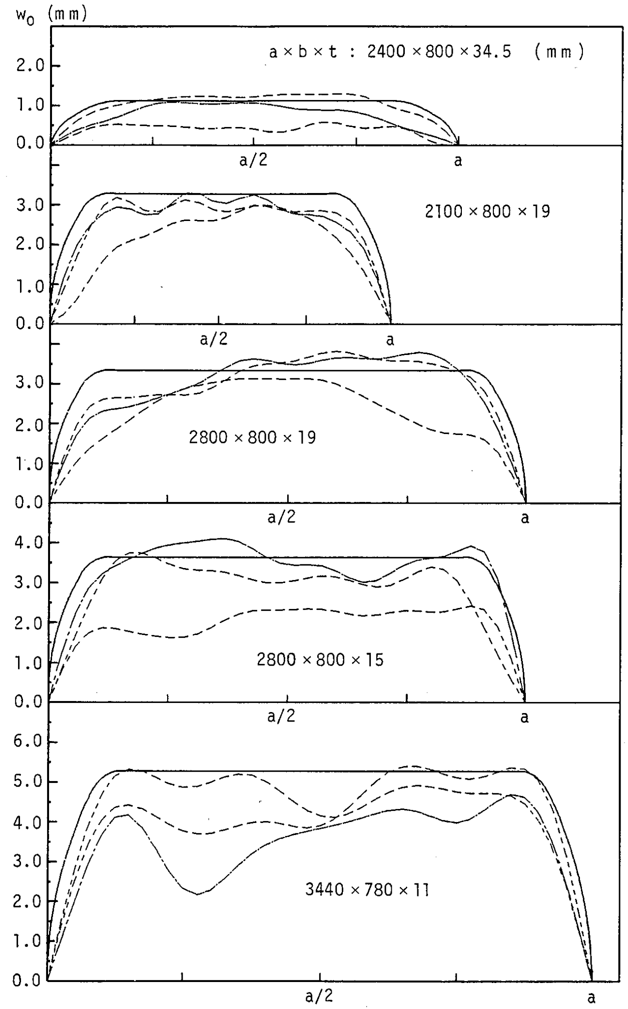


Fig. 9 Comparison between initial deflection of predicted one and measured oens.

4.2 Applicability to HT steel deck plate panels

On the assumption that the size of deck plates and the welding conditions of stiffeners are the same as the mild steel mentioned in the previous section, initial deflections of deck plates of HT steel (SM 53) with the yield stress 41 kgf/mm^2 are calculated.

Maximum initial deflections $w_{o\,max}$ of five kinds of HT panels, estimated by the method presented in this report, are shown in Fig. 7. Used in this estimation are the constants m, c_1 and c_2 shown in Table 1 for the case of auto-con welding of SM53 steel. Only the estimated values are shown since there is no measured results of deck plates of SM 53 steel. Thus estimated welding initial deflection of deck plates of SM 53 steel compares smaller than those of mild steel plates. The deflection is approximately 90% in thin plates and 60% in thick plates.

5. Conclusions

Presented in this study on deck plate panels of a ship's hull is an accurate method to estimate welding initial imperfections (initial deflection and residual stress) as simply as by hand calculation.

The main results are as follows:

(1) When longitudinal and transverse stiffeners are welded to a deck plate of a ship's hull, welding initial deflection and residual stress are produced in a panel surrounded by them. For such welding initial deflection and residual stress, simple and accurate estimating equations using only the sizes of the panel and stiffeners and welding conditions are presented (Eqs. (1) (or (2)) and (14) for initial deflection and Eq. (15) for residual stress).

(2) Using mild steel and HT steel deck plate panels, welding initial deflection was estimated by the above mentioned method. The estimate was compared with the measured value, and very good accuracy of the method was proved.

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