Buckling/Plastic Collapse Strength of Wide Rectangular Plate under Combined Pressure and Thrust

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Summary

A series of elastic/elastoplastic large deflection analyses is performed to clarify buckling/plastic collapse behaviour of a wide rectangular plate as a part of ship bottom plating subjected to combined lateral pressure and transverse thrust. A continuous plating with and without stiffeners is analysed to examine the influences of plate continuity and stiffeners on its buckling/plastic collapse behaviour.

Firstly, influence of loading sequence of pressure and thrust loads is examined. The difference between the results of analysis using double bay and triple bay models is also examined for the case of stiffened plate with angle-bar stiffeners.

Then, based on the results of elastic large deflection analyses, a semi-empirical formula is derived to evaluate the elastic buckling strength of a wide rectangular plate subjected to combined lateral pressure and transverse thrust considering the influence of plate continuity and stiffeners.

At the end, the influences of pattern and magnitude of initial deflection as well as stiffeners on the ultimate strength of a wide rectangular plate are discussed through elastoplastic large deflection analyses on continuous plating with and without stiffeners.

1. Introduction

When the buckling and ultimate strength of a ship bottom plating is considered, the minimum structural unit is a rectangular plate surrounded by longitudinal stiffeners and transverse frames. This rectangular plate is subjected to lateral pressure and bi-axial thrust in general.

In large ships, lateral pressure and transverse thrust become large for bottom plating of empty tanks/holds under deeper draft condition. On the other hand, thickness of ship plating is getting decreased owing to the wide use of HT steel. However, the spacing between bottom longitudinals cannot be reduced so much from the fabrication aspects, and that between transverse frames is also unchanged in general.

These factors make it necessary to give a special attention to the buckling strength when transverse thrust is dominant. Here, it was found in Refs. 1) and 2) that the buckling/plastic collapse behaviour is almost the same when the longitudinal/transverse stress ratio is roughly below 3/2. From this point of view, the attention is focused on the combination of lateral pressure and transverse thrust in the present paper.

Some research works can be seen on the buckling/ultimate strength of wide rectangular plates, but most of them are dealing with a single plate. According to Refs. 1) and 2), the interaction between adjacent panels and influence of stiffeners cannot be ignored when the buckling of ship bottom plating is considered.

In the present paper, buckling/plastic collapse strength of a wide rectangular plate as a part of ship bottom plating is discussed considering a continuous plating with and without stiffeners subjected to combined lateral pressure and transverse thrust.

At the beginning, the influence of loading sequence on buckling/plastic collapse behaviour is discussed when combined loads of lateral pressure and thrust are working. Differences between double bay and triple bay models used for the analysis of continuous stiffened plating with angle-bar stiffeners are also discussed.

Then, based on the results of elastic large deflection analysis on a continuous plating with and without stiffeners, a simple formula is derived to evaluate elastic buckling strength of a rectangular plate as a part of the continuous plating considering the influences of lateral pressure and stiffeners. A series of elastoplastic large deflection analyses is also performed on continu-

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ous plating with and without stiffeners, and the influences of the pattern and the magnitude of initial deflection on the ultimate strength are discussed. The obtained ultimate strength is compared with that for simply supported plates, and the influences of lateral pressure and stiffeners on the ultimate strength are also discussed. At the end, the rationality of the ultimate strength formula by DNV is examined.

2. Model for Analysis

A ship bottom plating can be regarded as continuous stiffened plating with equally spaced longitudinal stiffeners of the same size. Such stiffened plating can be modelled fundamentally as a double span-double bay model as indicated in Fig. 1. In the present paper, buckling/plastic collapse behaviour of a rectangular plate is investigated considering such a double span model with and without a stiffener.

Along the four sides of the model, symmetry condition is imposed. The transverse member is not modelled, but the deflection in z direction is constrained along the transverse member. This model is used for elastic and elastoplastic large deflection analyses. For the analysis to separately examine the influence of lateral pressure alone on buckling and ultimate strength, a continuous plating without stiffeners is analysed assuming that the plate is simply supported along the stiffener lines.

Dimensions of the fundamental models are indicated

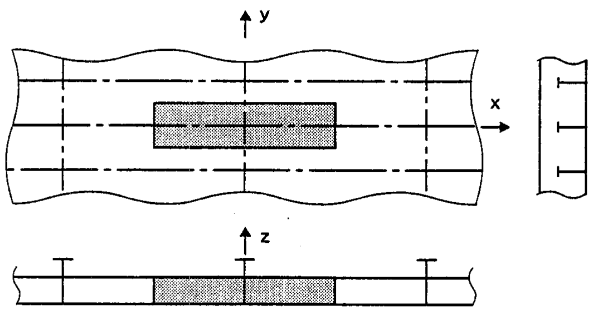


Fig. 1 Double span-double bay model

in Table 1. These models represent the bottom plating of existing ships. However, analyses are performed changing the thicknesses of the panels systematically so as to simulate various collapse behaviours which depend on the slenderness of the panel.

The applied lateral pressure ranges between 0 and 60 metres water head for the elastic large deflection analysis, and between 0 and 30 metres for the elastoplastic large deflection analysis.

Initial deflection of a hungry horse mode is assumed in the panel and an Eulerian buckling mode in the stiffener. Then, initial deflection in a stiffened plating can be expressed as:

$$w_0=\alpha_1\left|B_0 \sin\frac{\pi x}{a}\right|+\alpha_2\left|\sum_m A_{0m} \sin\frac{m\pi x}{a}\sin\frac{\pi y}{b}\right| \quad (1)$$

The origin of the coordinate system is indicated in Fig. 1. Equation (1) implies that initial deflection is in the same direction in all the panels and the stiffeners. The first term corresponds to the Eulerian buckling mode of the stiffener as a column. The magnitude of initial deflection of this mode is taken as $B_0/t=0.01$. The second term represents the initial deflection of a hungry horse mode in the panel. The coefficients, A_{0m}, are given in Table 2 when the maximum magnitude of initial deflection in the panel is 1% of the panel thickness. These coefficients comprises only the odd terms, which results in a hungry horse mode.

In the actual structures, magnitude of initial deflection changes panel by panel and stiffener by stiffener. Figure 2 shows distribution of measured maximum initial deflection on the deck of a Bulk Carrier[3]. Although no regularity can be observed in the measured results, four fundamental patterns are assumed for α_2 as indicated in Fig. 3. As for α_1, no measured data is available, and is assumed to be 1.01 and 1.02 at the adjacent spans. It should be noticed that it is important to change α_1 and α_2 in the adjacent spans or panels to get stable solution in the numerical analysis of buckling behaviour.

The magnitude of maximum initial deflection in local panels is calculated by the following equation:

$$w_{0max}/t=\eta(b/t\sqrt{\sigma_Y/E})^2 \quad (2)$$

Equation (2) was proposed by Smith et. al.,[4] and as for

Table 1 Stiffened plating for analysis

Type of ship	Panel ($a \times b \times t$)	Stiffeners	Yielding stress
Bulk Carrier	2,400 × 800 × 13.5 mm	250 × 90 × 9/15 mm (angle-bar)	313.6 MPa
VLCC	4,200 × 840 × 19.0 mm	625 × 14 + 200 × 30 mm (tee-bar)	352.8 MPa

Table 2 Coefficients of deflection components in initial deflection

Type of ship	A_{01}/t	A_{03}/t	A_{05}/t	A_{07}/t	A_{09}/t	A_{011}/t
Bulk Carrier	0.012358	0.003321	0.001236	0.0003527	0.0	-0.0000798
VLCC	0.012924	0.004152	0.002049	0.001142	0.000617	0.0002935

0.492	0.457
0.343	0.457
0.457	0.429
0.657	0.371
1.114	1.029
0.886	1.286
1.000	0.943
1.800	0.743

0.914	1.000
0.771	1.029
0.429	0.514
0.543	0.571
1.114	1.029
1.000	0.943
0.629	0.686
0.657	0.486
0.714	0.571

(in mm)

Fig. 2 Measured distribution of maximum initial deflection in deck plate

1.00	1.02
1.01	1.03

Type (a)

1.00	0.90
0.90	1.00

Type(b)

1.00	0.80
0.80	1.00

Type (c)

1.00	0.60
0.60	1.00

Type (d)

Fig. 3 Assumed distribution of initial deflection

η, three values, 0.025, 0.1 and 0.3, were suggested for slight, average and severe initial deflection based on statistical treatments on the measured results. In the present paper, η is taken as 0.025, 0.05 and 0.1 based on our measured results[3),5)].

All the members are modelled by shell elements, and the computer code"ULSAS"is used both for elastic and elastoplastic large deflection analyses. The pressure load is applied always perpendicularly to the panel surface. Thrust load is applied by forced displacement. For the analysis of elastic buckling behaviour, the Arc Length Method is applied.

3. Loading Condition and Boundary Condition for Analysis

3.1 Influence of loading sequence

When structural members are subjected to combined loads, the loading sequence may affect their buckling and/or plastic collapse behaviour. As for the combined inplane loads, however, it was concluded that the buckling strength interaction relationship is almost the same regardless of the loading sequence, and so are the ultimate strength interaction relationships[6)]. In the present paper, for the combination of lateral pressure and thrust, the influence of loading sequence on the elastic as well as elastoplastic buckling collapse behaviours is investigated.

Firstly, elastic large deflection analysis is performed on a continuous plating of a Bulk Carrier assuming the four cases of loading sequences indicated in Table 3. The initial deflection of Type (a) is assumed in the panel setting the maximum magnitude as 1% of the panel thickness. In Case 1, the lateral pressure is applied up to 30 metres water head, followed by the thrust. In Cases 2, 3 and 4, lateral pressure and thrust are applied simultaneously until the lateral pressure reaches 30 metres water head changing the ratio of thrust load to pressure load. Then, only the thrust load is applied.

The obtained average stress-deflection relationships are compared in Fig. 4. The average stress is non-dimensionalised by the buckling stress, σ_{cr}^{s}, under simply supported condition, and the deflection by panel thickness. The deflections are taken at the centres of the adjacent panels. In Case 2, the pressure loading ends at stress level a after the occurrence of buckling. On the other hand, in Cases 3 and 4, the pressure loading ends at stress levels b and c, respectively, before buckling takes place. It should be noticed that the loading sequence does not affect the elastic large deflection behaviour after the pressure load has been reached to the specified level.

Figure 5 shows the results of elastoplastic large deflection analysis on continuous stiffened plating of a Bulk Carrier with loading sequences of Cases 5, 6 and 7 in Table 3. Also for this analysis, initial deflection of Type (a) is assumed. In Case 5, yielding starts during the pressure loading before thrust is applied. In Case 6, the pressure loading ends at stress level a after the maximum thrust load is attained. Beyond the level a, the behaviour is almost the same with that of Case 5, and the second load peak appears. Similar behaviour is observed in Case 7, but the pressure loading ends before the maximum load is attained. Although the behaviour after the pressure loading has been ended is almost the same among the three cases, some differences are observed. This is because of the different plastic deformations accumulated through different strain histories.

Similar calculations are performed on other cases, and larger differences are observed in some cases in the behaviour depending on the different yielding states. However, the ultimate strength does not differ so much in all the cases as indicated in Fig. 5.

From the results indicated here, it can be concluded that the calculated ultimate strength is not so much affected by the loading sequence when a continuous plating with and without stiffeners is subjected to combined lateral pressure and thrust. Hereafter, thrust load is applied after lateral pressure load has been applied up to the specified level.

3.2 Consideration on boundary condition

When the collapse analysis is performed on continuous stiffened plating under thrust, a double bay-double span model in Fig. 1 is usually used. In this case, symmetry conditions are imposed along the four sides of the model. This model gives exact results as far as the stiffener has a symmetrical cross section such as a flat-bar or a tee-bar.

However, for stiffened plating with angle-bar stiffeners, a double bay-double span model in Fig. 1 can be used only when angle-bar stiffeners are placed as indicated in Fig. 6(a). In this case, the slope at the

Table 3 Assumed loading sequences

Case No.	First stage	Second stage	Analysis
1	w.p. up to 30 m w.h.	thrust	elastic
2	thrust with Δu = 0.025 mm + w.p. up to 30 m w.h.	thrust	elastic
3	thrust with Δu = 0.0125 mm + w.p. up to 30 m w.h.	thrust	elastic
4	thrust with Δu = 0.00625 mm + w.p. up to 30 m w.h.	thrust	elastic
5	w.p. up to 30 m w.h.	thrust	elastoplastic
6	thrust with Δu = 0.0125 mm + w.p. up to 30 m w.h.	thrust	elastoplastic
7	thrust with Δu = 0.00625 mm + w.p. up to 30 m w.h.	thrust	elastoplastic

Δu: applied inplane displacement increment for thrust
w.p.: applied water pressure with increment of water head, Δh = 0.5 m
w.h.: water head

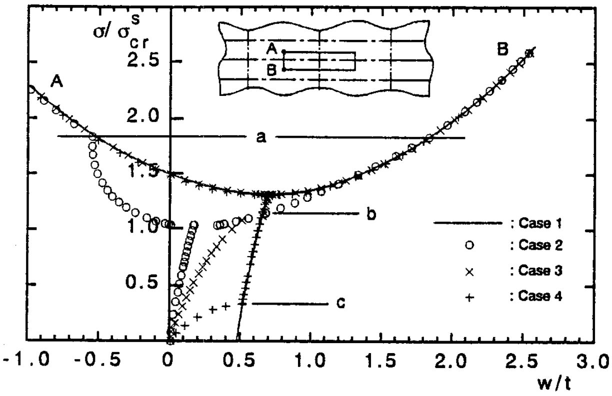


Fig. 4 Influence of loading sequence on elastic large deflection behaviour

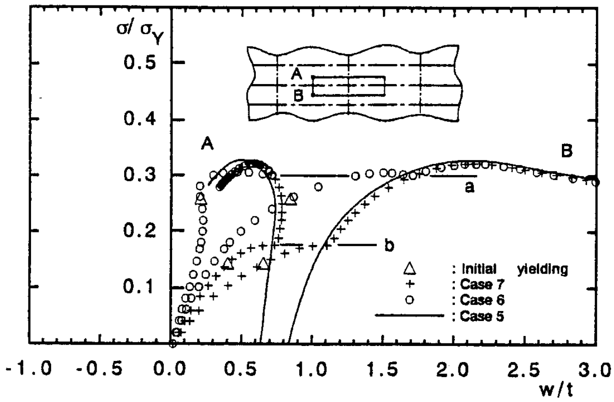
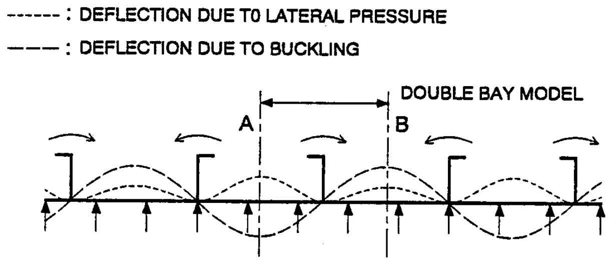


Fig. 5 Influence of loading sequence on elastoplastic large deflection behaviour

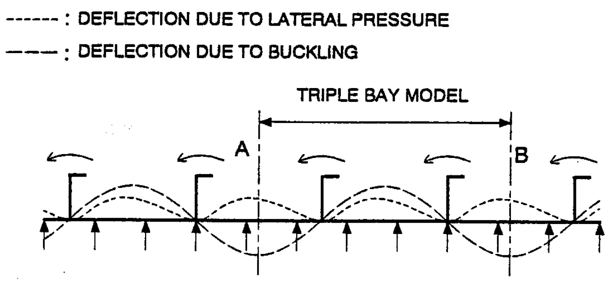
locations A and B can be set as zero introducing the symmetry condition. In general, however, angle-bar stiffeners are placed as indicated in Fig. 6(b). For this case, periodical condition has to be introduced, that is, the deflection and the slope at the locations A and B are set as the same, respectively. This is because angle-bar stiffeners tend to rotate to their backward direction under lateral pressure indicated in Fig. 6. Consequently, the deflection modes in both the models differ each other as illustrated by the dashed lines in Figs. 6(a) and (b). On the other hand, the buckling mode under thrust can be represented by the broken lines, which is the same for both the models.

As far as the elastic local buckling strength under inplane load is concerned, both models give the same buckling strength. However, when lateral load is working simultaneously, different behaviour appears.

Elastoplastic large deflection analysis is performed with double bay and triple bay models, respectively, assuming the initial deflection of Type (a). Average stress-deflection relationships obtained by double bay and triple bay models are compared in Figs. 7(a) and (b). When only the thrust load is applied, buckling behaviour is almost the same in both cases, and so is the collapse behaviour as indicated in Fig. 7 (a). Contrary to this, when a pressure load of 30 metres water head is



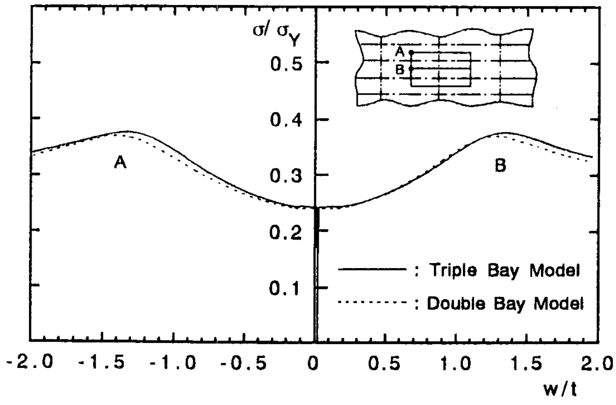
(a) Double bay model



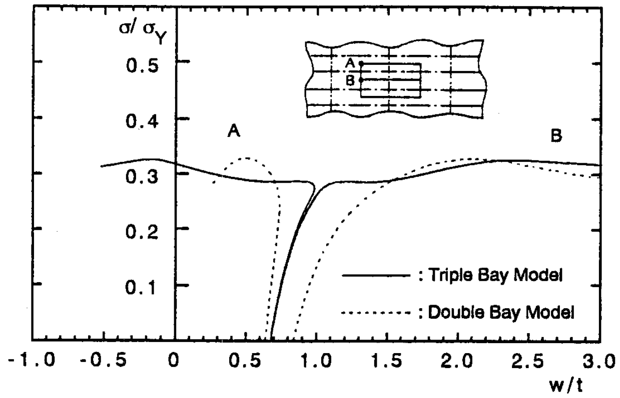
(b) Triple bay model

Fig. 6 Modelling of continuous stiffened plating with angle-bar stiffeners

applied before thrust loading, the deflection mode by the pressure load in double bay and triple bay models differ each other as is known from Fig. 6(b). That is, the



(a) Without lateral pressure



(b) With lateral pressure of 30 metres water head

Fig. 7 Comparison of elastoplastic large deflection behaviour between double bay and triple bay models

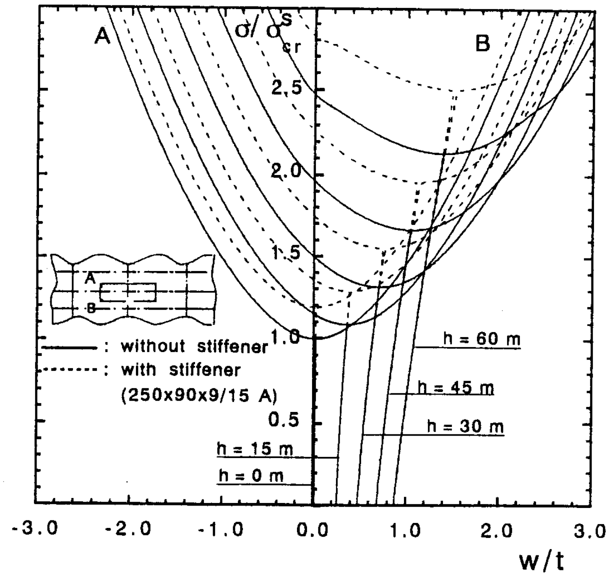
deflections in the adjacent panels differ each other. This is the reason why the deflections start to grow from different points on the horizontal axis when the thrust load is applied after pressure loading. However, both models give almost the same ultimate strength.

Another analysis has been performed with a pressure of 15 metres water head. In this case, the ultimate strength by a double bay model is found to be 8% higher than that of a triple bay model. This difference is caused by the difference in deflection mode at collapse and it depends on whether the mode is simply supported or clamped along the line of transverse frame. These are the results of analysis for limited cases, and more cases should be analysed to get general conclusions on the rationality of using a double bay model for stiffened plates with angle-bar stiffeners subjected to combined lateral pressure and thrust. However, when only thrust load is working, the use of a double bay model may be rational.

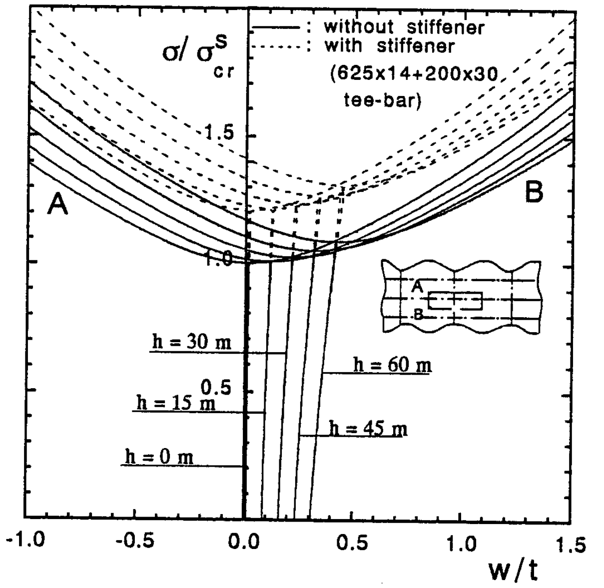
4. Buckling Strength

4.1 Influences of lateral pressure and stiffeners on elastic large deflection behaviour

A series of elastic large deflection analyses has been



(a) Bottom plating of a Bulk Carrier



(b) Bottom Plating of a VLCC

Fig. 8 Elastic large deflection behaviour of continuous plating with and without stiffeners subjected to combined lateral pressure and transverse thrust

performed to investigate into the influences of lateral pressure and stiffeners on elastic local buckling strength of a continuous plating. When the influence of lateral pressure alone is examined, the analysis is performed without stiffeners but assuming the plate to be simply supported along the stiffener lines. The initial deflection of Type (a) is assumed with the magnitude of maximum initial deflection as 1% of the panel thickness. The water head is changed from 0 to 60 metres.

The results of elastic large deflection analysis for the continuous plating with and without stiffeners are shown in Figs. 8(a) and (b) by the solid lines and the dashed lines, respectively. Figure 8(a) is for the bottom plating of an existing handy size Bulk Carrier, and Fig. 8(b) for that of an existing VLCC.

The assumed initial deflection of a hungry horse mode is in the same direction at all the panels, and the deflection of this mode is amplified by the lateral pressure. This deflection mode is different from the buckling mode. This may be the reason why a kind of bifurcation takes place with sudden mode change above the buckling load of a simply supported panel as indicated in Fig. 8. The load at which the deflection of the buckling mode rapidly appears is considered as the buckling load hereafter.

The buckling strength increases with the increase in applied water pressure, since deflection of a clamped mode becomes larger with higher lateral pressure. This increased deflection component of the clamped mode together with the action of pressure which tries to retain this mode delays the occurrence of a simply supported buckling mode under the action of thrust.

As is shown in Table 1, the panel thickness of the Bulk Carrier considered here is much thinner than that of the VLCC. Comparing the solid lines in Fig. 8(a) with those in Fig. 8(b), it is seen that the buckling strength is much increased by lateral pressure when the plate is slender. This is because the deflection produced by the same lateral pressure is larger when the plate is slender-er.

Through the comparison of the dashed lines and the solid lines in Fig. 8, it can be said that the buckling strength is further increased owing to the torsional rigidity of stiffeners.

4.2 Estimation of elastic buckling strength considering combined influences of lateral pressure and stiffeners

4.2.1 Influence of lateral pressure

According to the modal analysis of deflection, the deflection produced by lateral pressure is of a clamped mode, and that by thrust is of a simply supported mode[1]. So, the deflection of a continuous plating under combined lateral pressure and thrust can be represented as:

$$w=\sum_i\sum_j A_{ij}\sin\frac{\pi ix}{a}\sin\frac{\pi jy}{b}+\frac{1}{4}\sum_p\sum_q D_{pq}\left(1-\cos\frac{2\pi px}{a}\right)\left(1-\cos\frac{2\pi qy}{b}\right) \quad (3)$$

When only the terms, A_{11} and D_{11} are considered, the following equations are derived for elastic large deflection analysis.

$$\{\alpha_1\bar{A}_{11}^2+\alpha_2\bar{D}_{11}^2+(1-\sigma/\sigma_{cr}^s)\}\bar{A}_{11}=0 \quad (4)$$

$$\beta_1\bar{D}_{11}^3+\beta_2\bar{A}_{11}^2\bar{D}_{11}+(1-\sigma/\sigma_{cr}^c)\bar{D}_{11}-\beta_3(qb^4/Et^4)=0 \quad (5)$$

where σ and q are the average compressive stress and lateral pressure, respectively, and $\bar{A}_{11}=A_{11}/t$ and $\bar{D}_{11}=D_{11}/t$ are the non-dimensionalised deflection components. σ_{cr}^s and σ_{cr}^c are the buckling stress of a local panel when it is simply supported and clamped, respectively.

Before buckling takes place, $A_{11}=0$ is the solution for Eq. (4), and the relationship between average stress, σ, and deflection of a clamped mode, D_{11}, can be derived from Eq. (5) setting $A_{11}=0$ for the specified lateral pressure, q. With the increase in σ, only D_{11} increases until buckling takes place. At the instance of buckling, the inside of the parenthesis of Eq. (4) becomes zero, and hereafter non-zero A_{11} appears with the increase of σ. Therefore, the buckling stress at the specified level of q is obtained by simultaneously solving Eq. (5) and the equation obtained by setting the inside of parenthesis of Eq. (4) as zero with the condition that $A_{11}=0$.

The accuracy of the buckling strength calculated by Eqs. (4) and (5) is not so good when the lateral pressure becomes high. This is because the deflection produced by the lateral pressure cannot be represented accurately only by one deflection component, D_{11}, under high lateral pressure.

However, from these equations, it can be concluded that the increase in buckling strength due to lateral pressure can be represented in terms of qb^4/Et^4 and a/b, since the coefficients, α_2, β_1 and β_3 are the functions of the aspect ratio of a local panel, a/b.

A series of analyses has been performed changing the combination of these two parameters, and the buckling strength is calculated. Based on the obtained results, the following equation is derived to evaluate the local buckling strength for continuous plating subjected to combined lateral pressure and thrust.

$$\sigma_{cr}^w=\left(1+\frac{(qb^4/Et^4)^{1.75}}{160(a/b)^{0.95}}\right)\sigma_{cr}^s \quad (6)$$

The buckling strength predicted by Eq. (6) is compared with that obtained by the elastic large deflection analysis by the FEM in Figs. 9(a) and (b). It is known that Eq. (6) gives very accurate buckling strength of a wide rectangular plate subjected to combined lateral pressure and thrust.

4.2.2 Influence of stiffeners

An analytical expression of the buckling strength was derived for a continuous stiffened plating considering the interaction between the panel and the stiffeners in Ref. 1). According to this expression, the buckling strength under transverse thrust is expressed as:

$$\sigma_{cr}^t=(\kappa_5-\sqrt{\kappa_5^2-4\kappa_3\kappa_6})/2\kappa_3 \quad (7)$$

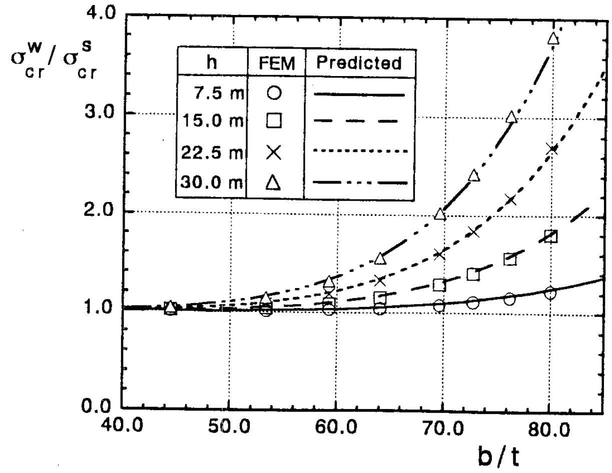
The coefficients, κ_3, κ_5 and κ_6 are given in Ref. 1). The accuracy of Eq. (7) has been confirmed by performing eigenvalue analysis applying the FEM in Refs. 1) and 2).

4.2.3 Combined influence of lateral pressure and stiffeners

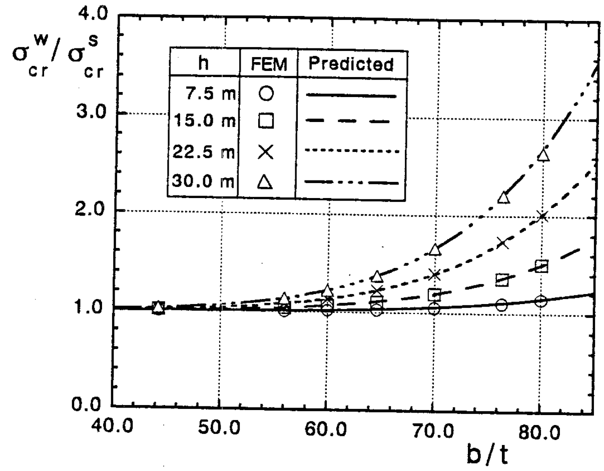
An empirical formula is derived to calculate the local buckling strength of a continuous stiffened plating subjected to combined lateral pressure and transverse thrust as:

$$\sigma_{cr}=\sigma_{cr}^w\times\frac{\sigma_{cr}^t}{\sigma_{cr}^s}=\left(1+\frac{(qb^4/Et^4)^{1.75}}{160(a/b)^{0.95}}\right)\sigma_{cr}^t \quad (8)$$

The buckling strength predicted by Eq. (8) is compared with that obtained by the elastic large deflection



(a) Plate with aspect ratio of 3.0



(b) Plate with aspect ratio of 5.0

Fig. 9 Comparison between predicted and calculated local buckling strength of continuous plating subjected to combined lateral pressure and transverse thrust

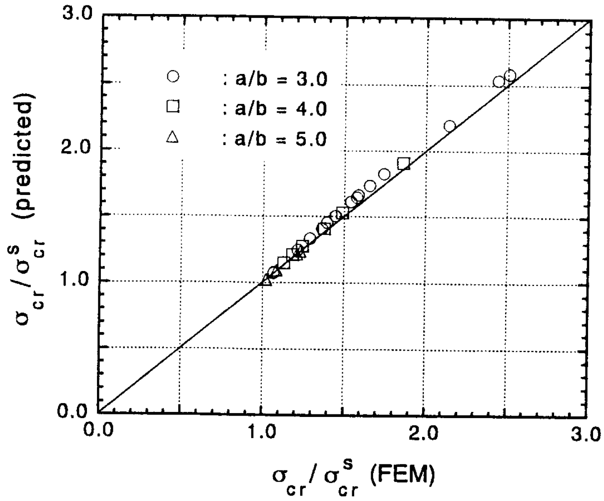


Fig. 10 Comparison between predicted and calculated local buckling strength of continuous stiffened plating subjected to combined lateral pressure and transverse thrust

analysis in Fig. 10.

When the increase of buckling strength is below 30%, the predicted results are very accurate. When it is over 30%, Eq. (8) slightly overestimates the buckling strength. However, ordinary ship bottom structures have scantlings such that the increase in buckling strength is at most 30%. In this sense, it can be concluded that Eq. (8) accurately predicts the local buckling strength of a continuous stiffened plating subjected to combined lateral pressure and transverse thrust.

5. Ultimate Strength

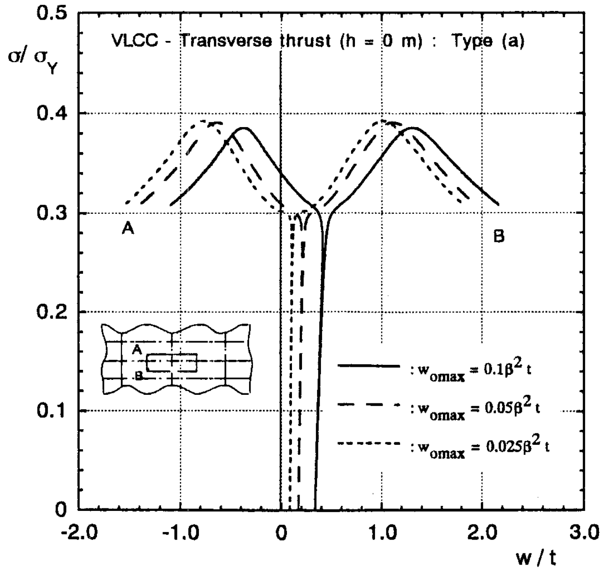
5.1 Ultimate strength of a continuous plating without stiffeners

A series of elastoplastic large deflection analyses has been performed firstly on continuous plating without stiffeners. Three cases are considered as for the magnitude of initial deflection changing η in Eq. (2) as 0.025, 0.05 and 0.1. All the types of initial deflection in Fig. 3 are considered. The average stress-deflection relationships for bottom plating of VLCC are summarised in Figs. 11(a) and (b) when no lateral pressure is working. For the analyses in Figs. 11(a) and (b), initial deflection of Types (a) and (d) are assumed, respectively. Deflections are taken at the centres of adjacent panels.

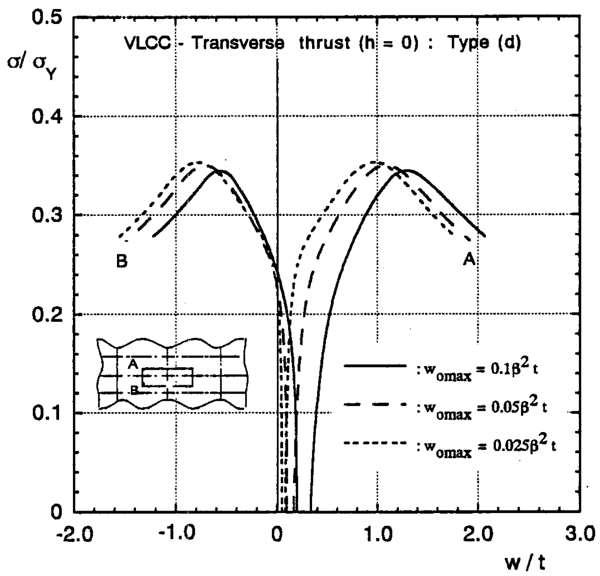
In both cases, the difference in ultimate strength is not so large within the assumed ranges of the magnitude of initial deflection. However, when initial deflection of Type (a) is assumed, deflection of the buckling mode does not grow so much until the average stress reaches near the buckling stress. This is because the magnitudes of initial deflection in four panels are almost the same, and this constrains the growth of deflection of a buckling mode. On the contrary, when initial deflection of Type (d) is assumed, magnitudes of initial deflection in the adjacent panels are different by 40%, and the deflection of a simply supported buckling mode grows from the start of thrust loading. Similar behaviour is observed under combined loads of lateral pressure and thrust.

Figures 12(a) and (b) show average stress-average strain relationships for the bottom plating of VLCC subjected to combined lateral pressure of 30 metres water head and transverse thrust. The parameter, η, representing the magnitude of initial deflection is taken as 0.025 and 0.1 in Figs. 12(a) and (b), respectively. Four types of initial deflection indicated in Fig. 3 are assumed.

When initial deflection is small (η=0.025), the ultimate strength of three cases with initial deflection of Types (b), (c) and (d) is almost the same, while the ultimate strength with initial deflection of Type (a) is about 8% higher than those of the remaining cases. A

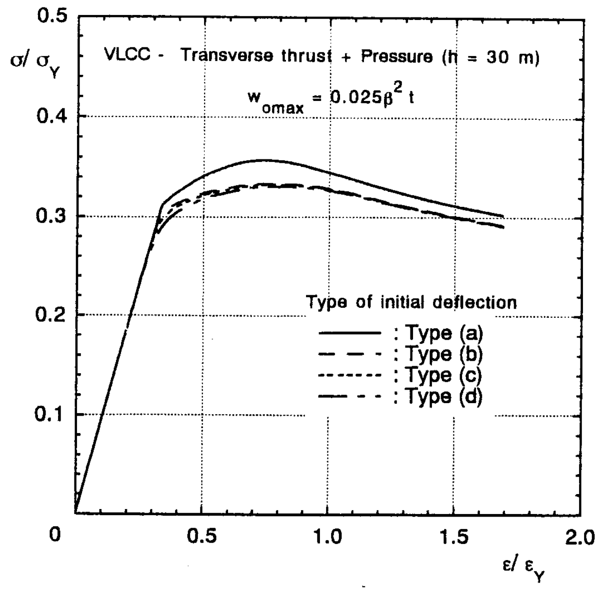


(a) With initial deflection of Type (a)

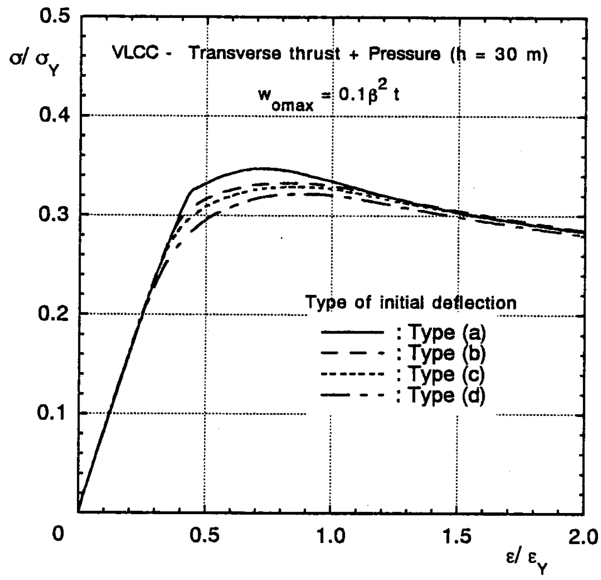


(b) With initial deflection of Type (d)

Fig. 11 Influence of magnitude of initial deflection on elastoplastic behaviour of continuous plating subjected to transverse thrust



(a) With maximum initial deflection of $0.025\beta^2 t$



(b) With maximum initial deflection of $0.1\beta^2 t$

Fig. 12 Influence of pattern of initial deflection on average stress-average strain relationships of continuous plating subjected to combined lateral pressure and transverse thrust

similar tendency is also observed in the ultimate strength with initial deflection of Type (a) when the initial deflection is large ($\eta=0.1$). However, the differences in ultimate strength among other three cases is larger than those for $\eta=0.025$. Similar results are obtained for the cases with different pressure loads including zero pressure.

5.2 Influence of lateral pressure and stiffeners on ultimate strength

A series of analyses is performed also on continuous stiffened plating subjected to combined lateral pressure and transverse thrust as well as on a simply supported plate. The obtained ultimate strength is summarised in Fig. 13 for the case of bottom plating of VLCC with initial deflection of Type (d).

When the plate is simply supported, the ultimate strength considerably decreases with the increase in applied pressure. This is because lateral pressure produces deflection of which the mode is fundamentally the same with the buckling mode. This deflection is accompanied by bending stresses, and plays a role of initial deflection when thrust load is applied. This is the reason for large strength reduction with higher lateral

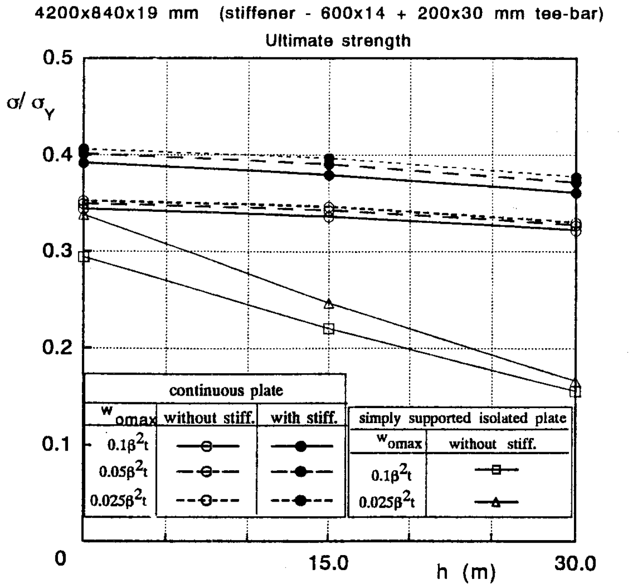


Fig. 13 Comparison of ultimate strength among simply supported plate and continuous plating with and without stiffeners subjected to combined lateral pressure and transverse thrust

pressure in case of a simply supported plate.

In case of continuous plating, the elastic buckling strength increases with lateral pressure as explained in Sec. 4. This may increase the ultimate strength. On the other hand, higher lateral pressure produces higher bending stresses, which may reduce the ultimate strength. Owing to these two factors having opposite influences, the ultimate strength of continuous plating does not decrease so much with lateral pressure.

In case of continuous stiffened plating, the buckling strength is further increased owing to the tortional rigidity of stiffeners, and so is the ultimate strength. The increase of ultimate strength is almost the same as that of buckling strength for the case shown in Fig. 13.

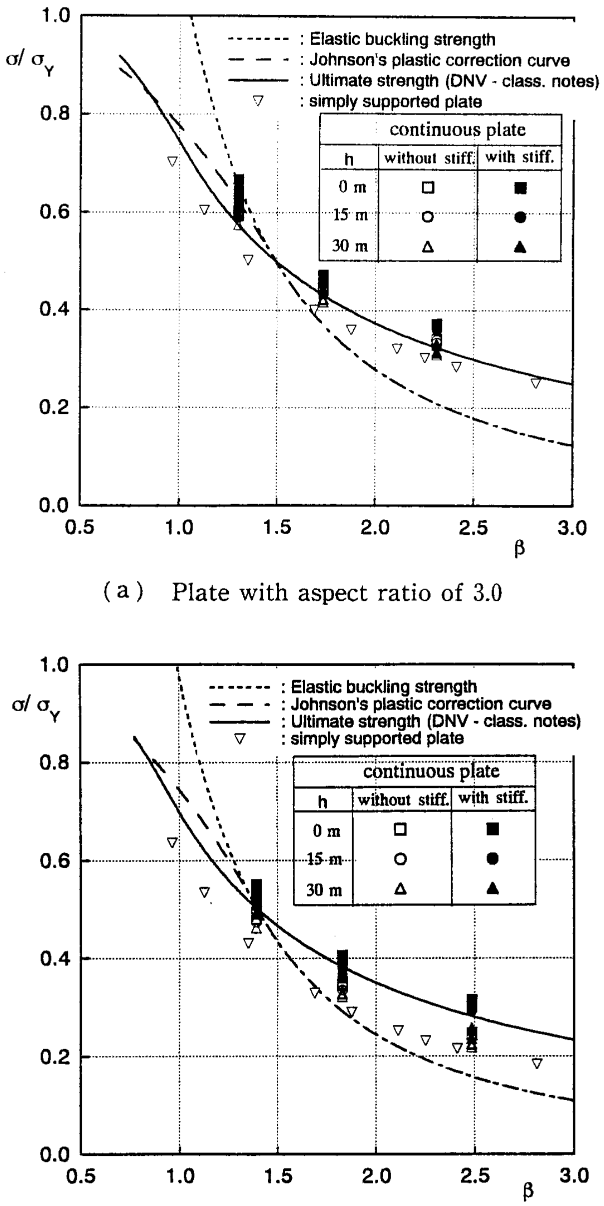
5.3 Assessment of existing design formulae to evaluate ultimate strength

The ultimate strength of continuous plating, of which aspect ratios of local panels are 3.0 and 5.0, are plotted against slenderness ratio of the panel in Figs. 14(a) and (b), respectively. The water head is changed as 0, 15 and 30 metres, and the magnitude of initial deflection as $\eta=0.025$, 0.05 and 0.1. The initial deflection of Type (d) is assumed in the analysis.

The ultimate strength of continuous stiffened plating is also plotted in Figs. 14(a) and (b).

On the other hand, the dashed line represents elastic buckling strength of a simply supported plate, and the broken line plastic buckling strength with Johnson's correction. The solid line is the ultimate strength evaluated by the DNV's formulae[7]. The symbol ▽ represents the ultimate strength of a simply supported plate obtained in Ref. 6) without lateral pressure.

The differences among ultimate strength of simply



(a) Plate with aspect ratio of 3.0

(b) Plate with aspect ratio of 5.0

Fig. 14 Comparison of predicted and calculated ultimate strength

supported plate and continuous plating with and without stiffeners observed in Fig. 13 can be seen also in Fig. 14 for all the ranges of the slenderness ratio.

When the aspect ratio of the local panel is 3.0, the ultimate strength predicted by the DNV's formula lies in the middle of the ultimate strength of continuous plating. When DNV's ultimate strength is compared with that of continuous stiffened plating, it is conservative enough when the plate is thick as shown in Fig. 14(a).

For the case of local aspect ratio being 5.0 shown in Fig. 14(b), the ultimate strength by the DNV's formula is higher than that of a simply supported plate in most cases, but shows average value for the ultimate strength of continuous stiffened plating.

The plastic buckling strength by Johnson's correction gives the average ultimate strength of continuous stiffened plating when the local aspect ratio is either 3.0 or 5.0.

From the above findings, it can be concluded that the ultimate strength of a wide rectangular plate in structural systems increases owing to the effect of continuity of the panel as well as to the torsional rigidity of stiffeners, and the ultimate strength assuming a simply supported condition is too conservative in many cases.

6. Conclusion

A series of elastic/elastoplastic large deflection analyses is performed to clarify buckling/plastic collapse strength of wide rectangular plate as a part of ship bottom plating subjected to combined lateral pressure and transverse thrust. Influence of loading sequence of pressure and thrust loads is examined as well as the differences in the results of analysis using double bay and triple bay models for the stiffened plate with angle-bar stiffeners. It has been found that:

(1) The loading sequence of lateral pressure and thrust does not affect the elastic large deflection behaviour after the pressure load has been applied to a specified level. Some differences are observed in the elastoplastic behaviour, but the ultimate strength is almost the same regardless of the loading sequence.

(2) Continuous stiffened plating with angle-bar stiffeners can be exactly analysed by a triple bay model making use of periodical boundary condition. Effects of unsymmetrical stiffeners are not observed under thrust, but some differences in deflection mode are obtained in the presence of lateral pressure. Ultimate strength of the latter case is to be further studied.

(3) Based on the results of series analyses, semi-empirical formula is derived to evaluate the elastic buckling strength of a wide rectangular plate as a part of continuous plating subjected to combined lateral pressure and transverse thrust. The influence of stiffeners is also considered and the accuracy of the proposed formula is found to be enough.

(4) The buckling strength of a rectangular plate as a part of bottom plating increases with the increase in lateral pressure, whereas the ultimate strength decreases. However, it does not decrease so much even when the applied lateral pressure is high.

(5) The DNV's formula gives average ultimate strength considering the influences of lateral pressure and stiffeners in most cases when continuous stiffened plating is considered.

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