DESIGN CRITERIA OF STIFFENED PLATE MADE OF HIGH-STRENGTH STEEL UNDER UNIAXIAL COMPRESSION

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ABSTRACT

Recently, high strength steel (HSS) has been widely applied in many parts of ship structures which are subjected to high longitudinal bending stresses, such as deck and bottom plates. Utilizing higher strength steel will lead to thinner structures than those with mild steel. Then, the dead weight capacity of ships will be increased. However, the reduction of plate thickness may lead to lower buckling strength. Therefore, new design criteria allowing the plate buckling are established for plate panels in order to use HSS. These are, namely; the maximum allowable stress, the ultimate strength and the load deflection. These criteria are applied on stiffened plate panels with different plate thicknesses constructed with HSS to ensure that the structural design is equivalent to that with mild steel. Parametric studies are performed to know the effect of stiffener space, plate thickness and the material yield strength on the plate carrying capacity.

Keywords: Stiffened plate, Plate buckling, High strength steel, Ultimate strength, Load deflection

INTRODUCTION

Among the trends of revolution in shipbuilding industry, high strength steel (HSS) is considered for use in many parts of ship structures such as deck and bottom plates. Lighter scantlings are expected when utilizing HSS. Such lighter scantlings may be lower in buckling strength than those of ship structures built using conventional MS. From practical viewpoint against improvement of buckling strength, reducing frame space is not an efficient way. This suggests an alternate way that buckling should be accepted in ship structures if the high strength of the material is aimed to be utilized.

The hull of a ship is usually composed of stiffened plates, which constitutes more than 50% of the steel structural elements. However, under various applied loads, the ship structure may be exposed to many modes of failure such as buckling, plastic collapse due to yielding, brittle fracture under excessive load, and/or fatigue fracture due to repeated action of stress fluctuations. Failure due to Buckling mode is considered in this study. Buckling in ship structures may be classified into column buckling, stiffened panel buckling and buckling of primary supporting members. In this paper , the buckling of stiffened panel will be investigated.

Generally, three modes of buckling of stiffened plate may be occurred, plate panel buckling, stiffeners buckling and overall buckling. Only effectively supported plate panels may be allowed to buckle when using the high strength steel in deck and bottom platings of the ship hull. However ,allowing buckling in ship structures will bring out several problems. Three subjects related to stiffened panel subjected to uniaxial compression are discussed. These are the maximum allowable stress, the ultimate strength, and the load deflection. A design philosophy and design criteria on allowing buckling are proposed. These criteria are applied on stiffened panel with different plate thicknesses to ensure that the capacity is the same when replacing the mild steel stiffened panel with different grades of high strength steel. Furthermore, the resultant deflection of replaced plates is checked [1].

STRENGTH ANALYSIS OF DECK AND BOTTOM PLATING

When a ship structure is subjected to longitudinal bending stress due to the action of sagging and hogging conditions. Developed stresses in deck and bottom plates will be distributed in tensile and compressive forms. When these stresses are increased, different failure modes will be developed such as buckling, yielding and fatigue fracture [2]. As stated before, when the hull girder constructing with the high strength steel, the plates thickness are reduced. In turn, the buckling strength of these plates will also reduce. Here, the most significant mode of failure in the hull girder constructing with high strength steel is the buckling mode. Consequently, the deck and bottom plantings will be subjected to the buckling failure. To perform this analysis, it is necessary to distinguish the buckling modes of stiffened plate. Where, the stiffened plate is considered the main constitutive member in deck and bottom platings.

To prevent the deck and bottom platings from collapsing under the action of external loadings it is stiffened on the inside with stiffeners attached to the plate and contribute the carrying loads. These stiffeners are arranged in three systems according to the function of the ship. These are, namely, transverse system, longitudinal system and combination system as shown in Figure 1. Therefore careful investigation is carried out on the stiffened plates to know their buckling modes of failure, since these plate constitutes more than 50 % of the steel structural elements. In the following sections, the possible modes of buckling in the stiffened plate will be discussed.

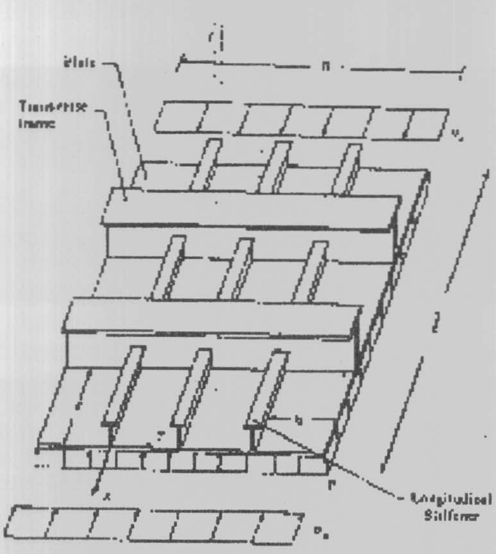


Figure 1 Stiffened plate.

Possible Modes of Buckling

The possible modes of buckling in the stiffened plate may be distinguished as follow [3]:

i- Local buckling: The plate panels between the stiffeners may be buckle but still continue to carry additional load after buckling.

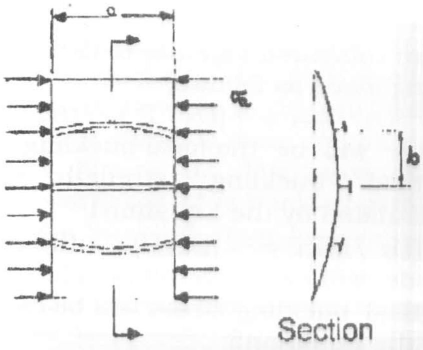
ii-Stiffeners buckling: the stiffeners may buckle while the plate still straight.

iii-Overall buckling: The stiffeners and plate panels are buckled, followed by overall collapse.

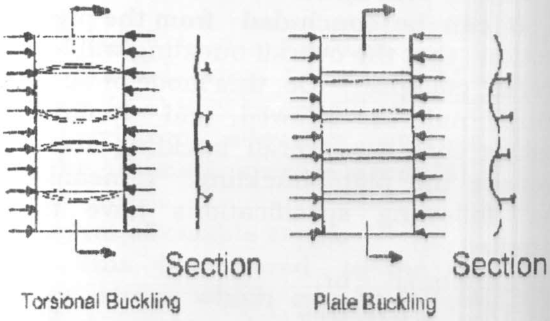
Figure 2 shows the three modes of the buckling, respectively.

Buckling Strength Analysis

As mentioned before, the stiffened plates are stiffened either longitudinally or transversely. In shipbuilding the longitudinal system of stiffened plate is usually applied. Since, the buckling strength of this system is four times than the transverse system[2]. Then, the buckling strength analysis is only performed for the longitudinal stiffened plates.



(a) Overall Buckling



(b) LOCAL BUCKLING

Figure 2 Modes of buckling of stiffened plate.

Local plate Buckling

A stiffened plate from the deck or the bottom of a ship is considered. This stiffened plate is assumed to be free from any imperfections, such as initial and / or welding residual stresses, and simply supported along its edges. When the stiffened plate is subjected to uniaxial compressive load, as shown in Figure 1, increasing the compressive load, the plate panels will buckle while the stiffeners will not buckle before the plate panels have reached their ultimate strength. The distribution of stresses will then becomes more complicated. Since, the center portion of the plate escapes from the axial shortening and a greater portion of the load must be supported by the region of plating near the sides as shown in Figure 3. However, as the load is further increased the deflection of the center region becomes more clear and the maximum stress at the sides increases more rapidly, until finally this stress reaches the yield stress.

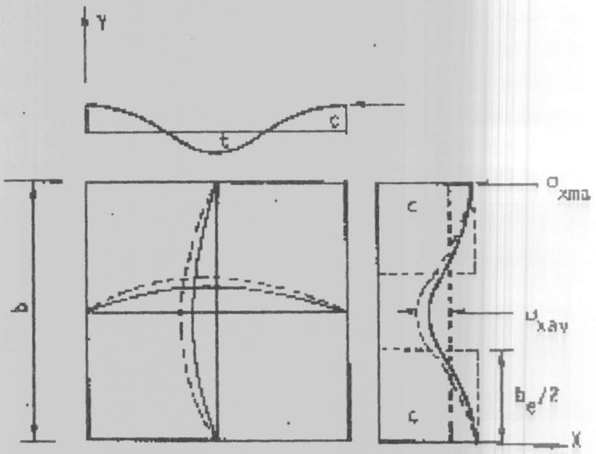


Figure 3 Stress distribution in a buckled plate under uniaxial compression

The critical buckling strength of the plate panel is given by [4];

$$\sigma_{cr} = K\, \pi^2 D / b^2 t \qquad (1)$$

where,

$K = \{(mb/l) + (l/mb)\}^2$

$D = E\, t^3 / 12(1-\nu^2)$.

The coefficient K is obtained for various values of m. For square plate it can be assumed that K = 4.

Stiffeners Buckling

Usually, the torsional and flexural rigidity of the stiffened plate is large enough to prevent the stiffener buckling. A simple check for the buckling of the longitudinal stiffener can be performed by the following formula [5];

$$\sigma_{cr})_{st} = \frac{\pi^2 E}{12 + \dfrac{4A_w}{A_f}} \left(\frac{b_f}{l}\right)^2 \qquad (2)$$

Where, A_w and A_f are the area of the web and flange, respectively, and b_f is the width of the flange.

Overall Buckling

In overall buckling mode the stiffened plate can be handled as an orthotropic plate as shown in Figure 4. Generally, the orthotropic plate have three different values of the rigidities, D_X in X direction, D_y in Y direction, and D_{xy} the torsional rigidity. However, in the longitudinally stiffened plate the rigidity value, assuming $D_Y \approx D_{XY} \approx D$, are [6]:

$D_X = D + E I_X / b$ (3)

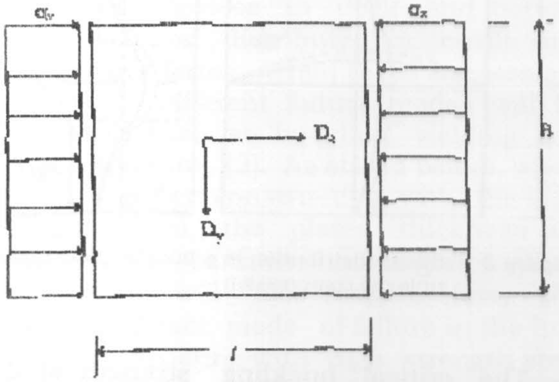


Figure 4 Orthotropic plate.

I_X is the stiffener moment of inertia relative to the plate middle plane. Generally, the determination of the buckling mode is controlled by the relative rigidity ratio of the orthotropic plate to the plate panel. That is,

$\gamma_x)_{act} = D_x / D$ (4)

The critical buckling stress for the orthotropic plate is usually given by[5] :

$\sigma_{cr})_{orth} = \pi^2 D_x / t_e l^2$ (5)

where,

t_e = The equivalent orthotropic thickness.

$t_e = t + A_x / b$

A_x= Area of each stiffener.

As mentioned before, the buckling stress of the plate panel between stiffeners was given by Equation 1. Then, the critical rigidity ratio can be determined by equating the value of minimum critical stress for the plate panel to that of the overall plate, as;

$(\gamma_x)_{cr} = (D_X/D)_{cr} = 4\, t_e (l/b)^2 / t$ (6)

The actual value of the stiffness of the stiffened plate is calculated as follows,

$(\gamma_x)_{act} = (D_X/D)_{act} = 1 + 12 I_X (1-\nu^2)/b^3$ (7)

However, the actual and the critical values of γ_x are compared together to determine the buckling mode as follows,

1. If $(D_X/D)_{act} \geq (D_X/D)_{cr}$, the buckling mode will be the local buckling and the critical buckling strength will be calculated by the Equation1
2. If $(D_X/D)_{act} < (D_X/D)_{cr}$, the buckling mode will be an overall buckling and the critical buckling stress will be calculated by the Equation5.

ALLOWABLE BUCKLING MODE WITH USING THE HIGH STRENGTH STEEL

It can be concluded from the previous section that the overall buckling will lead to overall collapse. So, this mode of buckling would not be allowed, and it must be ensure that the overall buckling does not precede the plate buckling. It means that the following specifications have to be satisfied :

$(\sigma_{cr})_{over} > \sigma_{cr})_p$ or,

$(D_X/D)_{act} \geq (D_X/D)_{cr}$ (8)

Practically, the stiffeners do not buckle prior to buckling of the plate panels (stiffeners are usually designed to satisfy this condition). It means that the following specification have to be satisfied :

$\sigma_{cr})_{st} > \sigma_{cr})_p$ (9)

Finally, to prevent the overall buckling and the stiffener buckling the following criteria would be applied :

overall buckling stress > stiffener buckling stress > local buckling stress. That is,

$\sigma_{cr})_{ov} > \sigma_{cr})_{st} > \sigma_{cr})_p$ (10)

Therefore, local buckling is considered less series among others modes. Only this mode of buckling will be allowed in thin structure fabricated from higher strength steel. Since, the plate panel could carry additional load as long as its edges are supported by the stiffeners. Practically, the designers suppose that the stiffeners does not buckle before the plate panels have reached their ultimate strength.

POST BUCKLING STRENGTH ANALYSIS

In this section, the strength of a plate panel after buckling is discussed. The distribution of stresses in the buckled plate, post buckling stage, is more complicated, as shown in Figure 3. The maximum and minimum stresses of a buckled plate panel in the post buckling stage are evaluated by solving the equilibrium and compatibility equations [7] . This gives,

$$\sigma_{xmax}=2\ \sigma_{xav}-\sigma_{xcr} \qquad (11)$$

$$\sigma_{ymin} = -\ \sigma_{xav} + \sigma_{xcr} \qquad (12)$$

Substituting maximum and minimum stresses in Von Mises equation as follows [6]:

$$\sigma_{VM}^2=7\sigma_{x\,av}^2-9\ \sigma_{x\,av}\sigma_{x\,cr} + 3\ \sigma_{x\,cr}^2 \qquad (13)$$

In the following, two cases of average stresses (σ_{xav}) may be considered. These are the maximum allowable average stress and the ultimate average stress [8].

Maximum allowable stress

This is referred to the maximum average stress which can be allowed after buckling and before yielding. By substituting σ_{VM} in Equation 13 by the allowable stress of the used steel, σ_{all}. Where, the allowable stress equals to the yielding strength of the steel divided by factor of safety. Then Equation 13 becomes:

$$\sigma_{all}^2=7\sigma_{xav}^2-9\sigma_{xav}\ \sigma_{xcr} + 3\ \sigma_{xcr}^2 \qquad (14)$$

σ_{xav} is the maximum allowable average stress at post buckling stage, as shown in Figure 3.

By solving Equation 14 for σ_{xav}, and dividing the correct solution by σ_{all} then:

$$\frac{\sigma_{xav}}{\sigma_{all}}=(1/14)\left[\frac{9c}{\beta_a^2}+\sqrt{-3\left(\frac{c}{\beta_a^2}\right)^2+28}\right] \qquad (15)$$

where,

$$c = 4\ \pi^2 \ /\ 12\ (1-\nu^2)$$

$$\beta_a = \frac{b}{t}\sqrt{\frac{\sigma_{all}}{E}}$$

Ultimate average stress

It is defined as the maximum average stress when the induced stresses satisfy the yield condition applicable to the material of the plate. When the plate can not carry further load, it is considered to reach its ultimate strength. The ultimate stress can be obtained by replacing σ_{xav} with σ_u and σ_{all} with σ_o into Equation 15. This gives:

$$\frac{\sigma_u}{\sigma_o}=(1/14)\left[\frac{9c}{\beta^2}+\sqrt{-3\left(\frac{c}{\beta^2}\right)^2+28}\right] \qquad (16)$$

where,

$$\beta=\frac{b}{t}\sqrt{\frac{\sigma_o}{E}}$$

PHILOSOPHY OF DESIGN

Reducing the thickness of plate panels constructing with high strength steel (HSS) leads to a lower buckling strength. A new philosophy of design will be suggested as follows;

Allowable local buckling

The new philosophy of design allows the local buckling since the stiffeners can carry substantial load after buckling. The criteria of the design philosophy is :

$$\sigma_{xav} > \sigma_{act}\sigma_u)_{HSS} \geq \sigma_u)_{MS} \qquad (17)$$

Allowable deflection

It is assumed that the load deflection of a perfect plate constructing with HSS due to buckling is supposed to be equal to the deflection due to imperfections. The American National Standard supposes that the allowable deflection, due to the imperfection, is equal to the plate thickness (W_a = t). The resultant deflection due to the uniaxial load can be computed by the following equation :

$$c_1\ W^3+ c_2\ W^2 + c_3W + c_4 = 0 \qquad (18)$$

where, c_1 , c_2 , c_3 and c_4 are given in Reference 7.

The proposed procedure of replacing MS with HSS plates

When a plate panel (length is *l* and width is the frame space) constructing with MS is replaced by HSS, a proposed procedure would be carried out to guarantee that the new plate can carry the same load on the original plate. The procedure is explained as follows :

1. Calculate the allowable load per unit length of the MS plate,$(F_{all})_{MS}$:

   $$F_{all})_{MS}=\sigma_{all})_{MS}\, t_{MS}=\sigma_{oMS}\;\; t_{MS}/\, f_b \qquad (19)$$

   Where, t_{MS} is the thickness of plate constructing with mild steel and σ_{oMS} is its yielding strength.
2. Determinate the equivalent thickness corresponding to the chosen grade of HSS.

   $$t_{HSS1}=\sigma_{oMS}\times\, t_{MS}\;/\;\sigma_{oHSS} \qquad (20)$$

   Where, σ_{oHSS} is the yield strength of HSS plate.
3. Calculate the buckling strength(σ_{cr}) of HSS plate. If the buckling strength is less than the allowable stress of HSS, the buckling could occur.
4. To prevent the buckling of the equivalent plate thickness(t_{HSS1}), the stiffener space have to be reduce, that means more stiffeners have to be added. Increasing the number of stiffeners is not an intelligent solution from the economical view point.
5. With the same stiffener space, the t_{HSS1} have to be increased to t_{HSS2} until the maximum allowable load of HSS plate (buckling occur) is equivalent to the allowable load. The maximum allowable load using Equation16 is as,

   $$F_{av}=\sigma_{xav}\times t_{HSS2} \qquad (21)$$
6. Then, the load deflection of the HSS plate is calculated using Equation 18. This deflection have to satisfy ($W \leq W_a$). If this specification is not satisfied the thickness t_{HSS2} should be increased to t_{HSS3}.
7. Calculate of the ultimate average stress of the HSS plate . This stress is calculated using Equation (17). Then the ultimate load can be determined as follows :

   $$F_u)_{HSS}=\sigma_u)_{HSS}\times t_{HSS2} \qquad (22)$$

When the previous procedure is carried out, design curves can be generated by using Equations 16 and 17.

EXAMPLES OF ANALYSIS

The procedure of replacement process would be applied to a stiffened plate. The standard longitudinal stiffened plate of conventional mild steel of yielding strength equals to 25 kg_f/mm^2 will be considered for the analysis. The stiffened plate is perfectly flat, without any initial imperfection, and subjected to uniaxial compression load. The specification of this plate are as follow, 10700 mm length, 14 mm thickness, 950 mm stiffener space and the number of stiffeners equals to 10. The procedure of replacing MS with three grades of HSS (grades 32, 36 and 40) will be as follows :-

1. Grades 32

1- Calculate the allowable load carried by the MS plate using Equation 19

$F_{all})_{MS}$ = 206 kg_f/mm^2

2- The equivalent thickness of the corresponding HSS using Equation 20. t_{HSS1} = 10.9 mm

3- Calculate the buckling strength of the HSS plate using Equation 1. $\sigma_{cr})_{HSS}$ = 9.7 kg_f/mm^2

While the allowable strength of grade 32 is 19 kg_f/mm^2 (f_b=1.5). It means that $(\sigma_{cr})_{HSS} < \sigma_{all})_{HSS}$), therefore, the buckling will occur.

4- To prevent the buckling occurrence, the stiffener space is reduced to 680 mm and four stiffeners should be added. It is not a practical solution. Therefore, the equivalent thickness of HSS plate at the same stiffener space has to be increased to t_{HSS2} = 13 mm

5- The deflection of t_{HSS2} is 6.9 mm using Equation18. This deflection is less than the allowable deflection (W_a = t_{HSS2} =13mm), therefore, t_{HSS2} is acceptable.The previous results can be obtained by applying Equations 16 and17 as shown in Figures 5 and 6.

6-The above procedures will be carried out for grades 36 and 40. The obtained results are shown in Table 1, and Figures 7 and 8, respectively.

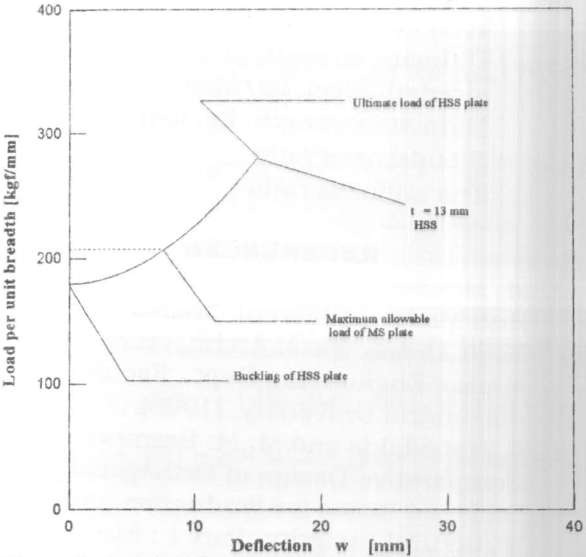


Figure 5 Load-deflection relationship in plate panel of HSS (32)

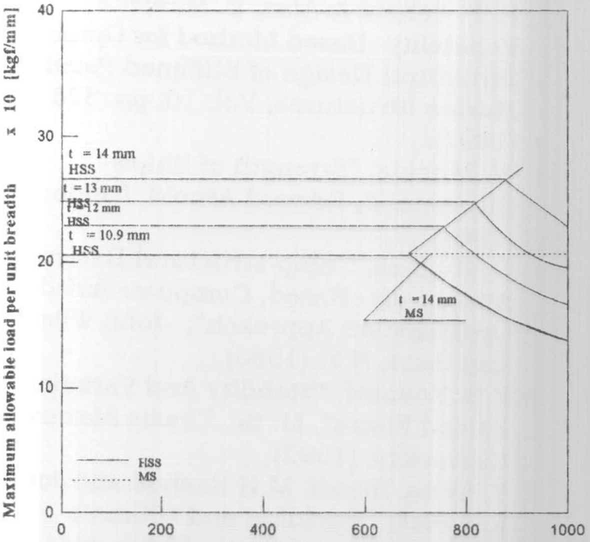


Figure 6 Relationships of the allowed load to stiffener space in plate panel of grade 32

It is found that the reduction of thickness achieved by using grade 40 is larger than other grades, but the decision of choosing the suitable grade of HSS instead of MS depends on the cost analysis for all grades. Here, This analysis is not considered.

Table 1 The obtained reduction of thickness with grades 36 and 40 of HSS

Grade	36	40
t_{HSS1} [mm]	9.7	8.75
t_{HSS2} [mm]	12.5	12
w [mm]	6.92	6.94

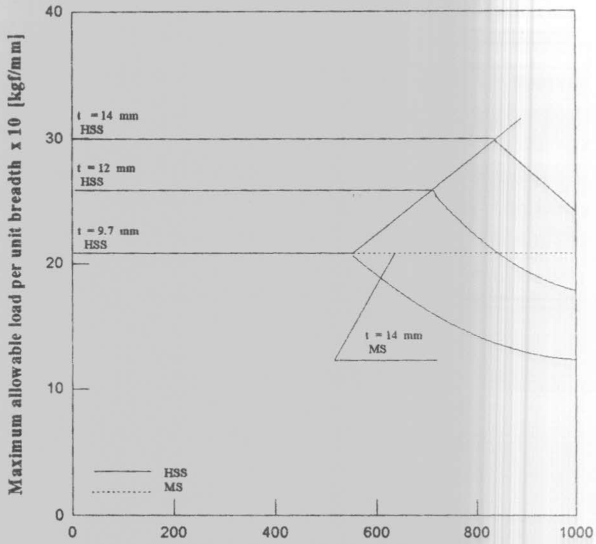


Figure 7 Relationship of maximum allowable load to stiffener space in plate panel of HSS 36

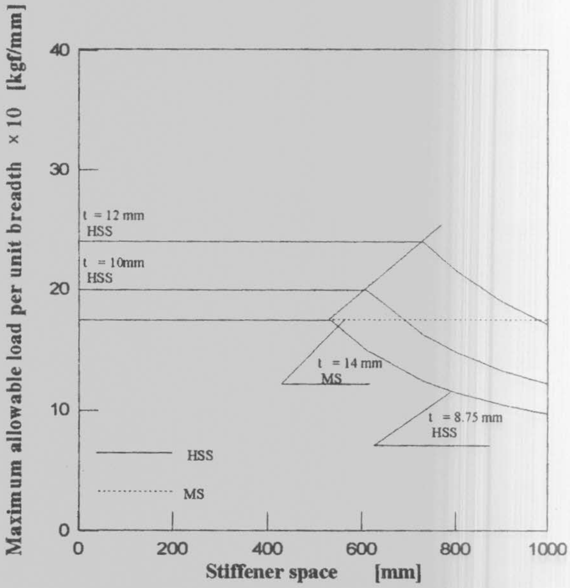


Figure 8 Relationships of maximum allowable load to stiffener space in plate panel of HSS 40

CONCLUSION

In this work, the use of higher strength steel(HSS) in deck and bottom platings of ships is considered. Using such steel will lead to thinner structures than those with the mild steel(MS). The reduction of thickness will lead to a lower buckling strength. In order to utilize effectively HSS, allowing plate buckling is suggested. Allowing buckling will bring out several problems namely: the maximum average stress , the ultimate stress and the load deflection. A design philosophy are proposed to ensure that the strength of HSS plates is equivalent to those with MS. Applying this design philosophy on stiffened plate with different grades of steel, a remarkable reduction of thickness may be achieved while satisfying the above criteria.

NOMENCLATURE

b	The frame space, mm
B	The breadth of stiffened panel, mm
D	Rigidity of the stiffened plate.
E	Young's modulus of elasticity, kg/mm^2
F_b	A factor of safety against yielding, mm
l	The length of stiffened panel, mm
m	The number of half sinusoidal waves.
T	Plate panel thickness, mm
t_e	The equivalent orthotropic thickness, mm
W_a	Allowable deflection, mm
W	Load deflection, mm
ν	Poisson's ratio.
σ_{all}	The allowable stress of the steel, kg/mm^2
σ_{ac}	The acting stress due to external loads, kg/mm^2
σ_o	The yielding strength of the material, kg/mm^2
σ_{xav}	The average compressive stress, kg/mm^2
σ_{cr}	The critical buckling stress,kg/mm^2
σ_{xmax}	The maximum compressive stress in X direction, kg/ mm^2
σ_{ymin}	The minimum stress in Y direction, kg/ mm^2
σ_{VM}	Von Mises stress, kg/mm^2
$\sigma_{u)MS}$	Ultimate strength of the mild steel, kg/mm^2.
$\sigma_{u)HSS}$	Ultimate strength of the high strength steel, kg/mm^2
σ_u	Ultimate strength, kg/mm^2
β_a	Slenderness ratio
γ	The stiffness ratio

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معايير التصميم للألواح المقواه والمصنعة من صلب عالى المقاومة تحت تأثير حمل ضغط أحادى

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ملخص البحث

استخدم صلب عالى المقاومة حديثا فى صناعة ألواح هياكل السفن استخداما واسعا لأجزاء كبيرة لهياكل السفن المعرضة لحمل ضغط مثل سطح وقاع السفينة. استخدام صلب عالى المقاومة سوف يؤدى الى تناقص سمك الألواح وبالتالى زيادة حمولة السفينة، الا ان حمل الانبعاج سوف يقل ولذلك وضعت معايير تصميم جديدة لكى تأخذ فى حسبانها انبعاج الالواح، وهذه المعايير هى المقاومة القصوى والحمل المتوسط والترخيم. طبقت هذه المعايير على ألواح مقواه ذات تخانات مختلفة ومصنعة من صلب عالى المقاومة للتأكد من كفاءة التصميم تم دراسة بارماترية لتأثير كل من سمك اللوح ومسافة الاعواد واجهاد الخضوع على معايير مختلفة.