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Reliability Assessment against Ultimate Bending Moment of Ships' Hull Girder

by

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선체의 최종굽힘 모멘트에 대한 신뢰성 검토

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Abstract

The ultimate bending moment of ships is one of the principle strength considered in ship design. Several methods have been proposed to predict the ultimate bending moment and its major part is, in general, predicting the ultimate compressive strength of stiffened panels. In this paper, made is the review on the methods and formulae of predicting the ultimate compressive strength and they are applied to predicting the ultimate bending moment. Safety levels of three bulk carriers have been derived evaluated for two loading conditions, say, light ship condition and full load condition, and wave bending by Classification Society Rule(ABS, DnV and Lloyd Rule). The present reliability analysis problem is strictly non-linear and the Advanced First-Order Reliability Method has been used. From the results of parametric studies, the methods of predicting the ultimate compressive strength of sitffened panels are compared from the view point of their applicability to the reliability assessment of ships structures. The paper ends with a brief discussion drawn from the parametric studies and the extension of the study is described.

요 약

선박의 최종굽힘 모멘트는 설계에 적용되는 주요강도로써 이를 추정하는 여러방법들이 제안되었는데, 판과 보강재로 이루어진 구조요소의 압축 최종강도에 대한 추정에서 시작되는 것이 일반적이다.

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본 논문에서는 최종굽힘 모멘트를 구하기 위해 보강판의 압축 강도추정을 지금까지 제안된 여러가지 방법을 정리하여 소개하고, 실선 설계에 적용될 수 있는 유용성 측면에서 검토하였다. 그 결과를 이용하여 3척의 살물선에 대한 신뢰성 해석을 수행하였다. 선박에 작용하는 파랑굽힘 모멘트는 선급규정에 의해 계산하였다.

본 연구의 신뢰성 해석문제는 안전여유식의 형태가 비선형임을 고려하여 Advanced First-Order Reliability Method를 이용하였다. 몇가지의 해석예로부터 선체구조의 신뢰성 검토측면에서 최종강도 추정방법을 비교하였다.

1. Introduction

The reliability analysis methods have prematured to be applied to practical design of marine structures. Since 1970's the method has been applied to the design of such structures. However most researches are concerned with offshore structures rather than ships structures. This may be due to conservatism in ship structural design, which may be an obstacle to accept a new design concept.

The application of reliability analysis to ships structures was initiated by Mansour and Faulkner [9], and the first discussion on the basic idea was back to the International Ship Structures Congress in 1967[10]. Since then, in spite of there being relatively less amount of work on ship structures than offshore structures, many papers have been presented in various judicial proceedings and transactions. For illustrations, Faulkner extended his own work with Sadden at Glasgow to Naval ships [1], Stiansen et al[11] Presented the fundamental procedures for reliability analysis of ship structures, Guedes Soares and Moan[12] were concerned with the effect of modelling uncertainty of the wave load.

Mansour et al[13] and Mansour[14] compared the reliability indices of 18 ships studied in ref.[9] evaluated by three methods. Other works can be found in the paper by Thayamballi et al[15], Ando et al.[16], White and Ayyub[17] and so on, Recently Soares[18] and Stiansen and Thayamballi[19] well described the various applications of reliability theory to marine structures and well reviewed the state-of-art in this field. Within this country, Yim et al[20] presented the work on the longitudinal strength of ships with some parametric studies.

Many portion of the previous works can find their merit from the simplicity nature in evaluating the reliability level. To more rationally treat all uncertainties in load and resistance, however, a more rigorous formulation of the problem is desirable.

This paper is an attempt to look at the reliability levels of bulk carriers for longitudinal bending strength against several Class Rules of predicting wave bending moments and against the methods of predicting the compressive ultimate strength of stiffened panels. The Advanced First-Order Reliability Method(AFORM) is employed in this study. Several parametric studies have been carried out to show the efficiency of the strength models from the view point of reliability analysis and the results are presented in terms of reliability indices. Made is the comparison between safety margin expression.

The results of such parametric studies lead to conclusion indicating the importance of selecting the strength model and safety margin expression for the sake of a more realistic assessment of structural safety of ships.

2. Strength Model

2.1 Ultimate longitudinal bending moment

There are several models for the ultimate longitudinal bending moments of ships. In this study, the model suggested by Faulkner and Sadden[1] is chosen as the mean ultimate bending moment.

$$M_u=\sigma_y Z[(1-\alpha_y+\alpha_c\phi)\alpha_y]\alpha_s \qquad (1)$$

where $\alpha=1+\zeta=1+$systematic error and ϕ is so called the compressive strength parameter of a stiffened panel defined as $\phi=\sigma_u/\sigma_y$ in which σ_u is the ultimate compressive stress. Z is section modulus and σ_y average yield stress of stiffened panel. The systematic errors, ζ_y,ζ_c and ζ_s can take account of the objective uncertainties in predicting yield stress, in using idealized design code to evaluate σ_u and in evaluating bending moment. they are given as[1] :

(1) systematic error in yield strength : $\zeta_y=0.10$
(2) systematic error in compression strength :
$\zeta_c=(1-\phi)(2+\zeta_y)\zeta_{co}$ where $\zeta_{co}=0.15$
(3) systematic error in section effects : $\zeta_s=0.15$

In evaluating the ultimate bending moment from eq.(1), ϕ is that of critical stiffened panel on deck or bottom.

2.2 Ultimate compression strength of stiffened panels

Several methods and formulae have been suggested to predict the compressive strength parameter of stiffened panels, ϕ (and hence the compression strength) and can be categorised as [2] :

- effective width approaches
- single parameter formulae
- two parameter formulae

Among of them the following four methods are adopted in this study.

(1) method by Faulkner

This method is based on the Johnson-Ostenfeld type formulation together with the effective width approach for plate behaviour, in which the effects of initial deflection and residual stress can be considered. The compressive strength parameter is given by :

$$\phi=\frac{\sigma_u}{\sigma_y}=\frac{\sigma_e}{\sigma_y}\left[\frac{A_{st}+b_e t}{A_{st}+bt}\right] \qquad (2)$$

where A_{st} is the sectional area of stiffener, and the edge stress σ_e(or effective stress) is governed by the compression collapse of the stiffener and its associated plating. The column collapse stress is given as :

$$\begin{aligned}\sigma_e&=\sigma_y(1-0.25\lambda_{ce}^2) && \text{for } \lambda_{ce}\leq 2\\ &=\sigma_{cr} && \text{for } \lambda_{ce}>2\end{aligned} \qquad (3)$$

where σ_{cr} is the Euler buckling stress. The reduced slenderness parameter, λ_{ce}, is given by :

$$\lambda_{ce}=\frac{L_e}{r_{ce}}\sqrt{\frac{\sigma_y}{E}} \qquad (4)$$

and $r_{ce}=\sqrt{I_e/(A_{st}+b_e t)}$ (5)

where L_e is the reduced effective length and I_e the moment of inertia associated with the reduced effective width given by :

$$\frac{b'_e}{b}=\frac{1}{\beta}\sqrt{\frac{\sigma_y}{\sigma_e}} \qquad (6)$$

where $\beta=b/t\sqrt{\sigma_y/E}$: plate slenderness

Due to the weld induced residual stress, the effective widths, b'_e and be, should be reduced by the factor R_r given by :

$$R_r=1-\frac{2\eta}{b/t-2\eta}\left[\frac{\beta^2}{2\beta-1}\right]\left[\frac{\beta-1}{1.5}\right] \qquad (7)$$

An iterative procedure to find σ_e is required as it features in the b_e and b_e' equations also.

(2) Perry–Robertson's formula

The compressive parameter, ϕ is given by :

$$\phi = \frac{\sigma_u}{\sigma_y} = \frac{(1+\xi+\lambda^2) - \sqrt{(1+\xi+\lambda^2)^2-4\lambda^2}}{2\lambda^2} \qquad (8)$$

where λ : column slenderness$=\sqrt{\sigma_y/\sigma_{cr}}$

$\sigma_{cr}=\dfrac{\pi^2 E}{(l/r)^2}$: Euler buckling stress

r : $\sqrt{I/A}$: radius of gyration

I, A : moment of inertia and sectional area when plate is fully effective

ξ : $|W_o|\,e/r^2$

W_o : initial deflection of stiffened panel

e : distance between plate midplane and neutral axis of section

(3) Lee's formula

Lee[2] proposed the following formula for ϕ, as a function of slenderness of plate, β and that of column, λ which has been derived to the best fit for the results of numerical analysis and experiments.

$$\phi=\sigma_u/\sigma_y=\frac{1}{f(\lambda)\sqrt{1+0.15\beta^2}} \qquad (9)$$

with function $f(\lambda)(=1/f_2(\lambda))$ given :

$$\begin{aligned} f_2(\lambda) &= 1+0.209\lambda^2+0.156\lambda^4 && \text{for } 0\leq\lambda\leq 1.59 \\ &= \lambda^2 && \text{for } 1.59\leq\lambda \end{aligned} \qquad (10)$$

(4) Rondal and Maquoi formula

Rondal and Maquoi suggested the following simple equation as a modified form of Bjorhovde's(see ref[3]).

$$\phi=\frac{\sigma_u}{\sigma_y}=\frac{Y-\sqrt{Y^2-4\lambda^2}}{2\lambda^2} \qquad (11)$$

where $Y=0.956+0.293\lambda+\lambda^2$

Table 1 shows comparison of the above four methods with the test data in ref.[4,5]. Faulkner's and Lee's methods show a good agreement with the test data and gives the mean bias close to unity and low COV.

While Perry-Robertson's and Rondal-Maquoi's show muon dispersion and higher and lower the mean bias than unity, respectively.

When stiffened panel is subjected to combined action of axial compression and lateral pressure, the following simple interaction equation may be used [2].

$$\frac{F_x}{F_{xu}}+\frac{W}{W_u}=1.0 \qquad (12)$$

Where F_x : axial compression force

W : lateral pressure

F_{xu}: axial collapse load$=\phi\sigma_y A$

W_u: central hinge collapse load given by $8M_p/l^2$with M_p : plastic bending moment of cross section

When the lateral pressure term is relatively smaller than the axial compression term, the axial collapse load under the lateral pressure can be obtained from the following equation,

$$F_x=F_{xu}(1-W/W_u)$$

and then in terms of compression strength parameter, the axial collapse load under lateral pressure is

$$\phi'=F_x/(A\sigma_y)=\phi(1-W/W_u) \qquad (13)$$

Table 1 Comparison of methods of predicting the ultimate strength of stiffened panels with experimental results by faulkner[4] and horne et al[5, 6]

test models	(experimental result)/(predicted result)			
	Faulkner	Perry-Robertson	Rondal-Maquoi	Lee
all models tested by Faulkner(22 models)	1.014 (6.9%)	1.120 (12.9%)	0.826 (26.7%)	0.996 (8.8%)
plate induced collapse models tested by Horne et al.(18 models)	1.002 (5.9%)	1.094 (7.4%)	0.866 (15.7%)	1.026 (6.1%)
stiffener induced collapse models tested by Horne et al (6 models)	0.946 (6.2%)	1.043 (4.2%)	0.976 (8.4%)	1.028 (6.2%)
overall collapse models tested by Horne et al (8 models)	1.011 (8.8%)	1.281 (9.5%)	0.986 (10.3%)	0.943 (6.0%)
all models by Faulkner and Horne et al.	1.002 (7.2%)	1.163 (12.4%)	0.880 (20.4%)	1.001 (7.8%)

where ϕ is the compression strength parameter when axial compression acts alone.

3. Loading Model

3.1 Still water bending moment

The bending moments of the minimum draft, i.e. light ship condition, and the maximum draft, i.e. full load condition, are calculated under given weight distribution.

3.2 Wave bending moment

Evaluation of wave bending moment at the midship is based on formulae specified in Class Rule. ABS, Dn V and Lloyd rules are used in this study.

4. Safety Margin

The safety margin for longitudinal strength of ships can be expressed in terms of the bending moments as follows including modelling parameters of resistance(strength) and loading :

$$M = X_{MR}M_u - (X_{MQS}MM_{SW} + X_{MQW}M_W) \qquad (14)$$

where M : safety margin

M_u : ultimate bending moment given by eq.(1)

M_{sw}, M_w : still water and wave bending moments, respectively

X_{MR} : strength modelling parameter

X_{MQS}, X_{MQW} : loading modelling parameter for still water and wave bending, respectively.

and the modelling parameter is usually defined as [6] :

$$X_M = \frac{\text{actual behaviour}}{\text{predicted behaviour}} \qquad (15)$$

Mean of X_M is referred to as the mean bias, and its COV modelling uncertainty. When discarding

Table 2 Ship models(bulk carriers)

		BC-1	BC-2	BC-3
length	L(m)	260	216	176
breadth	B(m)	44	32	30
depth	D(m)	24	18	16
draft	T(m)	17	13	11
dead weight	(ton)	150000	65000	42000
DECK				
plate thickness	(m)	0.03	0.025	0.015
frame space	(m)	4.68	4.8	4.0
longitudinal space	(m)	0.84	0.85	0.83
longitudinals	(m)	0.35×0.025	0.3×0.03	0.25×0.01×0.009×0.015
BOTTOM				
plate thickness	(m)	0.018	0.017	0.017
frame space	(m)	2.8	2.4	2.4
longitudinal space	(m)	0.83	0.81	0.80
longitudinals	(m)	0.35×0.018×0.1×0.017	0.25×0.012×0.09×0.016	0.141×0.009

systematic errors in eq. (1), the safety margin may be expressed in terms of compressive stress as :

$$M = X_{MR}\sigma_U - (X_{MQS}M_{SW} + X_{MQW}M_W)/Z \qquad (16)$$

where σ_u is the ultimate compressive stress evaluated by any method as illustrated in section 2.2.

5. Ship Models

Three bulk carriers have been chosen in this study and their principle dimensions and scantlings of deck and bottom longitudinals are presented in Table 2.

6. Reliability Study

6.1 Uncertainty modelling

In reliability analysis, choosing the probability distribution types of design variables can significantly affect the evaluated safety level. In this study all geometric properties are assumed to be normal and the elastic modulus and yield stress to be log-normal. Since strength is mainly affected by yield stress, the strength modelling parameter(X_{MR}) is assumed to be log-normal. Regarding the distribution of loading, it is sometimes taken as extreme type(for wave loading), but recent research on this suggests log-normal is more reasonable. Mean biases of load modelling parameters for still water and wave bending moment are assumed to be unity as can be seen in Table 3. COV of 10% for still water bending moment is reasonably accepted. If we consider all loading cases experienced by a ship during her life, the COV of still water bending moment may be larger than 10% and even that of wave bending moment. The COV of 10% for still water bending moment taken herein is just for the severe loading condition and not for all loading cases during ship's life. While the COV of wave bending moment ranges 10 to 15% [8], the COV is taken as 13% in this study. Table 3 summarises the uncertainty modelling of design variables for

Table 3 Uncertainty modelling

(1) resistance variables

variable	COV	distribution type
geometric properties	0.04	normal
elastic modulus	0.04	log-normal
yield stress	0.08	log-normal
strength modelling parameter	see Table 1	log-normal

(2) loading variables

variable	mean bias	COV	distribution type
still water bending moment	1.0	0.10	log-normal
wave bending moment	1.0	0.13	log-normal

the present reliability study.

6.2 Results and discussions

As can be seen in the safety margin, eq(14) or eq. (16), it is non-linear and hence the advanced first-order reliability method is suitable to evaluate the failure probabilities and consequently the reliability indices. Following summeries the present parametric studies :

—class rule : ABS, Dn V, Lloyd
—ϕ prediction : method by Faulkner and formulae of Perry-Robertson, Lee and Rondal-Maquoi
—loading condition : light ship condition(LC-1)
full load condition (LC-2)

Results for three bulk carriers of Table 2 are presented in Table 4. Throughout the parametric studies, the breadth of tension zone of welding residual stress, η is taken as 3.0 and the systematic error in section-effect, ζ_s as 0.15.

Regarding the reliability indices against the method of predicting the ultimate compressive strength of stiffened panels, Faulkner's and Lee's show similar tendencies as can be seen in Table 1, and Perry-Robertson's gives reasonable results in spite of its greater COV. While Rondal-Maquoi's show very lower reliability indices than the other three methods, This is due to its higher COV of X_{MR} than others and lower mean bias than unity.

Regardless of predicting methods for ϕ, Dn V rule shows significantly higher reliability indices than ABS and Lloyd. This is mainly because of lower wave bending moment of Dn V rule than ABS and Lloyd for the same ship. ABS and Lloyd give nearly the same levels of reliability. For three ship models, the minimum reliability index can be found under the full load condition.

From the above findings, it can be said that Faulkner's method and Lee's formula are acceptable in predicting the compression strength of stiffened panels. Considering this point and when load estimation is based on ABS rule, the reliability indices of BC-1, BC-2 and BC-3 are about 4.48, 3.39 and 3.88, respectively, and corresponding failure probabilities are 0.365×10^{-5} 0.352×10^{-3} and 0.521×10^{-4} , respectively.

Fig.1 is refer to reference 1 which shows the reliability index for longitudinal strength plotted against length of ship. The results of the present three bulk carriers are plotted on Fig.1. We can see that the present findings are reasonable. Table 5 compares the reliability induces to safety margin expressions of Eqs.(14) and in terms of compres-

Table 4 Summary of reliability analysis results (reliability index)

(1) ship model : BC-1

rule	ABS		DnV		Lloyd	
method \ LC	LC-1	LC-2	LC-1	LC-2	LC-1	LC-2
Faulkner	4.74	4.57	7.39	7.17	4.97	4.80
Perry-Robertson	5.01	4.87	7.09	6.89	5.20	5.05
Lee	4.65	4.48	7.23	7.01	4.88	4.71
Rondal-Maquoi	3.43	3.30	4.95	4.77	3.56	3.43

LC : loading condition LC-1 : light ship condition
LC-2 : full load condition

(2) ship model : BC-2

rule	ABS		DnV		Lloyd	
method \ LC	LC-1	LC-2	LC-1	LC-2	LC-1	LC-2
Faulkner	3.88	3.65	5.84	5.59	4.01	3.77
Perry-Robertson	4.00	3.81	5.67	5.43	4.10	3.90
Lee	3.63	3.39	5.97	5.45	3.76	3.51
Rondal-Maquoi	2.39	2.22	3.57	3.36	2.46	2.30

LC : loading condition LC-1 : light ship condition
LC-2 : full load condition

(3) ship model : BC-3

rule	ABS		DnV		Lloyd	
method \ LC	LC-1	LC-2	LC-1	LC-2	LC-1	LC-2
Faulkner	4.60	3.86	6.71	5.74	4.53	3.80
Perry-Robertson	4.61	3.98	6.78	5.48	4.56	3.93
Lee	4.63	3.88	6.78	5.81	4.56	3.82
Rondal-Maquoi	2.66	2.12	3.90	3.19	2.62	2.09

LC : loading condition LC-1 : light ship condition
LC-2 : full load condition

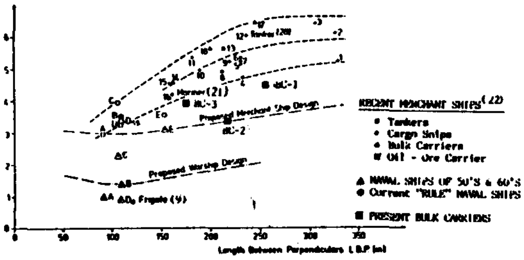

Fig. 1 Safety indices for naval and merchant ships (after reference 1)

Table 5 Reliability indices to safety margin expression

safety margin expressior	in terms of bending moment		in terms of compressive stress	
ship model \ LC	LC-1	LC-2	LC-1	LC-2
BC-1	4.65	4.48	3.73	3.55
BC-2	3.63	3.39	2.63	2.38
BC-3	4.63	3.38	3.68	2.88

note : compressive strength of stiffened panels are evaluated by Lee's
LC : loading condition LC-1 : light ship condition
LC-2 : full load condition

sive stress, Eq.(16). As can be expected, Eq.(16) gives much lower reliability indices than Eq.(14) does. It can be drawn that the reliability for longitudinal strength of ships should be assessed based on bending moment.

7. Conclusions

This study has been concerned with the reliability assessment of bulk carriers against longitudinal bending strength. Three models of bulk carrier as designed to Class Rule have been considered. Several parametric studies lead to followings.

(1) The present approach and modelling are rea-

sonable in assessing the safety level of ships under longitudinal bending moment.

(2) Faulkner's and Lee's methods may be recommended in predicting the ultimate strength of stiffened panels under compression due to their mean biases are close to unity and they also have low COVs, say less than 10%.

(3) The reliability levels of three bulk carriers found in this study lie on acceptable reliability range compared with other results.

The present formulation for reliability study can provide us with more reasonable level of reliability than the previous works found in many references. The developed computer code for reliability analysis can be easily handled to assess safety levels of ship structures at initial design stage and at the final design stage as well, and it can be added to the design procedure in presently use without much modification (when the designer is ready to accept the concept of reliability analysis of structures and appreciate its significant impact to structural design by adopting the concept with sufficient confidence on the uniform distribution of safety over the whole structure and surprising cost saving by doing so).

The extension of the present study would be :

— fatique consideration in the reliability analysis for a more complete assessment of reliability level of structures

— optimum structural design based on reliability analysis

— and development of safety check equation based on reliability study through a kind of parametric study, which has the same format as that presently in use.

The frameworks of these have been well already established and the works will be reported by the present authors in the near future.

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