Technical Paper

Transactions of the Society of Naval Architects of Korea
Vol. 29, No.4, November 1992
大韓造船學會論文集
第 29 卷 第 4 號 1992 年 11 月

Limit State Design of Ship Structures Based on Reliability Analysis

by

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신뢰성 해석에 기초한 선체구조의 극한설계

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Abstract

This paper is in principle concerned with the reliability analysis and its based design of midship section against the ultimate bending strength. Bulk carriers and oil tankers over 100m length are considered for this study.

Target reliability indices are derived with the results of reliability analysis of the present ship models. Reliability-based structural design code formats are proposed for use in design of midship section of bulk carriers and oil tankers. The proposed design formats have been success fully applied to re-design of midship section of the present ship types and show the reasonable results. It has been found that the proposed code formats in this paper are useful for the re-deign of midship section of such ship types.

요 약

본 논문은 최종굽힘강도에 대한 선박중앙부 구조의 신뢰성해석과 이에 기초한 설계에 대한 내용을 다루고 있다. 길이 100m 이상의 살물선과 유조선을 선박모델로 선택하였다.

선박모델들의 중앙부 구조에 대한 신뢰성해석 결과로 부터 허용신뢰성지수를 유도하였고, 이를 기초로 중앙부 구조설계를 위한 설계공식을 제안하였다. 이들을 몇척의 선박의 재설계에 적용하여 좋은 결과를 얻었으며, 이로부터 본 논문에서 제안하는 신뢰성해석에 기초한 중앙부 구조설계공식의 유용성을 확인할 수 있다.

발 표 : 1992년도 대한조선학회 춘계연구발표회('92. 4. 18.)
Manuscript received : May 20, 1992, revised manuscript received : July 11, 1992.
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1. Introduction

Reliability method has been well acknowledged as an efficient tool to treat the uncertainties in load and resistance. In the field of ship structures it has been already matured to apply the method to the development of reliability-based structural design code format as well as to safety assessment. This work is concerned with the development of reliability-based structural design code formats for use in design of midship section against the ultimate longitudinal strength. Bulk carriers and oil tankers over 100m length are selected for the present study. Target reliability indices of hull girders against the ultimate bending strength are derived. The uncertainty modelling of design variables is referred to the published data.

2. Ship Models

Fifteen ships are taken as ship models for the present study of which principal particulars are listed in Table 1. These are supposed to cover medium, large and very large sizes of ship. They were designed by Hyundai Heavy Industry(HHI) and Samsung Heavy Industry(SHI).

3. Reliability Analysis

3.1 Load and Strength Models for Reliability Analysis

○ Load model

Load effect usually has a great uncertainty due to its random nature and the imperfectness of the method used to predict. In the case of merchant ships, static load effect basically depends on the longitudinal distribution of weight and loading conditions. Thus its randomness may be analysed with its values at every possible loading condition which a ship can experience during her life time. Guedes Soares and Moan [1] reported the uncertainty level of still water bending moment of seven ship types through the statistical analysis with measured data collected from 2000 voyages for about 100 ships. Their statistical analysis results for bulk carriers and oil tankers are listed in Table 2 in which "P_E" is the probability of the loading condition that a ship can experience and is simply obtained based on the number of observations in reference 1. It can be seen that the COVs of still water bending moment are very great during operation but its means are much smaller than code values prescribed in the Rules of Classification Society. When the life time maximum of still water bending moment is used in reliability analysis, its COV usually lies between 8 to 12% and

Table 1 Principal particulars of the present ship models

Bulk Carrier					
Ship No.	Length	Breadth	Depth	Draft	Deadweight
BC-1	176.00	30.50	15.95	11.20	42000
BC-2	215.00	32.20	18.30	12.20	60000
BC-3	215.64	32.20	18.00	13.10	64000
BC-4	259.00	43.00	23.80	17.40	148000
BC-5	259.20	43.00	23.80	16.60	146000
BC-6	259.00	43.00	23.80	16.50	148000
BC-7	280.00	48.00	24.50	18.00	180000
BC-8	300.00	50.00	25.70	18.00	206900

Oil Tanker					
Ship No.	Length	Breadth	Depth	Draft	Deadweight
TK-1	171.00	26.89	16.40	10.66	32000
TK-2	233.00	41.80	20.00	12.20	95000
TK-3	233.00	41.80	20.00	12.20	95000
TK-4	258.00	43.20	24.90	17.50	150000
TK-5	264.00	47.80	22.80	14.60	148000
TK-6	264.00	43.90	24.40	16.16	153000
TK-7	310.00	56.00	31.40	20.70	280000

[note] dimension in meters ; dead weight in tons

Table 2 Statistical analysis results for still water bending moment for bulk carriers and oil tankers[after reference 1]

Ship Type	Loading Condition	Mean Bias*	COV	P_E
Bulk Carrier	part-load	0.135	2.496	0.332
	full-load	−0.079	3.494	0.668
	all load	−0.008	37.000	
Oil Tanker	part-load	0.330	0.636	0.234
	full-load	−0.263	0.814	0.766
	all load	−0.124	1.718	

* normalised by code value

its mean is greater than the code values by a factor of 1.10 to 1.40 [2]. For the present reliability study the statistical analysis results by Guedes and Moan [1] are used.

With regard to the wave bending moment, the extreme value by long term analysis with Weibull distribution is acceptable and its mean in general lies between 1.50 to 1.95 times the code value. The extreme wave bending moment is referred to the value corresponding to the probability of 10^{-8}. The COV of wave bending moment is unlikely to be greater than 20%. Assuming the modelling uncertainty of 11 to 12% and the random uncertainty of 10% gives a total uncertainty of 15−16% for extreme wave bending moment [3]. In this study 16% is taken.

The load combination of still water and wave bending moments is assumed to have the probability of occurrence of "P_E" to structural failure and thus the probability that failure occurs due to the load combination is assumed to be "P_E". That is, the computed failure probability is to be multiplied by "P_E" and then the corresponding reliability index is obtained from:

$$\beta=-\Phi^{-}(P_E \times P_f) \quad (1)$$

where P_f is the computed failure probability and Φ is the standard normal distribution function.

○ Strength model

The ultimate bending moment of hull girders can be given as:

$$M_u=Z\sigma_u=Z\phi_n\,\sigma_Y \quad (2)$$

where Z is section modulus of hull girder, $\sigma_u=\phi_n\,\sigma_Y$ is the minimum nominal ultimate strength of stiffened plates at deck or bottom. Considering the systematic error in section effect, α_s [4] Eq.(2) becomes:

$$M_u=Z\sigma_u\,\alpha_s \quad (3)$$

α_s is usually greater than unity. With the above equation (3), the mean ultimate bending moment is given by:

$$\overline{M}_u=Z\,\bar{\sigma}_u\,\alpha_s$$
$$=\sigma_Y\,Z\,\alpha_s(1-\alpha_Y\,\alpha_c\,\alpha_c\,\phi_n)\,\alpha_Y \quad (4)$$

where $\bar{\sigma}_u$ is the mean ultimate compressive strength of stiffened plate at deck or bottom, α_c and α_Y are the parameter accounting for the systematic errors in predicting collapse stress of stiffened plates and in yield stress, respectively. Details of deriving Eq.(4) can be found in references 4, 5 and so on. The systematic error, α_s is assumed to be 1.15.

The method proposed by Faulkner [6] is used to predict the ultimate compressive strength of stiffened plates which has mean bias of 0.99 and COV of 7.2% [5].

3.2 Uncertainty Modelling

The uncertainty modelling of design variables are given as Table 3 for the present study. The COVs of geometric and material variables are acceptable, and COV of ultimate compressive strength of stiffened plates is that of the method proposed by Faulkner [6] as mentioned in the previous section. Mean biases and modelling uncertainty for M_u are assumed to be unity and 10%, respectively. These may be reasonable. The uncertainty of bending moment is given with reference to the discussion in the previous section.

3.3 Safety margin and Reliability Analysis

The safety margin of the hull girder under longitudinal bending is given by:

$$g=X_{m1}\,X_{m2}\,M_u-(B_s\,M_s+M_d) \quad (5)$$

M_u is the ultimate bending moment of hull girder at amidship and predicted by Eq.(4). M_s and M_d are still water and wave bending moments, respectively. X_{m1} is the strength modelling parameter for σ_u and X_{m2} for M_u. B_s is the bias factor

Table 3 Uncertainty modelling for reliability analysis

variable	mean	COV	distribution type
geometric variable	nominal value	0.04	normal
material variable			
E	205000	0.04	log-normal
σ_Y	nominal value	0.04	log-normal
strength modelling parameter			
for σ_u	0.99	0.072	log-normal
for M_u	1.00	0.10	log-normal
still water bending moment			
BC under hogging	0.135	2.496	normal
BC under sagging	0.079	3.494	normal
TK under hogging	0.330	0.636	normal
TK under sagging	0.263	0.814	normal
wave bending moment	1.0	0.16	extreme type I

Table 4 Reliability index of hull girder under sagging

Ship	β	Ship	β
BC-1	2.90	TK-1	3.28
BC-2	3.19	TK-2	2.52
BC-3	3.93	TK-3	2.54
BC-4	3.31	TK-4	3.39
BC-5	3.38	TK-5	3.08
BC-6	3.63	TK-6	2.81
BC-7	3.67	TK-7	2.88
BC-8	3.81		
average	3.47	average	2.93

of still water bending moment given as in Table 2.

Table 4 shows reliability indices of the present fifteen ship models under sagging.

From Table 4 it is seen that reliability indices are not much scattered. The average reliability index of bulk carriers is 18% greater than that of oil tankers. This may be because the deck plate of bulk carriers is required to be much thicker than that of tankers to compensate for the hatch opening. For the present ship models the deck plate thickness of bulk carriers is 16.5-34.0mm and that of tankers is 13.5-19.0mm. The higher compressive strength of stiffened plates at deck of bulk carriers affects the reliability level of the hull girder under sagging.

4. Reliability-Based Design Code Format

4.1 Design Code Format

The design code format of hull girder under sagging is proposed to go along side with the present design procedure of midship section. Referring to Eq.(5) it has the form of :

$$\gamma_m\ \gamma_{R1}\ \gamma_{R2}\ \overline{M}_u > \gamma_s'\ M_s + \gamma_d'\ M_d \tag{6.a}$$

where γ's are partial safety factors defined as :

γ_m : strength reduction partial safety factors to account for random variation in strength variables

γ_{R1}, γ_{R2} : strength modelling partial safety factors for σ_u and M_u

γ_s', γ_d' : partial safety factors for still water and wave bending moment, respectively

$\overline{M}_u$ is mean ultimate bending moment of hull girder. M_s is rule required still water bending moment and M_d is the extreme wave bending moment. Expression of Eq.(6.a) in terms of nominal ultimate bending moment is :

$$C_R\ \gamma_m\ \gamma_{R1}\ \gamma_{R2} (M_u)_n > \gamma_s'\ M_s + \gamma_d'\ M_d \tag{6.b}$$

in which C_R is the ratio of ultimate bending moment to nominal one defined as :

$C_R = \overline{M}_u/(M_u)_n$ (6.c)

and $(M_u)_n$ is nominal ultimate bending moment given by :

$(M_u)_n = Z\ \sigma_Y\ \phi_n$ (7)

σ_Y and ϕ_n are nominal yield stress and nominal compressive strength parameter. Z is section modulus at deck. From Eq.(7) we can have the required nominal bending moment, $(M_u)_n$ as :

$(M_u)_n \geq \gamma_s\ M_s + \gamma_d\ M_d$ (8)

γ_s and γ_d are given as :

$\gamma_s = \delta_s' / C_R\ \gamma_m\ \gamma_{R1}\ \gamma_{R2}$
$\gamma_d = \delta_d' / C_R\ \gamma_m\ \gamma_{R1}\ \gamma_{R2}$

4.2 Target Reliability Index

Selection of the target reliability index is one of the most important tasks in the context of the reliability-based design philosophy. In this study the target reliability index is derived based on the reliability analysis results shown in the previous section. Although this study deals with only two ship types, the target reliability index may depend on ship type and on the structural type as well.

At present the designer carries out midship section design to satisfy the rule required section modulus at deck. Doing this usually gives high redundancy at bottom structure beyond the rule required section modulus at bottom. From the reliability analysis results of hull girders under sagging shown in Table 5, TK-2 and TK-3 show unlikely low reliability indices and without them the average reliabilty index is 3.09≒3.10. This value is selected as the target reliability index in the average sense. Meanwhile in the case of bulk carriers the target reliability index of hull girders under sagging can be taken less than the average reliability index since the deck design is to some degree redundant. For this, 3.45 is selected as a slightly conservative value in this study.

The target reliability indices, β_T, derived above are summarised as :

Bulk carriers : $\beta_T = 3.45$
Oil tankers : $\beta_T = 3.10$

These values are not unsafe and may be still conservative.

4.3 Partial Safety Factors

With the target reliability indices derived in the previous section, partial safety factors in design code format are calculated. Table 5 shows their average values and COV's. The number of ship models taken in this study is not, of course, enough but can cover medium, large and very large sizes as can be seen in Table 1. From Table 5 it can be seen that there is no correlation between partial safety factors and ship size. The average values of partial safety factors can be, hence, used for re-design procedure with design code formats of Eq.(8)

Table 5 Average partial safety factors(psf)

psf / ship	γ_s	γ_d
bulk carrier	0.44 (0.014)	1.42 (0.013)
oil tanker	0.45 (0.008)	1.30 (0.006)

Note : figures in ( ) are COVs of partial safety factors

4.4 Reliability-Based Re-design Examples

Based on the design code formats with partial safety factors in Table 5, the midship sections of the present ship models are re-designed. Eq.(8) is used to determine the plate thickness of decks. That is, the thickness is determined to satisfy the following condition :

$$\frac{(M_u)_n}{M_{req}} \leq 1.0 \pm \varepsilon \quad (9)$$

where M_{req} is the required design bending moment obtained from the right hand side of Eq.

(8) and ε is a prescribed small number, say 0.01.

Plate thickness is to be changed by increments of 0.5mm and web height(only of stiffener) by increments of 10mm. Table 6 shows the re-designed results for three each of the bulk carriers and oil tankers for illustration. The reliability indices of re-designed hull girder are also included in the same table. The reliability indices are not exactly same as the target reliability indices. The differences between target and re-evaluated reliability indices are 1−6%. If we consider the conservative values of target reliability index of hull girder, it can be said that the re-designed hull girders have sufficient reliability level.

Table 6 Re-design according to reliability-based design code format

Ship	original design		re-design		(Mu)n
	t_D(mm)	β	t_D(mm)	β	Mreq
BC−1	16.5	2.90	18.0	3.46	0.992
BC−4	25.0	3.63	24.5	3.28	0.996
BC−7	34.0	3.81	28.0	3.32	0.991
TK−1	13.5	3.28	12.5	3.00	1.009
TK−5	19.5	3.08	18.5	2.89	1.004
TK−7	18.5	2.88	19.0	2.93	0.993

note : t_D : deck plate thickness
β : reliability index of hull girder

5. Conclusion

This study has concerned reliability analysis and development of a reliability-based design code format for bulk carriers and oil tankers over 100 m length. The target reliability indices of hull girder under sagging bending moment are derived based on the present reliability analysis results. Partial safety factors in design code formats are obtained according to the derived target reliability indices. It has been found that providing a unique set of partial safety factors in design code format, which can be applied to all ship types, is not reasonable and they should probably be provided for each ship type and for each structural member type depending on loading conditions. Re-design examples are illustrated with the proposed code formats and show good results.

The work presented in this paper may be useful in providing the designer with a more rational structural design concept on the basis of ultimate strength and with design alternatives.

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