Safety Levels of Ship Hull Girders in Longitudinal Bending Designed by Different Criteria

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Motivations

- Essential elements for Safety Level Approach
  - To develop tools for quantifying safety level
  - To determine target safety level as a goal
- For setting appropriate level of goal, the safety level of existing ships has to be assessed.
- It is worthwhile to investigate how the safety level of ships has been affected by design rules in different times.

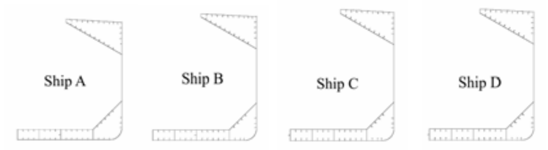
Objectives

- Development of a tool for reliability analysis of ship hull girder in longitudinal bending accounting for the effect of ship operations
- Reliability analysis of four Panamax-size bulk carriers designed on the basis of different rules
  - Pre-IACS UR
  - IACS UR S11
  - IACS UR S11&S25
  - IACS CSR
- Comparison of safety levels of four bulk carriers

Outline of Presentation

- Bulk Carriers for Analysis
- Probabilistic Models
  - Ultimate Longitudinal Strength of Hull Girder
  - Extreme Bending Moment
- Reliability Analysis
- Discussion on Safety Level
- Conclusions

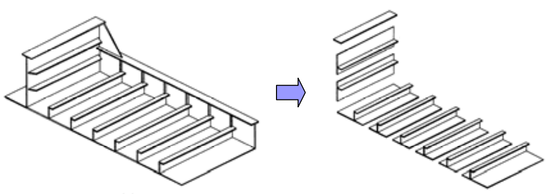
Bulk Carriers for Analysis



Ship	A	B	C	D
L (m)	217.000	217.00	219.000	219.000
B (m)	32.2360	32.260	32.240	32.240
D (m)	18.300	19.300	19.900	19.900
Year built	1987	1999	2007	Design stage
Design criteria	Pre-IACS UR	IACS UR S11	IACS UR S11 & S25	IACS CSR
		Unified & relaxed requirement for section modulus	Introduction of design requirement for various loading and ballasting conditions	Increased thickness and check of ultimate longitudinal strength
Materials	HT36 for upper deck, upper side shell plates and slant plates of top side tank, HT32 for other parts			HT36 for almost all

Ultimate Strength of Hull Girder

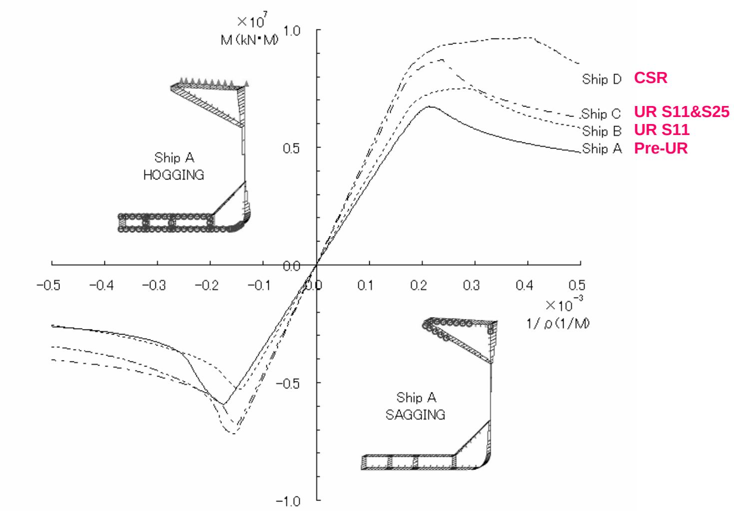
- Progressive collapse analysis of cross section using HULLST (Yao, 1992), which is based on Smith’s method
- A cross section is divided into elements composed of a stiffener and an attached plating.
- Average stress-average strain relationship of each element under axial load is derived considering yielding and buckling in panel and stiffener.
- In HULLST, the relationship is derived analytically.



Ultimate Strength of Hull Girder

- Progressive collapse analysis is performed giving a curvature on the cross section incrementally with the assumptions that
  - A plane cross-section remains plane;
  - No interaction exists between adjacent elements; and
  - Each element follows the average stress-average strain relationship derived in advance.
- Ultimate strength is obtained from the calculated bending moment-curvature relationship.

Ultimate Strength of Hull Girder



Bending moment-curvature relationship

Sensitivity of Ultimate Hull Girder Strength to Design Parameters

Variables		Mean	COV (%)
t_p	Thickness of panel	Nominal values	0.6
t_s	Thickness of stiffener	Nominal values	0.6
σ_{HT32}	Yield stress of HT32	363 MPa	7.0
σ_{HT36}	Yield stress of HT36	402 MPa	4.3
σ_{rc}	Compressive residual stress in plate	Calculated value	30.0

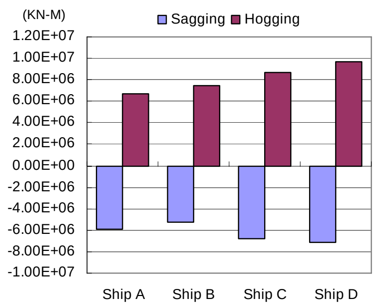
$$\overline{S_i} = \frac{\partial(M_u/\mu_{M_u})}{\partial(x_i/\mu_{x_i})} = \frac{\left(M_u^{+5\%} - M_u^{-5\%}\right)/\mu_{M_u}}{(1.05\mu_{x_i} - 0.95\mu_{x_i})/\mu_{x_i}}$$

Sensitivities

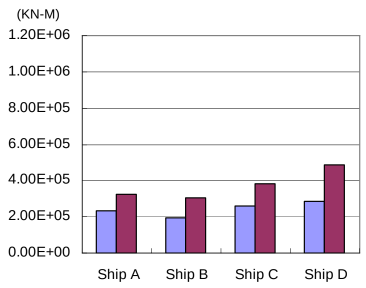
Ship	Variables	t_p	t_s	σ_{HT32}	σ_{HT36}	σ_{rc}
A	Sag.	1.016	0.154	0.057	0.816	-0.059
	Hog.	1.073	0.234	0.616	0.242	-0.057
B	Sag.	1.203	0.446	0.038	0.808	0.037
	Hog.	0.994	0.188	0.511	0.383	-0.018
C	Sag.	1.028	0.252	0.031	0.789	-0.053
	Hog.	0.980	0.231	0.585	0.312	-0.028
D	Sag.	0.943	0.247	-0.008	0.838	-0.050
	Hog.	0.789	0.039	-0.098	0.945	-0.094

Mean and Standard Deviation of Ultimate Hull Girder Strength

$$\mu_{M_u} = M_u\left(\mu_{t_p}, \mu_{t_s}, \mu_{\sigma_{HT32}}, \mu_{\sigma_{HT36}}, \mu_{\sigma_{rc}}\right) \qquad \sigma^2_{M_u} = \sum\left(\frac{\partial M_u}{\partial x_i}\sigma_{x_i}\right)^2$$



Mean



Standard deviation

COV=3.8～5.0%

Still-Water Bending Moment

- A homogeneous loading condition and an alternate loading condition are considered as typical full load conditions.
- The still-water bending moments are treated as the deterministic values in the reliability analysis.

Still-water bending moment at midship

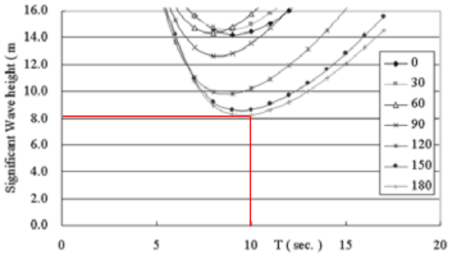
Ship	Homo. Loading (in sagging, KN-M)	Alt. loading (in hogging, KN-M)
A	162,483	1,224,180
B	217,458	785,752
C, D	199,859	1,296,058

Wave Condition to Estimate Extreme Wave Bending Moment

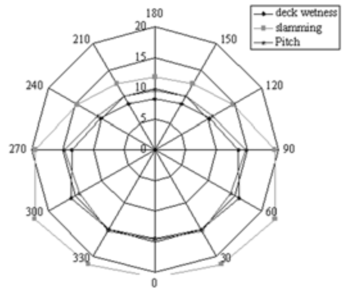
- The most severe wave condition that the ship can actually navigate
- The most severe wave condition is estimated based on the operational restriction with regard to deck wetness, bottom slamming and pitching angle.
- Threshold values assumed are
  - 1/25 in frequency for deck wetness
  - 1/12.5 in frequency for bottom slamming
  - 3.5 degrees for pitching angle
- The ship speed is assumed to be zero in a rough sea.

Wave Condition to Estimate Extreme Wave Bending Moment

Limit combinations of maximum significant wave height Hs and mean wave period T in short-term irregular wave (deck wetness condition; Ship A)



Polar diagram of maximum significant wave height with respect to heading angle (Ship A)

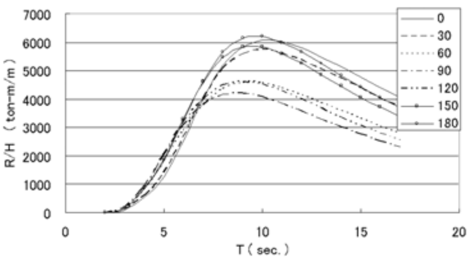


The most severe short-term wave condition is Hs of 8.5 meters and T of 10 seconds.

Deck wetness gives the most severe wave condition.

Wave Condition to Estimate Extreme Wave Bending Moment

Standard deviation of the wave-induced bending moment at mid-ship (Ship A, homogeneous loading)

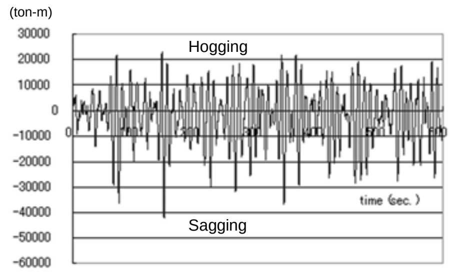


R : STD of Bending Moment
Hs: Significant wave height
T : Mean wave period

The combination of Hs of 8.5m and T of 10 seconds is taken as the most severe short-term irregular wave condition for all the four bulk carriers, which have similar hull forms and sizes.

Probability Distribution of Extreme Wave Bending Moment

A time-domain simulation of nonlinear ship motion in the most severe short-term irregular waves is performed for four ships using the computer code, TSURUGI, developed by Kawabe.



An example of time history of wave-induced bending moment at mid-ship (Ship A)

Probability Distribution of Extreme Wave Bending Moment

The Individual maxima of the response time-history : Weibul distribution

The maximum bending moment in N = 1,000 encounter waves : Gumbel distribution

Mean and Standard deviation of extreme wave bending moment

Ship	Loading condition		Mean (KN-M)	Standard Deviation (KN-M)	COV (%)
A	Homo.	Sag.	3,904,743	488,008	12.498
		Hog.	2,676,443	294,702	11.011
	Alt.	Sag.	4,646,408	542,925	11.685
		Hog.	2,543,507	265,213	10.427
B	Homo.	Sag.	3,563,541	428,658	12.029
		Hog.	2,718,753	295,909	10.884
	Alt.	Sag.	4,033,372	508,462	12.606
		Hog.	2,450,224	243,572	9.941
C, D	Homo.	Sag.	3,835,435	472,253	12.313
		Hog.	2,706,765	293,496	10.843
	Alt.	Sag.	4,072,877	503,263	12.356
		Hog.	2,450,224	243,572	9.941

Method of Reliability Analysis

- MVFOSM (Mean-Value First-Order Second-Moment Method) is applied.

- Performance function

$$Z = M_u - M_d$$

M_u : Ultimate hull girder strength
M_d : Total extreme bending moment

- Reliability Index

$$\beta = \frac{\mu_{M_u} - \mu_{M_d}}{\sqrt{\sigma_{M_u}^2 + \sigma_{M_d}^2}}$$

μ : Mean
σ : Standard deviation

- Probability of failure

$$P_f = 1 - \Phi(\beta)$$

Φ : Standard normal distribution function

Results of Reliability Analysis

Reliability Index

	Homo. loading		Alt. loading	
Ship	Sagging	Hogging	Sagging	Hogging
A	3.420	9.650	4.221	7.095
B	3.154	11.834	3.707	13.536
C	5.181	12.788	7.152	10.870
D	5.674	12.643	7.590	10.922

Probability of failure

	Homo. loading		Alt. loading	
Ship	Sagging	Hogging	Sagging	Hogging
A	3.13×10^{-4}	$<10^{-50}$	1.22×10^{-5}	6.49×10^{-13}
B	8.04×10^{-4}	$<10^{-50}$	1.05×10^{-4}	$<10^{-50}$
C	1.10×10^{-7}	$<10^{-50}$	4.29×10^{-13}	$<10^{-50}$
D	7.00×10^{-9}	$<10^{-50}$	1.61×10^{-14}	$<10^{-50}$

Discussion on Safety Levels (1/3)

1. Under the hogging condition, all the vessels show small probability of failure which is below 10^{-13} level, and the reliability indices are larger than seven.
2. Under the sagging condition, the probabilities of failure are below 10^{-4} level and the reliability indices are larger than three.
3. If Ship A is excluded, the capacity increases with the times and so as the safety level. The pre-UR rules sometimes give heavier scantlings which results in higher capacity and safety level.

Discussion on Safety Levels (2/3)

4. Mansour et al.(1997) analyzed the structural reliability of commercial and military vessels, and recommended a set of life-time target reliability as given in the table. The present results for older ships in the sagging condition shows the safety level close to the target level for ultimate limit state of commercial ships, and newer ships much higher level.

Limit state	Commercial ships	Naval ships
Ultimate	3.5	4.0
Secondary	2.5	3.0
Tertiary	2.0	3.0

(From Mansour AE et al. Assessment of reliability of existing ship structures. Ship Structure Committee Report No. SSC-398, Washington, DC, 1997)

Discussion on Safety Levels (3/3)

5. IACS (2006) reported, based on LRFP (Lloyds Register Fairplay), that the annual frequency of a total loss of bulk carriers was 3.5×10^{-3}. The probability of failure obtained by the present study is smaller than this. The reason for this is considered to be:
   - The hull girder collapse due to longitudinal bending is one possible failure mode that may lead to a total loss of ships. The statistics include other failure modes and scenarios, such as a flooding due to a side panel collapse and a hull girder collapse after collision or grounding.
   - The present analysis does not consider the effects of deteriorated or mechanical damages.
   - The present analysis does not consider the model uncertainty, particularly in the load model (e.g. operational limit and still-water bending moment).
   - MVFOSM, which is less accurate and more optimistic than AFOSM, is employed.

Conclusions

The ultimate hull girder strength of four Panamax-size bulk carriers designed based on the different criteria in different times has been assessed performing the reliability analysis. It has been found that

1. The safety level of four bulk carriers, particularly newer ships, satisfy the target safety level recommended by the previous study.
2. The strength capacity increases with the times, and so the safety level. The exception is the oldest ship designed by pre-UR rules in sagging, of which reliability index is higher than the newer ship designed by IACS UR.

The reliability analysis with consideration of deterioration effects is underway using AFOSM or MCS.