Article ID：1007−7294(2026)06−0984−11

Study on the Safety Margin of the Hull Beams for the Ore Carrier based on the Uncertain Loads Combination Method

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Abstract: The maritime environment and loading conditions encountered by large ore carriers are highly complex. It is a problem worth studying to scientifically describe the uncertain load of ore carriers and evaluate the safety margin of hull beams quantitatively. This paper investigated the stochastic characteristics of environmental loads and ship internal loads and explored methods for combining multiple loads and their nature mechanics. This research also revealed the still-water bending moment characteristics under typical loading conditions. WALCS hydrodynamic analysis software was used to calculate the wave load response function of the target ship. The extreme values of the wave bending moments were obtained using the extreme value type I (Gumbel type I) long-term forecasting method. The statistical characteristics of the wavebending moments were analyzed. Based on the uncertainty load combination method, the hull girder safety margin of the target ship was obtained as 1.10-1.20. The rationality of the load system specified in the CCS rules for ore carriers is further validated. The results show that the method can be applied to the formulation of relevant ore ship rules by CCS and effectively reveal the safety margins behind the rules. Understanding of the GBS-type ship rule has been enhanced. This research provides an important reference for the development of large ore carriers.

Key words: uncertain load; safety margin; still-water bending moment; wave bending moment; ore carrier

CLC number: U663.2 **Document code:** A **doi:** 10.3969/j.issn.1007−7294.2026.06.010

0 Introduction

The trend toward large-scale bulk ore carriers has become an inevitable industry evolution driven by market demands for enhanced transport efficiency. To balance the dual objectives of operational economy and structural safety in such mega-ships, a systematic analysis of the primary structural load components is imperative. This paper conducts a comprehensive study on the probabilistic modeling of uncertain load combinations for ore carriers, and quantitatively assesses the implicit safety margins embedded in existing classification society rules. Through multi-criteria reliability analysis and comparative rule-based evaluations,

Received date：2026−03−30

Foundation items：Supported by the National Key Research and Development Program of China (2024YFC2816303) and the Project of the Ministry of Industry and Information Technology (CBZ03N23-03)

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the study establishes a methodological framework for determining the characteristic values of coupled dynamic loads under different operational scenarios and reveals the inherent safety factors in prescriptive design requirements. The findings provide valuable insights for optimizing structural design while maintaining required safety levels, especially for next-generation ultra-large ore carriers.

During vessel operations, hull structures are continuously subjected to multiple stochastic loads. Crucially, the temporal distribution of these loads ensures that their peak values rarely coincide in time[1], so the combined maximum load typically remains below the arithmetic sum of individual maxima. This temporal decoupling poses significant challenges for large ore carriers, since current methodologies lack a universal framework for combining global longitudinal loads across diverse operational scenarios and load model variations[2−6]. For example, the Ferry-Borges-Castanheta method[7] is applicable to one load model, the load-coincidence method[8] was developed for Poisson-process-type loads, and the point-crossing method[9] is suited to general stochastic processes. The reliability-based computational framework has been established for evaluating still-water bending moments[10]. The corresponding generation mechanisms and dominant influencing factors were analyzed, and the effectiveness of the developed model was verified through statistical analysis and numerical simulation, providing a theoretical basis and supporting safety margin assessment for the optimal design of hull structures. Mansour[11−12] identified that a key issue in load combination involves combining the overall still-water bending moment with the midship bending moment induced by waves. Although various models (e.g. combination factors by Guedes Soares[4] and Moan[5]; Wen[9]; Mansour[11]) have been proposed to predict and improve combinations of still-water and wave bending moments, the issue of fully integrating uncertain loads remains unresolved[12−15]. Nevertheless, the implicit safety margin inherent in existing load combination methodologies has not been sufficiently quantified. In recent years, research advances have integrated probabilistic frameworks with the First-Order Reliability Method (FORM) and Monte Carlo simulations to better characterize load uncertainties, yet a unified approach applicable to ore carriers under variable operational conditions remains lacking[16−17]. For ultra-large ore carriers, graphical interface-based bending moment analysis and global-local combined load stress field reconstruction techniques further ensure the accuracy of load characteristic value determination[18].

In this paper, hydrostatic (still-water) loads are treated as quasi-static, and their uncertainties are quantified using probabilistic methods. Meanwhile, the global wave-induced bending moment is modeled as a narrowband Gaussian process whose maximum values follow a Gumbel distribution. Load combination factors are assigned according to the dominant load type in each scenario. Structural calculations for ore carriers are performed to evaluate the safety level and support the determination of design criteria in CCS rules[19−20].

1 Statistical analysis of the hydrostatic bending moment

Unlike wave-induced loads, which are predominantly governed by marine environmental conditions, hydrostatic loads are determined by the ship’s structural design and weight distribution. Consequently, once cargo loading configurations are specified, the calculated hydrostatic loads have negligible randomness and can be treated as fixed values. However, actual variations in cargo patterns between voyages introduce uncertainty in the hydrostatic bending moments. Accordingly, this study employs a probabilistic methodology to model the annual extreme hydrostatic loads, incorporating voyage-specific loading variations within a marine structural reliability framework.

1.1 Statistical analysis method

Large ore carriers exhibit distinctive hydrostatic bending moment characteristics: sagging moments dominate under normal operations and are significantly larger than the rarely occurring hogging moments. In particular, hydrostatic bending moments under full-load conditions substantially exceed those corresponding to other loading profiles. These quasi-static loads combine with wave-induced dynamic components during each voyage, which motivates a safety margin analysis focused on sagging-dominated conditions. Moreover, modern ore carriers are often equipped with multiple cargo holds, leading to compartmentalized loading patterns. In practice, this requires considering separate load cases for each cargo compartment in the safety assessment.

In the modeling of single-voyage loading conditions, hydrostatic bending moments are assumed to follow a Gaussian distribution. The mean value is set equal to the standard value specified by classification society rules (i.e., the rule-based bending moment), with a coefficient of variation (COV) of approximately 10%. Thus, in structural reliability terms, the characteristic (design) value of hydrostatic bending moment corresponds to this rule-defined standard moment.

The extreme-value behavior of hydrostatic moments tends toward the Type-I (Gumbel) distribution as sample size increases, regardless of the parent distribution. Therefore, a Gumbel distribution is employed to model the annual maximum hydrostatic bending moment. The sample size for a year is determined by the number of loading cycles (voyages and port operations). From statistics of the North Atlantic operations (with an average voyage of about 5 days), roughly 70 independent loading cycles per year are assumed. This sample size is sufficient for applying extreme value analysis under maritime structural reliability practice.

The Gumbel distribution of the annual extreme value of the hydrostatic bending moment is as follows

$$F_l(x) = \exp\{-\exp[-a(x-u)]\} \tag{1}$$

where $\mu = u + \dfrac{0.5772}{a}$ is the mean value of the normal distribution, and $\sigma = \dfrac{\pi}{\sqrt{6}a} = \dfrac{1.2826}{a}$ is the standard deviation of the normal distribution.

1.2 Statistical analysis of the hydrostatic bending moment

Considering non-uniform cargo distribution, prior studies indicate that the hydrostatic bending moment for a single voyage roughly follows a normal distribution. Its mean value corresponds to the maximum loading case in the loading manual and is not less than the minimum required by classification rules.

For the sample ore carrier operating in the North Atlantic, the average voyage duration is 5 days, resulting in about 70 voyages per year. When calculating the annual extreme value, the number of samples is n = 70. The annual extreme value distribution of the still-water bending moment of the sample ship is shown in Fig.1.

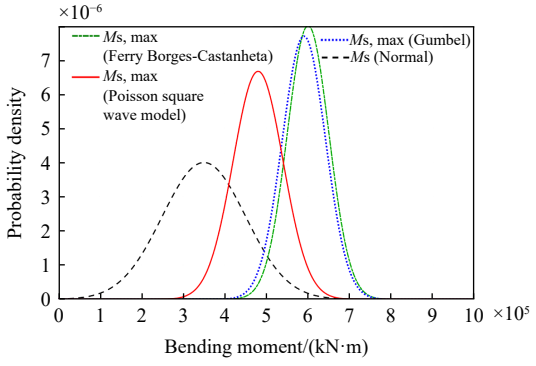


Fig.1 Annual extreme value distribution

The initial distribution in the figure shows that the hydrostatic bending moment of the ore carrier in a single voyage follows a normal distribution, and its probability density distribution of the hydrostatic bending moment is encountered during each voyage. The I-type extreme value distribution represents the annual extreme value probability density of the hydrostatic bending moment, obtained through the 25-year extreme value prediction based on the initial distribution.

Based on the draft variations specified in the loading manual, a series of representative operating conditions (LD1–LD5) are selected. The probabilistic distributions of hydrostatic bending moment under

these conditions are summarized in Tab.1. For each condition, the mean and standard deviation of the single-voyage normal distribution, as well as corresponding mean and standard deviation of the annual extreme (Gumbel) distribution of hydrostatic bending moment are listed.

Tab.1 Parameters of hydrostatic bending moment distribution

Working conditions	Single voyage distribution		Extremum prediction	
	Mean value/(kN·m)	Standard deviation	Mean value/(kN·m)	Standard deviation
LD1	3.7E+06	3.7E+05	8.5E+06	6.2E+05
LD2	4.8E+06	4.8E+05	9.6E+06	7.9E+05
LD3	5.1E+06	5.1E+05	1.0E+07	8.5E+05
LD4	3.6E+06	3.6E+05	6.4E+06	6.2E+05
LD5	4.2E+06	4.2E+05	7.9E+06	7.1E+05

2 Statistical analysis of the wave bending moment

Using three-dimensional linear potential flow theory and commercial numerical simulation software, the vertical wave-induced bending moment transfer function for the ore carrier's critical section was calculated. The resulting time series of wave bending moments was then analyzed statistically. It is assumed that the long-term distribution of wave bending moment amplitudes follows a Weibull law, while the distribution of single-voyage peak moments follows a Type-I (Gumbel) extreme value form. In practice, the long-term wave climate is modeled using the North Atlantic wave spectrum and wave dispersion relations, and sequential statistical methods are employed to estimate the parameters of the single-voyage extreme value distribution.

2.1 Principle of extreme value prediction of the vertical wave bending moment

Wave bending moment prediction methods are usually categorized into short-term and long-term methods. The time range of short-term prediction is 30 minutes to several hours. During this period, the ship's loading state, speed, heading angle, and waves can be assumed to remain constant. The time range of long-term forecasts is several years or the whole life period, during which the above factors change.

Short-term waves can be regarded as a stationary normal random process with a mean of zero. During this period, the ship's loading conditions, sea conditions, speed, and heading angle can be assumed to be constant, and short-term probability distribution is assumed to be independent of each other. The relationship between wave action and wave load can be simulated by stochastic process theory, as shown in Eq.(2)

$$S_{\mathrm{w}}(\omega, H_{1/3}, T_z, V, \beta+\theta) = H^2(\omega, V, \beta+\theta) S_{\zeta}(\omega, H_{1/3}, T_z, \theta) \tag{2}$$

where $S_{\zeta}(\omega, H_{1/3}, T_z, \theta)$ is the wave spectral density; $S_{\mathrm{w}}(\omega, H_{1/3}, T_z, V, \beta+\theta)$ is the spectral density of wave loads; $H(\omega, V, \beta+\theta)$ is the system transfer function; ω is the wave circular frequency; V is the speed of ships; θ is the the angle between the combined wave and the main wave direction; β is the course angle; $H_{1/3}$ is the significant wave height; T_z is the the characteristic period of waves.

For a narrow-banded wave spectrum, the amplitude of the wave-induced bending moment response x follows a Rayleigh distribution. Its probability density function and cumulative distribution function are given by

$$f(x) = \frac{x}{\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2}\right) \quad x \geqslant 0 \tag{3}$$

$$F(x) = 1 - \exp\left(-\frac{x^2}{2\sigma^2}\right) \quad x \geqslant 0 \tag{4}$$

Using these relations, various statistical quantities of the wave-induced response are obtained. In particular, the long-term distribution of the wave bending moment amplitude can be represented by a Weibull distribution. When predicting extreme values of many independent samples, the distribution of maxima tends toward a Type-I (Gumbel) law, regardless of the original distribution. Therefore, the Gumbel distribution is employed for extreme value predictions

$$F_G(y) = \exp\{-\exp[-a(y-u)]\} \tag{5}$$

Its probability density is

$$f_G(y) = a \cdot \exp\{-a(y-u) - \exp[-a(y-u)]\} \tag{6}$$

To apply this, it is assumed that the ore carrier makes about 70 voyages per year. Over a 25-year life, this results in the order of 10^8 wave encounters. From the wave load transfer function, the number of statistically independent wave bending moment samples per voyage is computed. Then, by using Eqs.(5) and (6), the extreme value distribution of the vertical wave bending moment for a single voyage can be obtained.

2.2 Hydrodynamic model and calculation parameters

The vertical wave bending moment RAO is calculated using the wave load direct calculation software COMPASS-WALCS-BASIC of the China Classification Society, which calculates the vertical shear force, vertical bending moment, torque, and horizontal bending moment on 19 transverse sections of the hull. First, the calculation model of the wave load is established, as shown in Fig.2.

Specifically, according to the actual operation of the ore carrier and the North Atlantic environment, considering a speed of 10 kn, the water depth is infinite, the calculation frequency range is 0.2-1.8 rad/s, and the wave direction is calculated to be 0°-180° (an interval of 15° and other probability distributions). The RAO curve of the midship section and its specific values are shown in Fig.3.

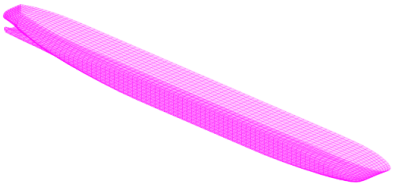


Fig.2 Grid of the wave load calculation model

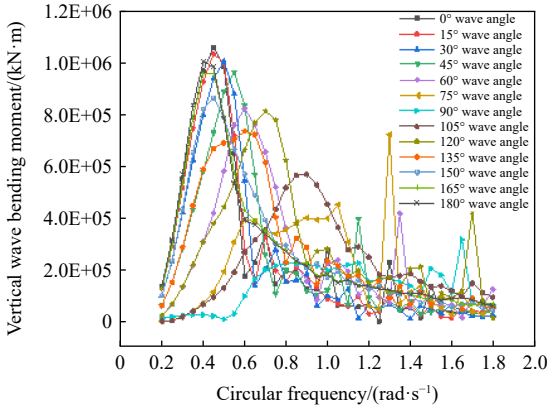


Fig.3 Transfer function of the vertical wave bending moment

After obtaining the vertical wave bending moment RAO of the critical section of the sample ship in each wave direction, long-term prediction is carried out based on the North Atlantic wave dispersion diagram and wave spectrum, and the long-term distribution parameters of the wave bending moment are obtained.

2.3 Prediction of the extreme wave bending moment

Using the computed RAOs, long-term predictions of the wave bending moments were carried out. The wave climate was modeled using the ISSC two-parameter wave spectrum (which includes long-period swell) and representative North Atlantic sea states. The ship heading was assumed uniformly distributed between 0° and 180°, and an exceedance probability of 10^8 was used. The ship speed was fixed (probability weight is 1). The software output provides, for each loading condition, the extreme vertical wave bending moment at each

section. As an example, Tab.2 shows the predicted extreme wave bending moment at the critical section for each of the five load conditions (LD1–LD5). In this table, the software's direct forecast values are compared with the Type-I extreme value predictions. The close agreement between the direct forecasts and the Type-I predictions indicates that the Gumbel extreme value method yields a credible long-term estimation of the vertical wave bending moment.

Based on the wave load transfer function, long-term prediction of the wave load of the sample ship is carried out. The wave spectrum includes the ISSC two-parameter spectrum, and long-period swell waves, and the long-term wave data include the North Atlantic sea states. The heading angle is selected as a probability distribution of 0°-180°; the exceedance probability is selected as 1.0E-8; and the ship speed probability is 1. The prediction results of the software are as follows: Taking LD1 as an example, the extreme value prediction of the wave bending moment in each section is shown in Fig.4. The forecast results are shown in Tab.2.

Tab.2 Prediction results for the extreme wave bending moment

Working conditions	Software forecast value/(kN·m)	Type I extreme value prediction/(kN·m)
LD1	1.23E+07	1.32E+07
LD2	1.53E+07	1.44E+07
LD3	1.92E+07	1.83E+07
LD4	1.13E+07	1.09E+07
LD5	1.47E+07	1.22E+07

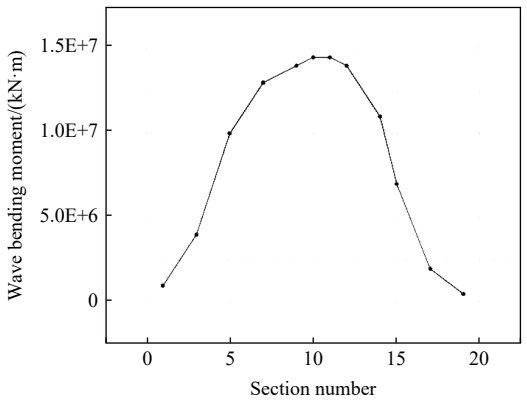


Fig.4 Prediction of the wave bending moment under LD1 condition

Tab.2 shows the direct calculation forecast value and the extreme value I forecast value of the WALCS software. The direct calculation forecast result of the software is close to the extreme value I forecast value, and the result is relatively stable, which reflects that the long-term forecast result of the VWM (vertical wave bending moment) using the extreme value I is credible.

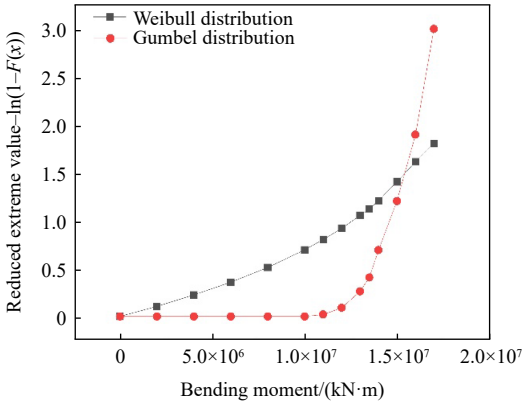


Fig.5 Probability density distribution of the wave bending moment

The long-term distribution of the wave bending moment and the probability density distribution of the extreme value distribution are shown in Fig.5. Compared with the long-term distribution of the wave bending moment, the extreme value distribution of the wave bending moment concentrates on higher bending moment values.

3 Uncertain load combination method and calculation

In earlier ship reliability analysis, the common practice was to simply sum the maximum still-water bending moment and the maximum wave bending moment to define the hull girder's extreme longitudinal

load. This linear superposition is over-conservative, since the probability of simultaneous occurrence of both individual maxima during a service life is very low. Therefore, more realistic load combination methods are essential to account for the stochastic nature of the loads.

3.1 Combination of still water bending moment and wave bending moment

Several methods exist for combining still-water and wave bending moments (e.g., the peak superposition method, crossing analysis, SRSS (Square Root of Sum of Squares), and point-crossing methods). However, studies have shown that simple peak superposition is too conservative, while SRSS or Turkstra methods tend to underpredict the combined moment. The Ferry-Borges method is generally considered the most reliable for estimating global bending moments. Accordingly, the Ferry-Borges combination model is adopted to compute the combined bending moment from the still-water bending moment M_s and the wave bending moment M_w. The cumulative distribution of the combined moment is given by a distribution function of the form shown in Eq.(7). Specifically, at any given time, the instantaneous maximum combined bending moment M_{cw} is determined by

$$F_M(M)=\int_0^M f_{M_s}(M-u)\left[F_{M_W}(u)\right]^m \mathrm{d}u=\int_0^M \frac{f_{M_s}(M-u)\,\mathrm{d}u}{1+v_W/v_s\left[1-F_{M_W}(u)\right]} \tag{7}$$

At a given time T, the maximum value of the combined bending moment is determined by the following equation

$$F(M)=1-1/(v_s\cdot T) \tag{8}$$

where M is the target combined bending moment, f_{M_S} is the probability density function of the still-water bending moment, f_{M_W} is the cumulative distribution function of the wave-induced bending moment, m is the expected number of peaks of the wave load within time T, and v_S is the up-crossing rate per unit time of the static load process at the target bending moment M.

3.2 Analysis of the uncertain load combination calculation

The calculation program is compiled in MATLAB. Combined with the still water bending moment and wave bending moment of the ore carrier under each specified working condition, the combined value of the uncertain load is calculated via Eq.(7) and Eq.(8). The specific results are shown in Tab.3.

Fig.6 shows that, compared with the relatively conservative results of the peak superposition method, the Ferry-Borges combination method is more reliable for calculating the combined bending moment.

Tab.3 Calculation results for the combined bending moment and combined factor

Working conditions	Combined bending moment/(kN·m)
LD1	1.87E+07
LD2	2.08E+07
LD3	2.48E+07
LD4	1.44E+07
LD5	1.72E+07

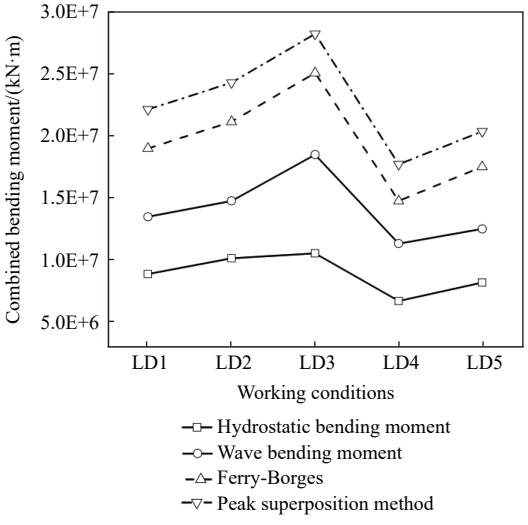


Fig.6 Combined bending moment results

Therefore, the Ferry-Borges combination method is employed to combine the still water bending moment and the wave bending moment in this paper.

4 Statistical analysis of the safety margin

In classification rules, the allowable still-water bending moments and shear forces are defined as envelope values (the maximum values under all operating conditions). However, many loading conditions occur in practice, and the chance that the maximum still-water bending moment coincides with the maximum wave bending moment is very small. The rules conservatively assume that the maximum wave moment occurs at the same time as the maximum still-water moment, effectively embedding an implicit safety margin into the design.

4.1 The principle of safety margin-related statistical analysis

To assess this implicit safety margin, one approach is to statistically combine the wave and still-water bending moment distributions. Wave loads are generally modeled by a Weibull distribution, with the 25-year extreme value used as the design standard. Hydrostatic bending moments can be treated similarly by deriving their statistical distribution and predicting a 25-year extreme as the allowable moment. By convolving the wave load distribution with the hydrostatic load distribution, one can estimate the combined longitudinal bending moment distribution and its ultimate value.

According to many published studies, the longitudinal ultimate bending moment is always smaller than the simple synthesis of the ultimate wave bending moment and the ultimate hydrostatic bending moment. Therefore, a local safety factor is introduced to apply the equivalent reduced load combination coefficient to the wave load or hydrostatic load.

To simplify the calculation process, the following combination of factors φ_s and φ_w for the still water bending moment and wave bending moment is introduced, and the total longitudinal bending moment $M(t)$ is expressed as follows

$$M(t) = \varphi_s M_s(t) + M_w(t) \tag{9}$$

$$M(t) = M_s(t) + \varphi_w M_w(t) \tag{10}$$

where $M_s(t)$ and $M_w(t)$ represent the still-water longitudinal bending moment and wave longitudinal bending moment, respectively; the former stems from static weight-buoyancy equilibrium and the latter from dynamic wave loads.

By calculating the combination factors of the still-water bending moment and wave bending moment, the safety margin of the hull girder hidden in the peak superposition method can be obtained. The specific formula is as follows

$$\gamma = \frac{M_s + M_w}{M_w + \phi_s M_s} = \frac{M_s + M_w}{\phi_w M_w + M_s} \tag{11}$$

4.2 Statistical analysis results of the safety margin

Tab.4 shows the combination factors and corresponding results for the still-water bending moment and the wave-induced bending moment. To determine these factors, the still-water and the wave-induced bending moments under different loading conditions are first statistically integrated: the total bending moment of the hull girder is derived from the mean values and standard deviations of the two load components, and the relative dominance of still-water or wave-induced bending moment in the total load is analyzed. Subsequently, the ratio M_s/M_w of the still-water bending moment to the wave-induced bending moment is

calculated for each condition, and the reduction (combination) factors are inversely solved via Eqs.(9) and (10) based on the load dominance and the calculated ratio. The combination factors vary with different loading conditions during the operation of the ore carrier, which is foreseeable because the probability of the maximum still-water bending moment and maximum wave-induced bending moment occurring simultaneously is extremely low over a long-term service period.

Tab.4 Results of the combination factor calculations

Working conditions	Hydrostatic bending moment combination factor φ_s	Wave bending moment combination factor φ_w
LD1	0.64	0.77
LD2	0.67	0.78
LD3	0.65	0.81
LD4	0.55	0.73
LD5	0.63	0.76

The safety margin calculation results are summarized in Tab.5, and a series of safety margins calculated by Guedes Soares[17]for tankers, Teixeira[6] for four tankers, and Huang[5] for two cruise ships and a bulk carrier is statistically analyzed. The results are shown in Fig.7.

The differences in the results in Fig.7 may be due to the different assumptions made on the selection of

Tab.5 Calculation results of safety margin

Working conditions	M_s/M_w	Safety allowance γ
LD1	0.64	1.16
LD2	0.66	1.15
LD3	0.54	1.14
LD4	0.58	1.20
LD5	0.64	1.17

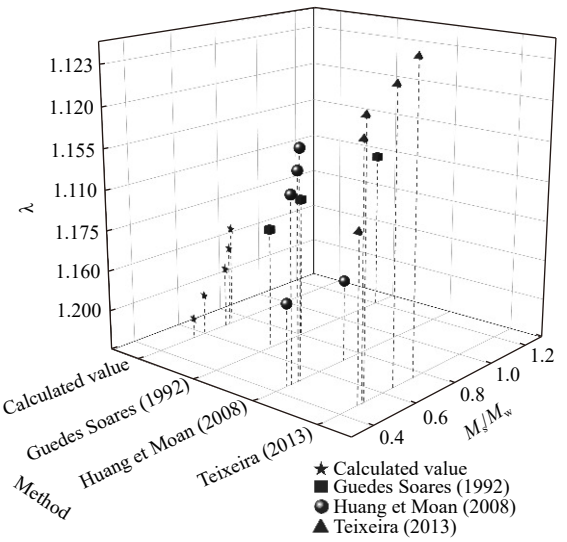


Fig.7 Results of safety margin

the hydrostatic load distribution and operating profiles and the number of voyages per year; however, it can also be verified that the method for calculating the safety margin in this paper is reasonable, and conclusions can be drawn. The range of the safety margin can be taken as [1.14-1.20].

5 Conclusions

The operating environment of large ore carriers is complex, and their cargo capacity is very high. To expose the implicit safety margins behind rule requirements and improve understanding of GBS-type ship regulations, this study aimed to characterize the uncertain loads on an ore carrier and quantitatively evaluate the hull girder's safety margin. From this work, the following conclusions can be drawn:

(1) The primary challenge is correctly representing the uncertainty of hull girder loads. A ship

encounters both still-water loads and wave loads during navigation, but these peaks do not occur at the same time. When the ship experiences its maximum still-water bending moment, it is exceedingly unlikely to also experience the maximum wave bending moment simultaneously (and vice versa). This temporal separation means the actual operational load state is inherently stochastic.

(2) In this paper, for the determination of the still water bending moment, the probability distribution of each working condition is assumed during the process of ship operation to obtain the mean and standard deviation of the still-water bending moment. WALCS software is used to calculate the wave bending moment response of the sample ship, and the extreme values of the medium- and long-term bending moments during the operation of the ship are predicted by the extreme value I method. The IACS literature was used to clarify the combination method of the total load of the hull girder.

(3) Based on standard structural rules, five typical loading conditions were selected for the ore carrier and comparative analysis of the key parameters affecting the safety margin were conducted. The variation in safety margin results depends on assumptions about the hydrostatic load distribution, the selection of the operational profile, and the number of annual voyages. Ultimately, it was found that the safety margin for the ore carrier is approximately 1.14.

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基于不确定载荷组合方法的矿砂船船体梁安全裕度研究

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摘要: 大型矿砂船所处的海洋环境及其承受的装载工况极为复杂, 如何科学描述矿砂船所受不确定载荷并定量评估船体梁的安全裕度, 是一个值得研究的问题。本文研究了环境载荷和船舶内部载荷的随机特性, 探讨了多种载荷组合方法及其力学本质, 并揭示了典型装载工况下静水弯矩的变化特征。采用 水动力直接分析软件计算目标船舶的波浪载荷响应函数, 利用极值Ⅰ型(Gumbel Ⅰ型)长期预报方法获得波浪弯矩的极值, 并分析了波浪弯矩的统计特征。基于不确定载荷组合方法, 得到目标船船体梁的安全裕度为 1.10~1.20, 进一步验证了中国船级社(CCS)规范中矿砂船载荷体系的合理性。结果表明, 该方法可应用于相关规范的制定, 并能够有效揭示规范背后的安全裕度水平, 提高了对目标型船舶规范的研制水平。本文研究为大型矿砂船的发展提供重要参考。

关键词: 不确定载荷; 安全裕度; 静水弯矩; 波浪弯矩; 矿砂船

中图分类号: U663.2　　**文献标识码:** A

基金项目: 国家重点研发计划(2024YFC2816303); 工信部项目资助(CBZ03N23-03)

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