Ultimate strength analysis of longitudinal bending of hull girder based on image analysis

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Abstract. In the traditional code, the allowable stress method is used to check the total longitudinal strength of hull girder, which has the characteristics of simple and quick calculation. However, this method is based on the assumption of elastic materials, and can not truly reflect the actual bearing capacity of the structure. Based on image analysis, a practical method for calculating the ultimate longitudinal strength of ship hull is studied. The average stress-strain relationship of the elements constituting the cross section of the hull girder under axial pressure is given, and the progressive collapse behavior of the hull girder in longitudinal bending is analyzed. Finally, the reliability analysis method for the ultimate strength of the hull girder in longitudinal bending is put forward, and a real ship example is given. The research results show that the proposed method is not only suitable for the safety assessment of ship structures in the conceptual design stage, but also meets the requirements of rapid prediction of real ship wave loads and structural strength reliability analysis.

Keywords: Image analysis; Ships; Hull beam; Ultimate strength of longitudinal bending

1. Introduction
With the development of large-scale ships, super-large oil tankers, bulk carriers, container ships and so on have appeared, and the structural safety of large ships has become increasingly prominent [1]. When a ship is sailing in waves, the load situation is changeable, and the hull members are subjected to abrupt stress and alternating stress for a long time, and accidents caused by insufficient hull strength and fatigue damage often occur [2]. Therefore, ensuring the safe operation of large ships has always been the focus of the shipping industry. Obviously, the research and progress of traditional ship mechanics can't guarantee the absolute safety of ships. The traditional method of nuclear hull strength (forecasting environmental load, calculating hull structural response and evaluating hull safety) can't accurately predict the environmental load of the hull at first, so it can only hinder the structural safety in a certain sense.

The ultimate strength of a ship is the ultimate bearing capacity of the hull structure. Since the concept of ultimate strength of hull girder was put forward, scholars at home and abroad have made extensive research. At present, the main analysis methods of ultimate strength of hull girder include direct calculation method, simplified progressive failure method, nonlinear finite element method and ideal structural element method [3]. With the study of the overall mechanical behavior of hull structure
under extreme loads gradually becoming a hot research topic in the field of international ship structural mechanics [4], the design method of ship structure has changed from the traditional allowable stress criterion design to the limit state design which can reflect the structural strength characteristics more accurately.

The simple method for calculating the ultimate strength of hull girder can be traced back to the middle of last century. Reference [5] puts forward that the ultimate bending moment of hull girder is related to the product of section modulus and buckling strength of hull compression plate. In reference [6], on the basis of the formula, considering the influence of system error and strength redundancy, the coefficient term is added to the formula. The decomposition algorithm given in reference [7] uses empirical formula, so it is called semi-empirical and semi-analytical method. This decomposition algorithm needs to calculate less hull parameters and its expression is simple. This will inevitably bring some disadvantages, that is, lack of theoretical basis. The empirical formula or the distribution of some mechanical parameters obtained through experience is not universal, so it is difficult to adapt to various load conditions of the hull [8]. In this paper, taking materials as ideal elastic-plastic materials, the relationship between stress and strain of structural elements is deduced by an analytical method based on image analysis. The initial imperfection of hull due to welding and the influence of buckling and yielding of plates and stiffeners are considered in the analysis. Then, according to Smith method, a program is compiled to analyze the progressive collapse behavior of hull beams in longitudinal bending, and the ultimate longitudinal strength of hull is obtained, and its statistics are calculated by partial increment method.

2. Ultimate strength analysis method based on image analysis

2.1. Ship image preprocessing

In order to extract the ship navigation target conveniently, it is necessary to study the ship image preprocessing, which is mainly divided into two parts: image filtering and image enhancement.

When shooting and transmitting ship navigation videos, they are usually disturbed by different degrees of noise, and noise will be introduced into the results in a certain link of image processing. Image filtering can suppress or eliminate the appearance of image noise while keeping the details of ship navigation as much as possible. Image filtering is an important part of image preprocessing.

In this paper, mean filtering is chosen as the main filtering method, which has the advantages of uniform Gaussian noise and simple algorithm implementation. The filter template is 3×3, which is shown as follows.

$$H = \frac{1}{9} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$ (1)

In the operation, the unprocessed pixels are placed in the center of the template, and the average value of the pixels in the window $H$ is assigned to the target center pixel, thus achieving the filtering effect.

In the course of sailing, ships often encounter cloudy days, heavy fog and other conditions with low visibility. At this time, because of the low visibility, the shooting effect is blurred, which affects the target recognition. Image enhancement method is usually used for image recognition when visibility is low, such as foggy days and cloudy days. In this paper, histogram equalization is selected for image enhancement.

2.2. Nonlinear finite element method

The brief flow chart of calculating the ultimate strength of hull girder by nonlinear finite element method is shown in Figure 1, and the key to its solution lies in the determination of the calculation scheme.
Because the finite element software involves both geometric nonlinearity and material nonlinearity in the process of simulating the gradual collapse of hull girder, the calculation is complicated. Therefore, when selecting structural loading mode, boundary conditions, grid size, material properties and other parameters, we should not only reflect the actual hull girder structure and its collapse process as accurately as possible, but also take into account the efficiency and cost of finite element modeling and calculation.

Image analysis gives a rough description of the calculation of ultimate strength by nonlinear finite element method, without giving detailed provisions on modeling range, boundary and mesh size of finite element model, but only explains several aspects that have important influence on nonlinear response, such as geometric nonlinear characteristics [9]; Inelastic characteristics of materials; Geometric roughness of plates and stiffeners; Synchronous acting load; Boundary conditions; Interaction between buckling modes; Interaction between structural components; Post-buckling ability.

Image analysis gives only qualitative index, but no quantitative index to the solution of nonlinear finite element method. In the specific application of nonlinear finite element method to calculate ultimate strength, a lot of modeling technology research is needed, so as to form an efficient and reasonable finite element analysis technology.

2.3. Bending of hull girder
In the pure bending theory of ordinary beams, the longitudinal strain can be considered to be linearly distributed along the thickness direction, and the strain at the neutral axis is zero, so the longitudinal strain can be expressed as:

\[
\varepsilon = \frac{M \cdot y}{E \cdot I} \tag{2}
\]

In the pure bending of hull beams, it is considered to obey the law of pure bending deformation of ordinary beams. Strictly speaking, the longitudinal strain caused by vertical bending moment and transverse bending moment at the same point in the proportional limit of material can be linearly superimposed, and the longitudinal strain caused by vertical bending moment and transverse bending moment at the same point in the elastic limit of material can be approximately considered as linearly superimposed.

Remember the total longitudinal bending moment as \( M_r \); Transverse bending moment is \( M^\mu \). It is defined that if the total longitudinal bending moment makes the middle arch of the ship positive, the transverse bending moment makes the starboard arch of the ship positive. The strain at point \( A, B \) can be expressed by linear superposition:
Strictly speaking, in addition, the relationship between load and longitudinal strain of parallel middle body is only applicable under the following conditions: (1) The proportion limit of hull material is within. (2) The hull only bears pure bending action.

However, in engineering application, in addition, the application scope of the load-longitudinal strain relationship of parallel middle body will be expanded. If the torque is small when bearing the torque, the relationship can still be considered to be valid, and the expression of the external load-longitudinal average strain relationship is also considered to be applicable to bulk carriers.

2.4. Reliability analysis
When the function is explicit, the reliability index and failure probability of the function (limit state equation) can be directly calculated by the first order second moment method. It can be seen from the foregoing that the reliability analysis of the ultimate strength in longitudinal bending of hull girder includes the calculation of the ultimate bending moment and external load of hull girder. The ultimate bending moment of hull girder can only be obtained by cyclic iteration. In this case, the Monte Carlo method, stochastic finite element method and response surface method can be used for reliability analysis.

The accuracy of Monte Carlo method is relatively high, but it is very uneconomic because it needs a large number of samples; Stochastic finite element method needs to modify the deterministic structural analysis program, but it is difficult to form a general stochastic finite element program to describe all kinds of randomness in engineering practice; In response surface method, an appropriate function that can be clearly expressed is used to approximate the function that cannot be clearly expressed [10], that is, a response surface

$$Z' = g'(X)$$

is fitted through a series of test points to replace the unknown and true limit state surface

$$Z = g_0(X).$$

Its advantage is that the existing deterministic structural analysis program can be directly used, and the programming is convenient, so it is easy to calculate the reliability index, which is widely used in practical engineering [11-12]. This paper uses this method to calculate the reliability index and failure probability of non-explicit function.

Generally, the response surface function is expressed by quadratic polynomial without cross terms (such as formula (5)),

$$Z' = g'(X) = a + \sum_{i=1}^{n} b_i X_i + \sum_{i=1}^{n} c_i X_i^2$$

(5)

Where $a, b_i, c_i$ is the undetermined coefficient, it can be seen that if there are $n$ variables, the undetermined coefficient is $2n + 1$.

In this paper, the reliability analysis of ultimate strength of total longitudinal bending moment is made, and the random variables considered include material elastic modulus $E$, yield limit $\sigma_y$ and
load variables (hydrostatic load $M_s$, wave load $M_w$), including 4 random variables ($n = 4$). Although the function cannot be expressed explicitly, the limit state equation may be written as:

$$Z = R(E, \sigma_e) - (\eta_1 M_s + \eta_2 M_w) = 0 \quad (6)$$

In which $\eta_1, \eta_2$ is the combination coefficient of $M_s$ and $M_w$ respectively, which is obtained by the previous calculation. Ultimate strength $R$, load and load combination coefficient can be obtained by the method described above. A total of $2n + 1 = 9$ test points are determined near the mean value of each variable ($\mu \pm 3\sigma$) to determine each coefficient in formula (5). After the function function is expressed as explicit formula (5), it can be combined with JC algorithm to calculate reliability index and failure probability.

3. Real ship analysis

3.1. Independent variable model

According to the parameters of real ship given in reference [13], taking the longitudinal bending yield failure mode of hull girder as an example, the reliability analysis of total longitudinal strength is made. The corresponding failure function adopts the nonlinear form of four basic variables:

$$G = Z_d e_y - M_s - M_w \quad (7)$$

In which: $Z_d$ is the section modulus of hull girder; $e_y$ is the yield limit of steel; $M_s$ is the hydrostatic bending moment of hull beam; $M_w$ is the wave bending moment of hull girder. $Z_d$ and $M_s$ are in normal distribution, $e_y$ is in lognormal distribution, $M_w$ is in extreme value type I distribution, and the coefficient of variation is 0.08, 0.09, 0.06 and 0.20, respectively. For convenience, the mean value of each basic variable is directly replaced by the nominal value, and its numerical characteristics are shown in Table 1.

| Code name | $L/m$ | $B/m$ | $C_B$ | $\bar{M}_s/(MNm)$ | $\bar{M}_w/(MNm)$ | $\bar{Z}_d/m^3$ | $\bar{e}_y/(N:mm^{-2})$ | $K$ |
|-----------|-------|-------|-------|-----------------|-----------------|----------------|----------------|-----|
| A         | 92.5  | 10.2  | 0.44  | 14.51           | 74.53           | 0.55           | 288.14         | 1.86|
| B         | 154.6 | 15.5  | 0.47  | 42.58           | 389.96          | 3.88           | 315.28         | 2.63|
| C         | 224.1 | 36.9  | 0.86  | 1127.36         | 2357.66         | 24.53          | 367.45         | 2.17|
| D         | 249.3 | 45.7  | 0.81  | 2967.82         | 3887.63         | 39.41          | 384.77         | 2.03|

Note: In the table, A and B are warships, and C and D are oil tankers; L, b, CB and k are captain, ship width, square coefficient and safety coefficient respectively.

3.2. Stress-strain relationship curve of compression unit

Fig. 2 shows the stress-strain relationship curves of several typical elements under compression under different bending conditions. It can be seen from these curves that the deck stiffened plate element is more likely to fail than the bottom stiffened plate element due to the difference in geometric dimensions, in which the side length ratio $a/b = 850/1250$, the plate thickness $t = 11mm$ and the initial deformation of the plate element are taken as $\delta = 13.5mm$. 
Figure 2 Stress-strain relationship curve of compression unit

Table 2 Load calculation under the condition of middle arch

| Calculate the number of years / a | Hydrostatic bending moment $M_s$ Mean value / KNm | Combination coefficient | Wave bending moment $M_w$ Mean value / KNm | Combination coefficient | Combined value $M_t$ Mean value / KNm |
|----------------------------------|---------------------------------|-----------------|---------------------------------|-----------------|-----------------|
| 1                                | $2.524 \times 10^5$             | 0.445           | $3.874 \times 10^5$             | 0.663           | $5.024 \times 10^5$ |
| 5                                | $3.044 \times 10^5$             | 0.356           | $4.223 \times 10^5$             | 0.528           | $5.336 \times 10^5$ |
| 10                               | $3.452 \times 10^5$             | 0.271           | $4.362 \times 10^5$             | 0.462           | $5.241 \times 10^5$ |
| 15                               | $3.586 \times 10^5$             | 0.255           | $4.486 \times 10^5$             | 0.447           | $5.472 \times 10^5$ |
| 20                               | $3.714 \times 10^5$             | 0.201           | $4.552 \times 10^5$             | 0.386           | $5.458 \times 10^5$ |

Table 3 Load calculation under vertical condition

| Calculate the number of years / a | Hydrostatic bending moment $M_s$ Mean value / KNm | Combination coefficient | Wave bending moment $M_w$ Mean value / KNm | Combination coefficient | Combined value $M_t$ Mean value / KNm |
|----------------------------------|---------------------------------|-----------------|---------------------------------|-----------------|-----------------|
| 1                                | $2.553 \times 10^5$             | 0.447           | $5.122 \times 10^5$             | 0.785           | $6.241 \times 10^5$ |
| 5                                | $2.863 \times 10^5$             | 0.369           | $5.569 \times 10^5$             | 0.682           | $6.639 \times 10^5$ |
| 10                               | $3.005 \times 10^5$             | 0.285           | $5.817 \times 10^5$             | 0.635           | $6.741 \times 10^5$ |
| 15                               | $3.038 \times 10^5$             | 0.254           | $5.963 \times 10^5$             | 0.614           | $6.778 \times 10^5$ |
| 20                               | $3.125 \times 10^5$             | 0.223           | $6.012 \times 10^5$             | 0.607           | $6.719 \times 10^5$ |

The load parameters corresponding to different calculation years are given in Table 2 and Table 3, respectively. It can be seen that the combination factor decreases with the increase of calculation years. This is predictable, because in a longer period of time, the probability of simultaneous occurrence of maximum hydrostatic bending moment and maximum wave bending moment will become smaller. This is predictable, because in a longer period of time, the probability of simultaneous occurrence of maximum hydrostatic bending moment and maximum wave bending moment will become smaller. This is because, on the one hand, the ultimate bending moment of the hull girder is smaller when it is vertically suspended, and on the other hand, considering the influence of nonlinear load, the wave bending moment is larger when it is vertically suspended. As a newly designed large-scale chemical ship, although the reliability index in the middle arch state is too large compared with the target safety index [14], considering that the strength of the ship bottom plate is weakened by local water pressure and corrosion, the reliability index of the ship hull is on the high
side in the middle arch state, so it can be considered that the preliminary design of the cross-section structure is reasonable.

3.3. Bending moment analysis
The total longitudinal bending moment error is shown in Figure 3:

![Figure 3 Total longitudinal bending moment error](image)

It can be seen from the error of total longitudinal bending moment that with the increase of interference torque, the error mean value and maximum value of total longitudinal bending moment do not change obviously, the error mean value of total longitudinal bending moment always hovers around 0.065%, and the maximum error value of total longitudinal bending moment never exceeds 0.25%. The result is satisfactory.

Bending moment variance is shown in Figure 4:

![Figure 4 Moment variance](image)

It can be seen from the error of transverse bending moment that with the increase of interference torque, the average error and maximum error of transverse bending moment gradually increase, and increase linearly with the increase of torque. It can be seen that the existence of torque has a great influence on the transverse bending moment, but it is always controlled within 1%. Comparing the total longitudinal bending moment error diagram with the transverse bending moment error diagram, it can be seen that the total longitudinal bending moment results are better than the transverse bending moment results, but they are all satisfactory.

4. Conclusion
The frequency response function of wave bending moment in regular waves and its statistical standard deviation are given in semi-analytical form. Considering the nonlinear influence of non-straight board and bottom impact on wave bending moment, the empirical fitting expression for calculating nonlinear wave bending moment is put forward, which makes the determination of extreme value and
distribution characteristics of wave bending moment quick, reliable and easy to realize. It is suitable for rapid prediction of wave load and structural reliability analysis in the conceptual design stage of ships. The research shows that the ultimate bending strength of the hull beam of the target ship meets the requirements and has a certain margin. The simplified progressive failure method for ultimate strength calculation in image analysis is mature, while the nonlinear finite element method needs to be further improved in modeling technology. Combined with the calculation results of nonlinear finite element method in this paper, it is considered that the ultimate strength calculation of undamaged hull structure can be simplified appropriately in the modeling of transverse members and the longitudinal scale of the calculation model, so as to reduce the calculation scale and improve the calculation efficiency.

References
[1] Alie M M, Sitepu G, Latumahin S I. The Assessment of the Ultimate Hull Girder Strength of RO-RO Ship after Damages. IOP Conference Series Earth and Environmental Science, vol. 135, no. 1, pp. 012004, 2018.
[2] Cui H W, Yang P. Ultimate Strength Assessment of Hull Girder under Cyclic Bending Based on Smith's Method. Journal of Ship Research, vol. 62, no. 2, pp. 77-88, 2018.
[3] Alie M, Adiputra R. INVESTIGATION ON THE SHIP HULL GIRDER STRENGTH WITH GROUNDING DAMAGE. Makara Journal of Technology, vol. 22, no. 2, pp. 88, 2018.
[4] Cui H W, Yang P. Ultimate strength and failure characteristics research on steel box girders under cyclic-bending moments. Journal of Marine Science and Technology, vol. 23, no. 4, pp. 1-11, 2018.
[5] Nouri Z, Khedmati M R. Progressive Collapse Analysis of an FPSO Vessel Hull Girder Under Vertical Bending Considering Different Corrosion Models. Journal of Marine Science and Application, vol. 19, no. 4, pp. 674-692, 2020.
[6] Kawasaki Y, Okada T, Kobayakawa H, et al. Strength Evaluation of Containerships Based on Dynamic Elastic Response Calculation of Hull Girder. 2nd Report - Influence of Hull Girder Rigidity and Correlation between Double Bottom Bending and Hull Girder Bending. Journal of the Japan Society of Naval Architects & Ocean Engineers, no. 25, 161-173, 2017.
[7] Kawasaki Y, Okada T, H Kobayakawa, et al. Strength Evaluation of Containerships Based on Dynamic Elastic Response Calculation of Hull Girder. Journal of the Japan Society of Naval Architects & Ocean Engineers, no. 25, pp. 191-203, 2017.
[8] Ma L, Yang P, Du J, et al. Study on Ultimate Strength of Ship Hull Girders with Pitting Corrosion Based on CSRB. Wuhan Ligong Daxue Xuebao (Jiaotong Kexue Yu Gongcheng Ban)/Journal of Wuhan University of Technology (Transportation Science and Engineering), vol. 42, no. 3, pp. 461-466, 2018.
[9] Alie M, Latumahina S I. Progressive Collapse Analysis of the Local Elements and Ultimate Strength of a Ro-Ro Ship. International Journal of Technology, vol. 10, no. 5, pp. 1065, 2019.
[10] Ugodo G, Tarnadukobipi D T, Ezebuchi A, et al. Estimation of Longitudinal Light Ship Hull Structure Shear Force and Bending Moment on Still Water. The Journal of Scientific and Engineering Research, vol. 6, no. 1, pp. 166-183, 2019.
[11] Ardiianti A, Nugraha A M, Sitepu G, et al. Study on Longitudinal Ship Strength Caused by the Placement of Beams and Girders on Upper Deck Side. EPI International Journal of Engineering, vol. 1, no. 2, pp. 74-80, 2018.
[12] Andric J, Prebeg P, Palaversa M, et al. Influence of different topological variants on optimized structural scantlings of passenger ship. Marine Structures, vol. 78, no. 3-4, pp. 102981, 2021.
[13] Xu W, Zhou X, Li C, et al. Post-ultimate strength behaviour and collapse severity of ship hull girder under extreme wave load by an analytical method. Ships and Offshore Structures, no. 109627, pp. 1-15, 2020.
[14] Hua L, Lyu Y, Wu F, et al. Discussions on reliability analysis method for ultimate longitudinal strength of hull structure under corrosion damage. Guofang Keji Daxue Xuebao/Journal of National University of Defense Technology, vol. 40, no. 2, pp. 156-160, 2018.
