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Analysis on time variant reliability of primary ship hull subjected to corrosion

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Abstract: A methodology to assess the time-variant reliability of the primary ship structure with hull girder degradation of corrosion is analyzed. The reliability function is calculated at discrete points during the ship's life. A sample calculation is performed for the reliability of a bulk carrier comparing with the present practice and traditional one. And it is shown that, whenever degradation is present, the time dependent reliability calculated with the present practice shows more accurate dynamic result towards the end of the ship's life.

Key words: reliability; corrosion; section modulus; bending moment; hull-resisting capacity
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船体在腐蚀损伤下随时间变化的可靠性分析

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摘 要:分析一种船体腐蚀影响下随时间变化的船体结构可靠性计算方法. 通过可靠性函数对船舶于规定运用期限内的不同时段的状况进行计算,并以一艘散货船为例,与传统的方法进行计算和比较,得出较为实时精确的结论.

关键词: **可靠性; 腐蚀; 剖面模数; 总弯矩; 船体抗极限能力**

0 Introduction

In the recent years, many reliability approaches have been applied to the assessment of probability of failure of the primary ship hull structure. Before 1970's, commonly used definiting method and structural reliability is evaluated over the lifetime of the structure. Formulation of reliability of ship hulls for such a long time frame is not taken into account on the different mechanisms of degradation of the structural resistance. And the approaches are one load and one strength variable, in which the variables are described by their probability distributions, and the measure of safety is provided by the probability of failure. Some approaches are described by the mean value and standard deviation of load and resistance, and safety of the

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structure is quantified by the reliability index with applications of First Order Second Moment (FOSM) methods [1,2].

In fact, ship hull structure will gradually degrade their structural performance during the lifetime. This degradation is a complex phenomenon with the influence of loading, environment, construction technology, structural form and material etc. These factors are in random nature, so, definiting method cannot reflect accurately for the reliability of ship in the whole life.

Therefore, time dependent reliability has become more updated and several authors have explored the different approaches. Some consider the various load processes of interest to determine the maximum combined value of the load effects. And some approach with the implication of a stationary load effect and a decreasing resisting capacity. [3]

This reliability study concentrates on the other aspect of time dependence, i. e. the influence of strength degradation and time variant loading effect on structural reliability. The time dependence of strength that considered here is the result of corrosion of the ship structure. Corrosion is an important strength degradation phenomenon and its action is increasing with the age increasement of the ship. This causes degradation of ship hull section modulus and decreases the hull resisting capacity.

Determining the load effects is one of the major objectives in the reliability assessment and hence time variant load model is considered. Based on these time variant factors, safety margin is considered as a time variant and the ship hull reliability is formulated as a time-variant problem. And a first order reliability method is applied to calculate the safety index and failure probability. In the sample calculation, it is considered that the structural strength has been constant during the structure lifetime and in more detail it has been described by more than one. The demand loading has been considered as the combination of the two main components: the still-water and the wave induced load effects, and both of the two components are time variant.

The main objective is to study the time variant formulation for the reliability of a ship hull with structural degradation and time variant load effect in the design life.

1 Reliability of the ship hull

The reliability of ship hull structure traditionally considers resistance or capability exceeding the predicted load or demand since the structural design of the primary structure of ship hulls is based on the concept of providing enough flexural modulus to the amidships section. The hull is modeled as a beam and its section modulus governs the levels of elastic stresses developed on the deck and bottom, which turns out to be used as a measure of the capability of the cross section against collapse. The resisting capability of the ship hull is given as the product of the section modulus by the yield stress of the material. The demand is the combined effect of the still-water and the wave induced vertical bending moments. Different approaches have been used to model the load variables. The common approach is to combine the still-water and the wave induced load effects by just summing them. [3]

However, being both random, their maxima will not be achieved at the same time which implies the need of a load combination factor that reduces one of the effects to account for that. The total vertical bending moment M_t in terms of the extreme values of the two components M_{se} and M_{we}

$$M_t = M_{se} + F_L M_{we} \tag{1}$$

where, F_L is the load combination factor and it varies between 0.6 and 0.8 depending on the particular ship under consideration. M_{se} and M_{we} are extreme still-water and wave induced bending moment.

Another possibility of taking the load combination into account is to make use of the Turkstra Rule 3 that basically says the maximum combined value occurs when one of the loads reaches its maximum and the other is at its random point in time value such as at its expected value. The total moment is defined as

$$M_t = \max[(M_{se} + M_w), (M_s + M_{we})] \tag{2}$$

where, M_s and M_w are the still-water and wave induced bending moments at a random point in time. The formulation that has been first used in a second moment approach to the ship's hull reliability defines the safety margin M as

$$M = M_c - M_s - M_w \tag{3}$$

Another common formulation consists in defining the safety margin of the ship structure as

$$M = M_c - M_s - M_{we} \quad (4)$$

where, M_{we} is the most probable maximum wave induced bending moment during the ship's lifetime. The most probable extreme value of the wave-induced loads, M_{we} i.e., mode, which we may refer to as a mean for convenience and its standard deviation σ_w can then be computed based on up-crossing analysis as follows

$$M_{we} = \sqrt{2\lambda_0 \ln N} + \frac{0.5772}{\sqrt{2\lambda_0 \ln N}} \quad (5)$$

$$\sigma_w = \frac{\pi}{\sqrt{6}} \sqrt{\frac{\lambda_0}{2 \ln N}} \quad (6)$$

here, $\sqrt{\lambda_0}$ is the root-mean-square value of the short-term wave-induced bending moment process at amidships. N is the expected number of wave bending peaks. M_c is the hull resisting capacity.

$$M_c = Z_0 F_y \quad (7)$$

where, Z_0 is the amidships section modulus and F_y is the yield stress of the material. For the assessment of time-invariant reliability, the value of Z_0 is the constant designed value for the whole ship life. In fact, load carrying capacity of ship hull section modulus and the demand bending moments are varying with time. Here, the value of section modulus is considered with time variant during the ship life and time variant combined bending moments.

1.1 Degradation of section modulus

The corrosion influence on the load carrying capacity is considered. The value of section modulus Z is decreased due to the degradation effect of corrosion. This is a process that leads to a monotonic loss of strength with time, decreasing the capability that the structure has for resisting the loads imposed. Generally, corrosion will occur in all structural elements, both in the plating and in the stiffeners, by decreasing the plate thickness at a rate (see Fig 1)[4]. Two levels of corrosion rates can be considered, namely the average and severe level, the former being based on all collected data of corrosion measurements and the latter being based on 95% and above band of the measurements.

So, corrosion rate may be different in the different structural elements and it depends on many factors including coating properties, cargo composition, inert gas properties, temperature of cargo, maintenance systems and practices. Therefore, the corrosion rate model should be appropriately based on the statistics of measurement data.

Fig. 1 Ship's structural damage due to corrosion

Practically, the time-variant corrosion rate model may be divided into three phases. In the first one, there is no corrosion because of the protection of coatings, and corrosion rate is zero. The second phase is initiated when the corrosion protection is damaged and corrosion occurs, which reduces the plate thickness. The third phase corresponds to a constant corrosion rate. There are different types of corrosion model to predict the corrosion degradation[5], and PAIK & THAYAMBALLI have suggested a model as

$$t_r = C_1 (T - T_c - T_t)^{C_2} \quad (8)$$

where, t_r is depth of corrosion (thickness loss due to corrosion); T_c is coating life; T_t is transition time between coating durability and corrosion initiation; T is structure age; C_1 and C_2 are the coefficients taking account of the characteristics of corrosion progress. For practical design purposes, it is often assumed that $C_2 = 1$.

The probability density function of the coefficient may then be assumed to follow the Weibull distribution

$$f_{C_1}(x) = \frac{\lambda}{\alpha}\left(\frac{x}{\alpha}\right)^{\lambda - 1} \exp\left[-\left(\frac{x}{\alpha}\right)^{\lambda}\right] \quad (9)$$

where, α and λ are scale and shape parameters, respectively, which will be determined through a probability density fit using the method of moments, the maximum likelihood method or other appropriate method. Mean and COV (Coefficient of Variation) of the coefficient can then be calculated by statistical analysis once the corrosion measurement data are available. The most probable (or average) level of corrosion damage will be predicted if all gathered corrosion measurement data are used for the statistical analysis

1.2 Hull girder loading

Determining the load effects is one of the major objectives in the reliability assessment When a ship is floating on still-water, there will be differences in the forces exerted upon the hull, which have to be taken into account when the ship is loaded. Alternate loading can result in shearing pressures, while uneven loading can cause the ship to sagging or result in hogging

When the ship is operating in the sea, these sagging and hogging bending moments can happen due to the combined action of wave effect and cargo distribution. While hull girder resistance is degrading due to corrosion, the demand loading will be also varied with the operation lifetime. Due to their variation, the reliability of the ship structure will also be varied with time. Since ship hull girders are predominantly subjected to combine actions of still-water and wave-induced bending moments, time variant total bending moment will be applied. For practical considerations, total bending moment at a specified operation life is

$$M_{t,T} = M_{s,T} + \Phi_w M_{w,T} \qquad (10)$$

where, Φ_w is a load reduction factor, $M_{w,T}$ and $M_{w,T}$ are still-water and wave-induced bending moment of a specified operation life, $M_{s,T}$ and $M_{w,T}$ can be determined for the sagging condition

$$\frac{M_{s,T}}{M_{s,o}} = \frac{\sqrt{\ln(v_s T)}}{\sqrt{\ln(v_s T_o)}}, \quad \frac{M_{w,T}}{M_{w,o}} = \frac{\sqrt{\ln(v_w T)}}{\sqrt{\ln(v_w T_o)}} \qquad (11)$$

and for the hogging condition

$$\frac{M_{s,T}}{M_{s,o}} = \frac{\sqrt{\ln(v_w T)}}{\sqrt{\ln(v_w T_o)}}, \quad \frac{M_{w,T}}{M_{w,o}} = \frac{\sqrt{\ln(v_w T)}}{\sqrt{\ln(v_w T_o)}} \qquad (12)$$

These are based on maximum still-water and wave-induced bending moment of 20-year design life.[6] v_s is the mean arrival rate of one load condition and v_w is the mean arrival rate of one wave cycle. The specified maximum still-water bending moment is already defined by IACS[7], and for the sagging and hogging condition respectively are

$$M_{s,0} = -0.065 C_w L^2 B (C_B + 0.7) \qquad (13)$$

$$M_{s,0} = C_w L^2 B (0.1225 - 0.015 C_B) \qquad (14)$$

in which, L, B and C_B are ship length, breadth and block coefficient, while CW is wave coefficient

$$C_w = 10.75 - [(300 - L)/100]^{3/2}, \quad 100 < L \leq 300$$

$$C_w = 10.75, \quad 300 < L \leq 350$$

$$C_w = 10.75 - [(L - 350)/150]^{3/2}, \quad L > 300 \qquad (15)$$

For the maximum wave induced bending moment defined by IACS is

$$M_{w,0} = -0.11 C_w L^2 B (C_B + 0.7) \ (\text{sagging}) \qquad (16)$$

$$M_{w,0} = 0.19 C_w L^2 B C_B \ (\text{hogging}) \qquad (17)$$

This value is normally taken as the mean value of the extreme wave-induced bending moment which the ship is likely to encounter during its life time. For convenience, the mean value of bending moment is often taken from the above empirical formula that has been suggested for a first cut estimation bending moment by some classification societies in the past The variation in still-water bending moment is usually assumed to follow the normal distribution. The COV associated with still-water bending moment of a merchant cargo vessel is normally large, perhaps as high as 0.4.[6] The COV associated with the wave-induced bending moment can be defined as σ_w / M_w from Eqs (5) and (6) on which the short-term response is based, while it is sometimes assumed to be 0.1 when predicted from Eq. (5).

1.3 Time-variant reliability

Load effect and resistance will be modeled as a stochastic process and the formulation of safety margin will be described as a time variation

$$M(t) = M_c(t) - M_t(t) \qquad (18)$$

here, $M_c(t)$ is the time dependent load resistance and $M_t(t)$ is the time variant total bending moment which can be calculated with Eq. (10).

The reliability index $\beta(t)$ is given by the ratios of the mean value $M(t)$ to the standard deviation $D_M(t)$ of the safety margin

$$\beta(t) = \frac{M(t)}{D_M(t)} \qquad (19)$$

and the time variant reliability index can be related with failure probability

$$P_f(t) = \Phi(-\beta(t)) \qquad (20)$$

Φ is the standardized normal distribution, $P_f(t)$ is the failure probability with time t

2 Sample mathematical text

The formulation presented above has been applied to the assessment of the reliability of a bulk carrier with deadweight of 170 000 t, length of 282 m, breadth of 50 m, depth of 26.75 m, block coefficient of 0.826 and service speed of 15 kn. The yield stress was considered to be 355 MPa with COV 35 MPa. The mean value of still-water bending moment and wave-induced bending moment in the sagging condition for the design life are 4.21 GN·m and 7.1 GN·m respectively. And their standard deviations are 1.6 GN·m and 0.0081 GN·m. Time variant total bending moment for the specified operation period is considered for sagging and can be obtained by applying Eq. (10). Variation of still-water and wave-induced bending moments can be seen in Fig. 2. The mean value of extreme wave induced bending moment is 5.93 GN·m and COV is 0.1.

ship hull sagging

ship hull hogging

Fig. 2 Ship hull sagging and hogging conditions

To quantify the time variation of the hull section modulus, typical values of severe corrosion rates have been determined. The corrosion depth of individual member categories is predicted from Eq. (8) with T_c = 7.5 a, excepting for inner bottom plates and lower slope plates which may take a shorter coating life, i.e. T_c = 5 a. The mean and COV of coefficient C_1 for the severe corrosion rates is considered according to reference [4] and assume C_2 = 1. If the corrosion rates are gotten, degradation of section modulus can be calculated.

The key factor to formulate a reliability problem is able to show the effect of the degradation of strength with time and still practically enough to use is the choice of the time duration to which structural reliability is referred to. The strength degradation induced by corrosion of plates is a very slow varying process which only yields noticeable changes in the section modulus after several years. Therefore, degradation of section modulus due to corrosion rates has been determined every four years for simplicity of calculations. The standard deviations of section modulus with a no repair assumption are 0.337, 0.525, 0.769, 1.046, and 1.305 respectively for every four years. The extreme corrosion situation of no repair during the ship's lifetime has been assumed although being aware that it is too severe. However, it shows more clearly the effect here. The coefficient of variant of these uncertainties has to be combined with the one of the yield stress to give the variance of the moment capacity. Mean value of section modulus is 43.454 m^3 and the variation of mean section modulus for every four years is shown in Fig. 3 and Fig. 4.

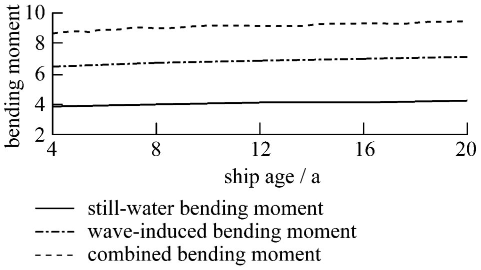

Fig. 3 Variation of mean value of still-water and wave-induced bending moments with operation time

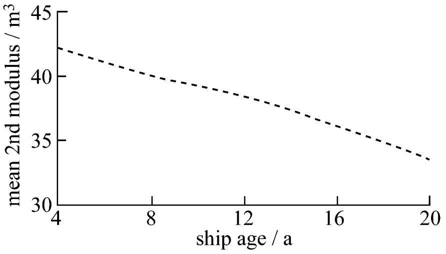

Fig. 4 Variation of mean value of ship section modulus due to corrosion

The problem is the time variant reliability with stochastic process of load effect and resistance of a ship structure. The reliability and probability of failure of primary ship structure are calculated with proposed method by accounting section modulus degradation and time variant bending moment, as well as the reliability with initial section modulus (without considering degradation of section modulus) and time variant load effect. And then the reliability with variant section modulus and stationary load effect (with extreme wave-induced bending moment) are calculated. The mean extreme wave-induced bending moment for this equation is calculated with Eq. (5) and variance with Eq. (6). This method is a common method of reliability calculation with hull degradation. The results are described by comparing with the results of proposed method The result time variant reliability and failure probabilities are shown in Fig 5 and Fig 6 Time variant reliability is calculated for shorter reference periods of four years for more accurate results And it is shown that the resultant reliability index without accounting strength degradation is obviously different from the results of considering it Moreover, whenever degradation is present, time dependent reliability calculated according to the present practice, comparing with the common method, shows some difference during 8 years of ship life, but after 8 years, it doesn 't show very high distinct of safety levels

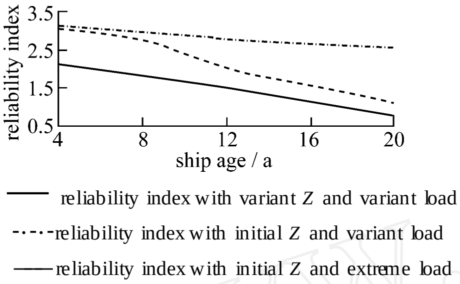

Fig 5 Time-dependent reliability index for a bulk carrier with corrosion

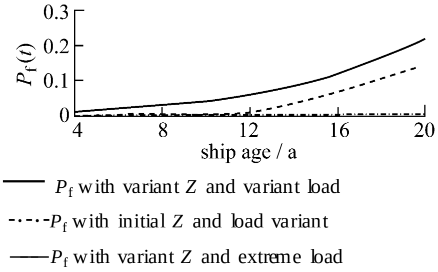

Fig 6 Time-dependent probabilities of failure for a bulk carrier with corrosion

3 Conclusion

A formulation is presented to quantify the time variation of the reliability of the ship primary structure, which is able to account for load variation and the effect of strength degradation due to corrosion It is shown that the present practice of calculating time variant reliability is simple, convenient, and the result is also more dynamically accurate than the common approach The calculation results may be useful in the reliability assessment of new ship construction, and inspection, maintenance and repair schemes of existing ships

For the practical work of ship hull reliability subjected to corrosion, operational parameters including maintenance, repair work should be paid attention Special attention should be given to preserve the integrity of the coatings inside the holds Once a hold becomes empty, surfaces should be cleaned thoroughly and wherever possible, and be given a final rinse with fresh water Ballast tank coatings should also be maintained in good order

A special examination should be made after a potentially corrosive cargo such as high sulphur coal has been carried Exceptional rates of corrosion have been reported, and additional checks are warranted

The main areas prone to corrosion such as the bracket toes at the connection of the main frames to the hopper and topside tanks, and the upper and lower boundaries of vertically corrugated transverse bulkheads should be closely examined on a regular basis and it should be repaired wherever necessary and carefully

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