Safety assessment for ship hull girders taking account of corrosion effects

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The demand for great reliability of a ship hull girder is one of the problems facing the ship structural designer. That is because the hull girder may experience different modes of failure during loading, ultimately leading to its collapse. This paper is devoted to present how the reliability analysis can be applied to ship hull girder. The ISUM is adopted to analyse the hull girder and determine the mean of ultimate strength. The mean of extreme vertical bending moment is estimated from DNV Rules. For reliability analysis, the cov's associated with uncertainties are quantified for both loads and strength based on existing data. Then, the safety index and probability of failure at collapse are assessed by FORM. Moreover, the degradation of primary members due to general corrosion is also considered with improving the ultimate strength of the aged hull through a coating renewal and /or steel replacement is suggested. A bulk carrier of 60,000 DWT is analyzed to predict the renewal actions.

يعتبر انهيار هياكل السفن من الحوادث التي تتسبب في خسارة الأرواح البشرية وكذلك تلوث البيئة .لذلك تم في هذا البحث اختيار طريقة الاحتمالات لتصميم بدن السفينة وحساب معامل الأمان لها و تحديد معوليه هيكل السفينة عند تعرضها للانهيار أو احتمال زيادة الأحمال على مقاومة هيكل السفينة.وتعمل طريقة الاحتمالات على الأخذ في الاعتبار المتغيرات المختلفة اللازمة لعملية التصميم. إن حساب معوليه السفينة تحتاج إلى حساب دقيق لمقاومتها العظمى عند تعرضها لأقصى حمل .تم استخدام طريقة الوحدة الإنشائية المثالية لتحديد المقاومة العظمى لهيكل السفينة ثم دمج الطريقتين معا لتقدير درجة معوليه هيكل السفينة. تم التركيز على أخذ ظاهرة الصدأ في السفن الناقلة للمواد الصب من جهة تأثيرها على معوليه السفينة .تم تطبيق الطريقة المقترحة على سفينة صب حمولة ٦٠.٠٠٠ طن لتحديد درجة معوليتها.

Keywords: Hull collapse, Ultimate strength, ISUM/FORM, Reliability, Bulk carriers, Corrosion effects

1. Introduction

One of the catastrophic events of ships is collapse of the hull girder. Such an event will imply a risk of loss of human lives and a risk of polluting the environment, dependent on ship type. In order to evaluate the reliability of the hull collapse, it is necessary to have a tool, which can calculate the strength of the hull girder. Moreover a probabilistic method for evaluation of the probability of failure is required. It is not only the acting load on the hull, which is an uncertain parameter. Also, the strength of the hull is uncertain due to uncertainties of the material properties and the geometry of plates and stiffeners. Therefore, the safety assessment of the ship's hull must take into account these uncertainties.

An integrated method, which calculates the safety level of the ship's hull and considering uncertainties mentioned above was developed [1]. The suggested method linked between the following two methods:

1- The Idealized Structural Unit Method (ISUM), which is used to calculate the ultimate strength of the ship's hull when subjected to vertical bending moment.

2- The First Order Reliability Method (FORM), which is used to determine the safety index against hull collapse and its corresponding probability of failure.

The developed method was implemented in a computer program (ISUM/ REL). The computer program was successfully applied to plate panels, stiffened plate panels and box girders [2]. For the sake of general applications, the method will be applied to an existing bulk carrier to determine the important variables, which affect on the safety level of ship's hull.

Furthermore, it has been reported that over 150 bulk carriers were lost during 1980-1990 [3]. It has been indicated that the age of most of these ships was over 15 years, and significant effects are related to corrosion. The suggested approach is used to examine the effect of corrosion on the safety level and ultimate strength of an existing 60,000 DWT bulk carrier. The probabilities of renewal actions for the same bulk carrier are predicted.

2. Evaluation of ship's hull strength

The ultimate strength of a ship may be defined as the acting bending moment, which leads to the collapse of the hull girder. The collapse of the hull girder is governed by buckling, yielding and brittle failure of materials. Moreover, the strength against each failure mode is influenced by the initial deflections, residual stresses; corrosion and fatigue cracks. Due to the complexity of the problem, the collapse of ship hulls must be investigated by numerical procedures such as Finite- Element Method (FEM). Several numerical methods for longitudinal strength analysis of ship hulls have been developed. The FEM is a powerful method, however, it requires large modeling efforts and computing time for large structures. Therefore, most efforts in the development of new calculation methods are focused on reducing modeling efforts and computing time. Ueda and Rashed developed a method called the Idealized Structural Unit Method (ISUM) [4]. The ISUM can effectively analyze the non- linear behavior of large size plated structure as in ship structures, under general loading conditions. Lots of elements have been developed to analyze the behavior of the overall ship structures taking into account the geometrical and material non-linearity and the post ultimate state [4, 5, 6]. In the present study, the application of ISUM to the hull girder will be demonstrated through an existing bulk carrier.

3. Corrosion in ship structures

Two main corrosion mechanisms are generally present in steel plates making up the ship's hull. One is a uniform wastage that is reflected in a generalized decrease of plate thickness. Another mechanism is pitting which consists of much localized corrosion with very deep holes appearing in the plate. According to [7], pitting does not affect the average in-plane stress distribution in bottom or deck plates and thus the compressive strength of the plates is not affected. However, pitting is considered when the fatigue analysis is required which is out of the scope of this study.

The corrosion rate of a steel hull is governed by external factors such as corrosion control device, vessel type, structural member location, temperature, humidity,...etc. However, losses of coating are defined as the main cause of corrosion. It was found from measured data that the plate thickness reduction of uncoated members may be four times that of comparable painted plates [8]. The suggested approach by the authors for safety assessment of ship hull could be successfully applied to assess the reliability of aged hull girders taking into account the degradation of strength of primary members due to corrosion.

3.1. Corrosion model

Two different times for corrosion initiation of the bulk carrier's hull can be assumed such as after 5 years or after 10 years [3]. From the structural surveying, the second suggestion of 10 years may be irrational. For the chosen bulk carrier, it is considered that the uniform corrosion starts after 5 years from the time of new building, which is chosen as an extreme (worst case) possibility. Paik et al. [9] developed a probabilistic corrosion rate for the longitudinal strength members of bulk carriers based on the statistical data for measured corrosion damage as follows:

1-The corrosion rate for the boundary plates between ballast tanks and cargo regions (inner bottom- hopper plates) are higher than those of the bottom and bilge plates.

2-Deck and side shell plates may be relatively corroded compared to other external surfaces.

3- Most of longitudinal stiffeners in ballast tanks have similar corrosion rates except for

the deck longitudinal stiffeners.
The previous corrosion model will be applied when the bulk carrier is analyzed.

3.2. Probabilistic model of corrosion rate

Permissible wastage of plates due to corrosion at different locations is commonly specified as percentages of original plate thickness. The severity of corrosive damage is often judged in terms of annual thickness reduction (mm/year). The conventional models of corrosion rates have been found to vary linearly with time. In this case, the effect of corrosion on plate thickness can be expressed by [10]:

$$t = t_o - r_c T = t_o - d(t), \qquad (1)$$

where,

t is the plate thickness after corrosion
t_o is the initial plate thickness
r_c is the annual corrosion rate.
T is the number of years in service.
$d(t)$ is the reduction of plate thickness

The experimental evidence of corrosion shows that a non- linear model is more practical. For the sake of simplicity, the linear model of corrosion is more appropriate for design purposes, and will be used in the present study. However, if any member is corroded more than a specified amount, it is practically renewed so that the structural condition is maintained at an acceptable level. The classification societies govern that the reduction of the ultimate strength due corrosion is not to be more than10 % of the original (as-built)[11]. After that, ship's hull needs a steel replacement routine for corroded members.

4. Limit state function

For the hull girder collapse, the vertical bending moment is a primary load component. Furthermore, the total bending moment is composed of two components, namely, the still water load component (M_{sw}) and the wave induced load component (M_w). The combinations of these components have been discussed in [12]. Then, the total bending moment (M_T) can be defined as:

$$M_T = \Psi_{sw} M_{sw} + \Psi_w M_w. \qquad (2)$$

Where, Ψ_{sw} is the moment combination coefficient for still water bending moment. Ψ_w is the moment combination coefficient for wave induced bending moment.

In general, the ship hull fails when the applied load exceeds the hull ability to carry that load. Thus, the limit state function associated with hull girder collapse can be written as:

$$g(\mathbf{X}) = M_u - (\Psi_{sw} M_{sw} + \Psi_w M_w) \geq 0. \qquad (3)$$

In the following, the probabilistic models of the ultimate strength and acting bending moment are described.

4.1. Probabilistic model of the ultimate strength

Generally, the ultimate strength, M_u, of the hull girder is a function of three variables, namely, t, σ_o and E. Thus, it can be written as: $M_u = M_u(t_i, \sigma_{oi}, E_i)$. Where the subscript i indicates the i^th^ primary member.

The exact form of the distribution of these variables is not known. However, the characteristics of these variables may be taken as indicated in table 1.

Table 1
Random variables related to inherent uncertainties in strength [13]

Random variables	Distribution	cov
Plate thickness, t	Normal	0.05
Yield strength, σ_o	Normal	0.1
Young s modulus, E	Log- normal	0.03

As mentioned before the ultimate hull strength is calculated using ISUM. It is considered to be normally distributed with a coefficient of variation of 15% [13].

4.2. Probabilistic model of vertical bending moment

The still water and wave induced bending moments are estimated by the DNV design formulae as follow [14].

1-Design still water bending moment: According to DNV, the specified maximum still water bending moment for a ship in a design lifetime of 20 years is given by the following formulae:

$$M_{sw} = 0.065C_w L^2 B (C_B+0.7) \text{ kN.m, (sagging),} \quad (4\text{-a})$$

$$M_{sw}=C_w L^2 B (0.1225-.015C_B) \text{kN.m, (hogging).} \quad (4\text{-b})$$

Where L and B are ship length and breadth in meter, C_w can be calculated from ref. [14].

Uncertainties in still water bending moment depends on the ship type, loading condition, voyage route, etc. Due to changes in cargo loading condition from voyage to voyage, the coefficient of variation (cov) of the still water bending moment is normally assumed to be a large value. It can be approximately given by the following formula [15]:

$$\delta_{sw} = 0.523/\exp[0.199475(\log N)^{1.1251}]. \quad (5)$$

N is number of loading cycles. Based on the analysis performed in the ship structure committee, values of cov range from 20% to 90 % [16]. The available statistical results have shown that a normal distribution may be appropriate for the still water bending moment.

2-Extreme wave induced bending moment: According to DNV, the specified maximum wave induced bending moment for a ship in a design lifetime of 20 years is given by the following formulae:

$$M_w=0.11C_w L^2B (C_B+0.7) \text{ kN.m, (sagging),} \quad (6.a)$$

$$M_w = 0.19C_w L^2 B C_B \text{ kN.m, (hogging).} \quad (6.b)$$

Paik et al. [15] suggested that the cov of extreme wave induced bending moment varies with the number of loading cycles N. This result may be approximated as follows:

$$\delta_w = 0.9760/\exp[1.272(\log N)^{0.361}]. \quad (7)$$

The peak amplitude of M_w follows an exponential distribution, which is defined at 10^{-8} exceedance probability. The maximum of a large number of realizations of an exponential distribution is distributed in accordance with a Type- I extreme value distribution [16].

4.3. Model uncertainties

The development of a reliability analysis depends to a large extent on the ability to quantify the uncertainties associated with the loads acting on a structure and with those associated with the strength. These uncertainties may be divided into two types, that is, inherent and modeling uncertainties [13]. Inherent uncertainties arise from the variability in physical quantities such as dimensions, material properties and loads. Modeling uncertainties are a result of simplifications, assumptions and inaccuracies in the prediction of a model for desired quantities such as structural response, loads and strength. Modeling uncertainties can be incorporated into a reliability analysis by introducing a modeling variable *x* to represent the ratio between actual and prediction model response or output.

Thus, the limit state function, eq. (2), can be rewritten by including additional random variables representing model uncertainties as follows:

$$g(\mathbf{X})=x_u M_u-(x_{sw}\Psi_{sw}M_{sw}+x_w \Psi_w M_w) \geq 0, \quad (8)$$

where, x_u is the model uncertainties associated with ultimate strength, and x_{sw}, x_w is the model uncertainties associated with still water or wave induced bending moment. It is assumed that the probability function of any random variable representing a model uncertainty follows the normal distribution [16].

5. Reliability analysis method

Since the reliability analysis is discussed in many references, such as [17] and [18], only a very brief description is given here. Generally, the probability of failure can be calculated as follows:

$$P_f = \int f_x(\mathbf{X})\, dx. \quad (9)$$

Where f(**X**) is the joint probability density function of the random variables, $\mathbf{X} = (x_1, x_2, .., x_n)$, associated with loading, material properties, geometrical characteristics, ..etc., and g(**X**) is the limit state function. g(**X**) is usually a complicated nonlinear function, and it is not easy to perform the integration of eq. (9) directly. Therefore, eq. (9) is normally solved by use of an approximate procedure [17]. One of these approximations is called First Order Reliability Method (FORM), since the limit surface is approximated at the design point by a tangent hyperplane. In other words, eq. (9) is solved numerically by transforming the basic correlated variables **X** to standard normal correlated variables **Y**, by using the Nataf model, see [19]. The limit state then becomes:

$$G_Y(y) = g_X(x) = 0. \qquad (10)$$

6. Numerical examples

6.1. Problem formulation

To evaluate the safety of a ship hull girder using the suggested approach, the hull girder of an existing 60,000 DWT class bulk carrier is considered. The principal dimension of the candidate ship is as follows.

Length(LBP) =190m Breadth(B_m) =32.26 m
Depth (D_m) =18.3m Block coeff.(C_b)=0.875

One web frame space of the hull girder at the midship will be modeled using ISUM plate and beam elements as shown in fig.1. The total numbers of the idealized plate units, beam units and nodal points are 84, 154 and 160, respectively. The hull girder is then assumed to be subjected to vertical bending moment. This bending moment is produced by applying increasing axial displacements over the cross section at x = 0,as shown in fig. 2. The extreme values of the still water bending moment and the wave- induced bending moment acting on the ship are calculated on the basis of eqs. (4) and (6), respectively. The involved variables can be summarized in table 2. The safety assessment of the bulk carrier will be determined in two cases, namely, *as- built and aged hull.* The collapse of the hull girder is attained when the acting bending moment exceeds its ultimate strength, as defined in eq. (8).

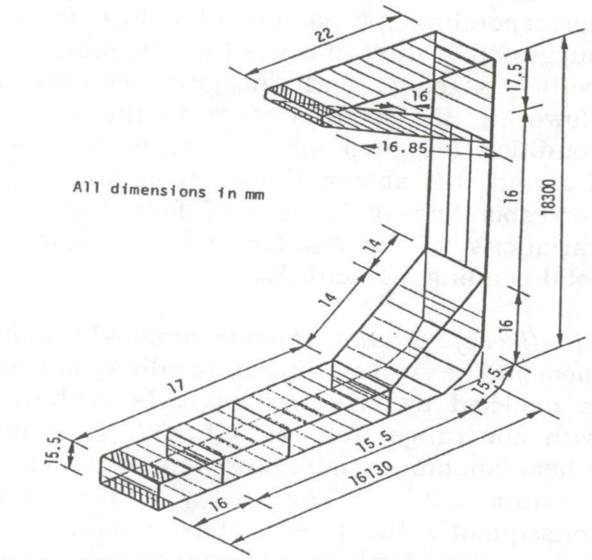

Fig.1. ISUM model of 60,000 DWT bulk carrier.

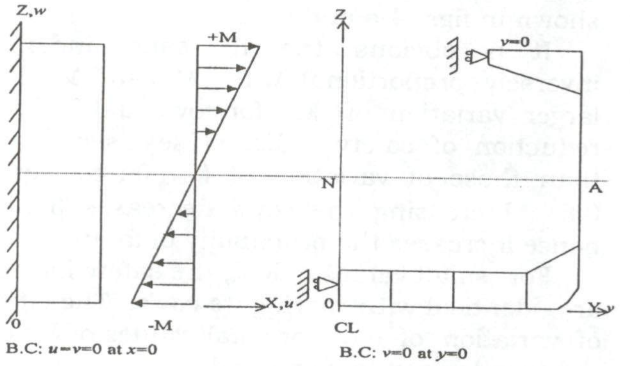

Fig. 2. Boundary and loading conditions for the hull module.

6.2. Numerical results

Using the developed computer program (ISUM / REL), the ultimate strength of the bulk carrier is firstly estimated. Then, the safety index and the corresponding probability of failure are calculated for different values of M_{sw} and M_w with varying of their cov's. The results are presented as follows.

6.2.1. As-built hull

a) Effect of variation of still water bending moment. The still water bending moment is modeled by a normal distribution with values of cov ranging from 0.2 to 0.9 [19], while other random variables are kept as indicated in table 2. The safety index and the corresponding probability of failure for the suggested values of cov is then calculated for both sagging and hogging conditions. However, the results due to the severity condition (sagging) are only presented. Figs. 3-a and 3-b shows the safety index and the corresponding probability of failure with the variations of the M_{sw} for different values of total bending moment (M_{act}).

b) Effect of variation of wave- induced bending moment. The wave-induced bending moment is modeled by an extreme type-I distribution with cov range from 0.15 to 0.6 [19], while other random variables are kept as indicated in table 2. The safety indices and consequently the probabilities of failure for the suggested values of M_T can be calculated. The results for the sagging_condition are shown in figs. 4-a and 4-b.

It is obvious that the safety index is inversely proportional with M_{sw} and M_w. For larger variation of M_{sw} for cov equal 0.9, the reduction of safety index is less significant than those of variation of M_w for cov equal 0.6. Increasing the cov's decreases β and hence increases the probability of failure.

For small values of M_{sw}, the safety indices are identical with varying its cov's. The effect of variation of cov for small values of M_w on safety index can be neglected.

6.2.2. Aged hull

a- Effect of corrosion initiation. Undoubtedly, the progress of corrosion will normally depend on the degradation of anti-corrosion coating. Therefore, the corrosion model can be divided into two parts, namely the life of coating and the progress of corrosion. It is assumed that the corrosion will start immediately after the loss of coating effectiveness. It is known that the mean value of coating life is normally from 5 to 10years.

Fig 5 shows the variation in ultimate strength of the corroded hull, using the corrosion rates indicated in fig. 6. It is seen from fig. 5, that the ultimate strength of the corroded hull (M_{uc}) should be significantly reduced with increase in the age of the ship. For instance, the ultimate strength of the hull girder after 20 years is only about 87 % of the original one (M_u). The time- variant safety index of the corroded hull for both sagging and hogging conditions is plotted in fig.7.

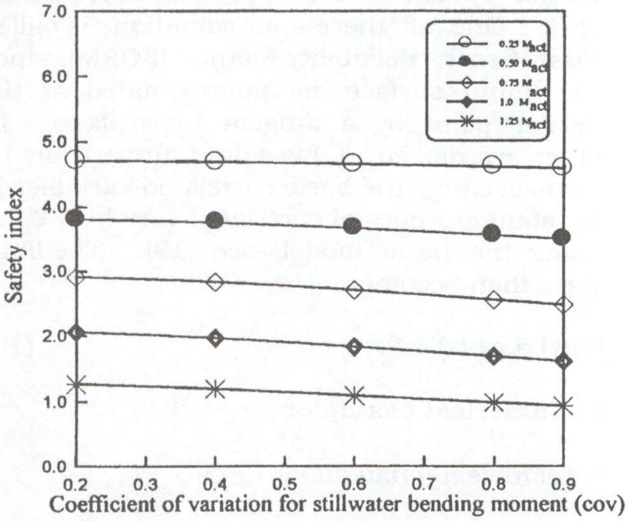

Fig.3-a. Effect of variation of still water bending moment on safety indexes (sagging condition).

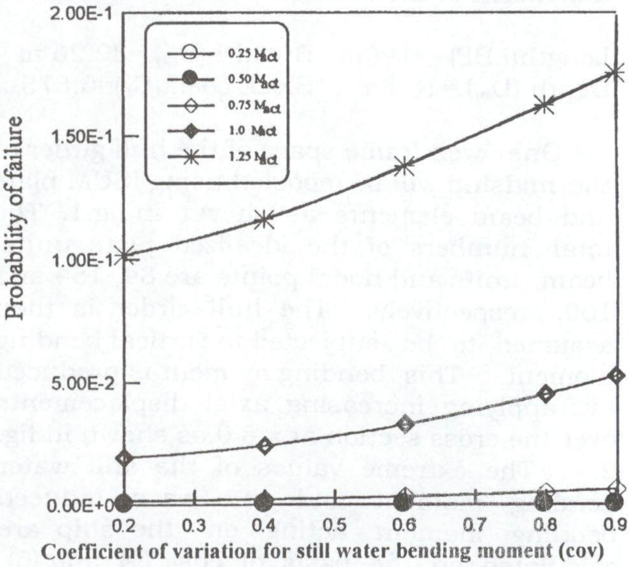

Fig.3-b. Effect of variation of still water bending moment on probability of failure (sagging condition).

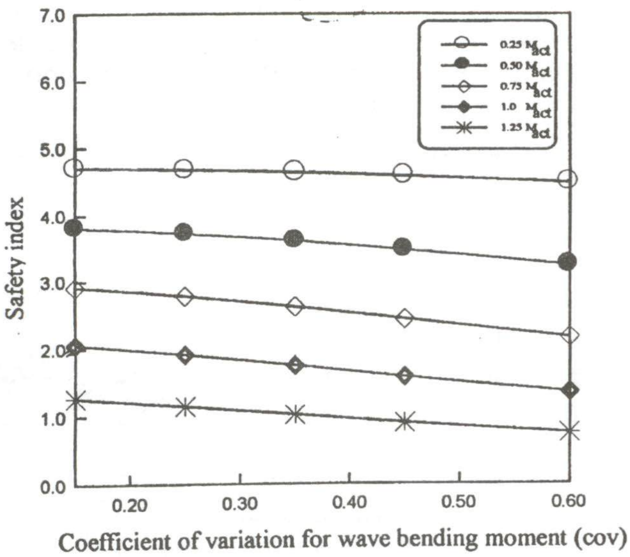

Fig.4-a. Effect of variation of wave bending moment on safety index (sagging condition).

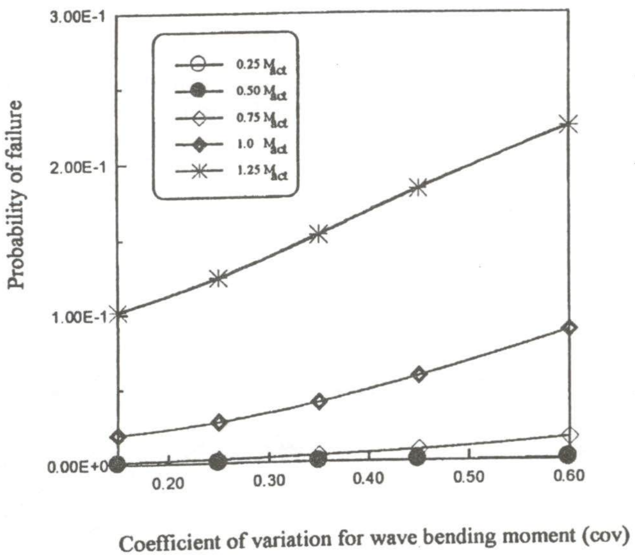

Fig.4-b. Effect of variation of wave bending moment on probability of failure (sagging condition).

It is seen that, the safety index for the hull after 20 years decreases from 2.177 to 1.695 in hogging, meaning about 22% reduction has occurred. Similarly, for the sagging condition, the safety index of the hull girder after 20 years reduces from 2.05 to 1.568, which is corresponding to 24% reduction.

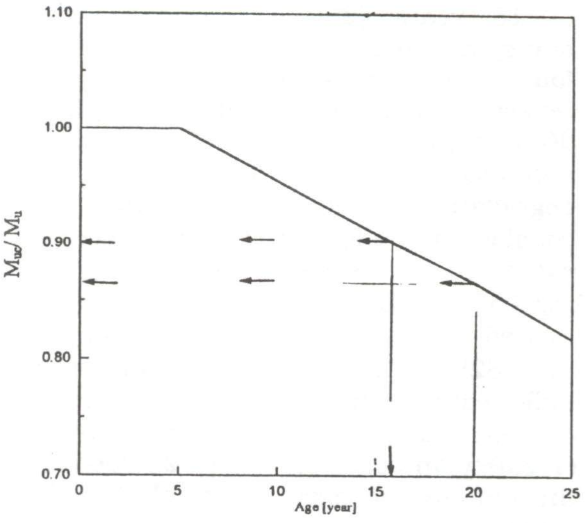

Fig. 5. Variation of ultimate strength with increase in the ship age.

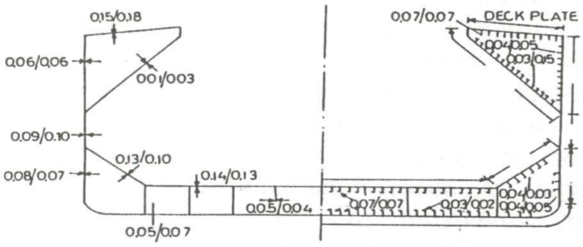

Fig.6. Probabilistic corrosion rate for the bulk carrier.

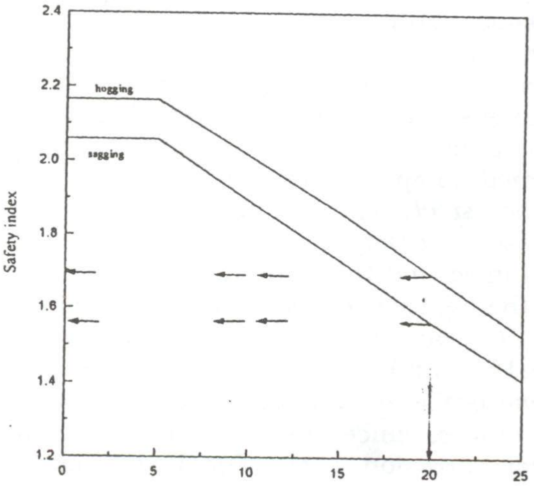

Fig.7. Variation of safety index with increase in the ship age.

b-Effect of renewal actions. As one would expect, the probability of renewal is normally increased as the ship gets older, and after 10 years from starting of corrosion, i.e. at the age of 15 years [20]. From the structural surveying and replacement practice, it is found that, a ship is subjected to steel renewal when its ultimate strength reaches 90% of the original, i.e. after 16 years. This specifies the limit of the ultimate strength degradation, which will be used for the considered bulk carrier. The corresponding safety index is 84 % of its original value (β_o=2.177). Equivalently, the steel renewal is carried out when the safety index becomes (β_c=1.82). Thus it is suggested here that the bulk carrier under the maximum allowed corrosion should stay between the two values of safety indices (2.177-1.82), depending on the amount of corroded steel. Possibility of increasing the safety index could be obtained through three suggestions of renewal actions. These are proper coating renewal or steel replacement or both. These will be discussed through the hogging condition as follows:

1-The coating renewal: It will undoubtedly increase the lifetime of steel according to the used system of coating. To illustrate some of the possibilities of the renewal actions, two types of coating renewal after the first 5 years are suggested, namely, every 5 years and 2.5 years. Then, the lifetime of shipbuilding steel will be increased to 19 years and about 25 years, respectively, in spite of the corrosion continuing with the same rates as shown in fig. 8. As one would expect, the renewal of coating every 2.5 years is the best to increase the safety level. In all cases, the safety index of the hull after steel renewal is assumed to approach its initial value.

2- The steel replacement: To predict the increase of safety index with steel renewal, it is assumed that the structural member which has the higher corrosion rate will be replaced after 10 years from starting of corrosion (i.e. after 15 years). As indicated in fig.5, the renewal probability of deck members is higher than others, since the deck is subjected to highest corrosion rate. For the chosen bulk carrier, deck (including plating and stiffeners) constitutes about 18% of the total cross section of the ship. When the deck is replaced by a new one after 15 years, the ultimate strength will increase from 91% to 96% of the original value, and also the safety index of the whole hull girder will increase from 1.86 to 2.05 as shown in fig.9. In other words, replacing about 18% of the whole hull (deck) will increase the ultimate strength about 5% and the safety index about 10%.

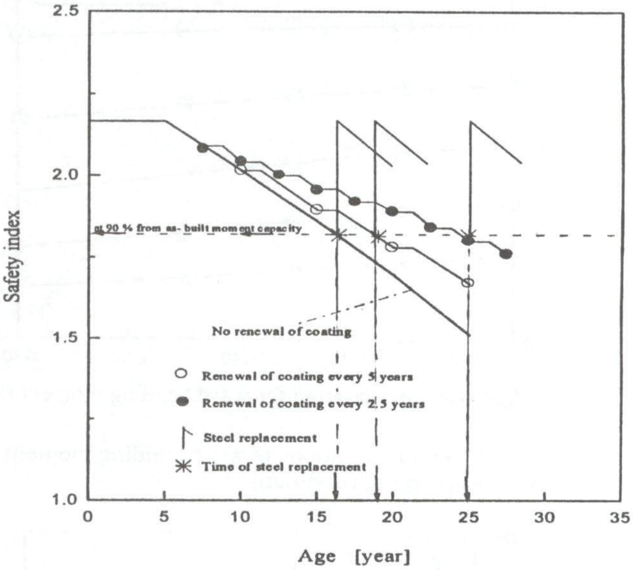

Fig. 8. Variation of safety index with increase in the ship age for different systems of coating.

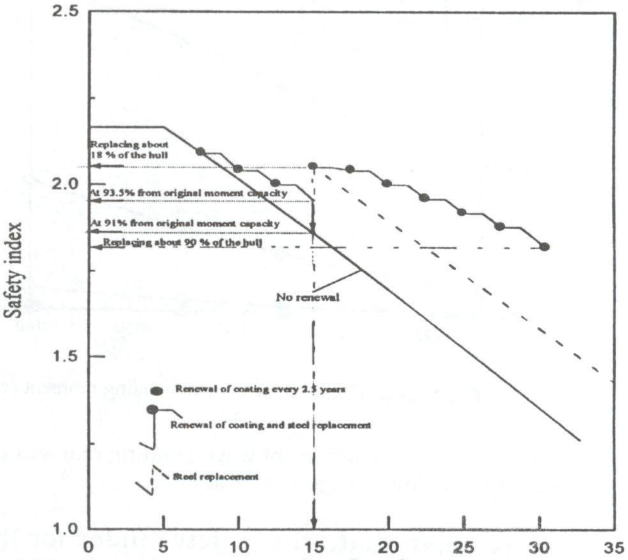

Fig. 9. Variation of safety index with increase in the ship age with renewal actions.

3-The coating renewal and steel replacement: When the coating renewal (every 2.5 years) and the deck replacement (after 15 years) are carried out simultaneously, the ultimate strength will increase from 93.5% to 96% of the original value, which is corresponding to 2.5% increase. Also, the safety index will increase from 1.955 to 2.05, which is corresponding to 5% increase.

By comparing the results obtained by renewal of coating and steel replacement, it is found that, if the deck is replaced by a new one the reduction of the ultimate strength of the hull girder is 5%. Moreover, if coating renewal and steel replacement are carried out simultaneously, the reduction of the ultimate strength is about 2.5%. That means, a saving of the required amount of replaced steel can be obtained, i.e. about 50%, to reach to the same level of strength (96% of the original). Also, the lifetime of the ship will be increased to 30 years, see fig.9.

The local plate replacement for the deck only will never restore the original hull strength and hence the original safety index. The hull strength in this example will reach 96% of the original and the safety index will be 93% of the original value after deck replacement, see fig. 9. That is because certain parts of the structure continue to remain in their corroded state even when other parts are renewed to their original state. In general terms, the global strength of the hull girder does not return to its original value. The results obtained from the possible

Table 2
The involved variables for the bulk carrier

Variables	Distribution	Mean	Unit	cov
M_{sw}	Normal	5.03404×10^5 (sag) 5.3812×10^5 (hog)	kNm kNm	0.2
M_w	Type- 1	10.6491×10^5 (sag) 9.8×10^5 (hog)	kNm kNm	0.15
x_u	Normal	1	-	0.1
x_{sw}	Normal	1	-	0.05
x_w	Normal	0.9	-	0.15

Table 3
Results of renewal actions for bulk carrier

Items Renewal actions	β	M_{uc}/ M_u [%]	Lifetime [year]	Increase of lifetime [year]	Figure
1- No renewal	1.82	90	16	-	Fig.8
2-Coating renewal every 5 years			19	3	
3-Coating renewal every 2.5 years			25	9	
4-Steel replacement [18 %]	2.05	96	22.5	6.5	Fig.9
5-Steel replacement and coating renewal every 2.5 years (3+4)			30	14	

renewal actions of the corroded bulk carrier may be summarized in table 3.

7. Conclusions

Some important observations may be made from the results of this analysis as follows:

1- The safety index is highly affected with two factors, namely the value of the cov of both M_{sw} and M_w and the acting bending moment. In which, at the smaller value of acting bending moment, the values of safety indices are almost identical for various cov. While, these values of safety indices are different for various cov, at the larger acting bending moment.

2- The ultimate strength of corroded hulls could significantly decrease when the ship gets older. For the bulk carrier chosen as a case study, it was found that the ultimate strength of its hull decreased about 10 % after 16 years due to corrosion. But the degree of decrease could be controlled by a proper coating renewal and/or proper steel replacement.

3- By appropriate coating renewal only, the lifetime of the bulk carrier could be increased. The lifetime of the investigated ship increases from 16 years to 25 years with renewal of coating every 2.5 years.

4- By appropriate steel replacement of corroded members, the level of reliability of the hull is increased immediately after repair. By replacing the deck platings after 15 years, the bulk carrier lifetime was increased to be 22.5 years instead of 16 years.

5- Moreover, the combining of the coating renewal together with the proper steel replacement is usually practical and it will save as much as 50 % of the required steel to be replaced to reach the same ultimate strength, as well, the lifetime of the ship increases by 87.5 %.

6- The suggested approach in the present study for safety assessment of ship's hull can be applied to any type of ships. Such approach can be linked to a ship design approach quite easily. This could be used in the future by ship classification societies for developing the reliability- based design.

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