Reliability of double hull tanker plates subject to different loads with corrosion effects

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The aim of the present paper is to demonstrate the effects of deterioration by corrosion on the reliability of double hull tanker plates subjected to different loading conditions. Classification of the loading to which a ship is subjected is presented. The uncertainties involved in the structural reliability analysis and in the modeling process are described. The difference between the conditional and the total reliabilities is discussed. Corrosion rate modeling techniques are considered focusing on the linear model for the general corrosion. The acting loads are calculated using DNV rules and transformed into still water and wave induced compressive stresses and pressure at the critical locations using the finite element program (GLFRAME). The proposed mean values and the COVs of the different random variables are indicated. The limit states discussed in this study are based on the API code and involve a plate element subject to uniaxial compression (ultimate) or lateral pressure (ultimate). Results of the reliability analysis are presented and discussed for a double hull tanker. The main conclusions of this study are presented.

الغرض من هذه الدراسة هو توضيح تأثير التآكل على معولية ناقلات البترول مزدوجة البدن تحت تأثير حالات تحميل مختلفة. تم فى هذه الدراسة تصنيف الأحمال المختلفة التى تتعرض لها السفن بالاضافة الى وصف لعناصر عدم التأكد فى التحليل المعولى الانشائى وعملية النمذجة. بعد ذلك، تمت مناقشة الفارق بين المعولية المشروطة والمعولية الكلية ومن ثم استعراض النماذج الرياضية لعملية التآكل مع التركيز على النموذج الخطى. وقد حسبت عزوم المياه الساكنة والعزوم الناتجة عن الامواج وقوى الضغط باستخدام قواعد هيئة التصنيف النرويجية (DNV) وحولت هذه الاحمال الى اجهادات فى المناطق الحرجة باستخدام برنامج الحاسب الآلى (GLFRAME) لطريقة العنصر المحدد. وقد تم بيان القيم المتوسطة ومعاملات الانحراف للمتغيرات العشوائية المختلفة بالاضافة الى حساب حدود الانهيار الناشئة عن الاحمال المختلفة وذلك باستخدام قواعد مؤسسة البترول الامريكية (API) . وفى نهاية البحث تم استعراض ومناقشة نتائج التحليل المعولى من خلال مثال رقمى لناقلة بترول مزدوجة البدن ثم استعراض أهم الاستنتاجات التى تم التوصل اليها من خلال الدراسة.

Keywords: Double hull tanker, Ship structural reliability, Corrosion, Corrosion rate and coating life

1. Introduction

During the life of the ship, the structure deteriorates to a lesser or greater degree. Such deterioration is due to a variety of causes. The main phenomenon, generally, is corrosion. Corrosion has a harmful consequence from the point of view of safety and can lead to thickness penetration, fatigue cracks, brittle fracture and unstable failure. This failure will imply a risk of loss of human lives and a risk of polluting the environment dependent on ship type. After the grounding of the Exxon Valdez in Alaska a new design practice is used for tankers. It is required that new tankers be built with double bottom and double sides in order to avoid/minimize oil outflow in case of grounding or collision.

Failure statistics reveal that corrosion is the most common defect in steel vessels and is the dominant cause of structural failures for ships older than 8 years. A corroded steel plate is not only thinner but also more brittle and is thus more prone to initiating fatigue cracks. High stress concentration induces microscopic cracks in the highly stressed parts of the steel structure. These cracks propagate also into the coating and act as pockets where corrosion action begins. It is therefore necessary to eliminate any critical defects prior to service and to prevent non-critical defects to grow to critical size during service [1].

In this study, a procedure is developed for time dependent reliability analysis of corroded steel plates of a double hull tanker, based on ultimate collapse of the plate elements, and taking into account the degradation of primary members due to general corrosion. The reliability and the reliability index (conditional and total) associated with the corroded plate are calculated using the First Order Reliability Method (FORM) [2].

2. Corrosion

Corrosion can be defined as the chemical or the electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties, fig. 1.

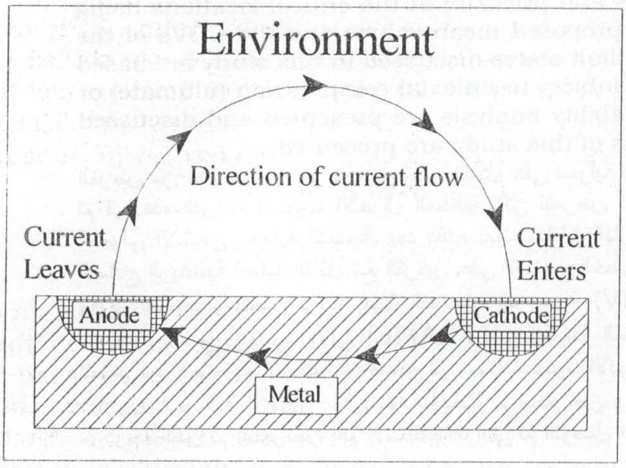

Fig. 1. Requirements of corrosion of metals.

In this study, we consider general corrosion. A layer of rust appears largely on surfaces that are uncoated. Over time, the rust scale continually breaks off, exposing fresh metal to corrosive attack. It is important to point out that, in addition to general corrosion, there are other types of more localized corrosion patterns identifiable in ships. Some of these are pitting, grooving and weld metal corrosion [3].

3. The double hull tanker

The double hull tanker is a ship for the carriage of oil cargo or oil products. The cargo area is protected from the environment by a double hull consisting of double side and double bottom spaces dedicated to the carriage of ballast water for ships of 5,000 dwt and above. These ballast spaces extend for the full length of the cargo area (fig. 2).

After the grounding of the Exxon Valdez in Alaska, the double hull tanker was adopted to improve ship safety with regard to environment through avoiding/minimizing oil outflow in grounding or collision. For tankers above 5,000 D.WT., the double side becomes mandatory and the minimum required breadth of wing ballast tank is increased from 1 metre to 2 metres as the deadweight rises to 20,000 D.WT. The double bottom is required to have a minimum depth of B/15 (B = breadth of ship) or 2 meters, whichever is less, and subject to a minimum depth of 1 metre [4].

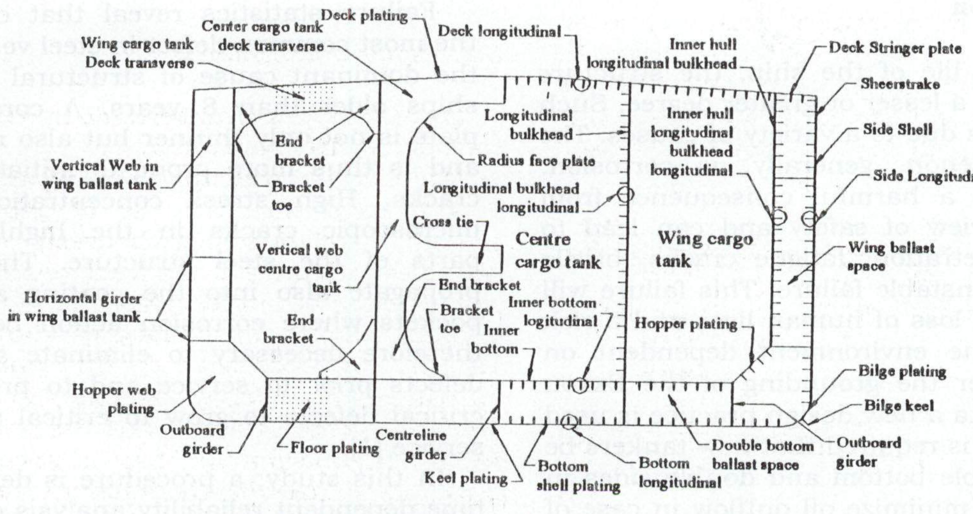

Fig. 2. Typical midship section of a double hull tanker.

Failure statistics reveal that corrosion is the most common defect in tankers. Therefore, in this paper, acting loads on a double hull tanker are calculated and transformed into stresses at critical locations with the effects of corrosion rate and coating life taken into account.

4. Loading conditions

A ship floating in still water has unevenly distributed weight owing to both cargo distribution and structural weight distribution. The buoyancy distribution is also non-uniform since the underwater sectional area is not constant along the length. Total weight and total buoyancy are of course balanced and the centres of gravity coincide, but at each section there will be a resultant force or load, either an excess of buoyancy or excess of load. Since the vessel remains intact there are vertical upward and downward forces tending to distort the vessel, which are referred to as vertical shearing forces. The variation in the vertical loading will tend to bend the vessel either to sagging or to hogging condition depending on the relative weight and buoyancy forces (fig. 3).

When a ship is in a seaway the waves with their troughs and crests produce a greater variation in the buoyancy forces and therefore can increase the bending moment, vertical shear forces and stresses. Classically, the extreme effects can be illustrated with the vessel balanced on a wave of length equal to that of the ship. If the crest of the wave is amidships the buoyancy forces will tend to hog the vessel. If the trough is amidships the buoyancy forces will tend to sag the vessel (fig. 4).

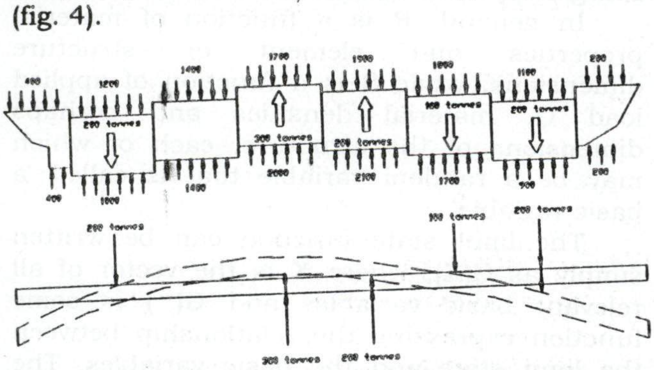

Fig. 3. Vertical shear and longitudinal bending in still water.

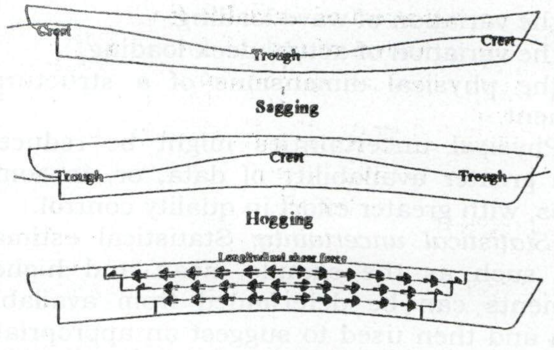

Fig. 4. Wave bending moments .

The still-water and wave induced vertical bending moments and the lateral pressure forces resulting from hydrostatic, hydrodynamic and cargo loading are those included in the analysis, there are other loading conditions but out of the scope of this study. These loading conditions are discussed in [5]. Loads are calculated using ref. [6].

5. Ship structural reliability

The development of a reliability analysis for a structure depends to a large extent on the ability to quantify the uncertainties associated with the loads acting on the structure and those associated with its strength. Next, comes the calculation and prediction of the probability of failure at any stage during its life. In the event of corrosion, the conditional probability of failure given that corrosion has occurred must be estimated.

5.1. Types of uncertainties

Different types of uncertainties need to be considered. To name a few:

(i) Modeling uncertainty: Modeling uncertainty is associated with the use of one or more simplified relationships between the basic variables to represent the 'real' relationship or phenomenon of interest. Modeling uncertainty is often simply due to lack of knowledge. It can be incorporated in the analysis by introducing a modeling variable χ to represent the ratio between the real and the predicted.

(ii) Physical uncertainty: Physical uncertainty is that identified with the inherent random nature of a basic variable. Examples include:

1) the variation in steel yield strength,

2) the variation of wave loading,
3) the variation of actual deck loading,
4) the physical dimensions of a structural element.

Physical uncertainties might be reduced with greater availability of data, or, in some cases, with greater effort in quality control.

(iii) Statistical uncertainty: Statistical estimators such as the sample mean and higher moments can be determined from available data and then used to suggest an appropriate density function and associated parameters. Generally the observations of the variable don't represent it perfectly and as a result there may be a bias in the data as recorded. In addition, different sample data sets will usually produce different statistical estimators.

(iv) Uncertainties due to human factors: These occur in the normal processes of design, documentation, construction and use of the structure within accepted procedures and those which are a direct result of ignorance or oversight of fundamental structural or service requirements [2].

5.2. Performance function and probability of failure

The basic structural reliability problem considers only one load S resisted by one resistance R. Each is described by a known probability density function $F_S(s)$ and $F_R(r)$, respectively.

The structural element will be considered to have failed if its resistance R is less than the stress resultant S acting on it. The probability of failure P_f of the structural element can be stated as follows:

$$P_f = P(R \leq S), \tag{1-a}$$

$$= P[G(R,S) \leq 0] \tag{1-b}$$

Where G(r,s) is termed the 'limit state function' and the probability of failure is identical with the probability of limit state violation. Quite general (marginal) density functions f_R and f_S for R and S respectively are shown in fig. 5 together with the joint (bivariate) density function $f_{RS}(r,s)$ for any infinitesimal element $(\Delta r \Delta s)$, the latter representing the probability that R takes on a value between r, and $r + \Delta r$ and S a value between s and $s + \Delta s$ as Δr and Δs each approach zero. In fig. 5, eq. (1) is represented by the hatched failure domain D, so that the failure probability becomes [7]:

$$P_f = P(R - S \leq 0) = \iint_D f_{RS}(r,s)\,dr\,ds, \tag{2}$$

when R and S are independent, $f_{RS}(r,s) = f_R(r) f_S(s)$, eq. (2) becomes:

$$P_f = P(R - S \leq 0) = \int_{-\infty}^{\infty}\int_{-\infty}^{s \geq r} f_R(r) f_S(s)\,dr\,ds. \tag{3}$$

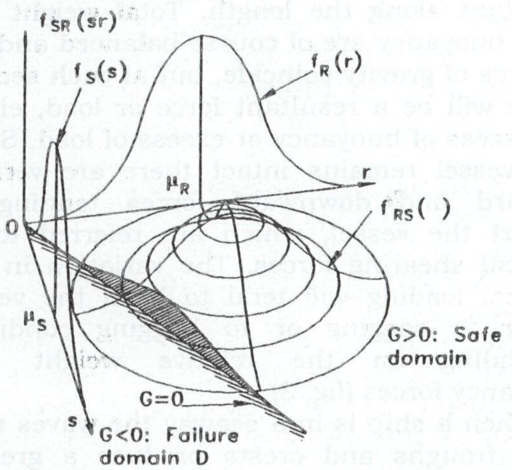

Fig. 5. Two random variable joint density function $f_{RS}(r,s)$, marginal density functions f_R and f_S and failure domain D.

For many problems, eq. (1) is not entirely adequate, since it may not be possible to reduce the structural reliability problem to a simple R versus S formulation with R and S being independent random variables.

In general, R is a function of material properties and element or structure dimensions, while S is a function of applied load Q, material densities and perhaps dimensions of the structure, each of which may be a random variable that is called 'a basic variable'.

The limit state function can be written simply as G(**X**), where **X** is the vector of all relevant basic variables and G( ) is some function expressing the relationship between the limit state and the basic variables. The limit state equation G(**X**) has three main domains in n-dimensional basic variable space:

$G(\mathbf{X}) = 0$ the failure surface.
$G(\mathbf{X}) > 0$ the satisfactory or 'safe' domain.
$G(\mathbf{X}) \leq 0$ the unsatisfactory or 'unsafe' domain.

With the limit state function expressed as $G(\mathbf{X})$, the generalization of eq. (2) becomes:

$$P_f = P[G(X) \leq 0] = \int \ldots \int_{G(X)\leq 0} f_x(x)\,dx\,. \quad (4)$$

For some special cases, the integration of eq. (4) over the failure domain $G(\mathbf{X}) \leq 0$ cannot be performed analytically. However, the solution of eq. (4) can be made more tractable by simplification through the use of the so-called first order reliability method (FORM) [2].

5.3. Conditional and total reliabilities

The probability estimated by eq. (4) becomes conditional when complete statistical information about the random variables $\mathbf{X}$ is not available. In this case the probability expressed by eq. (4) is a 'point estimate', given a particular set of assumptions about the probability distributions for $\mathbf{X}$. If the relevant statistical parameters are denoted θ and are considered as random variables, the probability estimate becomes a conditional estimate and is a function of θ. Further, the limit state function now will be a function of θ as well, $G(\mathbf{x},\theta) = 0$ and the joint probability function in $\mathbf{X}$ will be a function of θ also, thus $f_{\mathbf{X}|\theta}(\ )$. The net result is that the probability can now be expressed as a conditional probability estimate:

$$P_f(\theta) = \int_{G(\mathbf{x},\theta)\leq 0} f_{\mathbf{x}|\theta}(\mathbf{x} \mid \theta)\,dx\,. \quad (5)$$

Taking the expected value of the conditional probability estimate leads to the total probability described in [2]:

$$P_f = E[P_f(\theta)] = \int_\theta P_f(\theta) f_\theta(\theta)\,d\theta\,. \quad (6)$$

6. Corrosion effects on the conditional and total reliabilities

In this study, focus is on the plates of double hull tankers when they are subjected to corrosion. In the presence of corrosion phenomena, the probability of non-occurrence of failure (P_{nf}) due to corrosion may be expressed as a sum of two terms, which describe the contribution before corrosion action, and after it has started [8]:

$$P_{nf} = \{E_{1,1}(T < T_o) \cap E_{1,2}(T < T_o)\} \cup \{E_{2,1}(T \geq T_o) \cap E_{2,2}(T \geq T_o) \cap E_{2,3}(T \geq T_o)\}, \quad (7)$$

where T_o is the coating life and T_f is the lifetime.

The first event is sub-divided into two sub-cases which represent the probability that corrosion will not occur during the time T: ($E_{1,1}$), where $T \in [0,T_f]$ with probability $[1 - F_{To}(T)]$; and ($E_{1,2}$), the end of the coating life event with probability of non-failure $R_b(T)$ under the condition that corrosion does not appear before the end of the coating life.

The second event includes three sub-cases: the first one ($E_{2,1}$)is when corrosion occurs at time T_o where $T_o \in [0,T]$ with probability $f_{To}(T_o)dT_o$; the second sub-case ($E_{2,2}$) represents non failure before corrosion starts decreasing the thickness of the plate at time T_o and $T_o \in [0,T]$, with probability $R_b(T_o)$; the third sub-case ($E_{2,3}$) denotes non-failure under condition that the corrosion appears with probability $R_a(T - T_o)$.

The total reliability $R_T(T)$ is given by the reliability of the plate without corrosion plus the reliability of the plate with corrosion:

$$R_T(T) = [1 - F_{To}(T)]R_b(T) + \int_0^T R_b(T_o) R_a(T - T_o) f_{To}(T_o)\,dT_o,\ T \in [0, T_f]. \quad (8)$$

The first term in the right-hand side of this equation represents the probability that no corrosion appears and that failure does not occur in time [0, T]. The second term represents the probability of non-failure under the condition that the corrosion is initiated.

The reliability of the plate is estimated by the generalized index of reliability that is calculated from a multi-normal distribution.

Under this assumption, the reliability index β can be related to the probability of failure by:

$$\beta(T) = -\Phi^{-1}[P_f(T)] , \qquad (9)$$

where Φ is the standard normal distribution and $P_f(T)$ can be calculated from $P_f(T)=1-R_T(T)$.

7. Case study

We will now demonstrate the application of the proposed procedure to a double hull tanker fig. 6 [9]. By supplying the midship section characteristics to a finite element program (GLFRAME) we get all of the required geometric properties of this section [10].

7.1. The plate boundary conditions

In our study, it is assumed that the plate edges are simply supported, with zero deflection and zero rotational restraints along four edges, with all edges kept straight [11]. It should be noted that the coefficient of variation for plate thickness decreases with increase in thickness. The length and the width of the plate element and Poisson's ratio have a very small coefficient of variation, such that, they can be modeled as deterministic parameters having fixed values.

7.2. Loads and load effects modeling

The modeling of load processes may be quite difficult. Loading is usually the most uncertain factor in a reliability analysis. The magnitude of most loads varies with time and with location. These loads may be in the form of longitudinal or transverse bending moment, shear force, lateral pressure, ...etc. These loads will be transformed into stresses acting on the plate elements. The still-water and wave induced load components are considered uncorrelated, and load combination issues are neglected. In our approach, the maximum total load is thus calculated as the linear summation of the maximum still-water and extreme wave induced load components [11]. The hull girder longitudinal stress distribution, when the tanker is subjected to vertical bending moment, is obtained by using the linear simple relation σ = M / Z [9], and is shown in fig. 7 .

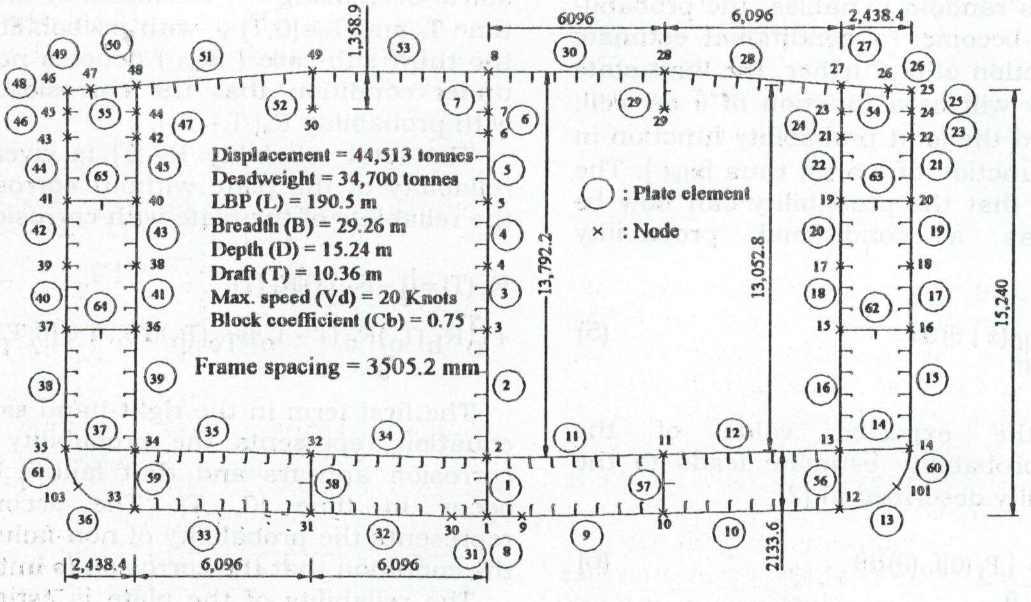

Fig. 6. Midship section design of a double hull tanker of 34,700 DWT.

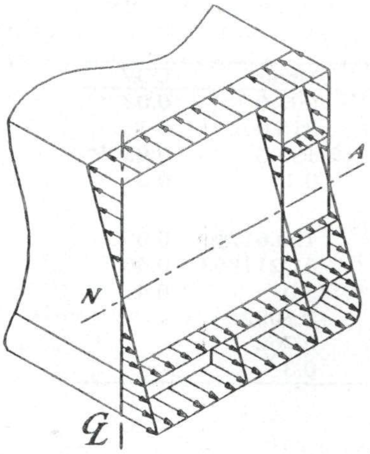

Fig. 7. Bending stress distribution .

7.3. Corrosion rate modeling

The conventional models of corrosion assume a constant corrosion rate, leading to a linear relationship between the material loss and time. There are various linear corrosion rate models, such as [8]:

$$d = 0.076 + 0.038T . \tag{10}$$

In this study, we consider the conventional general corrosion (uniform corrosion) [d = r.T]. The probabilistic characteristics of corrosion rate for each primary member in terms of mean values and COV 's are shown in fig. 8, which applies to a double hull tanker [3]. The probability density function of the corrosion rate is assumed to follow the Weibull distribution [9].

7.4. Analysis of plate element

In the reliability analysis of a corroded plate, two time periods are considered. The first is period "a" before coating failure ($T \le T_o$). In this period, the coating life is still effective and the probability of failure at any time T and hence the reliability are constant with time since the thickness t in this period is equal to the original thickness t_o. The second period is period " b " after coating failure ($T > T_o$). In this period, the coating system has lost its effectiveness and the thickness is reduced with time, such that the performance function and reliability become time dependent :

$$t = t_o - r .(T - T_o). \tag{11}$$

The following two cases of acting loads are considered in the analysis.

Case I

This case studies a plate element under uniaxial compression (ultimate), (table 1) [9, 12]. The last plate in the deck, number ' 28 ', of the double hull tanker described in fig. 6 is considered, with the models for the various random variables given in table 1.

Case II

This case studies a plate element under lateral pressure (ultimate). A plate in the inner bottom, number '11', of the double hull tanker is considered, with the models for the various random variables given in table 2 [9, 13].

The ultimate stresses for the two load cases are calculated using [14]. The program used in this analysis consists of subroutines performing the reliability analysis using FORM in addition to the subsequent corrosion subroutines which consider the case of uniform corrosion of a plate element. The program performs a parametric analysis to show the effect of the random variables (mean values and COVs) and the deterministic parameters on the plate reliability. The program evaluates the conditional reliability based on a predefined exact coating life value and also evaluates the total reliability considering the coating life as a random variable.

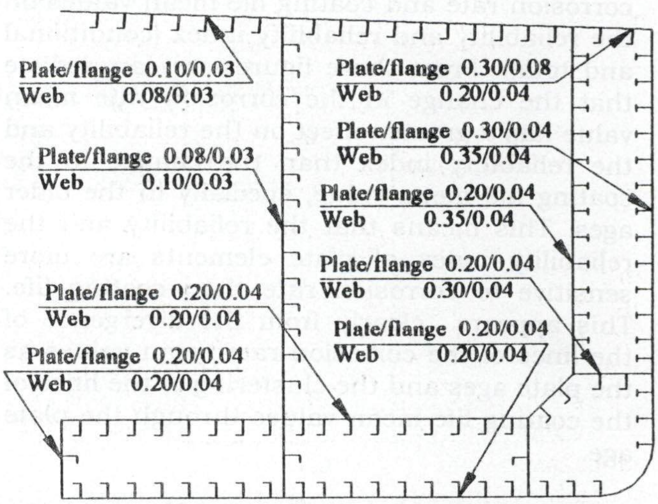

Fig. 8. Corrosion rate modeling for tankers [9].

Table 1
Random variables modeling [Case I]

Variable	Distribution	Mean	COV
Modulus of elasticity 'E' (GPa)	Log-normal	207.0	0.03
Yield strength ' σ_y ' (MPa)	Normal	315.0	0.1
Plate thickness ' t ' (mm)	Normal	19.05	0.05
Corrosion rate ' r ' (mm/year)	Weibull	0.1	0.3
Wave normal stress ' σ_{WT} ' (MPa)	Extreme 'I'	129.61293	0.093
Still water normal stress 'σ_S' (MPa)	Normal	61.211963	0.40
Coating life ' T_o ' (years)	Normal	5.0	0.4
Plate length ' a ' (m)	Fixed	3.5052	-
Plate width ' b ' (m)	Fixed	0.762	-
Poisson ratio ' υ '	Fixed	0.3	-

Table 2
Random variables modeling [Case II]

Variable	Distribution	Mean	COV
Modulus of elasticity 'E' (GPa)	Log-normal	207.0	0.03
Yield strength ' σ_y ' (MPa)	Normal	235.0	0.1
Plate thickness ' t ' (mm)	Normal	14.29	0.05
Corrosion rate ' r ' (mm/year)	Weibull	0.2	0.2
Wave pressure ' P_W ' (KPa)	Extreme 'I'	28.5448	0.07
Still water pressure ' P_S ' (KPa)	Normal	137.922	0.12
Coating life ' t_o ' (years)	Normal	5.0	0.4
Plate length ' a ' (m)	Fixed	3.5052	-
Plate width ' b ' (m)	Fixed	0.762	-
Poisson ratio ' υ '	Fixed	0.3	-

7.5. *Discussion of results*

The results of the parametric analysis are indicated in figs. 9 and 10 for a plate element under uniaxial compression (ultimate limit state) and in figs. 11 and 12 for a plate element under lateral pressure (ultimate limit state). These figures show the effects of the corrosion rate and coating life mean values on the reliability and reliability index (conditional and total). From these figures we can deduce that the change in the corrosion rate mean value has a greater effect on the reliability and the reliability index than the change in the coating life mean value, specially in the older ages. This means that the reliability and the reliability index of plate elements are more sensitive to corrosion rate than coating life. This appears clearly from the divergence of the lines of the corrosion rate mean values as the plate ages and the clustering of the lines of the coating life mean values through the plate age.

8. Conclusions

The following conclusions can be drawn based on the results of this study:

1. The use of probabilistic methods that take into consideration the uncertain factors affecting the safety of the hull structure must ideally be carried out in the ship structural safety assessment.
2. Every ship owner or ship operator must record a fully detailed description of the ship's conditions, operational characteristics, maintenance, repair, scantling conditions and hull deterioration from the first day of service until the last day of service. These records will provide statistical information for the random variable modeling.
3. The modeling of the uncertainties is a very important step in the design process and great care must be taken in the choice of COV's.
4. Corrosion is the most aggressive problem since it can lead to brittle fracture and fatigue cracking and other problems that endanger structural safety.

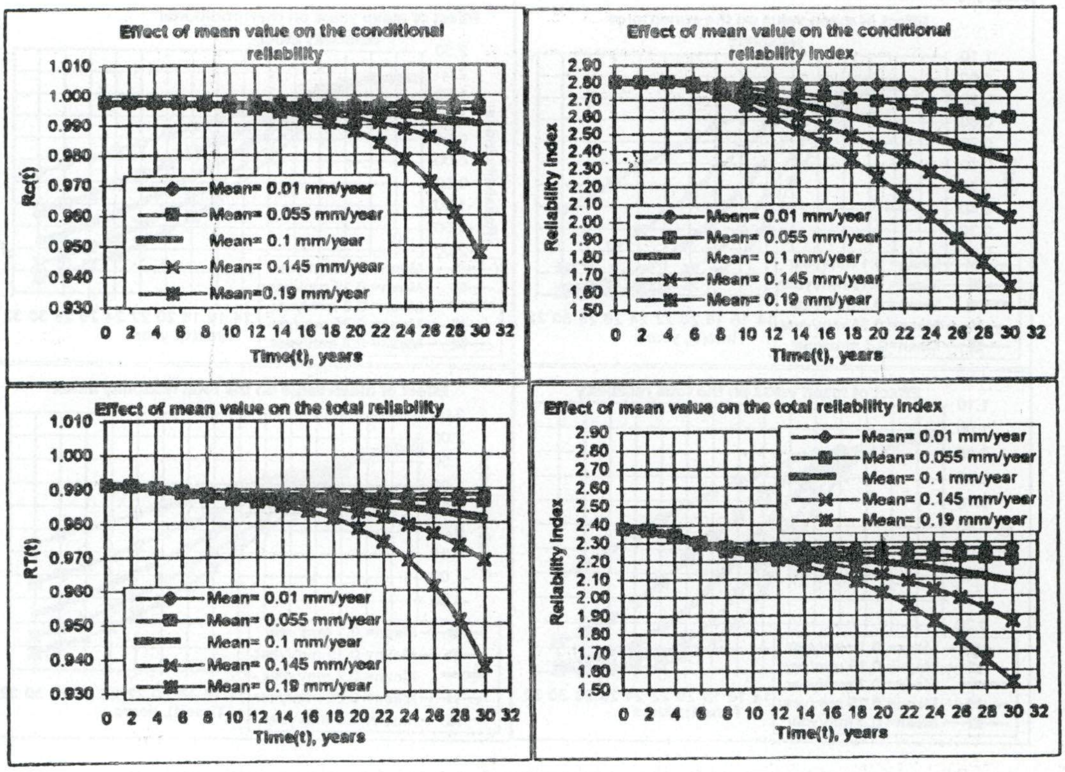

Fig. 9. Effect of corrosion rate mean value-uniaxial compression (ultimate).

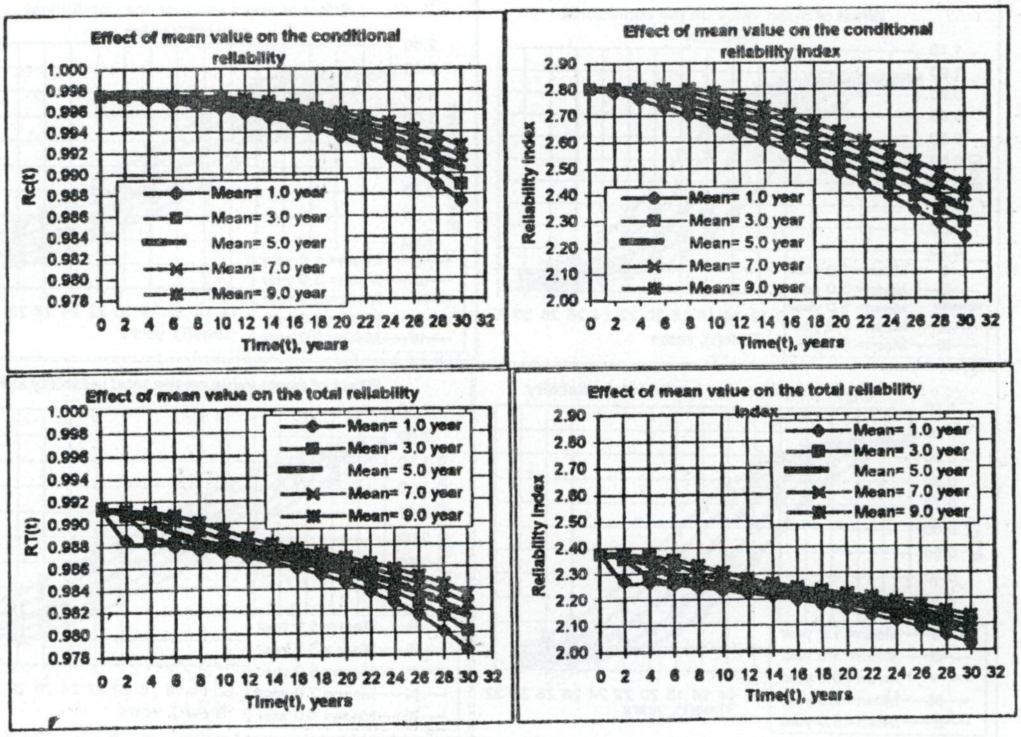

Fig. 10. Effect of coating life mean value-uniaxial compression (ultimate).

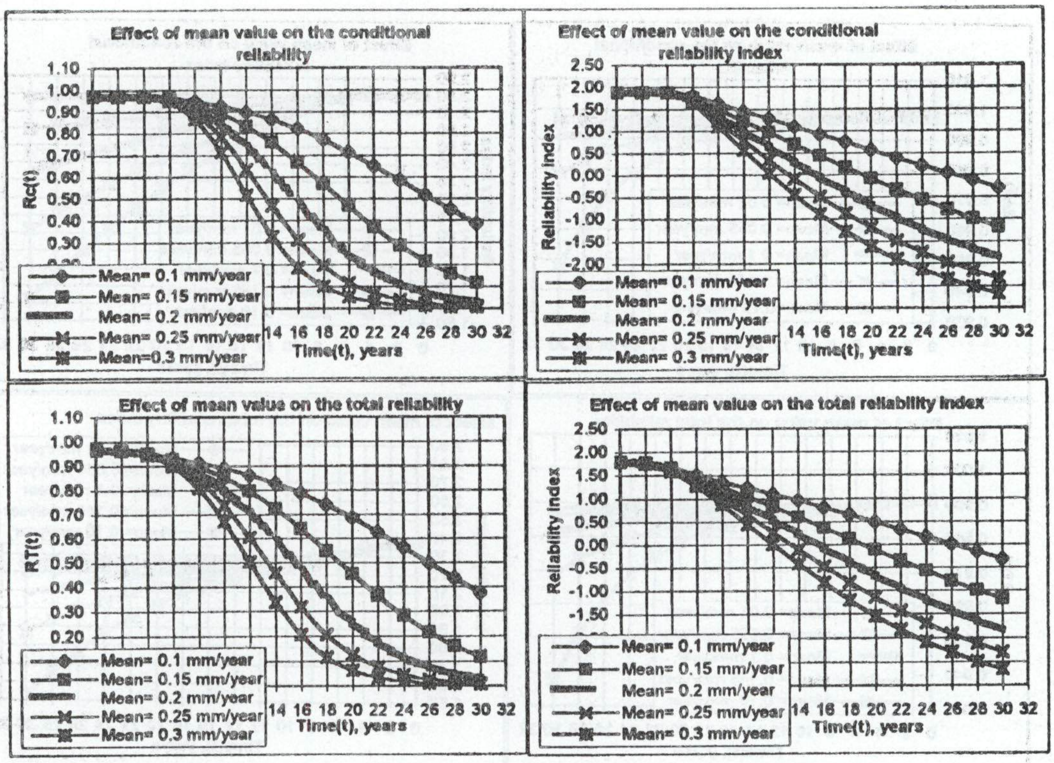

Fig. 11. Effect of corrosion rate mean value-lateral pressure (ultimate).

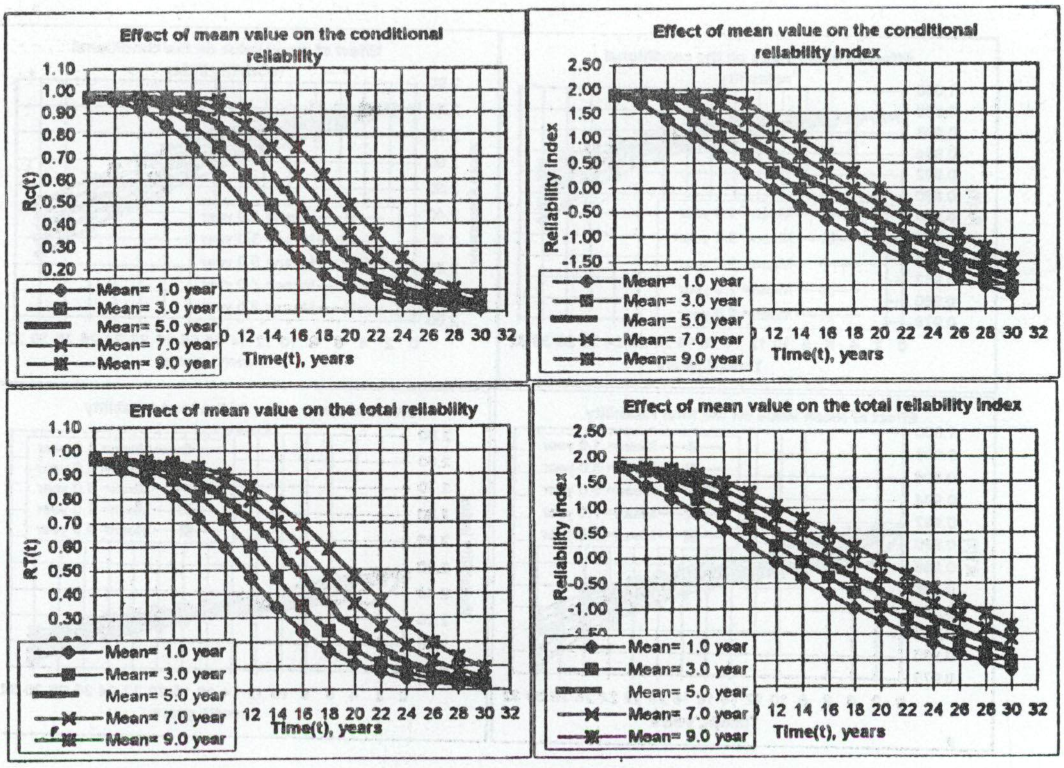

Fig. 12. Effect of coating life mean value-lateral pressure (ultimate).

5. The change in the corrosion rate mean value has the greatest effect on the reliability and reliability index of plate elements, especially as the plate ages.

References

[1] Shama M.A., "Impact on Ship Strength of Structural Degradation Due to Corrosion," Alexandria Engineering Journal, Vol. 34 (4), pp. 453 - 461 (1995).

[2] Melchers R.E., "Structural Reliability Analysis and Prediction" 2nd Edition, John Wiley & Sons (1999).

[3] Paik J.K., Thayamballi A.K., Kim S.K. & Yang S.H., "Ship Hull Ultimate Strength Reliability Considering Corrosion," Journal of Ship Research , Vol. 42 (2), pp. 154 – 165 (1998).

[4] Tanker Structure Co-Operative Forum & International Association of Classification Societies, "Guidelines for the Inspection and Maintenance of Double Hull Tanker Structures," Witherby & Co. Ltd. (1995).

[5] Chalmers, D.W., "Design of Ships' Structures," HMSO, London (1993).

[6] Det Norske Veritas, " Hull Structural Design, Ships with Length of 100 Meters and Above," Part 3, Chapter 1, January (1994).

[7] Mansour A.E., "Methods of Computing the Probability of Failure under Extreme Value of Bending Moment," Journal of Ship Research, June, pp. 113 - 123 (1972).

[8] Guedes Soares C. & Garbatov Y., "Reliability of Maintained, Corrosion Protected Plates Subjected to Non-Linear Corrosion and Compressive Loads," Marine Structures, pp. 425 - 445 (1999).

[9] Paik J.K., Kim S.K., Yang S.H. & Thayamballi A.K., "Ultimate Strength Reliability of Corroded Ship Hull," The Royal Institution of Naval Architects (RINA) Trans., pp. 1 – 18 (1997) .

[10] Germanischer Lloyd, "GLFRAME, A Finite Element Program, for Static and Dynamic Analysis," Version 4.0.

[11] Paik J.K., Thayamballi A.K. & Kim B.J., "Advanced Ultimate Strength Formulations for Ship Plating under Combined Biaxial Compression/Tension, Edge Shear, and Lateral Pressure Loads," Journal of Ship Research, January, pp. 9 – 25 (2001).

[12] Abdel-Nasser Y.A. & Leheta H.W., "Reliability of Initially Imperfect Plates under Biaxial Loading," Alexandria Engineering Journal, Vol. 35 (6), pp. 307 – 314 (1996).

[13] Leheta H.W. & Mansour A.E., "Reliability-Based Method for Optimal Structural Design of Stiffened Panels", Marine Structures, Vol. 10 (5), pp. 323 - 352 (1997).

[14] American Petroleum Institute (API), "Bulletin on the Design of Flat Plate Structures," July (1993).

Received June 6, 2002
Accepted July 13, 2002