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On Ship Reliability and Safety

by

Prof. Dr. M. A. Shama

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6- "Impact on Ship Strength of Structural Degradation Due to Corrosion", AEJ, July., (Egypt-1995), Shama, M. A.,

7- "Shear Strength of Damaged Coastal Oil Tanker under Vertical Shear Loading", AEJ, April, (Egypt-1996), Shama, M. A., Leheta, H. W. and Mahfouz, A. B.

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12-, "Impact of Recoating and Renewal on the Reliability of Corroded Hull Plating of Double Hull Tankers", AEJ. Vol. 41, No. 4, (Egypt-2002), Shama, M. A., H. W. Leheta, Y. A. Abdel Nasser and A. S. Zayed,

Impact of recoating and renewal on the reliability of corroded hull plating of double hull tankers

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This study demonstrates the impact of recoating and renewal of corroded double hull tanker plates on their reliability. The most common corrosion types attacking the marine structure are discussed along with the different factors affecting the corrosion rate. The allowable thickness reductions for the different locations through the ship's hull and the requirements of a classification society with regard to corrosion control are stated. Maintenance and repair of double hull tankers are briefly outlined. The effect of the recoating process on the plate reliability (conditional) and the plate renewal on the plate reliability (conditional and total) are studied for a plate element subjected to uniaxial compression (ultimate) and lateral pressure (ultimate). Results of the reliability analysis taking into account the impact of recoating and renewal are given and discussed for a typical double hull tanker. These results are important in the determination of the suitable time for carrying out maintenance and repair actions for the ship under consideration. It is recommended that such an analysis be performed for ships largely affected by corrosion problems.

تستعرض هذه الدراسة تأثير عملية اعادة الطلاء وتجديد الالواح المتآكلة على معولية ناقلات البترول مزدوجة البدن. تمت مناقشة أهم أنواع التآكل التى تهاجم المنشآت البحرية والعوامل التى تؤثر على معدل التآكل. وقد تم توضيح للتخانات المسموح بتآكلها فى الأماكن المختلفة من بدن السفينة بدون تجديد للألواح. ثم تم عرض متطلبات لحدى هيئات التصنيف فيما يختص بالسيطرة على التآكل. تم أيضا اعطاء فكرة مختصرة عن الصيانة والاصلاح لناقلات البترول مزدوجة البدن. وفى البحث، تم أيضا استعراض لدراسة حالة لتوضيح تأثير عملية اعادة الطلاء وتجديد الألواح المتآكلة على المعولية المشروطة والمعولية الكلية للألواح المعرضة لأحمال مختلفة وذلك لناقلة بترول مزدوجة البدن. وتمثل هذه الدراسة أهمية كبيرة لتحديد الموعد المناسب لعمليات الصيانة والاصلاح المختلفة الخاصة بناقلات البترول مزدوجة البدن والمعرضة لظاهرة التآكل. ولهذا البحث توصية هامة تكمن فى أهمية القيام بتحليل معولى للسفن التي تتعرض لمشاكل التآكل.

Keywords: Corrosion, Corrosion protection systems, Corrosion rate, Recoating, Renewal

1. Introduction

Plates are the main structural components of several important metal structures such as ships and box girder bridges. Their behaviour under the effect of different loading conditions is particularly important because the failure is generally in an unstable mode, which has harmful consequences from the point of view of safety. 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.

The assessments of the performance of the wide range of materials in the maritime environment are an essential part of the design and building process. Clearly, there are performance limits for the various structural materials, and exceeding these has led to failures of some maritime structures under a wide range of operational conditions. Failures include fracture at low temperatures and ship break-up due to fatigue cracking and corrosive degradation of hull material.

Although much has been learned from the break-up of the "liberty ships" in the 1940s (e.g. the USS *Schenectady*), modern merchant ships are still breaking-up in service in the 1990s. It is considered that this arises from changes in design, changes in service loading and from poor maintenance and, in some cases, inadequate inspection of the ships. The consequences of ship break-up (particularly oil tankers) can be gauged in terms of the loss of life, the magnitude of environmental damage (e.g. the *Exxon Valdez* oil spill) and the loss of valuable resources. It is well known that structural failure is often the result of fatigue cracking together with corrosive degradation. The structural loads on ships increased significantly over the 1960s and 1970s when the large bulk carriers were introduced into service. Recent failures suggest that loads on some structural members have increased significantly during the life of the ship and this may have occurred due to corrosive degradation of main members of the structure. Ductile fracture in the form of panel buckling, structural bending (e.g. the M/T Alvenus) and tearing also occur [1].

As for corrosion effects, guidelines for inspection of corroded hulls have been developed, recommendations for repair of corroded areas have been established and nominal design corrosion values of different parts of structure and vessel types have been developed [2,3,4]. A corrosion margin is added at the ship design stage to the initial plate thickness of structural hull members to compensate for predicted thickness diminution, which is the primary consideration to cope with the problem of corrosion and wear. Increased scantlings are also used to minimize the amount of material replacement required throughout the ship life [5].

In reference [6] the authors have discussed the geometric characteristics of the double hull tanker and the loading to which it is subjected. Ship structure reliability analysis methodology and the types of uncertainties were also discussed in [6]. The difference between the conditional and the total reliabilities considering corrosion effects were also clarified. Finally, a reliability analysis for a plate element taken from an aged double hull tanker showing the effect of corrosion rate and coating life means on the reliability and the reliability index was performed.

In this study, a procedure is developed showing the effect of recoating and renewal of the deteriorated plate on the time dependent reliability analysis of corroded plates, based on ultimate collapse of the plate elements, and taking into account the degradation of primary members due to general corrosion. The limit states are developed using API design code [7] taking into account the effect of plate thickness reduction of each primary member due to corrosion. The applied loads are established using simplified DNV rules [8]. The reliability and the reliability index (conditional and total) associated with the corroded plate are calculated by using the first order reliability method (FORM)[9].

2. Corrosion and corrosion effects

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 [10, 11].

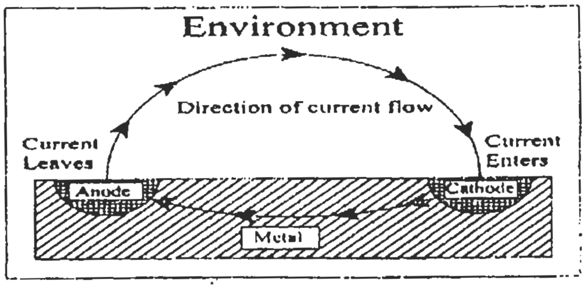

Fig. 1. Requirements of metal corrosion.

2.1. Types of corrosion

In this work, we consider general corrosion, which appears as a uniform layer on the surface of the metal that is uncoated. Over time, this layer 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 [12].

2.1.1. Pitting

Pitting is a localized form of corrosion and usually grows in the direction of gravity. It's also self-generating, starting from impurities in the metal, scale or other deposits, or some inhomogeneity in the metal [13]. Pitting corrosion typically occurs on bottom plating, other horizontal surfaces and at structural details that trap water, particularly at the aft bays of tanks. In coated surfaces, pitting produces deep and relatively small diameter pits that can lead to hull penetration in a random manner. Severe pitting can only be remedied by significant steel renewal, [14].

2.1.2. Grooving

Grooving corrosion is a localized, linear corrosion, which occurs at structural intersections where water collects. This corrosion is sometimes referred to as "in-line pitting attack".

2.1.3. Weld metal corrosion

Weld metal corrosion is defined as preferential corrosion of the weld deposit. The most likely reason for this attack is galvanic action with the base metal, which may initially lead to pitting. This often occurs in hand welds as opposed to machine welds fig. 2 [2].

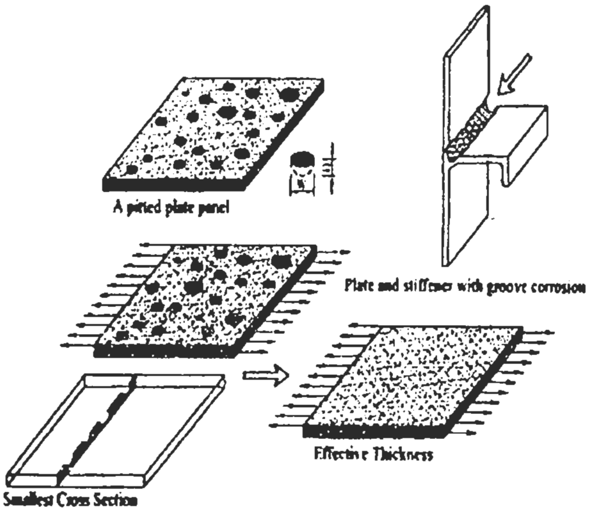

Fig. 2. Types of corrosion and definition of effective thickness by equivalent cross section area.

2.2. Factors influencing corrosion

Corrosion of ship structures represents one of the main causes of structural failures and is generally affected by the following factors, see fig. 3 [15]:

- Design parameters
- Fabrication parameters
- Protective coating parameters
- Operational parameters
- Maintenance and repair parameters
- Environmental parameters

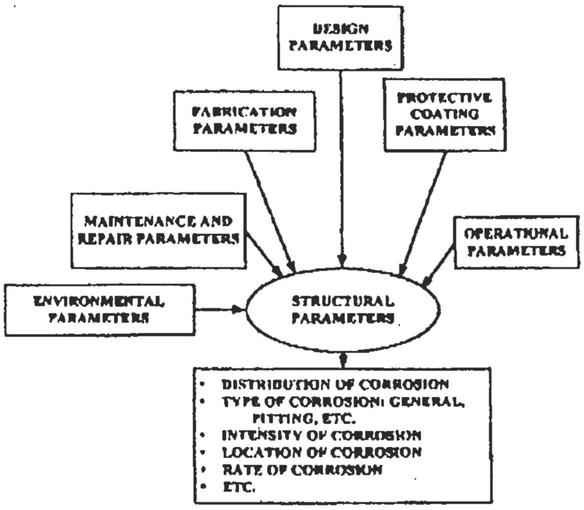

Fig. 3. Main factors affecting corrosion.

2.3 Factors affecting corrosion rate

Ship structures operate in a complex environment. Water properties such as salinity, temperature, oxygen content, pH level and chemical composition can vary according to location and water depth, [16]. The following are the important factors determining the corrosion rate in hull spaces of tankers [14].

2.3.1. Type of cargo

Carriage of certain types of cargo can lead to higher corrosion rates. For example, high oxygen cargoes such as gasoline lead to high corrosion rate. Refined product generally causes severe general corrosion (more than twice the rate observed in a crude oil tank). This is due to the fact that most products are less viscous than crude oil and don't provide the protective film of crude oil. Crude oils high in sulfur also contribute to tank corrosion. The sulfur compounds present may react with water and oxygen to produce sulfuric acid, which is corrosive to steel.

2.3.2. Corrosion protection effectiveness

In coated tanks, general corrosion rates are low initially until coating breakdown. In a relative sense, such breakdown is more likely in areas difficult to coat and areas of stress concentration. Anodes provide some protection when immersed in electrolytic solutions for a sufficient time.

2.3.3. Component location and orientation

Some locations in a hold are more susceptible to corrosion than others. Data indicate that in water ballast tanks, the heavier corrosion is found at the upper surface of horizontal members. In cargo tanks, likely candidates for heavy corrosion are structural members in vapor spaces of tanks (typically uncoated).

2.3.4. Temperature

This is a function of the cargo, heating coils, and vessel trade route. The higher the temperature, the higher the likely rates of corrosion, which explains increased corrosion on tropical routes. Trade routes also affect humidity (as can certain types of cargo). Higher levels of humidity lead to higher corrosion rates.

2.3.5. Tank washing

More frequent tank washings increase cargo tank corrosion, since tank washing removes the protective waxy film, formed by crude oil, from the tank internal surface, which can effectively protect the steel from corrosion. Seawater washing is more damaging than crude oil washing. Hot seawater is worse than cold seawater. The drip locations of washing guns are subject to increased rates of corrosion.

2.3.6. Inert gas

Inert gas systems are required to prevent explosions. This is done by supplying inert gas during discharge and gas freeing. Flue gas systems utilize scrubbed flue gas from the ship boilers. But use to date indicates that they also have an effect on tank corrosion since they introduce corrosive elements into a tank. Sulfur dioxide (SO_2) and sulfur trioxide (SO_3) contained in flue gases can combine with the warm moist atmosphere in a tank to form sulfuric acid, which can cause accelerated corrosion of either bare or coated tank surfaces.

2.3.7. Degree of local flexibility

Increased structural flexibility has been claimed to increase corrosion rates as time progresses. This is apparently because of serial increases in scale loss and structural flexibility. Flexibility is greater in HTS structures.

2.3.8. Mechanical coating damag:

This plays a minor role and results from wear and tear caused by crew members or other personnel walking and moving about the tank. Sand, sometimes contained in crude oils, can settle to the bottom and cause slight erosion by constantly sloshing in bays between structural members [4].

2.4. Consequences of corrosion

Corrosion of ship structures has a deleterious effect on maintenance, repair costs, hull girder and local safety, and ship's service life. The impacts of corrosion on structural strength and stiffness of the ship hull girder and local structural members are [15]:

(a) Reduction of local and hull girder scantlings,

a) increase of local and hull girder stresses,

b) reduction of hull girder and local load carrying capacity,

c) increase of local stress concentration,,

d) gnificant reduction of fatigue strength of structural connections,

e) uction of local and hull girder flexural rigidity and buckling strength,

f) uction of hull girder and local safety, i.e reduction in reliability and corresponding safety indices.

These structural deficiencies largely influence the ship's service life, reliability, and maintenance and repair actions and timing.

2.5. Requirement of classification societies with regard to corrosion control

In practice, if any member is corroded more than a specified amount, it should normally be renewed to maintain the structural condition at an acceptable level. For the so-called renewal criteria, various classification societies have their own suggestions, which may take the form of a minimum allowable thickness for structural members, or alternatively a maximum permissible percentage reduction of plate thickness due to corrosion. For our illustrative calculations, we will use renewal criteria shown in table 1 [14], which are based on those suggested by a particular classification society.

Table 1
Illustrative renewal criteria for seriously corroded local members [14]

Members	Max. local wastage
Top area	15%
Bottom area	15%
Strength deck plates	20%
Side shell plates	25%
Bottom plates	20%
Longitudinal bulkhead plates	20%
Transverse bulkhead plates	25%

In addition to such renewal criteria applicable to parts of the structure, classification societies typically also require that in no case the elastic section modulus of the hull girder is reduced by more than 10% of the minimum required. For certain vessel types, the area of the deck hull girder flange cannot be reduced by more than 10% of the initial value as well.

3. Maintenance/repair planning of double hull tankers

Double hull tanker structures are exposed to an intensively corrosive environment. Outer surfaces of the hull are permanently exposed to the sea. The inner surfaces of tanks on the other hand are in direct contact with sea water ballast, fresh water and a variety of liquid cargoes, mainly crude oil. Corrosive action is the major cause of wear of structural members. Wear leads to strength losses that may even lead to local collapse. Therefore, corrosion control measures must be applied with great care.

Maintenance and/or repair work is required when the properties of the structure deteriorate through age and use to the point where performance and/or safety are adversely affected [17]. Corrosion appears specially in the water ballast tanks. All tanks and decks are usually fitted with anticorrosive protecting coatings (paints) during construction. The coating will be damaged after a period of 5-10 years leading to increased rates of corrosion and a new coat will need to be reapplied. The recoating process is the process of applying a new coating layer due to aging of the previous coating one and losing of its performance in protecting the base metal from corrosion attack. The recoating period is dependent on the quality of the coating system. As the quality of the coating system improves the recoating period is extended. The recoating period is not only dependent on the coating system quality, but also it is dependent on operational characteristics such as temperature, salinity, time in ballast, tank washing and degree of local flexibility. Cleaning and preparing the surface of the metal and then applying the new layer before the corrosion attacks the base metal and reduces the thickness of the structural members must be carried out. The recoating period in this study is assumed pessimistically to be 5 years as recommended by Paik et al in [12] and [14]. It can be extended to more than 10 years in some coating systems. The main requirements of anticorrosive paints are shown in fig. 4.

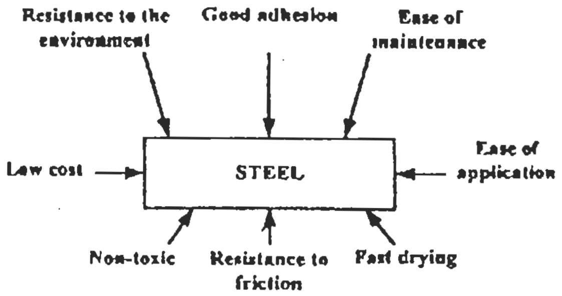

Fig. 4. Main requirements of anticorrosive paints [17].

If protective coatings are not maintained, extensive steel renewals will be required. The process of plate renewal is the process of replacing the aged plate which has a deteriorated thickness below the allowable limit permitted by the classification society recommendations with a new one. The renewal period as the recoating one is dependent on the coating quality, the operational characteristics and the corrosion allowance. Some ship owners prefer to use increased scantlings to reduce the amount of material replacement throughout the age of the ship. The allowable thickness reduction differs from one location to the other according to the load sharing capability of that structural member. The cost of installing a protective coating is approximately 10% of the cost of renewal of the plating concerned for a 12 mm thick plate [17]. In addition, steel renewals introduce problems such as residual stresses and weld defects. Recoating is the most cost-effective approach, rather than steel renewals.

Other than anticorrosive coats and steel renewals, cathodic protection is required for the underwater hull surface as well as particular internal spaces and components. The required dimensions and layout of sacrificial anodes are given in classification society rules and recommendations.

4. Case study

The effects of plate recoating and renewal on the reliability analysis of a double hull tanker's plates are considered. The principal dimensions of the candidate ship are shown in fig. 5 [14].

In [6] the plate boundary conditions and the load and load effect modeling were discussed. Reference [6] also discussed the corrosion rate modeling and the bending stress distribution using the finite element program (GLFRAME) [18]. The different cases of loading and the modeling of the various random variables (mean values and COV's) were described in [6].

4.1. Performance function and analysis of plate element

Two time periods are considered [6,16]. Period "a" before coating failure ($T \leq T_o$): In this period, the coating life is still effective and the probability of failure at any time ($0 - T_o$) and also, the reliability in the same range of time is constant with time since the thickness t at any time T in this region is equal to the original thickness t_o. 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:

$$t = t_o - r.(T - T_o),$$

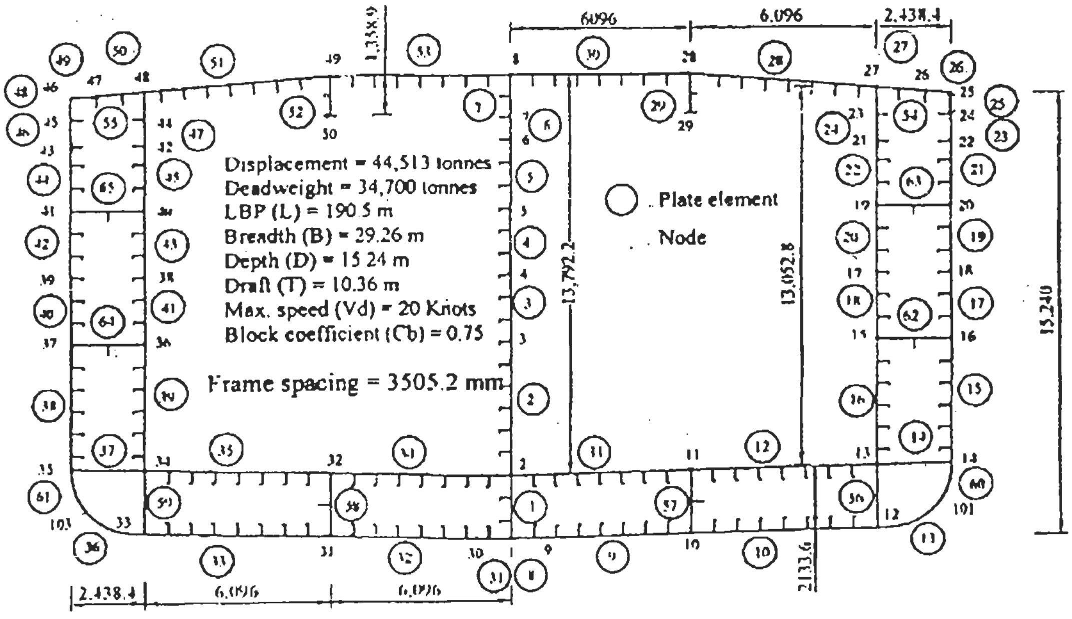

Fig. 5. Midship section design of a double hull tanker of 34,700 DWT.

so, the performance function is time dependent and also the reliability.

The program used in this analysis consists of subroutines performing reliability analysis using FORM in addition to the subsequent corrosion subroutines, which consider the case of uniform corrosion. The program performs a parametric analysis to show the effects of recoating and renewal periods, when the plate is under uniaxial compression or lateral pressure, on the plate reliability. The program evaluates the conditional reliability based on a predefined exact coating life value. In the renewal case, the total reliability is evaluated considering the coating life as a random variable.

4.2. Discussion of results

The results of the analysis are shown in figs. 6 and 7 for the recoating process, for uniaxial compression and lateral pressure respectively. The lateral pressure case is more critical with a smaller reliability index. The reliability is conditional on the life of the coating which is assumed to be 5 years. Figs. 8 and 9 show the conditional and total reliability and reliability index for the renewal process, for considered plate elements under uniaxial compression (ultimate limit state) and under lateral pressure (ultimate limit state) [6]. In the renewal case, no recoating is effected.

From the recoating diagrams, we can deduce that for a coating life of 5 years, i.e. the recoating process is executed every 5 years, the reliability and the reliability index will be fixed all over the plate age. But, if the recoating process is executed at intervals more than 5 years, the reliability and the reliability index will be fixed for the first 5 years - representing the coating life - and then decrease until the next recoating process, then the cycle is repeated every recoating process.

From the renewal diagrams we can deduce that if the renewal process is performed before coating failure the reliability and the reliability index will remain fixed all over the plate age. But, if the renewal process is performed after the coating failure the reliability and the reliability index will remain fixed during the coating life and then decrease until the next renewal process where the reliability and the reliability index retrieve their initial value again and the cycle is repeated again.

Diagrams such as those shown must be constructed for all newly built ships to aid the ship owner in developing adequate maintenance and repair plans throughout the life of the ship to ensure structural safety and integrity of the ship. An appropriate reliability level may be specified such that if the reliability drops below this level, one or both must be performed: recoating and renewal.

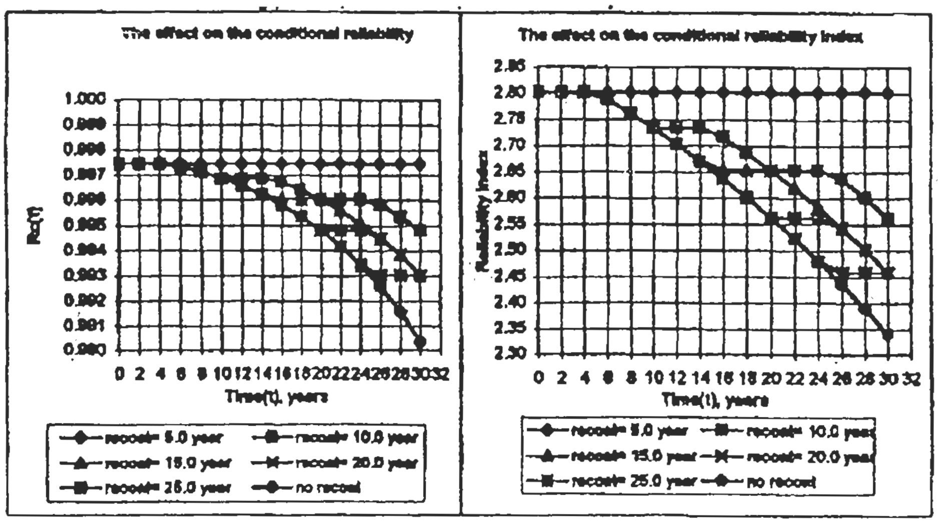

Fig. 6. Effect of recoating periods (uniaxial compression-ultimate).

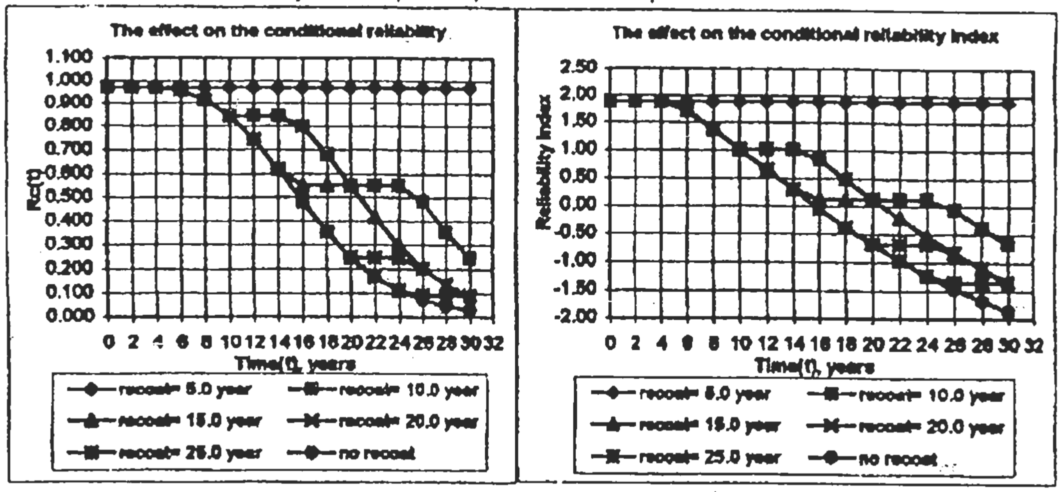

Fig. 7. Effect of recoating periods (Lateral pressure-ultimate).

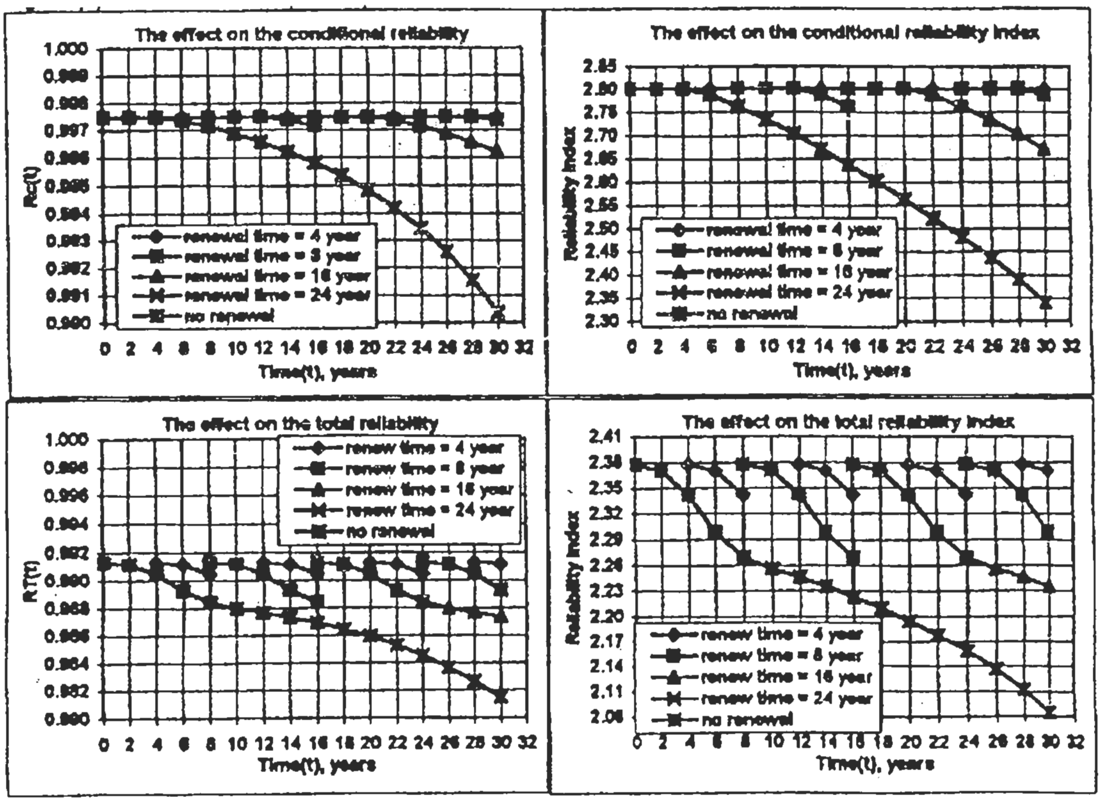

Fig. 8. Effect of renewal period (uniaxial compression-ultimate).

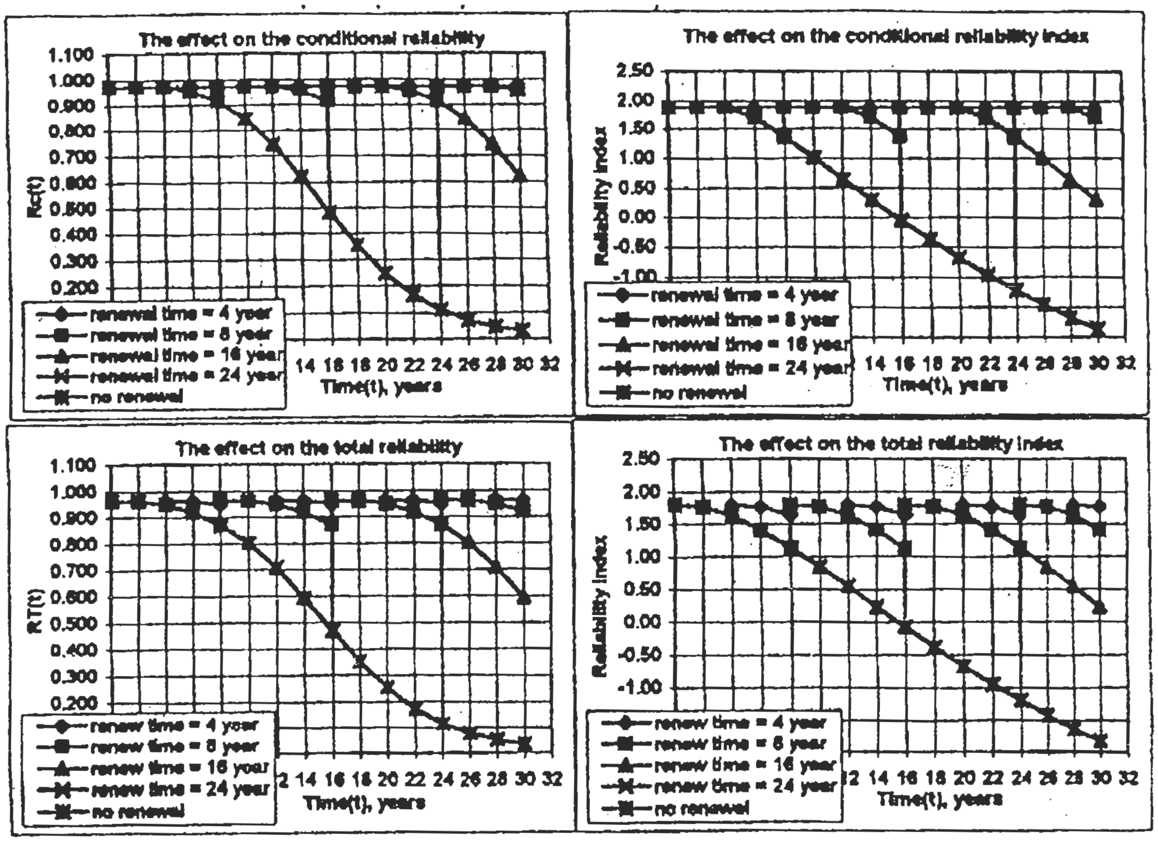

Fig. 9. Effect of renewal period (lateral pressure-ultimate).

5. Conclusions

From the results of this study the following conclusions were reached:

1. Probabilistic methods should be applied in the safety assessment of ships. Presented analyses should be extended for stiffeners, stiffened plates and hull girder.
2. Corrosion is the most aggressive problem that endangers the ship safety and threatens the ship strength integrity.
3. Local thickness deterioration of up to 25 % may be accepted for many parts of the vessel before replacement becomes necessary.
4. In order to prevent / reduce the initiation of the corrosion problem, it is necessary to eliminate any critical defects prior to service and to prevent non-critical defects to grow to critical size during service.
5. A good inspection, maintenance and monitoring system for assessing and protecting hull structures from corrosion is essential for reducing strength deterioration and extending ship life.
6. Effective optimization between the use of corrosion allowance and efficient coating systems is required to minimize the amount of material replacement throughout the life of the ship.
7. The analysis presented in this study may be applied to all ships such that ship owners are assisted in deciding the time for recoating or replacement of corroded steel plate.

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