IMPACT ON SHIP STRENGTH OF STRUCTURAL DEGRADATION DUE TO CORROSION

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ABSTRACT

The paper addresses the problem of corrosion of ship structures. The main environmental and operational factors affecting the initiation, spreading and rate of corrosion of ship structures are given. The main problems of general and local corrosion of cargo ships, bulk carriers and oil tankers are briefly discussed. The methods commonly used to control and prevent the initiation and spreading of corrosion are briefly indicated. The consequences of corrosion associated with degradation of structural strength of ship structures are stressed. The effect of material deterioration due to corrosion on the buckling strength and stiffness of a plate panel is investigated. Parabolic and exponential models are assumed to represent the variation of the rate of wastage with time. The effect of uniform corrosion on the section modulus and inertia of stiffeners having different geometrical configurations are presented. The impact of material wastage due to corrosion of the deck structure on the ship section geometrical characteristics is clarified. The effect of corrosion on the magnitude of the factor of safety and the probability of failure is examined. Structural degradation problems associated with the corrosion of HTS are clarified. It is shown that the buckling strength and the flexural rigidity of a panel of plating could be significantly reduced when the plate panel experiences the normal rates of wastage due to corrosion. The deterioration of the geometrical characteristics of stiffeners could vary between 15% and 38% depending on the section configuration. The deterioration of ship section modulus and inertia could be significant for the normal rates of corrosion of the deck structure.

Key words: Corrosion, Corrosion rates, Structural degradation, Structural failure, Material wastage.

INTRODUCTION

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. Corrosion of ship structures result mainly from: age, inadequate maintenance, chemical or corrosive action of cargoes, local wear of steel plating and sections, some improper features of structural design, etc. A corroded steel plate is not only thinner but 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. Local pitting can cause serious thinning of plates and sections at critical highly stressed areas. The cause of local pitting could be water condensation, lack of cathodic protection, material defects, faulty preparation and treatment of the material, etc.

The deterioration of a HTS plate due to general or pitting corrosion will be more significant than a mild steel plate having the same strength. Therefore, ships with greater use of HTS will experience serious problems of degradation of buckling and fatigue strength. This will certainly impair the expected service life of the vessel. Protection of hull structure against corrosion is, therefore, a crucial feature for the prolonged life of ships.

Higher values of wastage of material may be accepted in certain areas for ships built to scantlings higher than those required by classification societies. This increased scantlings are often used by owners to account for loss of material due to corrosion and also to minimise the amount of material replacement required throughout the life of the ship.
The paper, therefore, addresses the corrosion problem of ship structures with particular emphasis on the impact of material wastage due to corrosion on the strength and stiffness of stiffeners, plate panels and the geometrical characteristics of ship sections.

Factors Affecting Corrosion

Corrosion of ship structures represent one of the main causes of structural failures (1,2,3), see Figure (1), and is generally affected by the following factors (4), see Figure (2):

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

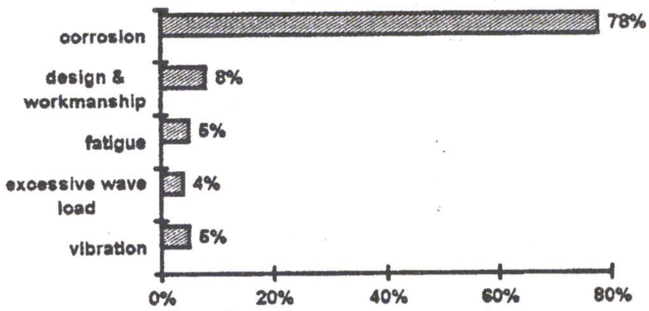

Figure 1. Main factors affecting hull structural failure.

The main environmental factors influencing the initiation of corrosion are: salinity of the sea water, temperature, pollution, marine fouling, humidity, presence of oxygen, etc.
The main operational factors participating in the initiation and spreading of corrosion are: type of cargo, cargo residues, speed of flow, mechanical abrasion, frequency of tank washing, presence of stray current, coating failure, etc. The main causes of coating failure are numerous, among them are:

- poor coating specifications
- poor handling of coated surfaces
- high stress concentration
- poor penetration resistance of the surface
- low coating thickness
- painting on moist surface
- contamination between coats
- insufficient curing time, etc.

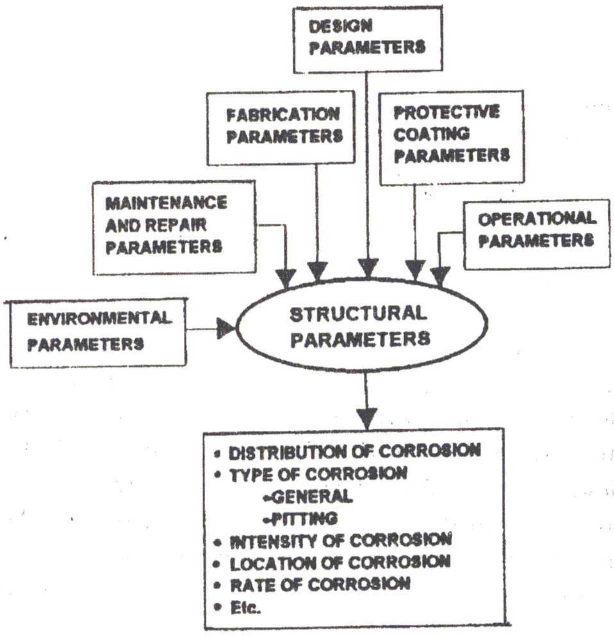

Figure 2. Main factors affecting corrosion.

Rates of corrosion

The rate of corrosion of ship structures varies with ships age, among ship types, over the same ship from one area to another, between bottom, vertical and top areas, see Figure (3). Bottom plating and horizontal areas suffer general and local corrosion whereas top areas suffer general corrosion.Corrosion occurs at a rate independent of plate thickness.
There are several factors affecting the rate of corrosion such as: type of corrosion, type of cargo carried, presence of sulphur, ships operating profile, characteristics of the environment, treatment of the steel before painting, presence of water, frequency and extent of inspection and maintenance, effectiveness of the corrosion control system, condition of coating, orientation of the surface, etc., see Figure (3).

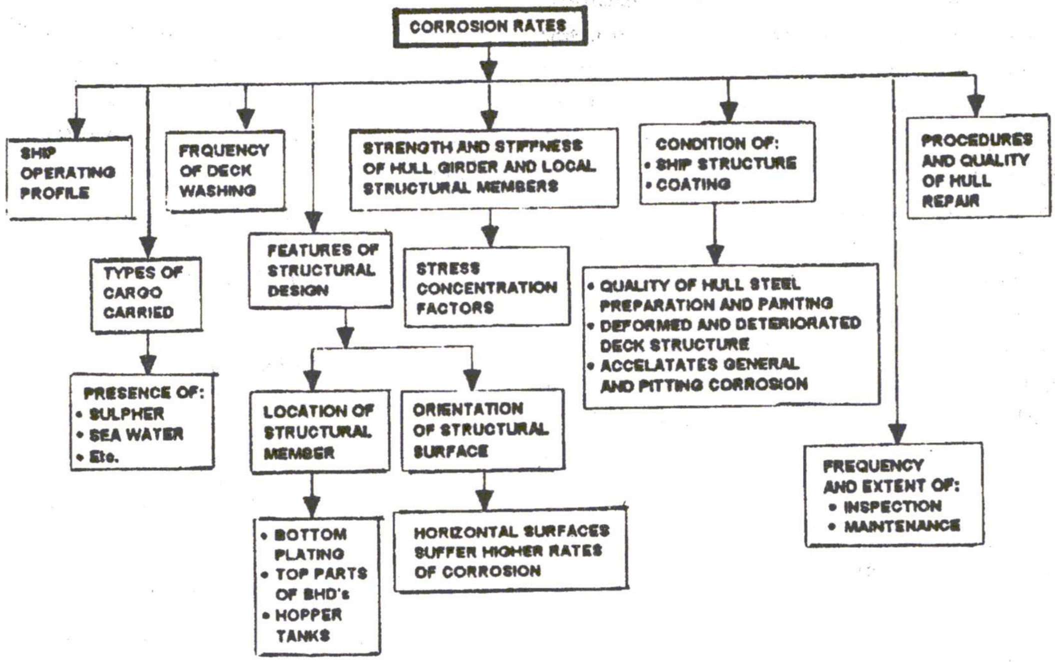

Figure 3. Main factors affecting corrosion rates of steel hulls.

The mean values of corrosion rates in mm / year for the different ship types are given in Table(1). These values are average values and are subjected to several sources of uncertainties. Corrosion rates, however, could be significantly reduced by controlling the main factors causing corrosion. Good flexible coatings could be very useful against stress-induced corrosion. Inert gas systems are effective in reducing the rate of corrosion in tankers. Cathodic protection, based on sacrificial or impressed current system is also used as a reliable and cost-effective measure against corrosion of steel ships.The proper specifications of coatings in the building stage may represent a crucial factor for reducing corrosion of hull structure.

Table 1.

Ship type	Average rate of corrosion, mm / year
general cargo	0.09
oil tankers	0.1
ore carriers	0.12
bulk carriers	0.17

Consequences of Corrosion

Corrosion of ship structures has a deleterious effect on maintenance, repair costs, hull girder, local strength and ships service life. The impact of corrosion on structural strength and stiffness of ship hull girder and local structural members are:

i- Reduction of local and hull girder scantlings
ii- Increase of local and hull girder stresses
iii- Reduction of hull girder and local load carrying capacity
vi- Increase of local stress concentration
v- Reduction of hull girder and local safety factors
vi- Significant reduction of fatigue strength of structural connections
vii- Reduction of local and hull girder flexural rigidity and buckling strength

These structural deficiencies have a pronounced deleterious effect on ships service life, maintenance and repair costs (5,6).

Design Considerations
General:

Deficient hull girder and local strength may result from errors in design, material, fabrication and operation (1). The main factor causing strength deficiency is structural deterioration by corrosion, see Figure (4). The effect of the quality of maintenance on the rate of strength deterioration is shown in Figure (5). Curve "A" indicates a cost-effective maintenance system. Curve "B" indicates an effective but costly maintenance system. Curve "C" indicates an inadequate maintenance system that will cause excessive structural deterioration and frequent structural failures (7). Figure (6) shows the effect of corrosion on the shape of the S-N curve. It is clear that uncontrolled corrosion of ship structure could lead to a significant reduction of the fatigue strength (8,9,10,11,12) .

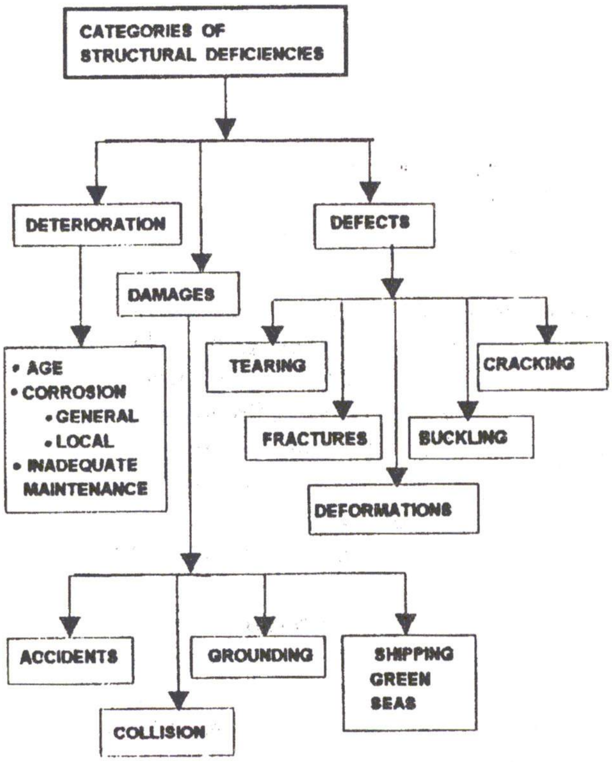

Figure 4. Categories of structural deficiencies.

Bottom plating sustains a major portion of the hull bending moment in addition to the local loads induced by hydrostatic pressure. Its strength may be reduced significantly by general and localized corrosion (13).

Deck plating comprises a highly stressed portion of the ship hull girder and is of critical importance to the longitudinal strength of the vessel. Corrosion of the deck structure is expected to occur because of the frequent deck washing, water condensations, local deck deformations, mechanical abuse from deck cargo, etc. Therefore, the deck plating should be carefully examined for cracks. leaks, signs of excessive corrosion, wear and tear, buckling, etc. (14).

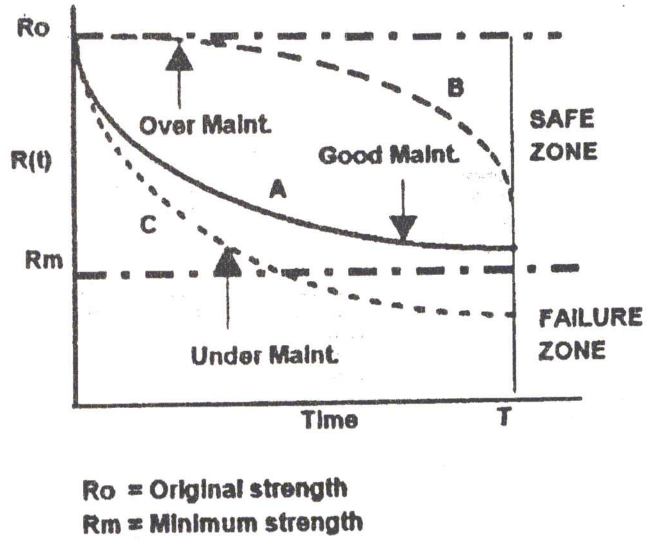

Figure 5. Variation of R(t) with time.

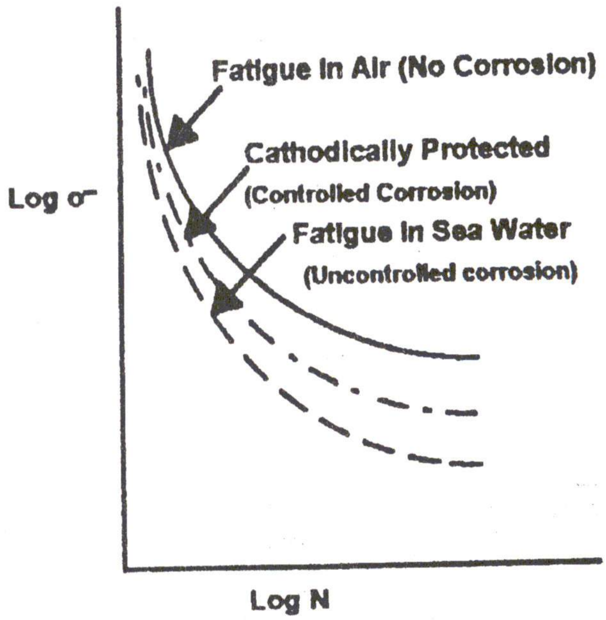

Figure 6. Effect of corrosion on fatigue curve.

The reduction of ship section geometrical characteristics due to material wastage of deck structure due to corrosion is shown in Figure (7). It is shown that a 30% reduction in the sectional area of the deck plating, due to corrosion, could cause a 15% reduction in ship section modulus. The variation of the critical buckling strength with time for a panel of plating is shown in Figure (8),for an assumed parabolic model for the material wastage due to corrosion, and in Figure (9) for an exponential model. It is shown that the critical buckling strength could be reduced by more than 30% when the thickness of the plate panel experiences the normal wastage due to corrosion.

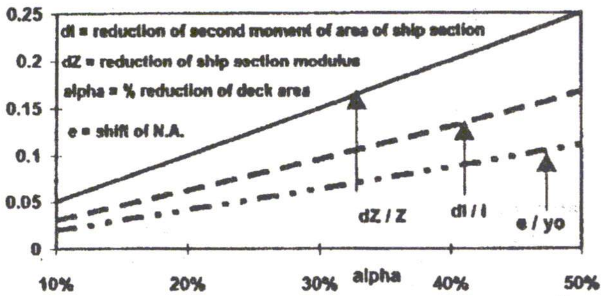

Figure 7. Variation of ship section characteristics with deck deterioration.

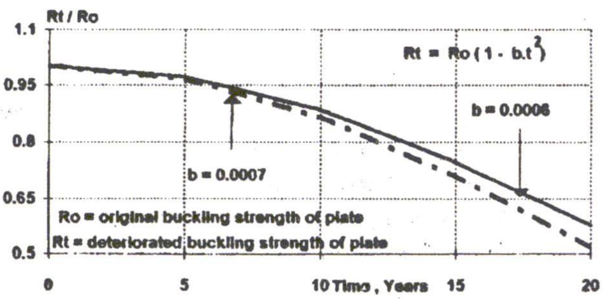

Figure 8. Variation of buckling strength with time, parabolic model.

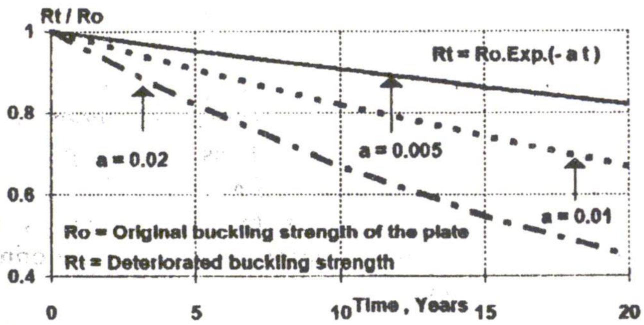

Figure 9. Variation of plate buckling strength with time, exponential model.

The effect of uniform corrosion of an angle section 200x100x13 mm on the section modulus and inertia is shown in Figure (10) and for an OBP section 430x20 mm. is shown in Figure (11). It is shown that the section modulus and inertia could be reduced by more than 25% for normal values of material wastage. Figure (12) shows the deterioration of section modulus with time for three different section configurations. It is shown that the deterioration of the section modulus and inertia vary between 15% and 38% depending on the section configuration.This may have a significant impact on the magnitude and distribution of flexural stresses over the web and flange of the section, particularly for asymmetrical sections (15).

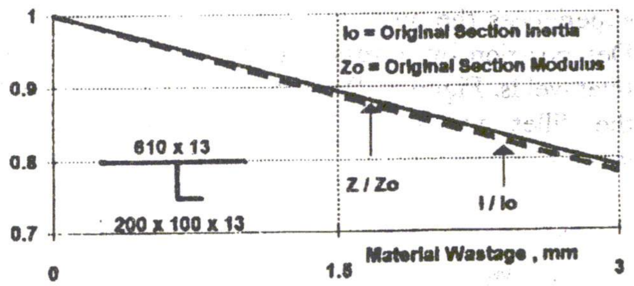

Figure 10. Effect of material wastage on Z/Z_o and I/I_o.

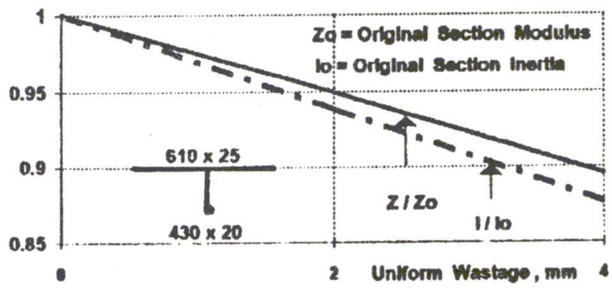

Figure 11. Effect of uniform wastage on Z/Zo and I/Io.

The increased flexibility of ship structures due to the extensive use of HTS or due to the improper distribution of material over the ship section may cause local breakdown of protective coatings and initiation of corrosion.

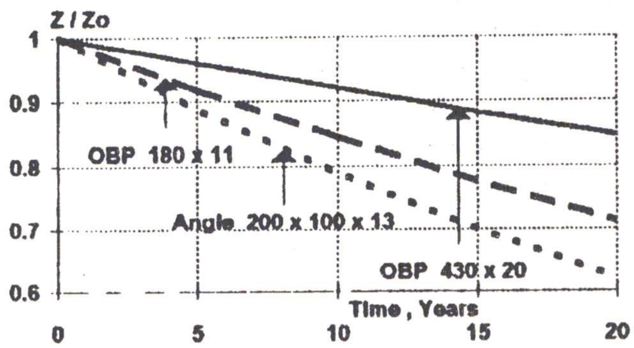

Figure 12. Variation of Z/Zo with time.

The effect of material wastage for a panel of plating on the flexural rigidity is shown in Figure (13) for three different plate thicknesses. It is clear from Figure (13) that the flexural rigidity could be significantly reduced when the plate panel experiences the normal wastage due to corrosion. Deterioration by corrosion may be excessive around fillet welds. Figure (14). shows local corrosion around the fillet welds of a stiffener attached to a longitudinal connection.

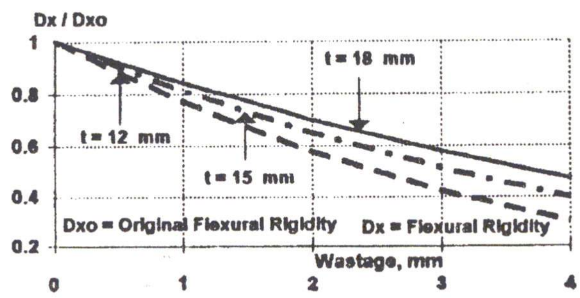

Figure 13. Effect of plating wastage on flexural rigidity.

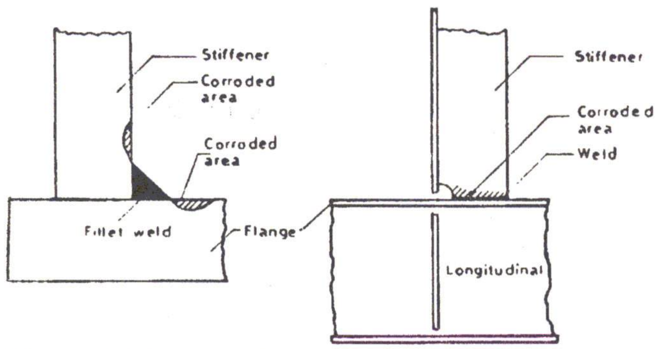

Figure 14. Corroded areas in a stiffener-longitudinal connection.

General Cargo Ships

For general cargo ships, corrosion occurs at several places such as the deck structure, the lower part of the holds or twin deck frames, the lower part of transverse bulkheads, aft end of double bottom tanks and certain areas of tank tops where water is trapped due to ineffective drainage system (1). Figure (15) shows the distribution of corrosion failures among the different structural elements of the deck structure. The distribution of crack and buckling failures over the deck structural elements are given in (1). Accelerated corrosion of the deck structure may aggrevate the consequences of these modes of failure.

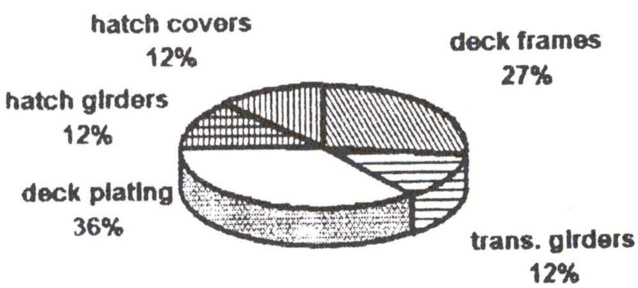

Figure 15. Corrosion failures of deck structure.

For transversely framed ships, severe buckling of bottom plating within the mid-ship region may result from general and local corrosion. Figure (16) shows the distribution of structural failure due to corrosion among the bottom structural elements. This can seriously impair hull girder and local strength of the midship section. The distribution of structural failures due to corrosion among the structural elements of the side shell structure is shown in Figure (17). Transverse bulkheads between cargo holds experience excessive corrosion in the lower boundaries and in way of bilge wells.
High wastage occurs in ballast tanks and in inaccessible structural areas where inspection and maintenance are difficult such as the top parts of transverse bulkheads. Ease of access to the various parts of cargo and ballast tanks is necessary if efficient inspection, maintenance and monitoring system are required.

Bulk Carriers

Hopper, top side and double bottom tanks, ballast holds and void spaces, etc. are subjected to excessive material wastage by corrosion. The tops of transverse bulkheads and the underside of the deck structure are also subjected to severe corrosion. Structural failures of bulk carriers due to corrosion have been recognised and reported in several papers (16). The strakes of side shell plating between wind and water are highly susceptible to severe uniform corrosion and localised pitting. This area is generally subjected to high values of shear stresses (17,18) particularly at about 0.3L and 0.7L from A.P. High material wastage of these areas could have an adverse effect on the shear buckling strength of the side shell plating, particularly for HTS. Therefore, the extensive use of HTS in bulk carriers is not recommended.

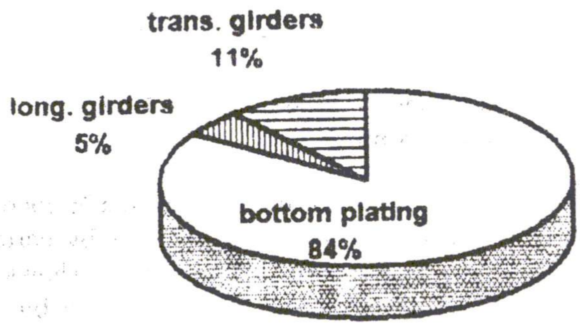

Figure 16. Failures of bottom structure due to corrosion.

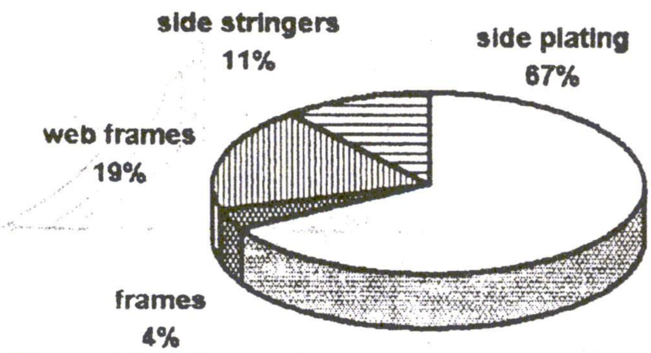

Figure 17. Failures of side shell structure due to corrosion.

Oil Tankers

Hull fractures and failures in oil tankers are generally attributed to detailed design aspects in areas of stress concentration at bracket toes and longitudinal connections to transverse web frames (1,19,20). The stress concentration factors at these connections are relatively high and could represent a serious hazard when material wastage due to corrosion reaches unacceptable values (21).

The rate of corrosion of oil tankers is significantly influenced by the following main factors: tank washing, tank contents, tank atmosphere when empty, presence of inert gas, etc.

All parts of ballast tanks and transverse bulkheads between cargo tanks and ballast tanks are subjected to severe corrosion. Lower and top strakes of transverse and longitudinal bulkheads are generally subjected to excessive corrosion.

Deterioration of deck longitudinals by corrosion may be more rapid and extensive than that of deck plating. The wastage may reach 50% in some parts. Figure (18). shows an example of corrosion in a deck longitudinal and a proposed method for reinforcement.

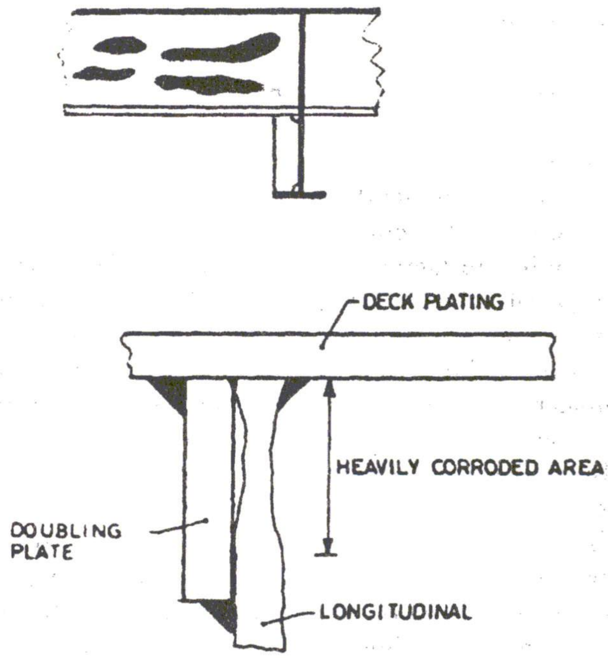

Figure 18. Corrosion of a deck longitudinal.

For Pre-Marpol, HTS was used for the DWT limited VLCC's to provide a weight saving and an increase in the DWT cargo capacity. However, because of the limited availability and high cost of HTS, the use of HTS was limited only to deck and bottom structures.

For Post-Marpol VLCC, all tankers over 30.000 DWT, the cargo carrying capability is volume limited and consequently weight savings due to the use of HTS is no longer valid for ship owners. However for shipbuilders weight saving through the use of HTS is advantageous as the difference in price between HTS and grade A mild steel is now very marginal.

The use of HTS allows lighter scantlings and results in a more flexible structure. Greater flexibility of primary structure results in more load being shed to secondary structures. In this case, the strength of the ship is more dependent on the integrity of the structure as a whole. Excessive flexibility may also lead to fatigue problems at design details. HTS structures exposed to stress cycling at higher stress levels will have a shorter fatigue life than the equivalent mild steel structure. Therefore, the deterioration of strength due to corrosion is far more significant for HTS than for mild steel.

Effect of corrosion on the probability of failure

It is evident that the deterioration of ship structural elements due to corrosion will have direct impacts on the critical buckling strength, fatigue strength, the factor of safety and the probability of structural failure, Pf. Figure (19) shows the variation with material wastage of the factor of safety and the critical buckling strength for a panel of plating subjected to compressive stresses. It is shown that the factor of safety for flexural buckling reduces by about 30% when the plate thickness experiences the normal uniform rate of wastage by corrosion.

The effect of strength deterioration due to poor maintenance and excessive corrosion on the shape of the density function of strength and the probability of failure, Pf, is shown in Figure (20). It is evident that the probability of failure, Pf, increases significantly with increasing deterioration due to corrosion.

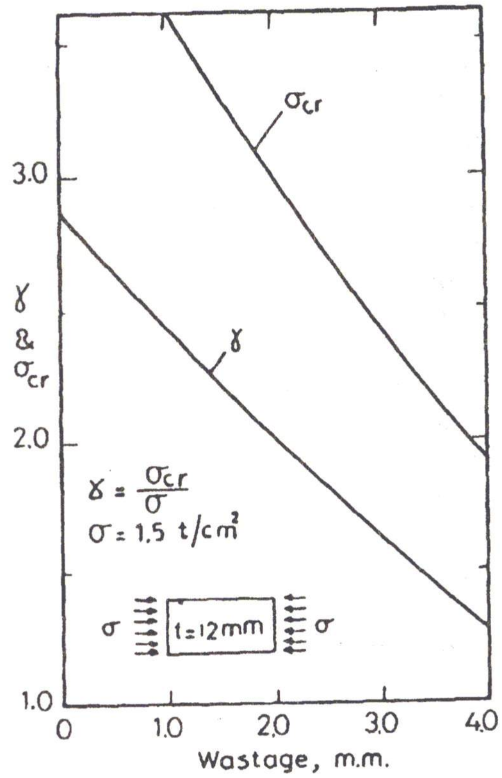

Figure 19. Variation of γ & σ_{cr} with wastage in mm.

Figure (20) shows that the shaded area "a" increases with increased structural deterioration by corrosion and poor maintenance. Figure (21) shows the increase with time of "Pf" for fatigue and buckling strength of a ship structural member subjected to the normal rates of corrosion.

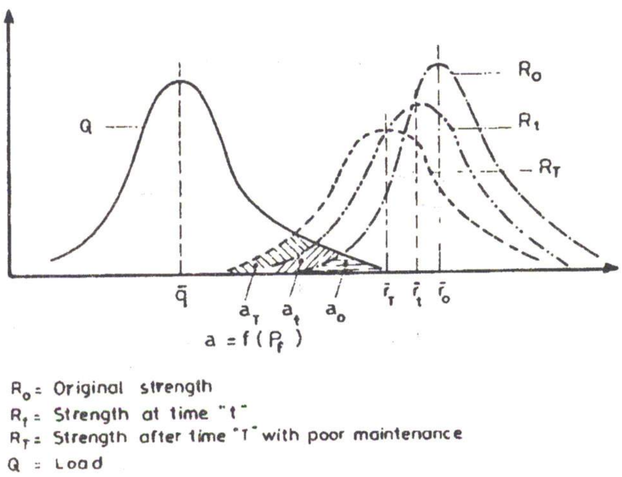

Figure 20. Effect of poor maintenance on P_f.

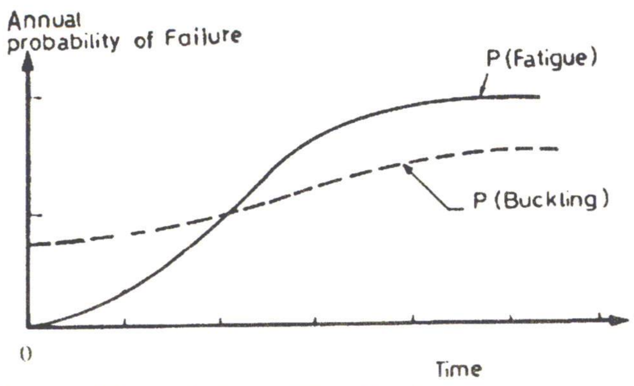

Figure 21. Variation of P_f with time.

CONCLUSIONS

The main conclusions drawn up from this investigation are:

1- The geometrical characteristics of ship sections could be seriously reduced when the deck and/or bottom structures experience the normal wastage due to corrosion.
2- The buckling strength and the flexural rigidity of a panel of plating could be significantly reduced when the plate panel experiences the normal rate of corrosion.
3- The deterioration of the section modulus of frames, longitudinals, stiffeners, etc. varies between 15% and 38% depending on the section configuration.
4- Local thickness deterioration of up to 25% may be accepted for many parts of the vessel before replacement becomes necessary.
5- In order to prevent / reduce the initiation of pitting corrosion, it is necessary to eliminate any critical defects prior to service and to prevent non-critical defects to grow to critical size during service.
6- A good inspection, maintenance and monitoring system for assessing and protecting hull structures from corrosion represent a main factor for reducing strength deficiencies and extending ships life.
7- High quality surface preparation and protective coatings have significant effects on reducing the rates of general and local corrosion.
8- The increased flexibility of ship structures due to the extensive use of HTS or due to the improper distribution of material over the ship section may cause local breakdown of protective coatings with subsequent initiation of corrosion.

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