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A Probabilistic Corrosion Rate Estimation Model for Longitudinal Strength Members of Bulk Carriers

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Abstract

Many bulk carrier losses have been reported of late, and one of the possible causes of such casualties is thought to be the structural failure of aging hulls in rough weather. Clearly, in such cases, vessels that start out being adequate somehow become marginal later in life. Fatigue and corrosion related potential problems may be the most important factors affecting such age related vessel damage. With respect to fatigue, extensive studies have been done worldwide both experimentally and theoretically, and the results have been applied to some extent. However, in the case of corrosion effects, additional research is still needed to better understand, clarify and address the various strength uncertainties and their effects on structural behavior. This paper develops a probabilistic corrosion rate estimation model for the longitudinal strength members of bulk carriers. The model is based on available statistical data for corrosion of existing bulk carriers. The corrosion data collected are documented for future use.

Keywords :Corrosion damage, longitudinal strength members, bulk carrier, probabilistic corrosion rate estimation model

1. Introduction

Since the beginning of 1980s to mid 1990s, over 150 bulk carriers are reported to have been lost, with a loss of more than 1,200 lives [RINA, 1996]. Some (nearly 20) of those vessels disappeared for no known cause. Many studies to reduce bulk carrier casualties have subsequently been undertaken by the International Maritime Organization (IMO), the International Association of Classification Societies (IACS) and also some of the leading classification societies themselves.

In case of bulk carriers, investigations [Arvin and Spence, 1992] indicate that the age of the most of the implicated vessels is over 15 years, and significant defects such as corrosion, fatigue cracks and structure deterioration may have been present. Also, more than 80% of the implicated vessels apparently encountered the incidents when they were carrying iron ore or coal, the former being one of the denser types of cargo, and the latter being one of the more corrosive.

Due to the casualties of aging vessels during the last decade, including the above mentioned bulk carrier losses, the safety assessment of hull structures subject to corrosion has been of increasing interest [Arvin and Spence, 1992; Pollard, 1991; Paik, 1994]. Also, there have always been vessels that continue to be operated over 20 to 25 years, bringing the consideration of various problems potentially associated with vessel age into focus [Emi et al., 1991; Emi et al., 1992; Emi et al., 1993a]. Recognizing that age alone is not the sole determinant of vessel performance, the International Maritime Organization (IMO), classification societies and ship owners continue to seek reasonable solutions to maintaining the structural integrity of aging ships and to minimize the repair and maintenance costs over the ship life cycle [Nakken and Valsgåd, 1994; Emi et al.,1993b; Tikka and Donnelly, 1991].

In a number of damage cases that have been reported, it is possible that corrosion damage and fatigue cracks may have existed in primary and other members. In any event, fatigue and corrosion are the two most important factors affecting structural performance over time. Several studies on assessment of fatigue strength of ship structures have been performed to date, and the analysis procedures for the fatigue problem as well as the fatigue design criteria have been estab-lished [Capanoglu, 1993].

As for corrosion effects, guidelines for inspection of corroded hulls have been developed [IACS, 1994] and recommendations for repair of corroded areas have been established. Nominal design corrosion values (NDCV) for different parts of structure and vessel types have been developed [ABS, 1995]. Corrosion in tankers has been extensively studied by the Tanker Structure Co-operative Forum [TSCF, 1992, 1997].

Based in part on the TSCF data, Lfseth et al. [1994] recently provided estimates of corrosion rate (mm/year) for primary members of tanker structural areas. Based on data for existing vessels, they provided mean value and COV (coefficient of variation) of corrosion rate for various types of primary members of single- and double-hull tankers. Differences due to location and corrosion severity of the space were taken into account. Tanker corrosion rates have also been studied by Pollard [1991], by Hart et al. [1985], and by Viner & Tozer [1985]. Most recently, Paik et al. [1997] performed comprehensive studies regarding the effect of corrosion on ship hull girder ultimate strength for tankers.

However, there are very few studies of comparable sophistication available for bulk carriers [Paik, 1994]. Ivanov [1986] developed a mathematical model for statistical evaluation of ship's hull cross section geometrical characteristics due to the corrosion wear where the normal distribution law for all characteristics was assumed and an example for bulk carrier was shown. Recently, Yamamoto & Ikegami [1996] developed a probabilistic corrosion rate estimation model for transverse bulkheads of bulk carriers. Apart from this, there seems to be little literature on bulk carriers, particularly regarding the probabilistic characteristics of longitudinal strength members of bulk carriers which are important to potential hull girder collapse.

For the structural safety assessment of corroded ships, we need to clarify how corrosion develops and proceeds in structural members, the spatial extents of member degradation, and what the likely effects are on ship strength. These considerations are complicated by the fact that corrosion is affected by a large number of factors, including type of protection employed, type of cargo, temperature, humidity, etc.

This paper develops a probabilistic corrosion rate estimation model for longitudinal strength members of bulk carriers. The model is based on available statistical data for corrosion damage of existing bulk carriers.

2. Corrosion Mechanics

The corrosion rate of hull structures is influenced by many factors including the corrosion protection system and various operational parameters. In general, the corrosion protection systems employed are coatings and anodes. The operational parameters include the percentage of time in ballast, frequency and method of tank cleaning, maintenance and repair, etc.

To predict likely corrosion damage tolerance a priori, it is necessary to have an estimate of the corrosion rate for each type of structural member. In this context, the theoretical prediction of the corrosion rate of structural members has been tried [Melchers, 1995], but is not an easy task. An easier alternative is to base the rate prediction on statistical analysis of past data for comparable situations.

There are four aspects related to corrosion that one ideally needs to define for a structural component in a tank or space:

- Where is corrosion likely?
- When does it start?
- What is its extent?
- What are the likely corrosion rates?

The first question would normally be answered using historical data of some form, e.g., results of previous surveys. As to when corrosion starts, this again is information that should come from prior surveys for the particular vessel. Assumptions as to time of start of corrosion can of course be made, depending on the use of protection system, characteristics of coatings, and anode residence time.

The extent of corrosion presumably increases with time, but our ability to predict the progress of corrosion remains meager. The only real alternative is then to pessimistically assume more of a corrosion extent than is really likely, such as what one would do in the case of nominal design corrosion values.

The following is a general discussion of the important factors determining the corrosion rate in hull spaces of bulk carriers:

Types of cargoes and time in ballast:

This determines the level of exposure to different corrosive media. In principle one could distinguish between six types of major cargoes / ballast situations in normal bulk carriers:

- Coal
- Iron ore
- Grain cargo
- Heavy ballast in holds
- Trimming ballast in holds
- Normal ballast in ballast tanks

In normal bulk carriers, the probabilities of carriage of the major cargoes are: coal about 40%, iron ore about 35% and grain about 20%, which indicates coal as a cargo to be the most probable, followed by iron ore as a close second. On a relative basis, carriage of such coal cargo can lead to higher corrosion rates especially in way of welded joints, as coal cargo may contain sulpher, humidity and sometimes high temperature.

Depending on trade route and weather condition, the frequency of ballasting in heavy ballast holds will be decided. Higher frequency of heavy ballast condition while seagoing can cause higher corrosion related damage at the critical areas. In typical bulk carriers, many such instances of damage have been recorded in way of heavy ballast holds.

In loading and unloading cargoes at harbour, in order to adjust trim, empty cargo holds may be partly filled with ballast water. Such ballast cycles will also accelerate local corrosion as the steel surface is repeatedly dry or wet by sea water.

In ballast tanks, corrosion will start in way of coating breakdown and high stress zones such as ends of elements and free edges of cutouts. Significant corrosion of elements in ballast tanks adjacent to fuel oil tanks is also possible. This is due to heat transferred from the fuel oil tanks.

Corrosion protection effectiveness:

In coated ballast tanks, general corrosion rates are low initially until coating breakdown. In a relative sense, such breakdown is more likely in areas difficult to coat, areas of stress concentration and re-entrant corners. Examples are slots and lightening holes in webs, floors and girders. Areas of local faults in coating are likely locations of increased corrosion, but difficult to predict beforehand. Anodes provide some protection when immersed in electrolytic solutions for a sufficient residence time. Location, number, and current density are additional factors in their effectiveness.

Component location and orientation:

Some locations in a hold are more susceptible to corrosion than others. Data indicate that the heavier corrosion is found at the following locations:

- Inner bottom, lower and upper sloping plates
- Hold frame and side shell plate
- Deck plate and shear strake
- Deck longitudinals

Ability to collect/trap sea water:

Horizontal members are more susceptible than vertical members. Wastage rates depend also on flow rate (which are higher near cut-outs and bell mouths) and also vessel trim. For vessels that trim by stern, the aft bays of holds and ballast tanks are more susceptible than the forward bays.

Level of oxygen:

Typically, the ullage areas and deckhead structures have higher corrosion rates than the splash and immersed zones in a ballast tank. Another location dependent aspect is one or two sided corrosion.

Temperature:

This is a function of the cargo, any heating used, and vessel trade route. The higher the temperature, the higher the likely rates of corrosion, which explains increased corrosion on tropical Table 1. Number of gathered data from thickness measurements for primary members of existing bulk carriersroutes. Trade routes also affect humidity (as can certain types of cargo). Higher levels of humidity lead to higher corrosion rates.

Table 1. Number of gathered data from thickness measurements for primary members of existing bulk carriers

No.	Members	Number of data
1	Bottom plates (BP)	673
2	Inner bottom plates (IBP)	556
3	Lower sloping plates (LSP)	220
4	Lower wing tank side shells (LWTSS)	152
5	Side shells (SS)	383
6	Upper wing tank side shells (UWTSS)	201
7	Upper sloping plates (UPS)	432
8	Upper deck plares (UDP)	361
9	Girders (GIR)	399
10	Bottom longitudinals (BL)	1,090
11	Inner bottom longitudinals (IBL)	848
12	Upper wing tank side longitudinals (UWTSL)	334
13	Upper sloping longitudinals (USL)	640
14	Upper deck longitudinals (UDL)	762
15	Lower wing tank side longitudinals (LWTSL)	184
16	Lower sloping longitudinals (LSL)	268
	Total	7,503

Degree of local flexibility:

Increased structural flexibility has been claimed to increase corrosion rates as time progresses, particularly as wear as a proportion of original thickness gets higher. This is apparently because of serial increases in scale loss and structural flexibility. Flexibility is greater in high tensile steel structures. Locations of necking and grooving are disproportionately affected.

3. Probabilistic Corrosion Rate Estimation Model

3.1. Survey of corrosion data on longitudinal members of existing bulk carriers

Measurements related to the wear of plate thickness in the longitudinal members of existing bulk carriers were collected. Corrosion rate would be normally different from each side of a member. For instance, inner bottom plates are exposed on one side to ballast water and the other side to cargo. However, the data have been gauged at one side of each member, because of difficulties in measuringcorroded plates at both sides, and they are total wear of plate thickness.

A total of 7,503 corrosion data for 44 existing bulk carriers were obtained. The corrosion data pertained to sixteen types of primary structural members of bulk carriers, see Table 1 and Figure 1. Table 2 indicates examples of the statistics of corrosion data for some primary member regions as a function of time. The corrosion data indicated in Table 2 are based on assumption that corrosion starts 5 years after newbuilding. Thus, the time, for instance, 4.75~5.00 in Table 2 indicates the

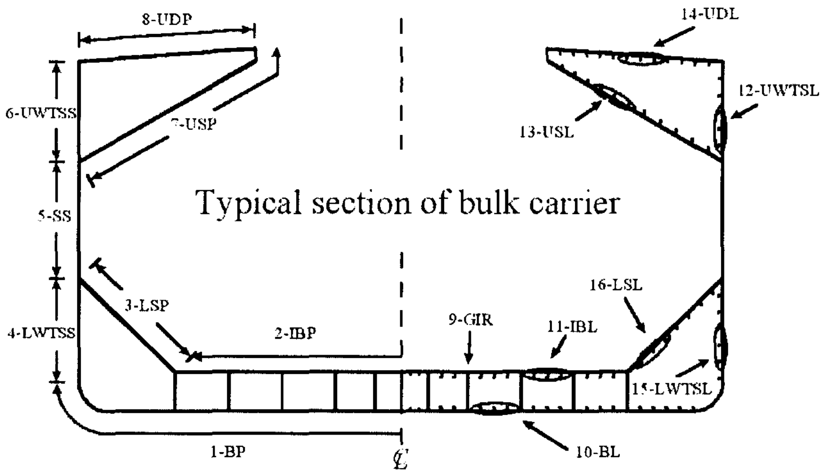

Figure 1. Longitudinal primary members of bulk carrier

Table 2. a. Wear of thickness due to corrosion for inner bottom plates of carriers

Time(year)	Depth of Corrosion (mm)									
	~0.0	~0.5	~1.0	~1.5	~2.0	~2.5	~3.0	~3.5	~4.0	~4.5
4.75 ~ 5.00	1	11	2							
6.00 ~ 6.25	2	5	6	3						
6.25 ~ 6.75		2	10	4	3	2				
7.25 ~ 7.50	6	14								
7.75 ~ 8.00						1	3	3	3	1
8.00 ~ 8.25		5	1		1	9	4			
10.00 ~ 10.25					3	15	1	3	4	3
11.00 ~ 11.25		1	1	12	6	2	10	11	3	4
11.75 ~ 12.00			3	11						
13.75 ~ 14.00				10	2					
14.00 ~ 14.25		2	1	5	2	3				
14.25 ~ 14.50			4	5	5	2				
14.50 ~ 14.75		1	4	6	4	1				
14.75 ~ 15.00		4	16	4	8	7	3	1		
15.00 ~ 15.25		21	16	4	2	8	18	10	3	2
16.00 ~ 16.25					1	5	10	2		
16.25 ~ 16.50					1	5	10	2		
17.00 ~ 17.25		1	4	1	3					
18.00 ~ 18.25			7	17	5	2				
20.00 ~ 20.25			7	2	10	5	7		4	1

Table 2. b. Wear of thickness due to corrosion for side shells of bulk carriers

Time(year)	Depth of Corrosion (mm)									
	~0.0	~0.5	~1.0	~1.5	~2.0	~2.5	3.0	3.5	4.0	4.5
4.75 ~ 5.00	6	4								
6.00 ~ 6.25	3	5								
6.25 ~ 6.50		10								
6.50 ~ 6.75	9	9	14	2						
7.25 ~ 7.50	4	4								
7.75 ~ 8.00			2	1	1					1
8.00 ~ 8.25	2	6	4	6						
10.00 ~ 10.25			9	6	1					3
11.00 ~ 11.25			6							
11.75 ~ 12.00		10								
13.00 ~ 13.25		12	12	1	1					4
13.75 ~ 14.00		5	6	1						
14.00 ~ 14.25	2	2	2							
14.25 ~ 14.50	3	17								
14.50 ~ 14.75		11	9							
14.75 ~ 15.00	9	16	3							
15.00 ~ 15.25	5	19	8	9	3					2
16.00 ~ 16.25	6		2	2	1					
16.25 ~ 16.50					5	5				
17.00 ~ 17.25		7	8							
18.00 ~ 18.25		10	10							
20.00 ~ 20.25	2	8	10	7	4	5				1

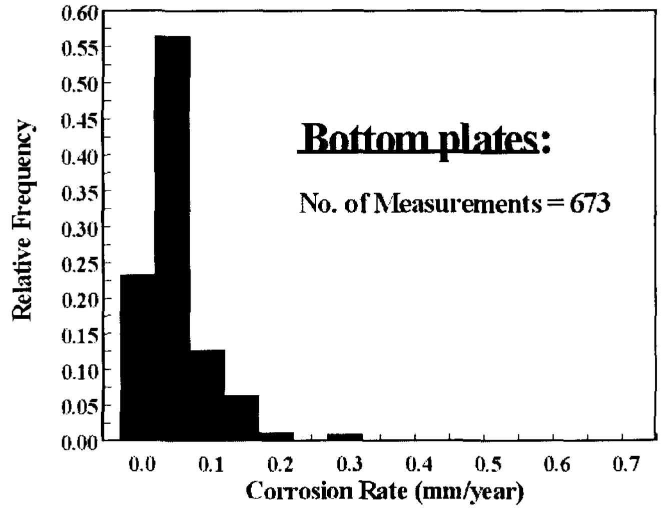

Figure 2. a. Frequency distributioin of corrosion rate for inner bottom plates of bulk carriers

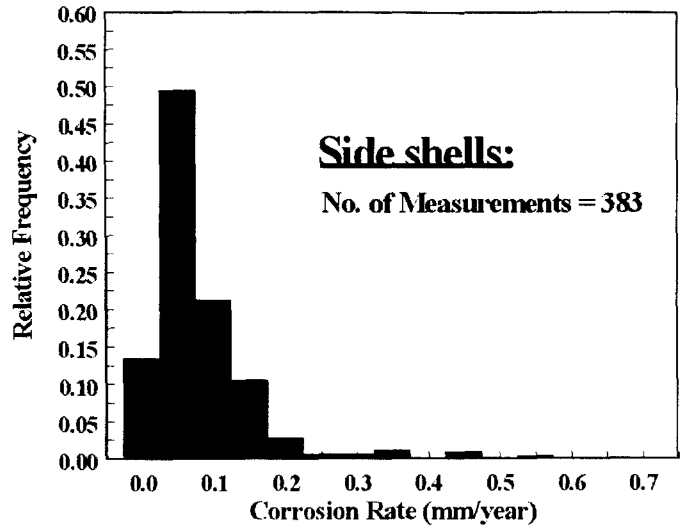

Figure 2. b. Frequency distributioin of corrosion rate for side shells of bulk carriers

ship age of 9.75~10.00 years. It should also be noted that some of the data obtained might be measured for repaired members, indicating even smaller wear of corrosion. This is in fact due to lack of measurement information. As will be noted later, therefore, the analysis is made based on some or all of the corrosion data collected.

From such data, Figure 2 shows the calculated relative frequency distribution of annual corrosion rate, e.g., wear of thickness due to corrosion divided by ship age (mm/year) for some member regions. It is seen that there is a large scatter in the corrosion rate data, and so a probabilistic treatment of the problem is needed.

3.2. Probabilistic formulation

In order to take into account of the various uncertainties associated with corrosion, a probabilistic formulation is now established. Where coatings are present, the progress of corrosion would normally very much depend on the degradation of such anti-corrosion coatings. Therefore, the corrosion model developed in the present study is divided into two parts, one related to the life of coating and the other related to progress of corrosion, where it is assumed that the corrosion starts immediately after coating effectiveness is lost.

(1) Life of coating

The life of coating essentially corresponds to the time when the corrosion starts after the newbuild of vessels. The life of coatings may be assumed to follow the normal distribution, given by

$$f(t) = \frac{1}{\sqrt{2\pi}\sigma_{cl}} \exp\left\{-\frac{(t-\mu_{cl})^2}{2\sigma_{cl}^2}\right\} \quad (1)$$

where

μ_{cl} = mean value of coating life

σ_{cl} = standard deviation of coating life

It is known that the mean value of coating life is normally 5 to 10 years [Lfseth et al., 1994]. In fact, a 5 year coating life may be considered to represent an undesirable situation, while 10 years would be representative of a relatively more desirable state of affairs. Also, according to Emi et al. [1993a], the coefficient of variation (COV) of coating life is about 0.4.

(2) Progress of corrosion

The wear of plate thickness due to corrosion may be generally expressed as a function of the time (year) after the corrosion starts, namely

$$r = c_1 t^{c_2} \tag{2}$$

where

r = wear of plate thickness due to corrosion
t = elapsed time after breakdown of coating = $T - T_0$
T = age of vessel
T_0 = life of coating
c_1, c_2 = coefficients

The coefficient in equation (2) may be usually assumed to be 1/3 [Kondo, 1987] or pessimistically assumed to be 1, while the coefficient c_1 is indicative of the annual corrosion rate. Yamamoto et al. [1994] found that the probability density function of the corrosion rate could be assumed to follow the Weibull distribution. Hence, the cumulative distribution function of the coefficientc_1 may be given by

$$f_{c_1} = 1 - \exp\left[-\left(\frac{x}{\alpha}\right)^{\lambda}\right] \tag{3}$$

where

α = unknown scale parameter
λ = unknown shape parameter

Equations (2) and (3) together define the probability density of the wear of plate thickness due to corrosion as follows:

$$f_{c_1} = \frac{\lambda}{\alpha}\left(\frac{x}{\alpha}\right)^{\lambda-1} \exp\left[-\left(\frac{x}{\alpha}\right)^{\lambda}\right] \tag{4}$$

It is thus necessary to determine mean and standard deviation of for evaluating the probabilistic characteristics of corrosion. Their direct calculation using equation (4) is usually not straightforward, and so an approximate procedure is used in the present study. In this context, equation (3) is rewritten in terms of

$$Y = \lambda X - \lambda \ln \alpha \tag{5}$$

where

X = $\ln x$
Y = $\ln[-\ln(1 - F_{c_1}(x))]$

By using the least squares method, the unknown parameters α and λ are determined for each primary member type. Once scale and shape parameters, i.e.,$\alpha$and λ are obtained, the mean value and standard deviation of the coefficient c_1 can be calculated in terms of the Gamma function as follows:

$$\begin{aligned} \mu_{c_1} &= \int_0^\infty x \cdot f_{c_1}(x)dx = \alpha\Gamma\left(1+\frac{1}{\lambda}\right) \\ \sigma_{c_1}^2 &= \int_0^\infty (x-\mu)^2 \cdot f_{c_1}(x)dx = \alpha^2\left[\Gamma\left(1+\frac{2}{\lambda}\right) - \left\{\Gamma\left(1+\frac{1}{\lambda}\right)\right\}^2\right] \end{aligned} \qquad (6)$$

4. Computed Results and Discussions

Applying the corrosion data for each primary member type as described in section 3.1, the probabilistic parameters, i.e., mean and standard deviation of the corrosion rate for primary member regions of bulk carriers can be obtained.

As previously noted, the corrosion data collected might include those gauged for renewal members due to heavy corrosion. Therefore, the analysis was carried out using some of the data, i.e., the data up to the ship age of 15.25 years or all data collected.

Figure 3 presents the computed results for mean and standard deviation of corrosion rate for each primary member type in a bulk carrier. Based on the computed results as shown in the figure, the following conclusions can be drawn:

1) The corrosion rate of boundary plating between ballast water and cargo regions, e.g., inner bottom, upper and lower sloping plate, is higher than that of bottom and bilge plates. This will be due to the fact that the former plates are exposed to both ballast and cargoes, while bottom and bilge plates are exposed to ballast water alone as the external (outer) surface is fully coated.

2) The corrosion rate of inner bottom plates is considerably high. This shows that inner bottom may be relatively rapidly corroded not only due to it being a boundary between ballast and cargoes, but also due to high mechanical wastage and accelerated local corrosion as a horizontal surface.

3) The corrosion rate of the side shell between lower wing tank and upper wing tank is slightly higher compared to the shell in way of lower wing tank and upper wing tank. This indicates that cargoes being carried may have been relatively more corrosive than the ballast water, possibly due to their higher humidity and / or temperature.

4) Deck in way of upper wing tanks show heavier corrosion when compared to the other external surfaces. This is perhaps due to frequent wet and dry cycles in the ullage areas of the top side ballast tank and also the heat of the sun.

5) Most longitudinals in the ballast tanks show quite similar corrosion rates except those at the deck. The higher corrosion rate of the deck longitudinals are presumably due to the same reasons as the deck plate, see 4) above.

6) The corrosion rate based on the data up to 15.25 years gives slightly higher values than those based on all data collected, especially in way of inner bottom and hopper plates, inner bottom longitudinals, side shell plates and deck plates. This would be due to the fact that the renewal of members due to heavy corrosion is usually made after the ship age of about 15 years. This also implies that the corrosion rate estimate model developed in this study may be not complete, and it should be further modified based on much more data of corrosion as they become available. Nev-

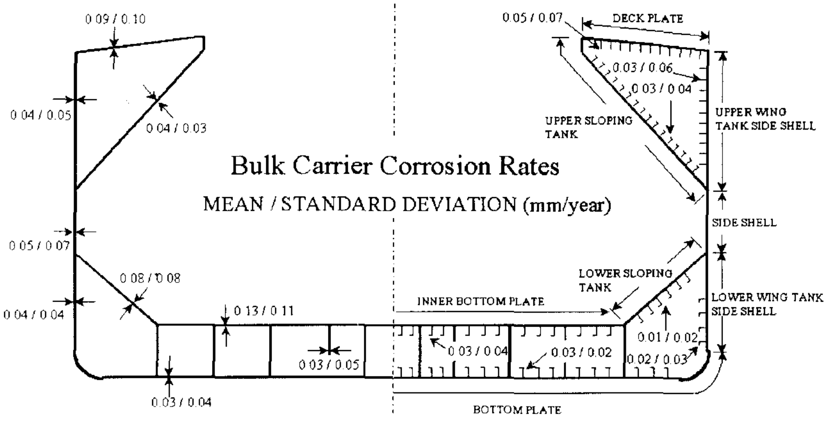

Figure 3. a. Mean and standard deviation of corrosion rate for each member type in an conventional bulk carrier based on all data collected, i.e., up to the ship age of 25.25 years

ertheless, it is concluded that the model developed in the present study quite reasonably represents the actual progress of corrosion for primary member regions of bulk carriers.

5. Concluding Remarks and Further Research

Due to several casualties in aging vessels since 1990, extensive investigations have been carried out as to their potential causes. As a result of such research and investigation, most interested parties in the shipbuilding industry are now in the process of establishing requirements and guidelines for corrosion protection measures, extent of close-up surveys, systems for recording and feedback of survey and gauging results, hull monitoring, etc.

Fatigue and corrosion are fundamental determinants of age related ship damage. In the case of the fatigue problem, extensive studies have been undertaken worldwide in the last 5 years, and the results have been applied to some extent. With respect to corrosion as well as fatigue, however, additional research is still needed especially for bulk carriers which to date have not been investigated systematically.

As any damage to an oil tanker may cause a spill and creates serious potential environmental pollution, fire or explosion, damage to tankers from corrosion and fatigue have been continuously discussed in technical conferences and bodies such as the Tanker Structure Cooperative Forum.

Through the discussions in such venues, corrosion damage estimation models for oil tanker are being better established. The characteristics of corrosion are quite uncertain in nature, and thus such models have normally been developed in a probabilistic form. For bulk carriers, however, the development effort related to such models is perhaps somewhat behind, compared to tankers.

The objective of the present study has been to develop a probabilistic corrosion rate estimation model for the longitudinal strength members of bulk carriers. A total of 7,503 corrosion data for sixteen primary member types in 44 existing bulk carriers have been collected. The progress of corrosion would depend on degradation of any anti-corrosion coating. Therefore, the corrosion model developed in the present study is divided into two parts, namely that for consideration of

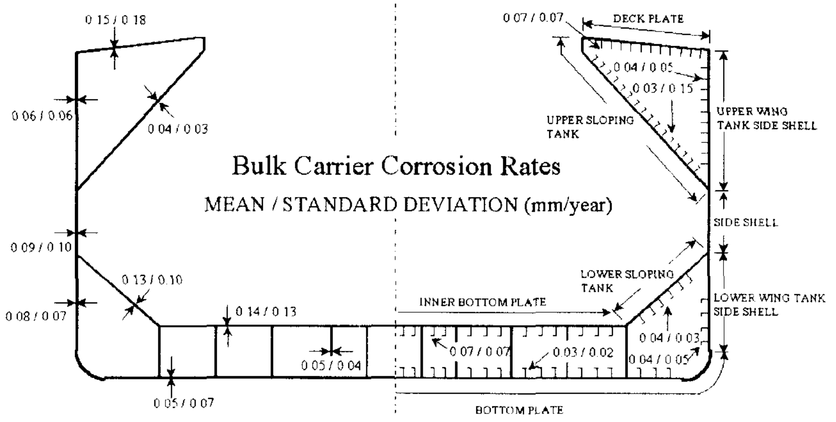

Figure 4. b. Mean and standard deviation of corrosion rate for each member type in an conventional bulk carrier based on all data collected, i.e., up to the ship age of 15.25 years

the life of the coating and that for the progress of corrosion once any coating effectiveness is lost. The probabilistic characteristics of the loss of coating life are assumed to follow the normal distribution, while the uncertainty on progress of corrosion is shown to follow the Weibull function. The coefficients of the random variables for the progress of corrosion are then determined based on analysis of the collected corrosion data.

It is concluded that the probabilistic corrosion rate estimate model developed in the present study quite reasonably represents the actual progress of corrosion for primary members of bulk carriers. The model will be very useful for evaluating the time variant hull girder strength reliability of corroded (aging) bulk carriers. Such work will be undertaken in near future.

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