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A Time-Dependent Corrosion Wastage Model for the Structures of Single- and Double-Hull Tankers and FSOs and FPSOs

Jeom Kee Paik,[1] **Jae Myung Lee,**[1] **Joon Sung Hwang,**[1] and **Young Il Park**[1]

This paper presents a mathematical model for predicting time-variant corrosion wastage of the structures of single- and double-hull tankers; floating, storage, and off-loading units (FSOs); and floating, production, storage, and off-loading units (FPSOs). The measurement data of corrosion depth (thickness loss) for single-skin oil tanker structures of various ages are collected, and the statistical characteristics (mean, variance, distribution) of measured corrosion data are quantified in terms of ship age. A set of time-dependent corrosion wastage models for 34 different structural member groups by type and location, considering plating, and webs and flanges of stiffening, are then developed by the statistical analysis of the corrosion measurements. The nominal design corrosion values for primary member locations/categories are also proposed. The results of this study can be updated as additional experience is accumulated. The procedures and insights developed in the present work will be useful for predicting the depth of corrosion in oil tanker structures. They will also be useful for establishing requirements and guidelines for the relevant corrosion protection measures and for designing corrosion-tolerant tanker structures in general.

Introduction

In the past decade, several casualties of merchant ships have occurred while they were under operation, and one of the possible causes of such casualties is thought to be the structural failure of aging ships in rough seas and weather. Clearly, in such cases the structures that started out being adequate somehow become marginal later in life. Corrosion- and fatigue-related potential problems are considered to be the two most important factors potentially leading to such age-related structural degradation of ships and, of course, many other types of steel structures.

To assess corrosion tolerance of a ship structure in advance, it is necessary to have a relevant estimate of the corrosion rate for every structural area. In this paper, a time-dependent corrosion wastage model for the structures of single- and double-hull tankers and floating, storage, and off-loading units (FSOs) and floating, production, storage, and off-loading units (FPSOs) is developed.

A number of studies related to corrosion evaluation in ship structures have been previously performed (Herring & Titcomb 1981, Ohyagi 1987, Pollard 1991, Yamamoto & Ikegami 1998, Paik et al 1998, 2003a, 2003b, TSCF 1997, Guedes Soares & Garbatov 1999, Gardiner & Melchers 2001, 2002, Qin & Cui 2003, among others). IACS (1998, 2001) provides guidelines for inspection of corroded ship hulls and has also established recommendations for the repair of such corroded areas. Various guidelines for coating systems for corrosion prevention of ship structures have also been developed and documented (TSCF 1995, IMO 1995, IACS 1998, DNV 1998, 1999). Nominal design corrosion values for different parts of structure and vessel types have been developed by classification societies (e.g., ABS 2000).

Although the previous studies and guidelines are useful to control the corrosion-related degradation of aged ship structures, we are still confronted with a number of questions due to the lack of precision of corrosion damage information. To more properly establish a corrosion model, it is necessary to base the same on a much greater number of statistical data for corrosion wastage of existing ships than has been generally the case. This would imply that the existing corrosion models are never 100% complete, and they should be continuously updated together with the future addition of more corrosion data as they become available.

It is normally not straightforward to develop a corrosion model solely based on theory, because corrosion is a function of many variables and uncertainties involved, such as type of corrosion protection system employed, type of cargo, temperature, humidity, and so forth. This implies that the corrosion model developed by statistical means will usually be different according to the types of ships and cargoes or structural member locations and categories. It also goes without saying that the corrosion wastage prediction models based on statistical analysis of past data or measurements for comparable situations should not be applied beyond that justified by the characteristics of the database underlying them.

The main contribution of the present work is to develop one such practical but somewhat sophisticated modeling procedure for predicting corrosion wastage in primary member location/category groups of single- and double-hull tankers and FSOs/FPSOs as a function of age. Corrosion wastage prediction models for the different member location/category groups by type and location considering plating, and webs and flanges of stiffeners are developed separately.

Mechanics of corrosion in tanker structures

Corrosion appears as nonprotective, friable rust, largely on internal surfaces that are unprotected. Over time, the rust scale continually breaks off, exposing fresh metal to corrosive attack. Thickness loss cannot sometimes be judged visually until excessive loss has occurred. Failure to remove mill scale during construction of the vessel can accelerate the corrosion experienced in service. Severe corrosion, usually characterized by heavy scale accumulation, can lead to significant steel renewals. It is important to point out that, in addition to general (uniform) corrosion, which reduces the plate thickness uniformly, there are other types of more localized corrosion patterns identifiable in ships (see Fig. 1). Some of these are:

[1] Department of Naval Architecture and Ocean Engineering, Pusan National University, Busan, Korea.

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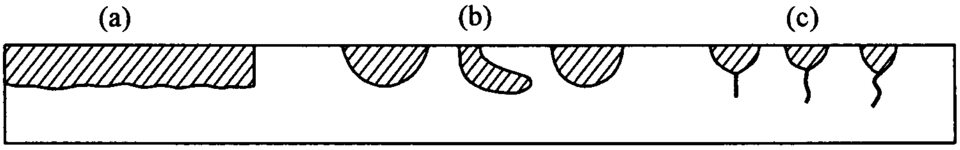

Fig. 1 Typical types of corrosion wastage: (a) general corrosion, (b) localized corrosion, (c) fatigue cracks arising from localized corrosion

- Pitting: Pitting is a localized form of corrosion that 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 patches (e.g., 800 mm diameter), resembling a condition of general corrosion. Severe pitting can lead to significant steel renewals.
- Grooving: Grooving corrosion is a localized, linear corrosion that occurs at structural intersections where water collects or flows. This corrosion is sometimes referred to as "in-line pitting attack" and can also occur on vertical members and flush sides of bulkheads in areas of flexing.
- 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.

The present study is concerned with localized corrosion noted above as well as general corrosion, because the corrosion wastage measurements have been collected for both types of corrosion, as will be described later on.

In most existing tankers, one can distinguish five types of cargo and ballast tank spaces. These are:

- Segregated ballast spaces
- Cargo/clean ballast spaces
- Cargo/dirty ballast spaces
- Cargo/storm ballast spaces
- Cargo-only spaces.

The areas of the ship most exposed to corrosion are wing ballast tanks, due to exposure of seawater, humidity, a salty atmosphere when empty, and increases in temperature when deck and sides are exposed to sunlight. Combined ballast and cargo tanks are somewhat less exposed to corrosion. They are, however, exposed to water washing, which can destroy protective oil film, thus exposing fresh steel for corrosion. In cargo-only tanks, the bottom area may suffer from acidic water setting out from the oil. At the sides and the top of these tanks, the oil normally provides a form of protection. The time in ballast is typically 50% for the first two types of spaces, and much less for the third (e.g., 5%). Cargo-only tanks are exposed to cargo about 50% of the time and are typically empty for the rest of the time.

The frequency of filling heavy ballast holds is decided by characteristics of the trade route and weather conditions. In loading and unloading cargoes at harbor, empty cargo holds may be partly filled with ballast water to adjust trim, which increases the possibility of wet and dry cycles, affecting corrosion rates therein.

The type of cargo carried affects corrosion rates. Typically, in tankers, certain types of oil can lead to higher corrosion rates. For example, a sour crude is worse than a sweet one, and cargoes that are higher in oxygen content, such as gasoline, lead to higher corrosion rates.

In any type of vessel, corrosion rates in a compartment depend on the structural component location and orientation and, of course, the type of corrosion protection employed. In ballast tanks, which are normally coated, corrosion will start in with coating breakdown and high stress zones, such as ends of structural elements and free edges of cutouts. Significant corrosion of elements in ballast tanks adjacent to heated cargo tanks or tanks with consumables is also possible. An increased degree of local 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. Locations of necking and grooving are disproportionately affected.

It is important to realize that the corrosion process of ship structures can be different from that of "at-sea" stationary immersion corrosion. Temperature inside ballast or cargo tanks can be warmer than that of the sea. In loading and unloading cargoes at harbor, ballasting and deballasting will also occur in order to adjust freeboard or trim. Such ballast cycles may accelerate corrosion process because the steel surface becomes repeatedly dry or wet by seawater.

Where coatings are present, the progress of corrosion will normally very much depend on the degradation characteristics of such anticorrosion coatings. Structural flexing resulting from wave loading could also increase corrosion rates due to the continuing loss of scale and exposure of new surface to corrosion. Although most classification societies usually recommend carrying out of maintenance for the corrosion protection system in time, this may not universally be the case in reality unless safety is likely to be compromised.

Figure 2 represents a plausible schematic of the proposed corrosion process model for a coated area in a marine steel structure. The corrosion behavior is in this model categorized into three phases, on account of (1) durability of coating, (2) transition to visibly obvious corrosion, and (3) progress of such corrosion (Paik & Thayamballi 2003).

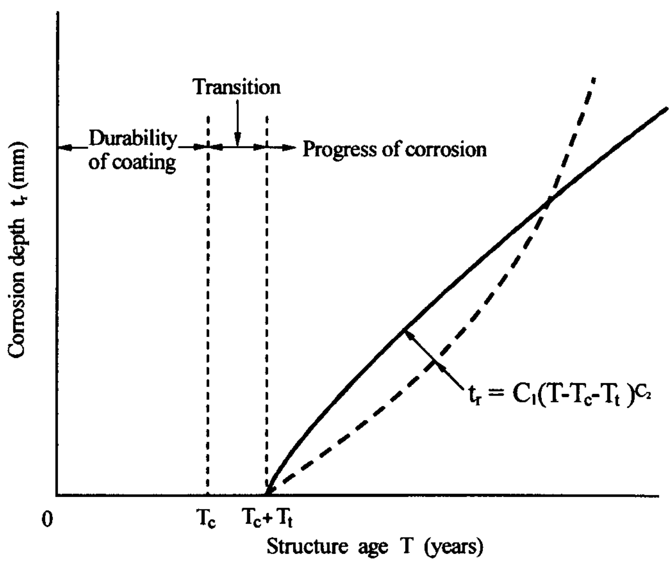

Fig. 2 A schematic of a corrosion process model for marine structures

The curve showing corrosion progression, as indicated by the solid line in Fig. 2, is convex, but it may in some cases be a concave (dotted line). The convex curve indicates that the corrosion rate (i.e., the curve gradient) is increasing in the beginning but is decreasing as the corrosion progress proceeds. This is because corroded material stays on the steel surface, protecting it from contact with the corrosive environment, and the corrosion process stops. This type of corrosion progression may be typical for statically loaded structures so that relatively static corrosion scale at the steel surface can disturb the corrosion progression.

On the other hand, the concave curve (dotted line) in Fig. 2 represents a case where the corrosion rate is accelerating as the corrosion progress proceeds. This type of corrosion progression may be likely to happen in dynamically loaded structures, such as ship structures where structural flexing due to wave loading continually exposes additional fresh surface to the corrosive attack.

The life (or durability) of a coating can in a specific case correspond to the time when a predefined and measurable extent of corrosion starts after either (1) the time when a ship enters service, (2) the application of coating in a previously bare case, or (3) repair of a failed coating area in an existing

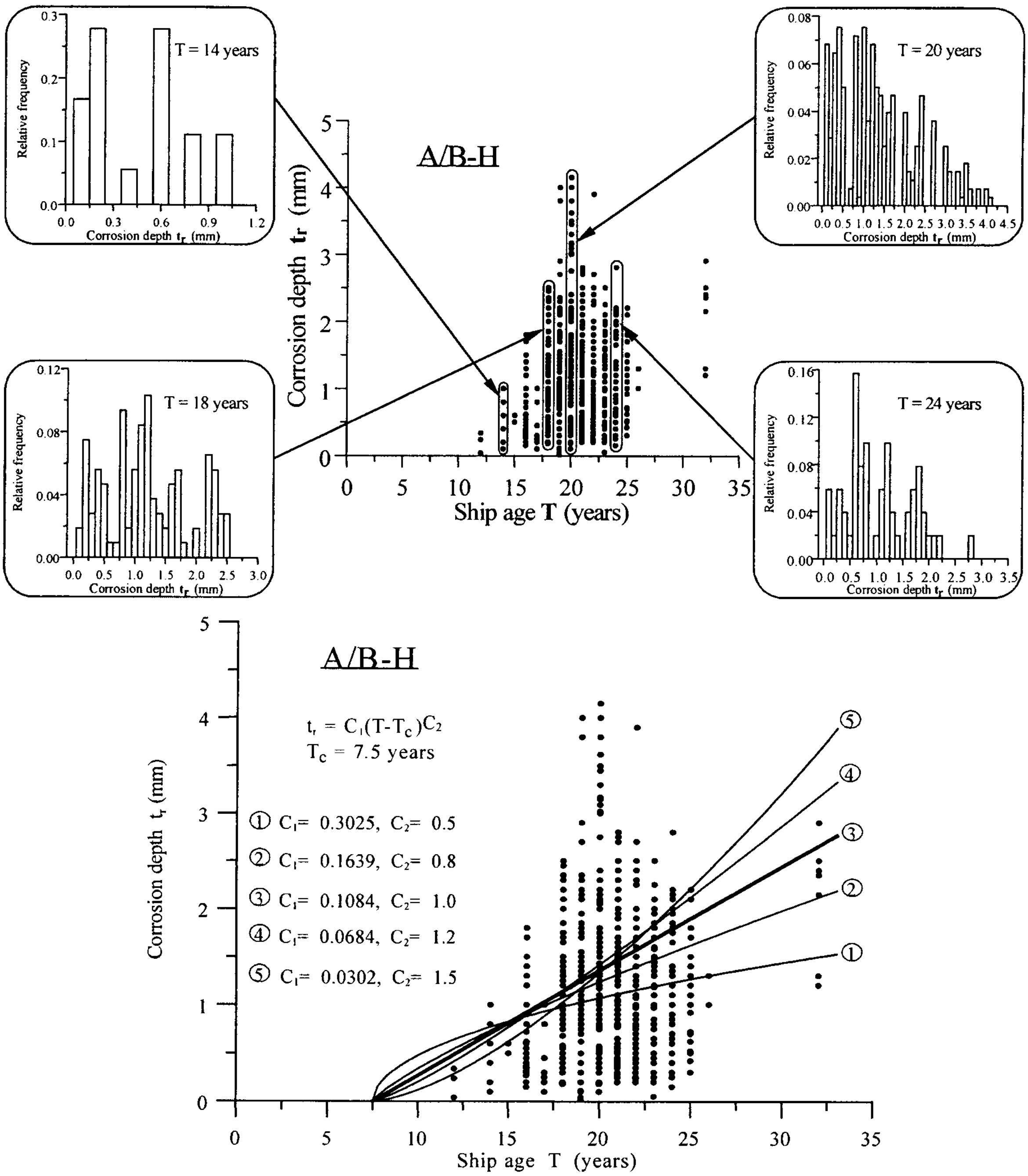

Fig. 3 (Top) The corrosion depth versus the ship age for the measurements of deck plating in sea-water tanks of tanker structures (A/B-H is defined later in Fig. 8). (Bottom) Sample best fit formulations of the corrosion depth measurements on A/B-H as a function of ship age, varying the coefficient C_2 (A/B-H is defined later in Fig. 8)

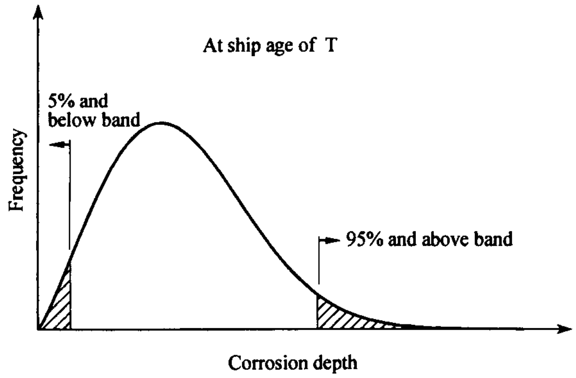

Fig. 4 The 95th percentile and above band (upper bound band) for developing severe corrosion wastage characteristics

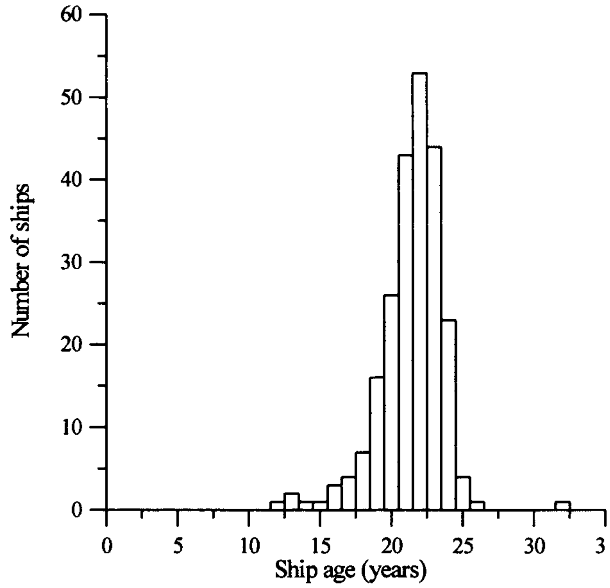

Fig. 5 The distribution of the age for the 230 single-skin tankers surveyed

structure to a good intact standard. The life of coating typically depends on the type of coating systems used, details of its application (e.g., surface preparation, stripe coats, film thickness, humidity and salt control during application, etc.), and relevant maintenance, among other factors. The coating life to a predefined state of breakdown is often assumed to follow the log-normal distribution (Yamamoto & Ikegami 1998).

After the effectiveness of coating is lost, some transition time, that is, duration between the time of coating effectiveness loss and the time of corrosion initiation, may be considered to exist before the corrosion "initiates" over a large enough and measurable area. The transition time is often considered to be an exponentially distributed random variable (Yamamoto & Ikegami 1998). As an example, the mean value of the transition time for transverse bulkhead struc-

Table 1 Number of gathered data from thickness measurements for 34 primary structural member groups in oil tanker structures

ID No.	Member Type	Example	No. of Data
1	B/S-H	Bottom shell plating (segregated ballast tank)	148
2	A/B-H	Deck plating (segregated ballast tank)	1,410
3	A/B-V	Side shell plating above draft line (segregated ballast tank)	33
4	B/S-V	Side shell plating below draft line (segregated ballast tank)	274
5	BLGB	Bilge plating (segregated ballast tank)	164
6	O/B-V	Longitudinal bulkhead plating (segregated ballast tank)	361
7	B/B-H	Stringer plating (segregated ballast tank)	19
8	O/S-H	Bottom shell plating (cargo oil tank)	849
9	A/O-H	Deck plating (cargo oil tank)	5,557
10	A/O-V	Side shell plating above draft line (cargo oil tank)	86
11	O/S-V	Side shell plating below draft line (cargo oil tank)	692
12	BLGC	Bilge plating (cargo oil tank)	348
13	O/O-V	Longitudinal bulkhead plating (cargo oil tank)	1,082
14	O/O-H	Stringer plating (cargo oil tank)	42
15	BSLB(W)	Bottom shell longitudinals in ballast tank, web	672
16	BSLB(F)	Bottom shell longitudinals in ballast tank, flange	678
17	DLB(W)	Deck longitudinals in ballast tank, web	975
18	SSLB(W)	Side shell longitudinals in ballast tank, web	913
19	SSLB(F)	Side shell longitudinals in ballast tank, flange	913
20	LBLB(W)	Longitudinal bulkhead longitudinals in ballast tank, web	1,024
21	LBLB(F)	Longitudinal bulkhead longitudinals in ballast tank, flange	973
22	BSLC(W)	Bottom shell longitudinals in cargo oil tank, web	2,030
23	BSLC(F)	Bottom shell longitudinals in cargo oil tank, flange	2,205
24	DLC(W)	Deck longitudinals in cargo oil tank, web	2,215
25	DLC(F)	Deck longitudinals in cargo oil tank, flange	34
26	SSLC(W)	Side shell longitudinals in cargo oil tank, web	2,187
27	SSLC(F)	Side shell longitudinals in cargo oil tank, flange	2,091
28	LBLC(W)	Longitudinal bulkhead longitudinals in cargo oil tank, web	2,850
29	LBLC(F)	Longitudinal bulkhead longitudinals in cargo oil tank, flange	2,634
30	BGLC(W)	Bottom girder longitudinals in cargo oil tank, web	154
31	BGLC(F)	Bottom girder longitudinals in cargo oil tank, flange	42
32	DGLC(W)	Deck girder longitudinals in cargo oil tank, web	94
33	DGLC(F)	Deck girder longitudinals in cargo oil tank, flange	36
34	SSTLC(W)	Side stringer longitudinals in cargo oil tank, web	35
		Total	33,820

tures of bulk carriers is shown to be 3 years for deep tank bulkheads, 2 years for watertight bulkheads, and 1.5 years for stool regions. When the transition time is assumed to be zero, it is of course implied that the corrosion will start immediately after the coating effectiveness is lost.

Procedures for developing the time-dependent corrosion wastage model

It is noted that the aim of the present study is to predict the wastage depth of general or localized corrosion, as shown in

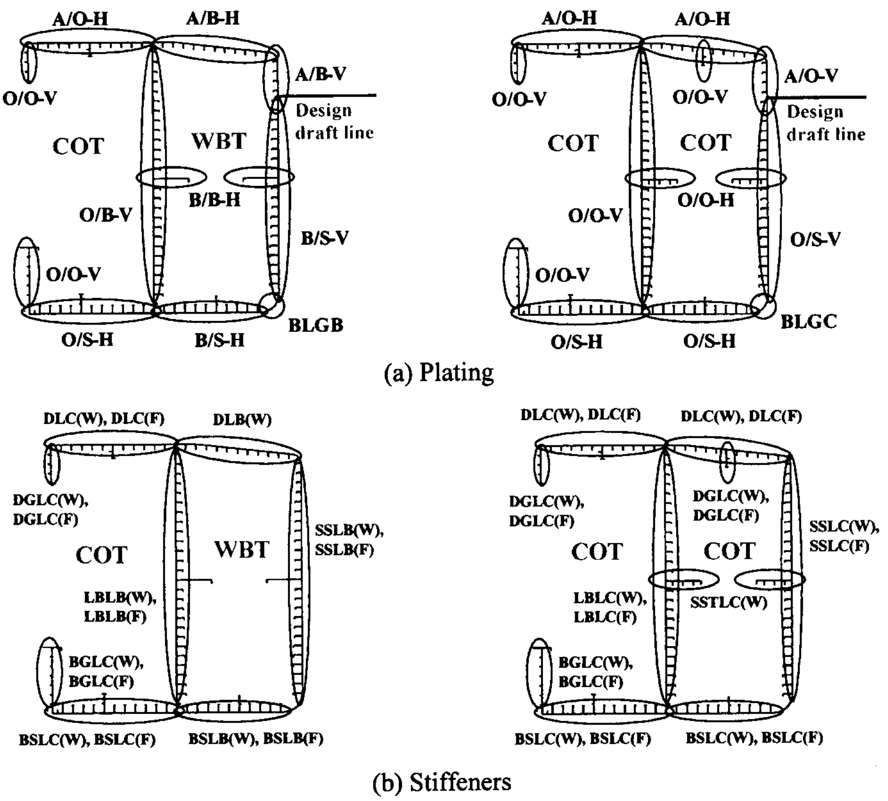

Fig. 6 The 34 member groups (defined by location, category, and corrosion environment) of typical single-skin tanker structures. A = air; B = ballast water; COT = cargo oil tank; F = flange; H = horizontal member; O = oil; S = seawater; V = vertical member; W = web; WBT = water ballast tank. See Table 1 for expanded versions of member type acronyms

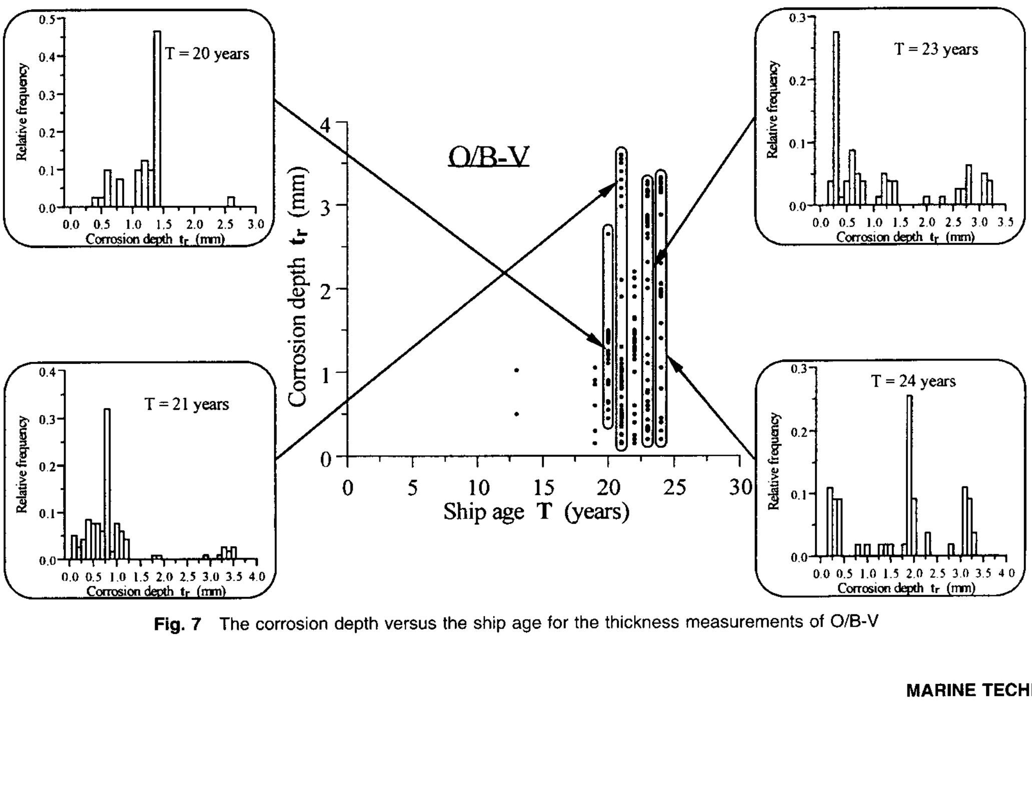

Fig. 7 The corrosion depth versus the ship age for the thickness measurements of O/B-V

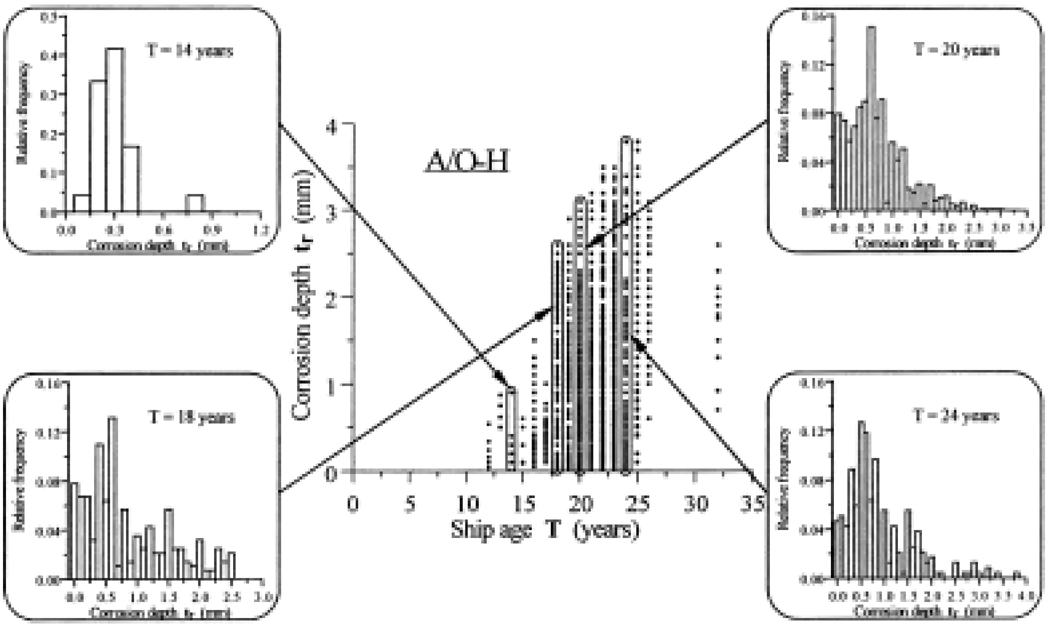

Fig. 8 The corrosion depth versus the ship age for the thickness measurements of A/O-H

Fig. 1. From Fig. 2 and the related discussions noted in the previous section, the corrosion behavior of steel may be expressible as a function of the time (year), as follows:

$$t_r = C_1 T_e^{\,C_2} \tag{1a}$$

$$r_r = C_1 C_2 T_e^{\,C_2 - 1} \tag{1b}$$

where t_r = depth of corrosion wastage (mm), r_r = annualized corrosion rate (mm/year), T_e = time of exposure under corrosion environment (year), which may be taken as $T_e = T - T_c - T_t$, with T = age of vessel (year), T_c = life of coating (year), and T_t = duration of transition (year), C_1, C_2 = coefficients to be determined by the statistical analysis of corrosion data.

Following the discussions made in the previous section, T_t may be pessimistically taken as $T_t = 0$, indicating that corrosion starts immediately after the breakdown of coating. Although the coating life, T_c, to a predefined state of breakdown must be a random variable, it will be treated as a constant parameter in the present study.

The coefficient C_2 in equation (1) determines the trend of corrosion progress, while the coefficient C_1 is in part indicative of the annualized corrosion rate, r_r, which can be obtained by differentiating equation (1a) with respect to time. These two coefficients closely interact, and in principle they can be simultaneously determined based on carefully collected statistical corrosion data for existing ship structures. However, this approach is in most cases not straightforward to apply, mainly because of differences in data collection sites typically visited over the life of the vessel and possibly also differing time between visits. That is, it is normally difficult to track corrosion at a particular site based on the typically available thickness gauging data for ships, which are mostly obtained at periodic inspections (surveys) of different "representative" regions of the structure. This is part of the reason for the relatively large scatter of corrosion data in many studies.

An easier alternative is thus to determine the coefficient C_1 at a constant value of the coefficient C_2. This is mathematically a simpler model, but it does not negate any of the limitations arising due to usual methods of data collection in surveys. It does, however, make possible the postulation of different modes of corrosion behavior over time depending on the value adopted for C_2 alone in an easy-to-understand way.

For corrosion of marine structures, some past studies indicate that the coefficient C_2 may be typically in the range of 0.3 – 1.5. Figure 3 (top) represents the depth of corrosion versus the ship age for deck plating of ballast tanks in oil tankers, which is based on the measured data. In reading Fig. 3 (top), it should be realized that the number of individual sampling points is meant to be neither one nor the same. Figure 3 (bottom) shows sample best fit formulation of equation (1a) using the least square method, varying C_2. Five cases were considered, varying the value of C_2 in the range of 0.5 to 1.5.

When C_2 is less than 1.0 (but larger than 0.0), the corrosion rates apparently decrease or stabilize over time, that is, showing the convex curve (solid line) in Fig. 2, or the curves

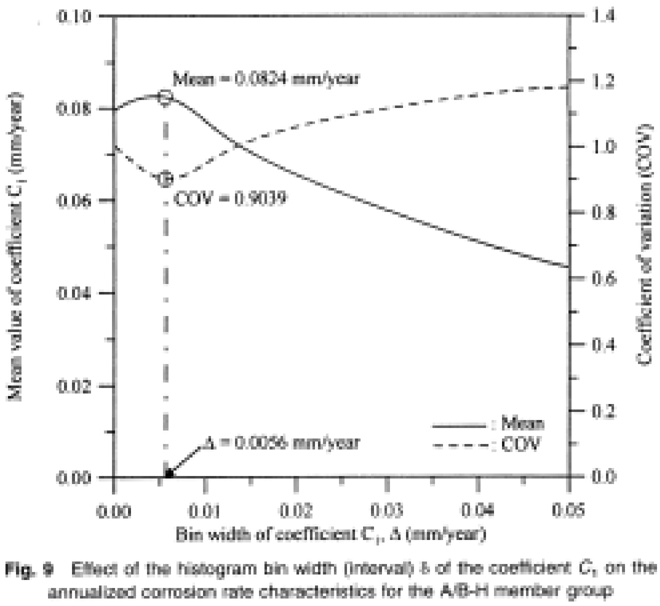

Fig. 9 Effect of the histogram bin width (interval) Δ of the coefficient C_1 on the annualized corrosion rate characteristics for the A/B-H member group

of numbers 1 and 2 in Fig. 3 (bottom). This corrosion behavior may typically be plausible for statically loaded structures. However, for dynamically loaded structures, such as ship structures subjected to wave loading in which corrosion scale is continually being lost and new material is being exposed to corrosion environment because of structural flexing, such values of C_2 may not always be appropriate, as represented by the concave curve (dotted line) in Fig. 2, or the curves of numbers 4 and 5 in Fig. 3 (bottom) with C_2 having a value greater than 1.0.

Clearly, the coefficient C_2 affects the implied trend of the corrosion progress. Considering the scatter of corrosion progress characteristics, as shown in Fig. 3, and also for the purpose of practical design, however, $C_2 = 1$ can be used, with the corrosion behavior perhaps linearized over convenient and small enough extents of time, as depicted by the curve of number 3 in Fig. 3 (bottom). In a summary of the discussions made above, equation (1) can now be simplified to

$$t_r = C_1(T - T_c) \tag{2a}$$

$$r_r = C_1. \tag{2b}$$

The only coefficient to be left undetermined is C_1 for now, while T_c is treated as a constant parameter. In the present study, mean and coefficient of variation (COV) of C_1 are determined by the statistical analysis of corrosion measurement data.

The sources of uncertainty involved in corrosion data are various, as previously mentioned, and the coating life is also a factor in such uncertainties. In corrosion loss measurements, information on the coating life is normally unclear. In fact, a 5-year coating life is considered to represent an undesirable situation, whereas 10 years or longer is a relatively more desirable state of affairs. In this regard, for any given set of corrosion data with several unknown or uncontrolled factors, a parametric approach will be used in the present study by varying the coating breakdown time, to say 5, 7.5, and 10 years.

With t_r and T_c known (t_r being from the corrosion measurement data, and T_c being assumed), C_1 can be readily given from equation (2a) for a sampling point, as follows:

$$C_1 = \frac{t_r}{(T - T_c)^{C_2}}. \tag{3}$$

For a given set of available statistical corrosion data, therefore, the statistical characteristics of the coefficients C_1 can be analyzed. As will be described later on, it is found that the statistical distribution of the coefficient C_1 at the most probable (average) trend follows one of the exponential family of distribution, such as a Weibull function. In the present study, therefore, the statistical characteristics (mean, variance) of the coefficient C_1 at the most probable trend were determined considering a Weibull function.

It is also noted that the statistical corrosion data are usually very scattered due to the many uncontrolled and sometimes unknown factors, as shown in Fig. 3. Therefore, it will be of interest to investigate the upper bound (severe) statistical characteristics of the coefficient C_1, based on data above the 95th percentile value alone, as shown in Fig. 4. As will be described later on, it is found that the statistical distribution of the coefficient C_1 at the upper bound trend more likely follows the normal function.

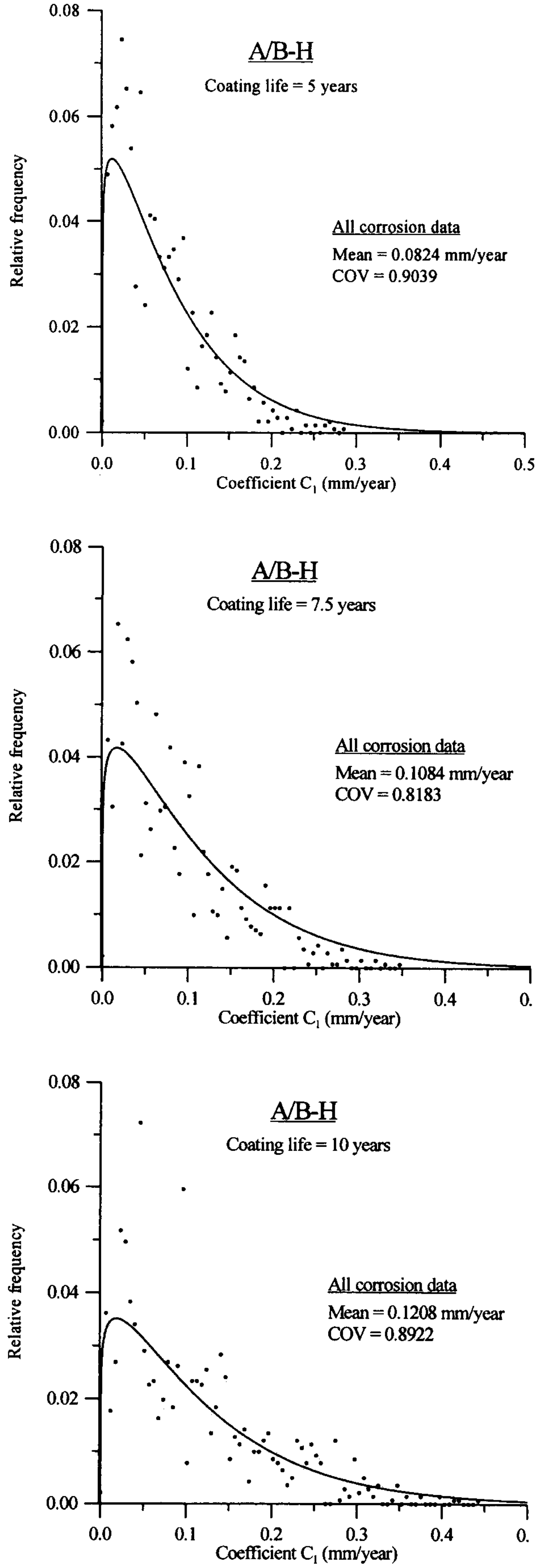

Fig. 10 (Top) The best fit of a Weibull distribution for the coefficient C_1 of A/B-H using all corrosion data and a coating life of 5 years. (Middle) The best fit of a Weibull distribution for the coefficient C_1 of A/B-H using all corrosion data and a coating life of 7.5 years. (Bottom) The best fit of a Weibull distribution for the coefficient C_1 of A/B-H using all corrosion data and a coating life of 10 years

In the present study, both average and severe corrosion wastage characteristics will be defined for any given group of corrosion measurement data.

Corrosion measurement data for single-skin tanker structures

Outer (external) surfaces of ship hulls are usually well coated, and significant corrosion may not start there due to effective coating maintenance considering visual impact. Although a corrosion protection scheme such as coating is also provided on the inner surfaces of the ballast tanks, a significant amount of corrosion may start in areas of coating breakdown as time goes on.

Measured data for the corrosion loss in structural members of ocean-going tankers have been collected. Data for renewed structural members were excluded. Corrosion loss was mostly measured by the technique of ultrasonic thickness measurements. This implies that the measurements were made at several points within a single plating, and a representative value (e.g., average) of the measured corrosion loss is then determined to be the depth of corrosion. In this regard, the corrosion model developed in the present study will be used for predicting localized (pit) corrosion as well as general corrosion.

Corrosion measurement data for a number of 230 aged ocean-going tankers carrying crude or product oil have been made available to this study. All of the tankers surveyed herein have single hull structures. The trading routes of the vessels expand worldwide, including the Korean sea. Although the corrosion wastage in some of the vessel structures might have been affected by tank heating, the related information is too insufficient to adequately describe the characteristics of the corrosion. Figure 5 represents the distribution of the ages of the ships that have been surveyed for this purpose. The average age of the vessels involved appears to be over 20 years, meaning that some vessels were built before the MARPOL (International Convention on Load Lines and the Convention on Marine Pollution) resolution, whereas others follow post-MARPOL tank usage patterns.

A total of 33,820 measurements for 34 different member groups, which include 14 categories of plate parts, 11 categories of stiffener webs, and 9 categories of stiffener flanges were obtained and available for this study, as indicated in Table 1 and Fig. 6. The member groups were defined by locations and categories of members. As shown in Fig. 6, the member groups also represent various corrosion environments. For instance, A/B-H indicates a horizontal member group located between air and ballast water and B/S-V represents a vertical member group located between ballast water and seawater. An example of A/B-H is deck plating on ballast tanks, and an example of B/S-V is side shell plating below draft line. For further description, see Table 1.

In some member groups, there are few data, as indicated in Table 1. Although the corrosion models developed for these member groups may still be meaningful, it is necessary to reestablish them as the related corrosion measurement data become available.

Figures 3 (top), 7, and 8 show the frequency distribution of corrosion depth (thickness loss) for three example mem-

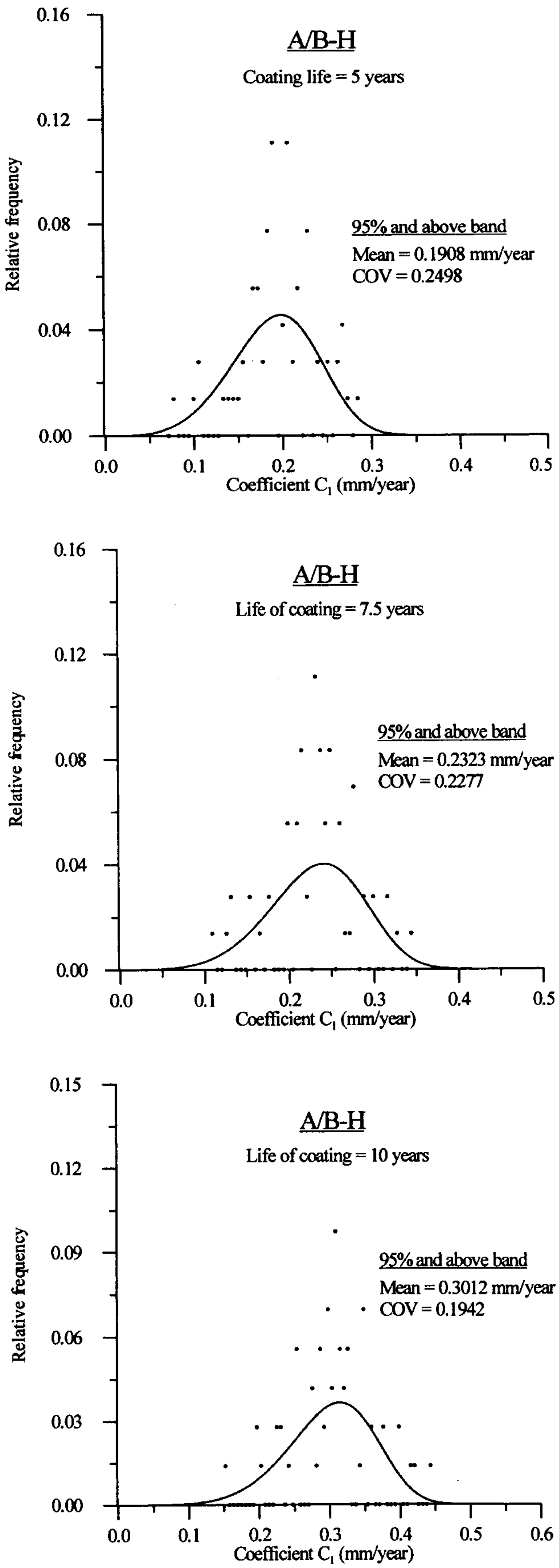

Fig. 11 (Top) The best fit of a Weibull distribution for the coefficient C_1 of A/B-H using the 95% and above band of the corrosion data and a coating life of 5 years. (Middle) The best fit of a Weibull distribution for the coefficient C_1 of A/B-H using the 95% and above band of the corrosion data and a coating life of 7.5 years. (Bottom) The best fit of a Weibull distribution for the coefficient C_1 of A/B-H using the 95% and above band of the corrosion data and a coating life of 10 years

ber (location/category) groups as a function of ship age. It is seen from the figures that the distribution of corrosion wastage is very scattered. The sources of such uncertainty involved are various, as previously mentioned, and the coating life is also a factor in such uncertainties. It should be noted that some of the data used in this study may pertain to uncoated spaces, especially in the cargo tanks, while any information about coating life is not available.

In the present study, we neither have nor do we specifically use any information about coating life, which essentially is implicit in the data for those parts of tanker structures that would be typically coated. The coating life is assumed and parametrically varied in the study. As may be seen from the figures of corrosion depth versus ship age, however, there is no (or very little) corrosion within the 5- to 7.5-year range of service lives. It is also not possible to separate out the corrosion and any mechanical damage for such structural parts. Therefore, a parametric analysis is carried out by varying the coating breakdown time, to say 5, 7.5, and 10 years.

From Figs. 3 (top), 7, and 8, it is interesting to note that the statistical frequency distribution of corrosion depth at a younger age tends to follow the normal function, while it more likely follows log-normal or exponential function for an older stage.

A time-dependent corrosion wastage model for oceangoing single-hull tanker structures

The fleet of tankers having single hulls is still large in number, although all tankers must have double hulls by the year 2015 (perhaps earlier, due to the recent *Prestige* accident). Furthermore, FSOs and FPSOs mostly have a single-skin type of hull structure, but some of them have double-skin structures. In this regard, development of the corrosion models for tankers having single hulls is of vital importance.

Applying the procedure described in the previous section, the mean values and COVs of the coefficient C_1 (annualized corrosion rate) for the 34 member groups of single-skin tanker structures are now computed by the statistical analysis of the measured data for the full range of corrosion wastage and also the upper bound range values.

In fact, the linearization intervals (bin widths) used for determining the histogram of the coefficient C_1, which is

Table 2a Mean and COV of the annualized corrosion rate (coefficient C_1) for plating in a single-skin tanker

			All Corrosion Data		95% and Above Band	
ID No.	Member Group	Coating Life (years)	Mean (mm/year)	COV	Mean (mm/year)	COV
1	B/S-H	5	0.0518	0.8439	0.1483	0.2387
		7.5	0.0597	0.9901	0.1717	0.2290
		10	0.0704	0.9894	0.2159	0.1974
2	A/B-H	5	0.0824	0.9039	0.1908	0.2498
		7.5	0.1084	0.8183	0.2323	0.2277
		10	0.1208	0.8922	0.3012	0.1942
3	A/B-V	5	0.0552	1.1258	0.1582	0.3227
		7.5	0.0661	1.1341	0.1897	0.3227
		10	0.0762	1.1147	0.2436	0.3207
4	B/S-V	5	0.0545	1.0033	0.1566	0.2387
		7.5	0.0622	1.0030	0.1823	0.2185
		10	0.0731	1.0020	0.2382	0.1942
5	BLGB	5	0.0539	0.9134	0.1525	0.3008
		7.5	0.0619	0.8821	0.1805	0.2167
		10	0.0728	0.8559	0.2371	0.2387
6	O/B-V	5	0.0792	0.8162	0.1616	0.2498
		7.5	0.1012	0.7994	0.1919	0.2277
		10	0.1184	0.8369	0.2483	0.1866
7	B/B-H	5	0.1111	0.2290	0.2206	0.0000
		7.5	0.1408	0.2704	0.2586	0.0000
		10	0.1790	0.2708	0.3125	0.0000
8	O/S-H	5	0.0526	0.8439	0.1503	0.2601
		7.5	0.0607	0.8248	0.1777	0.2167
		10	0.0709	0.7793	0.2217	0.2080
9	A/O-H	5	0.0489	0.8430	0.1434	0.2495
		7.5	0.0581	0.8262	0.1689	0.2290
		10	0.0682	0.8240	0.2113	0.1942
10	A/O-V	5	0.0444	1.0023	0.1339	0.2601
		7.5	0.0523	1.0111	0.1529	0.2167
		10	0.0633	0.9993	0.1928	0.1942
11	O/S-V	5	0.0346	0.9134	0.1318	0.2387
		7.5	0.0423	0.7601	0.1497	0.2290
		10	0.0532	0.7563	0.1841	0.1827
12	BLGC	5	0.0340	1.0010	0.1290	0.2704
		7.5	0.0414	1.0033	0.1446	0.2167
		10	0.0513	0.9993	0.1776	0.1827
13	O/O-V	5	0.0475	0.8108	0.1406	0.2498
		7.5	0.0577	0.8162	0.1621	0.2185
		10	0.0671	0.8170	0.2014	0.2055
14	O/O-H	5	0.0330	1.1979	0.1251	0.2495
		7.5	0.0405	1.1341	0.1423	0.2277
		10	0.0509	1.1258	0.1727	0.2080

computed from equation (3), affects the relative frequency distribution and thus the resulting mean value and COV of C_1. Figure 9 shows a possible "best" value of the interval for determining the coefficient C_1 for A/B-H. For this data set, the best bin width is found to be about 0.0056 mm/year, based on a minimum COV criterion. In the present study, therefore, the bin width of the coefficient C_1 was assumed to 0.0056 mm/year for the statistical analysis of corrosion data.

Figure 10 shows the relative frequency of corrosion wastage coefficient C_1 for A/B-H using all corrosion data gathered, by varying the coating life from 5 to 10 years parametrically.

Table 2b Mean and COV of the annualized corrosion rate (coefficient C_1) for longitudinal stiffeners in a single-skin tanker

			All Corrosion Data		95% and Above Band	
ID No.	Member Group	Coating Life (years)	Mean (mm/year)	COV	Mean (mm/year)	COV
15	BSLB(W)	5	0.1184	0.8922	0.2126	0.2495
		7.5	0.1367	0.7802	0.2461	0.2290
		10	0.1613	0.9325	0.3052	0.1942
16	BSLB(F)	5	0.0976	1.1147	0.2024	0.2704
		7.5	0.1127	1.0121	0.2343	0.1827
		10	0.1330	1.1433	0.2905	0.1942
17	DLB(W)	5	0.2081	1.0020	0.3667	0.2498
		7.5	0.2403	0.9165	0.4244	0.1942
		10	0.2836	1.0139	0.5263	0.1974
18	SSLB(W)	5	0.1224	0.8559	0.2242	0.2601
		7.5	0.1413	1.0097	0.2595	0.1942
		10	0.1667	0.9153	0.3218	0.2387
19	SSLB(F)	5	0.0764	0.9134	0.1408	0.2495
		7.5	0.0882	0.8966	0.1630	0.2167
		10	0.1041	1.0283	0.2021	0.1866
20	LBLB(W)	5	0.1697	0.7793	0.3318	0.2387
		7.5	0.1960	0.9993	0.3840	0.1827
		10	0.2313	0.7955	0.4762	0.1866
21	LBLB(F)	5	0.1543	0.9894	0.2985	0.2498
		7.5	0.1782	0.9941	0.3455	0.2055
		10	0.2103	1.0394	0.4284	0.1974
22	BSLC(W)	5	0.0404	0.8240	0.0767	0.3227
		7.5	0.0466	1.1156	0.0888	0.2387
		10	0.0550	0.9062	0.1101	0.1942
23	BSLC(F)	5	0.0378	0.9993	0.0723	0.2387
		7.5	0.0437	1.1341	0.0837	0.1866
		10	0.0516	1.0238	0.1038	0.1942
24	DLC(W)	5	0.0620	0.7563	0.1082	0.3008
		7.5	0.0716	0.8902	0.1252	0.2167
		10	0.0845	0.8263	0.1552	0.1827
25	DLC(F)	5	0.0509	0.9993	0.0916	0.2601
		7.5	0.0588	1.0032	0.1060	0.1866
		10	0.0694	1.0211	0.1314	0.2055
26	SSLC(W)	5	0.0364	1.0258	0.0700	0.2387
		7.5	0.0420	1.0517	0.0810	0.2185
		10	0.0496	1.1224	0.1004	0.2080
27	SSLC(F)	5	0.0344	1.0507	0.0683	0.3008
		7.5	0.0397	0.8551	0.0790	0.1866
		10	0.0468	1.1350	0.0980	0.2055
28	LBLC(W)	5	0.0476	0.9003	0.0814	0.2498
		7.5	0.0550	0.8129	0.0942	0.1758
		10	0.0649	0.9859	0.1168	0.2080
29	LBLC(F)	5	0.0440	1.1341	0.0796	0.2601
		7.5	0.0508	1.0012	0.0921	0.2167
		10	0.0599	1.1944	0.1142	0.1942
30	BGLC(W)	5	0.0326	1.0030	0.0617	0.2495
		7.5	0.0377	0.9824	0.0714	0.2395
		10	0.0445	1.1079	0.0885	0.1866
31	BGLC(F)	5	0.0276	0.8821	0.0499	0.2387
		7.5	0.0319	0.8439	0.0578	0.2290
		10	0.0376	0.9039	0.0717	0.2055
32	DGLC(W)	5	0.0413	0.9432	0.0778	0.3008
		7.5	0.0477	1.0818	0.0900	0.2277
		10	0.0563	1.0071	0.1116	0.2080
33	DGLC(F)	5	0.0389	0.8248	0.0745	0.2601
		7.5	0.0449	0.9533	0.0862	0.1974
		10	0.0530	0.8972	0.1069	0.1942
34	SSTLC(W)	5	0.0226	1.0111	0.0378	0.2495
		7.5	0.0261	1.0926	0.0437	0.1827
		10	0.0308	1.1255	0.0542	0.1974

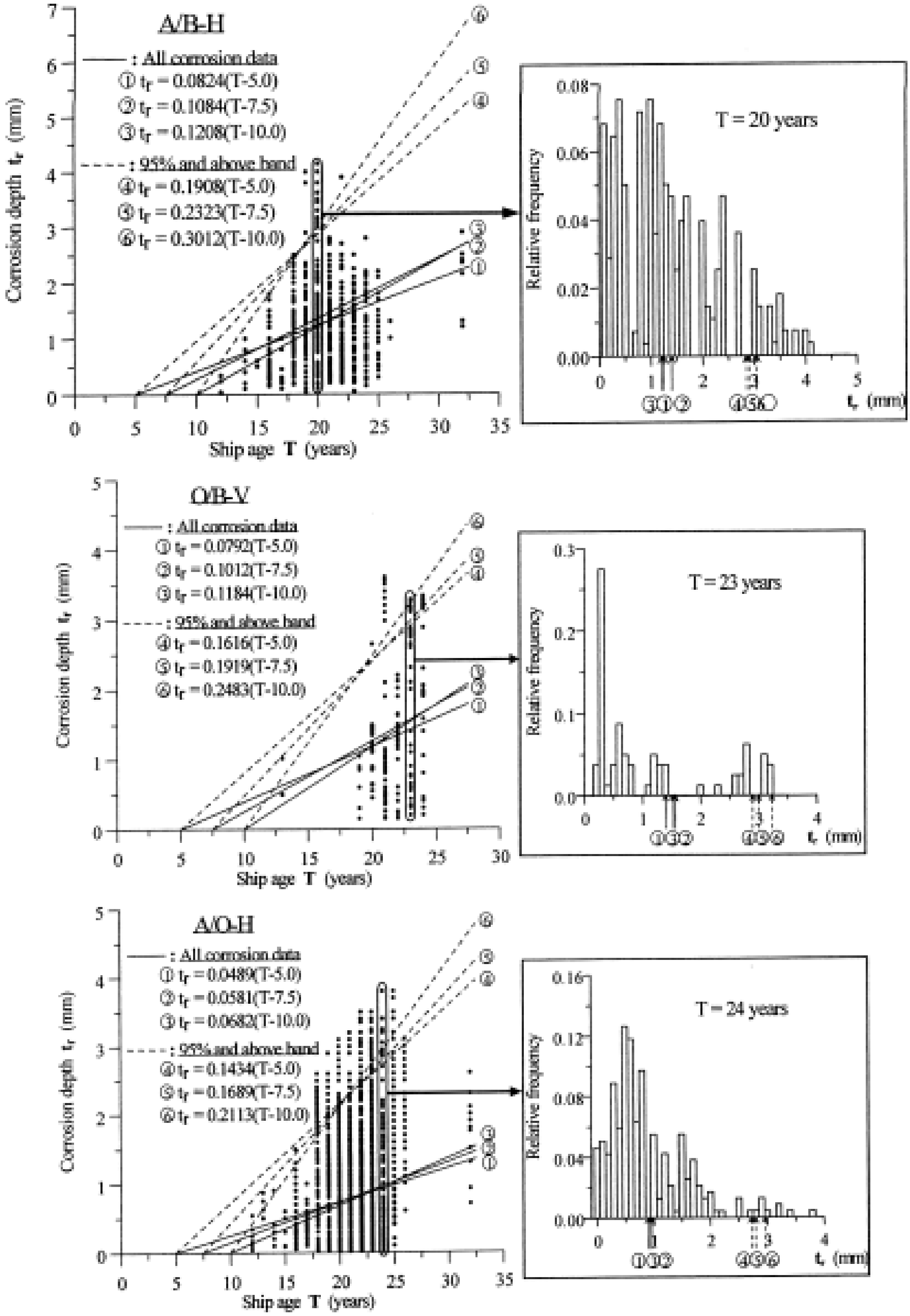

Fig. 12 Comparison of the time-dependent corrosion wastage formulations, together with the measured corrosion data for (top) A/B-H, (middle) O/B-V, and (bottom) A/O-H

Table 3 Ranking of an average value of the annualized corrosion rate (i.e., coefficient C_1) for each primary member group in a single-skin tanker

		Coating Life (years)					
		5		7.5		10	
ID No.	Member Type	C_1 (mm/year)	Ranking	C_1 (mm/year)	Ranking	C_1 (mm/year)	Ranking
1	B/S-H	0.0518	16	0.0597	16	0.0704	16
2	A/B-H	0.0824	8	0.1084	8	0.1208	8
3	A/B-V	0.0552	12	0.0661	12	0.0762	12
4	B/S-V	0.0545	13	0.0622	13	0.0731	13
5	BLGB	0.0539	14	0.0619	14	0.0728	14
6	O/B-V	0.0792	9	0.1012	9	0.1184	9
7	*B/B-H*	*0.1111*	*6*	*0.1408*	*5*	*0.1790*	*4*
8	O/S-H	0.0526	15	0.0607	15	0.0709	15
9	A/O-H	0.0489	18	0.0581	18	0.0682	18
10	A/O-V	0.0444	21	0.0523	21	0.0633	21
11	*O/S-V*	*0.0346*	*28*	*0.0423*	*27*	*0.0532*	*25*
12	BLGC	0.0340	30	0.0414	29	0.0513	28
13	O/O-V	0.0475	20	0.0577	19	0.0671	19
14	O/O-H	0.0330	31	0.0405	30	0.0509	29
15	BSLB(W)	0.1184	5	0.1367	6	0.1613	6
16	BSLB(F)	0.0976	7	0.1127	7	0.1330	7
17	DLB(W)	0.2081	1	0.2403	1	0.2836	1
18	SSLB(W)	0.1224	4	0.1413	4	0.1667	5
19	SSLB(F)	0.0764	10	0.0882	10	0.1041	10
20	LBLB(W)	0.1697	2	0.1960	2	0.2313	2
21	LBLB(F)	0.1543	3	0.1782	3	0.2103	3
22	BSLC(W)	0.0404	24	0.0466	24	0.0550	24
23	BSLC(F)	0.0378	26	0.0437	26	0.0516	27
24	DLC(W)	0.0620	11	0.0716	11	0.0845	11
25	DLC(F)	0.0509	17	0.0588	17	0.0694	17
26	SSLC(W)	0.0364	27	0.0420	28	0.0496	30
27	SSLC(F)	0.0344	29	0.0397	31	0.0468	31
28	LBLC(W)	0.0476	19	0.0550	20	0.0649	20
29	LBLC(F)	0.0440	22	0.0508	22	0.0599	22
30	BGLC(W)	0.0326	32	0.0377	32	0.0445	32
31	BGLC(F)	0.0276	33	0.0319	33	0.0376	33
32	DGLC(W)	0.0413	23	0.0477	23	0.0563	23
33	DGLC(F)	0.0389	25	0.0449	25	0.0530	26
34	SSTLC(W)	0.0226	34	0.0261	34	0.0308	34

It is also evident from Fig. 10 that the relative frequency distribution of the coefficient C_1 follows a Weibull function. Figure 11 shows the relative frequency of corrosion wastage for A/B-H as reflected by the coefficient C_1 using only the corrosion measurement data corresponding to the 95% and above band (i.e., omitting the data lower than the 95% band) and varying the coating life from 5 to 10 years. Although the Weibull function was also used to make fits numerically to the statistical distribution of corrosion data above the 95% band, it is in this band that the frequency distribution more likely follows the normal function. In this calculation, the same value of the interval of the coefficient C_1 (i.e., 0.0056 mm/year) was used as before.

The same data analysis methodology can be applied for the 34 various member group data. Table 2 summarizes the computed results for the mean value and COV of the coefficient C_1 for the 34 different member location/category groups. As previously mentioned, the mean value of the coefficient C_1 corresponds to the annual mean corrosion rate, as indicated in equation (2b).

Using the results of Tables 2 or 4, the corrosion behavior (thickness loss, annualized corrosion rate) of structural members for single-skin tankers over time can be predicted from equation (2) with ship age (T) and coating life (T_c) known. Figure 12 shows some example plots of the corrosion depth formulae so obtained together with the underlying corrosion wastage measurements themselves. The corrosion depth formulae noted above can hence be used to determine the relevant average or severe corrosion behavior of single-skin tanker structures.

Table 3 shows ranking of the annual corrosion rates for all primary member locations/categories varying the coating life. As previously noted, the life of coating has been assumed, as given in the present computations of the annual corrosion rates, with values in the range of practice, that is, approximately 5 to 10 years. In reality, however, earlier breakdown of coating will take place at more corrosive member locations, while the durability of coating could be longer for less corrosive member locations in specific cases. In this regard, the rankings of Table 3 are generic.

Table 4 represents a proposal on the mean value of the coefficient C_1 (which corresponds to annualized corrosion rate) and the related COV for each member location/category group at a "representative average" life of coating of 7.5 years. Table 5 compares the present corrosion rates with the Tanker Structure Co-operative Forum (TSCF) corrosion rates. It is found that both models correlate well, while a benefit of the present model is to provide corrosion rates for a greater variety of member groups.

A time-dependent corrosion wastage model for oceangoing double-hull tanker structures

The Exxon *Valdez* grounding in 1989 resulted in the passage of the U.S. Oil Pollution Act of 1990, which requires that

Table 4a Proposed average value of the annualized corrosion rate (i.e., coefficient C_1) for each primary member group in a single-skin tanker

ID No.	Member Type	Corrosion Rate (mm/year)	COV	Reference Coating Life (years)	Ranking of Corrosion Rate
1	B/S-H	0.0597	0.9901	7.5	16
2	A/B-H	0.1084	0.8183	7.5	8
3	A/B-V	0.0661	1.1341	7.5	12
4	B/S-V	0.0622	1.0030	7.5	13
5	BLGB	0.0619	0.8821	7.5	14
6	O/B-V	0.1012	0.7994	7.5	9
7	B/B-H	0.1408	0.2704	7.5	5
8	O/S-H	0.0607	0.8248	7.5	15
9	A/O-H	0.0581	0.8262	7.5	18
10	A/O-V	0.0523	1.0111	7.5	21
11	O/S-V	0.0423	0.7601	7.5	27
12	BLGC	0.0414	1.0033	7.5	29
13	O/O-V	0.0577	0.8162	7.5	19
14	O/O-H	0.0405	1.1341	7.5	30
15	BSLB(W)	0.1367	0.7802	7.5	6
16	BSLB(F)	0.1127	1.0121	7.5	7
17	DLB(W)	0.2403	0.9165	7.5	1
18	SSLB(W)	0.1413	1.0097	7.5	4
19	SSLB(F)	0.0882	0.8966	7.5	10
20	LBLB(W)	0.1960	0.9993	7.5	2
21	LBLB(F)	0.1782	0.9941	7.5	3
22	BSLC(W)	0.0466	1.1156	7.5	24
23	BSLC(F)	0.0437	1.1341	7.5	26
24	DLC(W)	0.0716	0.8902	7.5	11
25	DLC(F)	0.0588	1.0032	7.5	17
26	SSLC(W)	0.0420	1.0517	7.5	28
27	SSLC(F)	0.0397	0.8551	7.5	31
28	LBLC(W)	0.0550	0.8129	7.5	20
29	LBLC(F)	0.0508	1.0012	7.5	22
30	BGLC(W)	0.0377	0.9824	7.5	32
31	BGLC(F)	0.0319	0.8439	7.5	33
32	DGLC(W)	0.0477	1.0818	7.5	23
33	DGLC(F)	0.0449	0.9533	7.5	25
34	SSTLC(W)	0.0261	1.0926	7.5	34

Table 4b Proposed severe value of the annualized corrosion rate (i.e., coefficient C_1) for each primary member group in a single-skin tanker

ID No.	Member Type	Corrosion Rate (mm/year)	COV	Reference Coating Life (years)	Ranking of Corrosion Rate
1	B/S-H	0.1717	0.2290	7.5	14
2	A/B-H	0.2323	0.2277	7.5	8
3	A/B-V	0.1897	0.3227	7.5	10
4	B/S-V	0.1823	0.2185	7.5	11
5	BLGB	0.1805	0.2167	7.5	12
6	O/B-V	0.1919	0.2277	7.5	9
7	B/B-H	0.2586	0.0000	7.5	5
8	O/S-H	0.1777	0.2167	7.5	13
9	A/O-H	0.1689	0.2290	7.5	15
10	A/O-V	0.1529	0.2167	7.5	18
11	O/S-V	0.1497	0.2290	7.5	19
12	BLGC	0.1446	0.2167	7.5	20
13	O/O-V	0.1621	0.2185	7.5	17
14	O/O-H	0.1423	0.2277	7.5	21
15	BSLB(W)	0.2461	0.2290	7.5	6
16	BSLB(F)	0.2343	0.1827	7.5	7
17	DLB(W)	0.4244	0.1942	7.5	1
18	SSLB(W)	0.2595	0.1942	7.5	4
19	SSLB(F)	0.1630	0.2167	7.5	16
20	LBLB(W)	0.3840	0.1827	7.5	2
21	LBLB(F)	0.3455	0.2055	7.5	3
22	BSLC(W)	0.0888	0.2387	7.5	27
23	BSLC(F)	0.0837	0.1866	7.5	29
24	DLC(W)	0.1252	0.2167	7.5	22
25	DLC(F)	0.1060	0.1866	7.5	23
26	SSLC(W)	0.0810	0.2185	7.5	30
27	SSLC(F)	0.0790	0.1866	7.5	31
28	LBLC(W)	0.0942	0.1758	7.5	24
29	LBLC(F)	0.0921	0.2167	7.5	25
30	BGLC(W)	0.0714	0.2395	7.5	32
31	BGLC(F)	0.0578	0.2290	7.5	33
32	DGLC(W)	0.0900	0.2277	7.5	26
33	DGLC(F)	0.0862	0.1974	7.5	28
34	SSTLC(W)	0.0437	0.1827	7.5	34

all tankers operating in U.S. waters must have double hulls by the year 2015. The International Maritime Organization has established related requirements, which are now applied worldwide.

The fleet of aged double-hull tankers is not yet large in number, and thus their corrosion wastage measurement database is small in size. But the structural flexibility effects on corrosion behavior of oceangoing single-skin tankers are considered to be similar to those of oceangoing double-skin tankers. Therefore, it is fairly considered that the corrosion measurement data for single-hull tanker structures can be applied to corrosion prediction of double-hull tanker structures as long as the corrosion environment is similar.

In this regard, we propose the 34 member groups for structures of double-hull tankers defined by the similar corrosion environments of single-hull tanker structures, as illustrated in Fig. 13. Mean and COV of the annualized corrosion rate (i.e., the coefficient C_1) for each member group can then be obtained from Tables 2 and 4. Figure 14 shows mean and COV of the coefficient C_1 (corrosion rate) for the 34 member groups when the coating life is assumed to be 7.5 years.

A time-dependent corrosion wastage model for the structures of FSOs/FPSOs

Until now, the fleet of FSOs or FPSOs has been very small in number. The structural flexibility characteristics of oceangoing single- or double-skin tankers may be different from those of FSOs or FPSOs, which load and unload a lot more frequently, sometimes every week. Such frequent loading/unloading patterns of FSOs or FPSOs may accelerate the corrosion progress. On the other hand, FSOs or FPSOs typically operate at standstill at a specific sea site, and this aspect may likely mitigate the dynamic flexing, keeping the corrosive scale static, compared with that of oceangoing vessels. The two counteraspects may then offset the positive and negative effects on corrosion.

While further study is pending, it is considered that the corrosion models previously defined for oceangoing single- or double-skin tanker structures can be applied to corrosion prediction of the structures of FSOs or FPSOs as long as the corrosion environment is similar.

Using the results of Tables 2 or 4, therefore, the corrosion behavior (thickness loss, annualized corrosion rate) of structural member groups for FSOs or FPSOs over time can be predicted from equation (2) with ship age (T) and coating life (T_c) known. Again, the results of Fig. 14 are meant to be mean and COV of structural member groups of FSOs or FPSOs when the coating life is assumed to be 7.5 years.

Nominal design corrosion value

A design corrosion margin may also be determined so that a representative maximum predicted thickness loss for the entire life of a ship is added to the structure that has been designed for the relevant design demands (loads) alone. The

Table 5 Comparison of the proposed corrosion rates with the TSCF corrosion rates for tanker structures

ID No.	Member Type	Proposed "Average" Corrosion Rate (mm/year)	Corrosion Rate by TSCF (mm/year)
1	B/S-H	0.0597	0.04–0.10
2	A/B-H	0.1084	0.10–0.50
3	A/B-V	0.0661	0.06–0.10
4	B/S-V	0.0622	0.06–0.10
5	BLGB	0.0619	—
6	O/B-V	0.1012	0.10–0.30
7	B/B-H	0.1408	—
8	O/S-H	0.0607	0.04–0.10
9	A/O-H	0.0581	0.03–0.10
10	A/O-V	0.0523	0.03
11	O/S-V	0.0423	0.03
12	BLGC	0.0414	—
13	O/O-V	0.0577	0.03
14	O/O-H	0.0405	—
15	BSLB(W)	0.1367	—
16	BSLB(F)	0.1127	—
17	DLB(W)	0.2403	0.25–1.00
18	SSLB(W)	0.1413	0.10–0.25
19	SSLB(F)	0.0882	—
20	LBLB(W)	0.1960	0.20–1.20
21	LBLB(F)	0.1782	0.20–0.60
22	BSLC(W)	0.0466	0.03
23	BSLC(F)	0.0437	—
24	DLC(W)	0.0716	0.03–0.10
25	DLC(F)	0.0588	—
26	SSLC(W)	0.0420	0.03
27	SSLC(F)	0.0397	—
28	LBLC(W)	0.0550	0.03
29	LBLC(F)	0.0508	—
30	BGLC(W)	0.0377	—
31	BGLC(F)	0.0319	—
32	DGLC(W)	0.0477	—
33	DGLC(F)	0.0449	—
34	SSTLC(W)	0.0261	—

Table 6a Example corrosion margins for primary members of tanker structures based on a coating life of 5 years

ID No.	Member Type	Proposed C_1 (mm/year)	Proposed $C_1 \times 20$ years (mm)	NDCV (mm)
1	B/S-H	0.0518	1.0360	1.0
2	A/B-H	0.0824	1.6480	2.0
3	A/B-V	0.0552	1.1040	1.0
4	B/S-V	0.0545	1.0900	1.0
5	BLGB	0.0539	1.0780	1.0
6	O/B-V	0.0792	1.5840	1.5
7	B/B-H	0.1111	2.2220	2.5
8	O/S-H	0.0526	1.0520	1.0
9	A/O-H	0.0489	0.9780	1.0
10	A/O-V	0.0444	0.8880	1.0
11	O/S-V	0.0346	0.6920	1.0
12	BLGC	0.0340	0.6800	1.0
13	O/O-V	0.0475	0.9500	1.0
14	O/O-H	0.0330	0.6600	1.0
15	BSLB(W)	0.1184	2.3680	2.5
16	BSLB(F)	0.0976	1.9520	2.0
17	DLB(W)	0.2081	4.1620	4.0
18	SSLB(W)	0.1224	2.4480	2.5
19	SSLB(F)	0.0764	1.5280	1.5
20	LBLB(W)	0.1697	3.3940	3.5
21	LBLB(F)	0.1543	3.0860	3.0
22	BSLC(W)	0.0404	0.8080	1.0
23	BSLC(F)	0.0378	0.7560	1.0
24	DLC(W)	0.0620	1.2400	1.5
25	DLC(F)	0.0509	1.0180	1.0
26	SSLC(W)	0.0364	0.7280	1.0
27	SSLC(F)	0.0344	0.6880	1.0
28	LBLC(W)	0.0476	0.9520	1.0
29	LBLC(F)	0.0440	0.8800	1.0
30	BGLC(W)	0.0326	0.6520	1.0
31	BGLC(F)	0.0276	0.5520	0.5
32	DGLC(W)	0.0413	0.8260	1.0
33	DGLC(F)	0.0389	0.7780	1.0
34	SSTLC(W)	0.0226	0.4520	0.5

NDCV = nominal design corrosion values.

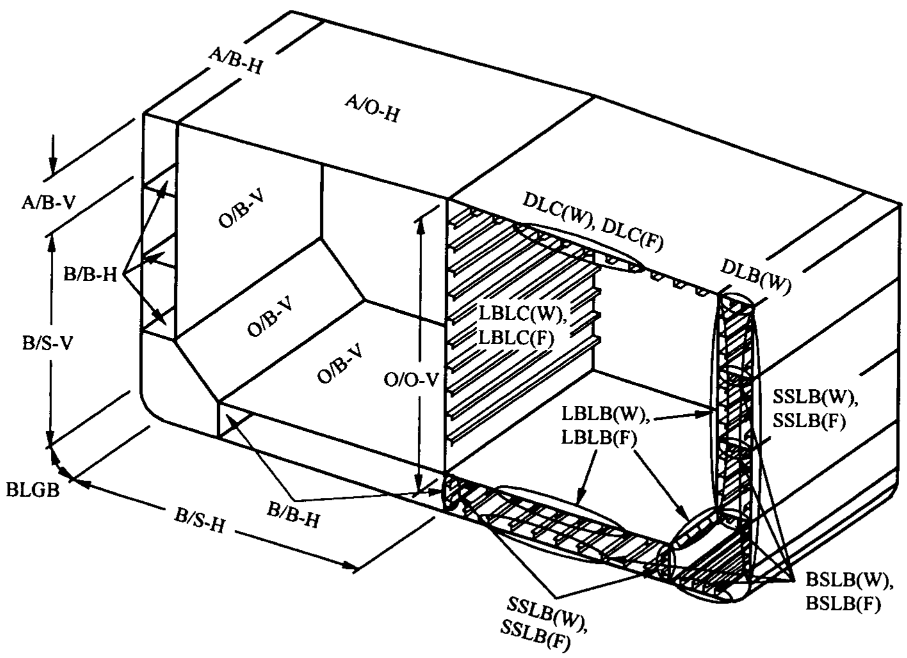

Fig. 13 A proposal on the 34 member groups of a double-hull tanker defined by the similar corrosion environment of a single-hull tanker. (For abbreviations, see Fig. 6.)

Table 6b Example corrosion margins for primary members of tanker structures based on a coating life of 7.5 years

ID No.	Member Type	Present		
		C_1 (mm/year)	$C_1 \times 17.5$ years (mm)	NDCV (mm)
1	B/S-H	0.0597	1.0448	1.0
2	A/B-H	0.1084	1.8970	2.0
3	A/B-V	0.0661	1.1568	1.0
4	B/S-V	0.0622	1.0885	1.0
5	BLGB	0.0619	1.0833	1.0
6	O/B-V	0.1012	1.7710	2.0
7	B/B-H	0.1408	2.4640	2.5
8	O/S-H	0.0607	1.0623	1.0
9	A/O-H	0.0581	1.0168	1.0
10	A/O-V	0.0523	0.9153	1.0
11	O/S-V	0.0423	0.7403	1.0
12	BLGC	0.0414	0.7245	1.0
13	O/O-V	0.0577	1.0098	1.0
14	O/O-H	0.0405	0.7088	1.0
15	BSLB(W)	0.1367	2.3923	2.5
16	BSLB(F)	0.1127	1.9723	2.0
17	DLB(W)	0.2403	4.2053	4.0
18	SSLB(W)	0.1413	2.4728	2.5
19	SSLB(F)	0.0882	1.5435	1.5
20	LBLB(W)	0.1960	3.4300	3.5
21	LBLB(F)	0.1782	3.1185	3.0
22	BSLC(W)	0.0466	0.8155	1.0
23	BSLC(F)	0.0437	0.7648	1.0
24	DLC(W)	0.0716	1.2530	1.5
25	DLC(F)	0.0588	1.0290	1.0
26	SSLC(W)	0.0420	0.7350	1.0
27	SSLC(F)	0.0397	0.6948	1.0
28	LBLC(W)	0.0550	0.9625	1.0
29	LBLC(F)	0.0508	0.8890	1.0
30	BGLC(W)	0.0377	0.6598	1.0
31	BGLC(F)	0.0319	0.5583	0.5
32	DGLC(W)	0.0477	0.8348	1.0
33	DGLC(F)	0.0449	0.7858	1.0
34	SSTLC(W)	0.0261	0.4568	0.5

NDCV = nominal design corrosion values.

Table 6c Example corrosion margins for primary members of tanker structures based on a coating life of 10 years

ID No.	Member Type	Proposed		
		C_1 (mm/year)	$C_1 \times 15$ years (mm)	NDCV (mm)
1	B/S-H	0.0704	1.0560	1.0
2	A/B-H	0.1208	1.8120	2.0
3	A/B-V	0.0762	1.1430	1.0
4	B/S-V	0.0731	1.0965	1.0
5	BLGB	0.0728	1.0920	1.0
6	O/B-V	0.1184	1.7760	2.0
7	B/B-H	0.1790	2.6850	3.0
8	O/S-H	0.0709	1.0635	1.0
9	A/O-H	0.0682	1.0230	1.0
10	A/O-V	0.0633	0.9495	1.0
11	O/S-V	0.0532	0.7980	1.0
12	BLGC	0.0513	0.7695	1.0
13	O/O-V	0.0671	1.0065	1.0
14	O/O-H	0.0509	0.7635	1.0
15	BSLB(W)	0.1613	2.4195	2.5
16	BSLB(F)	0.1330	1.9950	2.0
17	DLB(W)	0.2836	4.2540	4.5
18	SSLB(W)	0.1667	2.5005	2.5
19	SSLB(F)	0.1041	1.5615	1.5
20	LBLB(W)	0.2313	3.4695	3.5
21	LBLB(F)	0.2103	3.1545	3.5
22	BSLC(W)	0.0550	0.8250	1.0
23	BSLC(F)	0.0516	0.7740	1.0
24	DLC(W)	0.0845	1.2675	1.5
25	DLC(F)	0.0694	1.0410	1.0
26	SSLC(W)	0.0496	0.7440	1.0
27	SSLC(F)	0.0468	0.7020	1.0
28	LBLC(W)	0.0649	0.9735	1.0
29	LBLC(F)	0.0599	0.8985	1.0
30	BGLC(W)	0.0445	0.6675	1.0
31	BGLC(F)	0.0376	0.5640	0.5
32	DGLC(W)	0.0563	0.8445	1.0
33	DGLC(F)	0.0530	0.7950	1.0
34	SSTLC(W)	0.0308	0.4620	0.5

NDCV = nominal design corrosion values.

mean value of corrosion wastage (depth) can then be predicted from equation (2a), as follows:

$$t_r = C_1(T - T_c). \tag{4}$$

The corrosion margins may then be determined based on the corrosion wastages predicted at the age of, say, $T = 25$ years. Table 6 indicates the corrosion margin values so obtained for each primary member location/category group varying the coating life.

As previously noted, the life of coating has in the present study been presumed as a known value, whereas in reality the relevant coating life could differ from the assumptions. Figure 15 illustrates a set of the example design corrosion margins for each primary member group of a tanker structure having double hulls, when the coating life is assumed to be 7.5 years. A similar set of the nominal design corrosion value can readily be established for a tanker structure having single hulls.

Concluding remarks

In this paper, time-variant corrosion wastage prediction models for primary member (plating, web and flange) groups of the structures of single- and double-hull tankers or FSOs/FPSOs have been developed by the statistical analysis of a corrosion wastage measurement database. A total of 33,820 corrosion data measured for 230 single-skin tankers carrying crude or product oils were used for this purpose. Based on the corrosion models and insights developed in the proposed study, the following conclusions can be drawn:

(1) It is found that the statistical distribution of the annualized corrosion rate at the most probable (average) level follows a Weibull function, whereas it is closer to the normal function at the upper bound (severe) level.
(2) The annualized corrosion rate is different for the different member location/category groups considered. Results for 34 tanker structural member groups are presented. Results such as these can be updated as additional data become available and additional experience is accumulated.
(3) The average (most probable) annualized corrosion rate is in the range of approximately 0.0261 to 0.2403 mm/year for all gathered corrosion measurements in the database, but the severe (upper bound) values representing the 95% and above band of the corrosion data can be greater by a factor of three or more in some cases.
(4) The corrosion depth of primary structural members for generic design or repair planning can be predicted from the corrosion models developed in the present study, for single- and double-skin tankers, shuttle tankers, FSOs, and FPSOs.
(5) From the corrosion data analysis procedures proposed in the present study, example design corrosion values

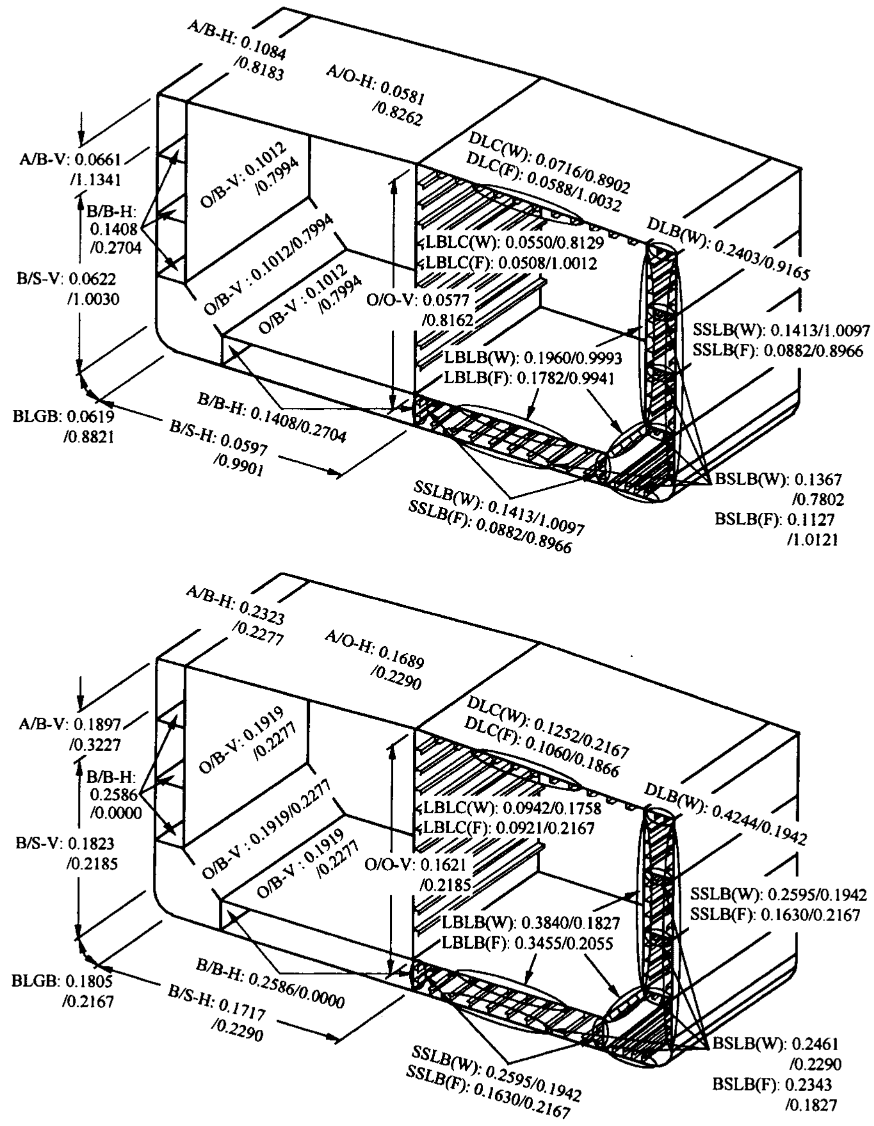

Fig. 14 (Top) Mean and COV of the average (most probable) corrosion rate (coefficient C_1) for the 34 member location/category groups of double-hull tanker structure considering all corrosion measurement data for a given group. (Bottom) Mean and COV of the severe (upper bound) corrosion rate (coefficient C_1) for the 34 member location/category groups of double-hull tanker structure considering only the 95% and above band of the corrosion data for a given group. (For abbreviations, see Fig. 6.)

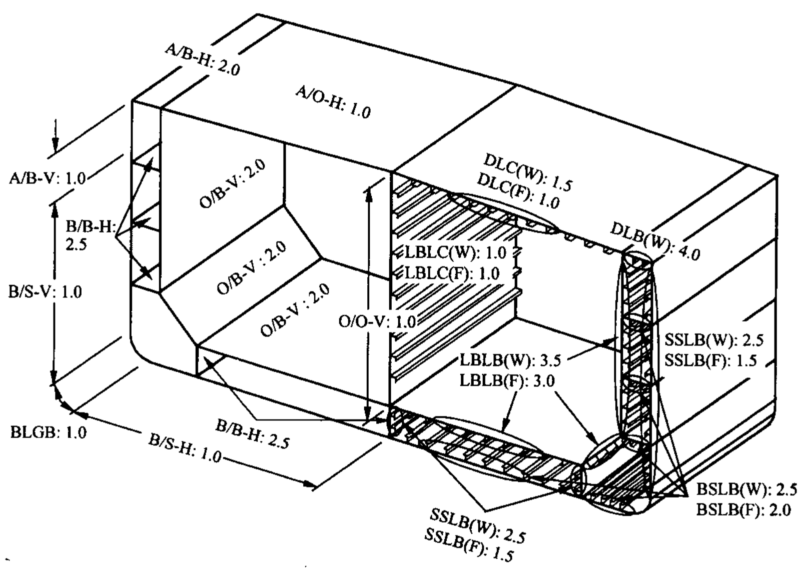

Fig.15 Example nominal design corrosion values (in millimeters) for primary member location/category groups of a tanker structure (having double hulls, for instance). (For abbreviations, see Fig. 6.)

(margins) were obtained, as noted in Fig. 15, for the 34 different member groups, when the coating life is assumed to be 7.5 years. These example design corrosion values are not definitive and are meant only as an illustration of results potentially obtainable from the proposed study procedures. For other durability of coating, see the results listed in Table 6.

(6) Mean and COV of the annualized corrosion rates defined in the present study will be useful for structural reliability analysis of aged tanker structures. Although the several uncertainties associated with the corrosion process and the procedures of the present study should be recognized, the corrosion modeling methodology and procedures presented in this study should be of value for the purposes intended and represent a useful improvement on related current state of the art.

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