Špiro Ivošević
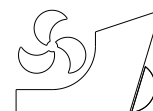*Romeo Meštrović*
Nataša Kovač

AN APPROACH TO THE PROBABILISTIC CORROSION RATE ESTIMATION MODEL FOR INNER BOTTOM PLATES OF BULK CARRIERS

Summary

This paper gives an approach to the probabilistic corrosion rate estimation model for inner bottom plates of bulk carriers. Firstly, by using the data from thickness measurements for inner bottom plates for considered 25 bulk carriers, the related best fitted linear model for the corrosion wastage is obtained as a function of ship's age. In this model it is assumed that life of coating is 4 years. The obtained related corrosion rate is equal to 0.135474 mm/year. Notice that the obtained linear model is a particular case of a power model proposed in some earlier investigations.

In view of the fact that the corrosion rate of ship hull structures is influenced by many factors, many of an uncertain nature, in recent studies several authors investigated a probabilistic model as more appropriate to describe the expected corrosion. Motivated by these investigations, and using 2926 thickness measurements for corrosion wastage of inner bottom plates of considered 38 special ships surveys, this paper examines the cumulative density function for the corrosion rate c_1 involved in the mentioned linear model, and considered here as a continuous random variable. The obtained statistical, numerical and graphical results show that the logistic distribution or normal distribution would be well appropriate for the probabilistic corrosion rate estimation model for inner bottom plates of bulk carriers. It is believed that this fact will be confirmed with greater statistical reliability in our future investigations including many more data collected on the considered corrosion.

1. Introduction

Up to now, in many published articles, authors identify corrosion, fatigue cracking and local dent as most influenced mechanisms of age related deterioration [1]. Among many different type of vessels, bulk carriers and tankers were recognised as more critical, due to a

lot of casualties in the last few decades. Much research focuses on degradation of aged bulk carrier members and identify corrosion as long-term degradation mechanism on ships integrity as it was presented in papers [2] and [3]. Bulk carriers are in continual contact with salt water, and simultaneously exposed to some unpredictable atmosphere, cargo and ballast effects. More precisely, aggressive environment, specifics of trade routes, dry and wet ballast circles, ratio of ballast and cargo, frequencies of cargo loading/unloading operations, etc., often affected serious bulk carriers' corrosion deteriorations [4, 5]. It is also to be emphasized that the corrosion might be aggravated by the negative effects of some cargoes, especially those like iron ore and coil [2, 4, 6].

In previous research, authors were motivated to investigate corrosion degradation of some specific structural members such as transversal bulkhead of bulk carriers [7] or deck plating of tankers [8, 9, 10, 11], or all structural members (see Paik et al. [4, 12, 13]).

1.1.   Subject of research

For the purpose of this research work, a large data base has been provided by the recognized ultrasonic measurements used from the INVAR-Ivošević Company (see Acknowledgement) during the last fifteen years. These data were collected through numerous standardized and very detailed measurements over almost all hull structure members of the group of analyzed aged bulk carriers. The present paper analyzes only gauging taken from Special Survey, which was done after every 5 years of exploitation.

However, in this article, only bulk carriers' fuel tanks time-dependent deteriorations caused by the general corrosion have been analyzed. The main reason for this lies in the fact that such kind of a problem is not covered by the previous research works in the field. Previous research covered mostly cargo holds and ballast tanks [6, 7, 15, 16].

The research in this paper is a continuation of previous research of both short and long term corrosion investigations on fuel oil tanks [14]. Monte Carlo simulation method has been used for assessing the value of damaged steel, expressed in percentage of the standard steel thickness, and Weibull probability analysis is used upon some cumulative negative time-dependent fuel tanks corrosion effects in long terms, i.e., during the whole period of their exploitation [14].

1.2.   The input data set brief description

Although the fuel tanks may be found either in the top-side tanks, or deep tanks, the subject of this paper concerns only oil (fuel) tanks placed in double bottom. Usually, these oil tanks are spatially positioned along the main axis of the bulk carrier, but they can be placed perpendicularly on it as well (Figure 1).

The total of 25 aging bulk carriers ranging from 5 to 25 years of age are investigated. All monitored bulk carriers were measured during the special surveys which were done after 5, 10, 15, 20 or 25 years of exploitation life cycle. In that sense, some of the bulk carriers were monitored two or three times during the previous 15 years, between 2005 and 2017. Finally, measuring data from 38 different special surveys were collected.
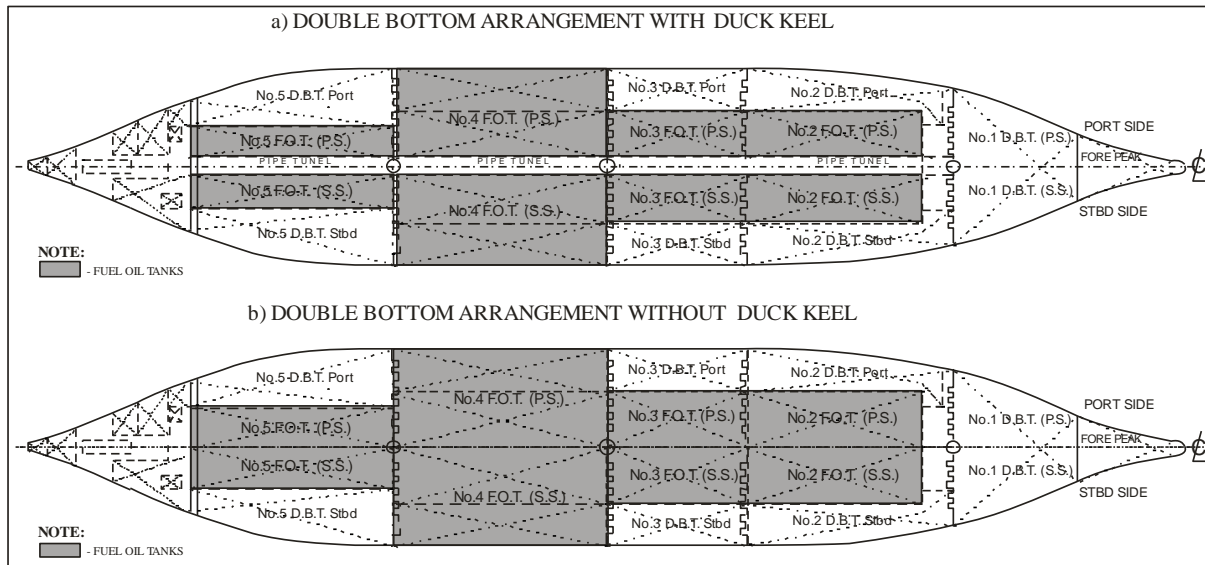
Fig. 1. Bulk carriers' different arrangements of fuel tanks: a) double bottom with duck keel, b) double bottom
without duck keel (Fuel oil tanks No.4 are wide to the shell plate)

In accordance with the corrosion measuring standards and some characteristics of operational parameters, the fuel tanks of bulk carriers are considered here through ten different segments, areas, or member locations. The analysed segments are presented schematically and listed below in the form of the legend in Figure 2.
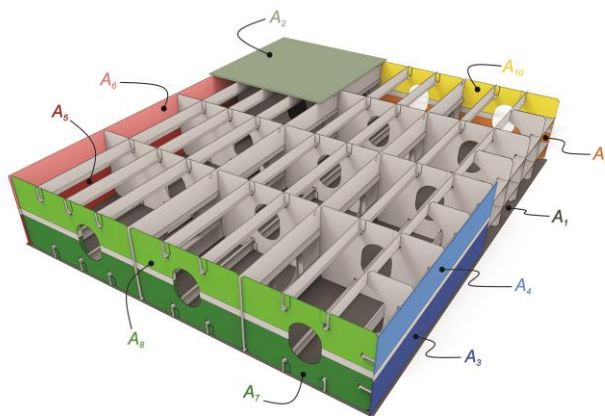
Legend:

A_1 – Bottom plate

A_2 – Inner bottom plate

A_3 – Inside girder (water tight), lower

A_4 – Inside girder (water tight), upper

A_5 – Side (water tight) girder, lower

A_6 – Side (water tight) girder, upper

A_7 – Floor after (water tight), lower

A_8 – Floor after (water tight), upper

A_9 – Floor fore (water tight), lower

A_{10} – Floor fore (water tight), upper

Fig. 2. Basic structural scheme of a bulk carrier's fuel tank areas (A_1 - A_{10})

The data on the general corrosion loss expressed in millimetres (mm) of steel thickness, were collected through regular measurements (surveys on site). The data are gathered over each of the previously mentioned areas (A_1-A_{10}) of the fuel tanks, through 10 or 20 different sections, depending on the number of fuel tanks, for both the left, or portside (P) and the right, or starboard (S) sides of considered bulk carriers. The data were collected during regular special surveys, in a way that each tank is divided into 5 sections: two sections for after and fore ends, and three sections at equal mutual distances in the middle, between ends of tanks. In total, 71 different fuel oil tanks are covered with sets of 570 measurements data with totally 2926 measuring points (one set of data includes all measuring points from each plate in corresponding transversal sections).

This paper gives an approach to the probabilistic corrosion rate estimation model for inner bottom plates (area A_2) of bulk carriers. The investigated model uses collected thickness measurements data for inner bottom plates of considered 38 ship's surveys, which were presented in Figure 3.
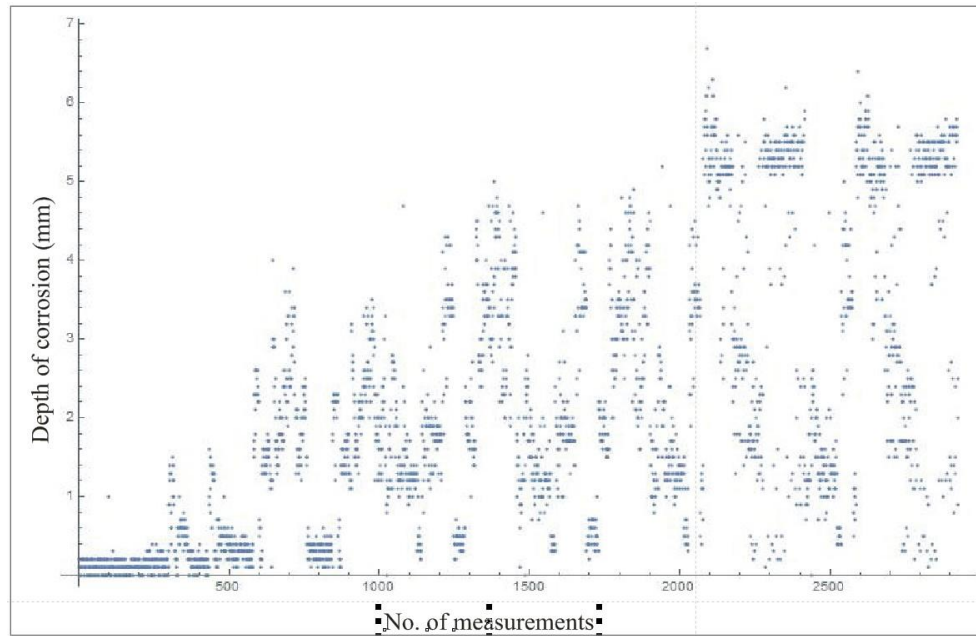
Fig. 3 Data of 2926 tthickness measurements for inner bottom plates of considered 38 ship's surveys

Figure 3 shows the raw data obtained from 2926 measurements related to the corrosion wastage for all inner bottom plates of considered 38 ship's surveys whose age was taken in the following intervals: 0-5 years, 5-10 years, 10-15 years, 15-20 years and 20-25 years. The x - axis shows how many measurements, i.e., the x - coordinate presents the number of the measurements, while the y - axis presents the values of related corrosion wastage (the depth of corrosion). These data are sorted and displayed chronologically by years (i.e., the following right bounds of the previous intervals are assumed: 5, 10, 15, 20 and 25 years). Because of that fact, the graph also points to the increasing tendency of corrosion wastage depending on the age of the ship.

This paper is organized as follows. Section 2 firstly gives a motivation for this study consisting in short survey of investigations of the analytic and probabilistic corrosion rate estimation model related to the ship hull structure. The attention is focused on this study related to corrosion wastage of inner bottom plates of bulk carriers. This investigation is also motivated by the additional well known fact that in general, the corrosion rate would be different for all ship hull structure elements. For example, inner bottom plates are exposed on one side to ballast water, dry space, fuel tanks, while on the second ones to cargo.

For bulk carriers considered here, fuel is located inside the bottom of a tank, so that corrosion comes only from a cargo hold, i.e., on top of the sheet. Thus, corrosion is measured from the cargo hold but not from the tank. It is pointed out that the selected area forms only a part of inner bottom plates and this is the part that on the bottom side is not exposed to the influence of air (dry area) or to ballast water (ballast tanks), and therefore, data may vary and they show a different distribution than those so far registered in [12].

By using the averages of data from thickness measurements for inner bottom plates of 38 considered ships surveys, in Section 2 the well suitable fitted linear model for the corrosion wastage is established. Next by using set of 570 measurements data of corrosion wastage of plate thickness for inner bottom plates of considered 38 ships surveys, the cumulative density function for the annual corrosion rate (random variable) c_1 (in mm/year) is examined, involving in the obtained linear fitted model of the form $d(t) = c_1(t-4)$, where $d(t)$ is the corrosion wastage as a function of ship age t.

While most authors assumed that corrosion starts after more than 5 years of newbuilding (see, e.g., [10] and [11], where deck plates and ballast tanks are considered), in this paper, it is assumed that corrosion starts after 4 years of newbuilding. This is justified on the basis of the known fact that the inner bottom plating is under constant contact of cargo inside cargo holds, under the influence of handling equipment and under the maintenance process which includes cleaning before and after cargo operations.

Related statistical, graphical and numerical results show that the logistic distribution or normal distribution (both determined with two parameters) could be very appropriate for probabilistic corrosion rate estimation model concerning inner bottom plates of bulk carriers. Notwithstanding the fact that this set of 570 measurements data is small in statistical terms for confirming this hypothesis with a sufficient level of confidence, it is believed that, by using the same analytical and statistical approach as presented here, this hypothesis will be confirmed in future investigations involving mach more data collected in respect to the considered corrosion wastage.

Concluding remarks and subject for further research are given in Section 4.

2. Motivation for research and preliminary results

For a good survey of investigations of the analytic and probabilistic corrosion rate estimation model for different hull structure elements of bulk carriers see the survey paper by Qin and Cui [17].

It is well known that the corrosion wastage, $d(t)$, may be generally expressed as a power function of the time (usually expressed in years) after the corrosion starts (see e.g., [17] and [18]), i .e.,

$$d(t) = c_1(t - T_{cl})^{c_2}, \tag{1}$$

where $d(t)$ is the corrosion wastage; t is the elapsed time after the plate is used; T_{cl} is life of coating; c_1 and c_2 are positive real coefficients. This model was proposed in [18]. The coefficient c_2 may be usually assumed to be 1/3 or pessimistically assumed to be 1, while the coefficient c_1 is indicative of the annual corrosion rate. As noticed in [17], in most of the studies on time-dependent reliability of ship structures (see, e.g., [19]–[23]), the effect of corrosion was represented by an uncertain but constant corrosion rate, which resulted in a linear decrease of plate thickness with time. However, several authors established that experimental evedince often show that some nonlinear model is more appropriate, such as Extended Southwell bilinear model, Melchers-Southwell nonlinear model, Melchers trilinear model, Melchers power model, the model proposed by Guedes Soares and Garbatov, and the model proposed by Qin and Cui (for more details on these models, see [17]).

Here the validity of the expression (1) with $c_2 = 1$ proposed by Paik, Kim and Lee [4] is verified, and as noticed above, it assumes $T_{cl} = 4$ years (i.e., $d(t) = c_1(t - 4)$) for the corrosion data related to inner bottom plates of considered 38 ships surveys. These measurements data are used from the INVAR-Ivošević Company. Notice that this linear model with other values of coefficient c_1 and the value T_{cl} was proposed by Paik and Thayamballi [18]. In order to determine the approximate value of c_1, the values of averages of corrosion wastage are used, $d(t)$, at age t (depth of corrosion in mm), for inner bottom plates of 38 ship's surveys, as it is presented in Table 1.

Table 1 Averages of plate thickness due to corrosion, $d(t)$ (depth of corrosion in mm), for inner bottom plates of 38 ships surveys

Ship's age (in year)	Number of ship's surveys	Ship 1	Ship 2	Ship 3	Ship 4	Ship 5	Ship 6	Ship 7	Ship 8	Ship 9	Ship 10	Ship 11	Ship 12	Ship 13	Averages of plate thickness (in mm)
0-5	4	0.1	0.1	0.1	0.1										0.1
5-10	4	0.2	0.1	0.8	0.5										0.4
10-15	7	0.3	0.3	1.5	1.4	2	2.8	1.9							1.4571
15-20	13	1.6	1.4	0.9	1.8	1.7	3.5	0.5	0.4	1.8	3.3	3.8	2.9	3	2.0462
20-25	10	1.8	1.5	1	3.5	4.7	4.7	3	2	4.2	4.3				3.07

Here, as always in the sequel, for related computational purposes, the software *Mathematica* 9 is used. By using the average data given in the last column of Table 1, the following best fitted linear model for $d(t)$ is obtained (see Figure 4):

$$d(t) = 0.135474(t - 4),\qquad(2)$$

where it is supposed that the corrosion starts 4 years after newbuilding. From Eq. (2) it follows that the related corrosion rate, $r(t)$, is equal to
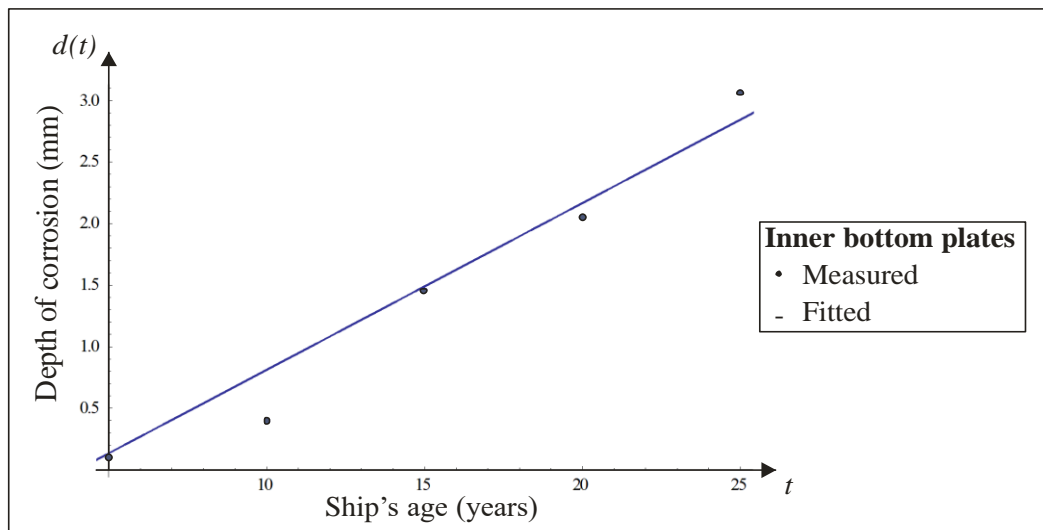
$$r(t) = d'(t) = 0.135474.\qquad(3)$$

Fig. 4 Linear fitted model for data of Table 1

The following information was obtained about the parameter estimates: standard error = 0.00832602, t-statistic =16.2711 and p-value=0.0000834878 show that the expression (2) is very appropriate for determining $d(t)$ (depth of corrosion) for inner bottom plates of bulk carriers. In particular, it can be seen from Eq. (3) that the corrosion rate is a constant equals to 0.135474.

Because the corrosion is a function of many variables, many of an uncertain nature, a probabilistic model is more appropriate to describe the expected corrosion (for more details see [17]). In particular, based on the probabilistic model proposed by Yamamoto et al. [24], [25] and Paik et al. [4], it was usually assumed that the probability density function of the corrosion rate follows the Weibull distribution. Hence, the cumulative distribution function and the probability density function of the coefficient c_1 from Eq. (1) are respectively given by

$$F_{c_1}(x) = 1 - \exp\left(-\left(\frac{x}{w}\right)^k\right),$$ (4)

$$f_{c_1}(x) = \frac{k}{w}\left(\frac{x}{w}\right)^{k-1} \exp\left(-\left(\frac{x}{w}\right)^k\right),$$ (5)

where w is the unknown scale parameter and k is unknown shape parameter. By using the least-squares method, the unknown parameters w and k can be determined from the corrosion data collected.

Motivated by the above considerations, the following section studies the probabilistic corrosion rate estimation model related only for inner bottom plates of bulk carriers.

3. The estimation of cumulative distribution function of corrosion rate c_1

This section proposes a statistical approach for approximating the cumulative distribution function of corrosion rate c_1 defined in the previous section, but considered here as a continuous random variable.

3.1 The appropriate statistical data related to measurements on inner bottom plates

Total set of 570 measurements of plate thickness due to corrosion, $d(t)$ (depth of corrosion in mm), for inner bottom plates of considered 38 ships surveys are graphically presented in Figure 5.
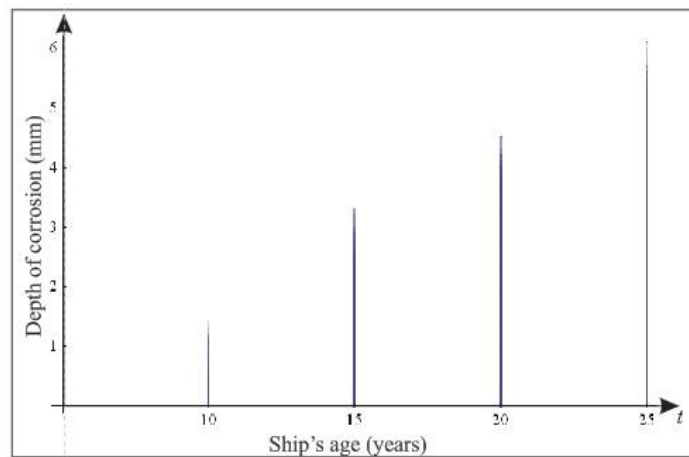

Fig. 5 Set of 570 measurements of plate thickness due to corrosion
for inner bottom plates of 38 ships surveys

A calculation based on the mentioned set of 570 measurements data shows that the average ships age is equal to 18.29 years, while the related average depth is equal to 1.91982 mm. Their standard deviations are respectively equal to 5.95933 years and 1.49155 mm.

Further, using a set of 570 mentioned measurements data, as in the previous section the following more refined fitted linear model for $d(t)$ than those given by (2) is obtained:

$$d(t) = 0.13679(t-4).$$ (6)

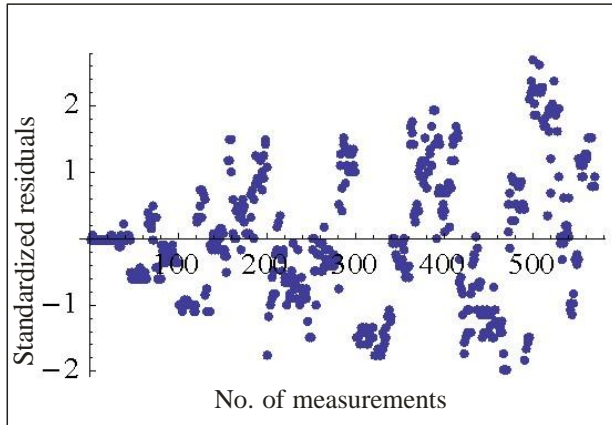Related standardized residuals and fit residuals are presented in Figure 6.

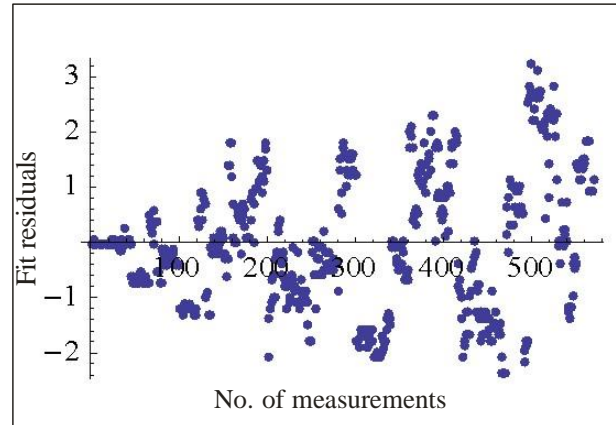**Fig. 6 a)** Extract and plot the standardized residuals

Fig. 6 b) Extract and plot the fit residuals

3.2 The estimation of a suitable cumulative distribution function of corrosion rate c_1

Since the constant $c_1 = 0.13679$ from Eq. (6) "analytically" presents the related corrosion rate, which in practice is not an absolute constant, it can be considered as a continuous random variable. As noticed above, in several related investigations it is assumed that c_1 follows a (three-parametric) Weibull distribution. The collections of thickness measurements of ship hull structure members are assumed to be independent of the choice of type of this member. In view of this fact and the above mentioned fact that the corrosion rate would be different from each ship hull structure member, it can be of interest to consider the same problem concerning only any fixed ship hull structure element. As noticed above, for these purposes, a set of 570 measurements of plate thickness due to corrosion, for inner bottom plates of considered 38 ships surveys is considered here.

Assuming that in view of the above assumptions and considerations, the fitted linear model for $d(t)$ of the form $d(t) = c_1(t-4)$ is statistically well-accepted, in order to examine the cumulative distribution function (in the sequel briefly written as CDF) of (a continuous random variable) c_1, it is needed to calculate the previously mentioned 570 statistical data for c_1 needs to be calculated by using the expression

$$c_1 = \frac{d(t)}{t-4}.$$ (7)

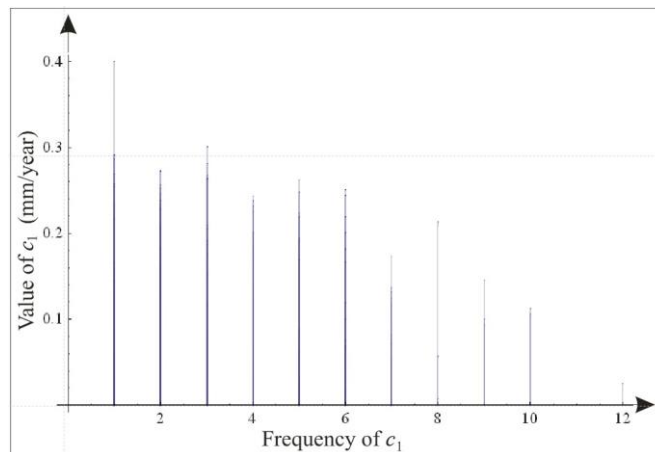By sorting the obtained data, they can be presented in Figure 7.

Fig. 7 The sorted values $c_1 = d(t)/(t-4)$ with related frequencies
related to the set of 570 measurements of plate thickness due to corrosion

Under these sorted data, mean of c_1 is equal to 0.12914 mm/year and its standard deviation is equal to 0.07685895 mm/year.

Now, relative frequencies (empirical PDF) related to the sorted data that correspond to Figure 7 in the intervals with step 0.02, i.e., the intervals of the form $[a, a + 0.02)$ with $a = 0.02$, 0.04,...,0.38 can be calculated, where the middles of related intervals are assumed for the first coordinate. Related histograms are shown in Figure 8.
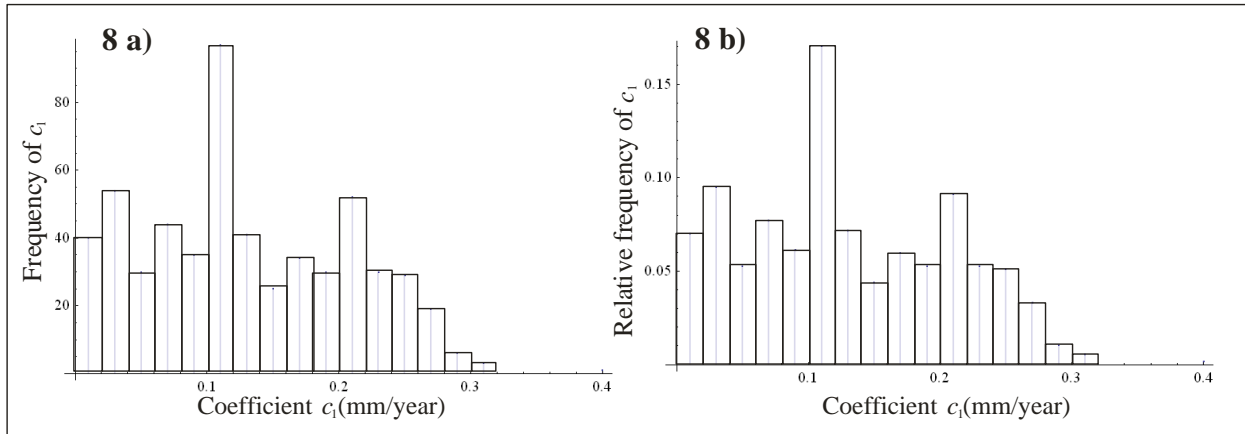

Fig. 8 Frequencies and relative frequencies of c_1 ($c_1 = d(t)/(t-4)$) related to

the set of 570 measurements data of plate thickness due to corrosion

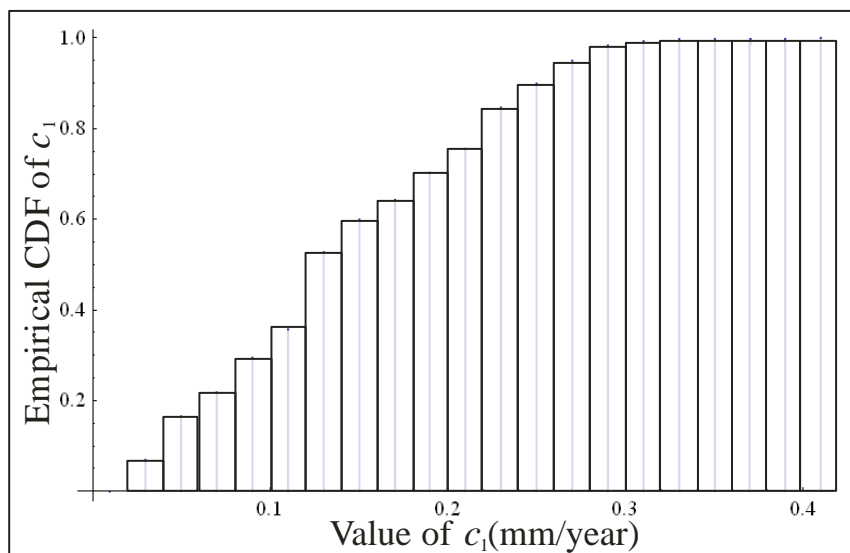The empirical CDF for the values $c_1 = d(t)/(t-4)$ given in Figure 8 b) is presented in Figure 9.

Fig. 9 The empirical CDF of the coefficient c_1 related to

the set of 570 measurements data of plate thickness due to corrosion

Now, by using the data presented in Figure 9, the corresponding fitted linear model for CDF of (random variable) c_1 is obtained. Related obtained computational results show that Weibull distributtion does not correspond to the estimation of CDF of c_1, while testing CDF of many other continuous random variables it is indicated that one or some of the following

four distributions should be served as a best fitted distribution for c_1: normal distribution, logistic distribution, beta distribution and gamma distribution (for a visual comparison of empirical data from Figure 9 and CDF of these four potential well fitted distributions, see Figures 10 a)-10 d)).
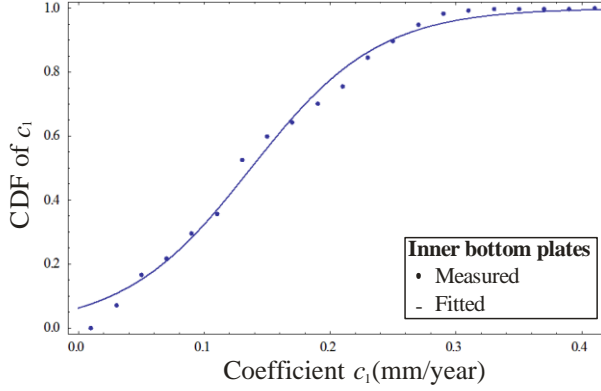

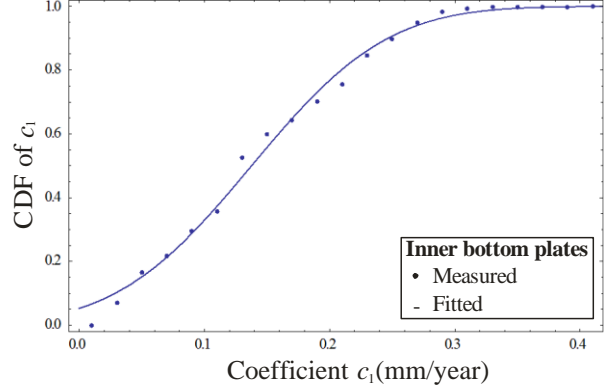**Fig. 10 a)** Fitted CDF of logistic distribution to data in Figure 9

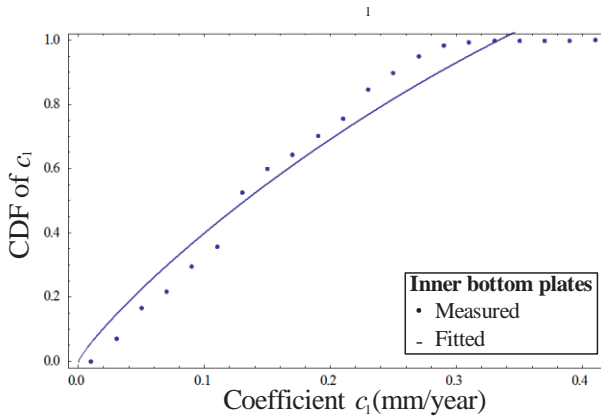**Fig. 10 b)** Fitted CDF of normal distribution to data in Figure 9

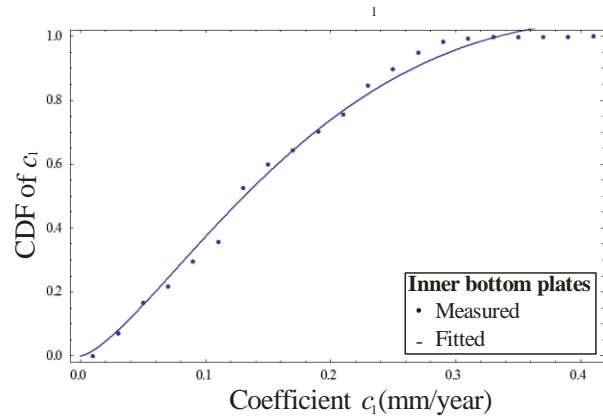**Fig. 10 c)** Fitted CDF of beta distribution to data in Figure 9

Fig. 10 d) Fitted CDF of gamma distribution to data in Figure 9

The expressions for fitted cumulative distribution function and the probability density function of logistic distribution of c_1 from Eq. (1), whose CDF is presented in Figure 10 a), are respectively given by

$$F_{c_1}^{(l)}(x) = \frac{1}{1+\exp(-(-0.137133+x)/0.050494)} = \frac{1}{1+\exp(2.715828-19.804333x)} \quad (8)$$

and

$$f_{c_1}(x) = \frac{d}{dx}F_{c_1}(x) = \frac{19.804333\exp(2.715828-19.804333x)}{(1+\exp(2.715828-19.804333x))^2}. \quad (9)$$

Then the corresponding mean and standard deviation of the coefficient c_1 are respectively equal to $\mu_{c_1}^{(l)} = 0.137133$ mm/year and $\sigma_{c_1}^{(l)} = 0.091587$ mm/year. Notice that the previous value $\mu_{c_1}^{(l)} = 0.137133$ is very close to the corrosion rate $r(t) = 0.135474$ arising from the linear fitted model for $d(t)$ given by Eq. (2).

Furthermore, the expressions for fitted cumulative distribution function and the probability density function of normal distribution of c_1 from Eq. (1), whose CDF is presented in Figure 10 b), are respectively given by

$$F_{c_1}^{(n)}(x) = 4.689687 \int_{-\infty}^{x} \exp(-69.093558(t - 0.137615)^2)\,dt \qquad (10)$$

and

$$f_{c_1}(x) = 4.689687 \exp(-69.093558(x - 0.137615)^2). \qquad (11)$$

Then the corresponding mean and standard deviation of the coefficient c_1 are given respectively as $\mu_{c_1}^{(n)} = 0.137165$ mm/year and $\sigma_{c_1}^{(n)} = 0.085068$ mm/year. As previously noted, it can be observed that the value $\mu_{c_1}^{(n)} = 0.137165$ is very close to the corrosion rate $r(t) = 0.135474$ arising from the linear fitted model for $d(t)$ given by Eq. (2).

Some empirical values and fitted values of cumulative distribution functions of logistic and normal distribution of c_1 which are defined by Eq. (8) and Eq. (10), respectively, are given in Table 2.

Table 2 The empirical values and fitted values of CDF for c_1

x	Empirical CDF of c_1	$F_{c_1}^{(l)}(x)$	$F_{c_1}^{(n)}(x)$	x	Empirical CDF of c_1	$F_{c_1}^{(l)}(x)$	$F_{c_1}^{(n)}(x)$
0.01	0.000000	0.074622	0.066784	0.23	0.845614	0.862849	0.861269
0.03	0.070175	0.107007	0.102923	0.25	0.898246	0.903370	0.906774
0.05	0.164912	0.151151	0.151515	0.27	0.949123	0.932850	0.940177
0.07	0.217544	0.209240	0.213351	0.29	0.982456	0.953797	0.963383
0.09	0.294737	0.282229	0.287829	0.31	0.992982	0.968431	0.978642
0.11	0.356140	0.368805	0.372732	0.33	0.998246	0.978534	0.988139
0.13	0.526316	0.464743	0.464336	0.35	0.998246	0.985452	0.993732
0.15	0.598246	0.563363	0.557879	0.37	0.998246	0.990163	0.996851
0.17	0.642105	0.657214	0.648289	0.39	0.998246	0.993359	0.998496
0.19	0.701754	0.740196	0.730992	0.41	1.000000	0.995521	0.999318
0.21	0.754386	0.808930	0.802595	0.43	1.000000	0.996982	0.999706

3.3 Another statistical approach to the examination of best fitted distribution of corrosion rate c_1

In Subsection 3.2, under a set of 570 measurements of plate thickness due to corrosion, $d(t)$ (depth of corrosion at age t, in mm), for inner bottom plates of 38 ship's surveys, it can be established that one of the following random continuous distributions: normal distribution, logistic distribution, beta distribution or gamma distribution, should be a good candidate for best fitted distribution for the constant c_1 involving in the fitted linear model for $d(t)$ expressed as:

$$d(t) = c_1(t - 4). \qquad (12)$$

By using this, and the obtained expressions for CDF and probality density function (in the sequel, briefly denoted as PDF) of the previously mentioned four distributions, the possible goodness of these fitted distributions in terms of their PDF is examined here. By applying

Anderson-Darling test to the sorted values of $c_1 = d(t)/(t-4)$ with frequencies presented in Figure 7 (related to a set of 570 measurements data of plate thickness due to corrosion), the positive p - values of this test is obtained only in the following two cases:

   a) the case of logistic distribution with mean 0.137133 and scale parameter 0.050494.

   Notice that the above logistic distribution coincides with those obtained in Subsection, 3.2 whose CDF is given by the expression (8).

   Graphics of PDF of this logistic distribution together with related empirical PDF is presented in Figure 11.

   b) the case of normal distribution with mean 0.137615 and standard deviation 0.085070.

   Notice that the above normal distribution coincides with those obtained in Subsection 3.2 whose CDF is given by the expression (10).
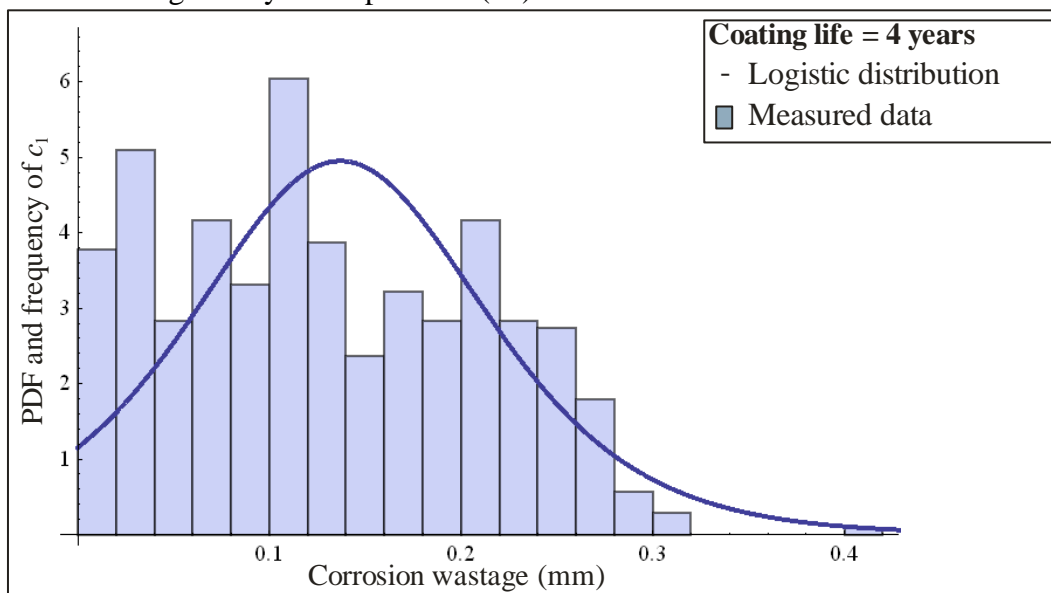

Fig. 11. Empirical PDF and graphic of PDF of fitted logistic distribution

   Hence, the logistic distribution or normal distribution would be well appropriate for the probabilistic corrosion rate estimation model for inner bottom plates of bulk carriers.

4. Conclusion

   The analytical and probabilistic corrosion rate estimation models for different hull structure elements of bulk carriers have been extensively investigated by many authors during the last two decades. Motivated by these investigations, this paper studies the probabilistic corrosion rate estimation model related only to inner bottom plates of bulk carriers. More precisely, by using the set of data consisting of 570 measurements of corrosion wastage for inner bottom plates of 38 ships surveys, this paper examines the cumulative density function for the constant (considered as a continuous random variable) c_1 from the obtained fitted linear model for corrosion wastage given by the expression $d(t) = c_1(t-4)$. In other words, the distribution of corrosion rate concerning inner bottom plates of the each of 38 ships surveys is approximated. The statistical, graphical and numerical results obtained in software Mathematica 9 show that the logistic distribution or normal distribution should be very appropriate for probabilistic corrosion rate estimation model related to inner bottom plates of bulk carriers. Namely, in Section 3, by applying Anderson-Darling test, it is showed that

under collection of mentioned set of 570 measurements data, the good candidates for the cumulative density function of c_1 between numerous continuous random variables are only the logistic and normal distribution. Accordingly, it is believed that under a larger set of mentioned measurements, this hypothesis will be confirmed in some future investigations with a good confidence level.

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