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THE WEIBULL TIME-DEPENDENT GROWTH MODEL OF MARINE CORROSION IN SEAWATER BALLAST TANK

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Abstract: This paper demonstrates the application of the probability distributions in modelling the time-dependent growth behaviour of corrosion pits in vessel's seawater ballast tanks. The proposed model is capable of projecting the likely growth pattern of corrosion pits in the future by eliminating the dependent factors governing to corrosion rate such as environmental factors, properties of material and operational condition. To express appropriately the high variability of corrosion wastage which contributes to the uncertainties in corrosion assessment, the Weibull probability distributions were proposed which are able to predict the growth of corrosion pit in seawater ballast tank. It is obvious that the provided information from the vessel inspections is full of uncertainties, owing to the nature of marine corrosion as reflected by the poor correlation result of averaged depth against time. In spite of the drawback, the research is able to demonstrate the optimisation of the data purposely for corrosion growth prediction. The predicted data as compared to actual data yields results with moderate accuracy based on Root-Mean-Square-Error (RMSE), yet still promising provided that better quality data can become available in the future. The proposed probabilistic models are intended to simplify the modelling process so that the available data can be fully utilised for prediction and structural evaluation purposes.

Keywords: *Corrosion; Weibull probability; Ballast Tank*

Abstrak: Kertas kerja ini menunjukkan bagaimana aplikasi taburan kebarangkalian dalam pemodelan sifat pertumbuhan lubang pengaratan sebagai fungsi masa bagi struktur tangki *ballast* kapal laut. Model yang dicadangkan berkeupayaan meramal corak pertumbuhan yang sebenar di masa hadapan tanpa mengambil kira faktor kebergantungan yang pada kebiasaannya mempengaruhi kadar pertumbuhan karat seperti faktor persekitaran, sifat bahan binaan dan juga faktor operasi. Untuk menggambarkan secara tepat serakan dimensi pengaratan yang tinggi yang sering menyebabkan ketidakpastian dalam penilaian pengaratan, taburan kebarangkalian Weibull telah dicadangkan supaya ramalan kedalaman pengaratan di dalam tangki *ballast* kapal laut di masa hadapan dapat dijalankan. Kajian jelas menunjukkan data pengaratan yang digunakan dipengaruhi oleh ketidakpastian disebabkan oleh faktor pengaratan marin itu sendiri seperti yang ditunjukkan oleh keputusan korelasi yang lemah di antara purata kedalaman lubang karat dan umur kapal. Di sebalik masalah yang dinyatakan, kajian ini masih mampu menunjukkan bagaimana penggunaan data pengaratan dapat dioptimakan bagi tujuan penilaian keutuhan struktur. Keputusan perbandingan di antara data sebenar dan data ramalan telah menunjukkan keputusan dengan ketepatan yang sederhana berdasarkan nilai ralat yang dikira menggunakan kaedah *Root-Mean-Square-Error* (RMSE) tetapi berpotensi jika lebih banyak data berkualiti dapat diperolehi. Model yang dicadangkan bertujuan untuk memudahkan proses pemodelan agar data yang diperolehi dapat digunakan sepenuhnya bagi tujuan ramalan dan penilaian keutuhan struktur.

Kata kunci *: Karat; Weibull; Tangki Ballast; Kebarangkalian*

1.0 Introduction

Problems arising from corrosion are considered to be among the most important age related factors affecting structural degradation of ships in complex seawater environments. Seawater properties such as oxygen content, seawater salinity, temperature, acidity (pH) level, and chemistry can vary according to site location as well as water depth, hence, making it difficult to predict the corrosion progress. Statistics for ship hulls show that 90% of ship failures are attributed to corrosion [Melchers, 1999]. Localised corrosion especially pitting, is among the major types of physical defects found largely on ship structures. Among the areas of a ship that most exposed to corrosion are wing ballast tanks. Such problem occurred mainly due to prolonged exposure to seawater, humidity differences and salty environment during empty condition.

The damage of steel structures in ships due to corrosion can be influenced by many factors such corrosion protection system (coating and inhibitor) and various operational parameters. The operational parameters include maintenance, repair, percentage of time in ballast, frequency of tank cleaning, temperature profiles, use of heating coils, humidity condition, water and sludge accumulation, microbial contamination, composition of inert gas, etc. To date, in the case of ship structures, rigorous work to understand the effect of many of these factors and their interactions is lacking (Paik and Thayambali, 2002). There are also very limited research efforts in this particular subject and the availability of corrosion measurement data for corrosion rates in tankers (Wang *et al*., 2003). As such, the discussions on the issue of corrosion wastage still remain largely qualitative rather than quantitative (Wang *et al*., 2003).

The objectives of this paper are as follows;

a) To propose an alternative approach in corrosion data assessment for marine structures especially ship ballast tank.

b) To minimise the probabilistic uncertainties related to inspection data in the assessment processes.

c) To improve the quality of prediction results, hence would provide a more proper inspection and maintenance scheduling in the future at optimal cost.

2.0 Previous Studies in Relation to the Present Approach

The corrosion data collected by previous researchers were extensively used in the present study. On similar study, Paik and Thayambali (2002), Paik (2004) and Paik *et al*. (2004) have carried out an extensive corrosion data collection from seawater ballast tanks to model the deterministic time-dependent corrosion wastage model. Thousand of measured data of the corrosion loss in structural members of seawater ballast tanks for ocean-going oil tankers and bulk carriers were available. According to Paik and Thayambali (2002), Paik (2004) and Paik *et al*. (2004), data for renewed structural members were excluded. A total of 1507 measurement points for seawater ballast tanks from the side and bottom shell plates were obtained and available for the study. The number of vessels involved in the data collection is remained unknown but covering vessel age from 11 years to 30 years old. Corrosion loss was measured mostly by the technique of ultrasonic thickness measurements. Such technique 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 was then determined to be the depth

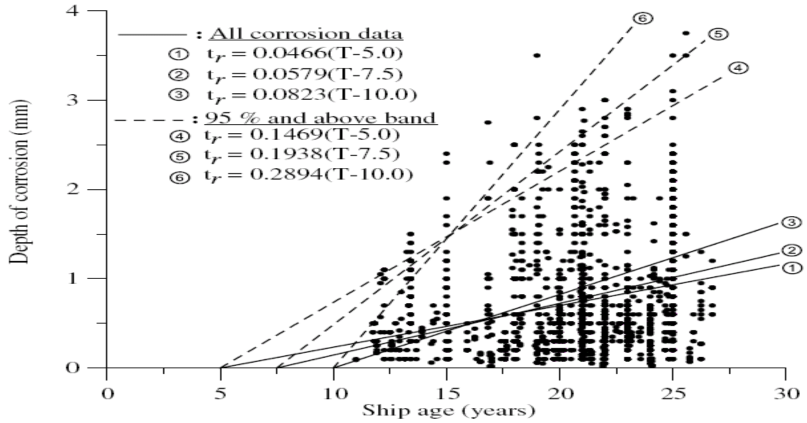

Figure 1: Comparison of annualized corrosion rate formulations, together with the measured corrosion data for seawater ballast tanks (Paik and Thayambali, 2001)

Table 1: Gathered number of measured data set of thickness loss due to corrosion in seawater ballast tanks of bulk carriers (Paik and Thayambali, 2001)

Time (year)-middle class	**Depth of corrosion, mm (middle class)**							
	0.25	**0.75**	**1.25**	**1.75**	**2.25**	**2.75**	**3.25**	**3.75**
11.25	2	0	0	0	0	0	0	0
11.75	18	5	0	0	0	0	0	0
12.25	6	3	9	0	0	0	0	0
12.75	23	2	0	0	0	0	0	0
13.25	16	26	30	2	0	0	0	0
13.75	9	0	0	0	0	0	0	0
14.25	3	3	0	0	0	0	0	0
14.75	1	2	0	0	0	0	0	0
15.25	22	13	10	3	2	0	0	0
15.75	9	1	0	0	0	0	0	0
16.25	5	0	0	0	0	0	0	0
16.75	12	8	5	2	1	1	0	0
17.25	19	1	0	0	0	0	0	0
17.75	84	1	2	4	0	0	0	0
18.25	34	26	37	9	4	3	0	0
18.75	1	0	2	0	0	0	0	0
19.25	52	10	5	8	6	1	0	1
19.75	84	9	1	0	2	0	0	0
20.25	165	29	9	1	0	0	0	0
20.75	10	14	11	10	16	2	0	0
21.25	69	42	11	7	2	4	0	0
21.75	9	1	1	2	2	0	0	0
22.25	3	5	0	0	0	0	0	0
22.75	8	18	1	3	0	0	0	0
23.25	31	13	4	1	0	0	0	0
23.75	8	3	1	0	0	0	0	0
24.25	7	11	7	2	0	0	0	0
24.75	18	15	2	0	0	0	0	0
25.25	30	49	48	57	40	2	2	1
25.75	10	1	1	2	0	0	0	2
26.25	8	8	1	0	0	0	0	0
26.75	0	7	1	0	0	0	0	0

of corrosion. Table 1 tabulates collected data of corrosion loss as a function of vessel age. The scatterdness of the data can be visualised in Figure 1. Prior to the analysis, the authors also postulated that the statistical frequency distribution of corrosion depth at a younger age tends to follow the normal distribution, while it follows a lognormal or exponential distribution for corrosion from an older stage.

3.0 Probabilistic Corrosion Model

The inspection and corrosion measurement activities were carried out once and randomly on different vessels using ultrasonic tools. The data was then grouped according to the age of vessel and defect depth. Since no information regarding the corrosion initiation time owing to coating resistance, the only way to estimate corrosion rate is by using the ‘defect-free’ method with the addition of assumed corrosion initiation time (Noor, 2007). The proposed deterministic model is assumed valid for all vessels even though, in reality, each vessel involved in the sample has different factors that affect the corrosion progress. Based on this assumption, an enhancement of the deterministic model as proposed by Paik and Thayambali (2002), Paik (2004) and Paik *et al*. [2004] has been developed to incorporate the variation of the corrosion data.

The works by Paik and Thayambali (2002), Paik (2004) and Paik *et al*. (2004) have been revised with the introduction of a statistical model for a time-dependent corrosion process based on the same corrosion data. In this section, two statistical models are proposed with the intention of minimising the effects of uncertainties caused by the scattered corrosion data. The works cited in the literature did not consider the effect that possible uncertainties and errors related to imperfect measurement by inspection tools and the complex seawater environment might have on estimation of growth.

3.1 Deterministic Time-dependent model

An average value and standard deviation of corrosion depth is estimated individually for each set of vessel age. The graphs of average and standard deviation value are plotted against vessel age to establish a relationship between the progress of averaged metal loss and the vessel age. The interception of regression line at t=0 indicating zero corrosion initiation time was not considered, hence resulting a non-zero value of averaged corrosion depth in the beginning of vessel operation. The regression line might approach zero interception with addition of new data, especially from vessel age under 11 years. From Figures 2 and 3, although the averaged metal loss is scattered over the time but the increment of the averaged depth and standard deviation as the vessels aging is evident. The linear increment can be expressed as a function of time using the regression equations as follows:

$$d_{ave} = 0.0251\,.t_v + 0.1511 \tag{1}$$

$$d_{std} = 0.0232\,.t_v - 0.037 \tag{2}$$

where:

d_{ave} = linear regression model of defect depth average
d_{ave} = linear regression model of defect depth standard deviation
t_v = age of vessel (year)

The linear regression equation is likely to contain some errors owing to the large scatter in the averaged corrosion depth for each class of vessel age. To minimise the errors, this deterministic equation will be combined with a probability distribution of corrosion depth representing all of the data.

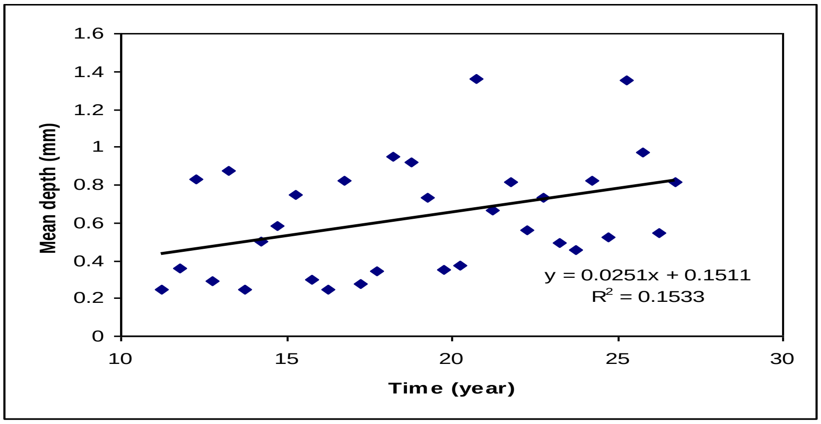

Figure 2: Linear regression analysis of mean value of defect depth and vessel age

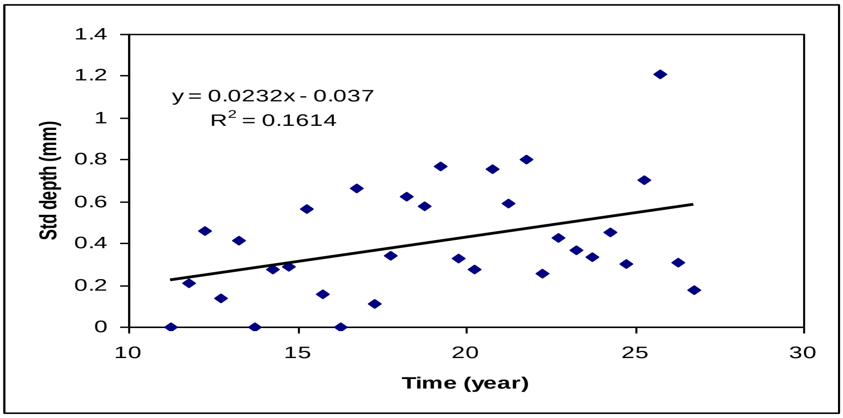

Figure 3: Linear regression analysis of *standard deviation* of defect depth and vessel age

3.2 The Weibull Model

The next step is to construct a distribution for all the data by removing the effects of time. This distribution of the entire data was found to be best reproduced by the Weibull distribution based on linear fitting of the probability plot and verified by the Chi-square goodness-of-fit test. Figures 4 and 5 show the histogram and the Weibull probability plot of all the data respectively. The Weibull distribution function for all of the data can be expressed as follows:

$$f_{x_d}(x_d) = \frac{1.1(x_d)^{0.1}}{1.27^{1.1}} \exp\left[-\left(\frac{x_d}{1.27}\right)^{1.1}\right] \qquad (3)$$

where:

x_d = corrosion depth

Unlike other simpler distributions such as the Exponential distribution, no direct expression of corrosion depth average can be found in Equation 3, hence the inclusion of linear regression model as shown by Equation 1 is not feasible. The only solution is to modify the presentation of the data. The first step towards this enhancement is to normalise the corrosion depth data based on the predicted averaged corrosion depth for each class of vessel age; this can be estimated using Equation 4.

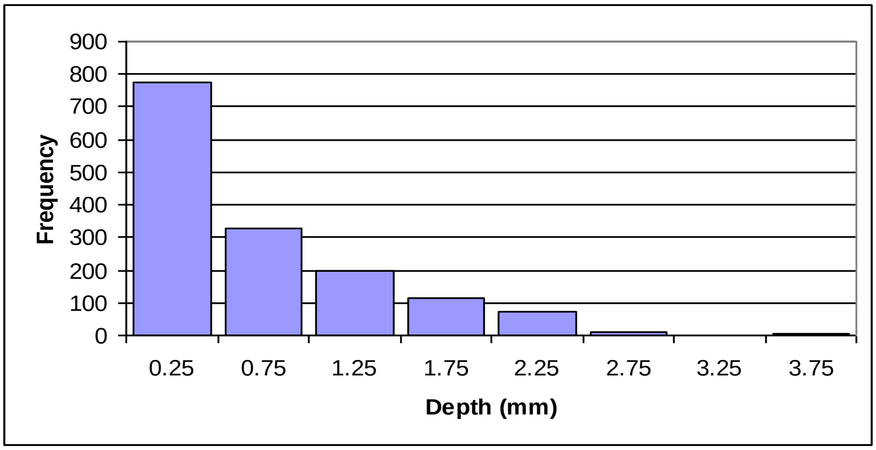

Figure 4: Histogram of the whole set of corrosion depth

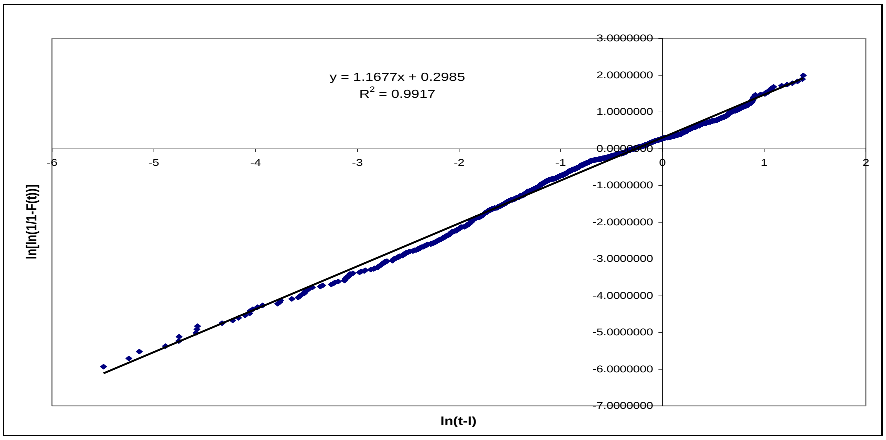

Figure 5: Weibull probability plot of measured data (actual)

The new corrosion depth can be expressed as:

$$x_{norm} = \frac{x_d}{d_{ave}(t_v)} \tag{4}$$

where:

x_{norm} = normalised depth

The effect of this normalising procedure has changed the value and variation of corrosion depth since the averaged depth is different for each class of vessel age. Each single histogram of corrosion depth grouped by the vessel age now has a different size of class/bin. All of the data with the new class of depth value must to be rescaled and regrouped so that a new histogram of the whole data can be constructed. The same procedure as that applied in Section 3.1 is repeated. An average value and standard deviation of corrosion depth are estimated individually for each class of vessel age. The graphs of average and standard deviation value have been plotted against vessel age to develop a relationship between the progress of normalised average of metal loss and time (vessel age). From Figure 6, it may be deduced that the averaged metal loss is still scattered over the time. However, there is an indication of the increment of averaged depth. The linear equation for the normalised average of corrosion depth over time is expressed as:

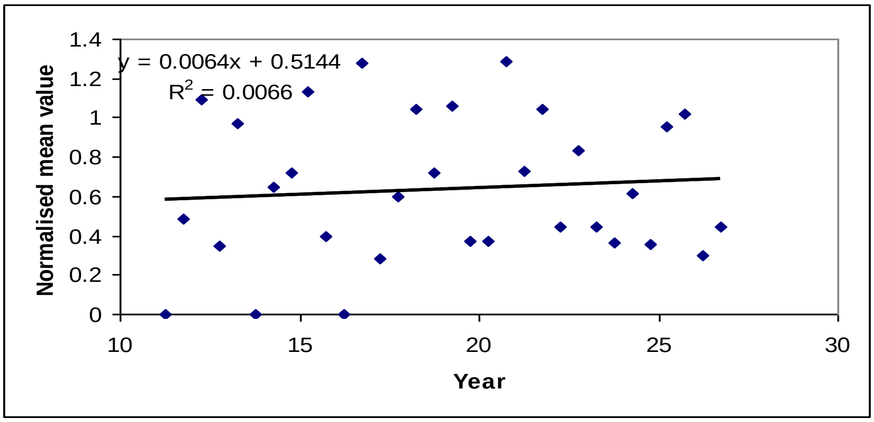

Figure 6: Linear regression analysis of mean depth and vessel age (rescaled data)

$$d_{ave} = 0.0064\,.t_v + 0.5144 \tag{5}$$

The new Weibull distribution function can be written as follows:

$$f_x(x_d) = \frac{1.05\,(x_{norm})^{0.05}}{0.87^{1.05}}\exp\left[-\left(\frac{x_{norm}}{0.87}\right)^{1.05}\right] \tag{6}$$

By inserting Equation 4 into Equation 6, the function can now be expressed as:

$$f_x(x_{norm}) = \frac{1.05\left(\dfrac{x_d}{d_{ave}(t_v)}\right)^{0.05}}{0.87^{1.05}}\exp\left[-\left(\frac{x_d}{0.87.d_{ave}(t_v)}\right)^{1.05}\right] \tag{7}$$

and the time effect is added by inserting Equation 5 into Equation 8.

$$f_x(x_{norm}) = \frac{1.05\left(\dfrac{x_d}{0.0064\,.t + 0.5144}\right)^{0.05}}{0.87^{1.05}}\exp\left[-\left(\frac{x_d}{0.0056\,.t + 0.4475}\right)^{1.05}\right] \tag{8}$$

The cumulative function then can be written as follows:

$$F(x_{norm}) = 1 - \exp\left[-\left(\frac{x_d}{0.0056.t_v + 0.4475}\right)^{1.05}\right] \tag{9}$$

The Weibull function of normalised depth can now be used to predict the distribution of corrosion depth at any points of time. The location parameter, δ the Weibull distributions of corrosion depth was assumed as zero for any prediction time. This implies the smallest measurement of corrosion depth at any time will be zero. The Weibull distribution model is having a constant shape factor, β over time whereas the scale parameter θ increases proportionally to the averaged normalised depth. This can be proven mathematically as follows.

The Weibull probability density function (PDF) of normalised data is presented as follows;

$$f_x(x_{norm}) = \frac{\beta\left(\frac{x_d}{d_{ave}(t_v)}\right)^{\beta-1}}{\theta^{\beta}} \exp\left[-\left(\frac{\left(\frac{x_d}{d_{ave}(t_v)}\right)}{\theta}\right)^{\beta}\right] \tag{10}$$

Equation 10 is rearranged to exclude the expression of linear regression model from the random value of corrosion depth, x_d.

$$f_x(x_{norm}) = \frac{\beta(x_d)^{\beta-1}}{(d_{ave}(t_v))^{\beta-1}.\theta^{\beta}} \exp\left[-\left(\frac{(x_d)}{d_{ave}(t_v).\theta}\right)^{\beta}\right] \tag{11}$$

and

$$f_x(x_{norm}) = \frac{\beta(x_d)^{\beta-1}}{\left(\frac{[d_{ave}(t_v)]^{\beta}}{[d_{ave}(t_v)]}\right).\theta^{\beta}} \exp\left[-\left(\frac{(x_d)}{d_{ave}(t_v).\theta}\right)^{\beta}\right] \tag{12}$$

Therefore, the final expression of Weibull function can be written as;

$$f_x(x_{norm}) = \frac{d_{ave}(t_v)\,\beta\,(x_d)^{\beta-1}}{(d_{ave}(t_v)\cdot\theta)^{\beta}} \exp\left[-\left(\frac{(x_d)}{d_{ave}(t_v)\cdot\theta}\right)^{\beta}\right] \quad (13)$$

The new scale parameter, θ_{new} can be expressed as;

$$\theta_{new} = d_{ave}(t_v)\cdot\theta \quad (14)$$

Equation 13 can now be written in a simpler form as follows;

$$f_x(x_{norm}) = \frac{d_{ave}(t_v)\,\beta\,(x_d)^{\beta-1}}{(\theta_{new})^{\beta}} \exp\left[-\left(\frac{(x_d)}{\theta_{new}}\right)^{\beta}\right] \quad (15)$$

Equation 15 shows that the new scale parameter, θ_{new} is proportional to the averaged depth which was derived from the linear regression model. The older the vessel, the deeper the averaged depth hence the larger the new scale parameter. The scale parameter then defines the mean and variance of the Weibull distribution. As a conclusion, when corrosion progresses, the increment of averaged depth will affect the scale parameter hence changes the mean and variation of the Weibull distribution. However, the distribution shape defined by the shape parameter, β still remained the same, unaffected by the time of prediction. The change of the distribution variation is due to the inclusion of new defects growth every time corrosion prediction is made (see Figure 7).

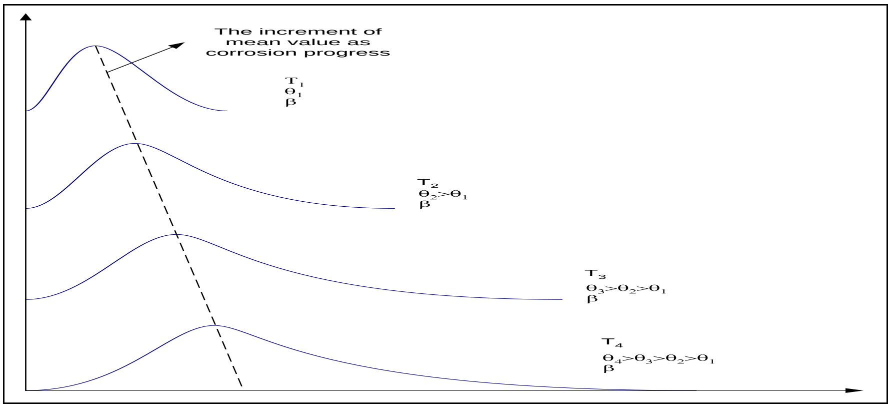

Figure 7: The increment of the Weibull scale parameter as corrosion progress for normalised data.

3.3 Results of the Prediction

Four sets of corrosion data were generated using numerical simulation and inverse transformation method for comparison purposes. The Weibull function model was used to produce histogram of corrosion data for vessel age of 18-18.5 years, 19.5-20 years, 20-20.5 years, and 21-21.5 years old (see Table 1). These age classes were chosen due to the high number of data collected during on site inspection. The generated data was then compared with the measured data in the same class of vessel age. Based on the comparison of histogram shown in Figures 8 to 11, the prediction results yield error values between ± 5.9 to ± 17.8 as estimated using Root-mean-square-error method (RMSE).

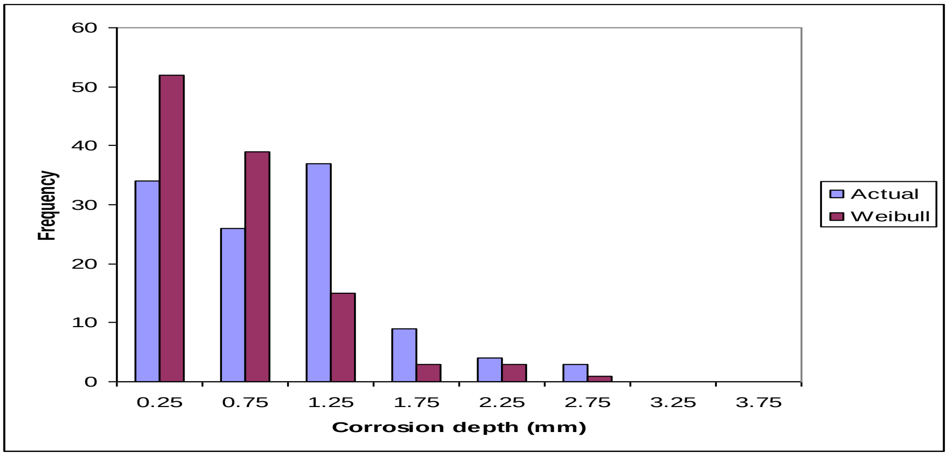

Figure 8: Comparison of predicted depth data to actual data for vessel age of 18-18.5 years old (RMSE of ±11.3)

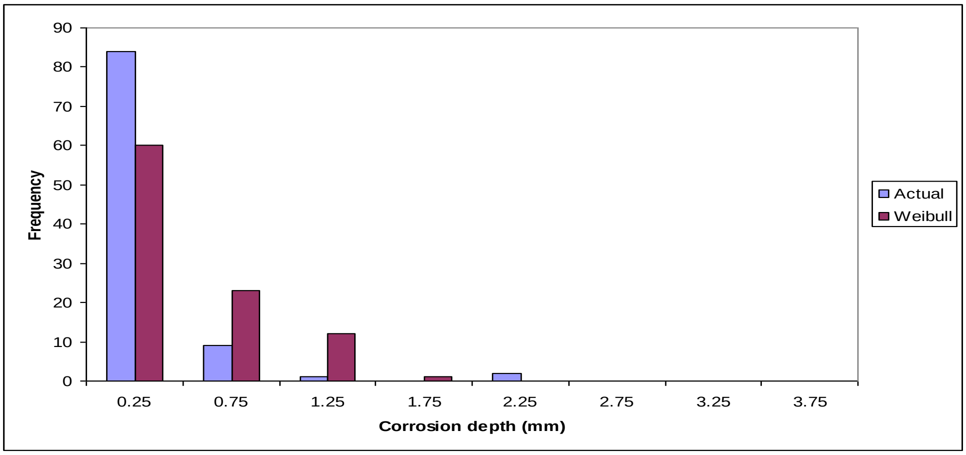

Figure 9: Comparison of predicted depth data to actual data for vessel age of 19.5-20 years old (RMSE of ±10.6)

The values of error can be reduced theoretically if data from next inspection can be included in the database, hence improving the reliability of the proposed model.

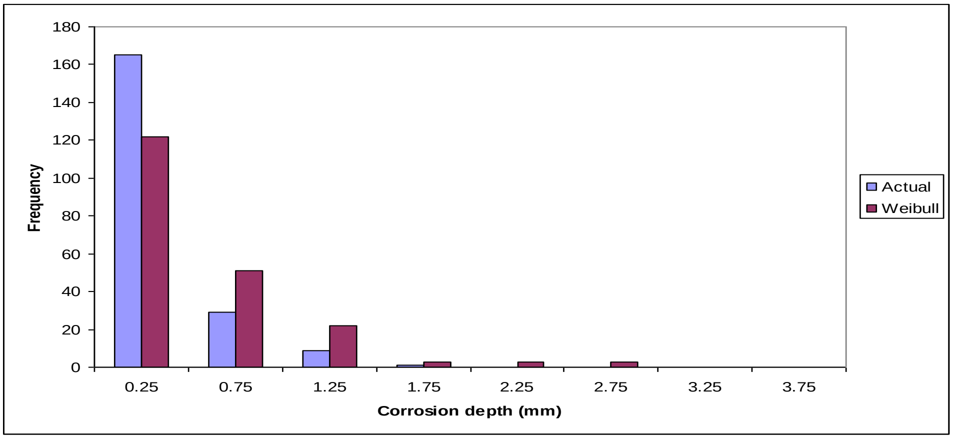

Figure 10: Comparison of predicted depth data to actual data for vessel age of 20-20.5 years old (RMSE of ±17.8)

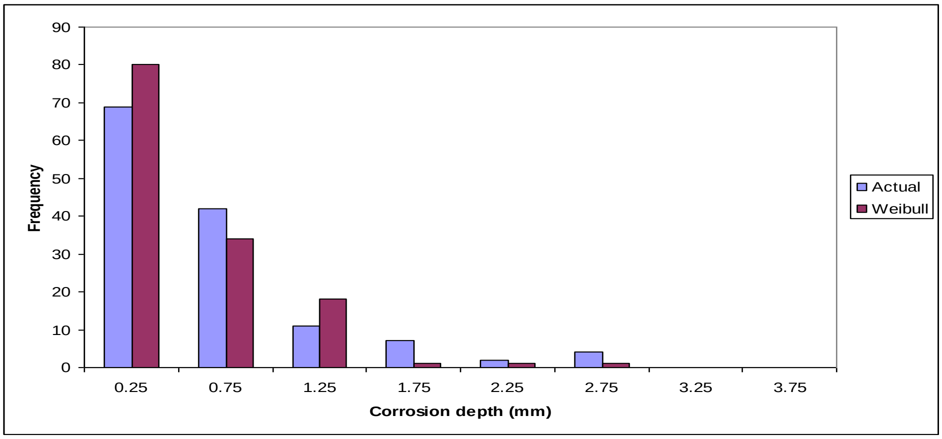

Figure 11: Comparison of predicted depth data to actual data for vessel age of 21-21.5 years old (RMSE of ±5.9)

4.0 Concluding Remarks

A probabilistic time-dependent growth model of marine corrosion has been developed as an alternative approach to analysing corrosion data randomly collected from a large number of like assets (in this case vessel's ballast tanks). Rather than making an assumption on the time to the start of the corrosion process and then develop a linear model of corrosion rate, two corrosion depth models which are a function of time have been proposed. The new model can be used to predict the likely variation of corrosion depth at any point of time without having to estimate the corrosion growth rate for each single defect. Even though the value of correlation coefficient were not more than 0.16 indicating poor correlation between averaged depth and vessel age, the incorporation of probability model into the analysis methodology can improve the reliability of the prediction results as well as minimising the errors. Furthermore, the linear regression can be improved once more data from further inspections are available, indicating the flexibility of the model. The provided information from the vessel inspections is full of uncertainties owing to the nature of marine corrosion. The proposed model simplified the modelling process so the available data can be fully utilised for prediction purposes. If more information can be revealed, the prediction model could be improved to achieve a high accuracy of depth prediction at any point of time.

5.0 Acknowledgement

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