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CORROSION MARGINS FOR REDUNDANT SHIP STRUCTURES

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ABSTRACT

The work presented here analyses the structural corrosion degradation of two sets of corrosion depth measurements collected with a one-decade difference. The corrosion degradation process is associated to a first order system, subjected to a sudden disturbance, where a step function is used as an input to define the solution of the differential equation of this system leads to the exponential corrosion degradation model as developed earlier. Corrosion margins of redundant ship structures with serious consequences of failure are derived and several conclusions related to the new trend in the ageing structures are presented and discussed. Partial safety factors with respect to the corrosion environment and corrosion margins are developed that can be used in the design, avoiding a complex probabilistic analysis.

1. INTRODUCTION

Corrosion degradation is one of the most spread causes of structural degradation of metal ageing structures and in the recent decades, many research works were dedicated to this issue.

Factors influencing the corrosion wastage of metal structures in different levels of severity of corrosion degradation were reported in [1, 2] for morphology in [3], stress concentrations and the crack growth in [4-6], plate surface conditions and material properties in [7-9], maintenance in [10] and reliability assessment in [11-13].

A very important study of factors governing marine corrosion environment on the identification of the governing corrosion factors and those rated for corrosion fatigue of ballast and cargo oil tanks was reported in [14-19].

Depending on the location of the ship structural components in the ship hull structure, the corrosion severity is different, and many real measurements of corrosion depths may be found in [20-40].

Recently, a study to analyze and identify the most appropriate corrosion degradation model, fitted with real corrosion depth measurement data sets and to generate a corroded steel plate surface using advanced statistical methods as presented in [8]. The employed approach identified that the exponential approach is the best-fitted model to real corrosion depth measurement data sets in most of the corrosion environmental conditions.

The work presented here analyses the structural corrosion degradation of two sets of corrosion depth measurements collected with a one-decade difference. Corrosion margins for redundant structures with serious consequences of failure are derived and several conclusions related to the new trend in the ageing structures are presented and discussed. In addition to that partial safety factors with respect to the corrosion environment and corrosion

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margins are developed that can be used in the design, avoiding a complex probabilistic analysis.

2. TIME-DEPENDENT DEGRADATION

The time-dependent structural degradation is an important issue that needs to be accounted for when the metal structures are designed. The time-dependent structural degradation is one of the most important failure modes and its' behavior needs to be identified with respect to how quickly a structure will degrade when the degradation will reach the acceptable level and to predict the end of the degradation process.

The structural degradation may also be considered as a dynamic system described by a transfer function with known input and output signals.

If the input is assumed to be a step, ramp impulse or sinusoidal functions, an analysis of the system can be performed. If the input is a gradually changing function of time, then a ramp function of time may be a good option to define the input. If the system is subjected to a sudden disturbance, a step function is a good candidate and, in the case, when the system is subjected to a shock input, an impulse function may be used as suggested in [41].

In the analysis here, the structural corrosion degradation process is assumed to be of the first order system, subjected to a sudden disturbance, where a step function is used to define the input signal and the objective is to predict its response.

The first order system as a degradation process is given as [42]:

$$\tau_t \frac{\partial d(t)}{\partial t} + d(t) = d_\infty' d_i \qquad (1)$$

where d(t) is the corrosion depth, the response of the degradation system, d_i is the input to the system, τ_t is the system time constant and d_∞' is the gain of the system. Using these parameters, different aspects of the response (corrosion depth) as a function of the input signal, d_i can be defined. The time constant, τ_t defines how the system is moving to the steady state, d_∞' determines the value of the steady state in the case when the input arrives at a constant value.

When the step input is employed, the gradient of the output changes instantly. Applying the Laplace transform [43] to Eqn (1) the transfer function, which is the output of the input is determined as:

$$\frac{d(s)}{d_i(s)} = \frac{d_\infty'}{[\tau s + 1]} \qquad (2)$$

Converting the first order differential equation to a frequency domain a step input is applied to determine the output.

The Laplace transform of this function is 1/s and if the step input is different from the unity, the Laplace transform is a/s. The input $d_i(s)$ is replaced in the Laplace transform equation with a/s, describing the output, d(s) in the s-domain:

$$d(s) = d_\infty' a \frac{1/\tau_t}{s(s + 1/\tau_t)} \qquad (3)$$

The inverse of this equation gives the output response in the time-domain for a step change of the input of a magnitude leading to $d_\infty = a\, d_\infty'$:

$$L^{-1}\left[\frac{1/\tau_t}{s(s+1/\tau_t)}\right] = 1 - e^{-t/\tau_t} \qquad (4)$$

$$d(t) = d_\infty \left(1 - e^{-t/\tau_t}\right) \qquad (5)$$

The output response has an exponential shape that represents the step response of a 1st order system. As the system approaches a steady state, the response approaches a constant value, d_∞. When the elapsed time is equal to a one-time constant, τ the process output will have achieved 63.2% of its final value, d_∞.

For $t \geq 4\ \tau_t$ the response remains 98% of the final value, d_∞. The steady-state is reached mathematically only after an infinite time. A reasonable estimate of the response time is the length of time, the response curve needs to reach the 98% of the final value, d_∞, $t_s \geq 4\ \tau_t$, where t_s is the setting time.

The step response is divided into two regions related to a transient region in which the system (structural degradation) is still responding dynamically, and a steady-state region, in which the system is assumed to have reached its final value, d_∞.

Further, when the exact starting point of the step response is defined, τ_c (coating life), the time delay and the response of the system may be calculated as:

$$d(t|\tau_t, \tau_c) = d_\infty \left(1 - e^{-\frac{t-\tau_c}{\tau_t}}\right) \qquad (6)$$

In fact, Eqn (6) has been proven to be a good solution in defining the corrosion depth progress of different ageing marine structures as a function of time, conditional of coating life and transitional time as reported in [8, 18, 38-40, 42, 44-48]

3. CORROSION DEGRADATION OF TANKER MODEL

The corrosion degradation model that is employed in the present analysis, was developed in [42], is based on a nonlinear function of time, Eqn (6) that describes the

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general corrosion wastage. The time-dependent model of the corrosion degradation is seen as a three-phase process. The first phase covers the time, where there is no corrosion because the protection of the metal surface works properly and it is associated with the coating life, τ_c ($t \in [O', \tau_c]$, Figure 1). The second phase starts when the corrosion protection fails and the corrosion degradation progress progressively decreases the thickness of the structural component ($t \in [\tau_c, 4\tau_t]$, Figure 1). The third phase is related to the stop in the corrosion process and the corrosion rate becomes close to zero ($t \geq 4\,\tau_t$, Figure 1).

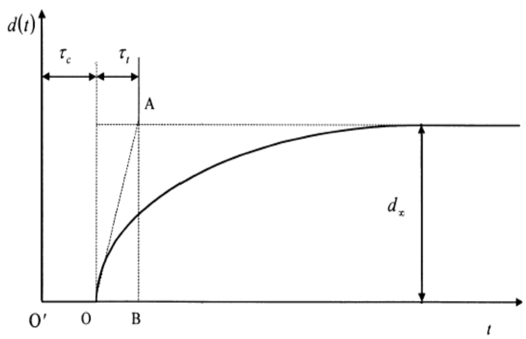

Figure 1 Corrosion model

The corroded material stays on the plate surface, protecting it from the contact with the corrosive environment and the corrosion process, in this case, may stop. Cleaning the surface or any involuntary action that removes the surface material will restart the non-linear corrosion growth process again.

The corrosion degradation model used in the present study is described as:

$$d(t) = \begin{cases} d_\infty \left(1 - e^{-\frac{t-\tau_c}{\tau_t}}\right), & t > \tau_c \\ 0, & t \leq \tau_c \end{cases} \text{, mm} \qquad (7)$$

where τ_c is the coating life in years, τ_t is the transition time in years, and d_∞ is the maximum corrosion depth in mm, achieved during the service life,

$$\tau_t = d_\infty / \tan\alpha \text{, years} \qquad (8)$$

where α is the angle defined by OA and OB in Figure 1. Eqn (6) represents the mean value of the corrosion depth, d(t) and the corrosion rate, r[d(t)] may be defined as:

$$r(t) = \partial\left[d(t)\right] / \partial t \text{, mm/year} \qquad (9)$$

To calculate the variances of the corrosion depth and rate the following equations may be used:

$$Var\left[d\left(t \middle| \tau_t, \tau_c, d_\infty\right)\right] = \sum_{i=1}^{3} \left(\frac{\partial d\left(t \middle| \tau_t, \tau_c, d_\infty\right)}{\partial x_i} \right)^2 \sigma_{x_i}^2 \qquad (10)$$

$$Var\left[r\left(t \middle| \tau_t, \tau_c, d_\infty\right)\right] = \sum_{i=1}^{3} \left(\frac{\partial^2 d\left(t \middle| \tau_t, \tau_c, d_\infty\right)}{\partial t \partial x_i} \right)^2 \sigma_{x_i}^2 \qquad (11)$$

where the standard deviation is calculated as $StDev = \sqrt{Var}$ and $i \in [1,3]$ taking the values of $x_1 = \tau_c$, $x_2 = \tau_t$ and $x_3 = d_\infty$.

4. CORROSION DEGRADATION OF TANKER SHIPS

A total of 1,226 corrosion depth measurements of deck plates of ballast tank (see Figure 2) and 4,104 measurements of deck plates of cargo tanks (see Figure 3) of double-hull tankers in different corrosive environments and service age are analyzed here.

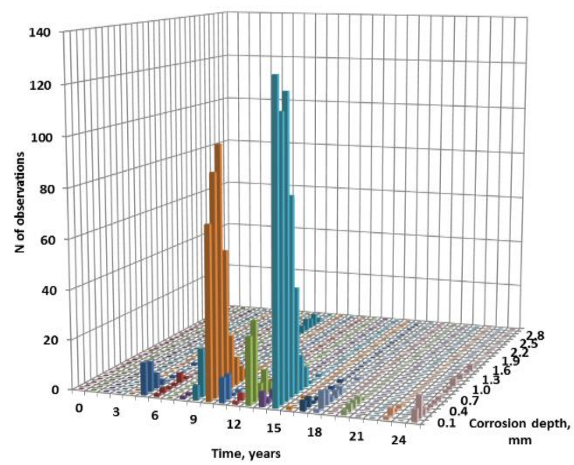

Figure 2 Corrosion depths of deck plates, ballast tanks, new

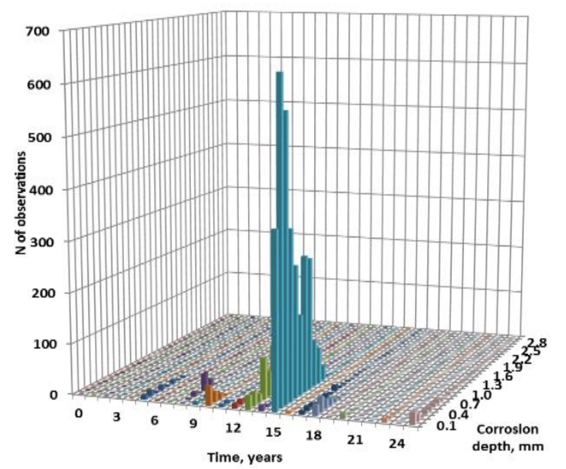

Figure 3 Corrosion depths of deck plates, cargo tanks, new

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Table 1 Statistical descriptors of corrosion depth

Structural components	$E(d_\infty)$; $StDev(d_\infty)$ mm, G (a, b)	$E(\tau_t)$; $StDev(\tau_t)$ years, G (a, b)	$E(\tau_c)$; $StDev(\tau_c)$ years, G (a, b)
Deck plates CT-Air (new)	0.63; 0.35 G (3.24, 0.19)	9.17; 5.62 G (2.66, 3.44)	6.86; 4.403 G (2.43, 3.44)
Deck plates BT-Air (new)	0.88; 0.25 G (12.39,0.07)	8.91; 5.32 G (2.80,3.18)	9.2; 3.095 G (8.84,1.04)
Deck plates CT-Air (old)	1.91; 0.701 G (7.42,0.26)	11.22; 7.83 G (2.05,5.46)	11.49; 2.84 G (16.37,0.7)
Deck plates BT-Air (old)	1.85; 0.60 G (9.51, 0.19)	17.14; 6.606 G (6.73, 2.55)	10.54; 3.66 G (8.29, 1.27)

The statistical descriptors of d_∞, τ_t and τ_c, analyzing the corrosion depth measurements, including the ones already reported in [38], are shown in Table 1, where the Gamma probability function is assumed as the most suitable one to fit the data.
It was observed that the corrosion depth of the new data, for the deck plates in cargo tanks is approximately 0.48 mm and for the water ballast tanks is 0.62 mm respectively in the 20th year (see Figure 4 and Figure 5). The corrosion depth of the deck plates of cargo tanks of double hull tankers is about 47 % from the corrosion depth measurements as reported in [38] and about 74% in the case of ballast tanks as can be seen in Figure 4 and Figure 5.
However, since many parameters and uncertainties are involved in the corrosion degradation process a probabilistic (reliability) analysis will be performed in the next section to identify the current trend.

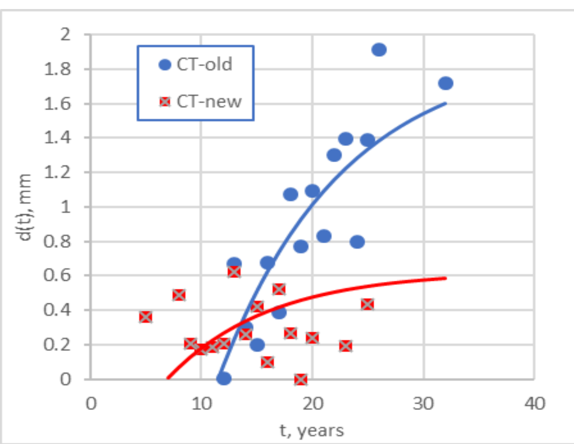

Figure 4 Average annual corrosion depth, deck plates, cargo tanks, old (circles) and new (rectangles)

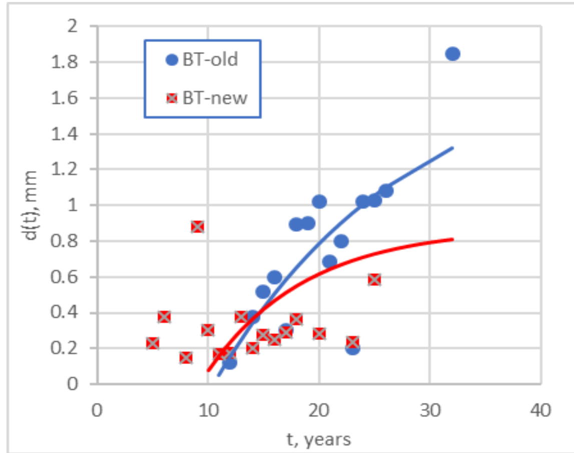

Figure 5 Average annual average annual corrosion depth, deck plates, ballast tanks, old (circles) and new (rectangles)

5. RELIABILITY ANALYSIS

The reliability analysis presented here is using the First Order Reliability Method (FORM) to identify a set of basic random variables, that influence the failure mode or the limit-state under consideration. FORM methods calculate the reliability with good accuracy for practical applications as follows from the methods proposed in [49-51].
Using a FORM and the corrosion degradation analysis, the limit state function is defined as:

$$g(\mathbf{X}) = d_u X_u - d_\infty X_\infty \left(1 - e^{-\frac{t-\tau_c X_c}{\tau_t X_t}}\right), \quad t > \tau_c X_c, \tau_t X_t > 0 \qquad (12)$$

where d_u is the plate corrosion margin with a model uncertainty factor X_u, which is assumed to be described by the Normal probability density function, N_u (1.0, 0.1). The model uncertainty factor X_∞ accounts for the uncertainties in the estimation of d_∞, N_∞ (1, 0.1) and X_c accounts for the uncertainties in the estimation of τ_c, N_c (1, 0.1) and the model uncertainty of τ_t is defined by X_t, N_t (1, 0.1).
This formulation that relates the (design) corrosion margin to the corrosion wastage of a plate, can be extended to calculate the hull section modulus reliability under corrosion conditions [52, 53].
The 5% confidence level value of the corrosion margin, $d_u^{5\%}$ is assumed as stipulated in [54] and additionally, it is assumed that COV is 0.1 leading to σ_{du}=0.1E(d_u) and it is fitted to the Normal probability density function:

$$E(d_u) \rightarrow F_{du}^{-1}\left[0.05, E(d_u), \sigma(d_u)\right] = d_u^{5\%} \qquad (13)$$

The mean value and the standard deviation of the corrosion margin used in the analysis are 4.79 and 0.49 respectively, respecting a 5% confidence level of a corrosion margin of

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4 mm.
FORM is used to calculate the reliability index of the corrosion degradation limit state. The reliability index β is obtained from the probability of failure as:

$$\beta = -\Phi^{-1}(P_f) \tag{14}$$

where Φ^{-1} is the standard normal probability distribution function.

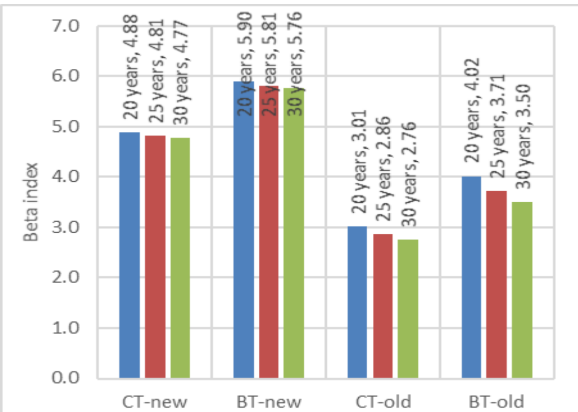

Figure 6 – Beta reliability index

The Beta reliability index as a function of the service life of 20, 25 and 30 years is presented in Figure 6. The new analyzed corroded deck plates with respect to the stipulated by the CSR corrosion margins are with a reliability Beta index bigger than 3.71. On the other hand, the corroded deck plates analyzed in [38] have a Beta index between 2.76 to 4.02.
The importance of the contribution of each stochastic variable to the uncertainty of the limit state function is assessed by analyzing the sensitivity factors, which are defined as:

$$\alpha_i = -\frac{\partial g(\underline{x})}{\partial x_i} \Big/ \sqrt{\sum_{i=1}^{\infty}\left(\frac{\partial g(\underline{x})}{\partial x_i}\right)^2} \tag{15}$$

Figure 7 shows the sensitivities of the limit state function with respect to the changes in the stochastic variables. A positive sensitivity indicates that with an increase in the variable results in an increase in the failure function and negatively contributes to reliability. The indexes of the x-axis of Figure 7 correspond to (1) = d_∞ and (2) = X_∞, (3) = τ_t, (4) = X_t, (5) = τ_c, (6) = X_c, (7) = d_u and (8) = X_u respectively.
It can be seen from Figure 7 that the most important in the uncertainty on the corrosion degradation of tankers is the uncertainties related to the parameter (1) = d_∞, the second and third are (3) = τ_t and followed by (7) = d_u, (8) = X_u and (2) = X_∞.

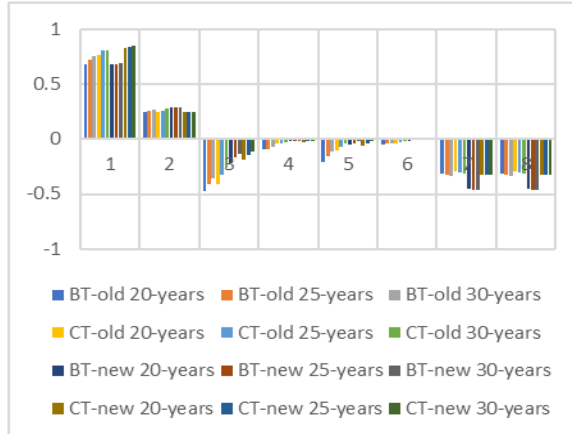

Figure 7 – Sensitivities of stochastic variables

Applying the reliability analysis as a decision tool, the estimated probability of failure (corrosion depth is reaching the corrosion margins) is compared to an accepted target level. The target levels depend on different factors as reported in [55]. The target level adapted here is related to failure cause and mode, which may result for redundant structure in P_f=10^{-3} (β=3.09) for less serious and P_f=10^{-4} (β=3.71) for serious consequences of failure values of acceptable annual probability of failure [56].

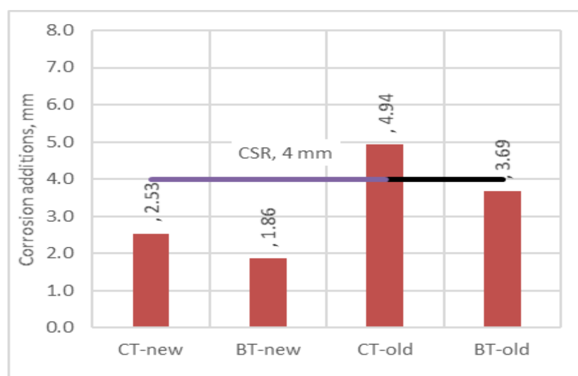

Figure 8 – Design values of corrosion margins, β=3.71, 25th year

In the present analysis of the new collected measurements of corroded plates, the estimated beta reliability index is bigger than the minimum acceptable for the normal operation β=3.09 and serious consequences β=3.71, which is not the case in all cases of the previously analyzed data in [38].
A conclusion may be derived here that the adopted

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corrosion degradation prevention policies in the last decades have shown a good achievement identifying that the ageing structures are kept on a good reliability level from the point of view of corrosion degradation.

It must be pointed out that the collected data cover a variety of corrosion environments, ship ages, ship flags and owners that may have a different impact on the final analysis.

To identify the corrosion margins for the corroded plates analyzed here satisfying the beta index of 3.71, inverse reliability analyses are presented, and the results are presented in Figure 8. As can be seen from Figure 8 the corrosion margin design value for the corroded plates of cargo tanks (new data) is 2.83 mm and for ballast tanks (new data) is 2.17 mm, which is much less than the one stipulated by CSR for the boundary between the ballast or cargo tank and atmosphere of 4 mm.

Partial safety factors may be estimated based on the characteristic values of d_u^c, d_∞^c, τ_t^c and τ_c^c calculated at the confidence level of the original probability density function as $d_u^{5\%}$, $d_\infty^{95\%}$, $\tau_t^{5\%}$ and $\tau_c^{5\%}$ respectively. The design values of all parameters involved in the limit state functions are d_u^*, d_∞^*, τ_t^c and τ_c^* respecting the Beta reliability index, which in the case of the design solution is assumed as β=3.71 at 25th year and the partial safety factors are defined as:

$$\gamma_u = \frac{d_u^c}{X_u^* d_u^*},\ \gamma_\infty = \frac{d_\infty^c}{X_\infty^* d_\infty^*},\ \gamma_t = \frac{X_t^* \tau_t^*}{\tau_t^c},\ \gamma_c = \frac{X_c^* d_c^*}{d_c^c} \quad (16)$$

Table 2 Partial safety factors/characteristic values; design values

	γ_∞; d_∞^c; d_∞^*	γ_t; τ_t^c; τ_t^*	γ_c; τ_c^c; τ_c^*	γ_u; d_u^c; d_u^*
CT-new	0.50; 1.29; 2.59	2.33; 2.24; 5.21	3.49; 1.52; 5.31	1.04; 2.64; 2.53
BT-new	0.71; 1.33; 1.88	1.56; 2.29; 3.58	1.80; 4.77; 8.56	1.14; 2.12; 1.86
CT-old	0.63; 3.19; 5.06	1.89; 2.06; 3.90	1.47; 7.25; 10.64	1.09; 5.38; 4.94
BT-old	0.70; 2.93; 4.21	1.03; 7.90; 8.12	1.51; 5.32; 8.06	1.08; 3.98; 3.69

The resulting partial safety factors may be used in ship structural design by satisfying the following design criterion:

$$\frac{d_u^c}{\gamma_u} \geq \frac{d_\infty^c}{\gamma_\infty}\left[1-\left(\exp\left(-\frac{25-\gamma_t \tau_t^c}{\gamma_c \tau_c^c}\right)\right)\right] \quad (17)$$

where the partial safety factors, characteristics and design values for the corrosion environment of CT-new, BT-new, CT-old and BT-old are given in Table 2.

6. CONCLUSIONS

The work presented here analyzed the structural corrosion degradation of two sets of corrosion depth measurements collected in a one-decade difference. The corrosion degradation process was associated to the first order system, subjected to a sudden disturbance, where a step function is used to define the input signal and the solution of the differential equation of this system lead to the exponential corrosion degradation model as developed in [42].

It was concluded that the corrosion depth of the new data, for the deck plates in cargo tanks is approximately 0.48 mm and for the water ballast tanks is 0.62 mm respectively at the 20th year, which represents about 47 % and 74% of the old corrosion depth measurements as reported in [38].

The estimated beta reliability index of the new collected measurements of corroded plates is bigger than the minimum acceptable for a normal ship operation assumed here as β=3.09, which is not the case for all previously analyzed data in [38]. To achieve β=3.71, the corrosion margin design value for the corroded plates of cargo tanks (new data) is 2.53 mm and for ballast tanks (new data) is 1.86 mm related to characteristic values of 2.64 mm and 2.12 mm, which is much less by the stipulated by CSR corrosion margin of 4 mm.

It is also concluded that the adopted corrosion degradation prevention policies in the last decades have shown a good achievement identifying that the ageing structures are kept on a good reliability level from the point of view of corrosion degradation.

Partial safety factors with respect to corrosion environment and corrosion margins were derived that can be used in ship structural design, avoiding a complex probabilistic analysis.

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