Development of Corrosion Wastage Assessment Methodology for Water Ballast Tanks: An Aging Bulk Carrier

Špiro Ivošević[1], Nataša Kovač[2], Nikola Momčilović[3]

Various environmental factors, operating conditions, transport routes, the type of transported cargo, maintenance practices, and other external and internal factors significantly influence the development of corrosion. Cargo holds and water ballast tanks are particularly susceptible to corrosion damage. This study investigates the extent to which steel thickness reduction due to corrosion contributes to the degradation of steel structures and whether this reduction aligns with the adopted Common Structural Rules (CSR). The analysis is based on an aging bulk carrier and three types of ballast tanks within the cargo hold area: top-side tanks, hopper-side tanks, and double-bottom tanks. Thickness measurements were conducted on nine specific transverse structural locations, and a corrosion wastage assessment methodology was developed based on a nonlinear stochastic model. The corrosion growth rate was modeled using a probabilistic approach where the corrosion rate parameter d0 follows a Weibull distribution. The model also incorporates 95% confidence intervals to reflect uncertainty and assess early risk exceedance relative to CSR corrosion margins. The results revealed significant differences in corrosion behavior among ballast tank areas and identified critical zones where corrosion thresholds are reached earlier than expected. The proposed methodology demonstrates its applicability in assessing structural degradation patterns and validating CSR-based corrosion allowances.

KEYWORDS

~ Corrosion wastage
~ Corrosion margin
~ Nonlinear behavior
~ Bulk carrier
~ Water ballast tanks
~ CSR

[1]University of Montenegro, Faculty of Maritime Studies Kotor, Montenegro
[2]University of Donja Gorica, Faculty of Applied Sciences, Podgorica, Montenegro
[3]University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia
e-mail: spiroi@ucg.ac.me
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1. INTRODUCTION

Hull structure degradation is influenced by various factors, with corrosion and fatigue recognized as the primary time-dependent contributors to a vessel's structural deterioration. Corrosion causes the reduction of the original thickness of structure over time, which can be expressed through mass loss, in millimeters or percentage of thickness diminution of steel element. Corrosion process can reduce the strength of ships, cause different types of failures and consequently, lead to pollution.

Various accidents over the past decades have led to an increasing number of studies focusing on different types of ships (Heij and Knapp, 2019; EMSA, 2019). Extensive research has been conducted to understand the mechanisms of corrosion and fatigue in various ship structures and their impact on sustainability (Kovač et al., 2024). Studies on structural members are crucial for planning maintenance and conducting inspections to ensure the ship meets its intended life cycle (Ivošević et al., 2021).

Due to their long operational lifespan of 25 years, ships are exposed to various influencing factors. Aggressive environmental conditions, specific trade routes, dry and wet ballast cycles, cargo type, ballast-to-cargo ratio, and the frequency of loading and unloading operations often contribute to severe corrosion in bulk carriers. These and other internal and external factors can contribute to various types of damage, including deformations, cracks, and corrosion. Furthermore, structural degradation can lead to pollution (Ivošević and Kovač, 2023) and often necessitates significant repairs to extend a ship's operational lifespan. To minimize harmful consequences, Flag State inspection, Port State Control (Peričin et al., 2024), Classification Society surveys, and other non-mandatory inspections, aim to mitigate adverse impacts on the maritime industry.

In recent decades, significant advancements in maritime regulations have been achieved, particularly through the strengthening of international conventions and the introduction of the ISM Code, PSPC standards, and Common Structural Rules - CSR (IACS, 2024). Under the International Association of Classification Societies (IACS), corrosion allowances for bulk carriers and tankers have been standardized following the new CSR, ensuring a projected vessel lifespan of 25 years. The corrosion allowance is determined through statistical analysis of thickness loss measurements, specific to the component's location and corrosion environment. It is set at the 95th percentile of the predicted corrosion depth over a 25-year service life (IACS, 2014; Woloszyk and Garbatov, 2022). CSR establishes exact corrosion margins at the ship design stage, expressed in millimeters of allowable diminution based on the exposure of each structural element. These margins ensure compliance with criteria required by classification societies, enhancing ship safety and longevity.

For the main structural elements, such as the face plate of primary members, the allowable wastage limit depends on their position within the tank, type of structure member and size of the vessel. According to CSR recommendations for corrosion margin of handy size bulk carriers, corrosion margin for face plate of primary members (web plates) in top side tanks and hopper tanks is 2.3 mm, whilst for flanges and floors in double bottom tanks is 3.0 and 2.5 mm, respectively (IACS, 2014). Consequently, corrosion margins for all structural members were proposed (IACS, 2014), in case of bulk carriers and tankers.

Considering corrosion damage of specific structural areas, authors considered different linear and non-linear models. The research in (Southwell et al., 1979) developed a linear model, while the following studies (Soares and Garbatov, 1999; Yamamoto et al., 1994; Paik et al., 2003; Melchers, 2003) and others developed different non-linear models. Among two-parameter continuous distributions, the Normal, Weibull, and Logistic distributions are the best-fitting models for probabilistic estimation of corrosion rates in various structural members. However, other distributions, such as the Error Distribution, Log-Pearson Type III, and Generalized Extreme Value (GEV), may also be applicable (Ivošević et al., 2019a). In that context, models are developed for structural areas such as ballast tanks, cargo storage, deck plates of bulk carriers (Garbatov and Soares, 2008), transverse bulkheads of bulk carriers (Yamamoto and Ikagaki, 1998), seawater ballast tanks (Paik et al., 2004), fuel oil tank structure plating (Ivošević et al., 2019b, Ivošević et al., 2022, Ivošević et al., 2024).

Based on previous studies, this paper analyses corrosion of transverse elements (web and floor plates) in ballast tanks. A methodology was developed for the assessment of corrosion wastage depending on the specific ballast tanks and depending on the location of the structural wear. The development of the corrosion model aims to establish a new methodology for assessing corrosion of ballast tanks to evaluate proposed values of adopted and recommended CSR margins. The limitation of this study lies in its application to a single ageing bulk carrier. Future research should expand the proposed assessment methodology to a larger dataset for broader validation.

The paper is structured into four sections. The second section presents the methodology, including the database and applied methods, while the third section showcases results. The fourth section provides concluding considerations and suggests directions for future research.

2. METHODOLOGY

According to the rules and requirements issued by the classification societies, ship managers are obliged to monitor the condition of the hull during the service life of the vessel. This includes measurements on ship's specific areas and elements. Measurements can be extended depending on ship age. These rules are derived from calculations and historical data analysis on structural damage, forming the basis of the Common Structural Rules (CSR). The research methodology follows a systematic approach to assessing the condition of ballast tank structural elements, with a particular emphasis on collecting, processing, and analyzing structural thickness measurements. Firstly, authors used data on the standard measured thickness of structural primary face plate members and other structure elements of all ballast tanks in the cargo areas and identified locations of measurement. For measurement, standardized ultrasound devices were used according to the rules of classification societies, which ensured the accuracy and validity of the obtained data. All the data which are obtained were systematized into three characteristic areas (Top side tank – Area 1, 2, 3; Hopper tanks – Area 4, 5, 6; and Double bottom tanks – Area 7, 8, 9). Moreover, within these three parts of ship cross section, specific locations are identified: outer ring (Area 1, Area 4, Area 7), mid ring (Area 2, Area 5, Area 8), and flange/openings (Area 3, Area 6, Area 9). Outer ring areas represent the lower part of depth of primary transverse elements in top side tank, hopper tank and double bottom. Mid ring includes upper part of depth of primary transverse elements in the same parts of the cross section, whilst the flanges are located at the top of those primary transverse elements. Furthermore, following the rules of classification societies, a measurement report was made with the actual build steel thickness value and measured data. Based on the rules of the classification societies, acceptance criteria for each structural element are defined. These criteria include minimum allowable thicknesses and degree of damage that can be tolerated depending on the function and location of the element (IACS, 2024; LR, 2024). After collecting and organizing the data, a detailed analysis and comparison with the standards for suggested corrosion allowance under the Common Structural Rules (CSR) was carried out.

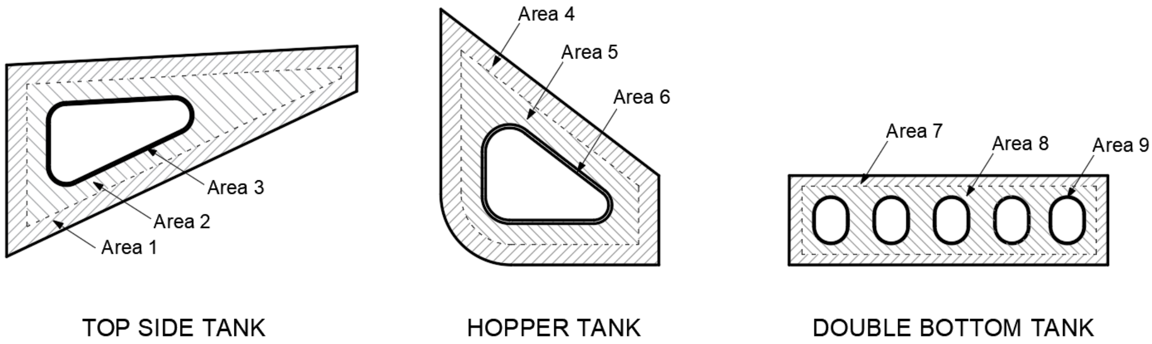


Figure 1. Three water ballast tanks and nine considered areas.

2.1. Database

In this paper, as the subject of the research, we used one ageing bulk carrier. As the entry database, ultrasonic thickness measurement report approved by a recognized classification society is used for the ship with GT-25743 and built in 1983. Considered ship have been in service for 25 years and transported different types of cargo, such as steel, ore, coal and another type of cargo. Approved operators and the company provided several thickness measurement data, which were collected in the final report (see Acknowledgement).

The database containing detailed corrosion damages measurement results is expressed in mm of corrosion diminution for each zone. The database is organized according to the frames of the ship, in which the data is divided according to the transversal elements within each tank - Top Side Tank, Hopper Tank and Double Bottom Tank. Each zone contains data on the depth of corrosion expressed in millimeters of diminution, with the values marked for the portside and starboard side measurements. Considering the database, it can be concluded that the greatest average damage is in the area of top side tanks (1.3 mm), then in double bottom tanks (0.9 mm) and finally in hopper side tanks (0.3 mm).

The dataset comprises corrosion thickness measurements (in mm) from nine distinct areas within the ballast tanks. Each row of the dataset represents 30 different observed thickness values per area after 25 years of service. To ensure robustness in statistical estimation, outliers were first removed using the Interquartile Range (IQR) method. For each area, the first (Q1) and third (Q3) quartiles were calculated, and the IQR was defined as IQR=Q3−Q1. Data points outside the range [Q1−1.5·IQR, Q3+1.5·IQR] were excluded from further analysis. Basic descriptive statistics (mean, standard deviation (Std), minimum (Min), maximum (Max), and quartiles (Q1, Q3)) were computed for each area after the outliers removal, as it is shown in Table 1.

Area	Count	Mean	Std	Min	Q1	Median	Q3	Max
Area 1	28	0.9657	0.4984	0.28	0.6275	0.855	1.1850	2.20
Area 2	29	0.8231	0.5461	0.28	0.4000	0.680	1.0600	2.11
Area 3	30	2.0637	1.6467	0.00	0.5075	2.045	2.9650	6.34
Area 4	29	0.2766	0.0515	0.19	0.2300	0.290	0.3100	0.37
Area 5	30	0.2787	0.0527	0.20	0.2600	0.270	0.3100	0.37
Area 6	26	0.1296	0.1256	0.00	0.0000	0.200	0.2300	0.30
Area 7	30	0.8833	0.5239	0.19	0.3625	0.920	1.1775	2.02
Area 8	30	0.4647	0.3233	0.18	0.2225	0.300	0.7575	1.45
Area 9	30	1.2863	1.1009	0.18	0.2200	1.420	1.8525	3.73

Table 1. Descriptive Statistics of Corrosion Thickness Values per Area after Outlier Removal.

Boxplots constructed for each area provide visual insight into the spread and symmetry of the examined corrosion thickness data (Figure 2).

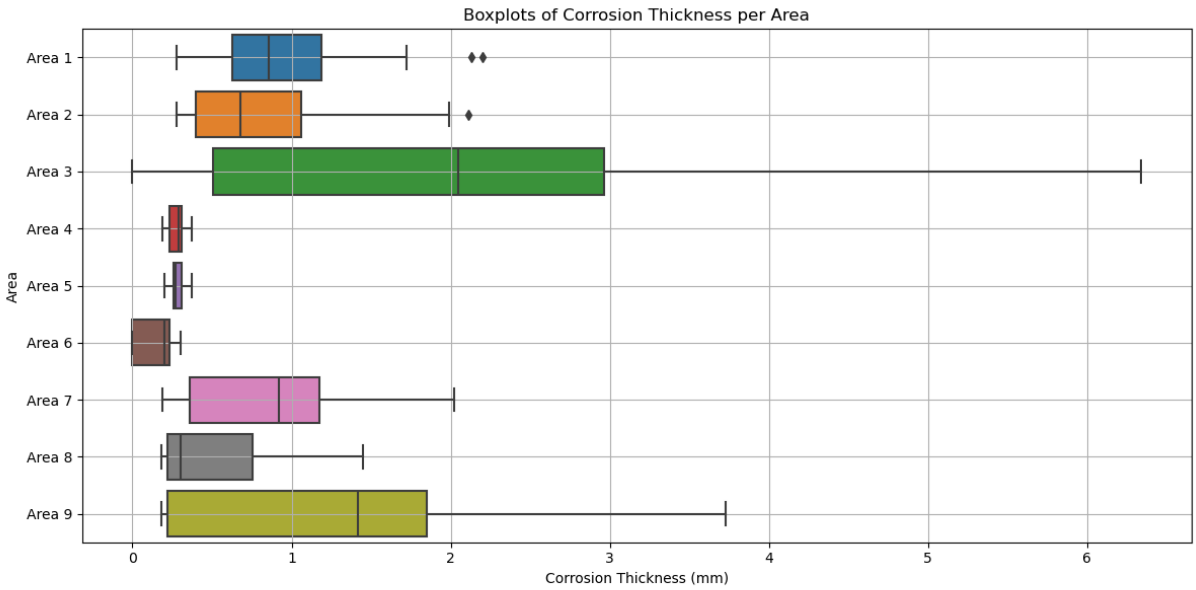


Figure 2. Boxplots of corrosion thickness values per area after outlier removal.

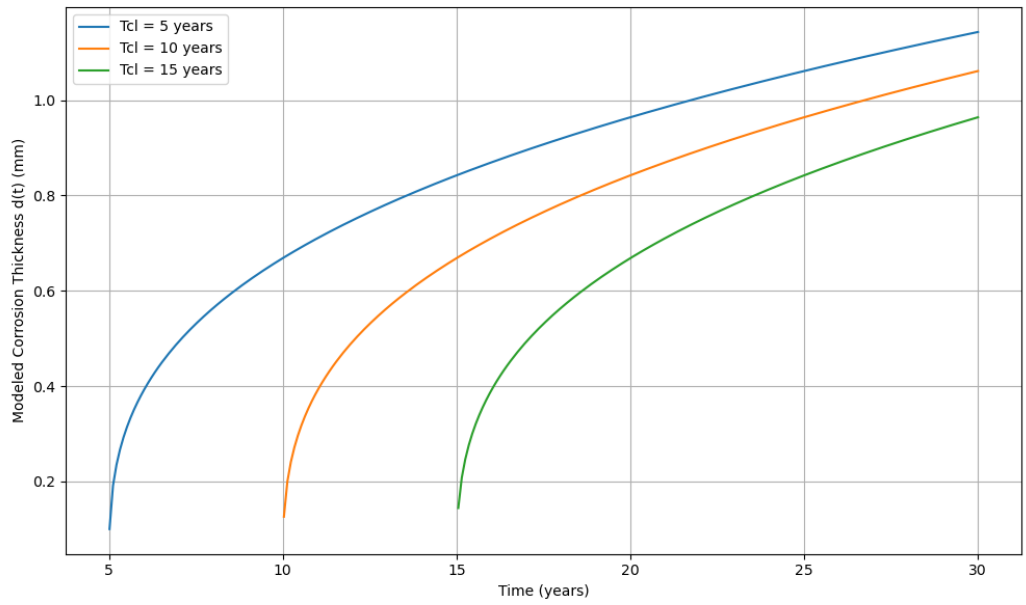
2.2. Methods

The methodology for assessing corrosion wastage in ballast tanks is developed under the assumption that corrosion progresses after an initiation time, referred to as the critical time of corrosion initiation (T_{cl}), and follows a stochastic nonlinear growth model. It is assumed that no measurable corrosion occurs before time T_{cl}. The corrosion thickness $d(t)$ over time t is modelled as a function of a random variable d_0, which characterizes the corrosion rate and is assumed to follow a Weibull probability distribution. The growth of corrosion thickness is expressed by:

$$d(t) = d_0 \cdot (t - T_{\mathrm{cl}})^{\alpha} \qquad (1)$$

where $d(t)$ is the corrosion wastage (in mm) at time t (in years), T_{cl} is the time of corrosion initiation, d_0 is the corrosion rate parameter, α is the corrosion growth exponent. For the analysis, the exponent was set to α=1/3, reflecting nonlinear corrosion behavior reported in marine environments. Two distinct T_{cl} values were considered based on known operational exposure data: T_{cl} = 5 years for Areas 1–3, and T_{cl} = 10 years for Areas 4–9. Measurements were performed at t = 25 years after commissioning. Model (1) captures inherent variability in corrosion behavior across different areas. Parameters T_{cl} and α significantly influence the corrosion thickness predictions and, consequently, the risk assessment outcomes. The value of T_{cl} adopted as 5 or 10 years is consistent with empirical observations reported in previous corrosion studies on marine structures (Paik et al., 2004; Melchers, 2003). The chosen growth exponent α=1/3 aligns with recognized nonlinear corrosion progression models extensively validated in marine structural corrosion literature (Guo et al., 2008; Qin

& Cui, 2003). Figure 3. shows the sensitivity of the corrosion predictions influenced by a variation in parameters T_{cl} and α and how they affect the rate and timing of predicted corrosion thicknesses, thus impacting both structural assessment and the reliability of the derived confidence intervals.



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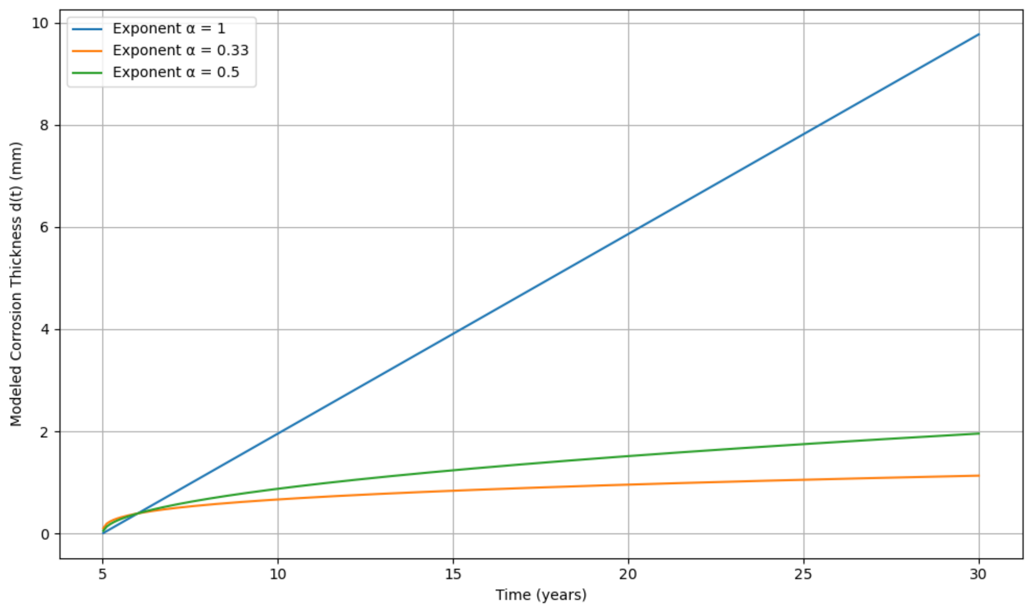


b)

Figure 3. Sensitivity of the corrosion predictions: a) sensitivity analysis of T_{cl} on $d(t)$ with α = 1/3, b) sensitivity analysis of α on $d(t)$ with T_{cl} = 5 years.

Also, 95% confidence intervals are computed around the expected growth curves to quantify the uncertainty of prediction, highlighting the stochastic framework adopted in this study. A confidence interval of 95% was selected as it is the most widely adopted standard in engineering practice and structural reliability analysis (Ang & Tang, 2007; Paik et al., 2004). This level ensures a balance between risk sensitivity and practical applicability, providing sufficient conservativeness for structural decision-making. The choice of confidence level is directly relevant to parameter uncertainties, particularly T_{cl} and α, which, due to their inherent variability, require adequate statistical margins to ensure robust predictions.

The greatest dispersion and outlier presence is evident in Area 3, corroborating the high variability captured in the fitted Weibull model. Areas 4 to 6 demonstrate tightly clustered values with minimal spread, consistent with their narrow Weibull distributions.

Post-outlier removal, the statistical distribution of the corrosion rate parameter d_0 was characterized using the Weibull distribution due to its flexibility in modelling skewed data. The two-parameter Weibull probability density function is given by:

$$f(d_0) = \frac{k}{\lambda}\left(\frac{d_0}{\lambda}\right)^{k-1} \exp\left(-\left(\frac{d_0}{\lambda}\right)^k\right) \qquad (2)$$

where k is the shape parameter and λ is the scale parameter. Maximum likelihood estimation was used to estimate the distribution parameters for each area individually. The mean corrosion rate parameter was calculated from the Weibull parameters using:

$$\mu_{d_0} = \lambda \cdot \Gamma\left(1 + \frac{1}{k}\right) \qquad (3)$$

where Γ denotes the Gamma function.

To quantify variability in corrosion prediction, 95% confidence intervals (CI) were constructed around the mean d(t) curves. The CI boundaries were derived using the sample standard deviation of the d_0 values:

$$d^{\text{CI}}_{\text{upper/lower}}(t) = \left(\mu_{d_0} \pm z \cdot \sigma_{d_0}\right) \cdot (t - T_{\text{cl}})^{\alpha} \qquad (4)$$

where z = 1.96 for the 95% confidence level and σ_{d_0} is the standard deviation.

Intersection points between modelled $d(t)$ curves and critical corrosion threshold lines (defined per area from reference data) were computed to assess the time at which critical wastage levels might be reached. Both central and upper CI-bound intersection times were observed to capture early risk possibilities.

3. RESULTS

Following outlier removal, the distribution of the corrosion rate parameter d_0 was modelled for each of the nine areas using the two-parameter Weibull distribution. The estimated shape (k) and scale (λ) parameters, along with the derived mean corrosion rate μ_{d0}. To evaluate the quality of fit, goodness-of-fit metrics were calculated for each area, including the coefficient of determination (R^2) from Weibull Q–Q plots, the Kolmogorov–Smirnov (KS) test statistic, and its associated p-value. These two statistical tools are chosen because they are complementary. R^2 gives a global fit indicator while the KS test provides a distributional and tail-sensitivity test. Obtained results are summarized in Table 2.

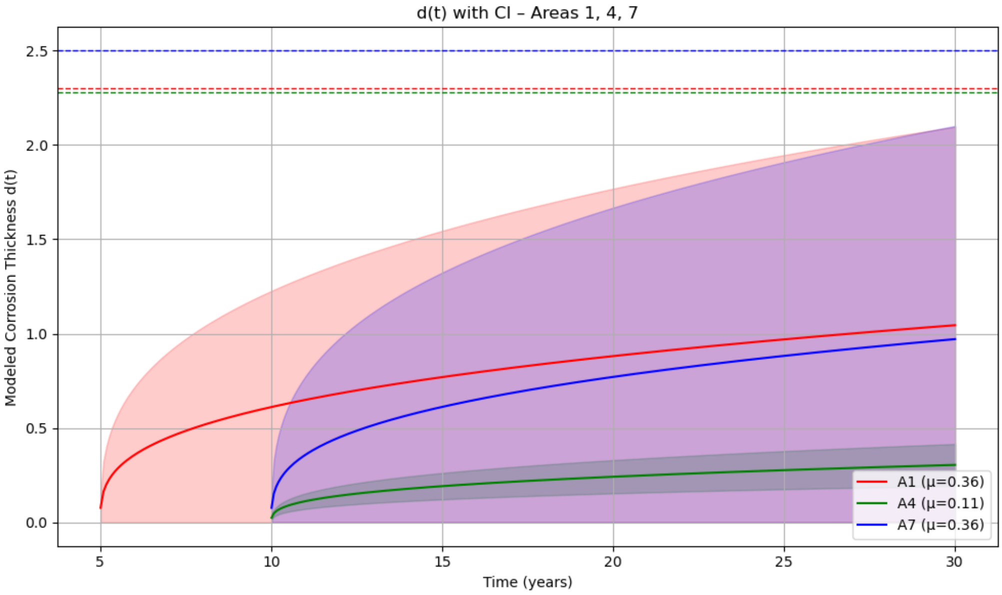
Area	T_{cl} (years)	Shape k	Scale λ	Mean d_0 (mm)	R^2	KS	KS p-value
Area 1	5	2.1077	0.4034	0.3573	0.9665	0.1097	0.8529
Area 2	5	1.6635	0.3424	0.3060	0.9441	0.1485	0.4983
Area 3	5	1.3552	0.8870	0.8128	0.9786	0.1206	0.7658
Area 4	10	6.2461	0.1207	0.1122	0.9486	0.1335	0.6317
Area 5	10	5.8500	0.1218	0.1129	0.9329	0.1490	0.4733
Area 6	10	6.6358	0.1044	0.0974	0.7797	0.3371	0.0638
Area 7	10	1.7363	0.4015	0.3578	0.9550	0.1814	0.2454
Area 8	10	1.6033	0.2124	0.1904	0.8881	0.2589	0.0292
Area 9	10	1.0711	0.5354	0.5213	0.9062	0.2484	0.0407

Table 2. Estimated Weibull distribution parameters for corrosion rate d_0 by area.

These results indicate considerable variability in corrosion progression across different areas. Area 3 exhibits the highest average corrosion rate parameter, reflecting greater material degradation compared to other regions. Areas 4 to 6, by contrast, show notably low d_0 values and high Weibull shape parameters, indicating more homogeneous corrosion behavior.

The corrosion thickness over time was modelled using the nonlinear function (1). The modelled curves for each area, along with 95% CI derived from the standard deviation of d0 values, were plotted to visualize the potential range of corrosion development over time (Figure 4).

For each group of areas, the plots indicate that the upper confidence bounds for some areas could intersect critical corrosion thresholds significantly earlier than the average trajectory. In Area 3, the upper confidence interval envelope intersects the defined threshold at approximately 8.52 years, signaling a possible early risk scenario for this region. Area 9 reaches its critical threshold under the upper confidence interval bound at 15.60 years, despite having a relatively moderate mean corrosion rate. Areas 4 to 6 consistently display low corrosion accumulation across both mean and confidence interval curves, indicating low-risk zones under both expected and extreme scenarios. Area 3 and Area 9 represent the most critical regions concerning early corrosion exceedance risk.



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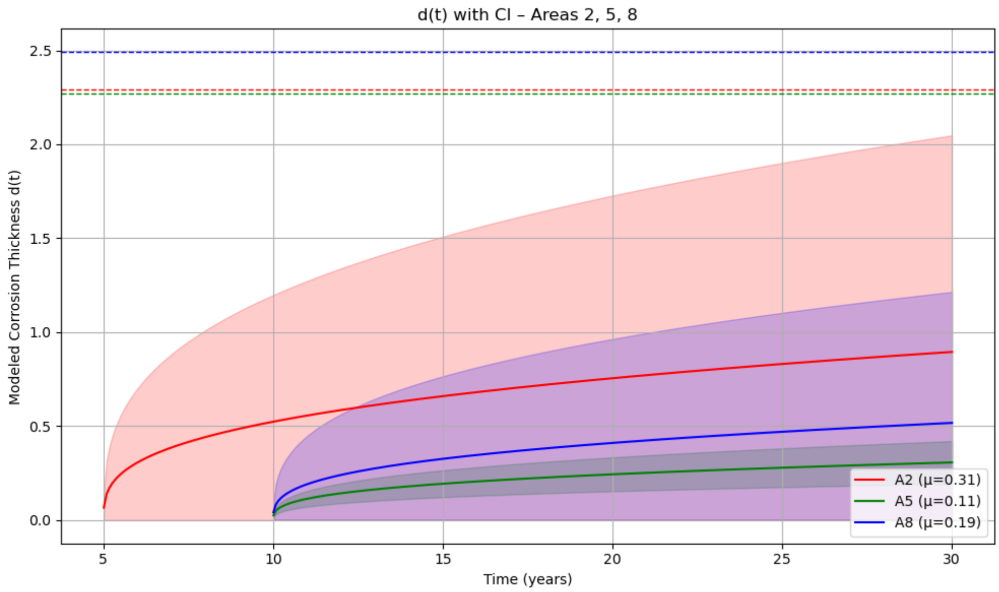

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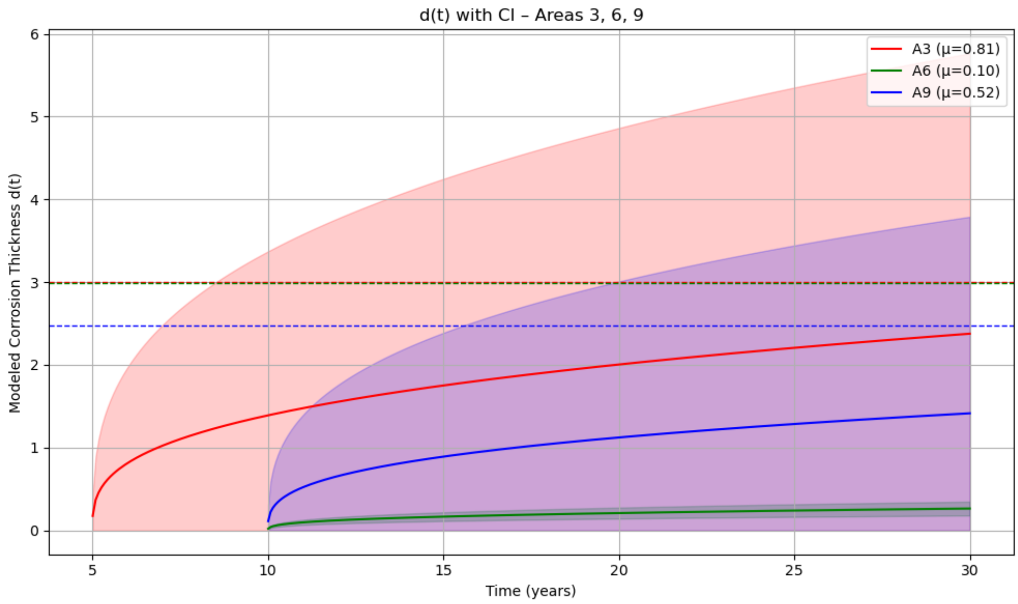

c)

Figure 4. Modelled corrosion thickness d(t) curves with 95% CI and critical thresholds: a) outer rings in three considered tanks, b) mid rings in three considered tanks, c) inner rings in three considered tanks.

Considering the established corrosion margins for each transverse structural element in the assessed ballast tanks, we can conclude that all steel plates in the three ballast tanks, as well as the three selected areas (outer, middle, and inner ring), meet the proposed corrosion margin.

The proposed methodology enables the identification of specific locations within structural areas, as part of the sub-areas of structural elements for which corrosion margins are suggested by CSR guidelines.

4. CONSLUSION

This paper presents the development and progression of corrosive processes in the water ballast tanks of an aging bulk carrier for nine specific locations. Assuming that the corrosion process starts after 5 and 10 years, we developed a corrosion wastage assessment methodology for three water ballast tanks. The developed methodology effectively demonstrates that the two-parameter Weibull distribution provides reliable results, which proves that the proposed corrosion allowance can adequately cover the CSR corrosion wastage of the structural members considered. Data show that Area 3 defined threshold is at approximately 8.52 years, and Area 9 reaches its critical threshold under the upper confidence interval bound at 15.60 years. Two areas signaling a possible early-risk scenario for this region have a significant corrosion rate. Comparing the obtained values, it can be concluded that regardless of the new methodology for assessing the corrosion state, which defines the specific locations of structural elements, all areas fit into the corrosion margins proposed by CSR. This research refers to area 3 (flange in top side tank) and area 9 (floor openings) as areas where critical values begin to appear much earlier than other areas, while areas 4 to 6 in the hopper ballast tank indicate more homogenous corrosion behavior.

Given that the evaluation was conducted on a single aging bulk carrier, future research could expand to include a broader range of similar vessels or explore alternative assessment methodologies, potentially focusing on the transverse member plates' connections to specific external environmental zones.

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and NKK. Currently, more than four hundred vessels (general cargo, bulk carriers, tankers, etc.) are being inspected by the Company.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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