An Analysis of Hull Structure Plating Failures Due to Corrosion

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Many different factors, such as cracks, damage, fatigue or corrosion, are indicative of hull structure degradation, of which fatigue and corrosion received the most attention in previous studies. Corrosion is the most frequent form of degradation that reduces the original thickness of materials over time, as manifested by weight loss, reduction of millimeters or percentage of thickness of steel plates. Corrosion can reduce the carrying capacity and longitudinal strength of vessels, cause different types of failures or result in environmental pollution. This study analyzes the corrosion of the structural element of the fuel tank of an old bulk carrier that has been in operation for 25 years. The database consists of thickness measurements expressed as the percentage of original plate thickness reduction and the analysis of the chemical compositions of the corroded and replacement steel plates. A total of 350 measurement data, collected after 5, 10, 15, 20 and 25 years of ship exploitation, as well as the chemical composition of the replacement steel plate have been examined. Linear corrosion models have been developed, while the chemical composition was analyzed using Energy Dispersive X-ray analysis of the samples from both sides of the corroded plate. The results obtained indicate that the degree of corrosion significantly varies depending on plate surroundings. Furthermore, the formulated linear corrosion model adequately follows the empirical data and the value of 1,55 %/year was obtained.

KEY WORDS

~ Corrosion
~ Failure
~ Linear model
~ Fuel tank
~ Bulk carrier

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1. INTRODUCTION

Corrosion is the result of interaction between metals and environmental conditions they are exposed to. Damage to different structural elements and areas affected by corrosion on vessels occurs due to changing environmental conditions and a variety of influencing factors during ship exploitation (typically for more than 25 years).

For example, bulk carriers and tankers are the main commercial ship types affected by corrosion. Previous studies looked into different influencing factors that contribute to the development of corrosion. Corrosion predictions are available in literature overview (Wang et al., 2021). So far, various studies focused on different ship characteristics (general information about the vessel, ballast tanks, cargo tanks, etc.) and environmental factors (atmosphere, immersion into water, etc.) (Wang et al., 2014; Ivošević et al., 2019). Many studies selected optimal corrosion models and analyzed corrosion mechanisms, the intensity of influencing factors, different types of corrosion, corrosion rates and depths. There are a number of studies conducted in real conditions that examined the effect of corrosion on welded constructions (Pastorčić et al., 2023; Vukelić et al., 2022) or stainless steal in a simulated environment (Gudić et al. 2022).

Long term exploitation can lead to different types of damage to ship structures that can further result in partial or total damage to the ship's structure and extensive repair works.

Severe damage can cause the total loss of ships or environmental pollution. Given that pollution caused by fuel leakage through ship plating (Figure 1) is manageable compared to more extensive damage resulting in excessive pollution, research on fuel tanks is of utmost importance (Ivošević et al., 2017; Ivošević et al., 2019; Ivošević et al., 2020.a).

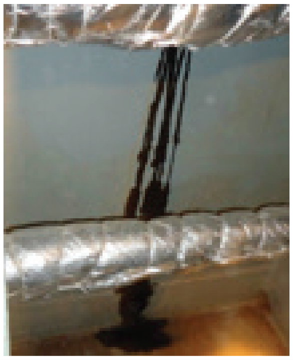


Figure 1.
Fuel oil tank leakage.

Bulk carriers and tankers, as vessels subject to corrosion, were previously studied in terms of damage to different structural ship parts (Chichi and Garbatov, 2019; Soares and Garbatov, 1998; Zareei and Iranmanesh, 2018; Garbatov and Soares, 2010), damage to bulk carrier transversal bulkhead (Soares and Garbatov, 1998.), general or pitting corrosion of bulk carrier deck plating, or corrosive reduction of all structural parts of bulk carriers (Caridis, 2001; Paik et al., 2004; Yamamoto and Ikagaki, 1998; Guo et al., 2008). The corrosion of metal structures can take different forms and reduce their weight. The most relevant research so far focused on the analysis of corrosion depth and rate (Paik et al., 2004; Garbatov and Soares, 2010; Wang et al., 2021; Soares and Garbatov, 1998). The rules of classification societies precisely define the allowable corrosion depth in millimeters, although some of the studies gave preference to the percentage of thickness reduction compared to the original thickness of installed steel plates (Ivošević et al., 2019; Ivošević et al., 2017; Ivošević et al., 2020.a).

This study examined the damage to the steel plates of fuel tanks of a bulk carrier that was in operation for more than 25 years. The second chapter analyzes the relevant fuel tanks and input databases along with methodology, the third chapter presents the results of the research, while the fourth chapter gives the conclusion.

2. MATERIALS AND METHODS

This study was based on the analysis of historical data on the wear and tear of the structural parts of the inner bottom, i.e. steel segments of the fuel tank of an aging bulk carrier that was in operation for more than 25 years. The data obtained by measurement, expressed as the percentage of wear and tear, were categorized based on thickness measurements performed during regular special surveys after 5, 10, 15, 20 and 25 years of operation. The wear and tear data were used to build a probabilistic model of corrosion development.

Over time, corrosion causes the wear and tear of steel plates deemed unacceptable under the regulations of classification societies, necessitating the replacement of certain structural segments or even entire steel plates and stiffeners. In that sense, the study analyzes the chemical composition of a corroded steel plate that was replaced after 25 years.

The research methodology has two directions:

- Assuming that corrosion starts to develop 4-8 years after ship construction, the study tested a linear corrosion model based on a unified and categorized database on the percentage of wear and tear of steel plates. The database also included information about wear and tear after 5, 10, 15, 20 and 25 years of exploitation.
- A corroded steel plate that was replaced due to excessive wear and tear, i.e. excessive thickness reduction (expressed as the percentage of wear and tear) was scanned using semi-quantitative analysis from both sides (the top side was close to the cargo, while the bottom side was close to the fuel), providing data on chemical composition changes of both sides of the damaged steel plate.

2.1. Materials

2.1.1. Database on the Percentage of Wear and Tear

The condition and wear and tear of structural elements due to corrosion have been established based on the measurements conducted on the vessel after 5, 10, 15, 20 and 25 years in accordance with the regulations of classification societies. The extensive measurements of steel plates and stiffeners were conducted. However, the study analyzes the steel plates of fuel tanks that were in contact with fuel inside the tanks or with cargo and dry spaces on the upper side of the tanks.

The analysis was conducted on the total of 4 fuel tanks, based on 350 measurement points. For categorization purposes, each tank was divided into 5 sections lengthwise, at equal distances. At each cross-section, plate reduction was analyzed and expressed in the percentage of wear and tear compared to original thickness, with the values obtained indicating the average wear of the plate (Ivošević et al., 2019; Ivošević et al., 2017; Ivošević et al., 2020.a). Figure 2 shows the obtained percentage values of the corrosive wear and tear of inner bottom plate (IBP) structural elements, grouped according to length of exploitation. Considering that exploitation length was 5, 10, 15, 20, or 25

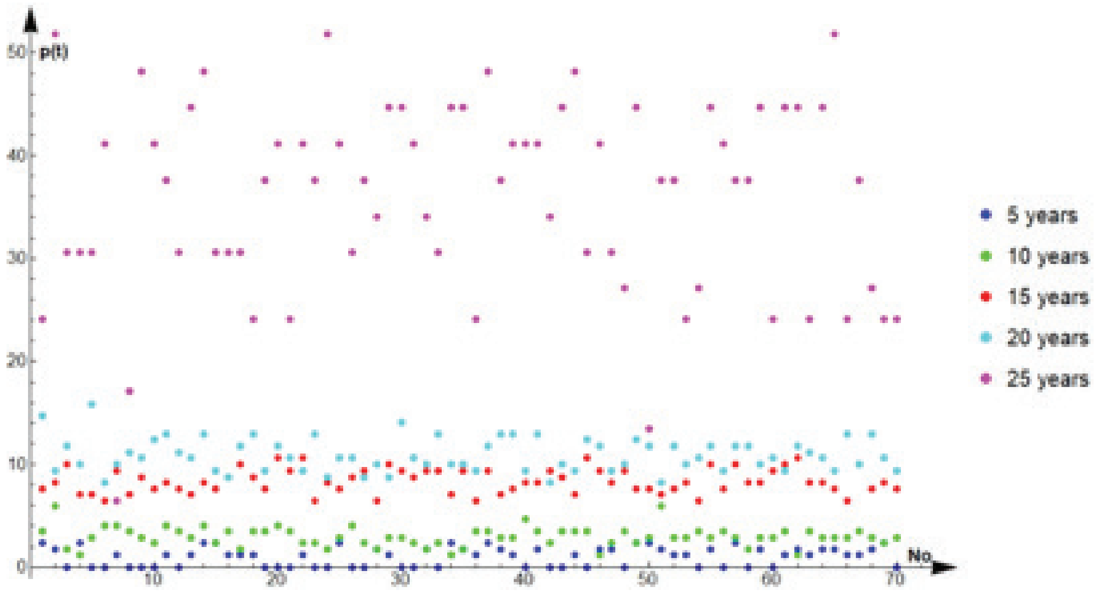
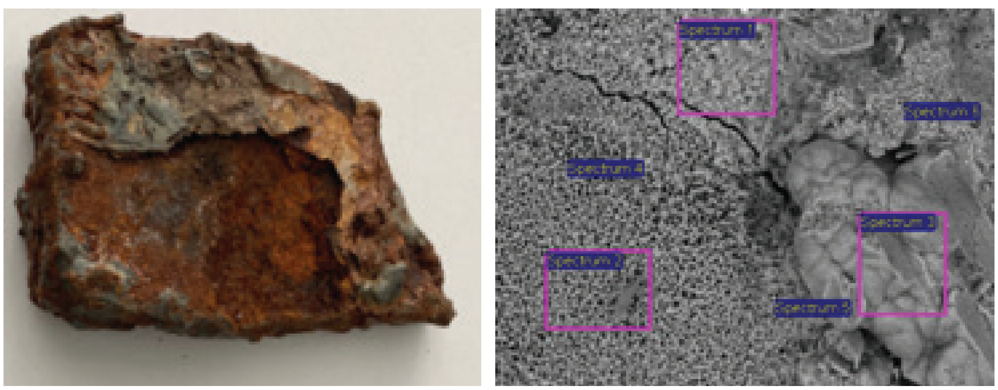


Figure 2.
The empirical database on the percentage of corrosive wear and tear of the inner bottom plate structure.

years, there were 5 different groups of empirical data which were subjected to further statistical analysis. Each group of data was assigned a different color in Figure 2. Furthermore, Figure 2 shows the ordinal numbers of corrosive wear measurements on the x-axis, while the corresponding percentage of the corrosive wear of the inner bottom structural plating is shown on the y-axis.

2.1.2. Database on the Chemical Composition of Damaged Plates

This database relies on the analysis of the chemical composition of the replaced steel plate taken from the corroded surface of fuel tank plating. More precisely, the steel plate and



a) b)

Figure 3.
Steal sample and corresponding EDX sample: a) sample from the bottom of the steel plate, b) a photo of the scanned sample from the bottom.

samples I11 and I12 faced the cargo hold (the top of the plate), while sample I21 faced the fuel tank (the bottom of the plate). The chemical composition of each plate was determined by means of Energy Dispersive X-ray analysis, where each sample was subjected to 6 spectrums under the magnification of 70, 100 and 200. Mean value, standard deviation, maximum and minimum values were calculated for each sample and each element - O, Cl, Fe and etc. The corresponding results of chemical composition analysis of all samples were covered by previous analysis (Ivošević et al., 2022).

2.2. Methods

The study relied on two methods. The first focused on the development of a linear corrosion model, while the second focused on the analysis of the chemical composition of the materials examined.

Corrosive processes are often described in literature (Paik and Thayamballi, 2002; Qin and Cui, 2003) with the following model:

$$d(t) = \begin{cases} c_1 (t - T_{cl})^{c_2}, & t > T_{cl} \\ o, & otherwise. \end{cases} \quad (1)$$

The above mathematical model shows the dependence of corrosion depth (d(t), expressed in nm or mm) on the length of exploitation (t) of a metal structure (expressed in months or years). In addition to the temporal component, the model also uses other parameters. The model takes into account the moment of the beginning of corrosive processes (T_{cl}). Additionally, parameter c_1 shows corrosion rate (expressed in mm/year or nm/month), while parameter c_2 is used to alter the intensity of time that affects corrosion processes. Frequently used values for parameter c_2 are 1 or 1/3, while the value of parameter c_1 is determined based on experimental data during statistical analysis.

In the statistical analysis presented in the following sections, the mathematical model (1) was used under the assumption that parameter c_2 has the value of 1, which means that corrosive process was intensive, while the value of parameter T_{cl} varied, so the model (1) was modified as follows:

$$d(t) = \begin{cases} c_1 (t - T_{cl}), & t > T_{cl} \\ o, & otherwise. \end{cases} \quad (2)$$

The paper analyzes the percentage values of corrosive wear and tear p(t) calculated based on the original average thickness (¯(d_0)) of the metal plates that were a part of the IBP of the ship structure. The incorporation of these factors into the model (2) resulted in a new model (3) which was subjected to statistical analysis:

$$p_t = \frac{d(t)}{\bar{d_0}} = \frac{c_1}{\bar{d_0}} (t-T_{cl}) = p_0 (t-T_{cl}) \quad (3)$$

The model (3) obtained indicated the functional dependence of the wear percentage of the original IBP metal structure on the length of ship exploitation. The model uses the p_0 parameter, which can be interpreted as annual wear percentage of metal structures based on the original average thickness of a metal plate (¯(d_0)).

As previously indicated, semi-quantitative Energy Dispersive X-ray analyses were used to analyze the chemical composition of the corroded plate structure of fuel oil tanks. A high-resolution Field Emission SEM Sirion 400 NC (FEI, USA) was equipped with an EDX detector - INCA 350 (Oxford instruments, UK). The EDX semi-quantitative analysis determined the content of chemical elements on the surface of the corroded samples with up to several spectrums per sample and under different magnifications.

3. RESULTS

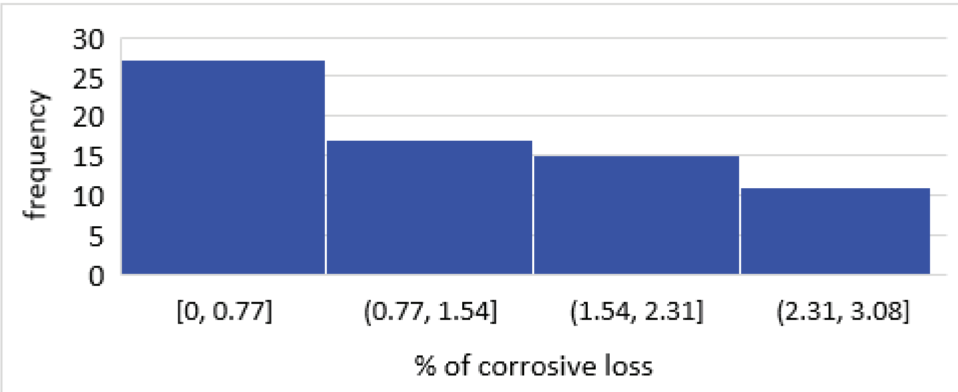
3.1. The Results of the Corrosive Reduction Percentage of Inner Bottom Plating

Table 1 provides the most important descriptive statistics of the corrosive wear percentage in order to give a more detailed account of empirical data groups. Table 1 shows numerical values for each observed interval of ship exploitation (5, 10, 15, 20, and 25 years). The presented values include the mean, standard error (SE), median, mode, standard deviation (SD), variance (Var), range, minimum (Min) and maximum (Max) values of the observed data, as well as the total value of the observed data (Sum) and the total number of measurements taken.

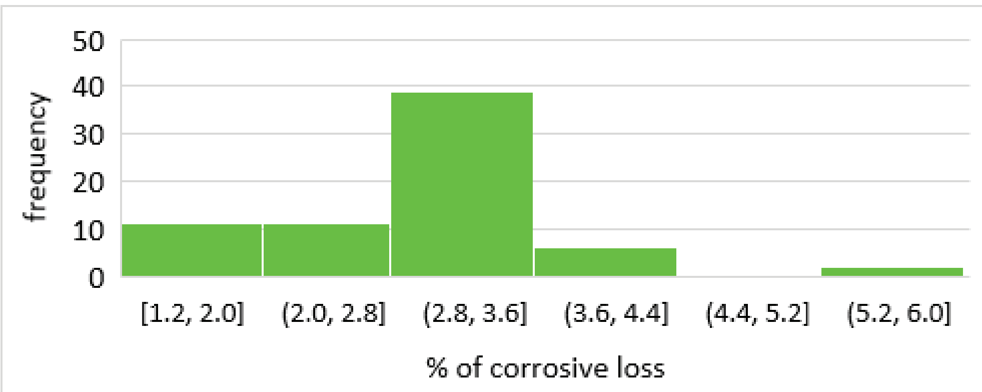
Figure 4 shows empirical data in the form of a histogram. There is one graphic representation for each observed interval of ship exploitation. The x-axis of these graphs shows the wear percentage intervals of the original steel plates caused by the influence of corrosive processes. The y-axis shows the number of measurements whose values correspond to the defined wear percentage intervals.

Table 1.
Values of descriptive statistics related to the empirical database.

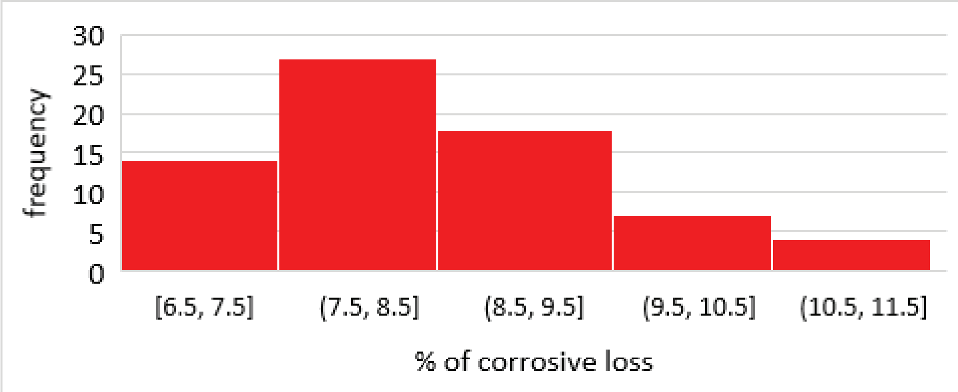
5 years		10 years		15 years		20 years		25 years	
Mean	1.03	Mean	3.00	Mean	8.39	Mean	10.90	Mean	35.89
SE	0.11	SE	0.11	SE	0.14	SE	0.19	SE	1.14
Median	1.18	Median	2.94	Median	8.24	Median	10.59	Median	37.65
Mode	0.00	Mode	2.94	Mode	7.65	Mode	9.41	Mode	44.71
SD	0.90	SD	0.94	SD	1.18	SD	1.62	SD	9.55
Var	0.82	Var	0.88	Var	1.38	Var	2.62	Var	91.23
Range	2.35	Range	4.71	Range	4.12	Range	7.65	Range	45.29
Min	0.00	Min	1.18	Min	6.47	Min	8.24	Min	6.47
Max	2.35	Max	5.88	Max	10.59	Max	15.88	Max	51.76
Sum	72.35	Sum	210.00	Sum	587.65	Sum	762.94	Sum	2512.35
Count	70	Count	70	Count	70	Count	70	Count	70



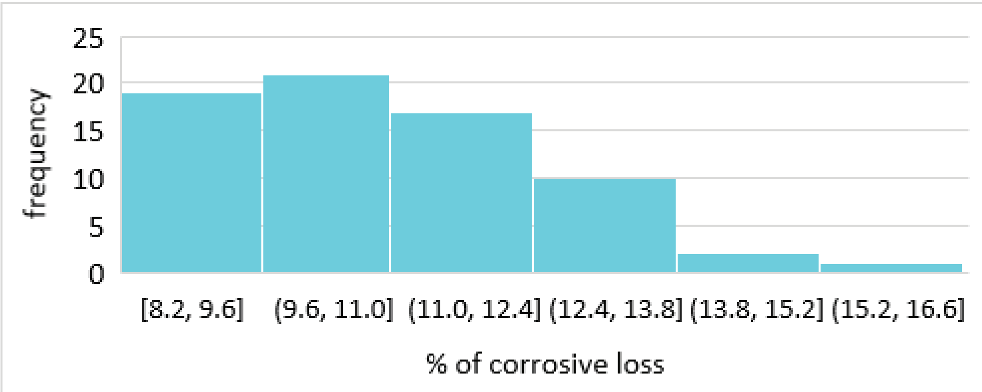
a) 5 years



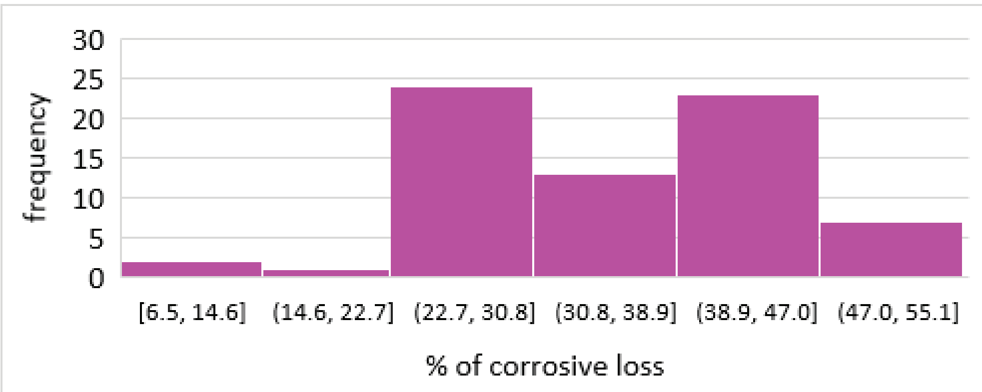
a) 10 years



a) 15 years



a) 20 years



a) 25 years

Figure 4.
Histograms of corrosive wear percentage grouped by the length of ship exploitation.

Statistical analysis was conducted to establish the linear dependence of the wear percentage on the length of exploitation to better understand corrosion processes in respect of the corrosive wear percentage of inner bottom plating metal structures. Additionally, the statistical analysis provided an insight into the value of the annual percentage of the corrosive wear and tear of the inner bottom plating of ship structures. The conducted statistical analysis was based on the established model described by expression (3). As previously mentioned, the statistical analysis was based on several assumptions:

- inner bottom plating structure is affected by intense corrosion processes; value 1 is adequate for parameter c_2;
- inner bottom plating structures are protected by an anti-corrosive coating that slows down the onset of corrosive wear. Therefore, parameter T_{cl} has an important role in the formation of a model that properly describes empirical data.

Scientific literature and previous studies by the same author (Ivošević et al., 2019; Ivošević et al., 2020.b) show that the best interval for observing inner bottom plating structures is between 4 and 8 years of exploitation, which means that parameter T_{cl} has the value of the interval i.e., between 4 and 8 years. Different models were obtained by including the assumed values from model (3), which needed to be fitted to empirical data. Hence, the value of parameter p_0 (the value of the annual corrosive wear percentage) was determined during the model fitting procedure, after which the following linear corrosion models were built for the IBP structure observed:

$$p_4(t) = 1.21546 \cdot (t - 4)\ (\text{given that } t > 4) \tag{4}$$

$$p_5(t) = 1.30668 \cdot (t - 5)\ (\text{given that } t > 5) \tag{5}$$

$$p_6(t) = 1.40579 \cdot (t - 6)\ (\text{given that } t > 6) \tag{6}$$

$$p_b(t) = 1.55146 \cdot (t - 7.4)\ (\text{given that } t > 7.4) \tag{7}$$

Models represented by expressions (4) - (6), i.e. p_4 (t), p_5 (t), and p_6 (t) models were obtained by using T_{cl} values 4, 5, and 6, respectively, along with the previously defined assumption: c_2=1. The best-fitted model was labeled as p_b (t) and is represented by formula (7). This model indicates that the most suitable T_{cl} value is 7.4 years.

The four linear models are graphically presented in Figure 5. The linear model that most adequately follows the empirical data of the corrosive wear percentage of the inner bottom plating structures is characterized by a slightly higher value of the p_0 parameter - p_0=1.55146 %/year.

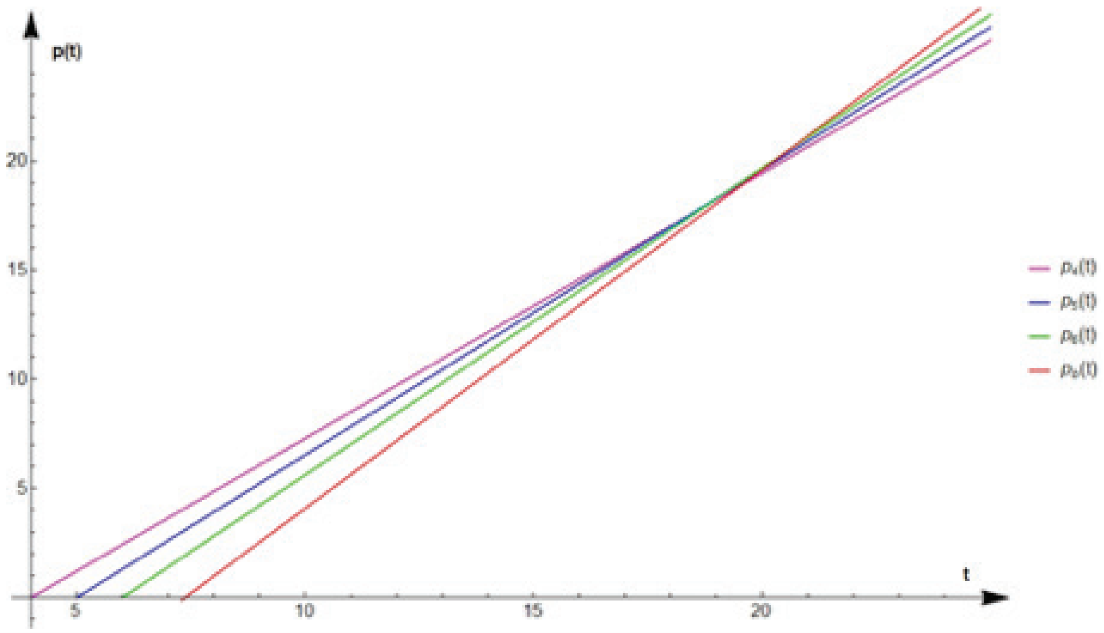


Figure 5.
Graphical representation of linear models of IBP structure wear percentage.

3.2. The results of the EDX analysis

Data presented in Figure 6 (the EDX results) clearly show that after extended exposure to corrosion, the side of the analyzed fuel tank steel plate facing the cargo hold (IBP 1.1 and IBP 1.2) has considerably different chemical composition than the side facing the fuel tank (IBP 2.1). Namely, the EDX analysis detected the presence of only iron, oxygen and a small amount of chloride ions on the steel plate of the inner bottom plating facing the cargo hold. By contrast, in addition to iron, oxygen and chloride ions, the analysis detected inorganic ions (Mg, Na, K, Al and Si) and organic components (carbon, sulfur) on the surface facing the fuel tank. While inorganic ions could be due to seawater exposure, organic components are considered to be the residues of fuel transported in the tank. All results presented in Figures 6 and 7 and Tables 2 and 3 are expressed in weight %.

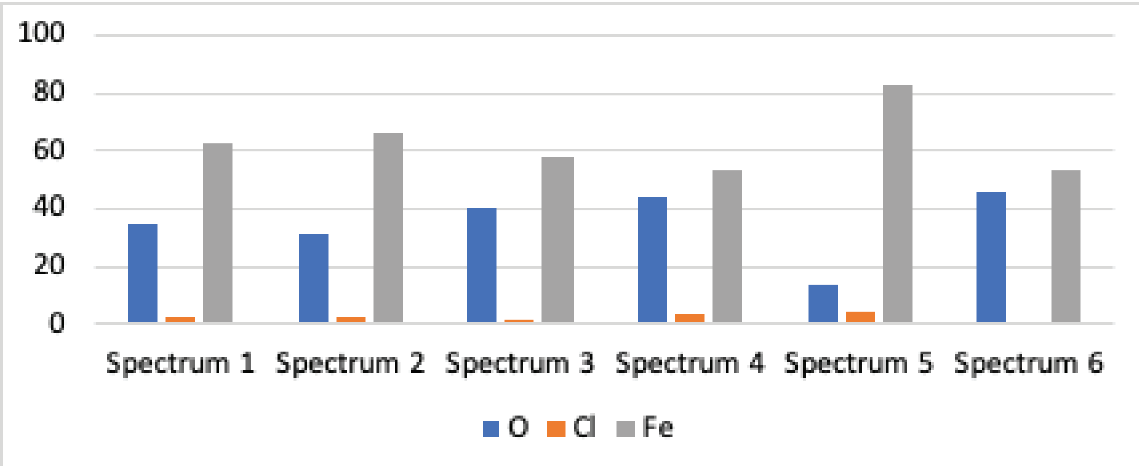


Figure 6.
Chemical composition of IBP 1.1 and Sample 1 (corroded steel plate facing the cargo holds).

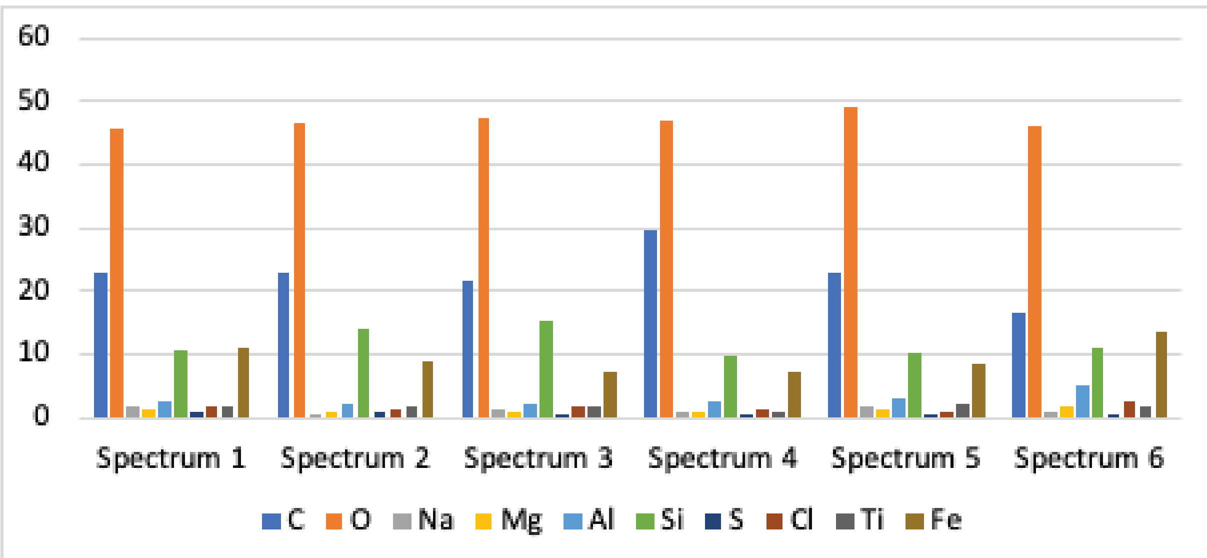


Figure 7.
Chemical composition of IBP 2.1 and Sample 1 (corroded steel plate facing the fuel tank).

Table 2.
Descriptive statistics of the chemical composition of IBP 1.1 and Sample 1 (corroded steel plate facing the cargo).

	O	Cl	Fe
Mean	34.95	2.52	62.53
Std. deviation	11.92	1.26	11.04
Max.	45.98	4.01	82.59
Min.	13.40	0.33	52.85

Table 3.
Descriptive statistics of the chemical composition of IBP 2.1 and Sample 1 (corroded steel plate facing the fuel tank).

	C	O	Na	Mg	Al	Si	S	Cl	Ti	Fe
Mean	22.75	47.05	1.23	1.13	2.86	11.89	0.48	1.56	1.62	9.41
Std. deviation	4.20	1.17	0.51	0.27	1.13	2.30	0.21	0.54	0.46	2.55
Max.	29.77	49.11	1.86	1.53	5.07	15.35	0.78	2.55	2.18	13.72
Min.	16.65	45.88	0.65	0.87	2.11	9.65	0.27	1.02	0.80	7.11

The presented results of the analysis of corroded steel plate chemical composition confirm that surroundings have a dominant effect on corrosion processes.

4. CONCLUSION

The findings obtained through statistical analysis confirm that:

- the best linear model indicates that the most suitable value of the start of corrosion T_{cl} is 7.4 years,
- the loss of material due to corrosion is 1.55146 %/year,
- the analyses of the chemical composition of both sides of the corroded plate indicate that surroundings have a significant effect on the chemical changes in materials.

Future research could apply the same methodology to separately analyse both sides of corroded plates from different ship areas, such as main deck plating, side shell plating, longitudinal girder plating, etc.

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CONFLICT OF INTEREST:

The authors declare no conflict of interest.

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