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Combining Weibull Distribution Function and Monte Carlo Simulations in Predicting Corrosion Losses Over Inner Bottom and Hoper Plating of Ageing Bulk-Carriers

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ABSTRACT

This article gives an overview of main operational parameters that influence corrosion over ageing bulk-carriers' member locations. The particular vessels' hull structure locations being affected intensively by these parameters are identified, as well. The zone identified as the most *vulnerable* one, i.e. inner bottom and hopper plating, has been probabilistically treated. Within the extensive previous probabilistic analysis of the corrosion losses over aging bulk carriers, it has been shown that the considered data exhibit great scattering. The same was with the data which were available to us for the purpose of this research work. In fact, it was difficult to fit the data collected by the regular and standardized ships' measurements on board by the UTM Company "Invar-Ivosevic"[1], to the most commonly used Weibull distribution, which usually in the best manner fits the corrosion wear over considered ageing ships. Consequently, an optimal procedure of pre-processing the collected data in order to better fit them into the Weibull distribution function, has been proposed in the article.

1. Introduction

The corrosion is one of the most important factors affecting structural safety and integrity of ageing bulk carriers. Though, the operational life extension of the bulk carriers' steel structures requires permanent consideration of the plates' thickness losses due to the corrosion. For commercial naval ships, like bulk carriers, the extent of the corrosion losses is usually measured through the classification society ships' surveys (Adamson, Brown, 1999). Besides the regular steel thickness measurements, corrosion protection measures are necessary, as well. These measures include paint coatings and sacrificial anode systems for immersed areas. Since these measures are not always wholly effective, continual maintenance is required, but not always applied (Gudze, Melchers, 2008). In order to provoke and support more intensive maintain measures, several bulk carriers' time-variant corrosion losses probability models have been developed up to now (Paik, Kim, Lee, Park, 1998; Paik, Lee, Park, Hwang, Kim, 2003; Paik, 2004; Paik, Thayamballi, Park, 2004). However, the researchers in this domain are usually faced with some serious difficulties, like: very complex character of the interaction of the ship with its environment and the interaction between the different parts of the ship's hull, the insufficient data for the ship's hull structures deterioration caused by the corrosion, and the lack of the data about the changes of the mechanical properties of the shipbuilding material during its operation and reparations (Ivanov, 2009). The large scattering of the data obtained by the different established corrosion probability, or time-dependant models has been noted. Additionally, most of the corrosion prediction models for the ships take little or no account of the operational parameters, and profile of the ships. Consequently, we did an effort through the analysis being presented in this article to stress the operational parameters that commonly affect the structural safety and stability of ageing bulk carriers' structural member locations (areas/zones), and intensify corrosion processes onboard.

2. On the bulk carriers' structural member locations

Up to now, the group of authors (Sone, Magaino, Yamamoto, and Harada) have analyzed some longitudinal and transversal elements of bulk carriers, i.e. twenty elements of the bulk carriers with the capacity over 50 000 DWT, and fourteen

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elements of the bulk carriers with the capacity less than 50 000 DWT, registered under the Japanese ClassNK register (Sone, Magaino, Yamamoto, Harada, 2003). In the work of Gardiner and Melchers, the cargo holds were examined (Gardiner, Melchers, 2003; Melchers, 2003; Melchers, 1999; Gardiner, C.P., Melchers, 2001; Gardiner, Melchers, 2002; Gardiner, Melchers, 2002; Sone, Magaino, Yamamoto, Harada, 2003; Gardiner, Melchers, 2001), while the ballast tanks have been examined in the study works of Noor, Soares, Gudze, et al., (Noor, Smith, Yahaya, 2007; Soares, Garbatov, Zayed, Wang, 2005; Gudze, Melchers, 2006), as the bulk carriers' areas with the highest risk of the structural errors occurrence. Paik and others (Paik, Lee, Park, Hwang, Kim, 2003) have analyzed the degree of corrosion over twenty-three different longitudinal structural elements of the ship, etc. The authors of this paper have analyzed fuel tanks (Bauk, Aleksić, Ivošević, 2011) as those located between several different media (fuel, cargo, ballast, air spaces, etc.) and consequently in great extent affect by the corrosion processes.

The shortage of the most of the previous research works in this domain is reflected in a limited number of available data on corrosion losses over ageing bulk carriers, and in detail investigation on only few structural elements of the ship. Though, due to our knowledge, there are no studies in this field considering the ship as a whole, including its both longitudinal and transversal structural elements (areas, zones), taking into account their position and orientation, but only its segments were treated separately. In this paper, the complete bulk carrier structure has been divided into eleven structural zones that include both longitudinal and transversal elements, and then they were matched with the operational parameters being previously identified and briefly described.

Within this article, through defining eleven distinguished zones, an effort has been done toward the entire ship analyzing due to the corrosion deteriorations, through both transversal and longitudinal stiffening and plates of its structure (Bauk, Nikolić, Ivošević, 2010; Bauk, Ivošević, 2010; Bauk, Ivošević, Nikolić, 2010). In such manner, the key areas of degradation, due to the operational factors that affect corrosion can be identified, and ultimately the ship's structural strength and stability can be analyzed more easily and effectively. Further analysis in this direction, within each area can determine the corrosion processes, and eventually allow their modeling for the entire ship's structure. The identified eleven areas of the bulk carriers are shown in Figure 1 and listed in Table 1.

Table 1. The longitudinal and transversal member locations of bulk carriers.

Member location/category	Abbreviation	Longitudinal components	Transversal components
1. Upper deck	UD	X	
2. Deck superstructure	DS	X	
3. Bottom and side shell plating	BSSP	X	
4. Hatch cover and coamings	HCC	X	X
5. Structure in top side tanks	STST	X	X
6. Cargo holds transverse bulkheads	CHTB		X
7. Cargo holds main frames	CHMF		X
8. Inner bottom and hopper plating	IBHP	X	X
9. Internal structure in double bottom tanks	ISDBT	X	X
10. After peak structure	APS	X	X
11. Fore peak structure	FPS	X	X

The main structural features of the above listed eleven member locations of bulk carriers (see Figure 1, and Table 1) are described in some more details in (Bauk, Ivošević, 2011; Bauk, Nikolić, Ivošević, 2010; Bauk, Ivošević, 2010; Bauk, Ivošević, Nikolić, 2010). Some operation parameters that usually affect bulk carriers' member locations are described in (Gudze, Melchers, 2008; Gardiner, Melchers, 2003), and they are only listed here, in Table 2.

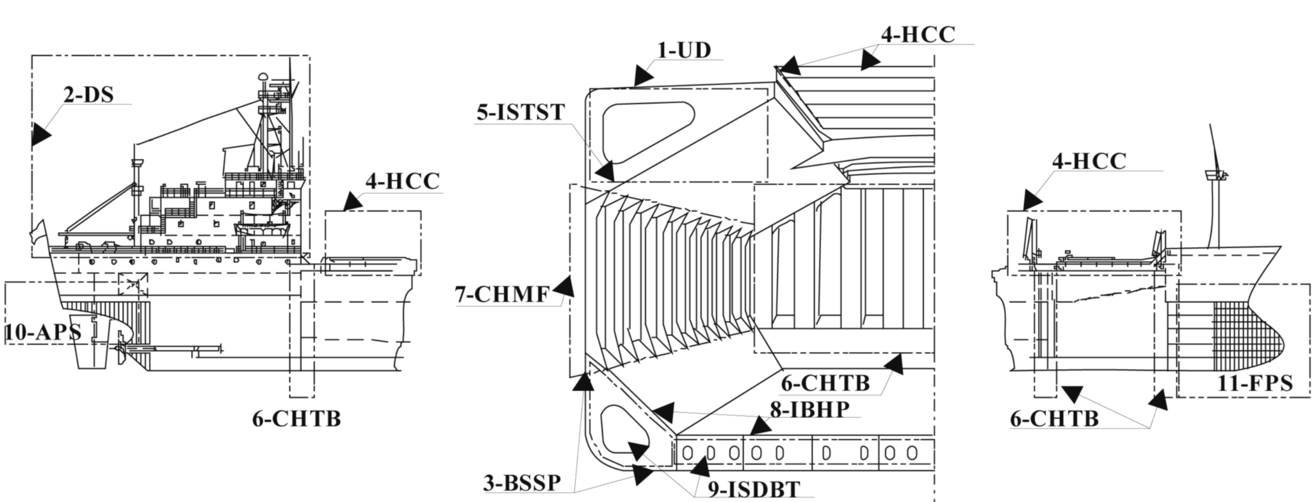


Figure 1. Member locations (longitudinal and transversal ones) of the bulk carrier hull structure.

Table 2. The operational parameters that usually influence corrosion.

Operational parameters affecting corrosion over bulk carriers in exploitation	
1. Sea water	6. Atmosphere
2. Ballast water	(semi-closed, voided spaces)
3. Fuel	7. Manipulative equipment
4. Cargo	8. Maintenance
5. Atmosphere	9. Contact zones
(open atmospheric conditions)	10. Temperature, etc.

Through the authors' previous research work (Bauk, Ivošević, 2011; Bauk, Nikolić, Ivošević, 2010; Bauk, Ivošević, 2010; Bauk, Ivošević, Nikolić, 2010), it has been found out that the most *vulnerable* member location of aging bulk carriers due to the above listed operational parameters (see Table 2), is the inner bottom and hoper plating (IBHP). Namely, during the operational cycle of ships, they carry various kinds of more or less corrosive cargo. The physical-mechanical properties of materials: density, bulk angle, the coefficient of friction, sulfur content, moisture, etc., are some of the factors that influence the progress of the corrosion process. More corrosive cargo will cause early removal of surface coatings (coal, iron ore), while the less corrosive materials (grains) contribute to a slight acceleration of the corrosion process. Increased frequency of cargo exchanges will also requires more frequent use of manipulative equipment. The use of manipulative equipment with abstraction heavy burden (heavy shovels and loading bucket) will contribute to the earlier removal of surface protection over some ships' member locations. Intensive operations with the corrosive cargos will require adequate maintenance system, whose absence will speed up the corrosion process. Cleaning and scraping double bottom cover, or IBHP will contribute significantly to earlier removal of surface protection of the steel plates of ships' holds, so that the corrosion process begin much earlier over this hull structure member area than with other structural elements and areas. A large number of strokes caused by the handling equipment over the double bottom produce the deformation of the steel plate covering the double bottom, which will cause cracking of the surface protection to the underside of the steel plate inside the tank. Due to intense ballasting and shifts wet and dry cycles, the early crack of the surface protection will contribute accelerating the corrosion of steel plate from bottom, or from the ballast tanks. Thus, the intensive corrosion process will occur in these structural areas on both sides, upper (from cargo holds) and lower (from web frames and fuel tanks), which is not the case with other constructive areas. That is why the intensity of corrosion of the IBHP structural zone is much higher than over other zones. Though, the further analysis are directed toward examining data on IBHP deterioration caused by the corrosion, being measured on board ships by UTM "Invar-Ivosevic" Company, and establishing the probabilistic time-dependent model of the corrosion depth over this member location. For this purpose, the particular combination of Weibull distribution function and Monte Carlo simulations has been employed, and the applied methodology is explained in some more detail within the next part of the paper.

3. Applied methodology

As it is still pointed out, in the previous probabilistic analysis of the corrosion losses over aging bulk carriers, it has been shown that the considered data exhibit great scattering (Paik, Kim, Lee, Park, 1998; Ivanov, 2009; Melchers, 2003; Melchers, 1999; Gudze, Melchers, 2006; Bauk, Nikolić, Ivošević, 2010; Bauk, Ivošević, 2010; Bauk, Ivošević, Nikolić, 2010; Wang, Lee, Ivanov, 2008; Ivanov, Wang, Seah, 2004). The same was with the data that were available for the purpose of this research. Namely, we were in position to realize some probabilistic analyses over 17 different aging bulk carriers (Table 3, note: some of the considered ships are the same, but analyzed in different periods of exploitation). More precisely, analysis have been done over 1841 gauged points. More precisely, the measured

Table 3. Features of the analyzed ships in the different points of their exploitation circles.

After 15 years of exploitation					
Ship	**Built**	**Years old at the moment of measuring**	**Classification society***	**GRT**	**DWT**
S1	1996.	15	BV	18495	29292
S2	1984.	15	BV	19045	48826
S3	1995.	15	NK	17040	27837
S4	1994.	15	NK	22147	37055
After 20 years of exploitation					
Ship	**Built**	**Years old at the moment of measuring**	**Classification society***	**GRT**	**DWT**
S1	1984.	20	BV	19045	48826
S2	1984.	20	BV	15200	41900
S3	1984.	20	BV	15220	41920
S4	1984.	20	NK	11368	19496
S5	1984.	20	NK	11356	19496
S6	1984.	20	DNV	24844	42312
S7	1982.	20	BV	17436	47871
After 25 years of exploitation					
Ship	**Built**	**Years old at the moment of measuring**	**Classification society***	**GRT**	**DWT**
S1	1984.	25	BV	19045	48826
S2	1984.	25	BV	15200	41900
S3	1984.	25	BV	15220	41920
S4	1984.	25	DNV	24844	42312
S5	1983.	25	LR	25742	41427
S6	1984.	25	ABS	17599	4239
S7	1978.	25	BV	22372	38972
S8	1983.	25	LR	22112	38110
S9	1982.	25	BV	25056	44504
S10	1982.	25	BV	25056	44504

**Legend:* BV- Bureau Veritas, LR – Lloyd's Register, DNV – Det Norske Veritas, ABS – American Bureau of Shipping, ClassNK –Nippon Kaiji Kyokai.

data on corrosion wear for four bulk carriers being in exploitation 15 years (297 gauged points), for eight bulks being in exploitation 20 years (637 gauged points), and for nine bulk carriers being in operation 25 years (917 gauged points), have been given to our disposal. The collected data set represent the corrosion wear (loss) in the form of corrosion depth [mm]. Namely, these data were provided by UTM "Invar-Ivosevic" Company. However, it was difficult to fit the data collected by regular and standardized ships' measurements on site to the most commonly used Weibull distribution, which usually (along with normal and lognormal distribution) best fits the corrosion wear over ageing bulk carriers (Paik, Kim, Lee, Park, 1998; Ivanov, 2009).

Consequently, it was necessary to find out an optimal way of pre-processing the collected data in the attempt to fit them better into Weibull distribution function. For that purpose generator of random numbers for inverse Weibull distribution function has been used. The proposed algorithm, being employed in the paper, should be explained briefly through the following steps:

- Inserting into the Excel worksheet measured values of the corrosion depth [mm], over the ageing bulk carriers' inner bottom and hopper plating member locations;
- Generating random numbers for the inverse Weibull distribution function with predefined subjectively estimated distribution parameters (α, β, γ);
- Examining where the measured values of corrosion wear, on board, correspond to the pseudo randomly generated numbers, and then forming the new series of that values;
- Identifying the frequencies of appearing of each different measured values in the new-formed series, and
- Finally, by the EasyFit software (ver. 5.5), finding out which of the numerous offered distributions within this software model database best fit the selected data from the set of measured values; while the selection of the data was done, as it is still noted, in accordance with randomly generated numbers from inverse Weibull distribution law. These steps were realized by the Excel special function NTRANDWEIBULL (α, β, γ), and Excel imbedded functions LOOKUP (value, range) and COUNTIF (range, criteria). The function NTRANDWEIBULL returns Weibull pseudo random numbers based on Mersenne Twister algorithm. The function LOOKUP (value, range) returns values from the input data set on corrosion losses being measured on site that belongs to the corresponding random numbers intervals being generated from inverse Weibull distribution. The whole process of finding out the correlation between measured values and random generated numbers has been in accordance to Monte Carlo simulation method. An example of NTRANDWEIBULL (α, β, γ) function realization along with Monte Carlo simulations in Excel worksheet is shown in Table 4.

Table 4. An example of combining random generated numbers from inverse Weibull pdf and Monte Carlo simulation method (segment of the Excel worksheet).

	A	B	C	D	E	F	G	
1	Corrosion [mm]	Weibull RAND	LOOKUP	Diff. corr. ware values	No. of appearing	Frequency		
2	0.0	4.181834	3.1	0.0	35.0	0.062724	Mean:	1.5
3	0.0	2.125919	2.1	0.1	60.0	0.107527	St. dev.:	1.5
4	0.1	1.448396	1.4	0.2	0.0	0.000000	Var.:	2.3
5	0.1	1.209807	1.2	0.3	26.0	0.046595		
6	0.1	2.525701	2.5	0.4	30.0	0.053763		
7	0.1	0.922361	0.9	0.5	37.0	0.066308		
8	0.1	2.065580	2.0	0.6	45.0	0.080645		
9	0.1	7.218747	4.7	0.7	0.0	0.000000		
10	0.1	2.609389	2.6	0.8	35.0	0.062724		
11	0.1	2.382233	2.3	0.9	0.0	0.000000		
12	0.1	0.823797	0.8	1.0	21.0	0.037634		
13	0.1	3.279766	3.1	1.1	22.0	0.039427		
14	0.1	0.093471	0.0	1.2	13.0	0.023297		
15	0.1	0.300497	0.3	1.3	14.0	0.025090		

20 years grain / 20 years iron

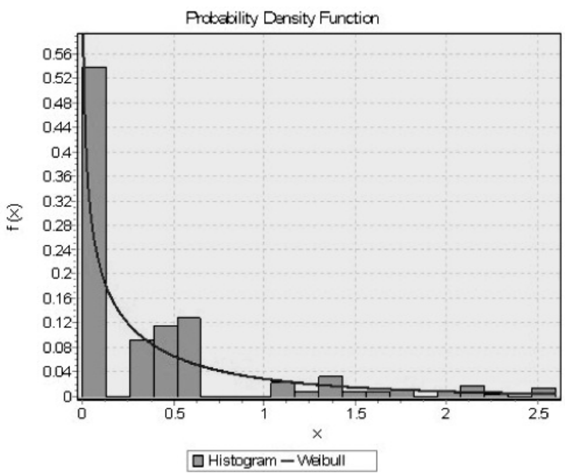
4. Numerical results

Within this subsection are presented some of the numerical, i.e. graphical results obtained by NTRANDWEIBULL function being imbedded into Excel, and combined with the Monte Carlo simulation concept of generating random numbers, along with examining how these random generated numbers correspond to the measured values of corrosion wear over IBHP member location of analyzed aging bulk carriers. Thus, probabilistically have been analyzed the data on the corrosion losses over ageing bulk carries within three different points of time, i.e. after 15th, 20th and 25th year of the ships' exploitation. Both bulk carriers for grain and other smallness (dusty) bulk cargos, and those for iron ore and coil have been taken into the consideration. Since the greater wear of the bulk carriers' structure steel due to the corrosion is observed over the ships which carry the iron ore and coil, than over those carrying grain or other light cargos, these two groups of bulks were treated separately by the previously proposed probabilistic-simulation method, and the following results have been obtained:

In the case of four ships for grain cargo, being in exploitation 15 years, the Weibull distribution function with noted parameters was found out as one that best fits the collected data on site, at 297 gauge points (see Figure 2).

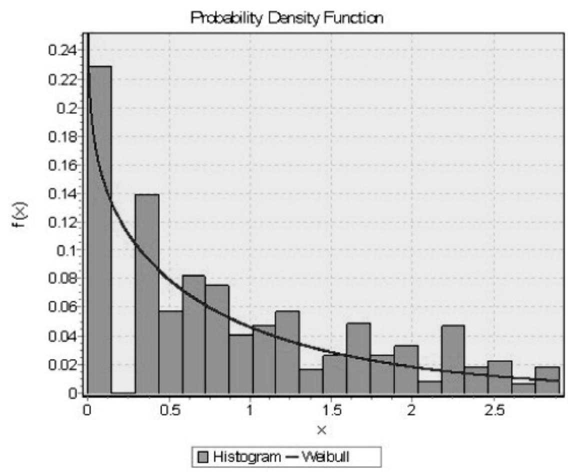
In the case of seven ships for grain and other smallness, dusty bulk cargos, being in exploitation 20 years, the Weibull distribution function, with below given parameters, has been found as one that best fits the collected data over 558 gauge points (see Figure 3). In the case of only one available ageing bulk carrier for iron ore and coil, being in service 20 years, the Weibull distribution has been identified again as one which best fits the gathered data over 79 gauge points (see Figure 4).

In the case of six bulk carries for transportation of iron ore and, being in exploitation 25 years, the Weibull distribution, with given parameters, was found out to best fits the collected data on the corrosion loss over even 679 gauged points (see Figure 5). These probabilistic data may be the subject of further more rigorous and detail analysis, but, they can give a general overview how and to what extent corrosion affects ageing bulk carriers in the certain



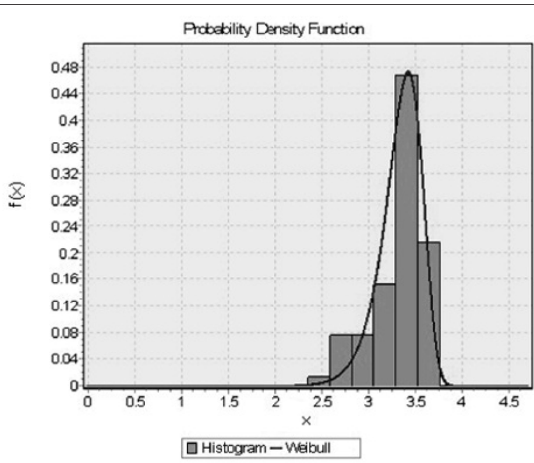
Parameters of the Weibull distribution function: $\alpha = 0.7$; $\beta = 0.51365$; $\gamma = 0$; Mean: 0.65019; Var.: 0.95085; St. Dev.: 1.4624

Figure 2. Corrosion depth [mm] measured over the bulk carriers being in exploitation 15 years (cargo: grain).



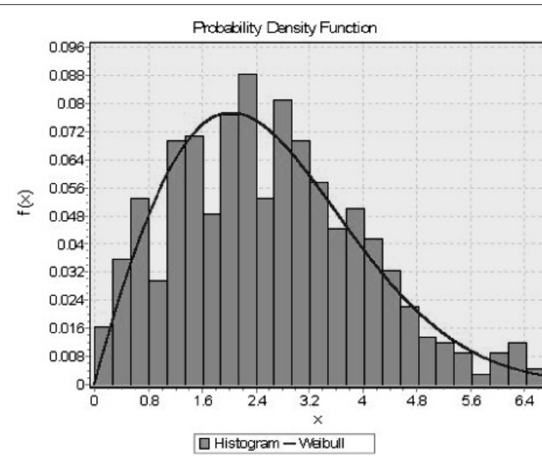
Parameters of the Weibull distribution function: $\alpha = 0.87$; $\beta = 1.0$; $\gamma = 0$; Mean: 1.5; Var.: 2.3; St. Dev.: 1.5

Figure 3. Corrosion depth [mm] measured over the bulk carriers being in exploitation 20 years (cargo: grain).



Parameters of the Weibull distribution function: $\alpha = 18.7$; $\beta = 3.4292$; $\gamma = 0$; Mean: 3.3326; Var.: 0.04858; St. Dev.: 0.22041

Figure 4. Corrosion depth [mm] measured over the bulk carriers being in exploitation 20 years (cargo: iron ore).



Parameters of the Weibull distribution function: $\alpha = 1.9548$; $\beta = 2.9351$; $\gamma = 0$; Mean: 2.6024; Var.: 1.9283; St. Dev.: 1.3886

Figure 5. Corrosion depth [mm] measured over the bulk carriers being in exploitation 25 years (cargo: iron ore).

point of time (after 15, 20, and 25 years of exploitation). What is obvious is that the corrosion wear rapidly grows with time, which the ship spends in exploitation. Namely, the parameter beta of Weibull distribution considerably grows as the time of service becomes longer. As well, the corrosion losses are much more in the cases when bulk carriers were used for the transportation of dense cargoes like iron ore and coil, than in the cases when they were used for the transportation of grain and other smallness, or dusty bulk cargos. By the proper modifications in the input data set (measured values of the corrosion losses on site) it is achieved that some of the collected data are well fitted into the Weibull distribution function, what can be used later effectively for predicting corrosion depth depending on time which bulk carrier spent in service. The modifications are based on matching the collected data by those randomly generated form the inverse Weibull distribution with arbitrary chosen parameters. This model might be proposed as general one for pre-processing data which are likely to be properly fitted to the Weibull distribution function.

5. Conclusions

The structural member locations of ageing bulk carriers are exposed to a range of corrosive environments. The existence and also the influence of each environment do not remain constant throughout the bulk carriers' service lives. Though, the attempts are directed toward developing as reliable as possible time-variant probabilistic based patterns of corrosion that are characteristic to each, and particularly to those spaces that are the most influenced due to the corrosion wear. Due to some previous analysis Bauk, Ivošević, 2011; (Bauk, Ivošević, 2010; Bauk, Ivošević, Nikolić, 2010; Wang, G., Lee, Ivanov, 2008) the IBHP has been identified as the most vulnerable member location (area/zone) of aging bulk carriers, and it was probabilistically treated on the basis of the set of original data on the corrosion losses over several analyzed bulk carriers on sites. The measured data have been pre-processed, or filtered, in accordance with randomly generated numbers from inverse Weibull distribution. It has been shown that the pre-processed measured data well follow the Weibull theoretical probability density function, and their main parameters (mean value, standard deviation, and variance) have been calculated for the bulk carriers' being in service 15, 20 and 25 years (in cases of grain and iron ore cargos). The observed scatterings in the Weibull functions parameters over analyzed data sets of measured corrosion depths, pointed the need for further more rigorous investigation in this field above the larger set of the original data being collected in shorter time intervals. Consequently, corrosion losses over ageing bulk carriers' member locations require paramagnet monitoring and profound analysis over each particular segment, and over the vessel hull structure as a whole, simultaneously.

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