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SCANNING FUEL TANKS' CORROSION WASTAGE OF SOME AGED BULK CARRIERS DUE TO SECURITY REASONS

ABSTRACT

This paper deals with two different approaches in modelling corrosion wastage over the fuel tanks' structures on the example of ten aged bulk carriers. The first applied method might be treated as a short-term, rather random oriented one, and it is based on the Monte Carlo simulation technique. This technique has been used in creating an appropriate predictive model for the characteristic steel damages over the bulk carriers' fuel tanks caused by general corrosion in relatively short time interval of two years, within the period between the 5th and the 25th year of the bulks' operational life. The second employed method might be treated as a long-term one, and it is based on a Weibull distribution analysis. The purpose of these analyses is optimal assessing of the average corrosion losses for the bulk carriers' fuel tanks areas at different points of time during the whole exploitation cycle, within the ultimate goal of raising the structural stability and safety of bulk carriers in operation.

KEY WORDS

bulk carriers, fuel tanks, corrosion wastage, Monte Carlo simulation, Weibull probability analysis

1. INTRODUCTION

It is well-known that corrosion is a serious problem for anything built of metal and exposed to the elements, but for any kind of ships, including here bulk carriers, it can be fatal. Corrosion is likely to be more extensive here and to act more rapidly than on other structures, simply because the bulk carriers are under complex influence of salt water, and simultaneously exposed to unpredictable atmosphere, cargo and ballast effects. More precisely, aggressive environment, specifics of the trade routes, dry and wet ballast circles, ballast and cargo ratio, frequencies of cargo loading/unloading operations, manipulative techniques, etc. often affect serious bulk carriers' deteriorations caused by the corrosion. It should also be emphasized that the corrosion might be intensified by the negative effects of some cargoes, especially those like iron ore and coal [1]. Though, during the past two decades, several casualties of bulk carriers have occurred while they were under operation and the possible causes for such casualties are thought to be the structural failure affected by the corrosion being intensified by rough sea and weather conditions. While protective paintings, cathode protection, and (or) tanks careful washing out are often employed, this is not always the case and, for a variety of reasons, they may not be wholly effective. Thus, particular attention is to be given to the harsh nature of the cargoes, loading/unloading operational procedures, as well as to the regular measurements and reporting on the ships' structural deterioration due to corrosion. This, however, is much easier said than done [2, 3, 4].

Frequent references to the iron ore, or coal, are significant because once laden bulk cargo carriers get into trouble, and the consequences can be very sudden. The bulk carriers are designed to withstand bad conditions, but not to operate with several holds flooded and the combination of iron ore and sudden inrush of sea water resulting in more weight than the structure can stand. Besides, cargo handling methods (loading/unloading operations) have also been criticized. Part of the problem is that modern loading and unloading techniques have been developed long after the bulk carriers they are intended to be loaded/unloaded have been built. Due to the inspections of the corrosion loss, there is also a great deal of steelwork to be checked. It is usually a daunting task that requires spatial staging, artificial light and a great amount of stamina on the part of the surveyor or surveyors being involved [5]. But, nevertheless, considerable efforts have been permanently done, aimed at the prevention of huge accidents that can be caused by bulk carriers sinking, and causing fatalities and environmental pollution. Accordingly, this paper should be a modest contribution to this ultimate goal.

2. THE PROBLEM DEFINITION

For the purpose of this research work a large database has been provided by the recognized ultrasonic measurements Company[1]. These data were collected through the standardized, numerous, and very detailed measurements over all hull structure members of a group of ten aged bulk carriers. However, in this article, only bulk carriers' fuel tanks time-dependant deteriorations caused by the general corrosion have been analyzed in detail, in both short and long terms. The main reason for this lies in the fact that this type of problem is not sufficiently covered by the previous research works in the field, due to our knowledge and some literature surveys [1-4; 6-9]. Previously mostly cargo holds and ballast tanks were treated [8, 9]. However, in the first part of the paper, the Monte Carlo simulation method has been used for assessing the value of damaged steel, expressed in percentage of the standard steel thickness, over certain fuel tank area that should be removed (replaced) during arbitrary selected two-year intervals of the bulk's exploitation cycle, within the period between the 5th and the 25th year of its operational life. The second part of the paper contains a Weibull probability analysis upon some cumulative negative time-dependant fuel tanks corrosion effects in long terms, i.e. during the whole period of their exploitation, or in other words, within the complete time interval between the 5th and the 25th year of the vessels' operation. Let us note here that the corrosion process does not usually start before the 5th year of exploitation [6-9].

Though the particular details related to the bulk carriers' structure in a pure mechanical and engineering sense are not included into the content of this research, it is to be mentioned that the fuel tanks may be found in the top side tanks, double bottom tanks, or deep tanks, but the subject of this article are oil (fuel) tanks placed only in double bottom areas. These oil tanks are usually spatially positioned along the main axis of the bulk carrier, but they can also be placed perpendicularly to it. These tanks placed along the

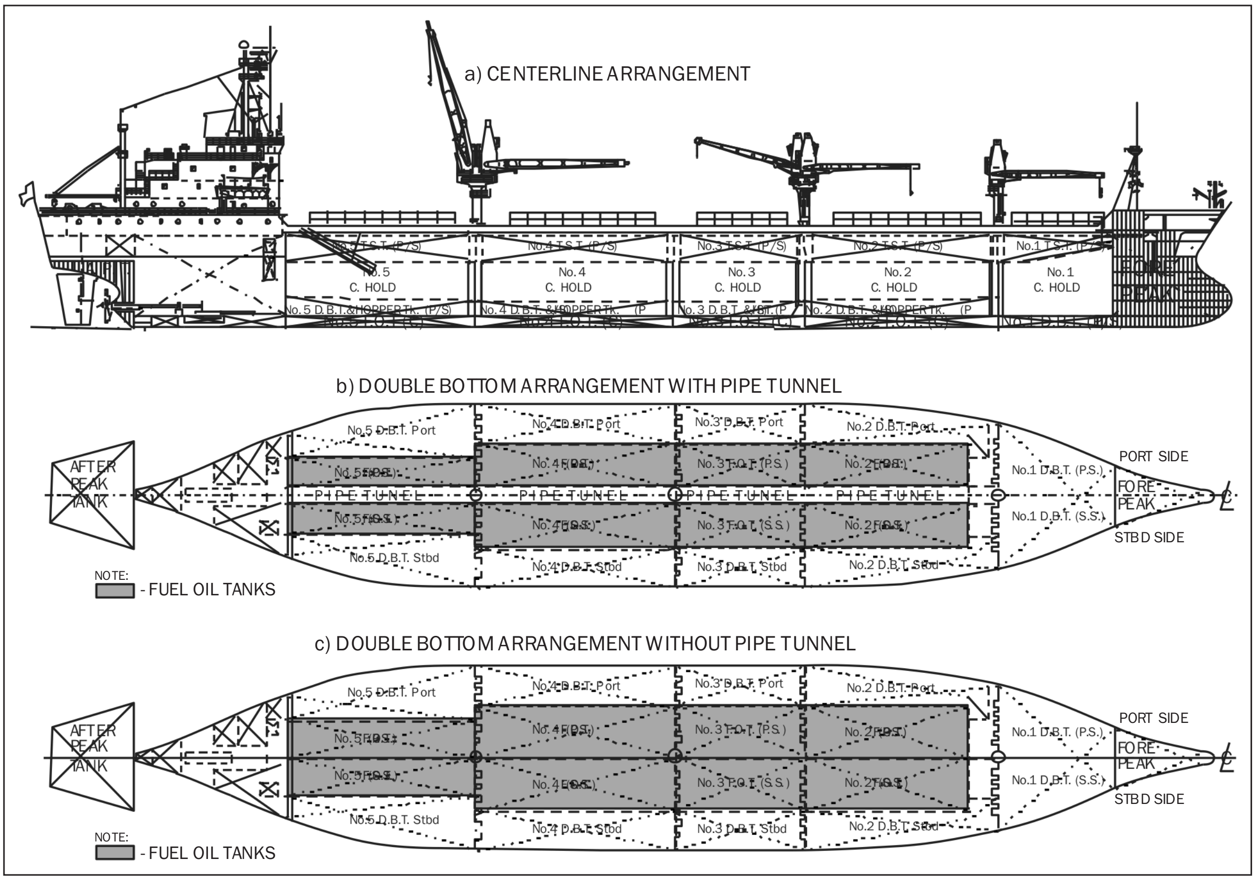

Figure 1 - Bulk carriers' different arrangements of fuel tanks: a) centerline, b) double bottom with pipe tunnel, c) double bottom without pipe tunnel

main axis (*Figure 1*.a) can be arranged with a pipe tunnel (*Figure 1*.b), or without it (*Figure 1*.c). The second mentioned case has been employed within the following simulations and probability analysis.

3. INPUT DATA SET BRIEF DESCRIPTION

In accordance with the corrosion measuring standards and some characteristic operational parameters, the considered bulk carriers' fuel tanks have been analyzed here throughout ten different segments, areas, or member locations. The analyzed segments are presented schematically and listed below in the form of the legend in *Figure 2*.

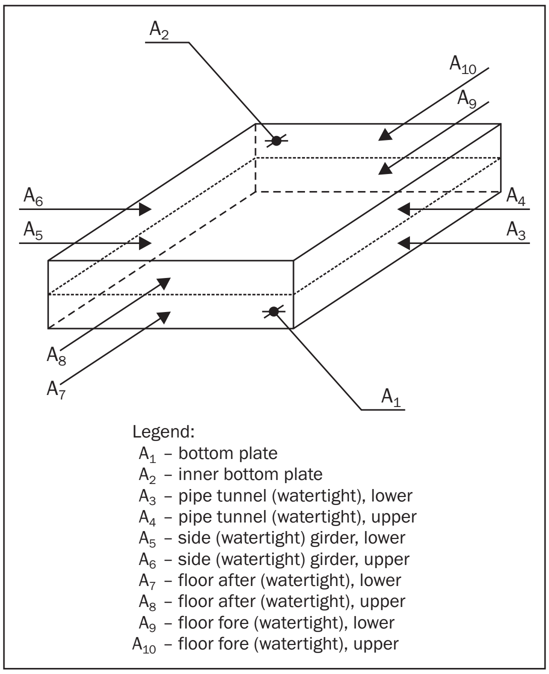

Figure 2 - The basic structural scheme of bulk carrier's fuel tank areas (A_1 to A_{10})

The cumulative data on the general corrosion loss expressed in percentages (%) of the standard average steel thickness, collected through the regular measurements (inspections on site), during the previous decade by the survey Company[1] are given in *Table 1*. The data are gathered over each of the previously noted area of the fuel tanks, through 10 ($BC_{1,7\text{-}10}$), or 20 different sections ($BC_{2\text{-}6}$), depending on the number of fuel tanks, with total 3,356 gauged points, for both

Table 1 - Corrosion loss expressed in percentages (%) of standard steel thickness over different bulk carrier fuel tanks' areas during the 20 years of the bulks' exploitation circle (P-portside and S-starboard ship's side)

		Percentages (%) of steel thickness damages									
Bulk carrier		BC_1		BC_2		BC_3		BC_4		BC_5	
Portside/Starboard		P	S	P	S	P	S	P	S	P	S
Fuel tanks' areas	A_1	1.8	1.9	1.2	1.1	1.7	2.1	1.3	1.4	1.3	1.3
	A_2	9.9	8.5	8.2	7.8	6.0	5.9	17.9	19.3	21.9	21.6
	A_3	1.5	1.6	1.1	1.2	1.9	1.5	0.0	0.0	0.0	0.0
	A_4	1.1	0.8	1.1	1.2	1.2	1.3	0.0	0.0	0.0	0.0
	A_5	0.0	0.0	13.3	16.5	19.6	28.0	2.1	1.9	6.2	9.2
	A_6	0.0	0.0	16.7	19.7	20.6	28.9	3.4	11.6	27.8	30.8
	A_7	1.7	1.4	11.6	13.1	13.1	12.7	2.7	2.8	9.1	8.8
	A_8	2.4	2.1	16.3	18.6	17.7	18.0	4.0	4.0	14.6	15.8
	A_9	1.5	1.4	29.4	29.0	31.0	31.3	4.3	3.7	2.2	2.3
	A_{10}	1.8	1.5	34.3	34.5	33.8	33.6	6.7	6.5	4.0	4.0
		Percentages (%) of steel thickness damages									
Bulk carrier		BC_6		BC_7		BC_8		BC_9		BC_{10}	
Portside/Starboard		P	S	P	S	P	S	P	S	P	S
Fuel tanks' areas	A_1	2.5	3.2	1.3	1.3	3.7	4.7	1.4	1.3	2.6	2.0
	A_2	26.1	26.3	19.6	19.5	11.6	12.0	23.1	22.2	23.2	23.1
	A_3	0.0	0.0	1.7	1.4	1.3	1.2	1.9	1.7	1.8	2.9
	A_4	0.0	0.0	1.6	1.5	1.4	1.2	1.9	1.7	1.6	2.1
	A_5	3.9	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	A_6	38.3	38.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	A_7	3.8	3.8	5.4	6.1	27.1	27.4	13.5	6.1	26.7	18.8
	A_8	22.5	31.0	9.2	14.9	28.8	29.5	16.7	22.2	28.2	23.0
	A_9	5.2	5.2	12.5	8.1	14.6	15.0	6.9	8.0	16.3	17.3
	A_{10}	9.8	9.3	12.6	17.3	15.6	15.3	16.2	23.5	22.2	21.7

Table 2 - The average percentages (%) of the corrosion losses over the considered bulk carriers' fuel tanks areas per two years

Bulk carrier		Percentages (%) of steel thickness damages per two years										Average (%)
		BC_1	BC_2	BC_3	BC_4	BC_5	BC_6	BC_7	BC_8	BC_9	BC_{10}	
Fuel tanks' areas	A_1	0.18	0.11	0.19	0.14	0.13	0.29	0.13	0.42	0.14	0.23	0.20 %
	A_2	0.92	0.80	0.59	1.86	2.18	2.62	1.96	1.18	2.26	2.31	1.67 %
	A_3	0.16	0.12	0.17	0.00	0.00	0.00	0.15	0.13	0.18	2.40	0.33 %
	A_4	0.10	0.12	0.13	0.00	0.00	0.00	0.15	0.13	0.18	0.19	0.10 %
	A_5	0.00	1.49	2.38	0.20	0.77	0.40	0.00	0.00	0.00	0.00	0.52 %
	A_6	0.00	1.82	2.48	0.75	2.93	3.83	0.00	0.00	0.00	0.00	1.18 %
	A_7	0.15	1.24	1.29	0.28	0.90	0.38	0.58	2.72	0.98	2.27	1.10 %
	A_8	0.23	1.74	1.79	0.40	1.52	2.68	1.16	2.93	1.94	2.56	1.69 %
	A_9	0.15	2.92	3.11	0.40	0.23	0.52	1.03	1.48	0.75	1.68	1.23 %
	A_{10}	0.17	3.44	3.37	0.66	0.40	0.96	1.49	1.55	1.98	2.19	1.62 %

the left, or portside (P) and the right, or starboard (S) side of the considered bulk carriers (BC_{1-10}). The data were collected by the regular, intermediate and special surveys, in a way that each tank has been divided into 5 sections: two sections for after and fore ends, and three sections at equal mutual distances in the middle, between ends of tanks.

The bulk carriers: BC_1, and BC_{7-10} are of different construction than the rest of the examined vessels. However, since they do not have, in fact, the areas A_5 and A_6, as the constitutive parts of their fuel tanks, they were in these segments partly excluded from some of the simulation analyses.

Similar data to these given in *Table 1* are given in *Table 2*, but in the form of average percentages of damaged steel for the fuel tanks over both, portside and starboard of the bulk carriers, and previously *reduced* to the time period of two years of the ships' operational lives. Namely, the data are not expressed cumulatively, as in the previous case, for the complete period of twenty years of vessels' exploitation, but for a considerably smaller period of only two operational years. The question that may arise accordingly is: Why the input simulation data are presented as average values for two-year interval of intensive exploitation? – The reason lies in the attempt to simulate the damaged percentages of the regular (normal) steel thickness that may be expected during two-year period over certain fuel tank's area, i.e. at the relatively short time interval in comparison to the whole bulk's exploitation life. In such case it is more appropriate and effective to apply simulation techniques, e.g. Monte Carlo, than mathematical expectation or probability-based analysis. In other words, in the short term, the corrosion lost may be quite different from the expected value, or probability values in the long term [10].

This is of importance in opening the prospective toward informing in a manner the owner of the bulk carrier about which percentage of the steel might be, most probably, expected to be damaged by corrosion, and removed/replaced over the fuel tanks, during the relatively short time interval of two years in the period of bulk carrier aging, i.e. between 5th and 25th year of its operation cycle. Consequently, through this research, and several similar ones [11, 12], particular efforts are given towards developing an appropriate Monte Carlo simulation model for assessing general corrosion wastage in short terms. Anyhow, it is to be noted that the Monte Carlo simulation method was employed successfully up to now in several research works in the domain of different naval structures phenomenon analysis [13, 14].

4. REALIZATION AND SOME RESULTS OF MONTE CARLO SIMULATIONS

When a problem contains elements that exhibit chance or probability in their behaviour, the Monte Carlo method is recommended. The basic idea of this simulation method is to randomly generate values for the unknown variables in the model through random sampling. The technique is broken down into three steps: a) establishment of a probability distribution for each variable in the model that is subject to change; b) usage of random numbers that simulate values from the probability distribution for each variable in the previous step; and, c) repetition of the process for a series of replications (runs, or trials). The function of computer generation of random numbers is the generation of decimal fractions randomly distributed over the interval from 0 up to, but not including 1, referring to the U(0,1) random number. The most common method of generating U(0,1) random numbers is called the *mixed congruential method* (MCM) [15]. The MCM generates a sequence of U(0,1) random numbers denoted by r_0, r_1, r_2, r_3,..., and so on. The first number in the sequence, r_0, is an arbitrary chosen decimal fraction between 0 and 1. Using r_0 to initialize the process, the MCM generates the next random number r_1 by using the previous random number and the following recurrent formula (1):

$$r_i = \frac{[(m \cdot a \cdot r_{i-1} + c)(\text{modulo}(m))]}{m} \qquad (1)$$

Where, *m* is a pre-specified positive integer known as modulus; *a* is a pre-specified positive integer less than *m* known as the multiplier; and, *c* is a pre-specified nonnegative integer less than *m* known as the increment. Strictly speaking, the sequence of numbers generated by MCM is not random in the sense of being unpredictable and irreproducible. Obviously, by specifying *m*, *a* and *c*, it is automatically determined what sequence of numbers shall be generated. For this reason, random numbers generated on a computer are often called *pseudo random* numbers. The looping behaviour of the MCM is inevitable, regardless of the choice of values for *m*, *a*, and *c*. Thus, the question is not whether the looping will occur, but when. Mathematicians have devised rules for choosing *m*, *a*, and *c* that delay the looping as long as possible and also lead to other desirable properties in the sequence of random numbers, but these rules are beyond the scope of this paper. For the needs of this paper the spreadsheet software has been used, i.e. the appropriate combination of Excel embedded functions, since here rather small-scale simulations have been performed.

The variable taken here into consideration is the average percentage of the damaged steel due to the corrosion over the previously identified bulk carriers' fuel tanks areas (see subsection 3), during two-year long period of their exploitation lives. As a sound base, namely, for applying the Monte Carlo method, the homogenous data collected by numerous measurements of the fuel tanks' structural steel thickness for the group of ten bulk carriers (BC_1-BC_{10}) during the years, for the period of twenty years between 5th and 25th year of the bulks' operation, have been used. Due to the frequencies of occurrence in the model of some percentages of the damaged steel thickness, and the total number of different percentages occurrences, the probabilities of each possible outcome of the variable have been calculated [11, 12].

Upon the probabilities determined for each percentage of the damaged steel occurring in the data set, the cumulative probabilities are to be calculated by summing all the previous probabilities up to the current one. Later on, in the process of setting the simulation process, the cumulative probabilities are used for generating the pseudorandom numbers from the intervals that correspond to the boundaries of the cumulative probabilities. There are several ways to pick random numbers: using a ball, a table, a roulette wheel, etc. Naturally, currently the most convenient method, based on a computer program, has been used in this paper. More explicitly, the Excel embedded functions RAND ( ), LOOKUP (*,*,*), and COUNTIF (*,*) have been exploited in the paper; and, it should be mentioned that these functions work properly for the simulation problems of relatively small dimensions (approximately up to 100,000 records). The adapted view of the Excel data sheet with the applied functions, and with several numerical examples among the series of Monte Carlo simulations is given in *Table 3*. Also, it has been noted here that with an aim to simplify the whole simulation procedure and to reduce the number of different simulation inputs, and meaningless scattering of the output data, few values close to the average percentage of the damaged steel thickness due to the corrosion over certain fuel tanks' areas, have been slightly modified before starting the Monte Carlo simulation process [11, 12]. Additionally, through the realization of the simulations, it becomes clear that the percentage with the highest frequency, i.e. with the greatest number of occurrences in the input data set, has more chance to become a *winner* in the output set of the Monte Carlo simulation runs.

In the next part of this section the overall results obtained after each of five sets of 50, 000 Monte Carlo

Table 3 - The Monte Carlo simulation realization and results for the percentages of steel thickness losses due to the corrosion over different bulk carriers' fuel tanks structure areas

A$_1$_ Bottom plate							
Damaged steel [%] per two years	Frequency	Probability	Cumulative probability	Interval of random numbers	RN	LOOKUP	COUNTIF
0.11	1	0.10000	0.10000	0.00000	0.90521	0.42	5,052
0.13	2	0.20000	0.30000	0.10000	0.72922	0.22	10,006
0.14	2	0.20000	0.50000	0.30000	0.78236	0.22	9,924
0.22	3	0.30000	0.80000	0.50000	0.85119	0.23	**14,957**
0.23	1	0.10000	0.90000	0.80000	0.75141	0.22	5,048
0.42	1	0.10000	1.00000	0.90000	0.42761	0.14	5,013
					0.79465	0.22	
Math. expectation: 0.196					0.11107	0.13	Total: 50,000
					…	…	

simulation runs, or trials, for each of ten considered fuel tanks' areas, and for each of the considered bulk carriers, are presented numerically in *Table 4*.

It is obvious that the percentages (%) of the steel thickness losses caused by the general corrosion over certain fuel tanks areas (A_1-A_{10}), given in the second column have the greatest number of occurrences within each cycle of the output data of Monte Carlo simulation 50,000 trials. However, these values are most likely to be expected to "occur" in the reality, within two-year period as those indicating in fact the amounts of the damaged steel which is to be elimi-

Table 3 (continued)

A_2_Inner bottom plate							
Damaged steel [%] per two years	Frequency	Probability	Cumulative probability	Interval of random numbers	RN	LOOKUP	COUNTIF
0.59	1	0.10000	0.10000	0.00000	0.69297	2.18	5,010
0.80	1	0.10000	0.20000	0.10000	0.22192	0.92	4,990
0.92	1	0.10000	0.30000	0.20000	0.63952	2.18	5,142
1.66	3	0.30000	0.60000	0.30000	0.95453	2.62	**14,942**
2.18	1	0.10000	0.70000	0.60000	0.60420	2.18	5,003
2.26	1	0.10000	0.80000	0.70000	0.03791	0.59	4,953
2.31	1	0.10000	0.90000	0.80000	0.53409	1.66	4,998
2.62	1	0.10000	1.00000	0.90000	0.50527	1.66	
Math. expectation: 1.666					0.39343	1.66	Total: 50,000
					…	…	

A_3_Pipe tunnel (watertight), lower							
Damaged steel [%] per two years	Frequency	Probability	Cumulative probability	Interval of random numbers	RN	LOOKUP	COUNTIF
0.00	3	0.30000	0.30000	0.00000	0.53666	0.16	15,178
0.12	1	0.10000	0.40000	0.30000	0.35631	0.12	5,081
0.13	1	0.10000	0.50000	0.40000	0.59048	0.16	5,052
0.16	4	0.40000	0.90000	0.50000	0.67543	0.16	**19,756**
2.40	1	0.10000	1.00000	0.90000	0.62188	0.16	4,933
Math. expectation: 0.329					0.43994	0.13	Total: 50,000
					…	…	

A_4_Pipe tunnel (watertight), upper							
Damaged steel [%] per two years	Frequency	Probability	Cumulative probability	Interval of random numbers	RN	LOOKUP	COUNTIF
0.00	3	0.30000	0.30000	0.00000	0.13794	0.00	14,917
0.12	4	0.40000	0.70000	0.30000	0.92515	0.19	**20,134**
0.15	1	0.10000	0.80000	0.70000	0.48546	0.12	5,060
0.18	1	0.10000	0.90000	0.80000	0.06957	0.00	4,993
0.19	1	0.10000	1.00000	0.90000	0.85255	0.18	4,896
Math. expectation: 0.100					0.36990	0.12	Total: 50,000
					…	…	

A_5_Side (watertight) girder, lower							
Damaged steel [%] per two years	Frequency	Probability	Cumulative probability	Interval of random numbers	RN	LOOKUP	COUNTIF
0.20	1	0.20000	0.20000	0.00000	0.35009	0.40	9,998
0.40	1	0.20000	0.40000	0.20000	0.73395	1.13	10,020
1.13	2	0.40000	0.80000	0.40000	0.65905	1.13	**19,971**
2.38	1	0.20000	1.00000	0.80000	0.67462	1.13	10,011
Math. expectation: 1.048					0.69082	1.13	Total: 50,000
					…	…	

Table 3 (continued)

A_6_Side (watertight) girder, upper

Damaged steel [%] per two years	Frequency	Probability	Cumulative probability	Interval of random numbers	RN	LOOKUP	COUNTIF
2.41	3	0.60000	0.60000	0.00000	0.31087	2.41	**30,117**
0.75	1	0.20000	0.80000	0.60000	0.47980	2.41	9,906
3.83	1	0.20000	1.00000	0.80000	0.50313	2.41	9,977
Math. expectation: 2.362					0.51936	2.41	Total: 50,000
					...	...	

A_7_Floor after (watertight), lower

Damaged steel [%] per two years	Frequency	Probability	Cumulative probability	Interval of random numbers	RN	LOOKUP	COUNTIF
0.15	1	0.10000	0.10000	0.00000	0.30720	0.58	4,979
0.28	1	0.10000	0.20000	0.10000	0.59781	1.14	4,912
0.38	1	0.10000	0.30000	0.20000	0.29548	0.38	5,058
0.58	1	0.10000	0.40000	0.30000	0.15796	0.28	5,045
0.98	1	0.10000	0.50000	0.40000	0.54068	1.14	5,030
1.14	3	0.30000	0.80000	0.50000	0.26319	0.38	**15,059**
2.27	1	0.10000	0.90000	0.80000	0.04116	0.15	4,935
2.72	1	0.10000	1.00000	0.90000	0.39843	0.58	Total: 50,000
Math. expectation: 1.078					0.20589	0.38	
					...	...	

A_8_Floor after (watertight), upper

Damaged steel [%] per two years	Frequency	Probability	Cumulative probability	Interval of random numbers	RN	LOOKUP	COUNTIF
0.23	1	0.10000	0.10000	0.00000	0.76368	2.56	5,024
0.40	1	0.10000	0.20000	0.10000	0.82827	2.68	5,118
1.16	1	0.10000	0.30000	0.20000	0.67209	1.74	5,099
1.74	4	0.40000	0.70000	0.30000	0.83943	2.68	**19,764**
2.56	1	0.10000	0.80000	0.70000	0.22524	1.16	4,898
2.68	1	0.10000	0.90000	0.80000	0.30643	1.74	5,042
2.93	1	0.10000	1.00000	0.90000	0.63356	1.74	Total: 50,000
Math. expectation: 1.692					0.44435	1.74	
					...	...	

A_9_Floor fore (watertight), lower

Damaged steel [%] per two years	Frequency	Probability	Cumulative probability	Interval of random numbers	RN	LOOKUP	COUNTIF
0.15	1	0.10000	0.10000	0.00000	0.02676	0.15	5,038
0.23	1	0.10000	0.20000	0.10000	0.44128	0.75	4,991
0.40	1	0.10000	0.30000	0.20000	0.01334	0.15	5,014
0.52	1	0.10000	0.40000	0.30000	0.25972	0.40	4,961
0.75	1	0.10000	0.50000	0.40000	0.96024	3.11	5,111
1.39	3	0.30000	0.80000	0.50000	0.69831	1.39	**14,983**
2.92	1	0.10000	0.90000	0.80000	0.33012	0.52	4,946
3.11	1	0.10000	1.00000	0.90000	0.34960	0.52	Total: 50,000
Math. expectation: 1.225					0.64992	1.39	
					...	...	

nated and replaced by new steel, aiming to keep bulk carriers' fuel tanks and overall bulks' structural integrity, stability and maritime safety, i.e. to prevent any possible accident(s).

Table 3 (continued)

A_{10}_Floor fore (watertight), upper							
Damaged steel [%] per two years	Frequency	Probability	Cumulative probability	Interval of random numbers	RN	LOOKUP	COUNTIF
0.17	1	0.10000	0.10000	0.00000	0.57061	1.67	5,022
0.40	1	0.10000	0.20000	0.10000	0.60320	1.67	5,045
0.66	1	0.10000	0.30000	0.20000	0.28173	0.66	5,096
0.96	1	0.10000	0.40000	0.30000	0.08195	0.17	4,981
1.67	3	0.30000	0.70000	0.40000	0.01657	0.17	**14,906**
2.19	1	0.10000	0.80000	0.70000	0.98636	3.44	4,934
3.37	1	0.10000	0.90000	0.80000	0.21789	0.66	5,076
3.44	1	0.10000	1.00000	0.90000	0.08199	0.17	Total: 50,000
Math. expectation: 0.620					0.47888	1.67	
					...	...	

Table 4 - The output Monte Carlo simulation results after five sequences of 50,000 trials

Area	Steel loss [%]	Rank due to the corrosion deterioration	1st 50,000 runs	2nd 50,000 runs	3rd 50,000 runs	4th 50,000 runs	5th 50,000 runs
			Max. no. of app.	Max. no. of app.	Max. no. of app.	Max. no. of app.	Max. no. of app.
A_1	0.22	8	14,989	15,039	15,289	14,976	14,818
A_2	1.66	4	14,902	15,037	15,126	15,003	14,928
A_3	0.16	9	19,988	20,096	20,123	19,972	20,015
A_4	0.12	10	19,908	20,086	19,960	19,995	20,207
A_5^*	1.13	6	29,921	30,008	29,915	30,218	30,157
A_6^*	2.41	1	29,941	30,185	29,798	30,077	29,989
A_7	1.14	7	15,055	15,211	14,991	15,107	14,928
A_8	1.74	2	20,116	19,931	19,984	20,032	20,148
A_9	1.39	5	15,069	15,018	15,019	15,016	14,958
A_{10}	1.67	3	15,001	14,968	15,035	15,053	15,014

By looking through the set of the Monte Carlo simulations obtained data, it can be concluded that the fuel tanks' pair of areas: A_5 – side (watertight) girder lower and A_6 – side (watertight) girder upper areas have the greatest deteriorations caused by corrosion. Also, it can be concluded that the areas A_2, A_8 and A_{10}, have seriously deteriorated by corrosion. Within the next section, an attempt has been made to give some qualitative explanations of this phenomenon.

5. SOME QUALITATIVE OBSERVATIONS

Due to the numerical results on corrosion wastage in the case of ten considered aged bulk carriers' fuel tanks areas, obtained by Monte Carlo simulations within the previous section, several observations about the fuel tanks' deteriorations caused by the general corrosion, can be given. Firstly, corrosion starts and progresses from the outside of the oil tanks, i.e. from the area intensively exposed to the changeable (mostly unpredictable) atmosphere, cargo and ballast effects. Also, it must be pointed out that the inner sides of the fuel tanks are not usually exposed to the corrosion to a greater extent, since the fuel is considerably less corrosive than salt water and marine environment in general. Furthermore, due to the obtained numerical results, three characteristic zones may be identified:

- Fuel tanks' areas with the corrosion deterioration less than 0.5 (%) over the area per two-year interval of exploitation. This should be denoted as minor or negligible deterioration (A_1, A_3, A_4);
- Fuel tanks' areas with the corrosion deterioration between 0.5 and 1.5 (%) over the area per two-year period during aging. It can be marked as considerable deterioration (A_5, A_7, A_9); and,

- Fuel tanks' areas with the corrosion deterioration greater than 1.5 (%) over the area per two-year intervals, that must be considered as serious or critical deterioration (A_2, A_6, A_8, A_{10}).

The appropriate illustration of these areas arrangement over the outside shell of a fuel tank is given in *Figure 3*. The first, the second and the third zones with different grades of the steel time-dependent corrosion deterioration are marked as the legend in *Figure 3*. The greatest deteriorations have been noticed over the boundary areas between fuel and ballast tanks; especially in the upper areas, caused by the ballast movement and frequent exchanges of its dry and wet cycles. Additionally, serious deteriorations have been noticed in the upper areas of the after and fore floors of the fuel tanks, as well as in the areas of inner bottom plates due to the frequent (different) cargo(s) loading/unloading operations.

It seems that the upper areas of the boundary zones between ballast and fuel tanks, as well as upper zones of the after and fore floors, deserve particular attention in the sense of more frequent thickness measurements and taking care more seriously about the coatings of these zones. The inner bottom plate is to be treated carefully, too; through cleaning cargo tanks, paintings and regular coating controlling and measurements of steel thickness. Anyway, some more extensive investigations should be done in this field toward gathering some more relevant data about corrosion wastage and zones over which the wastage is more intensive.

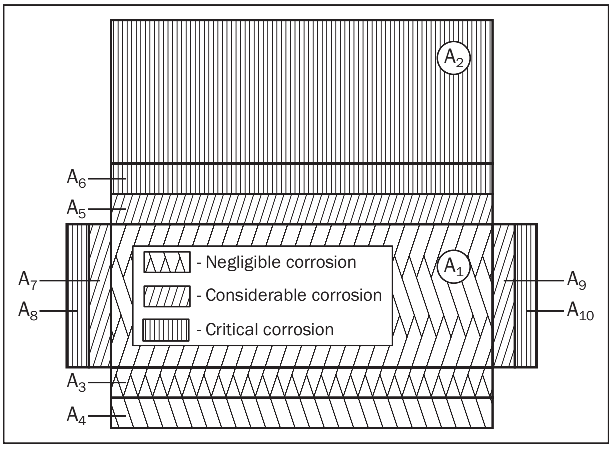

Figure 3 - Different zones of fuel tank (outside) deterioration

6. WEIBULL DISTRIBUTION IN DESCRIBING FUEL TANKS' CORROSION LOSS

The previously presented Monte Carlo simulation outcomes and the corresponding analysis of the corrosion wastage over different fuel tanks areas for the considered group of ten aged bulk carriers, on the basis of the homogenous historical data are rather short-term oriented. With the aim of scanning the behaviour of the corrosion deterioration over the bulk carriers' oil tanks in long terms, some probabilistic analyses based on Weibull distribution are realized in this part of the article.

The Weibull distribution, namely, can be successfully applied in describing the corrosion loss, i.e. the steel depth reduction [16], over different bulk carriers' fuel tanks member locations during the time. In general, the Weibull distribution is suitable for engineering analysis when small number of samples is available, which is not the case with other statistical distributions. It allows in a manner "economic" engineering analysis and offers simple and very useful graphic for characteristic parameters scanning and analyzing. However, Weibull distribution is widely used in (un)reliability analysis, including here the examined problem of the bulk carriers' fuel tanks structural strength reliability that is commonly affected by the corrosion.

The probability density function of the percentage of the damaged steel due to the standard (regular, normal) fuel tanks' steel depth (thickness) might be assumed to follow the most general three-parameter form of the Weibull distribution (2):

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1}\exp\left[-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right] \qquad (2)$$

Where, η is scale parameter; β is shape parameter (or slope), and γ is location parameter. The ReliaSoft_Weibill++ program has been employed here for determining and analyzing the Weibull distribution parameters. The available data set on the bulk carriers' fuel tanks thickness reduction due to the corrosion, collected during the time, i.e. from the 5th to the 25th year of the ships' exploitation has been plotted on the Weibull paper, and the parameters β and η, as most relevant for this research, have been automatically calculated (*Figure 4*).

In *Figure 5*, the horizontal axis denotes the time of the considered vessels' exploitation, and it is in certain correlation to the corrosion degradation of the steel over time. In other words, as time (t) increases, the unreliability $F(t)$ of the oil tanks integrity and structural stability increases. Or, more simply, the older the vessel, the deeper the averaged steel depth caused by the corrosion. The vertical axis represents the "life" of steel, or the (critical) percentage of the steel that is to be removed and replaced by new steel at certain point of time. According to the values obtained for the parameters β and η (*Figure 4*) it can be concluded that approximately after 28 years of bulk carriers' exploitation, more than 60%, or exactly, 63.2% of the fuel tanks areas constitutive steel is to be replaced. Additionally, parameter $\beta \geq 1$, or, more precisely $\beta = 3.049$, denotes the period of intensified corrosion degradation. The data upon which the Weibull graphic has been constructed in *Figure 4*, and some additional ones are given in *Table 5* (case 4). On the basis of these data it is

Table 5 - The bulk carriers' fuel tanks corrosion loss versus time and corresponding Weibull distribution parameters β and η calculated by ReliaSoft_Weibill++ program

Case1		Case 2		Case 3		Case 4		Case 5	
Years	Corrosion loss (%)	Years	Corrosion loss (%)	Years	Corrosion loss (%)	Years	Corrosion loss (%)	Years	Corrosion loss (%)
5	2 %	7.5	1 %	10	3 %	12.5	4 %	15	3 %
7.5	5 %	10	6 %	12.5	9 %	15	12 %	17.5	13 %
10	9 %	12.5	12 %	15	15 %	17.5	20 %	20	22 %
12.5	14 %	15	17 %	17.5	23 %	20	28 %	22.5	33 %
15	18 %	17.5	22 %	20	30 %	22.5	32 %	25	45 %
17.5	23 %	20	27 %	22.5	36 %	25	43 %		
20	28 %	22.5	32 %	25	42 %				
22.5	32 %	25	40 %						
25	39 %								
β = 1.939		β = 2.946		β = 3.049		β = 3.564		β = 5.596	
η = 35.177		η = 28.977		η = 28.640		η = 28.319		η = 26.463	

also possible, by simple linear approximation method, to scan the corrosion degradation versus time under the assumptions that the corrosion process starts, e.g. in the 5th, 7.5th, 10th, 12.5th, or in the 15th year of vessels' exploitation (cases 1-5, in *Table 5*). These might broaden in a way the boundaries of the analysis and offer an additional insight into the Weibull β and η parameters qualitative analysis, which should be the subject of further more rigorous investigations on a larger revealed sample data set(s).

The considered vessels are classified by four classification societies: Bureau Veritas, Det Norske Veritas, Lloyds' Register, and American Bureau Shipping. These societies have recommendations in their Rules for the levels of the acceptable corrosion deterioration for each element of the hull construction. In the analyzed case, the deterioration for each area of the fuel tanks is in the boundaries between 20 and 25%, depending on the classification society.

In the more restrictive conditions, i.e. in the situations when the fuel tanks are investigated as a whole, the average amount of the damaged steel should not exceed 10% of the regular thickness [17-20]. Under such, more rigorous conditions, the parameters of the Weibull distribution differ from those obtained upon the real data collected on site, as in the previously presented cases. These additional oil tanks structural stability and safety requirements imply the smaller values of Weibull parameters β and η, which is illustrated in *Figure 5*. Simply, in such strict conditions, more than 60% of steel has to be removed/replaced over oil tanks structures during the 15th year of their exploitation lives, which is considerably earlier than in the previously presented cases (see *Table 5*).

To summarize, such approach based on the Weibull distribution parameters analysis might be recommended as a practical tool for determination of both scale and shape parameters, i.e. the time when more than half of the fuel tanks' structures in general will be seriously damaged by the corrosion and necessarily replaced by new steel, or it might denote the time when the bulk carrier should retreat from operation. This is of utmost importance in controlling the structural strength and reliability of the fuel tanks and the whole bulk's hull structure, primarily due to the security and maritime safety reasons. However, the practical aspect of such analysis must be emphasized and further, more extensive and more rigorous investigations in this direction are to be encouraged.

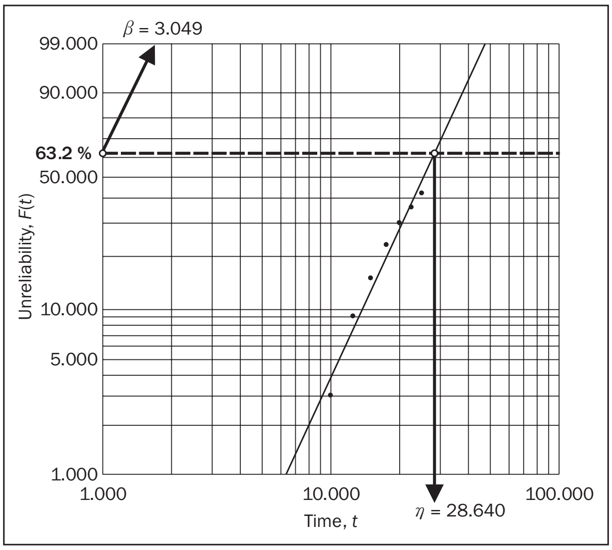

Figure 4 - The percentages (%) of the corrosion loss over bulk carriers' fuel tanks areas versus ages of the vessels' exploitation plotted on the Weibull paper

Also, it must be noted that some areas of the bulk carriers' fuel tanks are not exposed to a great extent to the corrosion mechanisms, such as A_1, A_3, A_4, and even A_5, A_7, and A_9, while some other, like A_2, A_6, A_8,

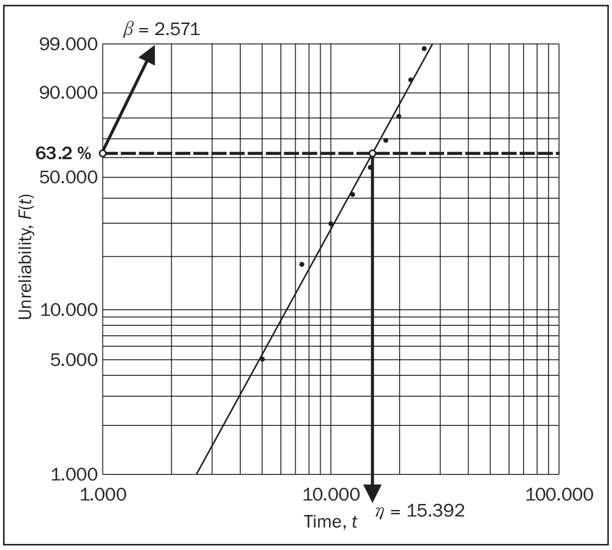

Figure 5 - The percentages (%) of the corrosion loss over bulk carriers' fuel tanks areas versus time for restrictive conditions

and A_{10}, are seriously deteriorated. Accordingly, the analysts and the surveyors have to be aware that some deeper operational insight into this problematic is required besides pure statistical analysis. In other words, in addition to the simulations and statistical observations, some more detailed qualitative analysis and discussions among the operators and experts are unavoidable as well.

7. CONCLUSION

The simulation (Monte Carlo) and the probabilistic (Weibull) rather simple models for scanning the corrosion loss over bulk carriers' fuel tanks member locations have been developed as experimental approaches to analyzing corrosion data collected during the years, by the ultrasonic thickness measurement Company[1]. While the simulation model gave the information on the percentage of steel depth reduction by the corrosion over the fuel tanks due to the normal (standard) steel depth, in relatively short period of time, i.e. two years, within the vessels' aging period; the probabilistic-Weibull model gave an insight into the long-term behaviour of steel degradation during the whole period of fuel tanks exploitation. Both models are from the experimental point of view rather satisfying; but, it is to be pointed out that the provided data from the vessels' regular, standardized inspections are unavoidably full of uncertainties owing to the specific nature of the bulk carriers and their fuel tanks constructions, and especially owing to the uncertain nature of marine environment and very specific sea water corrosion mechanisms. However, if considerably more data can be revealed, the prediction models should be improved to achieve a high accuracy of the proposed fuel tanks' steel depth reduction due to the marine corrosion phenomenon, at any point of time, i.e. year of bulk carrier's exploitation cycle.

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SAŽETAK

ISPITIVANJE KOROZIONOG GUBITKA KOD TANKOVA GORIVA NA STARIM BALK KERIERIMA IZ BEZBJEDNOSNIH RAZLOGA

Predmet rada su dva različita pristupa modeliranju korozionog gubitka strukturnih elemenata tankova goriva u slučaju deset starih balk keriera (brodova za rasuti teret). Prvi od korišćenih pristupa se može tretirati kao kratkoročni, slučajno orjentisan i baziran na Monte Karlo simulacionoj tehnici. Ova tehnika je u radu korišćena u kreiranju odgovarajućeg prediktivnog modela oštećenja tankova goriva balk keriera prouzrokovanih opštom korozijom, u relativno kratkom periodu od dvije godine, proizvoljno uzete iz vremenskog okvira od pete do dvadesetpete godine cjelokupnog operativnog ciklusa. Drugi korišćeni pristup se može tretirati kao dugoročan i baziran je na nekim analizama Weibull-ove raspodjele. Svrha ovih analiza je optimalno procjenjivanje prosječnog korozionog gubitka za tankove goriva balk keriera u različitim vremenskim presjecima u toku čitavog eksploatacionog vijeka, sa krajnjim ciljem povećanja njihove strukturne stabilnosti i bezbjednosti dok su u funkciji.

KLJUČNE RIJEČI

balk kerieri (brodovi za rasuti teret), tankovi goriva, korozioni gubitak, Monte Karlo simulacija, analize Weibull-ove raspodjele

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