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CORROSION WASTAGE MODELING FOR DIFFERENT MEMBER LOCATIONS OF AGED BULK CARRIERS

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Abstract

The paper considers two corrosion wastage models for some pre-specified member locations of several aged bulk carriers. Accordingly, the available statistical data of regular corrosion measurements for existing bulk carriers' structures have been analyzed, using two simulation models. The first considered model is based on Monte Carlo simulation method and it is developed upon cumulative data collected by measuring eleven structure categories of ten bulk carriers during the period between the twentieth and the thirtieth year of their operational life. The second considered model employs an inverse analysis of the corrosion process in the case of seven bulk carriers' inner bottoms plating areas at different ages of the ships' operational life, i.e. their exposure to the corrosion. Both models show certain convergence and enable predicting the steel amounts that are to be removed (replaced) from different corroded structural members in order to keep the ultimate bulk carriers' both transversal and longitudinal strength within the boundaries of required safety level.

Key words: aged bulk carriers, corrosion wastage, ships' structure strength control.

INTRODUCTION

In ageing process of bulk carriers, corrosion and fatigue cracks are two most important factors affecting structural safety and integrity. There are several types of corrosion. The most common ones are: general (uniform) corrosion, which uniformly

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reduces the member wall thickness, and localized (pitting or grooving) corrosion, that causes degradation in local regions. The corrosion, in general, is influenced by many factors including the corrosion protection system and various operational parameters. Most often, the corrosion protection systems for vessels are coatings and anodes. Among the operational parameters, the following might be included: maintenance, repair, type of cargo, kind of loading/unloading operations, i.e. manipulation techniques and equipment, percentage of time in ballast, frequency of tank cleaning, temperature profiles, use of heating coils, humidity conditions, water and sludge accumulation, microbial contamination, atmosphere effects, composition of fuels and inert gases, etc. Also, the various uncertainties associated with corrosion are to be taken into consideration, where a probabilistic treatment is essential. Now-a-days, the lack of understanding of all these factors and their mutual interactions is present, although related experiences for each of them looking solely have been documented and sometimes analyzed (Adey and Baynham, 2000; Guo et al, 2008; Paik et al 1998; Paik et al, 2003; Paik and Thayamballi, 2002; Qin and Cui, 2002).

Within this paper, two problems related to two groups of ten ageing bulk carriers shall be considered as well as their general (uniform) corrosion processes: (1) - predicting the appropriate value of the steel amount that is to be replaced at a certain member of the structure per year, by Monte Carlo simulations, and (2) - modeling the corrosion depth inverse function due to the past data collected on removed/replaced steel amounts during the various time segments (periods) of the observed bulk carriers operational life.

MONTE CARLO SIMULATION AND PREDICTIVE CORROSION WASTAGE MODEL FOR BULK CARRIERS STRUCTURES

Generally speaking, the concept of simulation involves developing a mathematical model that attempts to describe a real-world situation. The model's goal is to incorporate important variables and their interrelationships in such way that we can study the impact of different decisions on functioning of the whole system. This approach has many advantages over other decision modeling techniques and it is especially useful, when a problem is too complex or difficult to solve by other means. The Monte Carlo method of simulation uses random numbers to generate random variable values from probability distributions. The simulation procedure is conducted for several time periods to evaluate the long-term impact of each policy value being studied (Shogan, 1998).

Generating random numbers and setting up the simulation

The function of computer generation of random numbers is the generation of decimal fractions (e.g. 0.67185) randomly distributed over the interval from 0 up to, but not including, 1. Hereafter we refer to such random number as a U(0,1) random number. The most common method of generating U(0,1) random numbers is called the *mixed congruential method* (MCM). 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 using the previous random number and the following formula:

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

were

m – is prespecified positive integer known as modulus;
a – is prespecified positive integer less than m known as the multiplier;
c – is prespecified 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. It is obvious, 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. A computer needs only to generate U(0,1) random numbers because they in turn can be used to simulate any desired probability distribution.

No.	Bulk carrier structure members/categories	Acronyms
1.	Upper deck	UD
2.	Deck superstructure	DS
3.	Bottom and side shell plating	BSSP
4.	Hatch cover and coamings	HCC
5.	Internal structure in top side tanks	ISTST
6.	Cargo hold transverse bulkheads	CHTB
7.	Cargo hold main frames	CHMF
8.	Inner bottom and hopper plating	IBHP
9.	Internal structure in double bottom tanks	ISDBT
10.	After peak structures	APS
11.	Fore peak structures	FPS

Table 1. The primary members of the bulk carriers being taken into consideration.

The Monte Carlo simulation method has been used in the paper in creating the corrosion wastage predictive model in the sense of which amount of the steel in tons is to be removed/replaced at a certain member location of the considered bulk carriers overall hull structure. Accordingly, first of all, 11 member locations/categories have been specified, including both transversal and longitudinal segments. Some of these member locations/categories consist of only longitudinal members (UD, DS, BSSP, IBHP), or, only transversal members (CHTB, CHMF), while some consist of both longitudinal and transversal members (HCC, ISTST, ISDBT, APS, FPS). It is to be pointed out here that the previous studies in this domain included and treated mostly the longitudinal elements, only. The suggested division of the bulk carrier structure members/categories is given in Table 1.

In aim to get better insight into locations of the members distributed throughout the bulk carrier hull structure (Table 1), 2D bulk carrier's longitudinal view, and 3D cargo hold cross-section, are given in Figure 1.

To predict likely corrosion damage tolerance, or a steel amount to be replaced at a certain area *a priori*, it is necessary to make estimates of the corrosion rates for various structural members grouped by location and some other relevant parameters as it is

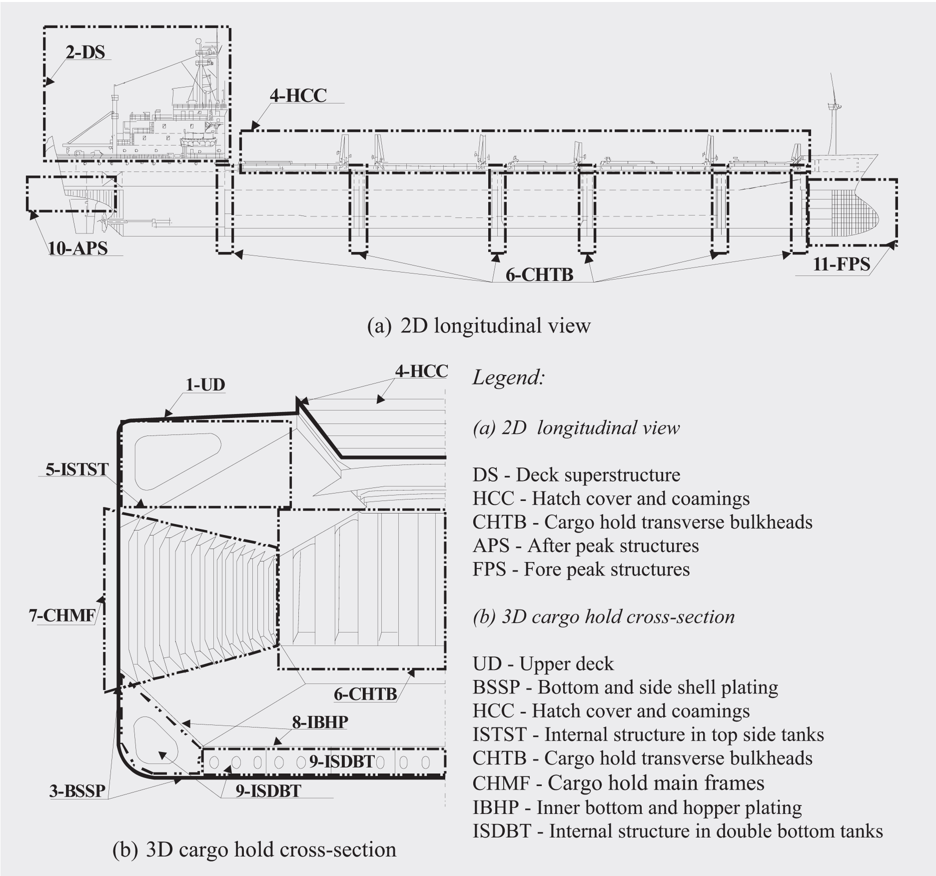


Figure 1. Structural categories identification.

previously done. The appropriate estimations are done in this research at two different levels. The first is the experimental one, realized by Monte Carlo simulation method, and the other one is experience based, i.e. it is based on the expert's knowledge in the domain, being gathered during the years of the working experiences, and later used in making corrections in the results obtained by Monte Carlo method. In other words, Monte Carlo has been used in predicting the amounts of the steel which are to be replaced at each of above identified bulk carriers' structure members per year. Afterwards, the comparison with the expert's knowledge has been performed and the proper corrections have been made in a way described later in the paper.

In aim to realize Monte Carlo simulation the set of homogenous historical data are collected over the previously specified primary transversal and longitudinal bulk carriers' structure members by the recommended standard measurements during the ten years period, that is, during the period between the twentieth and the thirtieth year of the ships operation life. The cumulative data, collected by measuring ten bulk carriers (BC_1-BC_{10}), or more precisely, by measuring more than 300.000 gauged points properly distributed throughout the bulk carriers' hull structures, are given in Table 2.

Table 2. The cumulative data on steel amounts [t] removed/replaced at ten bulk carriers structure members between its 20th and 30th year of operation

No.	Memb.	BC_1	BC_2	BC_3	BC_4	BC_5	BC_6	BC_7	BC_8	BC_9	BC_{10}
1.	UD	1	22	1	30	150	7	165	80	1	12
2.	DS	3	6	1	2	4	6	22	5	0	0
3.	BSSP	3	65	3	45	10	5	60	25	5	3
4.	HCC	7	15	3	15	35	32	40	35	3	25
5.	ISTST	8	9	25	30	45	75	160	120	45	6
6.	CHTB	2	65	25	170	32	45	145	220	24	16
7.	CHMF	3	45	16	85	22	32	85	110	26	25
8.	IBHP	5	550	15	650	440	150	650	85	120	110
9.	ISDBT	20	50	30	35	40	45	55	45	22	2
10.	APS	5	40	25	5	30	14	30	12	9	2
11.	UD	1	6	14	5	20	32	60	55	16	3

As numerous other simulation methods, Monte Carlo method is an experiment in which we attempt to understand how something will behave in reality by imitating its behavior in an artificial environment that approximates reality as closely as possible. Thus, a Monte Carlo simulation creates an artificial environment that approximates reality – here, in this paper, the real corrosion time-dependent process at the group of aged bulk carriers. It conducts computer based experiments over past data that would be too costly and time-consuming to perform in reality. Because Monte Carlo simulation generates random numbers (data), obtaining accurate results requires the simulation to consist of large number of repetitions or runs, or trials. Since it generates random data, there is no guarantee that the chosen policy is actually the optimal one, but the simulation results, undoubtedly, can offer some effective directives for further investigations and comparative analysis due to the expert knowledge.

Results and discussion

The simulation procedure has been realized using Microsoft Excel and it's built-in functions RAND ( ) and LOOKUP (*.*) (Balakrishnan, Render and Stair, 2007) over the data set presented in Table 2. In accordance to the Monte Carlo simulation method, the frequencies of each steel amounts [t] which are replaced at the certain ships' structure members are determined. Then, the probabilities of these amounts appearances in the model are calculated. Later on, the cumulative probabilities and the corresponding random numbers intervals have been set up. The Monte Carlo simulation has been realized throughout two sub-sets of 50.000 runs or trials, i.e. through 100.000 passes in total. Some of the simulation results obtained for the most specific, or, corrosion most sensitive segment of the observed bulk carrierrs' structures – IBHP, are shown in Table 3.

Table 3. Some Monte Carlo simulation results gained for the bulk carriers' IBHP structure members by Excel functions (RN, LOOKUP, COUNTIF)

Steel amounts [t] replaced per year	Frequency	Simulation results				
		RN		LOOKUP		COUNTIF
0.5	1	0.20390	0.04756	8.5	0.5	4981
1.5	1	0.84065	0.78524	65	55	5090
8.5	1	0.94182	0.84977	65	65	5203
11	1	0.97472	0.55561	65	15	4952
12	1	0.08724	0.42820	0.5	12	4944
15	1	0.25933	0.66248	8.5	44	4925
44	1	0.66063	0.97846	44	65	4942
55	1	0.56119	0.30718	15	11	4969
65	2	0.88060	0.68039	65	44	9994
		0.91545	0.61109	65	44	50000
		0.78696	0.08944	55	0.5	
		0.85812	0.30362	65	11	
		0.38058	0.92609	11	65	
		0.32778	0.66141	11	44	
		0.10183	0.44175	1.5	12	
		0.99021	0.15439	65	1.5	
		0.19375	0.93025	1.5	65	
		0.42175	0.79236	12	55	
		0.60576	0.97135	44	65	
		0.80586	0.16350	65	1.5	
		0.94447	0.96588	65	65	
		0.31684	0.17888	11	1.5	
		0.41117	0.26860	12	8.5	
		0.93964	0.00113	65	0.5	
		0.47111	0.25392	12	8.5	
		0.33747	0.99960	11	65	
		...	... up to 50000 trials	...	... up to 50000 trials	

The simulations presented in Table 3 have been realized through 50000 trials. This number of trials can be multiplied due to the level of simulation model reliability requirements. Similarly, the above presented procedure has been realized for the rest of considered bulk carriers' structure members, and the obtained results are presented in Table 4. Latter on, the obtained results have been confronted with the experts' expectations.

Table 4. The estimated steel amounts [t] that should be replaced at the certain ship structure member per year (shadowed fields), obtained by Monte Carlo simulation method.

Member		Steel amounts[t] / number of random appearances through the simulation process										Total number of runs
UD	Amount $^{Freq.}$	0.1^{3}	0.7^{1}	1.2^{1}	2.2^{1}	3.0^{1}	8.0^{1}	15.0^{1}	16.5^{1}			Σ 100 000
	Appearing no.	29964	9795	10088	10150	10055	9906	10085	9957			
DS	Amount $^{Freq.}$	0.0^{2}	0.1^{1}	0.2^{1}	0.3^{1}	0.4^{1}	0.5^{1}	0.6^{2}	2.2^{1}			Σ 100 000
	Appearing no.	19978	10072	10103	10058	9793	10085	19811	10100			
BSSP	Amount $^{Freq.}$	0.3^{3}	0.5^{2}	1.0^{1}	2.5^{1}	4.5^{1}	6.0^{1}	6.5^{1}				Σ 100 000
	Appearing no.	30068	20048	10029	10027	10026	9809	9993				
HCC	Amount $^{Freq.}$	0.3^{2}	0.7^{1}	1.5^{2}	2.5^{1}	3.2^{1}	3.5^{2}	4.0^{1}				Σ 100 000
	Appearing no.	19958	9977	19962	9944	10088	20074	9997				
ISTST	Amount $^{Freq.}$	0.6^{1}	0.8^{1}	0.9^{1}	2.5^{1}	3.0^{1}	4.5^{2}	7.5^{1}	12.0^{1}	16.0^{1}		Σ 100 000
	Appearing no.	9996	9968	9986	10031	9773	20114	10079	10032	10020		
CHTB	Amount $^{Freq.}$	0.2^{1}	1.6^{1}	2.4^{1}	2.5^{1}	3.2^{1}	4.5^{1}	6.5^{1}	14.5^{1}	17.0^{1}	22.0^{1}	Σ 100 000
	Appearing no.	9872	9992	10146	9968	10130	9923	9988	10045	10046	9890	
CHMF	Amount $^{Freq.}$	0.3^{1}	1.6^{1}	2.2^{1}	2.5^{1}	2.6^{1}	3.2^{1}	4.5^{1}	8.5^{2}	11.0^{1}		Σ 100 000
	Appearing no.	10053	9943	10066	9805	9994	10105	10096	20002	9936		
IBHP	Amount $^{Freq.}$	0.5^{1}	1.5^{1}	8.5^{1}	11.0^{1}	12.0^{1}	15.0^{1}	44.0^{1}	55.0^{1}	65.0^{2}		Σ 100 000
	Appearing no.	10185	9985	9817	9965	9970	10052	9957	10099	19970		
ISDBT	Amount $^{Freq.}$	0.2^{1}	2.0^{1}	2.2^{1}	3.0^{1}	3.5^{1}	4.0^{1}	4.5^{2}	5.0^{1}	5.5^{1}		Σ 100 000
	Appearing no.	9884	10138	9942	10122	9901	9901	9918	20071	9988		
APS	Amount $^{Freq.}$	0.2^{1}	0.5^{2}	0.9^{1}	1.2^{1}	1.4^{1}	2.5^{1}	3.0^{2}	4.0^{1}			Σ 100 000
	Appearing no.	10013	19905	10156	10000	10111	9995	19962	9858			
UD	Amount $^{Freq.}$	0.1^{1}	0.3^{1}	0.5^{1}	0.6^{1}	1.4^{1}	1.6^{1}	2.0^{1}	3.2^{1}	5.5^{1}	6.0^{1}	Σ 100 000
	Appearing no.	10243	10164	9789	10022	10026	10039	9962	10016	9860	9879	

The shadowed steel amounts represent the amounts that randomly appear in the biggest number of simulation trials. Those values should be the optimal ones to be replaced at the certain ship structure member per year, but since the simulation method includes random processes, random variables and their random values, it can not guarante that the obtained simulation results are indeed the optimal ones. Though, they are to be tested in such way to be compared later to the expert knowledge.

Improving the model

Due to the experts' knowledge, internal structure in top side tanks (ISTST), cargo hold transverse bulkheads (CHTB) and inner bottom and hopper plating (IBHP) are the most sensitive and important for the bulk carrier strength, though they should need additional analyzing and simulating in the process of finding optimal solution. Again, according to the experts' experiences the average value of the steel amounts which have to be replaced per year at certain member/category of the ship's structure might be the right orienteer in achieving improvements in the simulation model. In other words, the simulation model should be satisfying *reliable* if it gives *optimal* values that are close to the average values of the steel amounts [t] to be removed/replaced at above pointed member structure areas. The schematic representations of the experts' suggestions in the direction of Monte Carlo simulation model improving and the way of attempting to achieve them, is presented in Figure 2.

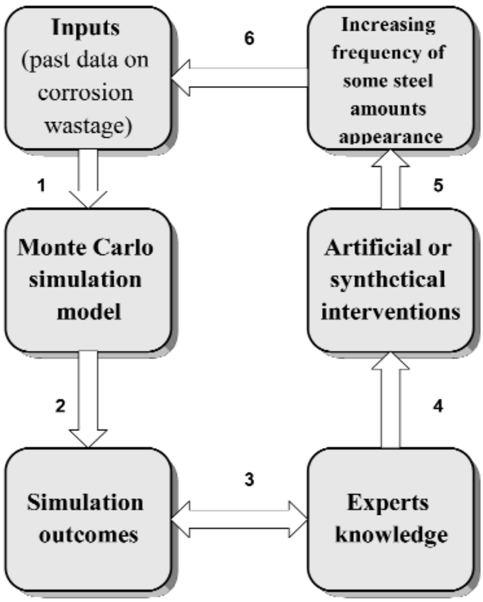


Figure 2. The scheme of possible improvements of the Monte Carlo simulation modeling.

Afterwards, the question is drawn: how to achieve the suggested *improvements* of the proposed and here applied Monte Carlo simulation model? - The simplest and the most effective way is to *artificially* adjust some values in the model (i.e. for ISTST, CHTB and IBHP) to be close, or closer, to the average values of steel amounts that are to be removed/replaced at each considered area. This could be done by adding / subtracting *artificially* appropriate small amounts of steel to the listed ones (see tables 3 and 4) in aim to increase frequencies of appearing the values close to the average one for the certain ship's structure member in the model. In such way, the possibilities for the *right* values appearance as the optimal ones at the end of numerous runs of the Monte Carlo simulation process shall be undoubtedly higher.

The frequency of a certain value appearance in the model initial (input) matrix of data is of the crucial importance for obtaining *wanted* or valid (final) results for the considered problem. Thus, the main qualitative contribution of these experiments might be: the frequency of a certain value appearing in the model input matrix is the crucial in obtaining the optimal solution after series of simulation runs. Additionally, due to the experts' knowledge in this domain, the best way to make simulation results closer to the real situation it is to adapt the initial model in a way to increase *artificially* frequencies of appearing the values close to the average one (by adding/subtracting enough small values for steel amounts). By such interventions model can be generally used in predicting the optimal amounts of the steel to be removed/replaced at each bulk carrier's structure area on the bases of the past collected data and their slight corrections due to experts' knowledge in the field.

The achieved improvements in the case of the considered problem are presented in the Table 5. It is obvious that the optimal results obtained by Monte Carlo simulation are considerably closer to the average amounts for ISTST, CHTB and IBHP bulk carrier's structure members, than in the first sequence of experiments (Table 4).

Table 5. The improved results of Monte Carlo simulation achieved owing to the experts' knowledge in the domain

Member	Steel amounts[t] / number of random appearances through the simulation process											Total number of runs
ISTST	Amount Freq.	0.6^1	0.8^1	0.9^1	2.5^1	3.0^1	4.5^2	7.5^1	12.0^1	16.0^1		0.52 (avg)
	Appearing no.	9996	9968	9986	10031	9773	20114	10079	10032	10020		Σ 100 000
ISTST(1)	Amount Freq.	0.5^3			2.5^1	3.0^1	4.5^2	7.5^1	12.0^1	16.0^1		
	Appearing no.	30284			10164	9882	19822	9796	10057	9995		Σ 100 000
CHTB	Amount Freq.	0.2^1	1.6^1	2.4^1	2.5^1	3.2^1	4.5^1	6.5^1	14.5^1	17.0^1	22.0^1	0.74 (avg)
	Appearing no.	9872	9992	10146	9968	10130	9923	9988	10045	10046	9890	Σ 100 000
CHTB(1)	Amount Freq.	0.7^3			2.5^1	3.2^1	4.5^1	6.5^1	14.5^1	17.0^1	22.0^1	
	Appearing no.	30108			9946	9963	10135	9961	9882	9930	10075	Σ 100 000
IBHP	Amount Freq.	0.5^1	1.5^1	8.5^1	11.0^1	12.0^1	15.0^1	44.0^1	55.0^1	65.0^2		2.78 (avg)
	Appearing no.	10185	9985	9817	9965	9970	10052	9957	10099	19970		Σ 100 000
IBHP(1)	Amount Freq.	3.0^3			11.0^1	12.0^1	15.0^1	44.0^1	55.0^1	65.0^2		
	Appearing no.	30039			10125	9869	9965	9926	10190	19886		Σ 100 000

The proposed way of improving *reliability* of Monte Carlo should be tested at greater amount of data, collected for example by different companies and/or ships' classification societies. Afterwards, the whole process should be *automated* by developing the appropriate software application for easier and quicker model realization.

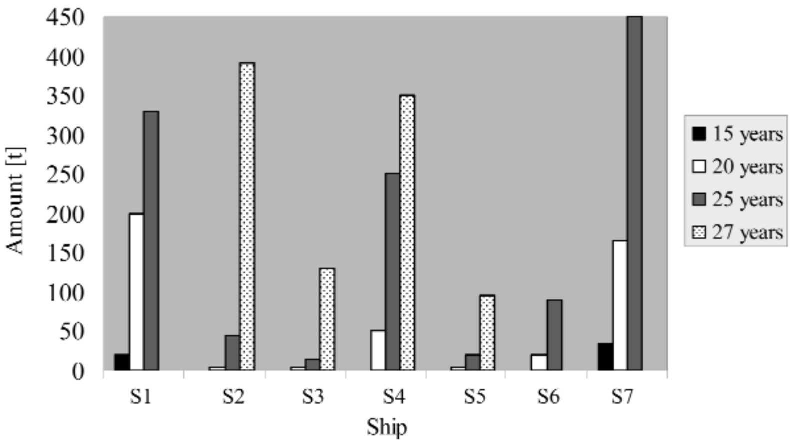
Within the next section, the second corresponding corrosion predictive model based upon rather uncommon inverse analysis of the time-dependent bulk carriers' corrosion wastage.

Some analysis of time-dependent corrosion wastage model

Up to now, several time-dependent corrosion wastage models have been developed upon the appropriate homogenous historical (statistical) data (Wang et al, 2008). Most of these models consider depth of steel degradation (d [mm/year]) at a certain ship's area. Here, within this paper an effort has been done to represent corrosion degradation through the amounts of steel which have been replaced at the certain bulk carrier's areas due to the severe corrosion wastage of the structure material.

Accordingly, the data collected by regular thickness measurements at the group of seven bulk carriers have been used. Since the inner bottom plating (IBHP) areas are in the greatest measure exposed to the corrosion, only these structure members were examined here. The Figure 3 shows the histogram of corrosion wastage (replaced amounts of steel [t]) of inner bottom plating at selected ship's ages (15, 20, 25, 27) over the examined set of seven bulk carriers.

Figure 3. The histogram of corrosion wastage of inner bottom plating at selected ship's ages at an exemplar of seven bulk carriers.



The durability of coating, transition between coating durability and corrosion initiation, and the process of corrosion, might be represented with a time-dependent functional equation of the following type [3] (Soares and Garbatov, 1999):

$$d(t) = d_{\infty}\left(1 - e^{-\frac{t-\hat{o}_c}{\hat{o}_t}}\right) \tag{2}$$

were

d(t) is the corrosion wastage at time t;
d∞ is the long-corrosion wastage;
τ_c is the time without corrosion to the start of failure of the corrosion protecting coating;
τ_t is the transition time duration.

Since corrosion data has a very large variability, the time-dependent functional equation (2) should not be taken into the consideration as "the only" or as "the best" one. It has been used here as an equation that satisfies the requirements of an approximation of corrosion wastage considered in the paper. Namely, it is well known, that most corrosion data are relatively largely scattered. What can be treated as novel here, due to the authors' experience is an attempt to realize some *inverse* analysis of the equation (2) in manner to find an approximate function which corresponds to the amounts of steel replaced during the ship exploitation circle. Mostly, previous works in this domain were oriented toward the depths of steel damages caused by the corrosion processes (Soares and Garbatov, 1999). However, here is presented an attempt to determine approximately functional equation that corresponds to the removed (replaced) steel amounts over certain ship structure area. After some analytical analysis and numerous simulation trials (in Matlab) it has been realized that function of type (3) might be used, with satisfying accuracy, in modeling the steel amounts to be replaced at bulk carriers' inner bottom plating areas during the time:

$$Q(t) = e^{\frac{t-\hat{o}_c}{\hat{o}_t}} - 1 \tag{3}$$

were

Q (t) is the steel amount replaced/removed over certain ship's area;
τ_c is the time without corrosion to the start of failure of the corrosion protecting coating;
τ_t is the transition time duration.

Figure 4 shows both functional equations (2) and (3), i.e. time-dependant corrosion depth expressed in [mm/year], and time-dependant removed/replaced steel amounts expressed in [t] units. Additionally, the time-variant removed/replaced steel amounts over pre-specified areas have been presented for different τ_c, i.e. $\tau_c \in$ [10, 12, 15]years.

Figure 4. Scheme of two different functional approximations for corrosion degradation of the bulk carrier's structure members (d, Q).

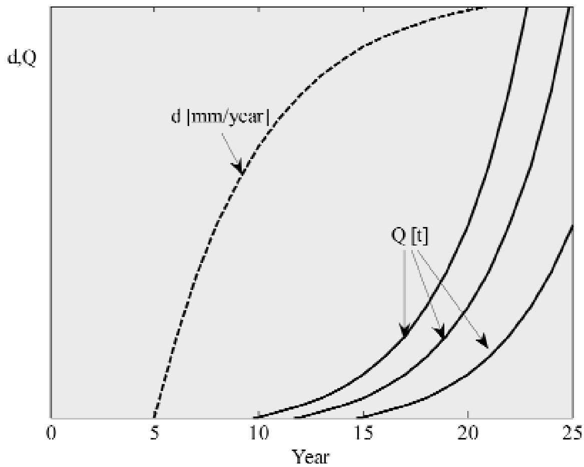
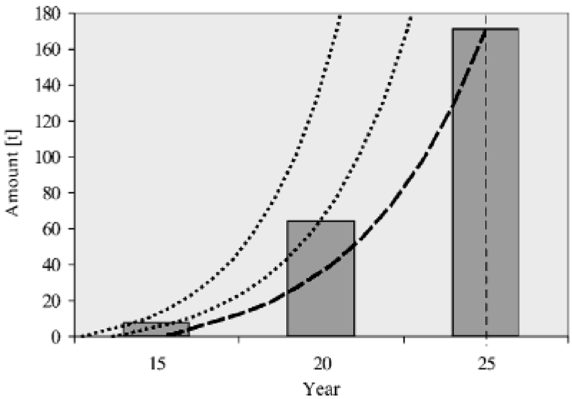


Figure 5. The inner bottom plating degradation: comparison of average removed steel amounts and predicted ones for different τ_c.



The curves Q[t] in Figure 4 have been *transposed* to the scheme of average removed/replaced steel amounts over bulk carriers' inner bottom plating areas in the case of examined set of seven aging bulk carriers, and the results are shown in Figure 5.

In the case of the experimental set of data collected from seven aged bulk carriers (Figure 5) the predicted Q(t) approximates curve for $\tau_c = 15$ best feats to the average values of steel replaced at 15, 20, and 25 year of ships' exposure to the corrosion process in the marine environment. The inner bottom plating areas were only considered here, since these areas are in the greatest extend exposed to the corrosion. An analog approach might be used in comparing each bulk carrier's member structure and proposed approximated functional equation (3). The proposed equation (3) should be evaluated by the larger amount of the statistical data, being collected by few companies and/or ships' classification societies. In the case of observed bulk carriers' inner bottom plating areas, for $\tau_c = 15$, rather complete steel construction amounts have been replaced at 25^{th} year of the ships' exploitation life. The last noted might be an indicative fact for forthcoming investigations in this domain.

CONCLUSION

In this paper, on the exemplar of a set of aged bulk carriers, Monte Carlo simulation method has been employed in predicting steel amounts that are to be replaced at a certain ships' structure category per year. Some improvements of the results obtained by the usage of *pure* Monte Carlo method have been suggested. The improvements should comprise a kind of "synthetic" or "artificial" interventions in the historical (empirical) simulation input data, in order to increase the frequency of appearing the most common amount of steel (due to the experts experiences) which is to be removed/replaced over the certain bulk carrier structure category (member) area per year. This might be treated as a particular *syncretism* of some quantitative and qualitative simulations analysis in the process of predicting steel amounts that are to be replaced over each longitudinal and transversal element of bulk carriers' structures, caused by the corrosion degradation during the period of the operational life. Toward further, more extensive, investigations in this domain, the larger input data base and its deeper proper segregation of each bulk carrier's structural areas into the considerably smaller segments are necessary.

The paper also proposes a novel approximate, predictive, time-variant functional model for steel amounts that might be replaced/removed over bulk carriers' inner bottom plating locations. The proposed model might be treated as rather original one in comparison to the previously developed several time-variant corrosion wastage depth models. But, it has to be tested (validated) over the larger input statistical data base. Though, the last mentioned is to become the subject of further more rigorous investigations in the wide domain of bulk carriers' hull structures corrosion damages modeling.

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REFERENCES

Adey, R. and Baynham J. (2000): *Predicting corrosion rated electrical and magnetic field*, Computational Mechanics BESAY Ltd., Southampton, Hampshire

Balakrishnan, N.; Render, B. and Stair. R. (2007): *Managerial Decision Modeling with Spreadsheets*, Part 10: Simulation Modeling, 2nd Edition, Pearson – Prentice Hall, New Jersey

Guedes Soares, C. and Garbatov, Y. (1999): Reliability of maintained corrosion protected plates subjected to non/linear corrosion and compressive loads, *Journal of Marine Structures*, No. 12, pp. 425-445

Guo, J.; Wang, G.: Ivanov, L. and Perakis, A.N. (2008): Time-varying ultimate strength of aging tanker deck plate considering corrosion effects, *Journal of Marine Structures*, Vol. 21, No. 4, pp. 402-419

Paik, J.K.; Kim, S.K.; Lee, S.K. and Park, J.E. (1998): A probabilistic corrosion rate estimation model for longitudinal strength members of bulk carriers, *Journal of Ships & Ocean Technology*, Vol. 2, No. 1, pp. 58-70

Paik ,J.K.; Lee, J.M.; Park, Y.; Hwang, J.S. and Kim ,C.W. (2003): Time-variant ultimate longitudinal strength of corroded bulk carriers, *Journal of Marine Structures*, Vol. 16, pp. 567-600

Paik, J.K.and Thayamballi, A.K. (2002): Ultimate strength of ageing ships, *Proc. Instn. Mech. Engrs.*, Vol. 216, Part M: Engineering for the Maritime Environment, pp. 57-77

Qin, S-P and Cui, W-C (2002): A discussion of the ultimate strength of ageing ships, with particular reference to the corrosion model, *Proc. Instn. Mech. Engrs.*, Vol. 216, Part M: Engineering for the Maritime Environment, pp. 155-160

Shogan, A.W. (1998): *Management Science*, Part 17: Simulation, University of California, Berkeley, Prentice-Hall Inc., New Jersey

Wang, G.; Lee, A.; Ivanov, L.; Lynch, J. T.; Serratella, C. and Basu, R. (2008) A Statistical Investigation of Time-variant Hull Girder Strength of Aging Ships and Coating Life, *Journal of Marine Structures*, Vol. 21 No. 2/3, pp. 240-256.