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AN APPROACH TO THE CORROSION ANALYSIS OF BULK CARRIER HULL STRUCTURE

ABSTRACT

Numerous bulk carrier hull structural damage analyses are based on the study of fatigue of materials and corrosion processes. Different theoretical and empirical models have been developed to describe the time-dependent characterization of corrosion of ship structures. In accordance with the existing rules of Maritime Classification Societies, the whole ship hull structure of each of the 12 almost 25-year-old bulk carriers considered in this paper, is divided into 11 structural areas. Motivated by Preliminary Risk Assessment, and using the data on the estimated amounts of the steel removed over these structural components during the whole exploitation period, here we estimate and compare the qualitative and quantitative risk levels related to the corrosion wastage over all bulk carriers' structural areas.

Key words:
bulk carrier, ship hull structure, corrosion, risk level.

INTRODUCTION

A large number of internal and external factors influence the structure of aging bulk carriers. These influencing factors can cause rapid deterioration of some structural elements, which can generate a number of structural damages, and ultimately can lead to the bulk carriers sinking.

Due to the numerous negative effects of ship's accidents on humans and the environment, numerous studies have been conducted, based on: age and size of vessels, causes of sinking, types of cargo transported, types of ships and their tonnage,

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transport routes, state flags, weather conditions, ports of departures, places of shipbuilding, etc. All analyzed parameters aimed towards determining the critical influencing factors and guidelines for their reduction [11].

In the studies conducted so far, it appears that bulk carriers are subject of numerous maritime accidents. During the last five decades, there were over 500 complete losses of aged bulk carriers, causing the loss of more than 2300 human lives [4, 10].

So far, the number of studies was examining the impacts of corrosion degradation on the structure and stability of the ship's hull [9]. Although the theoretical predictions based on the different protection and mostly operational parameters have been done in numerous investigations, such approach to the corrosion phenomenon is indeed a difficult task [5]. Recently, Wang et al. [12] presented a critical review of the corrosion mechanisms and fundamentals of steel-plated structures in the marine environment so far. An easier option, being used here, is to base the corrosion rate analysis on the homogenous historical data about the corrosion losses, including the work of the author of this study [2, 3, 6].

Recognizing the importance of the different influences that may negatively affect the exploitation of ships, the International Maritime Organization (IMO) has established the need to identify risk, or the risk analysis, risk assessment and risk management. That is why, through the IMO SOLAS Convention the ISM Code was introduced, as well as the *Guidelines for Formal Safety Assessment for use in the IMO Rule-Making Process*, as part of MSC Circ.1023 and MEPC Circ. 392, 5 April 2002 [7].

In this paper we use the appropriate base of empirical data on the state of the structural elements of the aging bulk carriers in exploitation, and as such it serves in the risk assessment of aging bulk carrier's structural areas which are subject to corrosion. In this sense, in this paper estimated cumulative amounts of steel replaced in the subject areas during the whole life cycle are analyzed, which are generated considering the condition of hull structural areas of aging bulk carriers.

The paper is organized as follows. In section 'Subject of research and input data for bulk carriers' we present basic technical data of investigated twelve almost 25-year-old bulk carriers. For each of these bulk carriers we analyzed its eleven hull structural areas which are subject to corrosion, in accordance with the related regulations and standards of classification societies. The amounts of the steel [t] replaced over some of the bulk carriers' hull structural areas during the whole exploitation period are divided in four classes. Motivated by Preliminary Risk Assessment, and using the mentioned data, in section 'An estimation of quantitative risk levels of the corrosion over bulk carriers' structural areas' we propose a simple method for estimating the quantitative risk levels related to the corrosion wastage over all bulk carriers' structural areas. The obtained results allow us to compare these risk levels with related qualitative risk levels concerning the same or different structural areas of all considered bulk carriers. Concluding remarks and directions for future research are given in section 'Conclusion'.

SUBJECT OF RESEARCH AND INPUT DATA FOR BULK CARRIERS

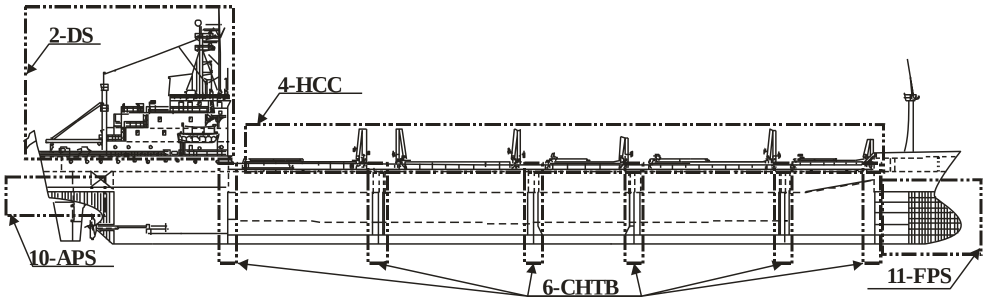
Previous studies in maritime accidents investigation have shown that the most sensitive vessels are bulk carriers and tankers. Namely, these studies were conducted on the structural areas of aged bulk carriers, which were in service for two decades.

The analyzed bulk carriers were built between 1978 and 1984, with deadweight between 38,000 and 45,000 tons, and under four different Classification Societies.

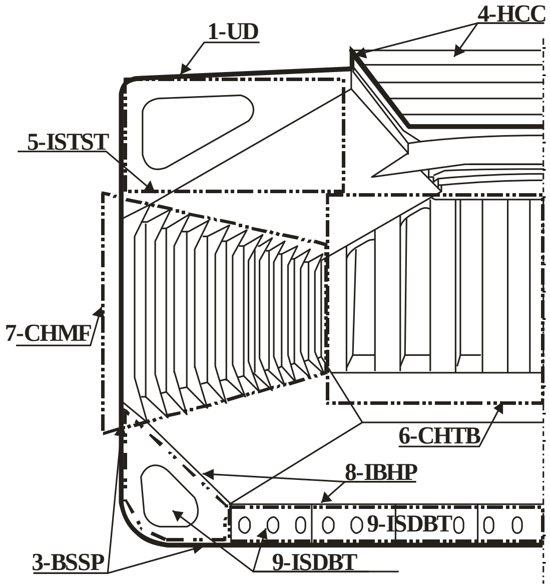
Considering the recommendations of Maritime Classification Societies on the scope and intensity measurements of various structural elements and areas, while respecting the logical judgment on the unification of certain areas (ballast tanks, dry spaces, cargo spaces), bulk carriers are fragmented into eleven specific areas. Each of these areas is presented in figure 1, as longitudinal view and Cargo Hold cross-sectional view of typical single hull bulk carrier. In this way, all these mentioned areas are subdivided into eleven units, of which some include steel plates (areas 1, 2, 3, 8 in figure 1), while other areas (areas 4, 5, 6, 7, 9, 10, 11 in figure 1) include steel plates and supported structure (stiffeners, brackets).

For each aging bulk carrier, the appropriate measurements of specific areas and elements which are subject to corrosion were conducted, in accordance with the related regulations and standards of classification societies. The measurements were performed by using ultrasonic measuring instruments, while data processing has been done by the sophisticated software applications of classification societies. With standardized data processing, the amounts of steel plates and supported structures that are to be replaced due to the corrosion were determined.

An idea was to process the collected data and estimate the amount of steel to be replaced at the end of a certain period. In this sense, the data were collected at the end of the bulk-carrier's twenty-fifth year of service in accordance with Cumulative data on the quantities of replaced steel within a particular area of the hull. The data are given in table 1.



(a) 2D longitudinal view



(b) 3D cargo hold cross-section

Fig. 1. Eleven hull structural areas of bulk carriers:
1-UD — upper deck, 2-DS — deck superstructure, 3-BSSP — bottom and side shell plating, 4-HCC — hatch cover and coaming, 5-ISTST — internal structure in top side tanks, 6-CHTB — cargo hold transverse bulkheads, 7-CHMF — cargo hold main frames, 8-IBHP — inner bottom and hopper plating, 9-ISDBT — internal structure in double bottom tanks, 10-APS — after peak structures, 11-FPS — fore peak structures

Table 1. The amounts of the steel [t] replaced over bulk carriers' hull structural areas during the whole exploitation period

Area / Ship	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}
1-UD	80	165	22	7	12	1	36	30	12	14	150	3
2-DS	5	22	6	6	14	0	2	2	5	11	4	2
3-BSSP	25	60	65	5	3	0	21	45	33	0	10	1
4-HCC	35	40	15	32	7	10	14	15	18	22	35	3

Area / Ship	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}
5-ISTST	120	160	9	75	14	5	16	30	187	35	45	10
6-CHTB	220	145	65	45	13	3	84	170	16	17	32	1
7-CHMF	110	85	45	32	3	0	25	85	7	0	22	4
8-IBHP	585	650	550	150	38	0	110	650	270	35	440	0
9-ISDBT	45	55	50	45	48	0	2	35	44	24	40	0
10-APS	12	30	40	14	5	0	2	5	3	2	30	0
11-FPS	55	60	6	32	26	2	19	5	1	15	20	1

AN ESTIMATION OF QUANTITATIVE RISK LEVELS OF THE CORROSION OVER BULK CARRIERS' STRUCTURAL AREAS

The concept of risk is used to assess and evaluate uncertainties associated with an event (see [1] and [7]). Risk can be defined as the potential of losses resulting from exposure to a hazard. Risk should be based on an identified failure scenario, its occurrence probability, its consequences, consequence significance, and the population at risk; however, it is commonly and can be fundamentally measured as a pair of the probability of occurrence of an event, and the outcomes of consequences associated with the event's occurrence. Accordingly, risk associated with an accidental event E is commonly evaluated as the product of occurrence and the impact of an accident (see [1, p. 77] and [7]), i.e.

$$R(E) = C(E) \cdot P(E)\,, \tag{1}$$

where E is a considered accidental event, $R(E)$ is the risk level of event E, $C(E)$ is the magnitude (level) of consequence of event E and $P(E)$ is the probability of occurrence of event E.

For our purposes, in this paper we use the above definition of risk, i.e., the formula (1), where the (theoretical) probability $P(E)$ is replaced with the usual relative frequency of the considered event E. We use data from table 1 in order to divide the amounts of steel [t] replaced over each particular bulk carriers' hull structural areas during the whole exploitation period into the following four intervals: 0–5 [t], 5–25 [t], 25–100 [t] and > 100 [t], denoted as I_1, I_2, I_3, I_4, respectively (in any of these intervals it is included its left bound but it is not included its right bound). Further, let E_{ij} ($i = 1, 2, 3, 4$; $j = 1, 2, \ldots, 11$) denote the event that in j-th bulk carriers' structural area it is replaced the amounts of the steel that belongs to the interval I_i. Then the average values of the bounds of first three of these intervals (equals to 2.5 t, 15 t, 62.5 t, respectively) and the value 100t for the fourth interval are assumed here as a 'measure' of magnitude (level) of consequence C_{ij} of related event E_{ij}. Moreover, for any fixed $j = 1, 2, \ldots, 11$, let F_{ij} ($i = 1, 2, 3, 4$) be the relative frequency of event E_{ij} calculated with respect to all twelve considered bulk carriers. Then, in view of formula (1), the quantitative risk level R_{ij} of event E_{ij} ($i = 1, 2, 3, 4$; $j = 1, 2, \ldots, 11$) can be defined as

$$R_{ij} = C(E_{ij}) \cdot F_{ij}, \tag{2}$$

where as noticed above, for all $j = 1, 2, \ldots, 11$

$$C(E_{1j}) = 2.5,\ C(E_{2j}) = 15,\ C(E_{3j}) = 62.5 \text{ and } C(E_{4j}) = 100. \tag{3}$$

On the other hand, it can be of interest to determine the qualitative risk levels of every event E_{ij} ($i = 1, 2, 3, 4$; $j = 1, 2, \ldots, 11$). For this purpose, we use a shortened and modified form of the 7 x 4 Risk Matrix introduced by the IMO (see, e.g., [8]; cf. [7]), reflecting the greater potential variation for frequencies than for consequences. Accordingly, the consequence severity categories and the frequency categories are defined in tables 2 and 3, respectively.

Table 2. Consequence severity categories

Severity of consequences	**Related intervals [t]**
A — Negligible	0–5 [t]
B — Marginal	5–25 [t]
C — Critical	25–100 [t]
D — Catastrophic	> 100 [t]

Table 3. Frequency categories

Accident frequency	**Related intervals**
I — *Frequent*	0,5–1,00
II — *Probable*	0,15–0,50
III — *Remote*	0,05–0,15
IV — *Improbable*	0,00–0,05

Here, as always in the sequel, we use the following notations: H — high risk (Unacceptable), M (B and C) — medium risk (Undesirable) and L — low risk (Insignificant). Then the 4 x 4 Risk Matrix concerning tables 2 and 3 is given as follows (cf. [7] and [8]).

Table 4. The actual Risk Matrix with the decision classes shown

	Consequence level			
Occurrence	Negligible (A)	Marginal (B)	Crtical (C)	Catastrophic (D)
Frequent (I)	M	M	**H**	**H**
Probable (II)	M	M	M	**H**
Occasional (= Occasional + Remote) (III)	L	M	M	M
Improbable (= Improbable + Incredible) (IV)	L	L	M	M

Table. 5. The quantitative (R_{ij}) and qualitative (H — high risk, M — medium risk, L — low risk) risk levels for four classes of all 11 structural areas of 12 bulk-carriers

Risks — R_{ij}	R_{1j}	R_{2j}	R_{3j}	R_{4j}
R_{i1}	0,42 (A2-M)	5,21 (B2-M)	15,63 (C2-M)	**16,67 (D4-M)**
R_{i2}	1,04 (A2-M)	**6,25 (B1-M)**	5,21 (C3-M)	0,00 (D4-M)
R_{i3}	0,83 (A2-M)	3,13 (B2-M)	**26,04 (C2-M)**	0,00 (D4-M)
R_{i4}	0,21 (A3-M)	7,29 (B1-M)	**20,83 (C2-M)**	0,00 (D4-M)
R_{i5}	0,00 (A4-L)	5,21 (B2-M)	20,83 (C2-M)	**25,00 (D2-H)**
R_{i6}	0,42 (A2-M)	3,13 (B2-M)	20,83 (C2-M)	**25,00 (D2-H)**
R_{i7}	0,83 (A2-M)	2,08 (B2-M)	**26,04 (C2-M)**	8,33 (D3-M)
R_{i8}	0,42 (A2-M)	0,00 (B4-L)	10,42 (C2-M)	**66,67 (D1-H)**
R_{i9}	0,63 (A2-M)	1,04 (B3-M)	**41,67 (C1-H)**	0,00 (D4-M)
R_{i10}	1,04 (A2-M)	4,17 (B2-M)	**15,63 (C2-M)**	0,00 (D4-M)
R_{i11}	0,63 (A2-M)	5,21 (B2-M)	**20,83 (C2-M)**	0,00 (D4-M)

The values R_{ij} from table 5 are obtained by using the formula (2) and the values given in (3), while related qualitative levels of risk are obtained by using tables 2–4. Moreover, the marked fields in table 5 correspond to the maximum values for the appropriate structural area. From table 5 we see that the qualitative and quantitative levels of risk are not coherent for all structural areas, in the sense that there for some pairs (i, j) and (k,l) $R_{ij} > R_{kl}$ but the associated qualitative risk to (i, j) is less than those to (k,l). For example, $26.04 = R_{37} > R_{45} = 25$, but to (3,7) is associated medium risk and to (4,5) are high risk. Furthermore, observe the unusual facts that $R_{4j} = 0$ for $j = 4, 9, 10, 11$, but to every of related structural areas corresponds the medium risk in qualitative sense. This is justified by the fact that in our meted a relatively small number of bulk carriers is considered.

From table 5 we also see that the structural areas 5, 6, 8 and 9 are more rapidly damaged due to corrosion process instead of other structural areas. The area 8 has been identified as an extremely critical area with catastrophic consequences.

CONCLUSION

In this article a detailed analysis of empirical data on the damaged aging bulk carriers due to corrosion was carried out. The aim of this study is to estimate the quantitative risk levels related to the corrosion wastage over all bulk carriers' structural areas and on the basis of the available data on the estimated cumulative amount of the replaced steel, using an approach to Preliminary qualitative risk assessment, to obtain data on the degree of criticality of certain structural areas exposed to corrosion.

The results showed that intense corrosion process and reducing the thickness of the bulk carrier's hull structural areas lead to an enormously large amount of steel replacement in Cargo holds of aging bulk carriers, i.e., in areas 8, 5 and 6.

We hope that our proposed method applied for a larger number of bulk carriers and the number of intervals greater than 4, should give better values of quantitative risk levels. Accordingly, we believe that these values will be more compatible with those of qualitative risk levels.

In order to provide more realistic data for different risk levels for corrosion damages, the proposed method in this paper which will include other type of ships or a larger number of bulk carriers, should be compared with some other methods concerning to quantitative, qualitative or/and semi-quantitative Preliminary Risk Analysis.

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PODEJŚCIE DO ANALIZY KOROZJI KADŁUBA MASOWCA

STRESZCZENIE

Wiele analiz strukturalnych uszkodzeń kadłubów masowców opartych jest na badaniu zmęczenia materiałów i procesów korozji. Opracowano różne modele teoretyczne i empiryczne w celu opisania charakterystyk zależnych od czasu korozji struktur okrętowych. Zgodnie z istniejącymi przepisami morskich towarzystw klasyfikacyjnych cała struktura kadłuba okrętowego każdego z dwunastu prawie dwudziestopięcioletnich masowców rozpatrywanych w niniejszym artykule jest podzielona na jedenaście obszarów strukturalnych. Zainspirowany wstępną oceną ryzyka, wykorzystując dane dotyczące oszacowanych ilości stali usuniętej ze strukturalnych komponentów w całym okresie eksploatacji, autor szacuje i porównuje jakościowe i ilościowe poziomy ryzyka w odniesieniu do strat korozyjnych w obszarach strukturalnych wszystkich masowców.

Słowa kluczowe:
masowiec, struktura kadłuba okrętowego, korozja, poziom ryzyka.