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THE RELIABILITY OF WATERTIGHT LONGITUDINAL GIRDERS OF FUEL TANKS ON AGING BULK CARRIERS

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Abstract. During the exploitation of bulk carriers, the condition of structural elements and areas depends on the type of the cargo transported, operational conditions and maintenance systems. Corrosion significantly accelerates the aging of metal plates and girders thus causing the deterioration of steel surfaces, which consequently reduces the reliability of structural elements, areas and ships in general.

The damage to metal structures can impair the stability of a ship, reduce longitudinal strength, cause the ingress of water into the hull as well as environmental pollution through fuel spills from the tanks. Therefore, the paper analyzes a part of a double bottom structure based on the available wear data on watertight longitudinal girders of fuel tanks. The research included 25 bulk carriers aged between 5 and 25 with the total of 110 fuel tanks. The reliability analysis of steel plates included the total of 1920 data measured. The allowable wear of structural plate thickness that equals 20% of the original thickness value was determined by the application of the acceptance criteria that were prescribed by classification societies. The calculations of the function of failure density, failure intensity and reliability determined the time when the condition of structural elements deteriorates due to corrosion up to the levels that require extensive maintenance services.

Keywords: corrosion; bulk carriers; reliability; wear

Introduction

Over the last decades, aging bulk carriers in exploitation received special attention. Recent research has identified collisions, fires and explosions, grounding, structural damage and flooding as the most frequent causes of the complete destruction of aging bulk carriers[1)] (Stephen et al. 2002) Such damage can cause the loss of human lives, environmental pollution or significant material damage. For that reason, during the last two decades, the International Safety Management Code has been introducing a system for the safe ship management during exploitation.

The monitoring of the changes in the condition of structures in operation enhances the identification of the critical areas and structural elements that are susceptible to accelerated aging and decay. Previous research identified cargo holds, ballast tanks and transverse bulkhead of bulk carriers as critical areas (Yamamoto et al. 1998; Paik et al. 2004; Norhazilan et al. 2007).

Based on the maritime trends that have been promoting the reduction of harmful influences of ships on the environment during the last two decades, the research focuses on the International Maritime Convention for the Prevention of Pollution from Ships (MARPOL). Recently, many studies have investigated the pollution caused by exhaust emissions and other harmful effects of oil, ballast water, garbage, etc.

Internal and external as well as predictable and unpredictable complex influences of the atmosphere (temperature, humidity), marine environment (temperature, salinity, conductivity) and ship-specific factors (ballast management, maintenance, navigation route) dominantly affect the deterioration of ship structures over time (Ivošević et al. 2017). Different deformations and structural damage emerge as a consequence of the complex environmental conditions. Previous research has shown that material fatigue and different physical forms of corrosion (uniform, pitting, stress, fatigue, intergranular, etc.) represent the most dominant causes of ship decay.

The more extensive damage and weakening of the structures of old ships require regular maintenance and inspection by classification societies and state administrations within the Flag and Port State Control. In that sense, classification societies individually or within the International Association of Classification Society (IACS) prescribe internal rules that regulate the scope and intensity of measurements of structural elements and areas during the life expectancy of ships and define the acceptance criteria in accordance with the internal rules of companies[2)]. These criteria determine the scope of critical structural areas as well as the areas that need to be replaced due to dilapidation and non-compliance with classification standards, which further requires the repairs and replacements of damaged surfaces[3)].

The scope of repairs often determines whether the ship exploitation can be continued. The information on the condition of structural areas and reliability of a ship is crucial for both, owners and ship management companies. Overhaul often requires the replacement of the considerable amounts of steel in certain areas and could therefore require partial or complete replacement of structural areas such as decks, inner bottom plating, transverse bulkheads, bottom and side shell, main frames, etc. (Damjanović at al. 2018). In terms of fuel tanks, repairs are particularly complex, due to fuel discharge, degassing of tanks and special safety measures for the manipulation of the steel surfaces that are in contact with the fuel.

So far, numerous studies calculated corrosion rates over time (Ivošević et al. 2017; Ivošević et al. 2019; Ivošević et al. 2020), assessed risks, reliability (Paik 1998) and the probability of the damage to particular structural areas (transverse bulkheads and inner bottom plating) (Qin et al. 2003; Guedes Soares et al. 1996), or to all structural elements and areas (Paik et al. 1998; Paik et al. 2003, 61 – 87; Paik et al. 2003, 567 – 600).

This paper contains 4 chapters. The second chapter analyzes fuel tanks i.e., one structural segment of fuel tanks (watertight longitudinal girder plates) and analyzes the base of old bulk carriers. The data collection and processing methodology is also explained in the second chapter. The third chapter presents the results of the research, while the fourth chapter contains the concluding remarks.

Materials and methodology

Database

Relying on previous research on fuel tanks, this paper analyzes the reliability of longitudinal watertight girder plates as the parts of the structural areas of fuel tanks. Previous research on fuel tanks has shown that besides inner bottom plating and longitudinal watertight girder plates, upper plates also suffer a significant thickness diminution due to by corrosion (Ivošević et al. 2017; Ivošević et al. 2020).

Considering the data on the importance of the percentage of thickness diminution of steel plates (Ivošević et al. 2020), this paper examines the reliability of steel plates of the longitudinal girder in upper and lower areas in accordance with the measurement locations in Figure 1.

The thickness values of inner bottom plating and longitudinal watertight girder plates were a part of the previous research (Ivošević et al. 2017; Ivošević et al. 2020). The measurements of the structural elements of ships are usually performed during intermediate and special surveys respectively, but the study investigates only the data from special surveys. More precisely, during the special surveys of bulk carriers, after 5, 10, 15, 20 and 25 years, the data on the thickness of all structural areas of bulk carriers were unified according to the requirements of classification societies. However, this research analyzes only 1920 of the thickness values of structural plates of watertight longitudinal girders of fuel tanks.

The research focuses only on the fuel tanks located in double bottom area (Ivošević et al. 2017). Each aging bulk carrier has between 2 and 4 fuel oil tanks and the total number of tanks is presented in Table 1. The research database includes the age of the ships, the number of special surveys, fuel tanks, measuring positions and the arithmetic mean of the wear percentage of steel plates in relation to the original values (Table 1).

Table 1. The database used for the research on longitudinal girder steel plates

The age of ships (years)	The number of ship surveys	The number of tanks	The number of measured points	The number of sections	The mean values of plate thickness diminution caused by corrosion (%)	
					Lower	Upper
0-5	4	9	180	45	0.3 %	0,4 %
5-10	4	10	200	55	0.6 %	1,4 %
10-15	7	19	380	100	1.1 %	6,7 %
15-20	13	43	800	220	4.8 %	9,9 %
20-25	10	29	360	150	9.6 %	23.0 %
Total:	**38**	**110**	**1920**	**570**		

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The methodology for calculating the data on the wear of steel plates was based on a uniform selection of samples from each tank. Each tank was divided into 5

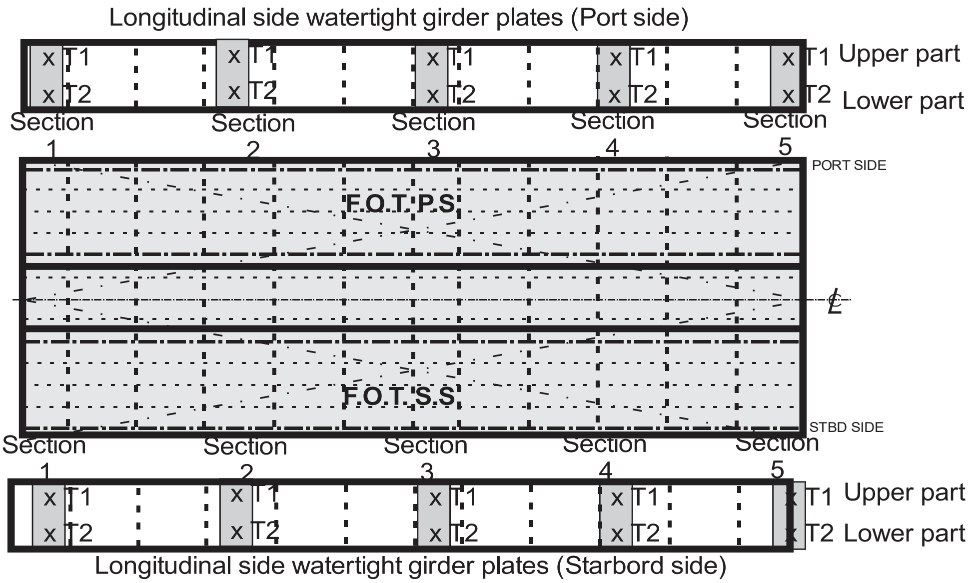

Figure 1. Data collection scheme for longitudinal watertight girder plates (upper and lower part).

equal sections (two ends and three imaginary cross sections between the ends) as shown in Figure 1. This paper analyzes the thickness diminution percentage of the measured values in relation to the original thickness values of steel plates.

The database on the wear of longitudinal watertight girder plates was based on the data sampling methodology described above and subjected to reliability analysis.

The database enabled the analysis of the wear and reliability of the steel plates of longitudinal watertight girders in upper and lower areas as well as the further assessment of fuel tank exploitation.

Data processing methodology and reliability calculation

The paper analyzes the reliability of longitudinal water tight girder plates of fuel tanks based on the diminution percentage of the original thickness caused by corrosion. The research was motivated by previous studies about thickness diminution percentage of inner bottom plating (Ivošević et al. 2020) and numerous papers that analyzed the millimeters of the wear of structural steel plates.

Common Structural Rules (CSR) were introduced in 2006 in order to enhance the strength and safety of ships. The CSR prevent potential competition among classification societies in terms of minimum safety standards which are related to the allowable wear of structural elements due to corrosion (Hussein et al. 2007). Corrosion addition varies among the elements. According to the CSR, corrosion addition is added to the net thickness in order to calculate the gross thickness (Figure 2.b). Traditional classification rules, however, defined corrosion addition as the percentage of plate thickness (Figure 2.a) (Damjanović et al. 2018; Hussein et al. 2007).

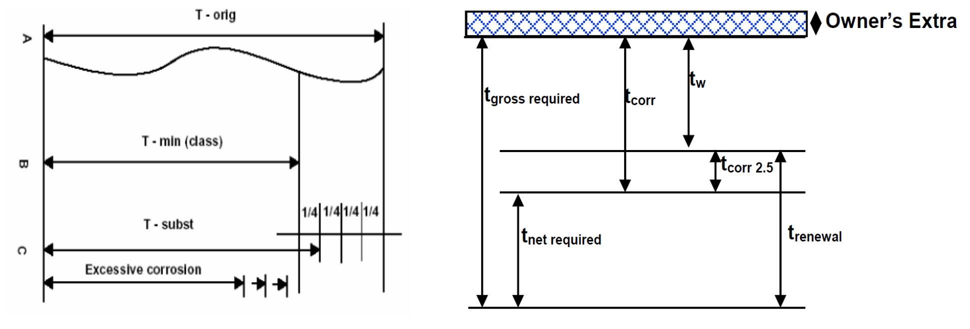

Figure 2. a) Typical DNV-GL corrosion calculation, b) New CSR Net Thickness Methodology (Damjanović et al. 2018; Hussein et al. 2007)

As the thickness of steel plates diminishes over time, classification societies prescribed the scope and intensity of thickness measurements and limits in relation to the original values. The deviations of watertight longitudinal girder plates can vary between 15% and 25% according to the rules of classification societies (Bureau Veritas - 15%, Rina and Lloyd's Register – 20%, Class NK 25%) (Ivošević 2005). Furthermore, classification societies allow the wear of 10% in particular structural areas i.e., accept the reliability level of 90% (Ivošević et al. 2020).

Since almost all aging bulk carriers examined were built in the last century and investigated between 2005 and 2017, this research relies on classification rules whereby corrosive wear is calculated as a thickness diminution percentage in relation to the original plate thickness.

The reliability calculations of the study are based on the allowable wear of 20% of the original thickness. Namely, the values that exceeded 20% of the original thickness were considered unacceptable i.e., interpreted as a failure. Although the remaining thickness ensures the impermeability of steel plates, classification societies still require the replacement of corroded surfaces in those cases. In that sense, the research determines the reliability, failure density and failure intensity for the steel plates of longitudinal watertight girders in upper and lower areas based on the acceptance criterion that equals the thickness diminution of 20% of the original thickness of the plates examined.

Theoretical bases for reliability correspond to the quotient of the number of acceptable measurement positions of steel plate thickness (n1) and the total number of the events i.e., measurement positions of steel plate thickness (n) at time t. This is shown in Formula 1:

$$R(t) = \frac{n_1(t)}{n}. \qquad (1)$$

The empirical function of the failure density fe(t) is calculated by means of Formula 2:

$$f_e(t) = \frac{n_1(t_i) - n_1(t_i - \Delta t_i)}{n \Delta t_i}, \qquad (2)$$

whereby $t_i \leq t \leq t_i + \Delta t_i$. This formula indicates the ratio of failures in a time interval (Δti) and the total number of events (n), which is divided by the length of the time interval (Δti).

The failure intensity function $\lambda_e(t)$ corresponds to the relationship between the number of failures in a time interval (Δti) and the number of events that did not fail at the beginning of the interval, which is divided by the length of the time interval (Δti). This is shown in Formula 3:

$$\chi_e(t) = \frac{n_1(t_i) - n_1(t_i + \Delta t_i)}{n_1(t_i) \Delta t_i}, \qquad (3)$$

whereby $t_i \leq t \leq t_i + \Delta t_i$

The function fe(t) is a measure of the overall failure rate, while $\lambda_e(t)$ is a measure of the current failure rate.

Failure density, failure intensity and reliability of all longitudinal watertight girder plates in upper and lower areas were calculated accordingly.

Results

Failure density, failure intensity and reliability are calculated based on the previously described database (Chapter 2.1.) on the wear of the steel plates of longitudinal watertight girders in upper and lower areas and on the equations (1) – (3) (Chapter 2.2). The values from Tables 2 and 3 are graphically presented in Figure 3. (a-f).

Table 2. The values of fe(t), $\lambda_e(t)$, Re(t) for the steel plates of the upper longitudinal girder.

		Number of	Failure density	Failure rate	Reliability
Gauging	**Δt_i (years)**	**Failures**	**$f_e(t)$**	**$\lambda_e(t)$**	**$R_e(t)$**
90	$0 \le \Delta t_i \le 5$	0	0	0	1
100	$5 \le \Delta t_i \le 10$	1	0.0009	0.0009	0.9955
190	$10 \le \Delta t_i \le 15$	21	0.0188	0.0188	0.9018
400	$15 \le \Delta t_i \le 20$	89	0.0795	0.0881	0.5045
180	$20 \le \Delta t_i \le 25$	113	0.1009	0.2000	0.0000
	Total:	224			

Table 3. The values of fe(t), $\lambda_e(t)$, Re(t) for the steel plates of the lower longitudinal girder

		Number of	Failure density	Failure rate	Reliability
Gauging	**Δt_i (years)**	**Failures**	**$f_e(t)$**	**$\lambda_e(t)$**	**$R_e(t)$**
90	0-5	0	0.0000	0.0000	1
100	5--10	0	0.0000	0.0000	1
190	10--15	0	0.0000	0.0000	1
400	15--20	32	0.0790	0.0790	0.6049
180	20--25	49	0.1210	0.2000	0.0000
	Total:	81			

The results analyzed include time intervals between 0 and 5 years because the data sampled correspond to the measurements during the special survey that was performed every five years of ship exploitation. Tables 2 and 3 exhibit the numbers of measurement positions that exceed the allowable 20% limit for each interval of five years. The corresponding values of failure density, failure intensity and reliability are shown in Tables 2 and 3. Graphical data on longitudinal girders in upper areas are shown in Figures a, c, e and the data on the longitudinal girders in lower areas in Figures b, d, f.

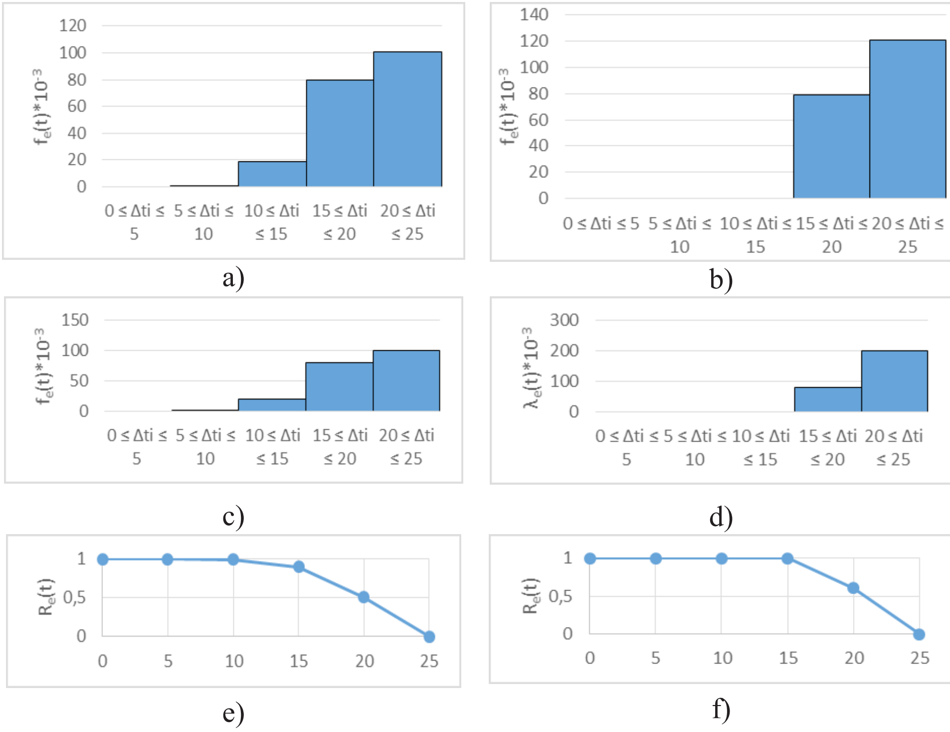

Figure 3. A graphical presentation of failure density, failure intensity and reliability of longitudinal watertight girder plates: upper part (a, c, e) and lower part (b, d, f).

For each time interval of five years, the analyzed number of measurement positions was determined by a corresponding number of failures i.e. the values of watertight girder plates that exceed the allowable deviations according to the rules of classification societies. The data on the number of failures indicate an increase in the number of failures over time, which indicates the failures caused by aging. Furthermore, the number of failures is higher in the upper areas than in the lower areas of watertight longitudinal girders. Similarly, the intensity of failures becomes more significant after 10 years in the upper areas of the girders and only after 15 years in the lower areas of the girders.

Since the projected life expectancy of ship structures is 25 years, it is expected that all structural areas meet the technological requirements during the entire life expectancy.

However, the research proves that one structural element (upper girder plates) reaches the upper limit of reliability (90%) already after 15 years of exploitation, which requires significant maintenance services of the steel plates of longitudinal watertight girders. As shown in diagram (Figure 2. (c, f)) the reliability in the lower area of girders after 15 years was at the maximum (reliability is 100%) while in the upper areas it was at the lowest limit of acceptability (90%). After 20 years of exploitation, the reliability dropped to 50% for the girders in lower areas, and to 60% for the girder in upper areas. This indicates the need for the replacement of corroded surfaces in girder areas and the repairs of fuel tank structures at the first inspection after 15 years of operation i.e. after the third intermediate survey. If the necessary repairs are not performed on time, fuel could leak into the neighboring ballast tanks and pollute the environment in case of ballast-fuel spills.

Conclusions

The paper investigated the reliability of the structural surfaces of fuel tanks on aging bulk carriers i.e. the steel plates of longitudinal watertight girders. It was proved that the reliability of the lower area of girder plates remains at the maximum level (100%) for up to 15 years, while in the upper area the reliability equals 90%. After 15 years of exploitation, the reliability drops below 90%, which requires the replacement of corroded surfaces because fuel and ballast water from adjacent ballast tanks could mix during further operation of fuel tanks. This research encourages ship management and maintenance companies to carefully examine girder areas especially after 10 years of exploitation i.e., during the second special survey. Monitoring and appropriate maintenance could prolong the life expectancy and maintenance while excessive repairs would thus be reduced.

The paper integrally examined all measurement positions. The data specific for particular tanks and ships were not analyzed, which could be the subject of the further research on the reliability of the same or different structural elements of fuel tanks or other structural areas of bulk carriers.

Acknowledgments

This research was supported by a thickness measurement company – INVAR-Ivošević. More information about the company is available at: http://www.invar.me/index.html. Namely, the data collected and systematized during the last twenty-five years by the company operators and experts were included into the abovementioned simulation and probabilistic analysis of the corrosion effects on the group of fuel

tanks on ten aged bulk carriers. It should be noted that INVAR-Ivošević Company provides marine services of ultrasonic thickness measurements of hull structures. The company has seven valid certificates issued by recognized classification societies and is currently inspecting more than three hundred vessels, mainly aged bulk carriers.

NOTES

1. Bulk carrier casualty report, IMO, MSC 83/INF.6, 3 July 2007.
2. IACS, Common Structural Rules for Bulk carriers 2006.
3. DNV, CLASS GUIDELINE, DNVGL-CG-0285, “Ultrasonic thickness measurements of ships”, 2016.

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