TRANSNAV
http://www.transnav.eu
the International Journal
on Marine Navigation
and Safety of Sea Transportation
Volume 18
Number 4
December 2024

DOI: 10.12716/1001.18.04.16

A Multistate Approach to Reliability Analyses of a Ship Hull Structure

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ABSTRACT: Structural damage in the form of corrosion, fatigue, damage, cracks and fouling can significantly reduce the structural integrity of ships in navigation and decrease the navigation safety. Therefore, numerous studies aim to improve international rules and regulations, and ensure proper maintenance of ships and timely inspections. Classification societies, flag states and port states strive to conduct appropriate inspections of ships with the aim of preventive detection of defects. Through the application of International Safety Management system, companies strive to improve maintenance systems, monitor the condition of ships and conduct risk assessments to reduce potential accidents and negative consequences for people, material goods and the environment. By means of advanced Structural Health Monitoring, the observation and analysis of the physical, chemical or electrical characteristics of components or systems are conducted over time. Such examinations tend to identify the variations that lead to degradation of the current or future performance of the inspected systems and their components. The condition of hull structures is monitored by mandatory requirements which are prescribed by classification societies e.g. the number of thickness measurements of hull structure areas and elements. The measurements create extensive databases that are further used to monitor the condition of existing ships and predict their future conditions. This study relies on a database of 25 bulk carriers aged between 5 and 25 years. The measurements were performed during regular special surveys on the total of 110 fuel tanks located in double bottom area of ships, which provided 3070 measured data in total. The values of the thickness diminution of steel plates due to corrosion were obtained through the measurements of the thickness of the steel plates by means of ultrasound thickness gauging equipment, in accordance with the rules of classification societies. Based on those rules and allowable substance and extensive corrosion, the paper considers the excessive corrosion values (above 20%) that were identified as failures and required the replacement of corroded surfaces. The multistate approach to the reliability analysis of the steel plates of inner bottom plating and the improvement of reliability after critical conditions showed that the usability of the analyzed ships significantly dropped after 15 years of exploitation.

1 INTRODUCTION

Extensive research conducted over previous decades was meant to detect different ship accidents [7], [6]. Accident investigation is a prerequisite for the identification of the causes that led to dramatic events, and caused partial or total loss of ships or human lives as well as environmental pollution.

The research published by Knapp et al. confirmed that general and dry cargo vessels exhibit the highest likelihood of accidents such as are collision, fire, explosion, flooding, loss of control, hull failure, contact, damage to ship equipment, grounding, etc. [16], [9]. Furthermore, the analysis of over 4700 sea accidents that occurred between 2004 and 2021 revealed that the collisions and contacts are the most frequent causes of sea accidents [2].

However, the most significant research was focused on tankers and bulk carriers as ships that are often associated with catastrophic accidents and consequences [5], [28]. The research conducted between 2011 and 2020 on 34 accidents that resulted in total losses of bulk carriers showed that the accidents were related to cargo shift and liquefaction, collision, structural failure, grounding, and fire explosion [19]. The research of accidents significantly affects the improvement of international regulations. For instance, Hermann [10] investigated the impact of bulk carrier disasters on the amendments to the SOLAS Convention.

Structural failures such as coating breakdown, cracks, deformation, corrosion, fouling or fatigue, can significantly decrease the safety of vessels and their projected lifespan. The influence of different types of environment, operation, maintenance procedures, ship route etc., accelerate different types of corrosion (general corrosion, pitting, stress-corrosion, corrosion fatigue, fretting, erosion, cavitation etc.). Previous research examined the corrosive degradation of structural areas (inner bottom plating [12], cargo hold transverse bulkheads [31], cargo hold mainframes [18], or the main deck [8]), the chemical or mechanical properties of materials and their behaviour in different types of environment [4] as well as the simulations of cavitation flows around propellers and rudders [20] etc. Furthermore, the examination of different structural problems required several reliability approaches such as: time-variant reliability formulation, failure probability and reliability, inspection and maintenance planning, reliability centred maintenance, etc. [29].

Previous studies contributed to the revision of international regulations and their improvements through national and international standards, rules and regulations. International Maritime Organization has significantly contributed to the changes in maritime conventions in terms of enhanced maritime safety and security. These conventions were an obligation for all participants in maritime industry and required an active participation of flag states, port states, classification societies, ship owners, ship management companies and other independent institutions.

In terms of ship maintenance and operation management, the most significant improvements were certainly the changes in the SOLAS convention and the introduction of the International Safety Management Code. Additionally, Common Structure Rules improved the design of ships in construction phases, which led to the stronger and heavier ships that resist corrosive damage over projected lifespans [11]. The Performance Standard for Protective Coating implemented in April 2006 enabled the application and maintenance of surface protection for a longer period, which delayed the onset of corrosion. Besides the postponed beginning of corrosion, the new standards also postponed the time for intensive replacement of the damaged and corroded structural surfaces that are a consequence of intensive corrosion processes. Furthermore, the impressed current cathodic protection (ICCP) [23] or sacrificial anodes and their influence on hull protection [24] significantly reduce corrosion.

Along with the development of international regulations, the progress of technology, innovation, and digitalization simplified the monitoring of ship conditions, as well as the application of the new technologies that offered an insight into the stages of construction and systems in real conditions. Likewise, the application of remote technical solutions enabled easier and more effective inspections of ships in navigation and ports. Traditional inspections (visual inspection, acoustic-based testing, electromagnetic testing, and imaging-based testing) and modern techniques utilizing robotics (underwater vehicles, unmanned aerial vehicles, or climbing robots) improved the effectiveness of inspections and reduced the number of accidents [22], [3].

Structural Health Monitoring integrates several engineering fields such as sensor technology, materials science, artificial intelligence and machine learning, data science and structural engineering, all of which enabled the optimization of design, operation and/or maintenance. The use of sensors prevents premature failures and ensures a satisfactory performance of structures by collecting various types of data on ship conditions e.g. vibrations, deformations, temperatures, pressure, and other parameters that indicate the health and stability of the SHM structure [21], [26].

A new artificial, neural, network-based data fusion model has recently been developed to provide tailored corrosion predictions [30]. The application of virtual reality for remote ship inspections and surveys and the application of virtual reality in related activities/procedures are yet to be researched [25].

This paper is organized into five paragraphs. The second paragraph presents the database of the steel plates damaged by corrosion and explains relevant classification criteria for the assessment of steel thickness. The third paragraph focuses on the theoretical aspects of the multistate approach to the reliability analysis of the steel plates and the improvement of reliability. The research results are presented in the fourth paragraph while the fifth paragraph contains concluding remarks.

2 DATABASE

The research relies on the database of 25 bulk carriers, whose exploitation varied between 5 and 25 years. The bulk carriers were subjected to 3070 measurements which inspected corrosive damage to the plates during the time of exposure. The considered thickness values were measured during regular special surveys by approved ultrasound measurement devices, operators and a company. All measured data which were connected to intermediate survey were included in special surveys, as well. The research takes into consideration five-year cycles of ship exploitation.

The measures focused on the inner bottom plating of cargo holds only in the areas of fuel tanks in double bottoms [12]-[15]. Each surveyed vessel has between 2 and 4 fuel oil tanks. Inner bottom plating near fuel oil tanks were analyzed, whereby each tank was divided in five parallel sections. Two sections at the end of tanks, one in the middle of tanks and two between the ends and the middle of tank lengths. The gauging was performed on the cross section of the steel plates of inner bottom plating to express steel damage caused by corrosion. The corrosive damage represents the diminution of steel thickness on the upper side of tanks (near cargo holds) and on the bottom side (near fuel oil tanks). Table 1 shows the main information about the database and ships.

Table 1. The database used for the research on inner bottom plating

The age of ships (years)	The ship surveys	The number of tanks	The number of measured data	Average of corrosion wastage (%)
0-5	4	9	230	0,5 %
5-10	4	10	296	2,2 %
10-15	7	19	530	8,9 %
15-20	13	43	998	11,7 %
20-25	10	29	1016	18,2 %
Total:	38	110	3070	

According to the rules, the measurement of the thickness of steel elements is expressed in millimetres or percentage of diminution, depending on the internal rules of classification societies. Each classification society in its internal rules clearly explains the criteria for the acceptance of steel damage for each element of a hull structure, and strictly defines the measured values that represent substantial and excessive corrosion. In that regard, the paper considers three specific categories of the obtained values expressed in percentage of damage to plate thickness compared to the original value, namely:

- Acceptable diminution – the measured steel plate thickness is acceptable (the values below 0.15% of the original thickness),
- Substantial corrosion – the measured steel plate thickness is not for replacement but should be annually monitored in the future (the values between 15% and 20% of the original thickness),
- Extensive corrosion – the measured steel plate thickness is not acceptable and should be renewed (the values exceed 20% of the original thickness).

The database created in this way clearly defined the condition of structures at the time of survey and inspection and identified the number and location of thickness measurements as well as the surface of structural plates damaged by corrosion (Figure 1).

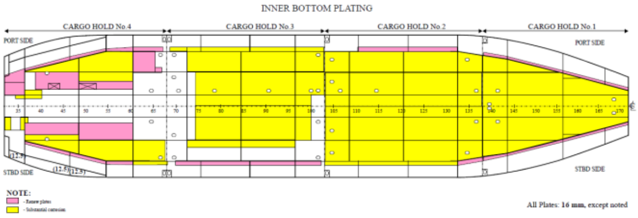

Figure 1. Substantial and renewal area of inner bottom plating

Each mandatory inspection of the ships identified the surfaces affected by excessive corrosion that had to be replaced before further use of the ships. Based on the procedure described, the database was used to define the values that are considered as extensive corrosion and are therefore unacceptable values for the research.

3 METHODOLOGY

3.1 *Multistate Approach to Reliability Analysis of Steel Plates of Inner Bottom Plating*

The study is based on an adapted multistate approach [17], [27] to the analysis of the reliability of the steel plates of inner bottom plating. Accordingly, there are several distinguishable reliability states e.g. $s = 0,1, \ldots, n$. For example, reliability state 1 or higher indicates that a steel plate is able to perform its tasks. Reliability state $s = 0$ is interpreted as a failure. For the purposes of this analysis, the steel plates of an inner bottom of one ship are considered as a system. The reliability function of the steel plates is thus defined as a vector [17], [27]

$$\mathrm{R}(t,\cdot)=\left[\mathrm{R}(t,0),\mathrm{R}(t,1),\ldots,\mathrm{R}(t,s),\ldots,\mathrm{R}(t,n)\right],\quad t\geq 0, \tag{1}$$

whereby the coordinate $R(t,s)$ of this vector is interpreted as the probability that a steel plate is in the reliability state subset $\{s,s+1,\ldots, n\}$, $s = 0, 1,\ldots, n$, at the moment t, whereas it was in the best reliability state n at the moment $t = 0$.

The above definition means that

$$\mathrm{R}(t,s)=\mathrm{P}(\mathrm{T}(s)>t),\quad t\geq 0,\quad s=0,1,\ldots,n \tag{2}$$

whereby $\mathrm{T}(s)$ is a random variable representing the lifespan of a steel plate in reliability state subset $\{s, s+1,\ldots, n\}$, $s = 0, 1,\ldots, n$.

Based on the expression (2), it follows that $\mathrm{R}(t,0)=1$ for $t \geqslant 0$, and the variable R will further be used in vector (1).

Another important reliability characteristic that can be determined is risk function. Risk function is defined as the probability that steel plates in a subset of reliability states are below critical reliability state (r), whereby the plates were in the best reliability state (n) at the moment $t = 0$, which can be represented by formula:

$$\mathrm{r}(t)=1-\mathrm{R}(t,r)=\mathrm{P}\left(\mathrm{T}(r)\leq t\right),t\geq 0, \tag{3}$$

In the formula $r\in\{1,2,\ldots,n\}$ and is an adapted (on the basis of expert opinions) critical reliability state, while $\mathrm{R}(t,r)$ is a coordinate of the reliability function of steel plates.

If an inverse function $\mathrm{r}^{-1}(t)$ of the risk function (3) exists, then τ can be determined as a moment when a steel plate risk exceeds a permitted threshold (δ).

$$\tau=\mathrm{r}^{-1}(\delta). \tag{4}$$

3.2 *Improving Reliability After a Critical State is Exceeded*

The improvement of the reliability of the steel plates of inner bottom plating is very important for the maintenance of system availability and safety in general. Multistate reliability approach assumes that a system (steel plate) needs repair after exceeding a critical reliability state, in accordance with certain reliability levels. In this study, critical state is defined as the state when the acceptable reliability level of 90% is exceeded. The replacement of a failed/corroded steel plate improves the reliability of a system, but does not necessarily provide the best reliability. The system will not work like a new one after the replacement because other components of the system, which were not replaced, may be in lower subsets of reliability state.

If the reliability of steel plates improves after exceeding a permitted threshold risk level (δ), after time (τ), as determined by formula (4), and if the time for the improvement of reliability (renovation time) is μ, then the coordinate of the function of reliability improvement in reliability state subsets {*r*, *r*+1,..., *n*}, *r* = 1, 2,..., *n*, are exemplified by the following formulas: [1]

$$R(t,r)=R(t-k\cdot(\tau+\mu),r) \text{ for } k\cdot(\tau+\mu)\le t<k\cdot(\tau+\mu)+\tau, \quad (5)$$

$$R(t,r)=R(\tau,r) \text{ for } k\cdot(\tau+\mu)+\tau\le t<(k+1)\cdot(\tau+\mu), \quad (6)$$

In the formulas above k=0,1,…,N, r=1,2,…,n, $t\geq0$ and N is the number of subsequent reliability improvements. Figure 2. illustrates the coordinate of an exemplary function of reliability improvement.

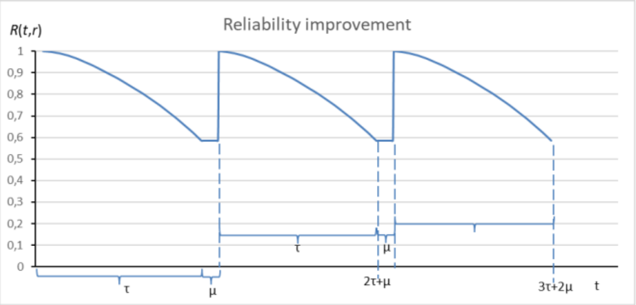

Figure 2. The coordinate of exemplary function of reliability improvement

Based on previously presented methodology, the subsequent steps for improving reliability are shown in the diagram in Figure 3.

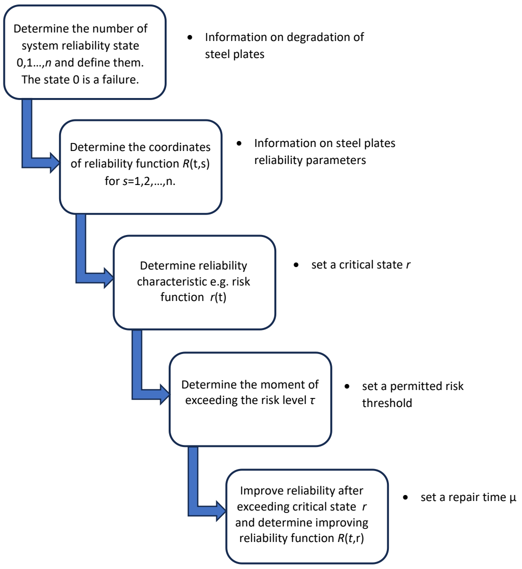

Figure 3. The diagram of procedure for reliability improvement after the critical state was exceeded

4 CASE STUDY OF RELIABILITY ANALYSIS OF THE STEEL PLATES OF INNER BOTTOM PLATING

4.1 *Reliability and Risk Evaluation*

Reliability analysis of the study is based on the allowable wear of 20% of the original thickness. Namely, the values that were below 80% 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.

According to experts, there are three distinct three reliability states:

- Reliability state 2 – the system performs its tasks and is completely safe, while the wear values are below 0,15% of the original thickness.
- Reliability state 1 – the system performs its tasks, but its operation is less safe because of the possibility for environmental pollution, cargo damage, ship's safety etc. The wear values are below 15% - 20% of the original thickness.
- Reliability state 0 – the system does not work (and does not fulfil the prescribed requirements). The wear values exceed 20% of the original thickness.

Critical state (r) adopted the reliability state 1, due to the fact that the limit of accepted reliability is 90% .

Reliability characteristics were estimated on the basis of the data from regular special surveys after 5, 10, 15, 20, 25 years, in accordance with a precisely defined methodology. The estimation detected the values of the reduction in the thickness of the steel plates due to corrosion over time.

Table 2 shows the number of the measurements of the steel plates of inner bottom plating in particular reliability states s, s = 0,1,2.

Table 2. The number of the measurements of the steel plates of inner bottom plating in particular reliability states *s*, *s* = 0,1,2.

Time (years)	Number of measurements that the values <0,15%) of the original thickness	Number of measurements that the values are <15%,20%) of the original thickness	Number of measurements that exceeded 20% of the original thickness.
5	230	0	0
10	296	0	0
15	427	78	25
20	673	129	196
25	456	108	452

Table 3 shows the number of measurements in reliability state subsets {*s*,*s+1*,…2}, *s* = 0,1,2.

Table 3. The numbers of the measurements of the steel plates of inner bottom plating in reliability state subsets {0,1,2}, {1,2}, {2}.

(1) Time (years)
(2) Number of measurements
(3) Number of measurements in the reliability state subset {0,1,2})
(4) Number of measurements in the reliability state subset {1,2})
(5) Number of measurements in the reliability state subset {2})

(1)	(2)	(3)	(4)	(5)
5	230	230	230	230
10	296	296	296	296
15	530	530	505	427
20	998	998	802	637
25	1016	1016	564	456

Based on the data from Table 3, further analysis determined the values of the reliability function coordinates *R*(*t*,*s*), *s* = 0,1,2, after 5, 10, 15, 20 and 25 years. These values were calculated as the probability that the steel plates of inner bottom plating are in reliability state subset {0,1,2}, {1,2} or {2} and are presented in Table 4.

Table 4. The reliability characteristics of the steel plates of inner bottom plating in reliability state subsets {0,1,2}, {1,2}, {2}.

Time (years)	R(t,0)	R(t,1)	R(t,2)
5	1	1	1
10	1	1	1
15	1	0,952	0,806
20	1	0,804	0,638
25	1	0,555	0,449

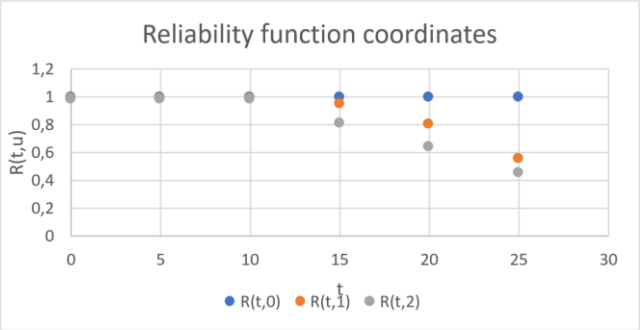

Figure 4. A graphical presentation of reliability function coordinates R(*t*,*s*), *s* = 0,1,2

The data presented in Table 4 show that, after 20 years of operation, the component of the reliability function R(*t*,1) is 0.804. This means that the reliability function in the subset of reliability states {1, 2} fell below the acceptable level of 90%. Moreover, the acceptable level of reliability will be exceeded after between 15 and 20 years of exploitation. The costs of the replacement of corroded surfaces are very high and require extensive preparation and a long retention of ships in yards. Therefore, it should be defined whether the acceptable level of reliability is exceeded after 15 or after 20 years of operation. Since the acceptance threshold is as high as 90%, postponing the replacement of corroded steel plates until the fourth special inspection (i.e. after 20 years of operation) is more cost-efficient. For this reason, it is important to determine the moment when the risk function exceeds the acceptable level of 0.1.

Since state 1 was considered as critical reliability state, the moment when a steel plate risk exceeds the permitted threshold is δ = 0.1. This finding answers the question whether reliability should be improved after 15 or after 20 years of ship exploitation.

This study does not observe the distributions of the components of reliability functions e.g. R(*t*,*s*), *s* = 1,2, because the system lifespans in reliability states subsets {1,2} and {2} were not available. The available values are related to the reliability functions of components at particular points (Table 4), which was estimated on the basis of thickness diminution measurements conducted during the surveys. From a mathematical point of view, if the values of a function at a finite number of points are known, then, for any distribution, such function can be interpolated by means of Lagrange polynomial interpolation. Thus, the component of reliability function can be described by the Lagrange interpolating polynomial in the following way:

$$\mathrm{R}(t,1) \approx \tilde{\mathrm{R}}(t,1) = \sum_{i=0}^{n} \mathrm{R}_i(t,1)\, l_i(t) \tag{7}$$

whereby Lagrange's basis polynomials are expressed as:

$$l_i(t) = \prod_{\substack{j=0 \\ j \neq i}}^{n} \frac{t - t_j}{t_i - t_j} \tag{8}$$

whereby:

i = 0 using the data from Table 4 and from expression (8) it follows that:

$$l_0(t) = \prod_{\substack{j=0 \\ j \neq 0}}^{4} \frac{t - t_j}{t_0 - t_j} = \frac{(t-t_1)(t-t_2)(t-t_3)(t-t_4)}{(t_0-t_1)(t_0-t_2)(t_0-t_3)(t_0-t_4)} = \frac{(t-10)(t-15)(t-20)(t-25)}{15000} \tag{9}$$

i = 1 using the data from Table 4 and from expression (8) it follows that:

$$l_1(t) = \prod_{\substack{j=0 \\ j \neq 1}}^{4} \frac{t - t_j}{t_1 - t_j} = \frac{(t-t_0)(t-t_2)(t-t_3)(t-t_4)}{(t_1-t_0)(t_1-t_2)(t_1-t_3)(t_1-t_4)} = -\frac{(t-5)(t-15)(t-20)(t-25)}{3750} \tag{10}$$

i = 2 using the data from Table 4 and expression (8) it follows that:

$$l_2(t)=\prod_{\substack{j=0\\ j\neq 2}}^{4}\frac{t-t_j}{t_2-t_j}=\frac{(t-t_0)(t-t_1)(t-t_3)(t-t_4)}{(t_2-t_0)(t_2-t_1)(t_2-t_3)(t_2-t_4)}=\frac{(t-5)(t-10)(t-20)(t-25)}{2500} \quad (11)$$

i = 3 using the data from Table 4 and from expression (8) it follows that:

$$l_3(t)=\prod_{\substack{j=0\\ j\neq 3}}^{4}\frac{t-t_j}{t_3-t_j}=\frac{(t-t_0)(t-t_1)(t-t_2)(t-t_4)}{(t_3-t_0)(t_3-t_1)(t_3-t_2)(t_3-t_4)}=-\frac{(t-5)(t-10)(t-15)(t-25)}{3750} \quad (12)$$

i = 4 using the data from Table 4 and from expression (8) it follows that:

$$l_4(t)=\prod_{\substack{j=0\\ j\neq 4}}^{4}\frac{t-t_j}{t_4-t_j}=\frac{(t-t_0)(t-t_1)(t-t_2)(t-t_3)}{(t_4-t_0)(t_4-t_1)(t_4-t_2)(t_4-t_3)}=\frac{(t-5)(t-10)(t-15)(t-20)}{15000} \quad (13)$$

According to the considerations above and based on formula (7), the reliability function in reliability state subset {1,2}, between 5 and 25 years, is given by the following approximate formula:

$$\begin{aligned}&\mathrm{R}(t,1)\approx\tilde{\mathrm{R}}(t,1)=\\&=\mathrm{R}_0(t,1)l_0(t)+\mathrm{R}_1(t,1)l_1(t)+\mathrm{R}_2(t,1)l_2(t)+\mathrm{R}_3(t,1)l_3(t)\mathrm{R}_4(t,1)l_4(t)=\\&=l_0(t)+l_1(t)+0.952l_2(t)+0{,}804l_3(t)+0{,}555l_4(t)\end{aligned} \quad (14)$$

whereby $l_0(t)$, $l_1(t)$, $l_2(t)$, $l_3(t)$, $l_4(t)$ are expressed in (9)-(13).

Furthermore, the study identifies the moment when the risk function of the steel plates exceeds the acceptable level of 0.1.

$$r(t)=1-R(t,1) \quad (15)$$

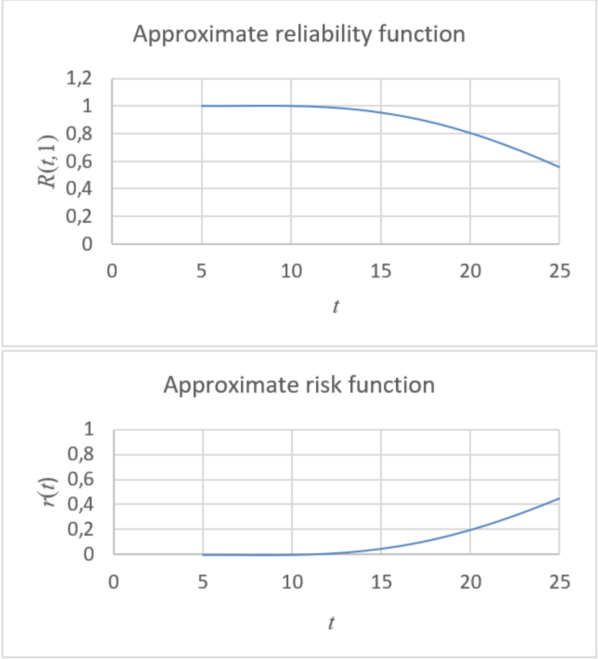

Figure 5. Approximate reliability and risk functions estimated by Lagrange interpolation

Table 5. Values for the approximate function $\tilde{\mathrm{R}}(t,1)$ and r(*t*) between 15 and 25 years

t	$\tilde{\mathrm{R}}(t,1)$	r(*t*)
15	0,952	0,048
16	0,931166	0,068834
17	0,905998	0,094002
17,1	0,903239	0,096761
17,2	0,900435	0,099565
17,3	0,897587	0,102413
18	0,876406	0,123594
19	0,842382	0,157618
20	0,804	0,196
21	0,761414	0,238586
22	0,714862	0,285138
23	0,664662	0,335338
24	0,611214	0,388786
25	0,555	0,445

Using formulas (14), (15) and (4), the moment (τ) when a steel plate risk exceeds the permitted threshold (δ =0.1) equals τ =17.2 years. The analysis above indicates that the risk function would exceed the acceptable level of 0.1 after only 17.2 years. This means that the reliability of steel plates should be improved by the replacement of corroded surfaces after the third special survey/inspection, i.e. after 15 years of operation. The replacement would reduce hazardous effects of corrosion such as the possibility for environmental pollution, structural damage or cargo contamination.

4.2 *The Improvement of Reliability*

The time needed for the replacement of corroded surfaces on a ship depends on many factors. However, according to previous studies, the average period that a ship must spend in a yard (renovation time μ) is one month. Based on (5)-(6), formulas (16) and (17) show the coordinate of the function of improved reliability of steel plates in reliability state subsets {1, 2}, assuming that the reliability is improved upon the third special survey, i.e. after 15 years.

$$\begin{aligned}&R(t,1)=R(t-k\cdot(15+0{,}083),1)\quad \mathit{for}\\&k\cdot(15+0{,}083)\le t<k\cdot(15+0{,}083)+15,\end{aligned} \quad (16)$$

$$\begin{aligned}&R(t,1)=R(15,1)\quad \mathit{for}\\&k\cdot(15+0{,}083)+15\le t<(k+1)\cdot(15+0{,}083),\end{aligned} \quad (17)$$

whereby *k*=0,1,…,N, t≥0.

As the operation time of a ship is around 25 years, the repair happens once in a ship's lifespan, in most cases. Therefore, the function of improved reliability takes the following form:

$$\begin{aligned}&R(t,1)=R(t-k\cdot(15+0{,}083),1)\quad \mathit{for}\\&k\cdot(15+0{,}083)\le t<k\cdot(15+0{,}083)+15,\\&k\ =\ 0{,}1,\end{aligned} \quad (18)$$

$$R(t,1)=R(15,1)\quad \mathit{for}\quad 15\le t<(15+0{,}083), \quad (19)$$

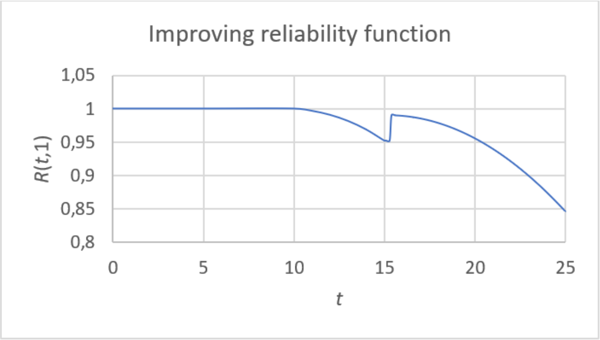

Figure 6. A graphical presentation of the function of improved reliability, coordinate R(t,1), after 15 years of operation

The analysis indicated that ship management and maintenance companies should carefully inspect the steel plates of inner bottom plating after 15 years of operation. Monitoring and appropriate preventive maintenance would improve reliability, extend the life expectancy of ships, ensure safety, and greatly reduce the costs of potential subsequent major repairs.

Considering the cost of the replacement of corroded surfaces and the retention of a ship out of service, many owners choose not to improve reliability of inner bottom plating after 15 years. Perhaps the owners consider it more cost-effective to operate their ship for additional few years and then to scrap the ship. For that reason, the problem of cost optimization for the replacement of corroded surfaces and the maintenance of ships seems a highly interesting research problem that requires further investigation.

5 CONCLUSION

This study applies reliability theory and multistate analysis with special improvements. The application was realized based on an empirical database regarding the structural damage to the inner bottom plating of fuel oil tanks inside bulk carriers during their lifespan.

Based on the theory of reliability, the research results showed that reliability drops significantly after 15 years of ship exploitation. The research further determined the error criterion at the moment when corrosion exceeds the wear of 20% of the original thickness prescribed by classification societies. The decrease in efficiency after 15 years is a result of maintenance interventions and replacement of damaged surfaces.

Future research should analyse the impact of new rules on the condition of ship structures and focus on a larger database and other structural elements.

REFERENCES

[1] Blokus-Dziula, A., Soszyńska-Budny, J. 2022. Condition-Based Maintenance and Availability Analysis of Wind Farm Infrastructure. Journal of Infrastructure Systems, Vol. 28 Issue 2, DOI: 10.1061/(ASCE)IS.1943-555X.0000675

[2] Bogalecka, M. 2024. Collision and Contact – Analysis of Accidents at Sea. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, Vol. 18, No. 1, 75-85, doi:10.12716/1001.18.01.06

[3] Bosen, L., Xinghui, D. 2023. Ship hull inspection: A survey, Ocean Engineering, 289,1, 1-36, https://doi.org/10.1016/j.oceaneng.2023.116281

[4] Brnic, J., Brcic, M., Balos, S., Vukelic, G., Krscanski, S., Milutinovic, M., Dramicanin, M. 2021. S235JRC+C Steel Response Analysis Subjected to Uniaxial Stress Tests in the Area of High Temperatures and Material Fatigue. Sustainability, 13, 5675. https://doi.org/10.3390/su13105675

[5] Bulk carrier casualty report. 2007. IMO, MSC 83/INF.6.

[6] Denev, Y. 2022. Ship Causalities – Reasons and Statistical Analyze. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, Vol. 16, No. 4, 607-610, doi:10.12716/1001.16.04.01

[7] EMSA, European Maritime Safety Agency. 2019. Annual overview of marine casualties and incidents 2019, Lisbon, Portugal. www.emsa.eu

[8] Garbatov, Y., Guedes Soares, C. 2008. Corrosion wastage modelling of deteriorated bulk carrier decks. International Shipbuilding Progress, 55, 109–125

[9] Heij, C., Knapp, S. 2019. Shipping inspections, detentions, and incidents: an empirical analysis of risk dimensions. Maritime Policy & Management. 46(7), 866–883, doi:10.1080/03088839.2019.1647362

[10] Hermann, W. 2024. Impact of Bulk Carrier Disasters on the Amendments To the SOLAS Convention. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, Vol. 18, No. 2, 287-294, doi:10.12716/1001.18.02.03

[11] International Association of Classification Societies, 2018. Common Structural Rules (BC & OT); International Association of Classification Societies: London, UK

[12] Ivošević, Š., Kovač, N., Momčilović, N., Vukelić, G. 2021. Analysis of corrosion depth percentage on the inner bottom plates of aging bulk carriers with an aim to optimize corrosion margin Shipbuilding: Theory and Practice of Naval Architecture, Vol.72, No.3, 97-123, ISSN 0007215X, 18455859, http://dx.doi.org/10.21278/brod72306

[13] Ivošević, Š., Kovač, N., Momčilović, N., Vukelić, G. 2022. Evaluation of the Corrosion Depth of Double Bottom Longitudinal Girder on Aging Bulk Carriers, Journal of Marine Science and Engineering, Vol. 10, No. 10, 1425, ISSN 20771312, https://doi.org/10.3390/jmse10101425

[14] Ivošević, Š., Meštrović, R., Kovač, N. 2017. An Approach to the Probabilistic Corrosion Rate Estimation Model for Inner Bottom Plates of Bulk Carrier. Brodogradnja, 68(4), 57-70, https://doi.org/10.21278/brod68404

[15] Ivošević, Š., Meštrović, R., Kovač, N. 2019. Probabilistic estimates of corrosion rate of fuel tank structures of aging bulk carriers, International Journal of Naval Architect and Ocean Engineering, 11(1), 165-177

[16] Knapp, S., Bijwaard, G., Heij, C. 2011. Estimated incident cost savings in shipping due to inspections. Accident Analysis and Prevention. 43:1532–1539

[17] Kołowrocki, K., Soszyńska-Budny, J. 2011. Reliability and Safety of Complex Technical Systems and Processes: Modeling - Identification - Prediction – Optimization. London, Dordrecht, Heildeberg, New York: Springer.

[18] Nakai, T., Matsushita, H., Yamamoto, N., Arai, H. 2004. Effect of pitting corrosion on local strength of hold frames of bulk carriers (1st report). Marine Structure, 17, 403–432. https://doi.org/10.1016/j.marstruc.2004.10.001

[19] Nwighe, T., Minami, K. 2022. Statistical Analysis of Bulk Carrier Accident from 2011 to 2020. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, Vol. 16, No. 1, 153-157, doi:10.12716/1001.16.01.18

[20] Perić, M. 2022. Prediction of cavitation on ships. Brodogradnja, 73(3), 39-58, https://doi.org/10.21278/brod73303

[21] Pezeshki, H., Adeli, H., Pavlou, D., Siriwardane, S. C. 2023. State of the art in structural health monitoring of offshore and marine structures. In Proceedings of the Institution of Civil Engineers-Maritime Engineering, Vol. 176, No. 2, 89-108

[22] Poggi, L., Gaggero, T., Gaiotti, M., Ravina, E., Rizzo, C. 2020. Recent developments in remote inspections of ship structures, International Journal of Naval Architect and Ocean Engineering, 12, 881–891, doi: https://doi.org/10.1016/j.ijnaoe.2020.09.001

[23] Ramanavasu, R., Vijayakumar, K., Fernandez, S.G. 2023. Integrated Nanogrid for the Impressed Current Cathodic Protection System in Desalination Plant. Sustainability, 15, 7088, https://doi.org/10.3390/su15097088

[24] Rodkina, A., Ivanova, O., Kramar, V., Dushko, V., Zhilenkov, A., Chernyi, S., Zinchenko, A. 2022. Simulation and selection of a protection types in the design stage of ships and offshore structures

[25] Sheriff A., Anantharaman M., Islam R., Nguyen H.O. 2023. Application of Virtual Reality for Remote Ship Inspections and Surveys – A Systematic Review. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, Vol. 17, No. 3, 587-594, doi:10.12716/1001.17.03.10

[26] Silva-Campillo, A., Pérez-Arribas, F., & Suárez-Bermejo, J. C. 2023. Health-Monitoring Systems for Marine Structures: A Review. Sensors, 23(4)

[27] Ivošević, Š., Meštrović, R., Kovač, N. 2019. Probabilistic estimates of corrosion rate of fuel tank structures of aging bulk carriers, International Journal of Naval Architect and Ocean Engineering, 11(1), 165-177

[28] Stephen, E., Roberts, M., Peter, B. 2002. Casualties in dry bulk shipping (1963–1996). Marine Policy 26, 437–450

[29] Wang, G., Boon, B. et al. 2009. Commıttee V.6, Condıtıon assessment of aged shıps and offshore structures,17th International ship and offshore structures congress, Seoul, Korea

[30] Wang, Z., Sobey, A.J. , Wang, Y. 2021. Corrosion prediction for bulk carrier via data fusion of survey and experimental measurements, Materials & Design 208, 109910

[31] Yamamoto, N., Ikagaki, K.A. 1998. Study on the Degradation of Coating and Corrosion on Ship's Hull Based on the Probabilistic Approach. Journal of Offshore Mechanics and Arctic Engineering, 120, 121-128. https://doi.org/10.1115/1.2829532