TransNav
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 19
Number 1
March 2025
DOI: 10.12716/1001.19.01.28

Lifetime Corrosion Loss of Bulk Carriers

N. Momčilović[1], N. Kovač[2] & Š. Ivošević[3]
[1] *University of Belgrade, Belgrade, Serbia*
[2] *University of Donja Gorica, Podgorica, Montenegro*
[3] *University of Montenegro, Kotor, Montenegro*

ABSTRACT: This paper analyzes the total steel replacement due to corrosion degradation in four Handymax-class bulk carriers, based on corrosion measurements recorded throughout their operational lifespan. Each ship was divided into 11 lightship mass subgroups, enabling detailed examination of cumulative lifetime corrosion losses for both entire ships and individual subgroups. Utilizing similar ship data obtained from the shipyard, the study also provides estimations of the total steel weights of each of lightship subgroups. The findings offer valuable insights into the overall aging effects on ship structures, crucial for maintenance planning, structural integrity assessments, and recycling, especially from the perspective of sustainable shipping. Additionally, the estimated weights of lightship subgroups can serve as reference data for preliminary ship design, aiding in the estimation of lightship weights and potential steel loss due to corrosion.

1 INTRODUCTION

Throughout their operational lifespan, ships are exposed to a wide range of environmental conditions that significantly influence the degradation of ship structures [1, 2]. These conditions primarily include atmospheric exposure, external seawater, internal ballast water, and operational factors such as loading and unloading sequences [3, 4]. Consequently, ship structures experience degradation due to corrosion, most notably observed as thickness reduction in structural elements [5, 6]. Hulls are particularly susceptible to surface degradations that compromise structural integrity and reduce service life of structural elements. The type and severity of corrosion depend on environmental conditions, operational duration, maintenance practices, and navigation routes. Corrosion mechanisms include general corrosion, pitting, intergranular corrosion, galvanic corrosion, stress corrosion, corrosion fatigue, fretting, microbiologically influenced corrosion, crevice corrosion, erosion, and cavitation [7].

Corrosion in ship structures has been extensively investigated in the literature, mainly focusing on protective coatings, identification of vulnerable hull regions, effects on ship aging, and estimation of corrosion rates [8]. Novel coatings that significantly delay the onset of corrosion have been explored [9], while the weight and effectiveness of corrosion protectives during the design phase are highlighted by [10]. Class NK's investigation into corrosion-related incidents emphasizes that ballast tanks and cargo holds are particularly susceptible to corrosion damage [11]. Cargo holds, especially in single-skin bulk carriers, face severe corrosion due to exposure to harsh external environments, corrosive cargo and manipulative equipment. Double-hulled ship designs, adopted in recent decades, enhance structural integrity but also present corrosion challenges, particularly in inner bottom plating exposed to loading and unloading, ballast operations, and wet-dry cycles. Developing accurate corrosion models necessitates extensive datasets, including thickness measurements, to estimate rates, predict degradation, and understand corrosion evolution through initial protective phases to active corrosion after coating failure.

Corrosion's influence on structural degradation and ship aging is well documented, though data on its actual effects remain dispersed. The Committee focusing on condition assessment of aging ships reported extensively on this phenomenon [12], while casualty reports highlight its impact [13, 14]. The authors' previous studies detail corrosion-induced thickness diminution in inner bottom platings and bottom longitudinal girders of bulk carriers [15, 16, 17]. Besides these studies, various corrosion models have been developed, including non-linear rate models [18], three-phase models [19], four-phase models [4, 20], and five-phase models [21, 22], each offering methods for estimating thickness diminution. On a larger scale, the effect of corrosion on the hull girder ultimate strength decay, considering both pitting and uniform corrosion, is quantified in studies such as [23, 24].

Corrosion loss estimation is also important for ship efficiency studies [25, 26, 27], with implications for energy efficiency regulations [28]. Corrosion-induced structural replacement is part of the issue regarding the IMO's recycling initiatives [29] and aligns with their sustainable development goals [30].

Corrosion impacts the weight of structures, especially the lightship mass. Estimation of lightship mass has been explored using machine learning based on main particulars [31], though primarily for tankers. General procedures for preliminary design weight estimation are provided by [32], with methods for early-stage design as revised by [33]. However, fundamental formulations for lightship mass calculation, essential for ship design, are provided in [34] and [35], with novel approaches proposed by [36]. Lightship mass distribution is critical for longitudinal strength calculations, ship stability, overall mass estimation, and cost assessments, as it governs the deadweight capacity of the ship.

To summarize, dry cargo ships such as bulk carriers are prone to accidents [37, 38, 39], particularly those partially induced by structural degradation. Although corrosion has been widely studied, most research focuses on coatings, strength impacts, and corrosion rate estimations, while comprehensive assessments of total and cumulative corrosion loss in specific ship parts are lacking. Such data are essential not only for structural optimization and recycling but also for estimating total renewal plating weights and lightship mass, which are important for preliminary design purposes. Ship weight estimation methods often provide a single hull steel weight value without differentiating between structural subgroups. This study addresses that gap by offering a detailed assessment of corrosion-induced steel loss across different structural components in bulk carriers.

Therefore, the contribution of this paper lies in several key aspects. The research delivers the total amount of steel that was replaced due to corrosion in four Handymax bulk carriers and their lightship subgroups during their exploitation period (25 years). Based on these data, and using the available data on similar ship recordings, we calculated the original weights of lightweight mass subgroups and their total corrosion wastage mass loss during exploitation period, offering valuable weight estimations which can be used for future preliminary design purposes.

2 DATA ON SHIPS

Four Handymax-class bulk carriers are monitored over the span of 25 years, depending on the particular ship. Their deadweights (DWT) span between 38110 t to 44504 t, and their lengths between 187 and 199 m, with two of them being sisterships. Although built in 1982 and 1983, ships exhibit standard cross-sectional features of today's similar size bulk carriers, which include double bottom with hopper tanks, single skin side with transversal framing and wing tanks, see Figure 1 and Figure 2. At the time, ships were classed by the most prominent classification societies, namely: Bureau Veritas (BV) and Lloyd's Register (LR). Their main data with respect to their length over all, breadth, year of built, years being monitored and corrosion measured, class, gross tonnage (GT), deadweight (DWT) and type of cargo carried during their service, is provided in Table 1.

Table 1. Data on ships.

Ship	S1	S2	S3	S4
Length overall	199	199	197.6	187
Breadth	29	29	28.3	28.40
Year of built	1982	1982	1983	1983
Years monitored	25	25	25	25
Class	BV	BV	LR	LR
GT	25056	25056	25742	22112
DWT	44504	44504	41427	38110
Type of cargo	Iron ore coal	Iron ore coal	Iron ore coal	Iron ore coal

To obtain the data on corrosion-induced degradation of structural elements in ships, ultrasonic measurements have been used over the lifespan of 25 years, depending on the particular ship from the database, see Table 1. Measurements have been collected by approved thickness measurement company (see Acknowledgement). The measurements were performed for almost all hull structures of the bulk carriers, according to the rules and regulation of classification societies. It should be noted, available criteria for steel replacement were considered under the specific rules and regulations the particular classification society (BV or LR in these cases) in the moment of gauging. Based on this corrosion measurements, the total amount of replaced steel weight is derived, see Table 2. The total amount of steel in tons replaced during the monitored period is given in Table 2. In there, ship lightweight mass is divided into 11 subgroups, also see Figure 1 and Figure 2, namely:

1. UD (upper deck). It extends from stern to bow, between the ship sides. UD area consists of flat plates, without stiffeners. This area is exposed to the influences of ballast tanks and cargo holds conditions, and to the multiple influences of atmospheric from the upper side of the deck.
2. DS (deck superstructure). DS is located in the aft part of a ship and above the upper deck and consist of flat plates, without internal structures. Upper DS

is exposed to specific conditions of outdoor atmosphere, while the lower DS is generally insulated and situated in closed atmospheric conditions.

3. BSSP (bottom and side shell platings). BSSP consists of flat and curved plates (without internal structures), which extend from the ship stern to bow. The influences of atmosphere and seawater form outside as well as the influences of ballast, cargo and dry or wet air from inside render this area specific and complex.
4. HCC (hatch cover and coaming). HCC consists of both plates and internal structures of hatch covers and hatch coaming structures. HCC ensures cargo holds watertightness and is exposed to atmospheric conditions.
5. ISTST (internal structure in top side tanks). ISTST includes all internal transverse and longitudinal structures, plates, brackets and stiffeners, as well as all sloping plates. ISTST is exposed to the changeable influences of ballast water or dry and humid air inside the tank. The tanks are exposed to atmospheric conditions from the outside (lateral and upper side) and depending on the conditions inside the holds, the tanks can be under the influence of atmospheric conditions or the cargo loaded.
6. CHTB (cargo holds transverse bulkheads). CHTB gathers flat or corrugated plates including their internal structures and stools, which are exposed to the influences of the cargo transported and atmospheric conditions inside the holds, when there is no cargo in hold. As there are bulkheads between adjacent holds, both sides of bulkheads are exposed to the influences of these holds, which significantly accelerates the decay of these structural elements. In this structural area the influence of manipulative operations is especially notable.
7. CHMF (cargo holds main frames with brackets). CHMF includes vertical stiffeners of shell plating inside the holds. This structural area is under direct influences of the medium, cargo and closed atmospheric conditions inside the holds as well as the skill at using the manipulative equipment.
8. IBHP (inner bottom and hopper platings). IBHP represents the bottom of a cargo hold consisting of steel plates which are under the direct influence of cargo or atmospheric conditions inside the cargo holds, and the influences of manipulative equipment form the upper side. From the lower side, the steel plates are exposed to the influences of inner ballast tanks (i.e., ballast water and dry or humid closed atmospheric conditions), fuel in the fuel tanks and dry atmospheric conditions.
9. ISDBT (internal structure in double bottom tank). ISDBT is a separate space at the bottom, wherein the lower part verges on the external flat bottom, the lateral parts on their sides rest on the vertical plates and, on their lower end, against the internal bottom. This area includes all internal structure area with transversal and longitudinal plates, stiffeners and brackets without surrounding platings. Considering that the ship shell plating and the cargo hold bottom are identified as separate areas, the remaining structure of the tanks is seen as a unique area, as well. Fuel, ballast, dry or humid air could be found inside the tanks, while seawater, cargo and atmosphere (within empty cargo holds) affect from the outside.
10. APS (aft peak tank). APS is located in the stern part of the ship. The inside of this area can be affected by the medium inside the tank, e.g., technical or drinking water, ballast water or dry and humid air within the tank. This area includes all internal structure area with transversal and longitudinal plates, stiffeners and brackets without surrounding areas, as well as tanks walls, except outer hull shell. The outer side is framed by shell plating which is affected by seawater, atmospheric conditions as well as the influences of closed or semi-closed atmospheric conditions.
11. FPS (fore peak tank). FPS is located in the front part of a ship. Its outer side is covered with shell plating and impermeable barrier separating it from the first cargo hold and the cover which usually extents toward the upper deck. This area includes all internal structure area with transversal and longitudinal plates, stiffeners and brackets without surrounding areas, as well as tanks walls, except outer hull shell. The inside of the tank is under the influence of ballast water or dry and humid air, while its outer side is framed by shell plating that is affected by seawater, atmospheric conditions as well as the influences of closed or semi-closed atmospheric conditions.

Table 2. Data on the amount of steel replaced (Δm_i) due to corrosion in tons.

Ship/Lightship mass subgroup -Δm_i [t]	S1	S2	S3	S4	Average
1. UD	80	165	22	7	68.5
2. DS	5	22	6	6	9.75
3. BSSP	25	60	65	5	38.75
4. HCC	35	40	15	32	30.5
5. ISTST	120	160	9	75	91
6. CHTB	220	145	65	45	118.75
7. CHMF	110	85	45	32	68
8. IBHP	585	650	550	150	483.75
9. ISDBT	45	55	50	45	48.75
10. APS	12	30	40	14	24
11. FPS	55	60	6	32	38.25
Total (1-11)	1292	1472	873	443	1020

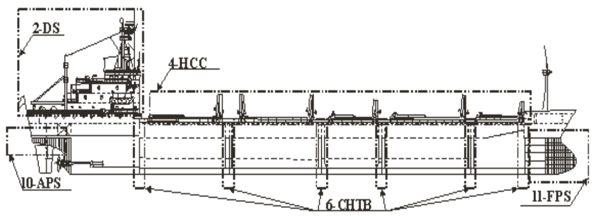

Figure 1. The lateral plan of a ship with subgroup identification.

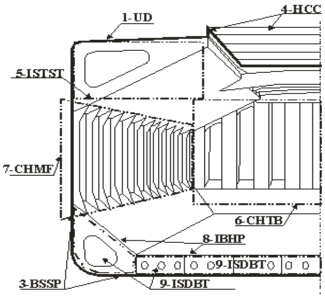

Figure 2. Cross section plan of a ship with subgroup identification.

Furthermore, a "similar" ship data is given in Table 3. In there, data were obtained from the shipyard on total weights in tons of 11 lightship subgroups and depending on ship deadweights. This table will provide a link to determine actual weight of 11 ships subgroups in relation to their dependance on deadweight. The data on bulk carriers used as a "similar" ship are the following: 29850 GT, 52000 t of DWT, 189.90 m (length overall), 32.24 m (width), Total weights of all of 11 lightship subgroups equals to 14.76% of ship's DWT.

Table 3. The amount of steel in tons and in relation to deadweight in each of 11 lightships subgroups -obtained for a "similar" bulk carrier.

Lightship mass subgroup	Share of subgroup weight to deadweight – bi [%[
1. UD	0.81
2. DS	0.88
3. BSSP	2.99
4. HCC	1.35
5. ISTST	1.57
6. CHTB	1.20
7. CHMF	0.55
8. IBHP	1.62
9. ISDBT	2.68
10. APS	0.42
11. FPS	0.69
Total	14.76

3 METHODOLOGY

3.1 *Original steel weight of the monitored structural subgroups*

The original steel weight of the replaced structure for bulk carriers and their lightship subgroups (mi) can be estimated using the data from the similar ship (Table 3), where the ratio between the steel structure subgroup weight and a deadweight is given for an available ship. Given that deadweights for ships are provided, we can estimate their subgroup mass using the relation from Eq. (1), in which mi is the estimated weight mass of subgroups for four bulk carriers, bi is the share of subgroup weight to deadweight (used from Table 3), and DWT_i is deadweight of each bulk carrier.

$$m_i = b_i \cdot DWT_i \tag{1}$$

3.2 *Share of steel weights replaced*

By dividing the actual corrosion-induced steel weight replaced (from Table 2) and estimated original structure subgroup weights from Eq. (1), we can derive the share of replaced corrosion-induced steel weight for each of subgroups with respect to original weight of the structure, see Eq. (2).

$$c_i = \frac{\Lambda m_i}{m_i} \tag{2}$$

3.3 *Corrosion wastage mass loss*

Corrosion wastage mass loss is estimated considering total amount of weights replaced and two criteria which are commonly used by classification societies for the decision elements renewal. This is assumed due to lack of data on actual on-site requirements for element renewal for each structural member. Namely, criteria for renewal state that structural element has to be replaced if the thickness diminution exceeds 15%, 20% or 25% of the original as-built thickness, for instance see [40, 41]. Thus, in this analysis, we used the average criteria: 20%, see Eq (3). This implies that the calculated mass of corrosion wastage represents a minimum value, as, in practice, the corrosion wastage of replaced elements meets or exceeds the stated criteria.

$$m_{corr,i} = 0.20 m_i \tag{3}$$

4 RESULTS & DISCUSSIONS

Based on methodology given in sect. 3, results include the calculated and estimated data regarding all selected ships and their lightweight subgroups. Thus, results consist of:

1. The total weights of steel replaced in each of 11 lightships subgroups (Figure 3), from Table 2. Fitting curves are not given due to large dispersion of data.
2. Estimated original weights of lightship mass subgroups, for which the elements were replaced, are provided in Table 4, as calculated according to Eq. (1). Diagrams and corresponding linear fitting curves based on data from Table 4 are shown in Figure 4 and Table 5.
3. Total estimated minimum weight loss due to corrosion wastage, for a 20% corrosion wastage criterion, is given in Table 6.
4. The share of the total estimated minimum weight loss due to corrosion wastage to ship deadweight is shown in Figure 5. Fitting curves are not given due to large dispersion of data.

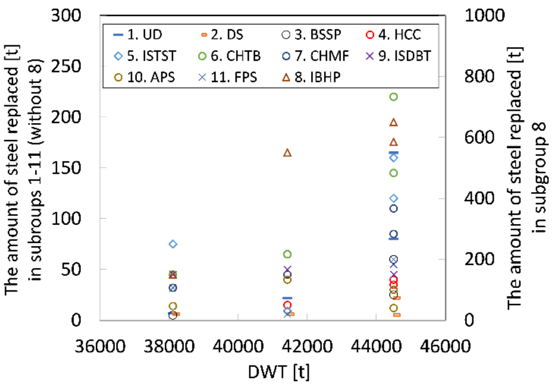

Figure 3. The amount of steel replaced according to 11 subgroups.

Table 4. Estimated original weights of subgroups.

Ship/Lightship mass subgroup	S1	S2	S3	S4	Average
1. UD	360.48	360.48	335.56	308.69	341.3
2. DS	391.64	391.64	364.56	335.37	370.8
3. BSSP	1330.67	1330.67	1238.67	1139.49	1259.9
4. HCC	600.80	600.80	559.26	514.49	568.8
5. ISTST	698.71	698.71	650.40	598.33	661.5
6. CHTB	534.05	534.05	497.12	457.32	505.6
7. CHMF	244.77	244.77	227.85	209.61	231.7
8. IBHP	720.96	720.96	671.12	617.38	682.6
9. ISDBT	1192.71	1192.71	1110.24	1021.35	1129.3
10. APS	186.92	186.92	173.99	160.06	177.0
11. FPS	307.08	307.08	285.85	262.96	290.7
Total (1-11)	360.48	360.48	335.56	308.69	6219.3

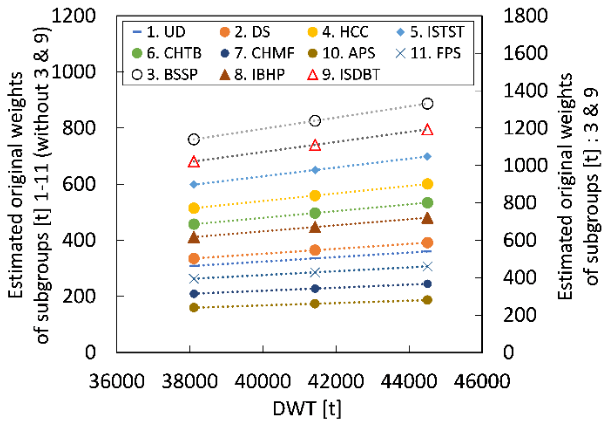

Figure 4. Estimated original weight of subgroups.

Table 5. Estimated original weights of subgroups: fitting curve linear equations (R2 =1 for all curves).

Ship/Lightship mass subgroup	Equations
1. UD	m_1=0.0081DWT+2E-11
2. DS	m_2=0.0088DWT-2E-11
3. BSSP	m_3=0.0299DWT+7E-11
4. HCC	m_4=0.0135DWT
5. ISTST	m_5=0.0157DWT
6. CHTB	m_6=0.012DWT-2E-11
7. CHMF	m_7=0.0055DWT-9E-12
8. IBHP	m_8=0.0162x
9. ISDBT	m_9=0.0268DWT
10. APS	m_{10}=0.042DWT
11. FPS	m_{11}=0.0069DWT+9E-12

Table 6. Corrosion wastage mass loss for 20% thickness diminution criterion.

Ship/Lightship mass subgroup [t]	S1	S2	S3	S4	Average
1. UD	16.0	33.0	4.4	1.4	13.7
2. DS	1.0	4.4	1.2	1.2	2.0
3. BSSP	5.0	12.0	13.0	1.0	7.8
4. HCC	7.0	8.0	3.0	6.4	6.1
5. ISTST	24.0	32.0	1.8	15.0	18.2
6. CHTB	44.0	29.0	13.0	9.0	23.8
7. CHMF	22.0	17.0	9.0	6.4	13.6
8. IBHP	117.0	130.0	110.0	30.0	96.8
9. ISDBT	9.0	11.0	10.0	9.0	9.8
10. APS	2.4	6.0	8.0	2.8	4.8
11. FPS	11.0	12.0	1.2	6.4	7.7
Total	240.8	265.4	163.3	77.9	186.9

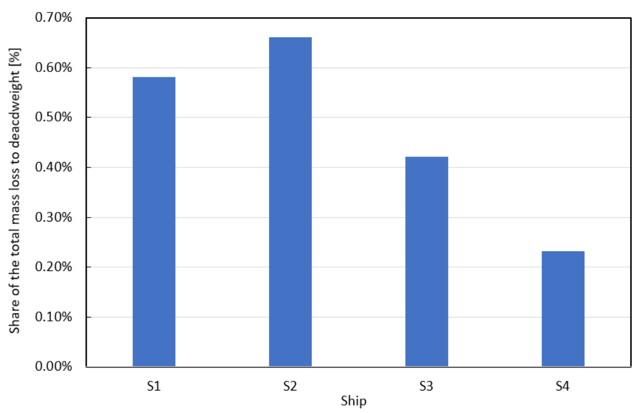

Figure 5. Share of the total mass loss to deadweight for four ships.

Figure 3 provides insights into the distribution of steel replacement across 11 structural subgroups due to corrosion, a dataset rarely found in existing literature. This diagram serves as a valuable tool for early estimation of the bandwidth range of corrosion-induced losses. However, its application as a reliable predictor is limited due to the significant data dispersion observed, which suggests variability in corrosion impacts across similar structural types and operational conditions. Nonetheless, it is evident that the inner bottom and hopper platings require the highest amount of steel replacement due to corrosion, which is understandable given their position and exposure during loading and unloading operations. In general, this is followed by the transverse bulkheads, the internal structures of the top side tanks, and the main frames of the cargo holds.

On the other, the estimated original weights of the subgroups are derived from analogous data on similar ships, as a function of deadweight (Tables 4 and 5, Figure 4). This methodology supports the reliability of the fitting curves used for interpolation of results, which can be applied to other similar-sized bulk carriers. The linear and simplistic nature of these equations makes them useful for preliminary estimates but not as definitive predictors of structural weight, marking this as a limitation of the study. The original weights of the structural subgroups increase with ship size. As shown in the diagram, the bottom and side shell plating constitute the largest subgroup (among the 11 considered) by mass, followed by the inner bottom and hopper plating subgroup.

Corrosion wastage weight loss for each of subgroups and ships is given in Table 6. Data shows large dispersion so authors could not provide reliable fitting curves. The quantified ship mass loss due to corrosion, ranging from 0.22% to 0.66% as shown in Figure 5, spans a wide range but offers a preliminary sense of the magnitude of corrosion impacts. This range provides a foundational estimate that can be used to gauge similar phenomena in comparable ships.

A closer examination of the data reveals that among all 11 subgroups, across all ships considered, the inner bottom and hopper platings (8. IBHP) experience the most significant corrosion wastage over the lifetime of these four Handymax bulk carriers. The corrosion wastage in this structural component is several times greater than that observed in the next most affected subgroups within the same range (Figure 3), namely: cargo hold transverse bulkheads (6. CHTB), cargo hold frames with brackets (5. ISTST), and internal structures in top-side tanks (7. CHMF). This is expected, as these ship sections are part of the cargo holds, which experience significant operational and environmental variations, including exposure to heavy handling equipment and high-density cargo, both of which contribute to accelerated corrosion compared to certain other bulk cargoes (see Table 1).

Although these components are part of the heavier structural groups, as shown in Table 4, they do not represent the heaviest structural elements. The minimum estimated original weights of subgroups indicate that the largest components are the bottom and side shell platings (3. BSSP) and the internal structures in the double bottom tank (9. ISDBT), which belong to the lower category of subgroups affected by corrosion. A direct correlation between the minimum estimated weight loss due to corrosion and the actual weight of steel structure replaced is not clearly established. Nevertheless, Table 6 shows that the maximum estimated corrosion wastage loss is most pronounced for the inner bottom and hopper platings (8. IBHP), leading to the conclusion that this structural component is the most affected by corrosion across all four ships. This can be attributed to the frequent loading and unloading cycles and the application of heavy manipulative equipment, to which this section is exposed, making it particularly susceptible to corrosion.

Nevertheless, the study faces inherent limitations due to the small sample size of just four bulk carriers, which restricts the generalizability of the predictions and the reliability of the ship weight estimations. The scarcity and inaccessibility of weight data, which shipyards, ship operators, classification societies, and surveyors typically do not disclose publicly, compound these limitations. Despite these constraints, the data presented can significantly contribute to preliminary designs or early assessments of corrosion-induced structural loss in bulk carriers of this class.

Moreover, the similarity in structural and dimensional features of the single-skin bulk carriers studied here lends credibility to the findings, suggesting that they may be representative of similar vessels.

An additional limitation is the lack of specific on-site criteria for the renewal of structural members, leading to reliance on assumptions in the analysis. Given that renewal decisions often depend on corrosion exceeding 20% or 30% of original thickness, the estimated corrosion-induced weight loss presented might be underrepresented, as our analysis assumes a minimum of 20% degradation without precise knowledge of the actual conditions.

In summary, while the study's limitations restrict its ability to provide definitive predictions, the findings offer valuable insights into corrosion patterns and their implications for ship maintenance and design strategies. This underscores the need for more extensive data collection and sharing within the maritime industry to enhance the accuracy and applicability of future research.

5 CONCLUSIONS

This research has analyzed corrosion-induced steel replacement in four Handymax-class bulk carriers, providing a detailed assessment of corrosion impacts across various structural subgroups. The assessment is based on an actual from shipyards data presented here, for ships monitored during their lifespan of 25 years. This makes one of the main contributions of the paper.

The study documents substantial variability in steel replacement across the structural subgroups. This can be understandable given the complex nature of corrosion occurrence, such as environmental exposure, operational factors, and maintenance practices. In that context, inner bottom and hopper platings shows the most dominant corrosion loss of all subgroups. This can be attributed to the frequent loading and unloading cycles to which this section is exposed, as well as the use of heavy manipulative equipment for such particular type of bulk cargo.

Although the data provided useful insights for estimating the extent of corrosion-related losses, the significant variability noted limits the applicability of these findings as universal predictors. The linear regression models derived from the data of similar ships serve as preliminary tools for estimating potential steel loss but should be applied cautiously, considering their limitations in prediction accuracy. The limited sample size and the unavailability of comprehensive weight and corrosion data restrict the generalizability of the findings. Future research should aim to include a larger dataset and collaborate closely with shipyards, classification societies, and operators to obtain more detailed operational and maintenance data. This would enhance the robustness of predictive models and the reliability of corrosion impact assessments.

The insights provided represent a significant advancement in understanding corrosion processes within ship structures. These results pave the way for more informed decisions in ship design, maintenance, and operational strategies, which are crucial for enhancing the safety and longevity of maritime assets. The findings underscore the necessity for ship designers and operators to consider enhanced corrosion protection strategies, and monitoring [42], particularly in highly susceptible areas. Adoption of improved design features and materials could mitigate corrosion risks and extend the service life of ship structures.

ACKNOWLEDGEMENT

This research is supported by the approved thickness measurement company - INVAR-Ivošević Company. More information about the company can be found at URL: http://www.invar.me/index.html. The data are collected and systematized during the lifetime of ships by the company operators and experts, and thus, used here for the analysis.

REFERENCES

[1] Ivošević Š., 2012. PhD Thesis, University of Montenegro, Maritime Faculty Kotor, Kotor, Montenegro.
[2] Ivošević Š., Meštrović R., Kovač N., 2019. Probabilistic estimates of corrosion rate of fuel tank structures of aging bulk carriers, International Journal of Naval Architecture and Ocean Engineering, 11(1): 165-177.
[3] Viner A.C., Tozer D.R, 1985. Influence of corrosion on ship structural performance, Hull New Construction Division No. 85/29, Lloyd's Register of Shipping.
[4] Paik J.K., Thayamballi A.K., 2002. Ultimate strength of aging ships, Journal of Engineering for the Maritime Environment, 1(1): 57-77.
[5] Pollard R.R., 1991. Evaluation of corrosion damage in crude and product carriers, Report No. SMP-I, Department of Naval Architecture & Offshore Engineering, University of California, Berkeley.
[6] Yamamoto N., Ikegami K., 1996. A study on the degradation of coating and corrosion of ship's hull based on the probabilistic approach, In: Proceedings of the International Offshore Mechanics and Arctic Engineering Symposium (OMAE'96), 2: 159–166.
[7] Barbulescu A., Dumitriu C.S., 2023. Fractal Characterization of Brass Corrosion in Cavitation Field in Seawater, Sustainability, 15.
[8] Paik J.K., Kim S.K., Lee S.K., 1998. A probabilistic corrosion rate estimation model for longitudinal strength

members of bulk carriers, Ocean Engineering, 25(10): 837–860.
[9] Zriouel W., Bentis A., Majid S., Hammouti B., Gmouh S., Umoren P.S., Umoren S.A., 2023. The Blue Tansy Essential Oil–Petra/Osiris/Molinspiration (POM) Analyses and Prediction of Its Corrosion Inhibition Performance Based on Chemical Composition, Sustainability, 15.
[10] 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, Brodogradnja, 73(2): 59-77.
[11] Ohyagi M., 1987. Statistical Survey on Wear of Ships´ Structural Members, Nippon Kaiji Kyokai, Technical Bulletin, 5.
[12] Paik J.F., Brennan F., Carlsen C.A., Daley C., Garbatov Y., Ivanov L., Rizzo C., Simonsen B.C, Yamamoto N., Zhuang H. Z., 2006. Report of Committee V.6 Condition Assessment of Aging Ships, 16th International Ship and Offshore Structures Congress, 20-25 August 2006, Southampton, UK.
[13] Roberts S.E., Marlow P.B., 2002. Casualties in dry bulk shipping (1963–1996), Marine Policy, 26: 437–450.
[14] IMO, 2007. Bulk carrier casualty report, IMO, MSC 83/INF.6, 3 July 2007.
[15] 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, Brodogradnja, 72(3).
[16] 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, 10(10).
[17] Kovač N., Ivošević Š., Momčilović N., 2024. Corrosion-induced thickness diminution of an ageing bulk carrier, Brodogradnja, 75.
[18] Soares C.G., Garbatov Y., 1999. Reliability of maintained, corrosion protected plates subjected to non–linear corrosion and compressive loads. Marine Structures, 12(6): 425–445.
[19] Yamamoto N., Kumano A., Matoba M., 1994. Effect of corrosion and its protection on hull strength (2nd Report), Journal of the Society of Naval Architects of Japan, 176: 281-289.
[20] Paik J.K., Lee J.M., Park Y.I., Hwang J.S., Kim C.W., 2003. Time–variant ultimate longitudinal strength of corroded bulk carriers. Marine Structures, 16: 567–600.
[21] Melchers R.E., 1999. Corrosion uncertainty modelling for steel structures. Journal of Constructional Steel Research, 52: 3–19.
[22] Melchers R.E., 2003. Probabilistic Model for Marine Corrosion of Steel for Structural Reliability Assessment, Journal of Structural Engineering, 129(11): 1484–1493.
[23] Momčilović N., Ilić N., Kalajdžić M., Ivošević Š., Petrović A., 2023. Pitting and uniform corrosion effects on ultimate strength of a bulk carrier, Procedia Structural Integrity, 48.
[24] Momčilović N., Ilić N., Kalajdžić M., Ivošević Š, Petrović A., 2024. Effect of Corrosion-Induced Structural Degradation on the Ultimate Strength of a High-Tensile-Steel Ship Hull, Journal of Marine Science and Engineering, 12.
[25] Inal O. B., 2024. Decarbonization of shipping: Hydrogen and fuel cells legislation in the maritime industry, Brodogradnja, 75.
[26] Prados J. M., Fernandez I. A., Gomez M. R., Parga M. N., 2024. The decarbonisation of the maritime sector: Horizon 2050, Brodogradnja, 75.
[27] Grlj C. G., Degiuli N., Martić I., 2024. Experimental and numerical assessment of the effect of speed and loading conditions on the nominal wake of a containership, Brodogradnja, 75.
[28] IMO, 2018. MEPC. Resolution MEPC.308(73) - Guidelines on the Method of Calculation of the attained Energy Efficiency Design Index (EEDI) for new ships: IMO, 2018/10/26.
[29] IMO, 2012. ANNEX 4 - Resolution MEPC.210(63) - Adopted on 2 March 2012 - 2012 Guidelines for safe and environmentally sound ship recycling, International Maritime Organization, London, UK.
[30] IMO, 2017. Linkages between IMO's Technical Assistance Work and the 2030 Agenda for Sustainable Development, London, UK.
[31] Frančić V., Hasanspahić N., Mandušić M, Strabić M., 2023. Estimation of Tanker Ships' Lightship Displacement Using Multiple Linear Regression and XGBoost Machine Learning, Journal of Marine Science and Engineering, 11.
[32] Aasen R., Bjorhovde S., 2010. Early stage weight and cog estimation using parametric formulas and regression on historical data, 69 Annual conference of Society of Allied Weight Engineers, Virginia, USA.
[33] Slapničar V., Zadro K, Ložar V., Ćatipović I, 2021. The lightship mass calculation model of a merchant ship by empirical methods, Pedagogika – Pedagogy, 93.
[34] Watson D.G.M., 1998. Practical Ship Design, Oxford, Elsevier Science Ltd.
[35] Schneekluth H., Bertram V., 1998. Ship Design for Efficiency and Economy. 2nd edition. Oxford: Butterworth-Heinemann.
[36] Papanikolaou A., 2014. Ship Design - Methodologies of Ship Design, Springer.
[37] Knapp S., Bijwaard G., Heij C., 2011. Estimated incident cost savings in shipping due to inspections. Accident Analysis and Prevention, 43: 1532–1539.
[38] Heij C., Knapp S., 2019. Shipping inspections, detentions, and incidents: an empirical analysis of risk dimensions, Maritime Policy & Management, 46(7): 866–883.
[39] Poggi L., Gaggero T., Gaiotti M., Ravina E., Rizzo C., 2020. Recent developments in remote inspections of ships structures, International Journal of Naval Architect and Ocean Engineering, 12: 881–891.
[40] BV, 2025. Rules for the classification of steel ships, Paris, France.
[41] LR, 2024. Rules and regulations for the classification of ships, London, UK.
[42] Jurczak W., Jurczak K., 2016. Possibility of corrosion monitoring resistance of austenitic steel for ship construction. Journal of KONES Powertrain and Transport, Vol. 23, No. 1.