

Risk-Based Inspection and Predictive Maintenance Strategy for Oil Tanker Ballast Tank Transverse Structures

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Abstract— Ballast tanks are among the most corrosive environments in oil tankers, with progressive thinning of transverse structures in the midship region posing a significant threat to hull girder integrity. Current maintenance practices are largely prescriptive, focusing on minimum-thickness compliance without explicitly relating measured conditions to the probability and consequences of failure. This often leads to reactive decisions and uniformly allocated inspection resources. This study aim was the structural integrity risk of transverse constructions in oil tanker ballast tanks by integrating the probability of failure with its consequences, and applies the resulting risk map to develop a risk-based inspection (RBI) and predictive maintenance (PdM) strategy. The methodology involves three stages: calibration of a probabilistic power-law corrosion model using Condition Assessment Program (CAP) thickness data from a double-hull product oil tanker; computation of ultimate bending capacity and probability of failure using the incremental-iterative method of the IACS Common Structural Rules, the First-Order Reliability Method, and Monte Carlo simulation; and quantification of each structural element's risk on a likelihood-severity matrix. Results show that risk is concentrated rather than uniformly distributed: deck and inner-shell longitudinals have the highest risk scores (9), followed by deck plating, longitudinal bulkhead, and stringer plates (score 8). The probability of failure at 35 years increases from approximately 10^{-5} to 2.9×10^{-3} when corrosion dispersion is considered. As risk is primarily governed by the dispersion of wastage rather than its mean, the proposed risk-based strategy is more efficient than conventional uniform periodic inspection.

Keywords— condition-based maintenance, corrosion dispersion, reliability index, risk matrix, structural integrity

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I. INTRODUCTION

Ballast tanks are essential to the stability and safety of oil tankers, yet they are among the most corrosive environments on board. Continuous wet-and-dry cycling of seawater, temperature fluctuations, dissolved oxygen, and sulfate-reducing bacteria accelerate the degradation of the steel plating, leading to a progressive loss of thickness known as corrosion wastage [1], [2]. In the midship region, the transverse construction carries the largest share of the hull-girder load, so wastage of its plates and stiffeners directly reduces the section modulus and ultimate bending capacity, ultimately threatening the ship's structural integrity [3], [4].

Substantial studies have modeled time-dependent corrosion and the residual strength of corroded ship structures. However, much of it remains incomplete: corrosion studies often stop at predicting the wastage rate without translating it into a loss of structural capacity [5], [6], [7], [8], whereas strength assessments commonly assume uniform thickness reduction, which does not

reflect the heterogeneous, spatially variable wastage observed in practice [9], [10], [11], [12], [13]. The dominant paradigm in industry remains compliance with the minimum thickness set by classification societies, without an explicit, quantitative link to the probability of failure and its consequences. As a result, maintenance decisions are often reactive and suboptimal in resource allocation [14], [15], [16]. The severity of the ballast-tank environment is best characterized by the combined effects of multiple degradation drivers acting simultaneously, rather than in isolation.

Alternating immersion and drainage during ballast exchange keep the upper internals in a permanently humid, oxygen-rich condition that favors the repeated formation and breakdown of protective rust layers, while the lower internals remain almost continuously immersed in warm, chloride-laden seawater. Microbiologically influenced corrosion driven by sulfate-reducing bacteria, the gradual breakdown of the protective coating after roughly the first decade of service, and the loss of effective cathodic protection in poorly accessible corners combine to produce wastage rates that are neither constant over time nor uniform in space [1], [2], [17]. The transverse web frames, brackets, and stringers that tie the deck, sides, and bottom into a single box girder are precisely the locations where these drivers concentrate, so their degradation is structurally the most consequential [3], [4].

Classification rules tackle deterioration by setting a minimum acceptable thickness and a renewal threshold, usually based on a fixed percentage of the original scantling. Although this offers a straightforward pass/fail standard during surveys, it relies on two

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oversimplifications that are harder to justify for an aging fleet. First, it reduces a plate's condition to a single measured value, ignoring the statistical variability of readings, which truly captures localized attack. Second, it considers compliance as a safety indicator without assessing how close the structure is to a limit state or how rapidly it is nearing one [5], [6], [14]. Research combining corrosion with residual strength consistently demonstrates that two plates with the same average thickness can differ greatly in reliability when accounting for the variability in wastage and the plate's position within the hull girder [9], [10], [18], [19], [20].

Risk-based inspection addresses the issue by evaluating not only whether an element remains compliant, but also the extent to which it contributes to the overall likelihood and cost of failure. By combining the likelihood of failure for each element with the severity of its loss, the resulting risk score enables ranking of structural components from most to least critical, thereby identifying the few members that dominate total risk [15], [21]. Predictive maintenance then uses the same probabilistic condition forecast to determine the optimal timing for interventions, such as plate renewal, to achieve the greatest risk reduction at a given cost, rather than following a fixed schedule [15], [22]. This study applies the complete analytical chain to a single-product oil tanker, progressing from measured wastage through a calibrated probabilistic corrosion model and a Common Structural Rules ultimate-strength calculation to an element-level reliability index and a risk map. The results indicate that the risk-informed plan is significantly more efficient than uniform periodic inspection.

The stakes for the integrity of the transverse construction are not abstract. The midship box girder carries the ship's peak longitudinal bending moment, and a loss of ultimate capacity there does not announce itself gradually but can manifest as a sudden buckling collapse of the deck or bottom flange. The history of structural failures in aging tankers and bulk carriers, several of which were traced to corrosion-thinned internals in ballast spaces, is precisely what drove classification societies and the International Association of Classification Societies to introduce Enhanced Survey Programs and the Common Structural Rules [3], [14]. The present work sits within that trajectory, using the condition data generated by those regimes to extract the quantitative risk picture they were ultimately intended to support.

A probabilistic approach, rather than a more elaborate deterministic one, is the appropriate response to this problem. The uncertainty present is not a modeling artifact that improved measurement could eliminate; it is an inherent property of the corrosion process, which produces genuinely different thickness losses at nominally identical locations. Deterministic calculations, regardless of refinement, require selection of a single representative thickness, resulting in either optimistic or overly conservative outcomes. Reliability calculations address this by propagating the entire distribution of wastage and reporting the probability that

the limit state is exceeded, which is the critical quantity for risk-based decision-making [21], [23], [24], [25].

In accordance with the title and objective of this paper, the relevant literature can be grouped into three streams. The first stream concerns corrosion modeling of ballast tank structures. Paik et al. [1] and Garbatov et al. [4] proposed time-dependent wastage models dedicated to ballast and cargo tanks, Melchers [2] developed phenomenological models of marine immersion corrosion, and later studies introduced Bayesian inference [7], machine learning [8], and diffusion-based formulations [25], while probabilistic time-variant models for seawater ballast tanks were presented by Lampe and Hamann [23] and Noor et al. [24]. The second stream concerns residual strength and reliability. The incremental-iterative ultimate-strength method and its application to corroded hulls are reviewed in [3] and [26], and hull-girder reliability under corrosion and fatigue has been examined for maintained hulls [9], [21], for designs governed by the Common Structural Rules [14], and in recent reliability-based assessments [19], [20]. The third stream concerns inspection and maintenance planning. The risk-based inspection framework is formalized in API RP 580 [27], Dong and Frangopol [15] optimized risk-informed life-cycle inspection of ship structures, Zou et al. [22] quantified the value of inspection information for maintenance decisions, and Woloszyk et al. [16] linked advanced corrosion degradation to risk-based ship design.

Closely related applied studies have also appeared in this journal. Widiarti et al. [28] classified the intensity of hull corrosion from ROV imagery to support maintenance decisions, Laili et al. [29] evaluated shipboard maintenance using the failure mode and effect analysis approach, and Firmanullah et al. [30] combined fault tree, event tree, and bowtie analyses for the risk management of subsea pipeline integrity, identifying failure to conduct periodic inspection and corrosion as dominant basic events. These works confirm the growing role of quantitative risk methods in marine integrity management. However, they address either the detection technique or the system-level risk framework, and none of them propagates measured hull thickness data through a strength and reliability chain to an element-level risk map, which is the specific contribution pursued here.

Based on this state of the art, three problems remain open. First, the corrosion of ballast tank structures is usually reported as a mean rate, whereas the measured wastage is strongly dispersed, and the effect of this dispersion on structural safety is rarely quantified. Second, corrosion prediction, ultimate strength, reliability, and inspection planning are commonly treated as separate studies, so a decision basis that links an integrated, quantitative risk picture to the inspection and maintenance plan is still missing. Third, most published risk matrices for ship structures are constructed from expert judgment rather than derived from measured thickness data of an operating vessel. Risk, defined as the product of the probability of failure and its consequence, can be mapped element by element to identify where the structure is most exposed [17], [21].

This paper addresses those problems. The primary contribution is a comprehensive, data-driven analysis chain applied to a single operating product oil tanker: more than 1,300 CAP thickness measurements from two survey cycles are used to calibrate a probabilistic power-law corrosion model, which is then propagated through a Common Structural Rules ultimate-strength and reliability analysis. The results are synthesized into an element-level likelihood-severity risk map that informs the inspection and maintenance strategy. To the authors' knowledge, no previous study of ballast tank transverse structures has linked measured CAP data to an element-level risk map in this manner, nor quantitatively demonstrated that wastage dispersion, rather than its mean, determines the risk ranking. The objective of this study is to determine the structural-integrity risk level of the transverse construction of an oil tanker's ballast tank by integrating the probability and consequence of failure, and to use the resulting risk map to develop a risk-based inspection (RBI) and condition-based predictive maintenance (PdM) strategy that optimizes resource allocation and intervention timing compare to conventional periodic inspection.

II. METHOD

A. Data Source and Case Study

The case study concerns a double-hull product oil tanker with a capacity of about 35,000 DWT (IMO No. 9295050, length $L = 161.75$ m, built in 2005). Primary data consist of historical thickness measurements from two Condition Assessment Program (CAP) reports: the 2023 cycle (Record No. SHA/74/23), with 542 readings on two transverse sections, and the 2025 cycle (Record No. SHA/65/25), with 774 readings on three transverse sections. Because the longitudinal positions differ between cycles, the comparison is interpreted as spatial variability in corrosion along a single hull rather than as repeated measurements at the same point [31], [32]. Secondary data include the midship scantling drawing, used to reconstruct the as-built geometry, and the steel material specification.

The Condition Assessment Program is a voluntary yet demanding thickness-survey regime in which a dense grid of ultrasonic gauging points is recorded across representative transverse sections, providing a spatial picture of wastage far richer than that of the routine close-up survey. For the present hull, the 2023 cycle supplied 542 readings across two sections, and the 2025 cycle 774 readings across three sections, for a combined population of more than 1,300 measurements, large enough to estimate not only the mean wastage of each structural category but also its dispersion [24], [31]. Each reading was paired with its as-built scantling from the midship drawing so that wastage could be expressed both as an absolute loss in millimeters and as a percentage of the original plate, the latter being the quantity on which classification renewal thresholds act.

Readings were grouped by structural category, namely deck plating, deck longitudinals, inner-shell plating and longitudinals, side and bottom structure, and longitudinal bulkhead and stringer plates, because elements within a category share a coating history, an

exposure condition, and a structural role, and therefore a common corrosion behavior. Because the gauging grids of the two cycles fall on different frames, the data are not interpreted as repeated measurements at the same point at two ages; instead, the difference between cycles is interpreted as variability in corrosion along the length of a single hull. This is a deliberately conservative reading of the data: rather than assuming that one section represents the whole ship, it accepts that nominally identical elements at different longitudinal positions corrode at different rates, and it carries that spatial scatter into the reliability calculation [23], [31].

Before fitting, the gauged thicknesses were screened for obvious recording errors and converted to wastage by subtracting each reading from its corresponding as-built scantling, then normalized by that scantling to yield a percentage loss. Expressing wastage as a percentage makes readings from plates of different original thicknesses directly comparable and allows the result to be compared directly with the renewal threshold, which is itself defined as a percentage. Because the two cycles together sample a wide range of longitudinal positions and structural roles, the resulting data set spans the full range from lightly attacked bottom plating to heavily wasted deck-zone stiffeners, exactly the range needed to characterize the dispersion rather than merely the central tendency of the corrosion [24], [31].

The vessel is representative of a large segment of the world tanker fleet rather than an extreme case. A double-hull product carrier of about 35,000 deadweight tonnes and 161.75 m in length, built in 2005, had reached roughly two decades of service at the time of the surveys, placing it in the age band where coating breakdown is well advanced, and corrosion has become the governing degradation mechanism. The double-hull arrangement, with its segregated ballast spaces flanking the cargo tanks, is precisely the configuration in which the transverse internals of the ballast space experience the aggressive wet-and-dry environment described earlier. Therefore, the wastage pattern observed here can reasonably be expected to recur in comparable hulls [4], [31].

B. Probabilistic Corrosion Model

Wastage is treated as a random variable. The time-dependent wastage of each structural category is described by a nonlinear power-law model [1], [4],

$$d(t) = C_1 (t - T_i)^{C_2}, \quad t > T_i \quad (1)$$

where $d(t)$ is the cumulative wastage, C_1 and C_2 are model coefficients obtained via nonlinear regression of the inspection data, and T_i is the corrosion-initiation period. Following classification practice, the initiation period is set to $T_i = 5$ years (systematic thickness gauging is first required at the renewal/special survey), yielding an effective exposure of 13 years for the 2023 cycle. The coefficients are random variables, not single values, and their dispersion is estimated from the data, so the uncertainty is propagated to later stages [5], [23].

The power-law form is preferred over a simple linear rate because immersion corrosion of mild and low-alloy steel in seawater slows as a layer of corrosion products and marine growth accumulates, so cumulative wastage grows sub-linearly with exposure time [1], [2], [18]. An

exponent C2 below unity captures this deceleration, and a value near 0.5 indicates that wastage scales roughly with the square root of the exposure period, consistent with diffusion-controlled degradation. The coefficient C1 sets the magnitude of the loss and accounts for the influence of coating quality, temperature, and water chemistry specific to each compartment. Fitting the model separately for each structural category, rather than forcing a single curve across the entire section, allows the deck zone, which loses its coating first and is exposed to the most aggressive humid air, to follow a steeper curve than the continuously immersed bottom structure [4], [6].

Crucially, C1 and C2 are not retained as deterministic best-fit constants. The regression residuals and the scatter of the category means are used to give each coefficient a probability distribution, so that the model returns not a single wastage curve but a band whose width grows with exposure time. The corrosion-initiation period T_i is fixed at five years in line with classification practice, reflecting the interval during which an intact protective coating suppresses measurable metal loss; only after coating breakdown does the power-law clock effectively start, which for the 2023 cycle leaves an effective exposure of thirteen years [1], [5]. Propagating the coefficient distributions forward in time later allows the reliability stage to separate the section's average condition from its credible worst case, and that separation ultimately drives the risk result.

The choice of a single power-law over more elaborate multi-phase formulations is a deliberate balance between fidelity and identifiability. Phenomenological models that resolve the early transient, the active corrosion phase, and a later near-steady phase can fit immersion data closely, but they require more parameters than the available readings can constrain reliably [2], [5]. With a five-year initiation period that encompasses the protected phase, the remaining metal loss is well represented by a single decelerating curve, and the high coefficient of determination in the calibration confirms that the simpler model loses little accuracy while remaining statistically robust. Keeping the model parsimonious is also what makes its coefficients interpretable as random variables with credible distributions, which is essential for the reliability stage that follows [18], [23].

C. Strength and Reliability Assessment

The projected thickness loss is converted into a reduced effective area, a shift of the neutral axis, and a reduced section modulus. The ultimate vertical bending capacity μ is computed using the incremental iterative or Smith method of the IACS Common Structural Rules [33] on a sectional model based on the actual scantling drawing. Structural safety is evaluated using the limit-state function $g = R - S$, where the resistance R is the residual ultimate capacity and the load S is the combined still-water and wave bending moment. The still-water moment M_{sw} is read from the ship loading manual for each loading condition (mean +0.242 GN·m, standard deviation 0.307 GN·m), and the wave moment M_w follows IACS UR S11. The probability of failure, P_f , and the reliability index, β , are obtained using the First-Order

Reliability Method (FORM) and confirmed by Monte Carlo simulation ($N = 400,000$ lognormal samples) [18], [24].

The residual ultimate bending capacity μ is the moment at which the hull girder, weakened by accumulated wastage, can no longer resist further curvature because its compressed elements buckle and its tensioned elements yield in sequence. The incremental-iterative or Smith method models this collapse by dividing the cross-section into discrete plate-and-stiffener elements, assigning each an average stress-strain curve that accounts for buckling and post-buckling behavior, and then imposing a slowly increasing curvature while summing the elemental forces until the resisting moment peaks and then falls [3], [26]. Applying the projected wastage to each element reduces its effective area, lowers its buckling strength, and shifts the neutral axis upward as the deck thins, so that μ declines gradually as the ship ages. Building the sectional model directly from the actual scantling drawing, rather than from a simplified box-girder idealization, ensures that the computed capacity reflects the actual distribution of material around the section.

Safety is expressed through the limit-state function $g = R - S$, where the resistance R is the residual ultimate capacity and the load S is the maximum longitudinal bending moment, obtained by adding the still-water moment read from the loading manual to the wave-induced moment given by the IACS unified requirement S11 [14], [18]. Treating R and S as random variables, with R inheriting the uncertainty of the corrosion model and the strength formulation, and S inheriting the variability of the loading condition and sea state, turns the deterministic check into a reliability problem. The First-Order Reliability Method locates the most probable failure point on the limit-state surface and returns the reliability index β , the number of standard deviations separating the mean state from failure, together with the probability of failure P_f . Because FORM linearizes the limit state, the result is verified by a Monte Carlo simulation of 400,000 lognormal samples, which does not make such an approximation; the close agreement between the two confirms that the reported probability of failure is trustworthy [18], [24].

The load side of the limit state comprises two components with markedly different characteristics. The still-water bending moment depends on how the ship is loaded and is read from the loading manual, condition by condition. Here, with a mean of about +0.242 GN·m and a standard deviation of 0.307 GN·m, the sign and spread reflect the range of cargo and ballast arrangements the vessel actually adopts. The wave-induced moment is an environmental quantity obtained from the IACS unified requirement S11, which encodes a long-term extreme based on the North Atlantic scatter diagram. Adding the two gives the total longitudinal bending demand, and treating both as random rather than as single design values allows the analysis to express safety as a probability rather than as a deterministic margin [14], [18].

The reliability index returned by this calculation is compared with a target value set by classification

practice, here of the order of $\beta \approx 3.0$, which corresponds to an acceptably small annual probability of hull-girder failure. Reporting β alongside the probability of failure serves two purposes: β gives an intuitive measure of how many standard deviations of margin remain, while the probability of failure is the quantity that feeds directly into the risk product. The use of a lognormal description for the strength and load variables, rather than a normal one, reflects the fact that neither capacity nor bending moment can be negative and that both are better described by a skewed, strictly positive distribution; this choice also improves the agreement between the FORM estimate and the Monte Carlo benchmark [18], [24].

D. Risk Quantification and Strategy

The final stage integrates the probability of failure with the potential consequence into a measure of risk [16],

$$\text{Risk} = P_f \times C \quad (2)$$

which is mapped onto a likelihood-severity matrix [27]. At the element level, the likelihood L is derived from the projected wastage percentage relative to its allowable limit and mapped to a 1–5 scale; the severity C is weighted on a 1–5 scale according to the element's criticality to hull-girder capacity. The risk map then provides the quantitative basis for three implementation steps: identifying the critical elements and the critical age, building a risk-prioritized inspection schedule in place of uniform periodic inspections, and recommending the optimal timing of maintenance interventions to allocate resources efficiently over the operating life [15], [17], [21].

Translating reliability into risk requires that both axes of the matrix be defined on a common, defensible scale. The likelihood L of each element is derived from its projected wastage as a fraction of the allowable limit, so that an element approaching its renewal threshold scores high and one with ample margin scores low; this ties the qualitative likelihood directly to the quantitative corrosion forecast rather than to expert judgment alone [15], [21]. The severity C reflects how much the loss of that element would degrade the hull-girder capacity, and is therefore highest for the deck and inner-shell members, whose distance from the neutral axis makes them the largest contributors to section modulus, and lower for elements close to the neutral axis, whose loss is structurally less consequential [3], [26]. Both axes are mapped to a one-to-five scale so that their product, the risk score, ranges from low single digits to the high-risk corner of the matrix.

The risk map is then used as a decision tool in three stages. First, it identifies the critical elements and the critical age, that is, the combination of location and time at which the risk first becomes unacceptable, thereby fixing the focus of any future survey. Second, it converts that ranking into a risk-prioritized inspection schedule in which gauging intensity and frequency are allocated in proportion to each element's risk contribution, concentrating effort on the few high-scoring members rather than spreading it evenly across the section. Third, it informs the timing of intervention, indicating the age at which renewing a critical element removes the most risk at the least cost, so that maintenance is planned

predictively rather than reactively triggered by a failed survey [15], [22]. In this way, the same probabilistic chain that produced the reliability index is carried through to an operational plan.

By standardizing both axes to a one-to-five scale, the matrix reflects an as-low-as-reasonably-practicable assessment approach: cells in the lower-left corner indicate tolerable conditions that require no special action, while those in the upper-right corner indicate conditions that require intervention. The diagonal band between these zones highlights where the benefits of additional risk reduction must be balanced against the associated costs. This mapping reduces a continuous reliability outcome to a few decision categories, enabling an inspection planner to act directly without losing the quantitative order that generated them [15], [21]. Therefore, the banding serves as a communication tool layered over the reliability assessment, not a replacement for it.

III. RESULTS AND DISCUSSION

A. Wastage Dispersion and Reliability

The statistical characterization of the CAP data shows that wastage is highly dispersed: the coefficient of variation ranges from 0.13 to 0.88 (mean 0.31) in the 2023 cycle and widens to 0.30–1.08 (mean 0.59) in the 2025 cycle. The mean corrosion rate is 0.019–0.025 mm/year for the 2023 sections but only 0.009–0.013 mm/year for the 2025 mid-hull sections, confirming strong spatial variability along the hull. The power-law model is well calibrated, with an exponent $C2 \approx 0.5$ and a coefficient of determination $R^2 = 0.96$. This level of dispersion is the first quantitative result of the study: wastage cannot be represented by a single deterministic value, and a probabilistic treatment becomes an empirical necessity [1], [2].

The reliability assessment is detailed in Table 1 and Fig. 1. At average wastage levels, the reliability index steadily declines from $\beta = 4.21$ at 18 years to $\beta = 4.10$ at 40 years, with failure probabilities around 10^{-5} . All these values stay above the target class value ($\beta_{\text{target}} \approx 3.0$), indicating the section generally meets safety standards. However, a critical point is that when corrosion dispersion is considered, the failure probability at 35 years increases to 2.9×10^{-3} , which is over 100 times higher than in the average-wastage scenario. This highlights that the variability in wastage, rather than its mean, primarily determines the risk level.

Two features of the dispersion statistics deserve emphasis. The coefficient of variation does not merely scatter randomly across categories but rises systematically for the thin, heavily exposed deck-zone elements and for the localized attack on the longitudinal bulkhead, while the thick, continuously immersed bottom plating remains comparatively tight. The widening of the mean coefficient of variation from 0.31 in the 2023 cycle to 0.59 in the 2025 cycle, even though the mean corrosion rate of the mid-hull sections is lower, shows that the spread of wastage and its average are largely independent; a section can have a modest mean loss yet a long upper tail of severely wasted points. It is

this upper tail, not the average, that brings individual elements close to a limit state.

The reliability results in Table 1 should therefore be interpreted at two levels. At the mean-wastage level, the section is comfortably safe throughout the projection window, with the reliability index well above the class target of about 3.0 and the probability of failure remaining on the order of 10^{-5} . At the dispersed-wastage level, however, the same section at age 35 reaches a

probability of failure of 2.9×10^{-3} , more than two orders of magnitude higher. The gap between these two readings is the central quantitative message of the analysis: an assessment that uses only the mean thickness will report a structure that comfortably passes, whereas an assessment that accounts for the measured scatter reveals a credible failure probability large enough to demand attention. Ignoring dispersion does not make the structure safer; it merely hides the risk [23], [24].

TABLE 1
RELIABILITY INDEX AND PROBABILITY OF FAILURE VERSUS SHIP AGE

Age (yr)	Mu (GN·m)	β	Pf
18	2.92	4.21	1.3×10^{-5}
25	2.91	4.17	1.5×10^{-5}
30	2.90	4.14	1.7×10^{-5}
35	2.89	4.12	1.9×10^{-5}
40	2.88	4.10	2.1×10^{-5}

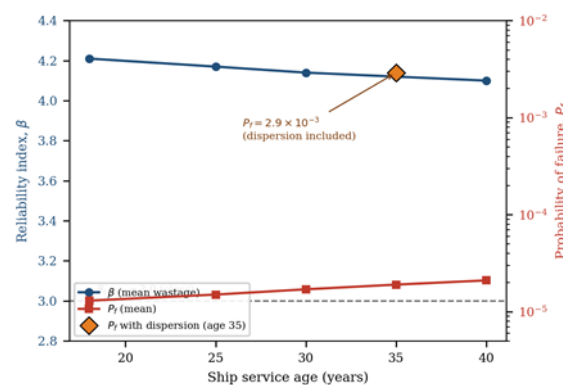


Figure 1. Reliability index β and probability of failure P_f versus ship age.
The marker at age 35 shows the jump in P_f once corrosion dispersion is included.

The quality of the underlying corrosion fit gives confidence in these reliability figures. An exponent close to 0.5, together with a coefficient of determination of 0.96, indicates that the decelerating power-law captures nearly all of the systematic trend in the data, leaving the residual scatter to be treated explicitly as dispersion rather than dismissed as noise. The gentle, monotonic decline of the mean reliability index from 4.21 at 18 years to 4.10 at 40 years is the signature of this slow capacity loss: at the mean level, the structure ages gracefully. The sharp contrast with the dispersed-wastage result at age 35, therefore, cannot be attributed to a poor fit or an unstable model; it is a genuine consequence of the long upper tail of the wastage distribution acting on the most highly stressed elements [18], [24].

B. Risk Quantification and Risk Map

Applying Eq. (2) at the element level for a projection age of 35 years yields the element risk score in Table 2. The risk is clearly not uniform and is concentrated on a few critical elements. The deck and inner-shell longitudinals carry the highest score (9), followed by the deck plating, sheer strake, longitudinal bulkhead, and stringer plates (score 8). This pattern is fully consistent with the categories that showed the highest coefficients of variation and with dispersion as the main driver of the probability of failure. It also confirms the dominance of

thin deck-zone elements as risk contributors [1], [4], [26].

The risk map (Fig. 2) places the highest-risk elements in the high-likelihood, high-severity quadrant and provides a direct, quantitative basis for prioritizing inspections. Because the risk is demonstrably concentrated on the thin-deck zone stiffeners, the stringer plates, and localized corrosion of the longitudinal bulkhead, inspection resources should be allocated in proportion to their risk contribution rather than uniformly.

The ranking in Table 2 follows directly from the interaction of the two matrix axes rather than from either axis alone. The deck and inner-shell longitudinals achieve the top score because they combine a high likelihood, inherited from the steep and widely dispersed wastage of the deck zone, with a high severity, inherited from their large lever arm about the neutral axis; weakening them erodes the section modulus quickly. The deck plating and sheer strake, the longitudinal bulkhead, and the stringer plates form a second tier, where a very high severity is paired with a more moderate likelihood. By contrast, the bottom and side longitudinals, the inner-bottom longitudinals, and the shell plating settle at a mid-range score, and the side girder, close to the neutral axis and only lightly wasted, sits at the bottom of the ranking [3], [26].

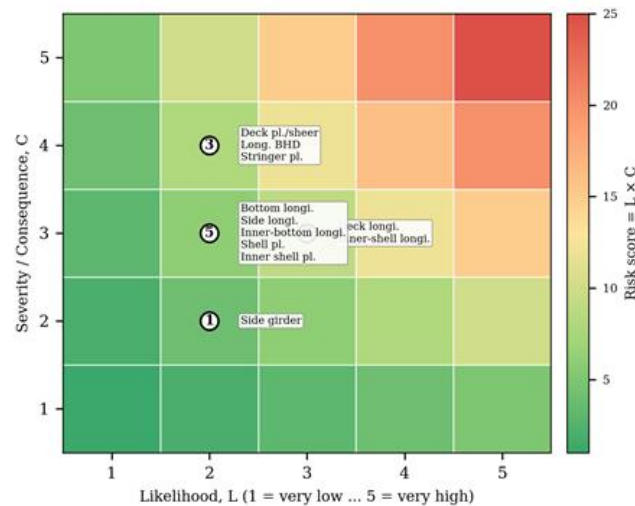


Figure 2. Likelihood-severity risk matrix.

The number inside a marker is how many elements share that cell; the highest-risk elements occupy the upper-right (high likelihood-severity) quadrant.

TABLE 2
ELEMENT-LEVEL RISK QUANTIFICATION AT 35-YEAR PROJECTION ($L \times C$)

Structural element	Wastage-35 (%)	L	C	Risk
Deck longitudinal	4.38	3	3	9
Inner-shell longitudinal	4.47	3	3	9
Deck plate & sheer strake	3.04	2	4	8
Longitudinal bulkhead	4.05	2	4	8
Stringer plate (LS/MS/US)	3.15	2	4	8
Bottom longitudinal	3.83	2	3	6
Side longitudinal	3.80	2	3	6
Inner-bottom longitudinal	3.48	2	3	6
Shell plating	3.51	2	3	6
Inner-shell plating	3.30	2	3	6
Side girder	3.08	2	2	4

Reading against the matrix in Fig. 2, the top tier occupies the upper-right cells, where both likelihood and severity are high; the second tier sits just inside, along the high-severity edge; and the remaining elements cluster toward the lower-left, where margin is ample. The visual concentration of markers in the upper-right is itself the result: a structure with truly uniform risks would scatter its elements evenly across the grid, whereas this hull packs its highest scores into a handful of cells. That clustering makes a prioritized inspection plan both possible and worthwhile, because it identifies a small, well-defined target set rather than an undifferentiated population [21], [26].

The findings can now be positioned against the previous studies reviewed in the introduction, which places the novelty of this work in context. The calibrated exponent $C2 \approx 0.5$ is consistent with the decelerating wastage reported for ballast tanks by Paik et al. [1] and Garbatov et al. [4], and the widening of the coefficient of variation with age agrees with the probabilistic ballast-tank models of Lampe and Hamann [23] and Noor et al. [24]. The finding that the dispersion of wastage, rather than its mean, governs the probability of failure sharpens the conclusions of reliability studies that assumed a uniform thickness reduction [9], [10], [12]: in the present

case, an assessment based on the mean thickness would report a probability of failure at 35 years more than two orders of magnitude lower than the dispersed-wastage result, and would therefore misjudge the true condition of the structure. The concentration of risk on the deck-zone stiffeners also refines the general, elevation-based severity argument of ultimate-strength studies [3], [26] into an explicit ranking derived from measured data. Furthermore, compared with the expert-judgment risk matrices commonly used in marine risk studies, including recent applications in this journal [29], [30], the likelihood axis here is derived directly from the calibrated corrosion forecast, so the map can be updated objectively at every future survey cycle rather than re-elicited from experts. In this respect, the study extends the risk-based inspection philosophy of API RP 580 [27], originally developed for process equipment, to the hull structure itself, and complements image-based corrosion detection techniques [28] by supplying the quantitative decision layer that such condition data ultimately serve.

C. Risk-Based Inspection and Predictive Maintenance

The implications of the chain of analysis are clear. Because the risk is not evenly distributed (Table 2) and the probability of failure is governed by the dispersion of

corrosion, an efficient inspection strategy should allocate inspection intensity and resources in proportion to each element's risk contribution rather than uniformly [15], [21]. The deck longitudinals, inner-shell longitudinals, stringer plates, and localized corrosion locations on the longitudinal bulkhead, which have the highest risk scores and the greatest consumption of safety margin, should be prioritized for monitoring at shorter intervals than the thick-plate elements, whose wastage is low and stable.

This approach supports the hypothesis that a risk-based inspection and maintenance strategy, derived from an integrated risk map, is more efficient than a conventional periodic strategy that treats all elements uniformly. Unlike prescriptive (fixed-schedule) or corrective (after-failure) maintenance, predictive maintenance schedules interventions based on the predicted condition and the estimated risk level, using the output of the corrosion model and the reliability assessment to identify when and where an intervention, such as plate renewal, is most needed [15], [22]. The availability of two inspection cycles on the same hull underscores the value of continuous condition monitoring: by comparing section conditions over time and across locations, the operator can determine the optimal time and place for intervention, thereby optimizing maintenance costs without sacrificing safety [15], [22].

For the shipping industry, the managerial implication is that the risk map can be embedded in the ship safety management system and the docking plan, shifting inspection and repair from reactive compliance to a predictive, risk-informed activity. Adopting a wastage-dispersion criterion, for example, an action threshold based on the coefficient of variation or the upper percentile of wastage, yields decisions that are more conservative and safer than those based on mean thickness alone, because dispersion is the main driver of risk [3], [24].

It is worth distinguishing the three maintenance philosophies that the risk map allows the operator to compare. Corrective maintenance waits for an element to fail or fall below the renewal limit before acting, which minimizes short-term costs but accepts the highest risk and the most disruptive unplanned repairs. Prescriptive or periodic maintenance renews and inspects on a fixed calendar regardless of condition, which is predictable but allocates effort uniformly, over-inspecting sound elements while potentially under-inspecting the few critical ones. Predictive maintenance, the strategy supported here, uses the corrosion forecast and the reliability assessment to act on elements that are actually approaching a limit state and at the time when intervention is most valuable, capturing most of the safety benefit of the periodic approach at a fraction of its cost [15], [22].

A practical implementation would translate the risk map into differentiated inspection intervals, with the high-score deck, inner-shell longitudinals, stringer plates, and localized corrosion zones of the longitudinal bulkhead inspected more frequently and with greater density than the stable bottom and side plating. Continuous condition monitoring across successive

survey cycles, as provided by the two Condition Assessment Program reports, sharpens the corrosion forecast over time and allows the renewal of a critical element to be timed to the point on the reliability curve that restores the greatest margin. Embedding this logic in the ship safety management system and the docking plan converts inspection from a reactive compliance exercise into a forward-looking, risk-informed activity. At this point, the analytical chain delivers a tangible operational benefit [14], [22], [34].

Framed in life-cycle terms, the value of the risk-based plan lies in directing inspection and renewal efforts where they yield the greatest reduction in expected failure cost. Each gauging campaign is, in effect, the purchase of information about the condition of the structure, and the value of that information is greatest for the high-risk elements whose state is both uncertain and consequential; spending equally on low-risk elements yields little new decision-relevant knowledge [22]. By concentrating effort on the elements identified in the risk map and timing renewal to the reliability curve, the operator approaches the life-cycle optimum, in which total expected cost, the sum of inspection, maintenance, and the residual risk of failure, is minimized without breaching the safety target [15], [22].

IV. CONCLUSION

In line with the objective stated in the abstract, the structural integrity risk level of the transverse construction of an oil tanker's ballast tank has been determined by combining the probability of failure with its consequence, and the resulting risk map has been used to formulate a risk-based inspection and predictive maintenance strategy. The first conclusion, answering the first part of the objective, is that the risk is concentrated rather than uniform. The risk map places the deck and inner-shell longitudinals at the highest risk, followed by the deck plating and sheer strake, the longitudinal bulkhead, and the stringer plates. Although the section satisfies the class reliability target at the mean wastage level ($\beta = 4.21 \rightarrow 4.10$ over 18–40 years, $P_f \approx 10^{-5}$), the probability of failure rises to 2.9×10^{-3} when corrosion dispersion is included. Therefore, the dispersion of wastage, not its mean, governs the risk.

The second conclusion, answering the second part of the objective, is that a risk-based inspection and predictive maintenance strategy focused on critical elements is the most appropriate way to maintain structural integrity while optimizing resource allocation, and it is more efficient than uniform periodic inspection. In practice, inspection and maintenance should be prioritized for the high-risk elements identified in the risk map. The action criterion should consider dispersion of wastage in addition to the mean minimum thickness, and the probabilistic risk map should be integrated into the ship safety management system and the docking plan so that decisions are predictive and risk-informed rather than reactive. Further work should leverage repeated multi-cycle inspections at the same section to tighten model calibration and extend the assessment to additional failure modes, such as fatigue and local pitting.

Beyond the specific numbers, the study carries a methodological message for assessing aging ship structures. The conventional acceptance criterion, framed around a mean or minimum thickness, is a necessary but insufficient guarantor of safety once corrosion becomes heterogeneous, because it is blind to the dispersion that actually governs the probability of failure. An assessment that propagates the measured scatter of wastage through an ultimate-strength and reliability calculation, and then condenses the outcome into an element-level risk map, recovers the information that the mean-thickness check discards and turns it into a ranked, actionable picture of where and when the structure is most exposed.

The approach is, of course, bounded by the data and the assumptions underlying it. The calibration rests on cross-sectional rather than truly longitudinal sampling; the corrosion-initiation period is taken from class convention rather than measured directly; and the assessment addresses ultimate hull-girder bending while setting aside fatigue and local pitting. None of these limitations weakens the central finding that dispersion governs risk; rather, they mark the natural directions for further work, in which repeated multi-cycle gauging at the same section would tighten the model, additional failure modes would broaden it, and application to other hull types would test how generally the concentration of risk observed here recurs [23], [24]. Until such extensions are made, the present results already provide a sound and transferable basis for prioritizing inspection and maintenance on the elements that dominate the risk.

Applied in practice, the findings recommend three concrete shifts in the inspection management of the ballast-tank transverse structure. Inspection density and frequency should be graded by risk, with the deck and inner-shell longitudinals, the stringer plates, and the bulkhead corrosion zones surveyed more closely than the stable bottom and side members. The acceptance criterion used in the survey should be supplemented with a dispersion-aware measure, such as an upper percentile or a coefficient of variation threshold, so that wide scatter draws attention even when the mean thickness still meets the criterion. The probabilistic risk map should be maintained as a living document within the safety management system and updated at each survey cycle, so that renewal timing can be guided by predicted reliability rather than by the calendar [15], [22], [24].

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REFERENCES

- [1] J. K. Paik, A. K. Thayamballi, Y. I. Park, and J. S. Hwang, "A time-dependent corrosion wastage model for seawater ballast tank structures of ships," *Corros. Sci.*, vol. 46, no. 2, pp. 471–486, 2004.
- [2] R. E. Melchers, "Modeling of marine immersion corrosion for mild and low-alloy steels—Part 1: Phenomenological model," *Corrosion*, vol. 59, no. 4, pp. 319–334, 2003.
- [3] Y. Garbatov and C. Guedes Soares, "Review of ultimate strength assessment of ageing and damaged ship structures," *J. Mar. Sci. Appl.*, vol. 19, no. 4, pp. 512–533, 2020.
- [4] Y. Garbatov, C. Guedes Soares, and G. Wang, "Nonlinear time dependent corrosion wastage of deck plates of ballast and cargo tanks of tankers," *J. Offshore Mech. Arct. Eng.*, vol. 129, no. 1, pp. 48–55, 2007.
- [5] J. K. Paik and D. K. Kim, "Advanced method for the development of an empirical model to predict time-dependent corrosion wastage," *Corros. Sci.*, vol. 63, pp. 51–58, 2012.
- [6] D. K. Kim, H. L. Lim, and N. K. Cho, "An advanced technique to predict time-dependent corrosion damage of onshore, offshore, nearshore and ship structures: Part II—Application to the ship's ballast tank," *Int. J. Nav. Archit. Ocean Eng.*, vol. 12, pp. 657–666, 2020.
- [7] C. Kim, S. Oterkus, E. Oterkus, and Y. Kim, "Probabilistic ship corrosion wastage model with Bayesian inference," *Ocean Eng.*, vol. 246, p. 110571, 2022.
- [8] X. He and C. Guedes Soares, "Corrosion prediction of FPSOs hull using machine learning," *Mater. Today Commun.*, vol. 39, p. 108591, 2024.
- [9] Y. Hu, W. C. Cui, and P. T. Pedersen, "Maintained ship hull girder ultimate strength reliability considering corrosion and fatigue," *Mar. Struct.*, vol. 17, no. 2, pp. 91–123, 2004.
- [10] A. Rahbar-Ranji, N. Niamir, and A. Zarookian, "Ultimate strength of stiffened plates with pitting corrosion," *Int. J. Nav. Archit. Ocean Eng.*, vol. 7, no. 3, pp. 509–525, 2015.
- [11] N. Momčilo, N. Ilić, M. Kalajdžić, Š. Ivošević, and A. Petrović, "Effect of corrosion-induced structural degradation on the ultimate strength of a high-tensile-steel ship hull," *J. Mar. Sci. Eng.*, vol. 12, no. 5, p. 745, 2024.
- [12] V. Piscopo and A. Scamardella, "Incidence of pitting corrosion wastage on the hull girder ultimate strength," *J. Mar. Sci. Appl.*, vol. 20, no. 3, pp. 477–490, 2021.
- [13] K. Woloszyk and Y. Garbatov, "Advanced numerical modeling for predicting residual compressive strength of corroded stiffened plates," *Thin-Walled Struct.*, vol. 183, p. 110380, 2023.
- [14] J. Parunov and C. Guedes Soares, "Effects of common structural rules on hull-girder reliability of an Aframax oil tanker," *Reliab. Eng. Syst. Saf.*, vol. 93, no. 9, pp. 1317–1327, 2008.
- [15] Y. Dong and D. M. Frangopol, "Risk-informed life-cycle optimum inspection and maintenance of ship structures considering corrosion and fatigue," *Ocean Eng.*, vol. 101, pp. 161–171, 2015.
- [16] K. Woloszyk, F. Goerlandt, and J. Montewka, "A framework to analyse the probability of accidental hull girder failure considering advanced corrosion degradation for risk-based ship design," *Reliab. Eng. Syst. Saf.*, vol. 251, p. 110336, 2024.
- [17] L. Xu, Y. Xin, L. Ma, H. Zhang, Z. Lin, and X. Li, "Challenges and solutions of cathodic protection for marine ships," *Corros. Commun.*, vol. 2, pp. 33–40, 2021.
- [18] S. Qin and W. Cui, "Effect of corrosion models on the time-dependent reliability of steel plated elements," *Mar. Struct.*, vol. 16, no. 1, pp. 15–34, 2003.
- [19] R. Adiputra, T. Yoshikawa, and E. Erwand, "Reliability-based assessment of ship hull girder ultimate strength," *Curved Layer. Struct.*, vol. 10, no. 1, p. 20220189, 2023.
- [20] F. Ahmadi and A. Rahbar-Ranji, "Reliability assessment of ship hull girders considering pitting corrosion and crack," *Eng. Res. Express*, vol. 6, no. 1, p. 015503, 2024.
- [21] C. Guedes Soares and Y. Garbatov, "Reliability of maintained ship hull girders subjected to corrosion and fatigue," *Struct. Saf.*, vol. 20, no. 3, pp. 201–219, 1998.
- [22] G. Zou, K. Banisoleiman, and A. González, "Bayesian maintenance decision optimisation based on computing the information value from condition inspections," *Proc. Inst. Mech. Eng. O, J. Risk Reliab.*, vol. 235, no. 5, pp. 901–916, 2021.
- [23] J. Lampe and R. Hamann, "Probabilistic model for corrosion degradation of tanker and bulk carrier," *Mar. Struct.*, vol. 61, pp. 309–325, 2018.
- [24] N. M. Noor, N. Yahaya, G. H. Smith, and S. H. M. Nor, "A probabilistic time-variant corrosion wastage model for seawater ballast tank," *Arab. J. Sci. Eng.*, vol. 38, no. 12, pp. 3253–3263, 2013.
- [25] Z. Feng et al., "A probabilistic time-dependent corrosion wastage model for offshore platforms based on reverse diffusion model," *Ocean Eng.*, vol. 313, p. 119426, 2024.
- [26] S. Saad-Eldeen, Y. Garbatov, and C. Guedes Soares, "Ultimate strength assessment of corroded box girders," *Ocean Eng.*, vol. 58, pp. 35–47, 2013.
- [27] American Petroleum Institute, "Risk-Based Inspection," API Recommended Practice 580, 3rd ed., Washington, DC, USA, Feb. 2016.
- [28] Y. Widiarti, E. Setiawan, H. A. Prasetyo, B. Prasetyo, I. Sutrisno, Andianto, and M. B. Rahmat, "Corrosion detection on ship hull using ROV based on convolutional neural network," *Int. J. Mar. Eng. Innov. Res.*, vol. 9, no. 1, pp. 218–229, 2024.
- [29] Q. Laili, A. Nugroho, S. D. Robbi, A. E. Kristiyono, I. Sianturi, and I. Sutrisno, "Evaluation of boiler maintenance using the

- failure mode and effect analysis approach at KM. Tilongkabila,” *Int. J. Mar. Eng. Innov. Res.*, vol. 11, no. 1, pp. 195–203, 2026.
- [30] H. L. Firmanullah, Silvianita, M. I. Purbawanto, and Y. Yonatan Eka Darma, “Risk management of subsea pipeline integrity and failure prevention,” *Int. J. Mar. Eng. Innov. Res.*, vol. 11, no. 2, pp. 766–784, 2026.
- [31] Š. Ivošević, N. Kovač, N. Momčilović, and G. Vukelić, “Evaluation of the corrosion depth of double bottom longitudinal girder on aging bulk carriers,” *J. Mar. Sci. Eng.*, vol. 10, no. 11, p. 1733, 2022.
- [32] Š. Ivošević and N. Kovač, “The analyses of the failures of hull structure plating caused by corrosion,” *Trans. Marit. Sci.*, vol. 12, no. 2, 2023.
- [33] International Association of Classification Societies, “Common Structural Rules for Bulk Carriers and Oil Tankers,” IACS, London, U.K., Jan. 2023.
- [34] S. Li and F. Brennan, “Digital twin enabled structural integrity management: critical review and framework development,” *Proc. Inst. Mech. Eng. Part M: J. Eng. Marit. Environ.*, vol. 238, no. 4, pp. 707–727, 2024.