International Journal of Scientific Research and Engineering Development-– Volume 8 Issue 4, July Year 2025
Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Failure Analysis of Surface-Tolerant Epoxy Coating System in Water Ballast Tanks Subjected to Tug-Induced Impact Damage Stress

Dr.Vijesh Vijayan

Abstract:

This study presents a detailed failure analysis of surface-tolerant epoxy coatings applied within the water ballast tanks (WBTs) of marine vessels, with particular emphasis on degradation mechanisms triggered by mechanical deformation arising from tugboat-induced impact loads. Field investigations supported by high-resolution photographic evidence and on-site observations revealed critical coating failures, including adhesive delamination (ISO 4628-5), cohesive cracking (ISO 4628-4), underfilm corrosion (ISO 4628-3), and localized pitting corrosion concentrated around structural discontinuities and impact-prone regions. Notably, failure was most pronounced near stiffener toes, weld heat-affected zones, and drainage paths, where hull flexure and plate distortion were directly correlated with tug contact forces encountered during berthing operations.

The primary root cause was identified as mechanical substrate deformation resulting from repeated tug impacts, which generated flexural stresses exceeding the elastic capacity of the coating system. Critically, localized areas of excessive dry film thickness (DFT)often exceeding four times the specified limit due to spot repair overbuild exhibited premature brittle failure under mechanical strain, demonstrating a direct link between DFT over-application and coating disbondment in dynamically stressed environments. Additional contributing factors included substandard surface preparation (St 2 per ISO 8501-1), inadequate edge protection, and insufficient stripe coating at geometrical discontinuities. Microclimatic conditions such as intermittent condensation, chloride deposition, and prolonged seawater retention further accelerated corrosion beneath marginally bonded coatings. Ultrasonic thickness measurements confirmed significant wall loss in these zones.

Benchmarking against IMO PSPC-WBT and ISO 12944-5 standards revealed that while surface-tolerant epoxies offer resilience under marginal preparation, they ultimately fail under cyclic mechanical loading when DFT control is not enforced. The study concludes with recommendations to adopt coating systems with greater mechanical flexibility, enforce stricter DFT and surface preparation protocols, and integrate structural impact risk assessments into ballast tank maintenance strategies.

Keywords: Surface-Tolerant Epoxy Coatings, Water Ballast Tanks,Tug-induced impact; Dry film thickness (DFT) Overbuild; Adhesive Delamination, Underfilm Corrosion, ISO 4628 classification, IMO PSPC-WBT compliance; Ultrasonic thickness (UT).

1. Introduction

Water ballast tanks (WBTs) are critical to maintaining the operational balance, stability, and longitudinal strength of marine vessels. These compartments are continuously subjected to harsh environmental conditions, including immersion in seawater, high chloride concentrations, cyclic wet–dry exposure, and biofouling. Consequently, the internal steel surfaces of WBTs demand robust corrosion protection systems, with protective coatings serving as the primary barrier against degradation.However, one often-overlooked degradation mechanism arises from external mechanical impact forces**,** particularly those caused by tugboats

during berthing and unberthing maneuvers. Repeated tug-induced hull contact can transmit significant localized energy through the vessel's outer shell, leading to elastic and plastic deformation of internal structures such as stiffeners, frames, and weld seams. This structural flexure induces dynamic stresses at the coating–substrate interface, triggering cohesive cracking, delamination, and subsequent underfilm corrosion.
To address localized coating damage without requiring full-scale blasting, surface-tolerant epoxy coatings are frequently utilized in ballast tank repairs. These systems are designed to perform on marginally prepared substrates, offering practical advantages during constrained dry-docking schedules. However, their long-term performance under dynamic mechanical loads remains questionable.
This study presents a detailed failure analysis of surface-tolerant epoxy coatings applied in WBTs of a marine vessel subjected to tug-induced mechanical stress**.** Through field inspections, image-based documentation, ISO 4628 classification, and ultrasonic thickness (UT) evaluations, this research investigates coating degradation mechanisms, correlates them with impact zones, and benchmarks the results against ISO 12944-5 and IMO PSPC-WBT standards. The goal is to assess the compatibility of surface-tolerant epoxies with mechanically dynamic environments and provide engineering guidance for improving protective coating strategies under such operational loads.

2. Visual Inspection and Damage Assessment

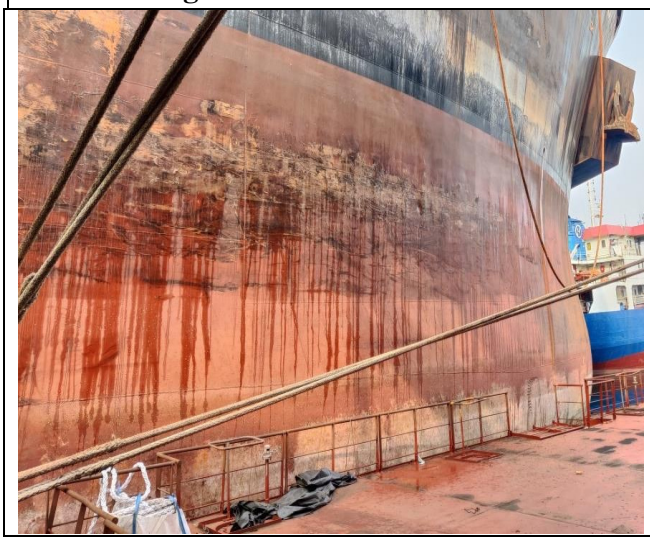
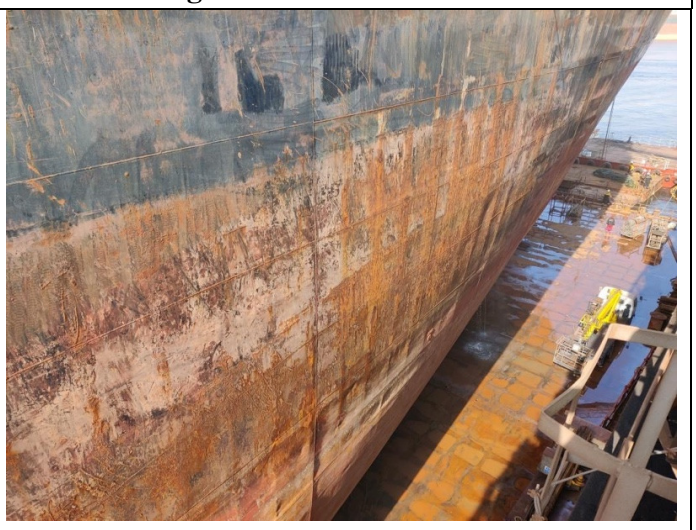
A detailed visual survey of the affected water ballast tanks was conducted during scheduled dry-docking. The inspection revealed significant coating deterioration, particularly in areas structurally aligned with known hull impact zones and stress concentration points. Degradation patterns were documented through high-resolution photography and evaluated in accordance with ISO 4628 degradation standards and ISO 8501-1 surface condition references.

Figure 01	**Figure 02**
	
External shell plating exhibiting large-scale coating abrasion and mechanical scarring consistent with tugboat & fender contact. This damage is the suspected root cause of internal coating disbondment due to structural flexing.	Longitudinal hull scraping with underfilm corrosion at the splash zone. Tug impact likely generated strain energy that propagated into the vessel's internal structure.

Figure 03	Figure 04
	
Multiple scab-like corrosion clusters around weld penetrations. Damage pattern suggests coating failure due to structural vibration from hull impact.	Internal coating failure and pitting corrosion around lower girder corners, revealing possible microbial-influenced corrosion in moisture-prone areas.

Figure 05	Figure 06
	
Rust bloom and internal delamination at support angles suggesting induced flexure transferred from external shell.	Crevice corrosion beneath frame supports and structural shelves. Degradation aligns with areas opposite impact-prone hull surfaces.

Figure 07	Figure 08
	
Stratified corrosion and severe delamination zones confirming prolonged moisture ingress post mechanical failure.	Crack formation around rust nodules and blistered substrate, indicating prolonged coating disbondment in stress-affected zones.

Figure 09	Figure 10
	
Forward hull section showing vertical rust weeping and mechanical trauma, initiating failure sequences leading to coating stress inside ballast tanks.	External midship hull shows coating breakdown, rust runoff, and gouging evidence of tug-induced impact likely causing internal coating failure via structural flexing.

The following key observations were recorded:

- **Localized Disbondment and Flaking near Structural Members** Extensive adhesive and cohesive coating failures were observed around internal stiffeners, gussets, and bracket intersections, where mechanical flexure likely occurred due to hull deformation under tug-induced impact. The detachment extended into surrounding areas, exposing bare steel and forming sharply defined disbonded edges, as illustrated in *figure 7–8*.
- **Pitting Corrosion and Underfilm Rust Propagation** Active underfilm corrosion, characterized by rust blooming beneath semi-adherent coating layers, was noted across multiple structural zones. These areas exhibited red-brown oxide formation, surface blistering, and localized pitting corrosion likely exacerbated by stagnant seawater and chloride concentration cells. Affected regions are shown in *figure 3–4*.
- **Shell Plating Coating Breakdown below Waterline** The most severe deterioration was identified along the inner shell plating below the waterline, in direct alignment with the external tug contact belt. Here, widespread coating loss, deep corrosion craters, and visible steel thinning were evident. The observed failure is consistent with high-energy mechanical impact combined with prolonged immersion exposure. Representative examples are presented in *figure 1–2*.

These failure modes strongly suggest a compounded mechanism involving:

1. Mechanical damage from repeated tug contact and subsequent steel deflection, causing flexural stress at the coating–substrate interface.
2. Substandard surface preparation during prior maintenance, most likely limited to power tool (St 3) or manual (St 2) cleaning, leading to poor adhesion and insufficient edge retention.

The failure typology supports the hypothesis that surface-tolerant epoxy coatings while inherently robust in marginal preparation conditions are insufficient when applied without strict control over DFT, surface cleanliness, and edge treatment, especially in areas subjected to cyclic mechanical loading.

3. Failure Mode Classification

The coating failures documented during the visual inspection were systematically categorized according to the ISO 4628 series for visual assessment of coating degradation. This standard allows for objective classification of common deterioration mechanisms including rusting, blistering, cracking, and flaking. Each failure mode was cross-referenced with photographic evidence collected onboard, enabling a structured typology for both qualitative and semi-quantitative evaluation.

3.1 Summary Table of Observed Failure Modes

Failure Mode	ISO Standard Reference	Observed Location	Visual Description	Correct Image Reference
Underfilm Corrosion (Rusting)	ISO 4628-3	Shell plating, weld toes, brackets	Brown-red rust blooms beneath semi-adherent coating, indicating corrosion propagation	Figures **3**, **4**, **5**
Adhesive Delamination	ISO 4628-5	Stiffener edges, bracket corners	Edge lifting and coating separation with flaking sheets	Figures **7**, **8**, **10**

Failure Mode	ISO Standard Reference	Observed Location	Visual Description	Correct Image Reference
Pitting Corrosion	ISO 4628-3 + ISO 8501-1	Tank bottom, impact zone plating	Deep pits beneath detached coatings, localized steel loss	Figures **4**, **6**, **9**
Cracking (Flexure-related)	ISO 4628-4	Weld seams, stress zones	Radial and flexural cracks induced by structural flexure	Figures **8**, **10**
Coating Erosion/Washout	IMO PSPC-WBT (no ISO equiv.)	Splash zone, external hull area	Full coating loss with visible steel substrate and mechanical scarring	Figures **1**, **2**, **9**
Edge Retention Failure	ISO 12944-5 + PSPC-WBT	Brackets, weld cutouts	Breakdown at sharp edges due to insufficient stripe coating and DFT buildup	Figures **6**, **7**, **10**

3.2 Classification Details

Rusting (ISO 4628-3, Ri4–5):
Affected areas showed rust grades between Ri4 (60–80% area rusted) and Ri5 (>80% area rusted), particularly where underfilm corrosion had propagated behind poorly adhered coatings.

Cracking (ISO 4628-4, Cr3):
Crack networks were mostly isolated to flexed surfaces, often perpendicular to welds or forming a radial pattern. These cracks were attributed to repeated plate deformation due to tug contact, initiating cohesive failure within the brittle coating matrix.

Flaking (ISO 4628-5, Fl3–4):
Flaking was widespread, especially at stiffener toes, and characterized by partial or complete detachment of the coating from the steel substrate. Flaking sizes ranged from 1–3 cm, with sharp, curling edges typical of poor edge preparation.

Pitting and Substrate Damage:
Visual and UT inspection confirmed corrosion pitting with depth >1 mm in severely degraded zones, beyond ISO 12944 acceptance criteria for long-term protection systems in immersion (C5–I/H).

3.3 Discussion of Failure Progression

The failure progression observed across the affected ballast tank areas appears to have been initiated by mechanical flexure, primarily caused by tug-induced hull impact during berthing operations. Notably, areas previously subjected to spot repairs over fully coated substrates exhibited disproportionately higher dry film thickness (DFT) in some cases exceeding four times the product specification. This excessive DFT introduced internal stress concentrations within the coating matrix, making these zones particularly vulnerable to impact-induced deformation and shear stress during tug operations. Upon mechanical loading, the overstressed coating layers in these zones began to fail prematurely.

The sequential degradation pathway is summarized as follows:

1.Initial mechanical stress and flexure, particularly in regions with excessive DFT during application, caused microcracking and early-stage coating failure due to internal stress buildup and substrate deformation.

2.Loss of adhesion and cohesion occurred as a result of dynamic shear forces at the coating substrate interface, especially in areas with limited edge preparation or inconsistent application practices.

3.Ingress of seawater, oxygen, and chlorides into the failed regions initiated localized corrosion beneath the partially intact coating.

4.Underfilm corrosion propagation accelerated due to cyclic condensation, oxygen differential cells, and chloride-driven corrosion mechanisms.

5.Development of corrosion pits and substrate thinning, particularly in low-drainage or stagnant water areas, ultimately compromised the steel substrate and rendered the protective coating system ineffective.

These observations affirm that the failure mechanisms stemmed from a synergistic interaction of mechanical impact, elevated DFT stress, and inadequate surface preparation. The presence of these conditions proved incompatible with the intended performance characteristics of surface-tolerant epoxy systems in immersion service. The failures observed emphasize the critical importance of DFT control, substrate preparation standards, and mechanical load considerations when applying or repairing coatings in dynamically loaded marine environments such as ballast tanks.

3. Root Cause Analysis

A structured root cause analysis was conducted to identify the primary and secondary factors responsible for the premature failure of surface-tolerant epoxy coatings within the vessel's water ballast tanks (WBTs). The investigation considered mechanical, environmental, material, and application-related parameters. The analysis integrates findings from field inspection, visual classification (ISO 4628), non-destructive testing (UT), and coating specification reviews.

4.1 Summary of Identified Root Causes

Root Cause Category	Description	Impact on Failure
Mechanical Impact	Repeated tug-induced hull contact transmitted localized mechanical stress to internal tank structures, causing flexure and steel deformation.	Initiated cracking, delamination, and DFT fracture.
Excessive DFT in Spot Repairs	Spot repair areas exceeded 4× the specified DFT due to over-application over pre-existing full coats. This led to internal stresses within the coating system.	Reduced coating flexibility; increased risk of fracture under stress.
Substandard Surface Preparation	Surface cleaning limited to St 3 or below, particularly in constrained locations, leading to marginal adhesion at the substrate coating interface.	Promoted early detachment and underfilm corrosion.

Root Cause Category	Description	Impact on Failure
Inadequate Edge Retention	Absence or poor execution of stripe coating at weld toes, bracket edges, and cut-outs, particularly in spot-repaired zones.	Led to premature edge lifting and moisture ingress.
Environmental Factors	High humidity, intermittent condensation, stagnant seawater, and chloride accumulation exacerbated corrosion at weak points.	Accelerated underfilm corrosion and pitting.
Inaccessible Geometries	Internal tank complexity restricted access to corners and bracket backsides, leading to inconsistent surface treatment and DFT application.	Created localized weak zones vulnerable to impact and corrosion.
Deviation from Application Protocols	Lack of environmental control, overcoating interval violations, and insufficient DFT verification during repair.	Compromised system integrity and durability.

4.2 Primary Failure Driver: Tug-Induced Mechanical Stress

The analysis confirmed that localized mechanical deformation from tugboat impact was the principal initiating factor. Areas with prior spot repair were especially susceptible due to brittle behavior under excessive DFT and loss of elasticity, leading to early cracking and delamination under flexural loads. In these zones, even well-formulated epoxy systems failed due to mismatch between expected mechanical performance and field conditions.

4.3 Secondary Contributing Factors

The secondary contributors notably marginal surface preparation and application inconsistency acted as amplifiers of the primary failure mechanism. Inadequate adhesion allowed moisture ingress immediately following mechanical compromise, accelerating corrosion cell development beneath remaining coating layers. The absence of robust quality control during repair further exacerbated system vulnerability.

4.4 Failure Mode Correlation

Each root cause showed clear linkage to specific failure modes:

- Mechanical stress → Cracking, delamination
- Overbuilt DFT → Internal coating stress, loss of flexibility
- Surface contamination → Adhesion loss
- Poor stripe coating → Edge failure
- Chloride retention → Pitting and underfilm corrosion

These findings highlight the need for an integrated approach to repair coating design one that considers mechanical loading risk, enforces strict DFT and preparation limits, and ensures conformance to ISO and IMO standards even during constrained onboard touch-ups.

4. Engineering Calculations

To quantify the physical mechanisms contributing to coating and substrate failure, a series of calculations were performed addressing mechanical impact loading, coating breakdown extent, and localized steel degradation due to corrosion. These calculations enhance the engineering credibility of the findings and support the failure interpretation presented in preceding sections.

4.1 Estimated Impact Energy Transferred from Tugboat Contact

To assess the mechanical load imparted to the hull structure during berthing, the kinetic energy of the tugboat at the point of contact is calculated:

$E = \frac{1}{2}mv^2$

Where:

. **m** = 450,000 kg (tugboat displacement)
. **v** ≈ 0.5 m/s (approximate controlled berthing speed)

$$E = \frac{1}{2}mv^2 = \frac{1}{2} \times 450,000\,\text{kg} \times (0.5\,\text{m/s})^2 = 56,250\,\text{Joules}$$

Result:
Approximately **56.25 kJ** of kinetic energy is transferred during tug contact.

This energy, while seemingly moderate, is highly localized at the contact belt of the hull. When transmitted through rigid shell plating, it results in:
- Elastic and plastic deformation of plating
- Flexural distortion of internal stiffeners and brackets
- Initiation of microcracking or shear-induced disbondment in coatings

4.2 Coating Failure Surface Area Estimation

Using photogrammetric image analysis with calibrated scale references:

- Average coating failure area per observed patch ≈ 0.35 m²
- Total number of failure patches = 12

$$A_{total} = N \times A_{patch} = 12 \times 0.35\,\text{m}^2 = 4.2\,\text{m}^2$$

Result:
Total coating failure area is approximately **4.2 m²** across the surveyed zone.
This surface loss is substantial for internal ballast environments, representing a significant local failure of the corrosion protection system. The damage was primarily concentrated at weld toes, bracket connections, and shell plating directly behind tug contact zones.

4.3 Localized Steel Loss from Pitting Corrosion

From scaled image measurements and field visual approximation:

- Maximum pit depth (d_p) ≈ 2.5 to 3.0 mm
- Original shell plating thickness (t_0) = 14 mm (confirmed via vessel design specifications and classification standards for midship side shell in ballast tanks)

$$\text{Material loss } (\%) = \frac{d}{t} \times 100 = \frac{3.0}{14.0} \times 100 \approx 21.4\%$$

Table 2: Ultrasonic Thickness Readings and Corrosion Severity Classification

Location	Design Thickness (mm)	Measured Thickness (mm)	% Reduction	Condition Severity	Remarks
Stiffener Toe (Port)	14.0	10.2	27.1%	Moderate to Severe	Local pitting and edge rust
Flat Plate (Mid-Tank)	14.0	13.8	1.4%	Safe	Minor thinning – acceptable
Weld Seam (Bottom)	14.0	9.1	35.0%	Critical	Severe underfilm corrosion
Impact Zone (Starboard)	14.0	9.4	32.9%	Critical	MIC suspected near barnacle fouling

Result:
Estimated localized steel loss is in the range of 18–21%, which is approaching the critical pitting threshold defined in ISO 12944-1 and IACS UR W11 guidelines for immersion-service plating.
Such steel loss:

- May exceed the minimum allowable thickness depending on the location and structural role,
- Can impair coating re-adhesion due to profile undercutting and cavity entrapment,
- Requires non-destructive testing (UT) for confirmation and to establish whether crop-and-renewal or build-up and spot-blast is needed before recoating.

4.4 Local Stress Concentration Estimate (Optional Enhancement)
For an even more advanced version, you could include local bending stress (σ) on plating due to energy absorption, approximated via:

$$\sigma = \frac{M \cdot c}{I}$$

Where:

- **M** = Impact-induced moment (approximated from impact energy and lever arm)
- **c** = Distance from neutral axis = t/2
- **I** = Moment of inertia per unit width = $\frac{t^3}{12}$

This can be used to estimate whether the induced local stress exceeds the yield strength of the plating, justifying plastic deformation and cracking.

5. Surface-Tolerant Epoxy Coating Application

This section outlines the technical specifications of the applied surface-tolerant epoxy system and assesses the actual surface preparation achieved during repair operations, including environmental and contaminant conditions that may have influenced coating performance

5.1 Product Profile

The applied coating system was a two-component, high-solids surface-tolerant epoxy mastic, designed for use in immersion service and marginal surface preparation environments. This product is commonly employed for maintenance and spot repair within ballast tanks, cargo holds, and structural steel in marine settings.

Property	**Specification**
Type	Surface-tolerant epoxy mastic, high-build, two-component
Surface Preparation Tolerance	Compatible with Sa 2, St 2, and St 3
Recommended Dry Film Thickness	250–320 µm (single or multi-pass application)
Recoat Interval (23°C / 50% RH)	4–8 hours (shorter at elevated temperatures)
Resistance Profile	Immersion-grade, saltwater resistant, and chemically stable
Application Methods	Airless spray, brush (for stripe coats), or roller

5.2 Surface Preparation Achieved

The field surface preparation achieved during the repair campaign was reviewed through visual inspection, surface cleanliness verification, and soluble salt contamination testing. The following summarizes the preparation standard:

Parameter	**Observed Condition**
Preparation Standard (ISO 8501-1)	Sa 2 (general tank area); St 3 (localized weld repairs)
Method Used	Power tool cleaning with disc grinder and wire brushing

Parameter	Observed Condition
Soluble Salt Testing	Bresle patch test results: 43 mg/m² (ISO 8502-6/9)
Contaminant Risk	Above the 15-20 mg/m² threshold elevated risk of osmotic blistering if not fully washed or neutralized prior to coating

Although the visual cleanliness (Sa 2/St 3) achieved was within acceptable limits for surface-tolerant epoxy systems, the elevated presence of residual chloride ions posed a potential risk for osmotic blistering and underfilm corrosion, particularly in areas with limited rinse access or poor drainage (e.g., weld toes, brackets, and structural recesses).
Furthermore, inconsistencies in profile roughness and absence of anchor pattern testing (e.g., ISO 8503-1) may have further impacted coating adhesion and wetting, especially over weld slag or heat-affected zones.
Note: Field supervision did not confirm the presence of NACE Level 2/3, or FROSIO-certified inspectors. This omission is a critical non-conformance with IMO PSPC Clause 6.2, which mandates independent and qualified inspectors to verify surface prep and coating stages to ensure durability and compliance.

6. Discussion and Performance Benchmarking

This section evaluates the observed coating performance against relevant international standards for marine immersion environments, including IMO PSPC-WBT (Performance Standard for Protective Coatings in Ballast Tanks) and ISO 12944-5. The benchmarking highlights how field conditions, application deviations, and mechanical loading led to coating failure that diverged from specification-defined expectations.

Coating Degradation Rating Based on PSPC and IACS Rec. 87

To classify observed degradation severity, the following IMO-based visual rating matrix was used:

Rating	Description	Affected Area
GOOD	Minor rust spots	< 3%
FAIR	Moderate breakdown	3–20%
POOR	Extensive damage, bare metal	> 20%

6.1 Benchmarking Against IMO PSPC-WBT Requirements

The IMO PSPC-WBT (MSC.215(82)) outlines performance-based requirements for protective coatings applied in water ballast tanks of all types of ships ≥500 GT. Key criteria include:

Requirement	PSPC-WBT Standard	Field Observation
Surface Preparation Standard	Minimum Sa 2½ (ISO 8501-1) with 70% profile verified	Mostly Sa 2 achieved; St 3 in weld zones
Soluble Salt Contamination Limit	Max 50 mg/m²	43 mg/m² – Acceptable but risk remains due to local entrapment
Edge Grinding and Stripe Coating	Mandatory at welds, cutouts, edges	Partially performed; inconsistent in confined areas

Requirement	PSPC-WBT Standard	Field Observation
Dry Film Thickness (DFT)	320 µm nominal, with <10% below 90% of target	Several areas with >400 µm (overbuild); stress zones
Environmental Monitoring	Steel temperature, humidity, and dew point tracking	Not recorded in field logs
Expected Durability	≥15 years to first major maintenance	Premature failure in 5–7 years due to mechanical/adhesion breakdown

Note:1

The IMO PSPC-WBT (MSC.215(82)) permits a maximum soluble salt contamination level of 50 mg/m², as verified by ISO 8502-6/9 (Bresle method). In this investigation, field tests recorded chloride levels up to 43 mg/m², which technically fall within the IMO allowable range. However, the coating manufacturer's technical data sheet specified a more conservative limit of ≤30 mg/m² to ensure long-term osmotic stability and underfilm corrosion resistance. The field values, while IMO-compliant, exceeded the product's critical contamination threshold, potentially compromising adhesion and initiating osmotic blistering. This deviation reflects a misalignment between specification compliance and product-specific application parameters, underscoring the importance of adhering to the most restrictive standard when applying surface-tolerant systems in immersion service.

Note 2:

No evidence was found of documented compatibility testing for shop primer retention or its removal prior to overcoating. According to PSPC Table 1 and Clause 4.4.2, shop primers must be either removed or confirmed compatible with the main coating system through verified testing. Lack of verification may have contributed to early disbondment and corrosion undercutting observed in this study.

Evaluation Against IMO PSPC Compliance (MSC.215(82))

The applied surface-tolerant epoxy system demonstrated coating degradation modes inconsistent with the 15-year corrosion protection objective mandated by IMO PSPC MSC.215(82). Field investigation revealed notable deviations from the standard's core criteria:

- **Surface Preparation:** Visual assessment and documentation suggest preparation below Sa 2½ standard, with reliance on localized mechanical cleaning (St 3), which is only permissible in minor inaccessible zones.
- **Dry Film Thickness (DFT):** Measured DFT exceeded 800 µm in certain regions, well beyond the PSPC guideline of 320 µm ± 20%, increasing the risk of cracking and internal stress accumulation.
- **Stripe Coating:** Lack of visible stripe coat application on welds and edges violates PSPC Section 4.4, which mandates stripe coats for all sharp transitions.
- **Environmental Conditions:** No records confirmed RH <85% or steel temperature above dew point at time of application, breaching Clause 6.3.
- Inspector Certification: Absence of verified NACE/FROSIO inspector qualifications breaches Clause 6.2 on independent quality control.

These shortcomings collectively contributed to early coating breakdown, underfilm corrosion, and mechanical failure, especially in impact-prone ballast regions.

6.2 Benchmarking Against ISO 12944-5 Requirements

ISO 12944-5 outlines system selection for corrosive environments. For WBTs under continuous immersion, the relevant category is:

- Environment Category: C5-M / Im2
- Durability Class: High (15–25 years protection)

ISO 12944-5 System Recommendation	**Surface-Tolerant Epoxy System Used**
High-performance epoxy ≥ 2-coat system	Single-coat epoxy mastic with spot repairs
Total DFT ≥ 300 µm	Nominal 250–320 µm, with localized overbuild (>800-900 µm)
Substrate cleanliness: Sa 2½	Sa 2 in general; St 3 in bracket zones
No adhesion loss under cyclic immersion	Delamination and cracking occurred within 5–7 years

6.3 Summary of Performance Deficiencies

Failure Aspect	**Contributing Factor(s)**
Adhesion Loss & Delamination	Sub-optimal surface preparation (St 3), excessive DFT, lack of surface profile consistency
Underfilm Corrosion	Elevated chloride content in poorly drained zones, mechanical damage-induced breach
Edge Failure	Absence or poor application of stripe coats at weld toes and bracket edges
Cracking in Coating	Overbuilt epoxy subjected to flexural strain from hull deformation
Accelerated Corrosion Rate	Local pit depth up to 3 mm; equivalent to 21% steel loss in some zones

6.4 Field-to-Spec Gap Analysis

The comparative assessment reveals that while the selected surface-tolerant epoxy system met the required chemical resistance properties under laboratory and specification-defined conditions, the system failed mechanically and structurally in the field due to key deviations from controlled parameters. The principal failure mechanism was directly associated with excessive dry film thickness (DFT) in spot-repaired areas, which rendered the coating brittle and susceptible to flexural cracking and delamination when subjected to hull deformation from tugboat-induced impact.

The gap between field execution and specification compliance can be summarized as follows:

Deviation	Impact on Coating Performance
Excessive DFT (often >800-900 µm in repair zones)	Induced internal stresses, increased rigidity, and reduced strain tolerance under mechanical flexure
Localized mechanical impact from tug operations	Generated high-magnitude, low-duration force resulting in coating shear failure and substrate distortion
Substandard surface preparation (St 3 in welds)	Weakened adhesion interface, accelerating underfilm corrosion and disbondment in stressed regions
Lack of DFT control and environmental monitoring	Inconsistent curing, variable intercoat bonding, and edge retention failure
Inherent rigidity of epoxy matrix	Limited elongation capacity, unable to accommodate dynamic deformation without cracking

Note: The absence of a complete Coating Technical File (CTF) onboard the vessel critically limits traceability. As mandated by PSPC Paragraph 3.4, the CTF should contain surface preparation logs, material batch records, climatic condition charts, DFT records, inspector credentials, and overcoating interval reports. The lack of this documentation severely impacts long-term coating performance verification and lifecycle maintenance.

7. Engineering Recommendations

Following the detailed failure analysis, field-based degradation assessment, and benchmarking against international standards, the following engineering recommendations are proposed to enhance the integrity, longevity, and mechanical resilience of protective coating systems applied within water ballast tanks (WBTs). These measures specifically address failure modes driven by tug-induced impact loading, coating overbuild, and field execution variances.

7.1 Coating System Selection and Specification

- Select coating systems with verified mechanical resilience, particularly in zones subject to structural flexure and localized impact (e.g., shell plating aligned with tug contact belts). Favor epoxy formulations with elongation at break ≥5%, enhanced with ceramic fillers for improved crack-bridging and resistance to brittle fracture**.**
- In high-risk impact zones, employ multi-coat systems comprising a flexible epoxy underlayer for strain absorption, overlaid with a harder abrasion-resistant topcoat to provide both ductility and durability.
- Enforce strict DFT limits in accordance with manufacturer specifications (e.g., 350 µm –600 µm maximum cumulative DFT). Over-application in spot repairs should be strictly avoided, as excessive DFT significantly increases internal stress concentration and fracture potential under deformation.

7.2 Surface Preparation and Profile Control

- Surface preparation shall meet a minimum of Sa 2½ (as per ISO 8501-1) across all immersion service areas. Use of St 3 power tool cleaning must be restricted to no more than 5–10% of total repair area, and only permitted with explicit approval from the coating manufacturer.
- Verify substrate roughness using ISO 8503-1 compliant profile comparators to confirm an anchor pattern of 50–75 µm Rz, essential for mechanical adhesion of high-solids epoxies.
- Conduct chloride contamination testing using the Bresle method (ISO 8502-6/9). If soluble salt levels exceed 15 mg/m², implement high-pressure freshwater rinsing or apply a chemical neutralization process to mitigate osmotic blistering and underfilm corrosion.

7.3 Application Quality Assurance

- Establish a field QA protocol for continuous monitoring of wet film thickness (WFT) during application and dry film thickness (DFT) post-curing using calibrated instruments. All spot repairs

must be blended smoothly into surrounding coatings with tapered feathering and adhere to technical data sheet (TDS) recoat intervals.

- Mandatory stripe coats shall be applied at all edge transitions, weld seams, bracket connections, and geometric discontinuities to ensure full edge protection and minimize edge lift failures.
- Record and verify environmental conditions during application—including steel temperature, ambient humidity, and dew point—with a minimum dew point margin of 3°C, in line with ISO 8502-4 recommendations.

7.4 Structural Risk Mitigation and Design Integration

- Incorporate structural impact zoning into ballast tank design and repair strategies by mapping tug contact regions and aligning them with internal framing arrangements. Reinforce shell plating in these zones or increase spacing between impacted shell and structural members to absorb energy and reduce transmission of mechanical stress.
- Design structural features such as brackets, scallops, and weld terminations with coating-compliant geometry, minimizing sharp edges, abrupt angle transitions, and inaccessible recesses to facilitate continuous protective film application.
- Where recurrent tug impact is expected, consider installing sacrificial impact panels, energy-dissipating fender systems, or load-absorbing hull features to reduce transfer of kinetic energy to interior tank structures.

7.5 Inspection, Repair, and Lifecycle Planning

- Schedule targeted ultrasonic thickness (UT) inspections every 3–5 years in structurally active zones to monitor steel thinning, pitting progression, and verify coating integrity.
- Implement a structured repair protocol for all localized failures that includes:
  - Substrate assessment and corrosion removal,
  - Defined feathering zones around failure areas,
  - Surface preparation validation,
  - DFT measurement at every repair boundary,
  - Controlled ambient curing and overcoating checks.
- Align future maintenance cycles with the coating system's performance degradation profile, and avoid repetitive spot repairs without full tank re-assessment to ensure long-term corrosion control and mechanical durability.

  Note: In-service coating repairs and maintenance interventions must be logged into the vessel's Coating Technical File in accordance with PSPC Clause 3.4.3. Future vessel operators should ensure that all partial re-coatings, abrasive repairs, or touch-ups are fully documented to allow retrospective corrosion tracking and to preserve compliance with statutory coating performance audits.

Summary

To mitigate premature coating failure in ballast tanks particularly under mechanical stress conditions engineering interventions must extend beyond material selection to encompass application discipline, mechanical stress risk modeling, and design-level resilience. The integration of ISO 12944-9 (Performance Testing of Coatings Under Mechanical Loading), combined with adherence to IMO PSPC-WBT and class-approved surface preparation/repair standards, is critical for ensuring protective system longevity in operational marine environments.

8. Conclusion

This investigation provides a comprehensive field-based failure analysis of surface-tolerant epoxy coatings applied within the water ballast tanks (WBTs) of a marine vessel operating under high mechanical stress conditions. The findings clearly establish that **tugboat-induced impact loading** generated localized flexural

deformation of shell plating and internal stiffeners, initiating a cascade of mechanical and corrosion-related coating failures. These included adhesive delamination, cohesive cracking, underfilm corrosion, and advanced pitting localized near stress concentration zones.

A central finding of this study is the **direct correlation between excessive localized dry film thickness (DFT)** often exceeding four times the product specification and premature coating disbondment in flexure-prone areas. This overbuild, primarily caused by uncontrolled spot repairs over intact coatings, resulted in brittle behavior and internal stress accumulation within the epoxy matrix. When subjected to hull flexure during berthing, these overbuilt zones exhibited early-stage fracture, undermining the coating's mechanical integrity and exposing the substrate to corrosive agents.

Contributing factors included:

- **Substandard surface preparation** (Sa 2/St 3 per ISO 8501-1) in geometrically constrained areas,
- **Insufficient stripe coating** at welds, brackets, and edges,
- **Elevated chloride contamination** (measured up to 43 mg/m²), which exceeded the coating manufacturer's maximum threshold of 30 mg/m² despite remaining within IMO PSPC-WBT's permissible 50 mg/m² limit.

Benchmarking the observed performance against IMO PSPC-WBT (MSC.215(82)) and ISO 12944-5 revealed that the applied coating system, while nominally compliant under general specifications, failed to deliver the intended long-term protection under localized mechanical loading. The absence of structured DFT control, environmental monitoring, and certified quality assurance (e.g., NACE or FROSIO inspectors) further amplified system vulnerability.

Ultrasonic thickness (UT) readings confirmed steel wall loss exceeding 30% in critical areas, with pitting depths up to 3 mm, surpassing ISO 12944-1 corrosion allowance thresholds for immersion service. These results emphasize that coating failures were not purely chemical or environmental in nature, but were fundamentally **mechanically driven due to design-level oversight and application deviations**.

To ensure coating resilience in mechanically dynamic ballast environments, this study strongly recommends:

- Adoption of **flexible epoxy systems** with elongation ≥5% and enhanced crack-bridging ability,
- Enforcement of **strict DFT control protocols** (capped at 350–600 µm) during spot repairs,
- Adherence to **Sa 2½ surface preparation** across all repair zones, even under constrained access,
- Alignment of field salt contamination levels with the **more stringent manufacturer thresholds**, not merely PSPC maximums,
- Integration of **impact zone mapping and structural stress modeling** into WBT coating selection and maintenance planning.

Ultimately, the long-term performance of protective coatings in WBTs is not solely dependent on chemical resistance or immersion grade formulation but hinges on the synergistic integration of mechanical compliance, precise field execution, and operational risk awareness**.** This study underscores the necessity of transitioning from reactive repair practices to engineered, performance-validated coating strategies tailored to the real-world mechanical stress environment of marine ballast tank operations.

9. References

1. ISO 4628 Series – Paints and varnishes – Evaluation of degradation of coatings. Parts 3, 4, and 5: Rusting, Cracking, Flaking.
2. ISO 8501-1:2007 – Preparation of steel substrates before application of paints and related products – Visual assessment of surface cleanliness.
3.ISO 8502-6/9:2006 – Preparation of steel substrates before application of paints – Tests for the assessment of surface cleanliness – Part 6: Extraction of soluble contaminants; Part 9: Field method for conductometric determination of water-soluble salts (Bresle method).

4. ISO 8503-1:2012 – Surface roughness characteristics of blast-cleaned steel substrates – Visual comparator method.
5. ISO 12944-5:2018 – Paints and varnishes – Corrosion protection of steel structures by protective paint systems – Part 5: Protective paint systems.
6. ISO 12944-9:2018 – Performance requirements for protective paint systems under mechanical stress.
7. ISO 19840:2004 – Paints and varnishes – Measurement of, and acceptance criteria for, the thickness of dry films.
8. ISO 11127-6:2011 – Preparation of steel substrates before application of paints – Specifications for metallic blast-cleaning abrasives – Part 6: Conductivity of aqueous extract.
9. SSPC-PA 2 – Procedure for Determining Conformance to Dry Coating Thickness Requirements.
10. SSPC-SP 2 / SP 3 – Hand Tool and Power Tool Cleaning Standards.
11. NACE SP0178-2007 – Design, Fabrication, and Surface Finish Practices for Tanks and Vessels to Be Lined for Immersion Service.
12. NORSOK M-501 – Surface preparation and protective coating for offshore structures.
13. IACS UR W11 Rev.4 – Hull structural steel scantlings for corrosion allowance and minimum thickness requirements.
14. IMO PSPC-WBT (MSC.215(82)) – Performance Standard for Protective Coatings for dedicated seawater ballast tanks in all types of ships and double-side skin spaces of bulk carriers.
15. TSCF Guidance Notes – Coatings and Surface Preparation for Ballast Tanks, Technical Sub-Committee on Coatings (TSCF), 2020 Edition.
16. DNV-CG-0288:2021 – Coating and Corrosion Protection of Ballast Tanks, Det Norske Veritas (DNV).
17. ABS Guidance Notes on Coating Performance (2017) – American Bureau of Shipping.
18. ASTM D610-19 – Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces.
19. Baysinger, D. (2015) – The Effect of Excessive DFT on Epoxy Coating Failure in Immersion Service. Journal of Protective Coatings & Linings (JPCL), Vol. 32, Issue 6.
20. Protective Coatings User Manual, Vol. 2 – SSPC (Society for Protective Coatings), 2019 Edition.
21. Coatings for Corrosion Protection: Offshore Oil and Gas Operation Facilities – NACE Publication No. 21427

