A REVIEW ON STRUCTURAL INTEGRITY OF WELDED JOINTS IN NAVAL SHIP SYSTEMS: FAILURE MECHANISMS AND PREDICTIVE MODELLING APPROACH

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Abstract
This review investigates the structural integrity of welded joints in naval ship systems, focusing on failure mechanisms and predictive modelling. Welded joints, vital to naval vessels, endure harsh conditions like cyclic loading, corrosive marine environments, and impact stresses, leading to failure modes such as fatigue cracking, hydrogen-induced cracking, corrosion-fatigue, and brittle fracture, often worsened by weld imperfections like porosity and residual stresses. Microstructural changes in the heat-affected zone further compromise durability. The study evaluates advanced predictive approaches, including finite element analysis, fracture mechanics, probabilistic models, and emerging machine learning and digital twin technologies for real-time assessment. Case studies of naval failures highlight the need for multi-scale modelling to improve reliability. Challenges in model validation, due to limited in-service data and multi-physics complexity, are discussed, with recommendations for standardized testing and hybrid modelling frameworks. This work underscores the importance of interdisciplinary advancements to enhance design, maintenance, and regulatory standards, ensuring safety, longevity, and cost-effectiveness in naval architectures.

Keywords
Welded Joints, Structural Integrity, Naval Systems, Failure Mechanisms, Predictive

1. INTRODUCTION

Welded joints are fundamental to the structural integrity, safety, and functionality of naval ship systems, serving as the primary method for connecting hull plates, bulkheads, and critical components such as propulsion and weapon systems (Corigliano and Crupi, 2022; Chen et al., 2024). These joints must withstand extreme operational stresses, including dynamic loads from waves, internal pressures, and shock impacts from combat scenarios (Xia et al., 2025). The failure of a single weld can compromise watertight integrity, leading to catastrophic consequences, such as flooding or structural collapse, underscoring the necessity of high-quality welding practices in naval architecture. Advanced welding techniques, including Tungsten Inert Gas (TIG) and Metal Inert Gas (MIG) welding, are employed to ensure leak-proof seams and corrosion-resistant connections, which are vital for maintaining the vessel's longevity and operational readiness in harsh marine environments (Tai et al., 2025). Additionally, welded joints contribute to weight reduction and streamlined hull designs, enhancing fuel efficiency and maneuverability, which are critical for naval operations. The adherence to international standards, such as those set by the American Bureau of Shipping (ABS) and Lloyd's Register, further highlights the importance of welding quality in ensuring the reliability and safety of naval vessels (Ghani et al., 2025).

Naval welded joints face relentless operational challenges in marine environments, including corrosion from saltwater, cyclic loading leading to fatigue, and biofouling from marine organisms. Corrosion is exacerbated by electrochemical reactions in saline water, particularly in crevices or stagnant areas, accelerating material degradation and necessitating corrosion-resistant materials like stainless steel or protective coatings (Ao et al., 2025). Fatigue arises from constant wave-induced stresses and operational loads, often initiating cracks at weld toes where stress concentrations are highest, while residual stresses from thermal cycling during welding can further reduce fatigue life. Biofouling—the accumulation of organisms like algae and barnacles—increases hydrodynamic drag and promotes corrosion, requiring antifouling measures that complicate maintenance (Sindi et al., 2024). Additionally, extreme pressures at depth and temperature fluctuations affect material properties, necessitating robust designs and pressure-tolerant components. Human-induced challenges, such as pollution and invasive species, indirectly impact welded structures by altering marine ecosystems and increasing corrosive agents in water. These multifaceted challenges demand continuous innovation in welding technologies and materials to ensure joint durability and structural reliability (Rodríguez et al., 2024).

This review comprehensively examines the failure mechanisms and predictive modelling approaches for welded joints in naval ship systems, aiming to bridge gaps between theoretical research and practical applications. The scope encompasses an analysis of common failure modes, such as corrosion-fatigue interactions, stress corrosion cracking, and brittle fracture, while also evaluating advanced predictive models, including multiscale simulations, finite element analysis (FEA), and artificial intelligence (AI)-driven tools for fatigue life prediction and defect detection (Magliano et al., 2024). The objectives are threefold: (1) to synthesize current knowledge on weld defect origins and progression, such as porosity, slag inclusions, and lamellar tearing, and their impact on structural integrity; (2) to assess the efficacy of emerging technologies, like real-time weld monitoring and robotic automation, in enhancing joint reliability and compliance with international standards; and (3) to identify future research directions, including the integration of AI for predictive maintenance and the development of corrosion-resistant alloys tailored for naval applications. By addressing these areas, this review aims to provide a foundational framework for improving the design, maintenance, and safety of welded joints in naval systems, ultimately contributing to the advancement of marine engineering practices.

2. FAILURE MECHANISMS IN WELDED JOINTS OF NAVAL SHIP SYSTEMS

Welded joints in naval ship systems are critical structural elements, and their failure can have catastrophic consequences. Understanding the mechanisms by which these joints fail is essential for both design and maintenance. The following mechanisms represent the primary ways welded joints can fail in this challenging application (Sindi et al., 2024).

2.1 Fatigue Cracking Under Cyclic Loading

Fatigue cracking is arguably the most prevalent failure mechanism in ship structures, particularly in areas subjected to the dynamic, constantly changing loads of the marine environment. These cyclic stresses, arising from wave action, engine vibration, and maneuvering, initiate microscopic cracks, often at stress concentrators like the weld toe or defects within the weld metal. Over time, each loading cycle causes the crack to propagate (Li and Brennan, 2024), initially slowly, but accelerating as the crack size increases, until the remaining cross-section can no longer bear the applied load, leading to sudden, final fracture. The S-N curve (stress versus number of cycles) is a primary tool used to predict the life of a welded component under a given stress range, though the effective stress range is heavily influenced by the joint's geometry and the severity of local weld defects (Kadayath et al., 2024). Figure 1 presents a typical failure mechanism in welded joint metal parts.

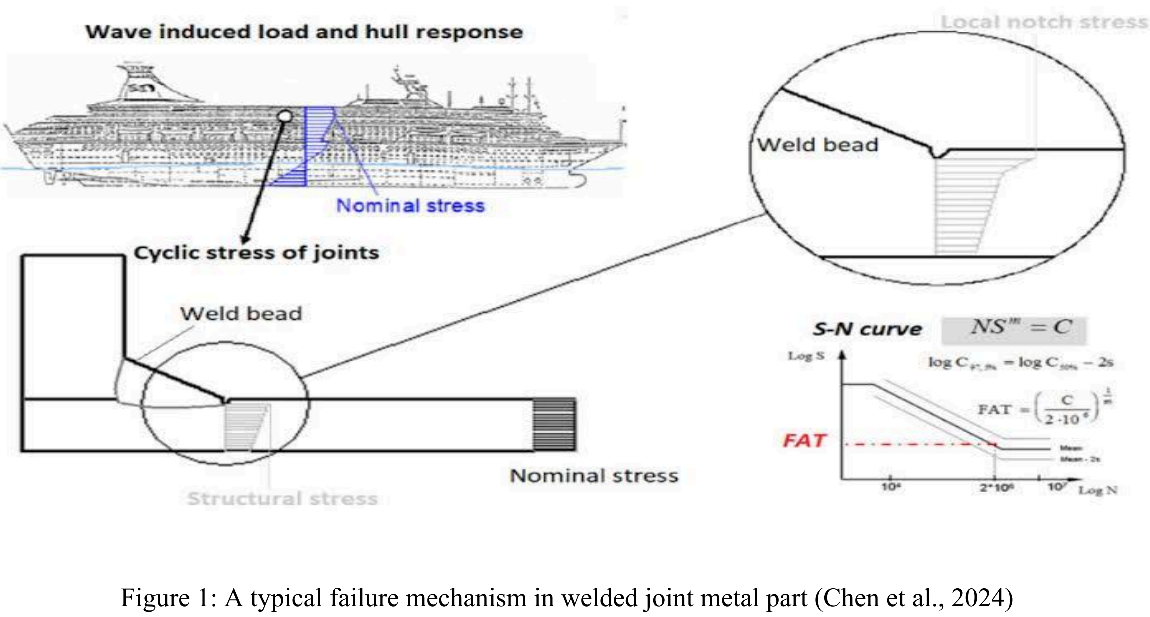

Figure 1: A typical failure mechanism in welded joint metal part (Chen et al., 2024)

2.2 Hydrogen-Induced Cracking

Hydrogen-induced cracking (HIC), also known as cold cracking, is a delayed failure mechanism that occurs after the weld has cooled, typically within a few hours or days. It is a complex process requiring three concurrent factors: a susceptible microstructure (often the hard, brittle martensite formed in the weld's heat-affected zone (HAZ)), sufficient tensile stress (residual or applied), and the presence of diffusible hydrogen (sourced from moisture in the electrode coating, rust, or the base metal). Atomic hydrogen diffuses into the susceptible, high-stress region, where it embrittles the steel, reducing its ductility and making it vulnerable to cracking along grain boundaries or through the material lattice (Okuma and Oreko, 2023; Oyewo et al., 2024). Proper preheating, low-hydrogen consumables, and post-weld heat treatment are used to mitigate this significant risk in high-strength steels.

2.3 Corrosion-Fatigue Interactions in Marine Environments

Corrosion-fatigue is an accelerated failure process specific to environments where cyclic mechanical stress and a corrosive medium act simultaneously, which is characteristic of naval ship hulls exposed to seawater. Seawater acts as a highly effective electrolyte, attacking the bare metal at the surface (Ling et al., 2023). Crucially, the corrosive action preferentially sharpens the tips of fatigue cracks as they form and propagate, acting like a chemical wedge that dramatically increases the stress intensity factor at the crack tip. This synergistic interaction means the life of the joint is significantly shorter than the life predicted by considering either corrosion damage or fatigue damage in isolation, demanding robust protective coatings and the use of corrosion-resistant alloys (Imran et al., 2023; Fakorede et al., 2025).

2.4 Brittle Fracture and Weld Imperfections

Brittle fracture is characterized by rapid crack propagation with little or no macroscopic plastic deformation, leading to catastrophic failure, often without warning. This mechanism is primarily governed by the material's fracture toughness, the service temperature (lower temperatures drastically reduce toughness), and the presence of significant stress concentrators or imperfections within the weld. Weld imperfections such as porosity (gas bubbles), slag inclusions (trapped non-metallic compounds), and sharp, geometric features like inadequate weld profile or undercuts, act as critical initial flaws. Furthermore, high residual stresses, locked into the joint during the rapid cooling of the welding process, add to the applied operational stresses, pushing the effective stress intensity at the flaw tip past the material's critical fracture toughness limit (Gbagba et al., 2023).

2.5 Role of Microstructural Changes in the Heat-Affected Zone

The Heat-Affected Zone (HAZ), the region of the base metal immediately adjacent to the weld metal, undergoes rapid heating and cooling cycles that profoundly alter its microstructure, often making it the weakest link in the joint. Depending on the base metal's composition and the welding process's cooling rate, the HAZ can develop detrimental phases such as hard, brittle martensite, coarse grain structures, or zones of softening (particularly in tempered or precipitation-hardened steels). These microstructural changes directly impact local mechanical properties, lowering the toughness (increasing susceptibility to HIC and brittle fracture) or reducing the yield strength, thereby concentrating strain and making the HAZ a preferential site for crack initiation under both static and cyclic loading (Bharti et al., 2023). Figure 2 presents the Welded Materials Workpiece.

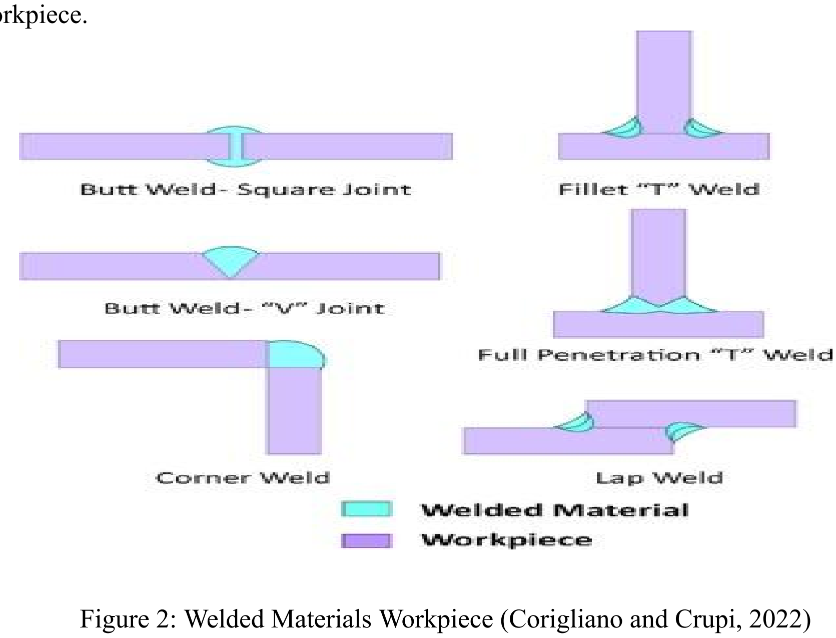

Figure 2: Welded Materials Workpiece (Corigliano and Crupi, 2022)

3. PROBABILISTIC MODELS FOR UNCERTAINTY IN MATERIAL PROPERTIES AND LOADING

3.1 Deterministic Methods: Finite Element Analysis and Fracture Mechanics

Deterministic methods such as finite element analysis (FEA) and fracture mechanics provide a robust framework for evaluating the structural integrity of welded joints in naval ship systems by simulating stress distributions, crack initiation, and propagation under controlled loading conditions without accounting for random uncertainties (Chandramohan et al., 2022). FEA is widely employed to model the complex geometry and residual stresses in welded joints, enabling detailed assessments of fatigue failure mechanisms; for instance, in analyzing box-shaped welded structures, linear elastic fracture mechanics (LEFM) integrated with FEA can predict fatigue strength by evaluating parameters like lack of weld penetration, load positioning, and plate thickness variations, often yielding results comparable to experimental data. Similarly, extended FEA techniques have been applied to investigate multiple defects in welded joints under uniaxial tensile loading, revealing that misalignment defects significantly reduce bearing capacity and structural integrity by considering interactions among defects rather than isolated ones (Yang, 2021). Fracture mechanics complements FEA by quantifying crack growth rates using stress intensity factors (SIFs) and J-integrals, as demonstrated in studies of overmatched welded joints where crack tip fields in the heat-affected zone (HAZ) influence fracture behavior based on material properties and surrounding region sizes. In naval applications, these methods are crucial for assessing ship structural connections, such as tee joints, where non-linear fracture mechanics evaluates short cracks in residual stress-bearing bodies, ensuring safe service life through path-independent J-integral calculations (Singh et al., 2021). Furthermore, deterministic approaches have been used to simulate cyclic plastic deformation and fatigue performance in pressure-bearing equipment, incorporating three-dimensional FEA to compute SIFs and predict propagation life in spot-welded junctions. Thus, integrating FEA with fracture mechanics allows for precise failure mode predictions in marine structures, including ultimate and fatigue limit states, by modelling temperature effects, post-fabrication treatments, and weld toe geometry. This synergy is particularly valuable for non-linear simulations of explosive welded joints in shipbuilding, correlating hardness measurements to mechanical properties and assessing intermetallic effects on joint quality (Allahveranov, 2021).

3.2 Probabilistic Models for Uncertainty in Material Properties and Loading

To address the significant uncertainties inherent in welded structures, probabilistic models are employed. These approaches treat key variables—such as material yield strength, fracture toughness, weld flaw size and location, and the magnitude of operational loads—not as single values but as statistical distributions (e.g., Weibull, normal, or log-normal). Techniques like Monte Carlo simulation or First-Order Reliability Methods (FORM) are then used to compute the probability of failure or reliability index for a welded component (Kadayath et al., 2024). This is particularly critical for naval systems, where the exact loading from slamming waves or the precise toughness of a weld HAZ is uncertain. Probabilistic fracture mechanics allows for a more rational and robust assessment of structural integrity, directly informing risk-based inspection schedules and maintenance planning to ensure operational safety despite inherent uncertainties (Kadayath et al., 2024).

3.3 Data-Driven Techniques: Machine Learning and Digital Twins

The increasing availability of inspection and structural health monitoring (SHM) data has spurred the use of data-driven techniques like machine learning (ML) and digital twins. ML algorithms, including artificial neural networks (ANNs) and random forests, can be trained on historical data to identify complex, non-linear patterns that predict failure, often surpassing the speed of traditional FEA. For instance, ANNs can correlate acoustic emission signals with specific crack growth stages in a welded detail (Okuma and Oreko,2023). A digital twin represents the most integrated approach: a high-fidelity virtual model of a specific ship structure that is continuously updated with real-time data from sensors (strain, temperature, acoustics) on the physical asset. This creates a dynamic, living model that can predict remaining useful life, simulate the effect of potential damage, and optimize maintenance actions in a proactive manner, revolutionizing the management of naval structural integrity.

3.4 Multi-Scale Modelling for Integrated Failure Prediction

Multi-scale modelling is a powerful framework that integrates simulations across different length scales—from the atomic microstructure to the full-scale ship structure—to capture failure mechanisms that originate at the micro-level but manifest macro-copically. For example, a simulation might couple a micro-scale model of grain growth and phase transformations in the weld HAZ with a meso-scale model of void nucleation and coalescence (a ductile fracture mechanism) and finally with a macro-scale FEA model of an entire welded panel under load (Ling et al., 2023). This approach is essential for accurately predicting phenomena like hydrogen-induced cold cracking or fatigue initiation at micro-defects, which are governed by microstructural properties. By bridging these scales, multi-scale modelling provides a more fundamental and physically rigorous understanding of failure, moving beyond empirical correlations to truly predictive science for naval welded joints (Imran et al., 2023).

4. CASE STUDIES AND PRACTICAL IMPLICATIONS OF WELDED JOINT INTEGRITY IN NAVAL SHIP SYSTEMS

Historical failures of naval and merchant vessels have profoundly shaped modern material science, design codes, and maintenance strategies. These incidents serve as critical, often catastrophic, case studies that highlight the real-world consequences of poor weld quality and inadequate structural analysis (Okuma and Oreko, 2023).

4.1 Analysis of Historical Naval Incidents Involving Welded Joint Failures

The most defining historical case studies are the brittle fractures of all-welded Liberty and T2 Tanker ships during and after World War II, many of which split in two suddenly in cold weather or while docked. Investigations revealed that the combination of three critical factors—high stress concentrations at design discontinuities (like square hatch corners), the presence of weld defects (such as crack-like flaws and severe residual stresses from all-welded construction), and the use of low-toughness steel (especially susceptible to brittle fracture at low temperatures)—resulted in catastrophic failure (Corigliano and Crupi, 2022). A more recent, though distinct, incident was the 2000 Kursk submarine disaster, where a faulty weld in a practice torpedo casing is believed to have failed, leaking High-Test Peroxide (HTP) which initiated a catastrophic internal explosion, illustrating that weld integrity is vital not just for hull strength but for internal system safety (Chandramohan et al., 2022).

4.2 Lessons Learned for Design and Maintenance Strategies

The lessons derived from historical failures have led to fundamental shifts in naval and marine engineering practices. In design, the emphasis moved from simple strength calculations to fracture mechanics principles, ensuring that designs can tolerate a critical size of flaw without catastrophic failure; sharp geometric details have been eliminated in favor of rounded corners to reduce stress concentrations (Chen et al., 2024). For maintenance, the industry adopted stringent requirements for non-destructive testing (NDT) of critical welds and incorporated advanced predictive modeling (like Probabilistic Fracture Mechanics) to schedule inspections based on calculated risk rather than fixed intervals. Furthermore, strict material specifications now mandate minimum Charpy V-notch toughness at operating temperatures to ensure ductility and prevent brittle fracture, and welding procedures strictly control hydrogen content and residual stresses to prevent cold cracking (Li and Brennan, 2024).

5.0 Challenges and Future Directions

5.1 Limitations in Model Validation and In-Service Data Availability

A significant challenge in predictive modeling for welded joints in naval ship systems is the scarcity of high-fidelity in-service data for model validation. While finite element analysis (FEM) and computational tools like SYSWELD enable detailed simulations of welding processes (e.g., residual stress and distortion predictions), these models often rely on laboratory-scale experimental data for calibration (Chen et al., 2024). However, operational conditions—such as cyclic loading, corrosive marine environments, and variable thermal stresses—are difficult to replicate in controlled settings. For instance, structural life assessment for naval vessels must account for fatigue, corrosion, and sudden collisions, yet in-service data on crack propagation in welded joints under these conditions are rarely available due to operational confidentiality and measurement difficulties. This gap limits the accuracy of lifetime predictions and failure assessments. Future efforts must prioritize collaborative data-sharing initiatives between naval agencies and research institutions, alongside embedded sensor technologies in ship structures to collect real-time performance data (Singh et al., 2021).

5.2 Complexity of Multi-Physics Simulations

The integration of multi-physics phenomena—thermal, metallurgical, mechanical, and environmental factors—in welding simulations presents substantial computational and methodological challenges. For example, thermo-elastic-plastic (TEP) models require capturing transient heat sources, phase transformations, and residual stresses, which are computationally intensive for large-scale structures like ship hulls Yang, 2021). Advanced software tools like SYSWELD and ABAQUS can simulate coupled processes, but they demand precise input parameters (e.g., heat source geometry, material properties at high temperatures) that are often uncertain or variable. Additionally, simulating non-proportional hardening effects under multiaxial loading, as observed in the heat-affected zone (HAZ) of welded steel joints, requires sophisticated constitutive models (e.g., Armstrong-Frederick kinematic hardening rules) that are difficult to calibrate. Future directions should focus on developing reduced-order models and leveraging artificial intelligence (AI) to optimize parameters, as seen in fuzzy finite element models (fFEM) that use genetic algorithms to predict welding distortions efficiently (Chen et al., 2024).

5.3 Recommendations for Standardized Testing Protocols

Standardized testing protocols are critical for ensuring the reliability and comparability of data used in predictive models. Current destructive testing methods—such as tensile tests, Charpy V-notch impact tests, and metallographic examinations—provide valuable insights into mechanical properties and defect detection (Chen et al., 2024). However, inconsistencies in specimen preparation, loading conditions, and evaluation criteria across studies hinder the development of universal models. For instance, bend tests for weld ductility use varying width-to-thickness ratios, making results non-comparable without strict standardization. Similarly, corrosion testing procedures for marine environments must simulate specific conditions (e.g., seawater exposure, cyclic loading) to yield actionable data. To address this, future protocols should align with international standards (e.g., ASTM, IIW) and incorporate multimodal approaches that combine destructive tests (e.g., fracture toughness tests) with non-destructive techniques (e.g., ultrasonic evaluation). This would enhance data consistency for model calibration and validation (Bharti et al., 2023).

5.4 Development of Hybrid Modeling Frameworks

Hybrid modeling frameworks, which integrate physics-based simulations with data-driven approaches, represent a promising future direction for improving predictive accuracy. Traditional physics-based models (e.g., TEP-FEM) are limited by computational cost and empirical assumptions, while purely data-driven models (e.g., AI) require extensive datasets that are often unavailable (Ling et al., 2023). Hybrid frameworks, such as fuzzy finite element models (fFEM) combined with genetic algorithms, can bridge this gap by using limited experimental data to optimize inherent strain parameters in welding simulations. Similarly, machine learning algorithms can predict crack growth in welded joints by incorporating in-service loading conditions and material heterogeneity (imran et al., 2023). For naval applications, these frameworks must also account for environmental factors like corrosion and hydrogen embrittlement, which are critical for structural integrity. Future research should prioritize hybrid models that leverage real-time sensor data and probabilistic methods to address uncertainties in material behaviour and loading conditions (Okuma and Oreko, 2023).

6.0 Conclusions

The assessment of structural integrity in naval ship welded joints demands a multi-faceted and integrated approach, moving beyond simple deterministic design to embrace advanced predictive modeling. Failure is inherently complex, driven primarily by fatigue crack growth initiating at stress concentration points, magnified by residual stresses from welding and environmental factors like corrosion-fatigue. Modern integrity management must integrate Deterministic methods, such as high-fidelity Finite Element Analysis and Fracture Mechanics, with Probabilistic models like Monte Carlo simulation to quantify uncertainty in material properties and dynamic ocean loading. The future lies in Hybrid Modelling Frameworks and Digital Twins, which fuse physics-based models with real-time in-service data assimilated via Machine Learning, allowing for the precise, risk-informed prediction of Remaining Useful Life, addressing historical lessons learned from brittle fracture incidents, and ensuring the continued operational readiness and safety of critical naval assets.

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