Review

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Mechanism-Based Degradation and Structural Integrity of Marine Renewable Energy Systems: Multiscale Modelling, Materials Challenges, and Future Qualification Frameworks

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Abstract

Marine renewable energy systems, including offshore wind, tidal, and wave technologies, are central to global net-zero strategies but remain constrained by reliability-driven costs and uncertainty in structural performance. In harsh offshore environments, interacting degradation mechanisms (such as corrosion–fatigue, hydrogen embrittlement, variable-amplitude loading, wear, and manufacturing-induced variability) govern failure, yet are not adequately captured by existing empirical design frameworks. This review presents a comprehensive, mechanism-based perspective on structural integrity in marine renewable energy systems, explicitly linking microstructure-sensitive deformation and damage processes to engineering-scale performance and reliability. The materials landscape, including structural steels, titanium alloys, fibre-reinforced composites, and additively manufactured materials, is critically examined with emphasis on process–structure–property–performance relationships. Multiscale modelling approaches are synthesised, spanning crystal plasticity finite element modelling, mesoscale damage formulations, fracture mechanics, structural reliability methods, and emerging digital twin and data-driven frameworks. A key contribution of this work is the integration of microstructure-resolved modelling with system-level reliability and qualification, addressing a critical gap between materials physics and engineering design standards. The review identifies critical limitations in current practices, including the lack of explicit treatment of coupled degradation mechanisms, insufficient representation of manufacturing variability, and the absence of consistent uncertainty propagation across scales. Building on these insights, an integrated, mechanism-resolved framework is proposed that combines multiscale modelling, manufacturing-aware qualification, inspection-informed updating, and hybrid physics–data approaches. This framework supports a transition from static, empirical design towards predictive, lifecycle-based structural integrity assessment, enabling improved reliability, reduced uncertainty, and more cost-effective deployment of next-generation marine renewable energy systems.

Keywords: offshore wind; marine renewable energy; structural integrity; multiscale modelling; crystal plasticity; corrosion-fatigue; hydrogen embrittlement; digital twin; manufacturing variability; qualification frameworks

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1. Introduction

Despite significant advances in materials, design methodologies, and numerical modelling, reliability remains the principal barrier to large-scale deployment of marine renewable energy systems. Existing approaches to structural integrity and lifetime prediction are predominantly based on empirical design rules, simplified fatigue formulations, and loosely coupled modelling frameworks. While these methods have enabled initial deployment, they often fail to capture the underlying physical mechanisms governing degradation in aggressive offshore environments, particularly when multiple damage processes, such as corrosion-fatigue interaction, hydrogen assisted cracking, and microstructure-sensitive deformation, act concurrently.

A number of review studies have addressed individual aspects of this challenge, including material selection, corrosion mechanisms, fatigue behaviour, and numerical modelling techniques [1–6]. However, these contributions are typically fragmented, focusing either on specific material classes or isolated degradation mechanisms, and rarely provide an integrated perspective linking material behaviour, multiscale modelling, and structural qualification. There remains a lack of frameworks that connect microstructural damage evolution to engineering-scale design and certification procedures in a physically consistent manner. This limitation becomes particularly critical in marine renewable systems where interacting degradation mechanisms govern failure.

1.1. Global Expansion of Marine Renewable Energy

Global offshore wind is expanding rapidly as countries accelerate decarbonisation efforts and pursue net-zero emissions targets. Recent statistics indicate that installed offshore wind capacity is now on the order of 80–85 GW worldwide, reflecting strong year-on-year growth from a comparatively small base. Looking ahead, the International Renewable Energy Agency, together with the Global Offshore Wind Alliance, projects that offshore wind will need to scale to roughly 2,000 GW by 2050 in 1.5 °C-aligned pathways, implying an order-of-magnitude increase over coming decades [7–9]. Although offshore wind still accounts for a relatively modest share of total renewable capacity additions compared with onshore wind and solar photovoltaics, its role in future power systems is expected to grow substantially, driven by high resource quality and proximity to coastal load centres. Deployment to date has been dominated by China, European countries, and the United States, which together account for the majority of existing offshore installations and near-term project pipelines.

Fixed-bottom offshore wind turbines dominate current deployments in shallow waters, primarily utilizing monopile and jacket substructures [10,11]. However, floating offshore wind technology is emerging as a transformative solution for accessing deeper waters where 80% of global offshore wind resources are located [10–12] (Figure 1). Floating platforms—including spar-buoy, semi-submersible, and tension leg platform (TLP) configurations—enable deployment in regions with steep continental shelves, such as offshore Japan, the U.S. West Coast, and the Mediterranean [12–14].

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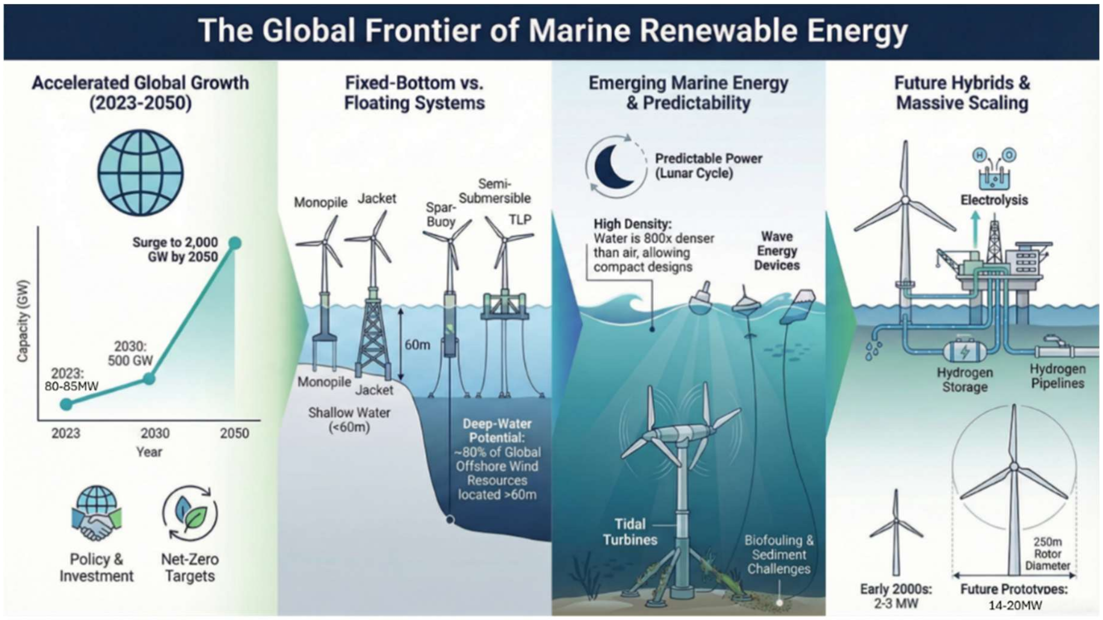

Figure 1. Overview of the global frontier of marine renewable energy, illustrating (i) the rapid growth trajectory of offshore wind capacity from ~80 GW today towards ~2,000 GW by 2050, (ii) comparison of fixed-bottom and floating offshore wind systems across water depths, (iii) emerging marine energy technologies including tidal and wave energy with predictable power characteristics, and (iv) future hybrid energy systems integrating offshore wind with hydrogen production, storage, and transport infrastructure, enabling large-scale decarbonized energy systems.

Beyond wind energy, tidal and wave energy systems represent emerging marine renewable technologies. The tidal energy sector benefits from highly predictable power generation due to gravitational forcing by the moon and sun, with water density approximately hundreds of times greater than air enabling compact turbine designs [15]. The International Energy Agency (IEA) Ocean Energy Systems estimates 300 GW of combined wave and tidal capacity could be developed by 2050, creating 680,000 jobs and $42 billion in economic value [16]. Recent market studies value the global wave and tidal sector at approximately USD 0.6–2 billion today, with forecast compound annual growth rates typically ranging from about 9% up to >15% over the next decade [17,18].

Hybrid marine energy systems integrating offshore wind with hydrogen production represent a frontier for renewable energy (Figure 1). Direct offshore hydrogen generation via electrolysis offers advantages including reduced transmission losses, grid flexibility, and energy storage capabilities [19]. Projects such as Germany's H2Mare initiative and various North Sea developments aim to establish integrated offshore wind-to-hydrogen value chains [20]. These hybrid systems, however, introduce additional structural and material challenges due to chemical process equipment integration and harsh subsea environments.

The expanding scale and complexity of marine renewable installations impose increasingly severe structural and operational demands. Over the past two decades, offshore wind turbines have evolved from early multi-MW designs to large prototypes exceeding 15 MW in capacity, accompanied by substantial increases in rotor diameter and support-structure size [21]. Floating platforms must withstand combined aerodynamic-hydrodynamic loading, and extreme environmental conditions including 50-year storm events. Tidal turbines operate in high-velocity currents with biofouling, sediment abrasion, and seawater corrosivity continuously degrading structural components [22,23]. This rapid scale-up amplifies structural integrity challenges, as larger systems operating further offshore in harsher environments are increasingly sensitive to degradation-driven failures.

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1.2. Reliability as the Primary Barrier to Cost Reduction

Despite technological advances, reliability remains the dominant economic barrier to widespread marine renewable energy deployment. Operations and maintenance (O&M) account for a substantially larger share of lifetime costs in offshore wind than in onshore projects, with offshore O&M typically contributing on the order of 20–30% of levelised cost of energy compared with single-digit percentages for onshore wind [24,25]. For a representative 1 GW floating offshore wind farm, indicative annual O&M costs are about £98 million, including insurance and other owner costs. Detailed cost breakdowns show that marine logistics and vessel operations dominate many offshore O&M activities, particularly for remote sites, and that annual operational expenditures of order 80,000 £/MW are typical for large fixed-bottom projects, increasing with distance from shore and water depth [26–28] (see Figure 2). This rapid build-out and movement into more challenging sites amplifies structural integrity and access challenges, as larger systems operating further offshore in harsher environments are increasingly sensitive to degradation-driven failures.

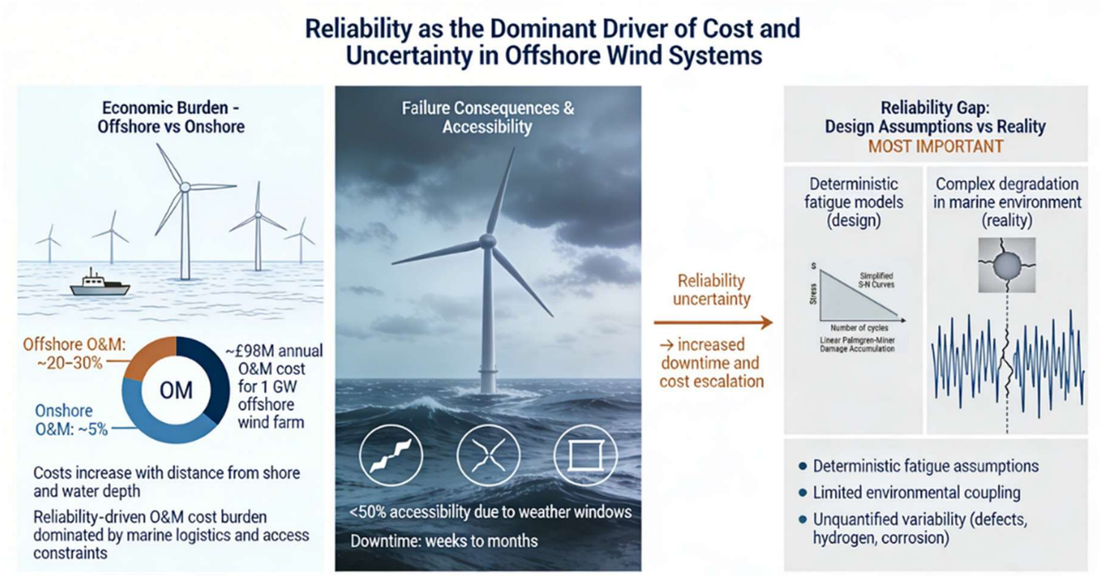

Figure 2. Reliability-driven challenges in offshore wind systems. Offshore O&M costs are significantly higher than onshore due to limited accessibility and harsh environmental conditions, leading to extended downtime. Current deterministic design approaches do not fully capture complex degradation mechanisms, including corrosion–fatigue, hydrogen effects, and manufacturing variability. This results in unquantified reliability margins, contributing to increased costs and uncertainty in lifecycle performance.

Failure consequences in offshore environments are substantially more severe than onshore equivalents. Accessibility limitations due to weather windows mean unscheduled downtime can extend weeks or even months [29]. Major component failures, such as gearbox, generator, blade structural damage, or foundation cracking, often require specialised heavy-lift vessels and complex offshore operations [30]. For floating systems, station-keeping failures involving mooring line or anchor damage can result in complete platform loss and the need for full turbine replacement [31].

Current deterministic design approaches, primarily based on empirical S-N fatigue curves and linear damage accumulation (Palmgren-Miner rule), demonstrate significant limitations when applied to marine renewable structures [32,33]. These methods, largely adapted from offshore oil and gas standards (e.g., DNV-RP-C203, API RP 2A), do not adequately capture:

1. Corrosion-fatigue synergistic effects*:* Marine environments accelerate fatigue crack growth rates by 2-10× compared to laboratory air conditions due to electrochemical interactions at crack tips [34,35]. Standard S-N curves with simple environmental reduction factors fail to represent the time-dependent corrosion mechanisms.

2. Hydrogen embrittlement from cathodic protection*:* Cathodic protection systems, essential for corrosion mitigation, generate hydrogen at steel surfaces. High-strength steels (>900 MPa yield strength) used in advanced designs are susceptible to hydrogen-assisted cracking, yet qualification procedures inadequately assess this degradation mode [36,37].

3. Spectrum loading and sequence effects*:* Offshore structures experience variable amplitude loading from wind gusts, wave spectra, and turbine operation with complex cycle counting and load sequence effects that violate Palmgren-Miner linear damage assumptions [38].

4. Manufacturing variability*:* Welded joint quality, residual stress distributions, and geometric imperfections vary significantly between fabrication facilities and even within single structures, introducing scatter factors of 3-5× in fatigue life predictions (see [39] and references therein).

Collectively, these limitations highlight that current qualification approaches remain fundamentally empirical and insufficiently linked to the underlying physical mechanisms governing damage evolution. Recent offshore wind failures underscore these limitations. The Hywind Scotland floating wind farm has required a heavy offshore maintenance campaign, including towing turbines to port for major component exchange in 2023–2024 [40]. Earlier generations of German North Sea monopile foundations experienced grouted connection performance issues that necessitated extensive retrofit programmes, highlighting the sensitivity of welded and grouted details to fatigue and installation assumptions. [41]. These incidents, while not catastrophic, demonstrate that current qualification approaches leave substantial reliability margins unquantified.

1.3. Need for Mechanism-Resolved Structural Integrity Assessment

Despite advances in modelling techniques, integration of these scales into engineering design remains limited. Addressing the reliability-cost challenge requires a fundamental shift from empirical, component-level qualification to mechanism-resolved, physics-based structural integrity assessment. This paradigm recognizes that understanding degradation requires linking environmental loading → material microstructure behaviour → structural system reliability across multiple length and time scales (Figure 3).

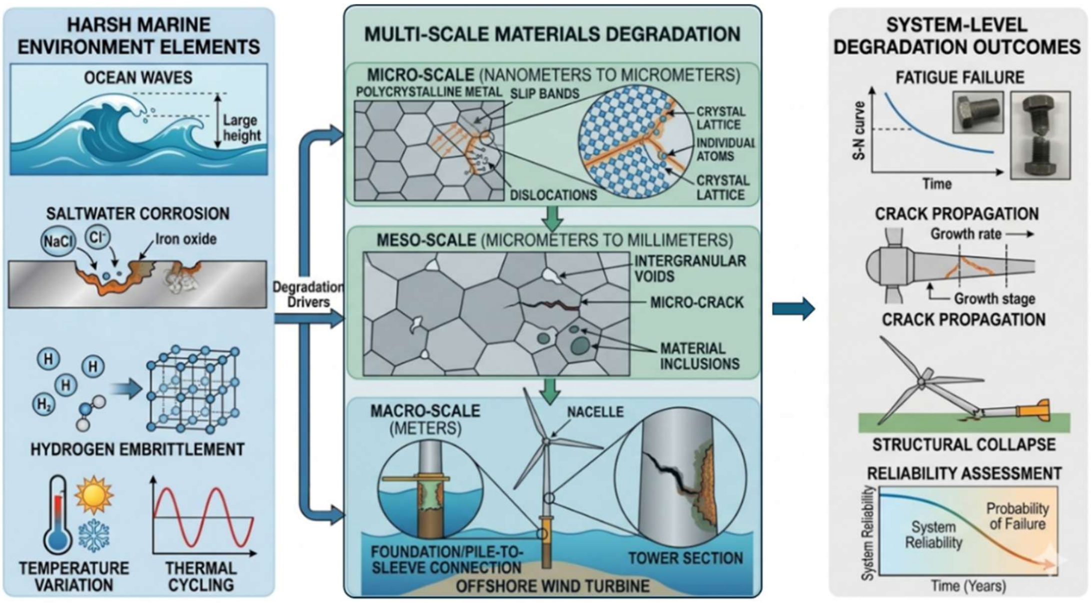

Figure 3. Schematic representation of multiscale degradation in marine renewable energy structures, linking harsh marine environmental drivers (wave loading, saltwater corrosion, hydrogen embrittlement, and thermal cycling) to material response across length scales, from micro-scale dislocation activity and slip localisation, through mesoscale void formation and microcrack development, to macro-scale structural components of offshore wind systems. These interacting mechanisms collectively lead to system-level degradation outcomes,

including fatigue failure, crack propagation, and potential structural collapse, ultimately governing reliability, and lifetime performance.

At the microstructural scale (1-100 μm), damage initiation in metallic structures is governed by such as crystallographic slip localisation in favourably oriented grains, incompatibilities at grain and phase boundaries that create local stress concentrations, void nucleation at second-phase particles and inclusions, and hydrogen trapping at microstructural features that can lower crack nucleation thresholds. These processes are sensitive to processing history, heat treatment, and local chemistry, as illustrated by crystal plasticity and fatigue studies on steels and advanced titanium alloys [42,43].

At the mesoscale (0.1-10 mm), crack propagation behaviour transitions from microstructurally controlled short-crack growth to long-crack regimes where continuum fracture mechanics become applicable, a scale transition that cannot be captured by macroscopic S-N curves alone [44]. Cohesive zone formulations, phase field approaches, and extended finite element methods (XFEM) provide powerful tools to model crack nucleation and propagation across this transition when calibrated to underlying microstructural mechanisms [45,46].

At the structural scale (1-100 m), system-level reliability assessment must account for load redistribution following local damage, redundancy in jacket and semi-submersible structures, and progressive degradation of multiple components, issues that are increasingly treated using probabilistic and Bayesian methods for offshore structures. Traditional component-level safety factors can therefore be over-conservative for highly redundant systems or unconservative for non-redundant, critical details [47].

Importantly, mechanism-based, and multiscale approaches enable predictive capability for new materials, geometries, and loading conditions beyond existing empirical databases. As marine renewable energy systems adopt titanium alloys (Ti-5553, Ti-6Al-4V) for high-performance applications, high-strength structural steels (e.g. S420-S460, and emerging use of S690, and S960 grades) for weight reduction, and additive manufacturing for complex geometries, qualification cannot rely solely on historical test data [48–54]. Physics-based models calibrated to fundamental deformation and damage mechanisms provide the necessary predictive confidence. These multiscale interactions underscore the need for integrated frameworks that can translate mechanism-level understanding into engineering-scale qualification procedures.

1.4. Scope and Contributions of This Review

This review provides a comprehensive synthesis of mechanism-based structural integrity assessment for marine renewable energy systems, with particular emphasis on integrating microstructural degradation physics with engineering-scale reliability prediction. The novelty and contributions of this work include:

1. Integration of microstructure-scale degradation physics: Unlike previous reviews focused on macroscopic fatigue or corrosion, this work explicitly links crystal-level deformation mechanisms (slip, twinning, phase transformation) to crack initiation and propagation in marine environments. Attention is given to dual-phase alloys (titanium α/β systems, steel ferrite/martensite) where phase interaction governs damage evolution.

2. Multiscale modelling approaches: A critical assessment of computational methodologies spanning crystal plasticity finite element modelling (CPFEM), cohesive zone models, phase field damage mechanics, and digital twin frameworks. Emphasis is placed on hierarchical information flow from microstructure to component to system scales, and model validation requirements.

3. Manufacturing and material variability: Recognition that as-manufactured material state—residual stress, microstructural gradients, defect populations—often dominates service life variability. Welding, additive manufacturing, and surface treatment effects are examined as critical qualification challenges.

4. Framework for future qualification methodologies: Synthesis of emerging approaches combining in-service monitoring, Bayesian reliability updating, and adaptive inspection strategies

into an integrated mechanism-resolved qualification framework aligned with Industry 4.0 and digital engineering paradigms.

The review is structured to guide readers from fundamental degradation mechanisms (Sections 2-4) through modelling methodologies (Section 5) to practical implementation considerations (Sections 6-8), culminating in a proposed future qualification framework (Section 9). Throughout, we emphasize the specific challenges of marine renewable energy systems, long design lives (25-30 years), harsh cyclic environments, limited accessibility, and cost-driven design optimization, which distinguish these structures from other offshore applications. By consolidating current understanding and identifying key limitations in existing approaches, this review aims to support the development of more reliable and physically informed design and qualification strategies for next-generation marine renewable energy systems.

2. Marine Renewable Energy Systems and Structural Components

2.1. Offshore Wind Energy Structures

Offshore wind energy systems comprise multiple structural subsystems, each subjected to distinct loading regimes and degradation environments. Fixed-bottom turbines currently dominate European offshore wind deployments, with monopile designs widely used for shallow to intermediate water depths [55]. The transition piece and adjacent regions, including the mudline and splash zone, are recognised as fatigue-critical areas due to combined mechanical loading and corrosive exposure [56].

Jacket structures, adapted from offshore oil and gas platforms, provide increased stiffness for deeper waters and larger turbines and consist of welded tubular members connected at complex nodal joints [39]. Fatigue assessment focuses on chord-brace intersections where geometric stress concentrations lead to increased hotspot stresses relative to nominal levels [57]. Multi-axial stress states and weld toe geometry variability complicate fatigue life prediction.

Floating wind platforms enable deployment in deeper waters and are realised as semi-submersible, spar-buoy, or tension-leg concepts [29], each with characteristic fatigue-critical regions such as brace connections and mooring interfaces [13]. Dynamic export and inter-array cables connecting floating or fixed platforms to shore-based infrastructure are emerging integrity hot-spots, with armour-wire fatigue, polymer degradation and water ingress identified as key concerns for long-term operation [58].

Turbine towers and blades, while not the primary focus of this structural integrity review, merit mention for completeness. Towers, typically fabricated from rolled steel plate with longitudinal and circumferential welds, experience fatigue from turbine start-stop cycles, yaw manoeuvres, and vortex-induced vibration during shutdown periods [59]. Blades, constructed from glass and carbon fibre-reinforced polymer composites, degrade via matrix cracking, fibre-matrix debonding, delamination, and leading-edge erosion. These composite failure mechanisms differ fundamentally from metallic structural failures but share common themes of multi-scale damage accumulation [60,61]. These structural configurations introduce diverse fatigue-critical regions and degradation environments, highlighting that structural integrity in offshore wind systems is inherently location-dependent. The interaction between geometry-induced stress concentrations, environmental exposure (e.g., splash zone corrosion), and loading complexity underscores the limitations of uniform design approaches and motivates mechanism-resolved assessment strategies.

2.2. Wave and Tidal Energy Devices

Wave and tidal energy technologies represent diverse device concepts, each with specific structural integrity requirements. Oscillating water column (OWC) systems employ a partially submerged chamber where wave action drives air through a turbine. Structural components include the concrete or steel chamber walls subjected to wave impact loads (pressures up to 500 kPa), air turbine housings experiencing high-frequency cyclic stresses, and mooring systems for floating OWC variants [62]. The combination of wave impact fatigue and marine corrosion in the splash zone creates severe degradation conditions.

Tidal energy converters operate in energetic tidal currents and are often described as "underwater wind turbines," typically using horizontal-axis rotor configurations analogous to conventional wind turbines [16]. Structural elements such as rotors, support structures and foundations are subjected to cyclic hydrodynamic loading and to continuous seawater exposure, including biofouling and corrosion processes that affect efficiency and durability [20]

Because these devices operate fully submerged and commonly use metallic components protected by cathodic systems, hydrogen-related degradation mechanisms identified in offshore applications, such as hydrogen embrittlement in high-strength alloys, are a relevant concern for material selection and qualification strategies [63]. Compared to offshore wind systems, the continuous submersion and higher fluid density in tidal and wave environments introduce distinct degradation pathways, particularly in relation to corrosion-fatigue interaction, cavitation erosion, and biofouling, necessitating tailored integrity assessment approaches.

2.3. Hybrid Marine Energy Systems

Hybrid offshore wind-to-hydrogen systems integrate renewable power generation with electrolysis, compression, and storage infrastructure. The H2Mare project (Germany) and similar initiatives aim to produce green hydrogen directly offshore, reducing transmission losses and enabling long-term energy storage [19,64]. Structural integrity challenges unique to hybrid systems include:

- Electrolyser platforms supporting electrolysis capacity, with process equipment weights on semi-submersible or barge-type floaters
- Hydrogen storage systems either as pressurized gas in steel or composite pressure vessels, or liquid hydrogen in cryogenic tanks, both imposing extreme material requirements
- Subsea hydrogen pipelines transporting compressed hydrogen to shore, facing hydrogen permeation through steel walls, embrittlement of pipeline and weld materials, and fatigue from flow-induced vibration [65]
- Offshore substations converting variable wind power to stable voltage and frequency for electrolysis, with transformer and switchgear structures requiring seismic and fatigue qualification

The intersection of marine structural engineering with chemical process safety represents new qualification territory, requiring integration of pressure vessel codes (ASME Section VIII, EN 13445) with offshore structural standards (API, ISO, DNV). The integration of marine structures with hydrogen processing systems introduces coupled mechanical–chemical degradation mechanisms that are not adequately addressed by existing offshore or pressure vessel standards alone, reinforcing the need for unified, mechanism-consistent qualification frameworks.

2.4. Structural Loading Environments

Marine renewable energy structures experience complex multi-axial loading from simultaneous environmental and operational sources. These loading conditions form the primary drivers of degradation mechanisms discussed in subsequent sections. Cyclic wave loading dominates fatigue damage accumulation. Ocean waves impose periodic forces and moments on submerged and surface-piercing structures at frequencies 0.05-0.3 Hz (wave periods 3-20 seconds) [26]. Spectral fatigue analysis must account for Jonswap or Pierson–Moskowitz wave spectra representing distribution of wave energy across frequencies, directionality with waves approaching from multiple headings over a structure's lifetime, and long-term statistics combining operational sea states with extreme events [25]. For a typical North Sea offshore wind site, fatigue analysis considers 100+ sea-state bins, each contributing damage according to occurrence probability and resulting stress-range distribution [32]. The dominant loading conditions and associated failure modes for key marine renewable subsystems are summarised in Table 1.

Combined aerodynamic–hydrodynamic loading couples wind forces on turbine and tower with wave/current forces on the substructure. For floating systems, this coupling generates complex multi-frequency response: rotor frequencies (P, 3P, 6P harmonics at 0.1–0.5 Hz), platform natural frequencies (surge/sway: 0.01–0.03 Hz, heave: 0.04–0.08 Hz, pitch/roll: 0.02–0.05 Hz), and wave excitation frequencies (0.05–0.3 Hz). Resonance between excitation and structural natural frequencies amplifies response and accelerates fatigue damage. Control systems (blade pitch, generator torque) interact with structural dynamics, potentially mitigating or exacerbating fatigue loads depending on tuning [66].

Thermal gradients arise from daily and seasonal temperature variations, solar heating of splash zone regions, and process heat in hybrid systems. While marine environments exhibit modest temperature swings (0-25°C annually), thermal cycling contributes to stress range in constrained components and affects corrosion rates. For electrolysis platforms, process temperatures (60-90°C for PEM/alkaline electrolysers) introduce thermal expansion mismatches between process equipment and structural steel [58].

Corrosive environments in marine settings involve multiple simultaneous mechanisms: chloride-induced pitting initiating localized corrosion at defects in passive films, crevice corrosion in occluded geometries (flange gaps, weld overlaps) where oxygen depletion creates aggressive chemistry, galvanic corrosion at dissimilar metal junctions (steel–aluminium, steel–copper), and microbiologically influenced corrosion (MIC) from biofilm formation in subsea regions [22]. The splash zone (±5 m around mean water level) experiences the most aggressive corrosion due to continuous wet–dry cycling, high dissolved-oxygen availability, and maximum UV exposure. Corrosion rates in this zone can reach 0.3–0.8 mm/year for unprotected carbon steel, compared to 0.05–0.15 mm/year for fully submerged regions with cathodic protection [38].

Sediment and abrasion effects predominantly affect tidal turbines and monopile foundations in sandy seabeds. Suspended sediment particles (sand, silt) impacting structural surfaces at velocities 1-5 m/s cause erosion-corrosion, removing protective coatings and accelerating material loss. Leading edges of tidal turbine blades can experience erosion rates 0.5-2 mm/year in sediment-laden flows [60]. Foundation scour—removal of seabed sediment around structures—alters support conditions and increases structural loading, indirectly affecting fatigue life [67]. These complex, multi-axial, and multi-scale loading conditions do not act independently but interact to drive coupled degradation processes such as corrosion-fatigue, hydrogen-assisted cracking, and fretting fatigue. Consequently, structural integrity assessment must move beyond isolated loading scenarios toward integrated, mechanism-based approaches.

Table 1. Dominant loading and failure modes across marine renewable energy subsystems.

System	Key Components	Dominant Loads	Critical Failure Modes
Offshore wind	Monopile, jacket	Wave + wind	Fatigue, corrosion
Floating	Moorings, cables	Multi-frequency	Fatigue, fretting
Tidal	Blades, drivetrain	Hydrodynamic	Cavitation, erosion
Hybrid	Pipelines, vessels	Mechanical + chemical	Hydrogen embrittlement

3. Materials Landscape in Marine Renewable Energy Systems

3.1. Structural Steels

Structural steels remain the dominant material class for marine renewable energy substructures due to established manufacturing infrastructure, weldability, and cost-effectiveness. However, the marine environment and cyclic loading impose specific material challenges.

Fatigue and corrosion sensitivity: Carbon-manganese steels and low-alloy steels traditionally used in offshore structures exhibit significant fatigue strength degradation in seawater environments. DNV-RP-C203 reflects this effect by using more onerous S-N curves for seawater with cathodic protection (e.g. W-series curves) compared with in-air classifications, indicating substantially reduced fatigue strength at high cycles [57]. Experimental studies also show a marked reduction in fatigue crack growth thresholds in seawater compared with air, promoting crack propagation from smaller initial defects [68].

High-strength steels (S690, S960) offer potential for weight and cost reduction in next-generation designs. These steels achieve substantially higher yield strengths than conventional offshore grades, typically through quenching and tempering or thermomechanical processing. However, high strength correlates with increased hydrogen embrittlement susceptibility, particularly under cathodic protection where hydrogen generation rates are elevated [69]. Existing offshore standards (DNV, API) limit design strength to reduce brittleness risk, potentially negating weight savings.

Welded joint behaviour: Welded connections represent critical fatigue locations due to geometric stress concentrations, residual stresses, and microstructural gradients. Arc welding processes (SMAW, FCAW, GMAW) introduce heat-affected zones (HAZ) with altered microstructure (grain growth, phase transformations) extending from fusion line. Residual tensile stresses approaching yield strength magnitude near weld toes, reducing effective fatigue threshold. Weld toe geometry characterised by toe radius and angle, producing higher stress concentration factors [41].

Post-weld improvement techniques including grinding, hammer peening, and high-frequency mechanical impact (HFMI) can shift fatigue classification by introducing compressive residual stresses and smoothing weld toe geometry [41]. However, the effectiveness of these treatments is reduced in corrosive seawater environments, and long-term optimisation of corrosion-fatigue life remains an active research topic [56].

Microstructural heterogeneity: Modern high-strength low-alloy (HSLA) steels used in offshore structures are produced via controlled thermomechanical processing to develop microstructures that balance strength and toughness. Typical weld and HAZ microstructures include bainitic–ferritic mixtures, granular bainite with martensite–austenite (MA) constituents, and acicular ferrite in multi-pass welds, all of which influence fatigue and fracture behaviour [39].

This microstructural complexity introduces spatial variability in mechanical properties across welded joints, and locally hardened regions in the heat-affected zone are particularly susceptible to hydrogen-assisted cracking during fabrication and service [37]. Despite their widespread use, structural steels exhibit significant vulnerability to corrosion-fatigue interaction and hydrogen-assisted degradation, particularly in welded regions, making them a primary focus for improved mechanism-based integrity assessment.

3.2. Titanium and Advanced Alloys

Titanium alloys present attractive properties for marine applications, high specific strength (strength-to-weight ratio), excellent corrosion resistance in seawater, and fatigue performance competitive with steel in corrosive environments. However, high material and fabrication costs (5-10× steel equivalent) restrict applications to critical, high-performance components. High strength-to-weight advantages: Ti-6Al-4V (Ti64), the most widely used titanium alloy, provides tensile strength 900-1000 MPa at density 4.43 g/cm^3, compared to S355 steel with 550 MPa strength at 7.85 g/cm^3. For floating platforms where weight penalty impacts stability and mooring loads, this 40% density reduction enables significant system-level benefits. Ti-5Al-5Mo-5V-3Cr (Ti-5553), a near-β titanium alloy, achieves 1200-1400 MPa strength with excellent fracture toughness (70-90 MPa√m), making it suitable for highly loaded connections and dynamically loaded fasteners [44,48].

Titanium forms a stable, self-healing TiO_2 passive film in seawater, providing near immunity to pitting, crevice corrosion, and stress corrosion cracking across the full range of marine temperatures and salinities [63]. This eliminates cathodic protection requirements, avoiding hydrogen embrittlement concerns. However, galvanic coupling of titanium (noble cathode) with steel (active anode) accelerates steel corrosion and requires careful design of dissimilar metal joints with isolation barriers [70]. For $\alpha + \beta$ alloys like Ti-6Al-4V, microstructure morphology profoundly affects fatigue crack growth resistance. Bimodal microstructures (primary equiaxed α grains in transformed β matrix) provide optimal balance of crack initiation resistance (fine grain size) and propagation resistance (crack deflection at α/β interfaces) [71]. Fully lamellar microstructures (parallel α plates in prior β grains) exhibit superior crack growth resistance due to extensive crack deflection, but lower fatigue limit due to coarse effective grain size [72]. The Burgers orientation relationship (BOR) between α and β phases create crystallographic alignment affecting slip transfer across phase boundaries [73,74]. Crystal plasticity simulations reveal heterogeneous strain partitioning, with β matrix accumulating 2-3× higher plastic strain than α phase under uniaxial loading [71]. This strain incompatibility generates high stresses at α/β interfaces (300-500 MPa local stress elevation), serving as preferential sites for void nucleation and fatigue crack initiation [43,74]. While titanium alloys offer superior corrosion resistance and fatigue performance, their microstructure-sensitive deformation behaviour and excessive cost necessitate advanced modelling approaches and selective application in critical components.

3.3. Fibre Reinforced Composites

Fiber-reinforced polymer (FRP) composites dominate wind turbine blade construction, with emerging applications in tidal turbine blades, lightweight floating platform components, and repair systems for damaged metallic structures.

Blade structures: Modern wind turbine blades employ, glass fibre-reinforced epoxy (GFRE) in spar caps and aerodynamic shells, providing tensile strength at lower density. carbon fibre-reinforced epoxy (CFRE) in highly loaded spar regions, offering strength 1500-2500 MPa and stiffness 130-180 GPa but at 5-10× material cost. Sandwich construction with foam or balsa wood cores providing high bending stiffness at minimal weight [60]. Fabrication is via vacuum-assisted resin transfer moulding (VARTM) or resin infusion which introduces fibre misalignment, resin-rich regions, and porosity that serve as damage initiation sites [61].

Moisture absorption: Epoxy resins absorb seawater (saturation levels 1-3% by weight after 3-12 months immersion), causing matrix plasticisation and interfacial degradation. Moisture diffusion follows Fickian behaviour with diffusion coefficient ≈ 10^{-8} mm²/s at 20°C, accelerating at elevated temperatures (diffusion coefficient doubles per 15-20°C increase) [75]. Absorbed moisture reduces glass transition temperature (Tg) by 20-40°C and decreases interlaminar shear strength by 15-30% [76].

Delamination mechanisms: Interlaminar delamination, separation between composite plies, initiates from manufacturing defects, impact damage, or fatigue cycling. Mode I (opening), Mode II (sliding shear), and mixed-mode fracture characterise delamination growth, with critical energy release rates G_{Ic} = 200-400 J/m² and G_{IIc} = 800-1500 J/m² for typical GFRE laminates (see [77] and references therein). Fatigue delamination growth follows Paris law form $da/dN = C(\Delta G)^m$ with exponents m = 4-8, indicating high sensitivity to cyclic energy release rate range [61].

Delamination critically reduces compression strength due to sub laminate buckling. Ultrasonic inspection, thermography, and acoustic emission monitoring enable delamination detection, but repair strategies remain challenging for offshore installed blades [76]. Unlike metallic materials, composite degradation is governed by interfacial and matrix-dominated mechanisms, requiring different modelling and inspection strategies, but still reflecting the broader theme of multi-scale damage accumulation.

3.4. Additively Manufactured Materials

Additive manufacturing (AM), particularly wire arc additive manufacturing (WAAM) and laser powder bed fusion (LPBF), offers potential for customised geometries, rapid prototyping, and on-site repair. However, AM-specific material characteristics require qualification frameworks distinct from wrought materials.

Microstructural anisotropy: Layer-by-layer deposition creates columnar grain structures aligned with build direction, producing mechanical property anisotropy. LPBF Ti-6Al-4V exhibits tensile strength variation 950 MPa (vertical, parallel to build) vs. 1050 MPa (horizontal, perpendicular to build), with corresponding ductility variation 10% vs. 14% [78]. Columnar prior-β grains (100-500 μm width, mm-scale length) contain fine α lamellae (1-5 μm thickness), providing different crack propagation resistance depending on loading direction [79].

Residual stress influence: Rapid thermal cycling during AM (heating rates 10^3-10^6 °C/s, cooling rates 10^2-10^4 °C/s) generates steep temperature gradients and associated residual stresses. Tensile residual stresses commonly occur in as-built components, approaching or exceeding yield strength [80]. These stresses cause part distortion during build or post-processing and reduce fatigue performance by elevating mean stress. Stress-relief heat treatment reduces residual stresses by 60-80% but also coarsens microstructure [79]. Surface residual stress distributions exhibit characteristic "Christmas tree" profile with maximum tension at 0.5-1.5 mm depth due to constrained thermal contraction [78]. Surface machining removes the compressive surface layer but exposes subsurface tensile region, potentially degrading fatigue strength unless followed by shot peening or similar treatment [81].

Qualification challenges: AM components face additional qualification barriers, gas porosity, lack-of-fusion defects, and unmelted powder particles create statistical defect distributions requiring probabilistic assessment [82]. Process parameter produces batch-to-batch property variations exceeding wrought material variability by 2-3 times. Laboratory coupon properties may not represent structural component behaviour due to thermal history differences in large builds. As-built surface finish degrades fatigue strength by 40-60% compared to machined surfaces [79].

Despite these challenges, AM enables optimised topologies (lattice structures, biomimetic designs) and functionally graded materials potentially offering superior performance/weight ratios once qualification methodologies mature [78]. The variability, defect populations, and anisotropy inherent in additively manufactured materials challenge traditional qualification approaches, reinforcing the need for probabilistic and mechanism-informed assessment frameworks.

3.5. Material Selection Trade-Offs

From a structural integrity perspective, material classes exhibit distinct trade-offs (Table 2). Structural steels offer cost-effective solutions but are highly susceptible to corrosion-fatigue and hydrogen-related degradation, particularly in welded joints. Titanium alloys mitigate corrosion-related mechanisms but introduce cost and galvanic challenges, limiting widespread adoption. Composites eliminate corrosion but are governed by delamination and moisture-driven degradation, requiring fundamentally different modelling approaches. Additively manufactured materials offer design flexibility but introduce variability and defect-driven uncertainty. These contrasts highlight that no single material system provides a universal solution, reinforcing the need for application-specific, mechanism-based material selection and qualification.

Material selection for marine renewable energy structures involves multi-objective optimisation balancing durability, cost, and manufacturability. Titanium alloys offer superior corrosion resistance and fatigue performance but cost 5-10 times structural steel equivalents. Life-cycle cost analysis must account for, initial material cost, fabrication complexity, inspection frequency (corrosion-resistant materials enable extended inspection intervals), and replacement costs (premature failure necessitating offshore heavy lift operations) [26].

For components with high failure consequences (mooring connectors, primary load paths in non-redundant structures), premium materials may prove economically justified despite higher acquisition costs [29]. High-strength steels necessitate controlled welding procedures (preheating, interpass temperature limits, post-weld heat treatment) to avoid HAZ hardening and hydrogen cracking. Titanium alloys demand electron beam or friction stir welding for thick sections, or inert

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gas purging for arc welding. Carbon fibre composites require autoclave curing for aerospace-quality properties, versus lower-cost out-of-autoclave processes with property compromises [83].

Manufacturing constraints influence design, with standard rolled steel plate and tubular sections enabling lower-cost fabrication compared to custom forgings or AM components. Supply chain availability—particularly for large-diameter monopiles requiring specialized rolling mills—affects project schedules and costs [28]. Limiting material grades to a small set (e.g., S355, S420 for structures; Ti-6Al-4V for titanium applications; standard GFRE for blades) enables:

- Accumulated inspection database for reliability quantification
- Simplified welding procedure qualification (WPS/PQR development)
- Reduced inventory and logistics complexity for offshore operations [57]

However, standardisation may preclude optimisation opportunities from emerging materials (advanced titanium, advanced HSLA steels, thermoplastic composites) offering superior properties.

Table 2. Qualitative comparison of material classes for marine renewable energy structures.

Material	Strength	Corrosion	Fatigue	Key Risk	Modelling Need
Steel	Moderate - high	Poor in seawater	Moderate	Corrosion-fatigue, H-assisted cracks	Empirical S-N + physics
Titanium	High	Excellent	High	Cost + microstructure sensitivity	Crystal plasticity / micromechanics
Composite	High (specific)	No metallic corrosion	Variable	Delamination, moisture degradation	Fracture / damage mechanics
AM metal	Variable	Environment dependent	Poor–moderate (as-built)	Defects, anisotropy, residual stress	Probabilistic, defect-based

Overall, material selection in marine renewable energy systems is governed not only by strength and corrosion resistance, but by the interaction between microstructural characteristics, environmental exposure, and loading conditions. Structural steels remain dominant due to cost and manufacturability but suffer from corrosion-fatigue and hydrogen-related degradation. Titanium alloys offer superior durability but introduce cost and galvanic challenges, while composites and additively manufactured materials introduce new failure modes linked to anisotropy and defect populations. These trade-offs highlight the need for mechanism-based material qualification approaches, which are explored in subsequent sections.

4. Mechanism-Based Degradation Processes in Marine Renewable Systems

Marine renewable energy structures are exposed to multiple degradation mechanisms that rarely act in isolation. Instead, failure typically arises from the interaction of electrochemical, mechanical, and microstructural processes operating across different length and time scales. The dominant degradation pathway depends on material selection, environmental exposure, loading characteristics, and protection strategies such as coatings and cathodic protection. Coupled mechanisms, such as corrosion-fatigue, hydrogen-assisted cracking, and wear-corrosion, govern structural performance in offshore systems, necessitating integrated, mechanism-based assessment approaches.

4.1. Corrosion and Corrosion-Fatigue

Marine environments impose aggressive electrochemical conditions, with corrosion and fatigue mechanisms interacting synergistically rather than occurring independently. Seawater, typically characterised by salinity of approximately 3–4% and pH in the range 7.5–8.5, provides a conductive

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electrolyte with electrical conductivity on the order of a few S/m, thereby facilitating electrochemical charge transfer in corrosion processes [38]:

Anodic reaction (metal dissolution):

$Fe \rightarrow Fe^{2+} + 2e^{-}$ ($E^{0} = -0.44$ Volts, V relative to the Standard Hydrogen Electrode, SHE)

Cathodic reaction (oxygen reduction):

$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$ ($E^{0} = +0.40\,V$ vs. SHE)

where E^{0} denotes the standard electrode potential measured relative to the Standard Hydrogen Electrode (SHE), which serves as the universal reference in electrochemical systems.

The resulting potential difference provides a strong thermodynamic driving force for corrosion. Dissolved oxygen concentration, typically reported in the range of several mg/L in aerated seawater, governs cathodic reaction kinetics, with oxygen diffusion often limiting current densities to values on the order of tens of $\mu A/cm^{2}$ under quiescent conditions [34]. Passive film breakdown at microscale defects initiates localised corrosion. Chloride ions adsorb at film defects, penetrating the Fe_2O_3/Fe_3O_4 oxide layer and establishing autocatalytic pitting [22]:

Pit initiation: Cl^{-} penetration generates locally acidified chemistry (pH typically reported in the range of ~3–5 within pits) due to metal cation hydrolysis.

Pit propagation: Ohmic potential drop in pit solution maintains active dissolution while external surface remains passive.

Critical pit depth: Shallow pits (on the order of tens of microns) may repassivate, whereas deeper pits can propagate at rates broadly reported in the range of sub-millimetre to millimetre per year depending on environment and material [56]

Manganese sulphide (MnS) inclusions in structural steels serve as preferential pit initiation sites due to local galvanic coupling [34,41,69]. Typical inclusion densities (on the order of tens to hundreds per mm²) introduce a statistical distribution of pit initiation times.

Fatigue loading disrupts passive films via cyclic plastic strain at crack tips, exposing bare metal to continuous corrosion attack. This corrosion-fatigue synergy manifests as [68]:

Enhanced crack growth rate: crack growth rates in seawater are commonly reported to be several times higher (often in the range of ~3–10 times) than in air at lower ΔK levels, with convergence at higher ΔK where mechanical effects dominate.

Reduction or effective elimination of fatigue threshold: ΔK_{th} in seawater is typically significantly reduced compared to air, enabling crack propagation from smaller initial defects.

Load frequency dependence: Lower frequencies (e.g. those associated with wave loading) allow increased time for electrochemical reactions per cycle, often leading to elevated crack growth rates compared to higher-frequency laboratory conditions [35]

Surface pits act as stress concentrators, with stress concentration factors typically in the range of ~2–4 depending on pit geometry. For representative pit geometries, local stress amplification can enable crack nucleation at nominal stress ranges substantially below those of smooth specimens [38]. Combined with accelerated crack growth, overall fatigue life reductions of several times (commonly reported in the range of ~5–10 times) are observed for offshore structures relative to air environments [35]. Corrosion–fatigue therefore represents one of the dominant degradation mechanisms in offshore wind and marine steel structures, particularly in welded joints and splash zone regions, where environmental and mechanical effects combine to significantly reduce structural integrity and service life.

4.2 Hydrogen Embrittlement

Hydrogen embrittlement (HE) represents a critical yet often under-appreciated degradation mode in marine structures, particularly those employing cathodic protection or high-strength steels. Hydrogen enters steel via multiple pathways [36]:

1. Cathodic protection reactions: Applied cathodic potential (typically $-0.80\,to - 1.05\,V$ vs. $Ag/AgCl$ reference) shifts steel surface into hydrogen evolution regime:

$2H^{+} + 2e^{-} \rightarrow H_2$ (acidic solution)

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$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ (alkaline/neutral solution)

Not all generated hydrogen forms H_2 gas; only a small fraction of generated hydrogen is absorbed as atomic hydrogen (typically a few percent), which can nevertheless be sufficient to induce embrittlement in susceptible materials [70].

2. Corrosion reactions: Anodic metal dissolution produces electrons consumed by cathodic hydrogen evolution even without applied cathodic protection. Particularly severe in crevices and under marine growth where local acidification enhances hydrogen generation [37].

3. Galvanic coupling: Dissimilar metal junctions (steel/aluminium, steel/copper) create local galvanic cells with hydrogen evolution at cathodic (more noble) locations.

Offshore structures employ sacrificial anodes (aluminium alloy) or impressed current cathodic protection (ICCP) to prevent corrosion. However, excessive cathodic polarisation (typically more negative than recommended protection potentials) dramatically increases hydrogen uptake. Marine growth (barnacles, mussels, algae) accumulating on anodes concentrates current density, creating localized over-protection zones [63]. Hydrogen diffusivity in BCC iron is typically reported on the order of $10^{-9} - 10^{-8}\, m^2/s$ at ambient temperatures, enabling relatively rapid penetration into the lattice [37] through grain boundaries, where trapping energy generally reported in the range of tens of kJ/mol, increase local hydrogen concentration 10-100 times over lattice levels. Similarly, carbide/matrix interfaces, such as TiC, NbC precipitates serve as reversible traps. Also, microvoids and dislocations act as irreversible traps accumulating hydrogen during service life[84].

High-strength steels with fine microstructure (grain size <10 μm) provide increased trap density, but also increased trap saturation at high hydrogen concentrations, potentially exacerbating embrittlement [63]. Embrittlement manifests through multiple mechanisms [63]:

Hydrogen-enhanced decohesion (HEDE): Hydrogen accumulation at crack tip reduces interatomic bond strength, significantly reducing fracture toughness, in some cases by more than 50% depending on material strength and hydrogen concentration.

Hydrogen-enhanced localised plasticity (HELP): Hydrogen increases dislocation mobility, concentrating plastic deformation in narrow bands ahead of crack tip and facilitating ductile void coalescence.

Adsorption-induced dislocation emission (AIDE): Hydrogen adsorption at crack tip surfaces enhances dislocation nucleation, promoting crack blunting or sharpening depending on microstructure.

Crack growth rates under sustained loading are typically reported over several orders of magnitude (e.g., $\sim 10^{-9}\ to\ 10^{-6}\ m/s$), depending on stress intensity and environmental conditions [63]. For mooring chain connectors in offshore service, hydrogen-assisted subcritical crack growth under sustained tension is a recognised risk, particularly when hardness limits are exceeded, and can ultimately lead to brittle fracture under otherwise acceptable loads [70]. Hydrogen embrittlement is therefore particularly critical in offshore components subjected to sustained tensile loading and cathodic protection, such as mooring chains, connectors, and subsea pipelines, where local hydrogen accumulation can lead to premature and often unexpected failure.

4.3. Fatigue and Multiaxial Cyclic Damage

Fatigue is the dominant failure mode in marine renewable structures, accounting for 60-80% of predicted damage accumulation over design life [32]. The fatigue response is governed by a combination of high-cycle fatigue (HCF) at the structural scale and localised low-cycle fatigue (LCF) arising from stress concentrations.

Marine structures predominantly operate in the HCF regime ($N > 10^4$ cycles), characterised by nominally elastic strains and long crack initiation phases, where fatigue life is largely governed by crack nucleation and early growth [33]. However, geometric discontinuities such as weld toes, notches, and connection interfaces introduce local plasticity, leading to LCF behaviour in confined regions where crack initiation occurs rapidly and propagation is accelerated [35]. This transition is particularly evident in monopile grouted connections, where local slip and cyclic contact stresses generate plastic strain accumulation and early crack initiation at grout–steel interfaces [34,41,69], with field observations indicating relatively short initiation periods under adverse conditions [39].

A defining feature of offshore fatigue loading is the highly variable amplitude nature of environmental excitation. Wave-driven loading produces a broad spectrum of stress ranges spanning several orders of magnitude, with operational, design, and extreme sea states contributing differently to cumulative damage [25]. Fatigue assessment therefore relies on cycle counting techniques, such as rainflow analysis, combined with linear damage accumulation models of the Palmgren–Miner form:

$$D = \Sigma \left(n_{\mathrm{i}} / N_{\mathrm{i}}\right)$$

where n_{i} represents the number of applied cycles at a given stress range $\Delta\sigma_{\mathrm{i}}$, and N_{i} is the corresponding fatigue life from S–N data. While widely adopted, this linear framework does not capture load sequence effects, which are particularly relevant in marine environments characterised by irregular loading histories [35]. Overload–underload interactions can induce crack growth retardation or acceleration, leading to significant deviations from linear damage accumulation, with effective failure damage ratios departing from unity under different loading sequences.

Current offshore design standards (e.g., DNV-RP-C203) address these uncertainties through partial safety factors and conservative S–N formulations; however, they do not explicitly resolve the underlying physical mechanisms governing sequence effects, thereby limiting predictive capability and potentially obscuring optimisation opportunities [57].

Fatigue performance is further dominated by welded joint behaviour, where geometric and metallurgical discontinuities create pronounced stress concentrations. Tubular joints typical of jacket structures exhibit stress concentration factors (SCFs) that can vary widely depending on joint configuration [39]:

$$SCF = \sigma_{hotspot}/\sigma_{nominal}$$

For representative K-joints, hotspot stresses may be several times higher than nominal stresses, particularly at chord crown and saddle locations [34,41,69]. When combined with local weld toe effects, total stress amplification can become substantial, such that even relatively low nominal stress ranges produce local stress levels sufficient to initiate fatigue cracking [32].

Overall, fatigue in marine renewable systems is inherently multiscale and strongly influenced by environmental variability, structural detail, and material response. The combined effects of variable amplitude loading, low-frequency excitation, and localised plasticity challenge conventional linear damage models, underscoring the need for mechanism-informed approaches capable of capturing sequence effects and microstructure-sensitive fatigue behaviour.

4.4. Wear and Abrasion

Tribological degradation plays a significant role in components subjected to relative motion or particulate impact, particularly in sediment-rich marine environments.

Sediment-induced erosion is a key concern for tidal turbines operating in high-suspended-solids conditions. Particulate-laden flows induce material removal on leading edges, blade surfaces, and sealing interfaces, with erosion rates governed by particle velocity, impact angle, and material response [60]. Empirical relationships typically express erosion rate as a function of velocity and impact angle, with exponents dependent on material ductility and particle characteristics. For metallic materials such as carbon steels, erosion rates increase strongly with particle velocity and are maximised at near-normal impact conditions [50]. Under representative tidal flow conditions, material loss may accumulate over operational lifetimes, necessitating periodic repair or replacement of exposed components [16].

In addition to erosion, contact and fretting damage are critical in components experiencing small-amplitude cyclic motion. Bolted connections, grouted interfaces, and mooring chain links are particularly susceptible to fretting fatigue, where repeated micro-slip leads to surface damage, oxide debris formation, and accelerated crack initiation [81]. The combined action of mechanical wear and oxidation generates surface features that act as stress concentrators, significantly reducing fatigue resistance compared to plain fatigue conditions [70]. In offshore mooring systems, cyclic contact at chain links can produce measurable wear scars over service periods, progressively reducing cross-section and fatigue capacity [31].

Seal and bearing systems represent another critical class of tribological components. Progressive wear of seals can lead to loss of sealing integrity, allowing seawater ingress and contamination of lubricants. This accelerates degradation of bearings through combined rolling contact fatigue, adhesive wear, and corrosion processes [16]. Such coupled degradation mechanisms are often difficult to detect early and can lead to rapid functional failure.

Overall, wear and abrasion are highly system-dependent but can dominate degradation in specific components such as tidal turbine blades, mooring systems, and mechanical interfaces. In these cases, material loss and surface damage not only reduce load-bearing capacity but also act as precursors to fatigue and corrosion-driven failure, highlighting the need for integrated tribological and structural integrity assessment.

4.5. Residual Stress and Manufacturing Defects

The as-manufactured condition of structural components plays a critical role in determining in-service performance, often governing variability in fatigue and fracture behaviour. Residual stresses generated during welding arise from severe thermal gradients and constrained contraction during cooling [34]. These stresses are typically tensile within the weld metal and heat-affected zone (HAZ), with magnitudes that can approach a significant fraction of the material yield strength and are balanced by compressive regions in the surrounding base material [69]. Such residual stress fields modify the effective stress ratio experienced under cyclic loading, elevating mean stress and thereby accelerating fatigue crack initiation and growth. Even moderate tensile residual stresses can significantly reduce fatigue life when combined with service loading, as captured through standard mean stress correction approaches [35].

Additive manufacturing processes, including wire arc additive manufacturing (WAAM) and laser powder bed fusion (LPBF), introduce additional complexity through spatially varying thermal histories. These processes generate pronounced microstructural gradients along the build direction and within individual layers due to repeated thermal cycling and melt pool interactions [78,79]. The resulting heterogeneity in grain structure and phase distribution leads to local variations in mechanical properties, necessitating statistical treatment in structural assessment [34,41,69].

Surface modification techniques further alter near-surface stress states and fatigue performance. Mechanical treatments such as shot peening introduce compressive residual stresses in the surface layer, which can significantly enhance fatigue resistance, although associated surface roughness may partially offset these benefits [34,41,69]. Advanced methods such as laser peening achieve deeper compressive layers with reduced surface damage, albeit at higher cost [81]. Conversely, coating processes used for corrosion protection may introduce tensile stresses within the coating system, with corresponding implications for crack initiation if adhesion or integrity is compromised [38]. Overall, residual stresses and manufacturing-induced defects rarely act as independent failure mechanisms but play a critical role in accelerating other degradation processes. By increasing local stress intensity and reducing effective crack initiation thresholds, they strongly influence fatigue, corrosion–fatigue, and hydrogen-assisted cracking behaviour, underscoring the need for manufacturing-aware structural integrity assessment.

4.6. Microstructure-Driven Failure Mechanisms

Macroscopic structural failure originates from microstructural mechanisms governed by crystallography, phase distribution, and defect populations. These mechanisms control damage initiation and early crack propagation, particularly under cyclic loading [68,85].

Plastic deformation in metallic polycrystals is accommodated by dislocation glide on crystallographic slip systems, the nature of which depends on crystal structure. FCC materials exhibit multiple equivalent slip systems, while BCC and HCP materials display more complex, temperature- and orientation-dependent slip behaviour [86,87]. As a result, deformation is inherently heterogeneous, with grains favourably oriented with respect to the applied stress (high Schmid factor) deforming preferentially.

This heterogeneity leads to slip localisation, where cyclic plastic strain accumulates within persistent slip bands (PSBs). These localised deformation regions act as precursors to fatigue crack initiation, particularly at free surfaces where intrusions and extrusions develop and concentrate stress [88,89]. Crack nucleation is therefore strongly governed by microstructural orientation and localised plasticity rather than bulk stress alone [44].

Ductile fracture mechanisms are similarly controlled at the microscale through void nucleation, growth, and coalescence. Voids preferentially nucleate at microstructural heterogeneities such as second-phase particles, inclusions, and grain boundaries, where local stress concentrations exceed interfacial strength [43]. Subsequent void growth is strongly influenced by stress triaxiality, with higher hydrostatic stress promoting accelerated growth and coalescence, consistent with established micromechanical models [90,91].

In multiphase materials, such as titanium alloys and advanced steels, phase interactions introduce additional sources of damage. Mechanical incompatibility between phases, arising from differences in elastic modulus, yield strength, and slip behaviour, leads to local strain partitioning and stress concentration at phase boundaries [92,93]. These interfaces therefore act as preferential sites for damage initiation. Microstructure-resolved simulations, such as CPFEM, consistently predict significant local stress amplification at phase boundaries, providing mechanistic explanation for experimentally observed crack nucleation behaviour [94].

At larger scales, microstructural heterogeneity manifests through grain clusters or orientation domains, which deform collectively and form mesoscale deformation bands. These bands can concentrate damage, influence crack propagation paths, and contribute to scatter in fatigue life due to their stochastic spatial distribution [44]. Quantifying such effects requires statistical characterisation of microstructure (e.g., via EBSD) combined with representative volume modelling approaches [42,95,96].

Importantly, these microstructure-driven mechanisms do not act in isolation. In marine environments, they interact with corrosion, hydrogen embrittlement, and cyclic loading to produce coupled, non-linear degradation pathways. For example, corrosion pits act as microstructural stress concentrators, hydrogen accumulates at defects and interfaces, and manufacturing-induced heterogeneity further amplifies local damage evolution. Consequently, structural failure is governed by the interaction of multiple mechanisms operating across scales, rather than a single dominant process. These interacting degradation mechanisms and their structural implications are summarised in Table 3.

This inherent multiscale and multiphysics coupling highlights the limitations of traditional empirical design approaches and provides the fundamental motivation for mechanism-resolved modelling frameworks, as discussed in the following section.

Table 3. Dominant degradation mechanisms in marine renewable energy systems and their structural implications.

Mechanism	Dominant Materials/Components	Key Drivers	Structural Impact
Corrosion-fatigue	Steel (monopiles, jackets)	Seawater + cyclic loading	Accelerated crack initiation/growth
Hydrogen embrittlement	High-strength steels, chains	Cathodic protection	Reduced toughness, brittle cracking
Fatigue	All structural components	Variable amplitude loading	Life-limiting damage
Wear/abrasion	Tidal blades, moorings	Sediment, contact	Material loss, surface damage
Defects/residual stress	Welded joints, AM components	Manufacturing processes	Early crack initiation

5. Multiscale Modelling Frameworks for Degradation and Structural Integrity

Bridging the gap between microstructure-scale degradation mechanisms and structural system reliability requires hierarchical computational frameworks that integrate physics across multiple length scales. While a wide range of modelling approaches exists, their application to marine renewable energy systems remains fragmented, with limited consistency in information transfer across scales. Microstructure-resolved models provide detailed insight into fundamental deformation and damage mechanisms but are computationally demanding, whereas structural-scale models are efficient but rely heavily on empirical or homogenised assumptions. A key challenge, therefore, lies in developing hierarchical multiscale frameworks that enable consistent parameter transfer and uncertainty propagation across scales, allowing physically informed and computationally tractable structural integrity assessment. This hierarchical framework is illustrated schematically in Figure 4:.

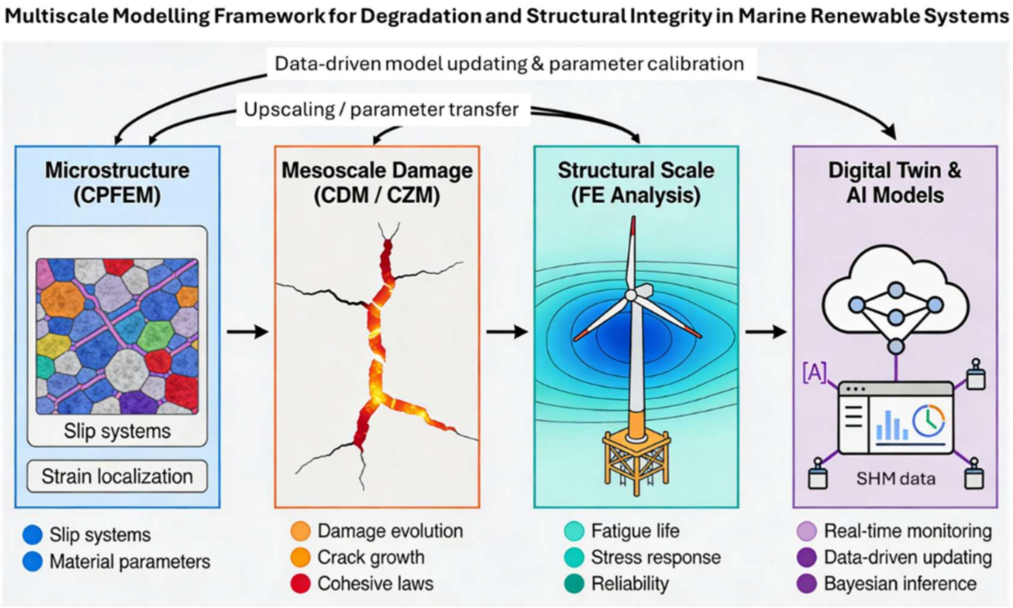

Figure 4. Schematic illustration of a hierarchical multiscale modelling framework for structural integrity assessment in marine renewable energy systems. Microstructure-resolved modelling (e.g., CPFEM) captures slip

behaviour and strain localisation, which inform mesoscale damage evolution models (e.g., CDM/CZM). These are subsequently integrated into structural-scale finite element analyses for predicting stress response, fatigue life, and reliability. Data-driven model updating and parameter calibration, supported by structural health monitoring (SHM) and digital twin frameworks, enable feedback across scales, ensuring consistent transfer of information and improved predictive capability.

5.1. Microstructure-Resolved Modelling

Crystal plasticity finite element modelling (CPFEM) provides a physically grounded framework for capturing microstructure-sensitive deformation by explicitly resolving crystallographic slip at the grain scale [94,97,98]. This enables a direct link between microstructural attributes, such as grain orientation, phase distribution, and slip activity, and macroscopic mechanical response.

Within CPFEM, the deformation gradient $\boldsymbol{F}$ is multiplicatively decomposed into elastic ($\boldsymbol{F}^{\mathrm{e}}$) and plastic ($\boldsymbol{F}^{\mathrm{p}}$) components:

$$\boldsymbol{F} = \boldsymbol{F}^e \cdot \boldsymbol{F}^p$$

Plastic deformation arises from slip on discrete crystallographic systems, with the plastic velocity gradient defined as:

$$\boldsymbol{L}^p = \dot{\boldsymbol{F}}^p \cdot (\boldsymbol{F}^p)^{-1} = \sum_{\alpha} \dot{\gamma}^{\alpha} (\boldsymbol{s}^{\alpha} \otimes \boldsymbol{m}^{\alpha})$$

where s^{α} and m^{α} denote the slip direction and slip plane normal, respectively. The slip rate typically follows a viscoplastic power-law formulation:

$$\dot{\gamma}^{\alpha} = \dot{\gamma}^{0} \left|\frac{\tau^{\alpha}}{g^{\alpha}}\right|^{n} sign(\frac{\tau^{\alpha}}{g^{\alpha}})$$

where $\tau^{\alpha}$is the resolved shear stress, $g^{\alpha}$is the evolving slip resistance, $\dot{\gamma}_0$is a reference strain rate, and $n$is the rate sensitivity exponent.

A key advantage of CPFEM lies in its ability to provide mechanistically informed damage indicators. These include accumulated plastic strain energy density, often used as a fatigue indicator parameter (FIP) [99], grain boundary stress concentrations associated with decohesion [100], and dislocation density evolution linked to strain gradients [101]. These metrics enable identification of preferential crack initiation sites within heterogeneous microstructures. When combined with experimentally derived crack nucleation statistics, CPFEM outputs can be incorporated into probabilistic life prediction frameworks that explicitly account for microstructural variability [102].

Despite its predictive capability, CPFEM remains computationally intensive and requires extensive calibration using multiscale experimental data [94]. As a result, its primary role within multiscale frameworks is not direct structural analysis, but rather the generation of physically informed constitutive behaviour, damage metrics, and variability descriptors that can be transferred to higher-scale models.

A significant challenge in integrating CPFEM into a multiscale framework is the potential for information loss during the transition between scales. Traditional homogenisation techniques often rely on averaging methods that may inadvertently 'smear' the local driving forces—such as extreme-value fatigue indicator parameters—into mean-field properties[103]. This is particularly critical for marine structures, where failure is often governed by localized stochastic events rather than average material response. Recent studies [104] have highlighted the need to consider uncertainties from the microstructural scale to structural-level reliability metrics. By treating damage indicators and material parameters as statistical distributions rather than deterministic quantities, these approaches enable a more consistent transfer of physically relevant information across scales. This facilitates improved linkage between microstructure-informed modelling and engineering-scale reliability assessment.

5.2. Mesoscale Structural Damage Modelling

Mesoscale damage models provide a critical bridge between microstructure-resolved deformation mechanisms and structural-scale integrity assessment. At this scale, damage is represented either explicitly through discrete crack models or implicitly via continuum degradation approaches.

Cohesive zone modelling (CZM) describes crack initiation and propagation through traction–separation relationships defined along predefined or evolving interfaces [45]. Cohesive elements can be introduced at grain boundaries, phase interfaces, or within continuum meshes, enabling crack paths to emerge without the need for remeshing. A commonly adopted formulation is the bilinear traction–separation law, characterised by a peak cohesive strength, a critical separation at failure, and an associated fracture energy corresponding to the area under the traction–separation curve [45,105].

For Mode I loading, the traction–separation response evolves with increasing separation, with damage initiation occurring at peak traction and progressive degradation governed by a scalar damage variable until complete separation is reached. CZM frameworks are particularly effective in capturing interface-dominated failure, including crack deflection, penetration, and debonding phenomena. The competition between these mechanisms is governed by relative fracture energies and interface strengths, enabling the construction of “fracture maps” for heterogeneous materials [45].

Complementary to CZM, continuum damage mechanics (CDM) represents material degradation through internal state variables that reduce the effective stiffness of the material [45,105,106]. In this framework, damage evolves according to thermodynamically consistent laws driven by quantities such as equivalent strain or energy release rate. Widely used formulations, such as the Lemaitre damage model, incorporate stress triaxiality and plastic strain effects, allowing the representation of ductile damage processes under multiaxial loading conditions relevant to offshore structures [107]. These models capture the acceleration of damage under elevated hydrostatic stress, consistent with micromechanical observations of void growth.

For cyclic loading, crack propagation is often described using fracture mechanics approaches, most notably Paris-type laws relating crack growth rate to stress intensity factor range. In marine environments, corrosion effects can significantly enhance crack growth rates compared to inert conditions, while loading frequency influences the extent of environmental interaction per cycle [56,69]. These effects are typically incorporated through modified crack growth relationships or environmental correction factors.

Overall, mesoscale approaches such as CZM and CDM provide a practical framework for translating microstructure-informed behaviour into forms suitable for structural analysis. However, their predictive capability is highly dependent on parameter calibration, which is often derived from lower-scale simulations or targeted experiments. This underscores the importance of consistent multiscale integration, where physically informed parameters from microstructure-resolved models are systematically transferred to mesoscale descriptions.

5.3. Macroscale Structural Integrity Assessment

At the structural scale, integrity assessment frameworks integrate loading, stress analysis, and damage accumulation to evaluate fatigue life and reliability of marine renewable energy systems. These approaches form the foundation of current engineering design practice. Structural fatigue assessment typically follows a workflow combining environmental loading, dynamic response simulation, and cumulative damage evaluation [33]. Metocean data are first used to define long-term loading statistics, which are then applied within aero-hydro-servo-elastic models to generate time-domain structural responses. These responses are processed using cycle counting techniques, such as the rainflow method, to obtain stress range distributions, which are subsequently used in conjunction with S–N curves to estimate fatigue damage accumulation.

The total accumulated damage over the design life can be expressed as:

$$D_{total} = \sum_{i} \left[p_i \times \sum_{j} \left(\frac{n_{ij}}{N_{ij}} \right) \right] \times T_{design}$$

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where p_i represents the occurrence probability of a given sea state, n_{ij} the number of cycles at a given stress range, and N_{ij} the corresponding fatigue capacity [32]. Failure is typically assumed when cumulative damage reaches a critical threshold based on linear damage accumulation concepts.

For components containing defects or detected cracks, fracture mechanics approaches are employed to estimate remaining life. Crack growth is commonly described using Paris-type relationships, with the remaining number of cycles obtained by integrating crack growth rate from an initial to a critical crack size:

$$N_{remaining} = \int_{a_{initial}}^{a_{critical}} \frac{da}{C(\Delta K)^m}$$

where the stress intensity factor range is defined as $\Delta K = Y\Delta\sigma\sqrt{\pi a}$, with Y representing a geometry correction factor. The critical crack size is determined from material fracture toughness, providing a basis for inspection planning and maintenance decisions [35].

To account for uncertainties in loading, material behaviour, and modelling assumptions, reliability-based design frameworks are widely adopted. These approaches define a limit state function:

$$g(X) = R - S$$

where resistance and load effects are treated as random variables [108]. The probability of failure is then evaluated using analytical or simulation-based methods, such as the First-Order Reliability Method (FORM) or Monte Carlo approaches [108–111]. Target reliability levels are specified based on consequence class and acceptable risk levels in offshore design.

In fatigue reliability formulations, uncertainties arise from multiple sources, including S–N curve parameters, stress concentration factors, loading variability, and damage accumulation models [47]. These uncertainties are typically incorporated through probabilistic distributions, enabling estimation of reliability indices and failure probabilities.

While these structural-scale methods form the basis of current design practice, their reliance on empirical relationships and simplified damage accumulation models limits their ability to capture complex degradation mechanisms, particularly under variable amplitude loading and harsh marine environments.

5.4. Coupled Multiphysics Modelling

In marine environments, structural degradation is inherently governed by the interaction of mechanical loading with electrochemical, hydrogen, and thermal processes. Accurate prediction of structural integrity therefore requires coupled multiphysics formulations that capture these interactions within a unified framework.

A key example is corrosion–mechanics coupling, where electrochemical reactions and mechanical fields interact through evolving geometry and stress redistribution. In such formulations, the electrolyte potential is typically obtained by solving the Laplace equation, with boundary conditions defined by electrochemical kinetics (e.g., Butler–Volmer relationships) at the metal surface [56]. The resulting current density governs material dissolution through Faraday's law, which drives local geometry evolution. This evolving surface geometry is then passed to the mechanical solver, where stress redistribution and strain localisation further influence corrosion kinetics, particularly at crack tips [38]. This feedback loop can lead to significant acceleration of local corrosion rates, especially under conditions of high stress concentration [56].

Hydrogen-assisted degradation represents another critical multiphysics interaction. Hydrogen transport within the material is coupled to the stress field through diffusion equations incorporating both concentration gradients and stress-driven flux terms [37]. The latter results in hydrogen accumulation in regions of tensile hydrostatic stress, such as crack tips, while depletion occurs in compressive regions. This coupling is increasingly implemented within finite element frameworks, enabling simultaneous solution of mechanical and diffusion fields [63]. At the material level, hydrogen reduces cohesive strength and alters fracture behaviour, which can be incorporated into

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mesoscale models such as CZM through concentration-dependent traction–separation relationships [63].

Thermomechanical effects provide an additional coupling mechanism, particularly relevant in offshore energy systems integrating thermal processes such as electrolysis. Temperature gradients induce thermal strains that interact with mechanical loading, generating additional stress components that contribute to fatigue damage accumulation. These effects can be described through standard thermomechanical formulations, where total strain includes elastic, plastic, and thermal contributions [58].

Collectively, these multiphysics interactions highlight the strongly coupled nature of degradation processes in marine environments. While significant progress has been made in developing coupled electrochemical–mechanical, hydrogen–mechanical, and thermomechanical models, their application remains largely limited to component-scale studies due to computational cost and model complexity. Extending these approaches to structural-scale simulations therefore remains a key challenge for the development of predictive, mechanism-resolved integrity frameworks.

5.5. Digital Twins and Data-Driven Modelling

Data-driven modelling and digital twin frameworks provide a pathway for integrating physics-based modelling with real-time operational data (i.e., adaptive structural integrity assessment). However, their practical deployment in marine renewable systems remains limited by several technical challenges.

A typical digital twin architecture consists of (i) a physical asset instrumented with sensors (e.g., strain, acceleration, temperature), (ii) a data acquisition and communication layer, (iii) A computational model, often reduced-order FE or surrogate-based, (iv) an updating algorithm, typically Bayesian or filtering-based. While numerous studies report promising results, several limitations remain. Examples of these limitations include: (i) sensor reliability in harsh marine environments, (ii) sparse and noisy data, particularly for subsea components, (iii) model-form uncertainty in degradation models, and (iv) computational cost for real-time updating. Importantly, purely data-driven approaches lack physical interpretability and may fail under extrapolation. As such, hybrid frameworks combining physics-based models with data-driven correction are increasingly recognised as the most robust approach.

Machine learning models trained on inspection data, structural health monitoring (SHM) measurements, and simulation outputs can capture complex, non-linear relationships that are difficult to represent using purely mechanistic formulations [111].

A range of approaches has been explored in this context. Convolutional neural networks (CNNs) are widely used for image-based damage detection from visual inspection and ultrasonic data, while recurrent neural networks (RNNs) and long short-term memory (LSTM) models enable time-series prediction of structural response, including strain, vibration, and corrosion evolution. Tree-based methods such as XGBoost and Random Forest are commonly applied for regression tasks, particularly for remaining useful life (RUL) estimation incorporating operational history, environmental exposure, and material parameters (see [111] and references therein). While reported performance is often high under controlled conditions, generalisation to field environments remains dependent on data quality and representativeness. A key advantage of modern data-driven approaches is the ability to quantify uncertainty. Bayesian neural networks and probabilistic machine learning frameworks enable propagation of epistemic (model-form) and aleatoric (data-driven) uncertainties, providing confidence bounds on predictions that are essential for risk-informed decision-making [111].

To ensure that data-driven predictions remain physically consistent, increasing attention has been given to hybrid digital twin frameworks that integrate physics-informed machine learning (PIML). Unlike purely data-driven approaches, PIML methods, such as physics-informed neural networks (PINNs), incorporate governing partial differential equations directly into the learning process, for example through the loss function [112]. This enables the model to retain consistency with known physical laws, such as fluid dynamics or diffusion–stress coupling, while reducing reliance on large training datasets. Such hybrid approaches are particularly relevant for offshore applications, where limited data availability and complex multiphysics interactions pose challenges for purely data-driven models. By embedding physical constraints within the learning framework, PIML offers a promising pathway to enhance the robustness and reliability of digital twin predictions for safety-critical marine infrastructure.

Integration with inspection data is typically achieved through Bayesian updating, where prior distributions derived from design-stage analysis are refined using inspection evidence [108]. For example, crack size distributions can be updated using probability of detection (POD) functions, with non-detection events shifting the posterior distribution towards smaller defect sizes and reduced failure probability [47]. Sequential inspections progressively reduce uncertainty, with convergence towards the underlying damage state generally achieved over multiple inspection cycles [110].

Digital twins extend this concept by embedding data-driven and physics-based models within a cyber-physical system. In offshore applications, the digital twin comprises the physical asset instrumented with sensors, a communication layer transmitting data, and a computational model that assimilates measurements to update the structural state in near real time [113]. Sensor networks typically measure strain, acceleration, temperature, and environmental conditions, while reduced order or surrogate models enable computationally efficient updating. Bayesian inference or filtering techniques are then used to estimate damage evolution and trigger maintenance actions when reliability thresholds are exceeded [114].

Demonstrations in offshore energy systems highlight the potential of this approach. For instance, digital twin implementations have been used for structural monitoring and model updating in floating wind systems, as well as for rapid identification of damage in offshore jacket structure [113,115]. However, widespread deployment remains limited by several challenges, including sensor durability in harsh marine environments, data management and transmission requirements, computational cost for real-time updating, and the need for robust validation frameworks to ensure model credibility [116].

Overall, digital twin and data-driven approaches offer significant potential for enhancing structural integrity assessment through continuous monitoring and adaptive decision-making. However, their reliability depends critically on integration with physics-based models, ensuring that predictions remain physically consistent and interpretable. Within a multiscale framework, data-driven models should therefore be viewed not as replacements for mechanistic approaches, but as complementary tools that enhance predictive capability through data assimilation and uncertainty quantification.

More broadly, effective multiscale modelling for marine renewable energy systems requires a hierarchical and consistent information flow across length scales. Microstructure-resolved models provide insight into damage initiation mechanisms, mesoscale formulations capture crack propagation and interface behaviour, and macroscale approaches enable structural design and life prediction. Digital twin and data-driven methods close this loop by incorporating real-world observations, enabling continuous refinement of model predictions throughout the service life. The development of such integrated frameworks is essential for achieving reliable, mechanism-based qualification and lifecycle management of marine renewable energy infrastructure.

Despite rapid growth in digital twin research, most implementations remain at demonstration level. Industrial adoption requires validated workflows, standardised architectures, and clear metrics for model credibility and decision reliability.

5.6. Comparative Assessment of Modelling Approaches

To contextualise the applicability of different modelling approaches, Table 4 provides a comparative overview of their capabilities, limitations, and industrial readiness. No single approach is sufficient in isolation. Effective integrity assessment requires hierarchical integration, where lower-scale models inform constitutive behaviour and uncertainty bounds at higher scales.

Table 4. Summary of modelling approaches, along with their length scale, strength, limitation and readiness levels.

Approach	Scale	Strength	Limitation	Readiness
CPFEM	Micro	Captures microstructure-sensitive behaviour	High cost, calibration intensive	Low–Medium
CZM	Meso	Explicit crack modelling	Parameter identification required	Medium
CDM	Meso	Efficient damage representation	Limited physical interpretability	Medium–High
Fracture Mechanics	Structural	Inspection-compatible, robust	Requires initial crack	High
S–N + Miner	Structural	Simple, standardised	No physics, ignores sequence effects	Very High

6. Manufacturing-Induced Performance Variability

Manufacturing processes fundamentally define the as-built material state, which governs subsequent degradation behaviour and structural performance in marine renewable systems. Variability introduced during fabrication, through process-induced heterogeneity, residual stress fields, and defect populations, represents a major source of uncertainty in fatigue life prediction and structural reliability, often exceeding the influence of nominal material properties.

These effects are intrinsically linked to the degradation mechanisms discussed in Section 4 but are not typically treated explicitly within conventional design methodologies. Instead, manufacturing variability is commonly incorporated through empirical safety factors or simplified assumptions, which do not fully capture its mechanistic influence on damage initiation and evolution.

As marine renewable systems increasingly utilise advanced materials, complex welded geometries, and additive manufacturing processes, the role of manufacturing-induced variability becomes more pronounced and spatially heterogeneous. This necessitates a shift towards process-informed structural integrity assessment, in which fabrication history is explicitly linked to material behaviour and structural performance.

The following sections examine key manufacturing processes and their associated sources of variability, highlighting their impact on degradation mechanisms and structural reliability.

6.1. Welding and Joining Effects

Welded joints represent the dominant source of manufacturing-induced variability in offshore steel structures and are widely recognised as critical locations for fatigue crack initiation and structural degradation.

Thermal cycles associated with welding significantly modify the microstructure within the heat-affected zone (HAZ), leading to spatial variations in toughness and fatigue resistance. The HAZ is commonly divided into three characteristic regions based on peak temperature exposure [34]. The coarse-grained HAZ (CGHAZ), formed at high peak temperatures, undergoes substantial austenite grain growth followed by transformation to coarse bainitic or martensitic microstructures upon cooling, resulting in reduced toughness compared to the base material. In contrast, the fine-grained HAZ (FGHAZ) experiences lower peak temperatures, producing refined microstructures with comparatively improved toughness. The inter-critical HAZ (ICHAZ), subjected to partial phase transformation, often contains heterogeneous microstructures with hard martensite–austenite (MA) constituents, which can act as local brittle zones [69].

In multi-pass welds, additional complexity arises from reheating effects, leading to the formation of inter-critically reheated CGHAZ (ICCGHAZ), which is frequently associated with the lowest toughness within the welded region and can act as a preferential crack propagation path [39].

For high-strength steels, welding-induced metallurgical transformations may result in the formation of hard, brittle phases such as untempered martensite, increasing susceptibility to hydrogen-assisted cracking. Welding procedure specifications (WPS), including control of preheat, interpass temperature, and heat input, are therefore critical in managing cooling rates and microstructural evolution [69].

In addition to microstructural variability, weld defects such as porosity, lack of fusion, and slag inclusions introduce local stress concentrations that significantly reduce fatigue strength. Experimental and fracture mechanics-based studies indicate that such defects can reduce fatigue life by factors on the order of 1.5–3, depending on defect size, morphology, and location [35]. From a fracture mechanics perspective, these defects can be treated as initial cracks, with conservative estimates often based on a fraction of the defect size. For typical defect dimensions, the resulting stress intensity factors may exceed fatigue thresholds in marine environments, leading to immediate crack propagation and substantial reduction in fatigue life [47].

Inspection strategies must therefore balance detection capability with practical limitations. Non-destructive examination (NDE) techniques, such as ultrasonic testing, typically achieve detection thresholds on the order of a few millimetres, which may be comparable to critical defect sizes for fatigue initiation [57]. As a result, some defects may remain undetected yet still contribute to early-stage crack growth under service loading.

Overall, welding introduces coupled variations in microstructure, residual stress, and defect populations, all of which act to accelerate fatigue crack initiation and growth. These effects make welded joints the most critical regions for structural integrity in offshore systems, necessitating conservative design approaches and enhanced inspection and monitoring strategies.

6.2. Additive Manufacturing and Hybrid Manufacturing

Additive manufacturing (AM) provides significant design flexibility and enables complex geometries that are difficult to achieve using conventional processes. However, the layer-by-layer nature of AM introduces process-specific variability that strongly influences residual stress, microstructure, and defect populations, with direct implications for structural performance.

Residual stress formation in AM differs fundamentally from welding due to repeated thermal cycling and localized heat input during layer deposition. This leads to complex residual stress distributions, including gradients along the build direction and spatially varying patterns associated with scan strategies and melt pool overlap [79]. Such residual stresses can promote distortion during fabrication and contribute to crack initiation and fatigue damage under service loading [78].

Microstructural evolution in AM is governed by solidification conditions, particularly the thermal gradient and solidification velocity. These parameters influence grain morphology, with high thermal gradients favouring columnar grain growth aligned with the build direction, while lower gradients promote more equiaxed microstructures [117]. Consequently, AM components often exhibit pronounced anisotropy and spatial heterogeneity in mechanical properties, which can significantly affect deformation behaviour and crack propagation.

Process control strategies have been developed to mitigate these effects. Techniques such as interlayer temperature control, scan strategy optimisation, and in-situ mechanical treatments (e.g., rolling or peening) can refine microstructure and modify residual stress states [78]. Nevertheless, complete elimination of variability remains challenging, particularly for large-scale components and complex geometries.

A key challenge in AM is the elevated statistical variability of mechanical properties compared to conventionally manufactured materials. Reported coefficients of variation for strength, ductility, and fatigue performance are generally higher than those observed in wrought materials, reflecting the influence of defects, microstructural heterogeneity, and process fluctuations [82]. This variability complicates direct application of traditional deterministic design approaches.

Qualification of AM components therefore requires new methodologies that account for process–structure–property relationships. Current approaches include the use of in-situ monitoring techniques (e.g., melt pool imaging and thermal sensing) for defect detection, physics-based process modelling to predict residual stress and microstructure, and efforts to establish transferability between coupon-level testing and component-scale performance [117]. However, robust standards and universally accepted qualification frameworks are still evolving.

Overall, the inherent variability and defect sensitivity associated with additive manufacturing necessitates a shift towards probabilistic design and qualification strategies. Incorporating process-informed variability into structural integrity assessment is essential to ensure reliable performance of AM components in marine renewable energy applications.

6.3. Surface Engineering and Coatings

Surface engineering techniques are widely employed to enhance corrosion and wear resistance in marine renewable energy systems by modifying near-surface properties. However, the effectiveness of such treatments is inherently dependent on coating integrity, adhesion, and long-term durability under combined environmental and mechanical loading.

Wear-resistant coatings, such as thermal spray systems based on WC–Co or Cr_3C_2–NiCr, are commonly applied to components exposed to erosive environments, including tidal turbine blades and leading edges. These coatings provide substantially improved hardness and erosion resistance compared to steel substrates, thereby reducing material loss under particulate impact [60]. However, their performance is strongly influenced by coating microstructure, including residual porosity and interfacial bonding quality. Porosity inherent to thermal spray processes can allow seawater ingress, promoting under-coating corrosion, while insufficient adhesion may lead to coating spallation under cyclic or impact loading [50].

For corrosion protection, multilayer coating systems are typically employed, particularly in aggressive regions such as the splash zone. These systems generally comprise surface preparation (e.g., abrasive blasting to achieve adequate cleanliness and roughness), followed by a zinc-rich primer for galvanic protection, intermediate barrier coatings to limit moisture and ion transport, and a topcoat providing environmental and UV resistance [38]. The overall performance of such systems depends on maintaining coating continuity and preventing defect formation during application and service.

In addition to providing environmental protection, surface treatments influence the local mechanical state. Coating processes may introduce residual stresses due to deposition and thermal mismatch between coating and substrate materials. These stresses, together with differences in thermal expansion behaviour, can lead to additional stress development during service, particularly under temperature fluctuations. While well-adhered coatings may have a neutral or mildly beneficial effect on fatigue performance, coating degradation, through cracking, debonding, or local damage, can promote crevice formation and accelerate corrosion-driven fatigue processes [81].

Overall, surface engineering plays a critical role in mitigating degradation; however, coatings should not be considered as permanent barriers. Their degradation often acts as a trigger for accelerated damage in the underlying material, linking surface condition directly to long-term structural integrity. This highlights the need for inspection and maintenance strategies that explicitly account for coating performance and degradation over time.

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6.4. Process→Structure→Property→Performance Linkages

The process–structure–property–performance (PSPP) paradigm provides a unifying framework for linking manufacturing processes to structural integrity, enabling systematic understanding of how fabrication-induced variability governs degradation behaviour and service life. Within this framework, manufacturing is not treated as an external factor, but as a primary driver of material state, which subsequently determines mechanical response and structural performance across multiple length scales [118].

At the process level, manufacturing conditions such as thermal history, cooling rate, and heat input define the evolution of material structure. For example, thermal analyses in welding or multiphysics simulations in additive manufacturing provide spatially varying temperature fields and solidification conditions, which directly influence microstructural development. These conditions govern phase transformations, grain morphology, and defect formation, leading to heterogeneous microstructures characterised by variations in phase fraction and grain size.

These microstructural features, in turn, determine local mechanical properties. Established relationships, such as grain size strengthening and phase mixture models, enable estimation of spatially varying properties, including yield strength, ductility, and fracture resistance. Importantly, these properties are not uniform within a component but reflect the underlying process-induced heterogeneity.

At the structural level, incorporation of such spatial variability into finite element analyses enables more realistic prediction of stress distribution, damage initiation, and fatigue life. In contrast to conventional approaches based on nominal material properties, process-informed models capture localised effects associated with heat-affected zones, residual stresses, and defects, which often dominate failure behaviour [118].

Illustrative studies on welded structures demonstrate that accounting for manufacturing-induced microstructural degradation can lead to substantial differences in predicted structural performance. For example, inclusion of heat-affected zone properties and residual stresses in structural analysis can result in significant reductions in predicted fatigue life compared to idealised uniform-property assumptions [39]. Such findings highlight the sensitivity of structural integrity predictions to the as-manufactured material state.

More broadly, PSPP relationships provide a framework for integrating manufacturing variability into multiscale modelling approaches. By linking process simulations, microstructure evolution, property prediction, and structural analysis, these approaches enable consistent transfer of information across scales, reducing reliance on empirical assumptions. Table 5 summarises key sources of manufacturing-induced variability and their primary structural implications.

Overall, manufacturing-induced variability acts as a critical link between material behaviour and structural performance, influencing crack initiation, damage evolution, and failure probability. The interaction between defects, residual stresses, and environmental degradation mechanisms further amplifies uncertainty in marine renewable systems. Addressing this complexity requires integration of manufacturing-aware models within structural integrity assessment frameworks, providing a direct pathway toward the mechanism-resolved approaches discussed in subsequent sections.

Table 5. Summary of key manufacturing processes, sources of variability, and their primary implications for structural performance in marine renewable energy systems.

Process	Key Variability Source	Main Effect	Structural Impact
Welding	HAZ, residual stress, defects	Microstructure change	Fatigue crack initiation
AM	Porosity, anisotropy	Property scatter	Reduced reliability
Coating	Adhesion, degradation	Surface protection loss	Corrosion initiation

7. Inspection, Monitoring, and Lifetime Prediction

Inspection and monitoring systems provide the critical link between predicted and actual structural behaviour, enabling validation and continuous updating of degradation models under real operating conditions. In marine renewable energy systems, where environmental variability and manufacturing-induced uncertainty are significant, inspection data plays a vital role in reducing uncertainty and improving reliability through adaptive, data-informed structural integrity assessment.

As illustrated in Figure 5, inspection, monitoring, and decision-making form a closed-loop framework in which information flows continuously between data acquisition, model updating, and maintenance planning. Non-destructive evaluation (NDE) techniques and structural health monitoring (SHM) systems provide raw data on structural condition, which is subsequently processed and integrated into physics-based and data-driven models. These models are then updated using Bayesian or statistical approaches, reducing uncertainty in damage state estimation, and remaining useful life (RUL) prediction.

The updated predictions inform risk-based inspection scheduling and maintenance decisions, which in turn influence future inspection strategies. This feedback loop enables a transition from static, design-stage assessment toward dynamic lifecycle management, where structural integrity is continuously refined based on operational evidence.

This integrated approach is particularly important for marine renewable systems, where complex loading conditions, harsh environments, and manufacturing variability limit the reliability of purely predictive models. By incorporating inspection data into the modelling framework, it becomes possible to achieve more accurate and robust predictions of degradation evolution and structural reliability.

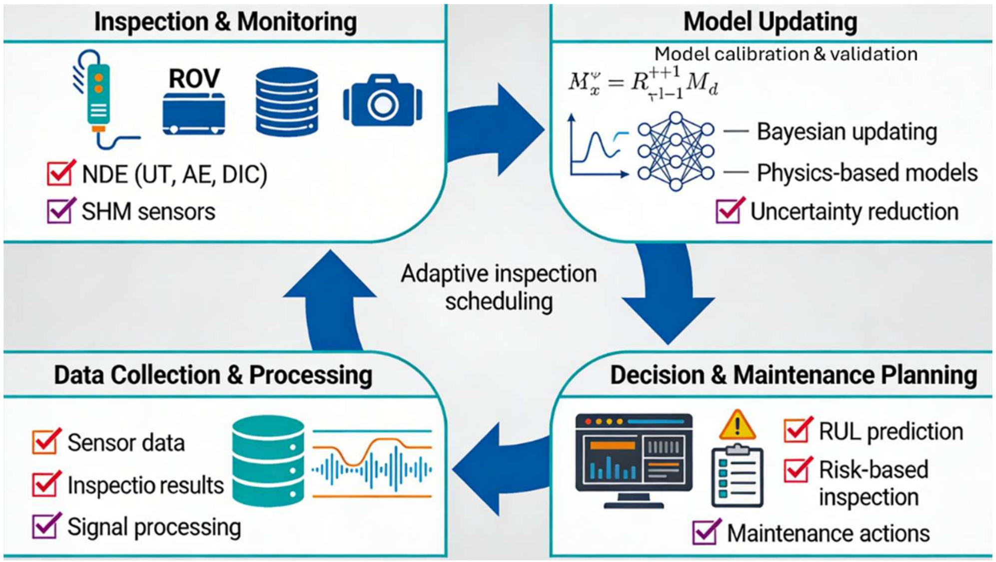

Figure 5. Closed-loop framework for inspection, monitoring, and adaptive structural integrity management in marine renewable energy systems, illustrating the integration of inspection data, signal processing, model

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updating (including Bayesian and physics-based approaches), and decision-making for maintenance and risk-based inspection planning.

7.1. Non-Destructive Evaluation Techniques

Non-destructive evaluation (NDE) techniques form the foundation of inspection and monitoring systems, providing critical information on structural condition without interrupting operation. In offshore environments, inspection methods must balance detection capability, cost, and accessibility constraints, particularly for subsea and hard-to-reach components.

Ultrasonic inspection, particularly phased array ultrasonic testing (PAUT), is widely used for volumetric examination of welds and base material [116]. Under favourable conditions, PAUT can detect defects of millimetre-scale dimensions with high probability of detection (POD), making it a primary tool for identifying fatigue cracks in offshore structures. However, its effectiveness is influenced by surface condition, geometry, and accessibility. Rough as-welded surfaces, complex joint configurations, and marine growth can reduce signal quality, often necessitating surface preparation prior to inspection. Deployment in offshore environments is typically achieved using remotely operated vehicle (ROV)-mounted systems, although inspection rates remain constrained by operational limitation [113].

Acoustic emission (AE) techniques provide a complementary approach by enabling passive monitoring of active damage processes [111]. Instead of detecting existing defects, AE systems identify transient elastic waves generated by phenomena such as crack growth or corrosion activity. Sensor networks distributed across the structure allow approximate localisation of damage sources, while machine learning methods are increasingly used to distinguish genuine damage signals from environmental or operational noise. The principal advantage of AE lies in its ability to provide continuous, large-area monitoring; however, its reliability is often limited by false positives, calibration requirements, and sensor durability in harsh marine environments [114].

Digital image correlation (DIC) offers full-field strain measurement by tracking surface deformation patterns between successive images [67]. This technique enables detailed characterisation of strain localisation, particularly in critical regions such as welded joints and crack tips. While DIC is widely used in laboratory validation, its offshore application remains more limited, typically involving fixed camera systems monitoring selected regions at discrete intervals [113].

In addition to periodic inspection techniques, structural health monitoring (SHM) systems provide continuous measurement of structural response through permanently installed sensors. These systems may include strain gauges, accelerometers, tiltmeters, corrosion probes, and distributed fibre optic sensing, enabling spatially distributed measurement of strain, temperature, and dynamic behaviour over large structures [119,120]. SHM data supports fatigue assessment, damage detection through changes in dynamic response, and long-term tracking of degradation processes.

No single inspection technique provides complete coverage of all relevant damage mechanisms. Ultrasonic methods are effective for detecting existing defects, AE systems capture active damage processes, and SHM sensors provide continuous operational data. Consequently, effective structural integrity assessment relies on the integration of multiple inspection modalities, as illustrated in Figure 5, enabling both detection of damage and monitoring of its evolution over time.

7.2. Inspection-Driven Structural Integrity Models

Inspection-driven structural integrity models provide a formal mechanism for integrating field observations with physics-based degradation models, enabling continuous refinement of structural integrity predictions throughout the service life. Within this framework, inspection data is not treated solely as a diagnostic input, but as a key component of probabilistic model updating.

Bayesian approaches are widely employed to incorporate inspection results into reliability assessment by updating prior assumptions on damage state using observed evidence [108]. In this context, the structural condition, such as crack size, is represented as a probabilistic variable, with an initial (prior) distribution derived from design-stage analysis and modelling.

Inspection outcomes are incorporated through likelihood functions, typically defined using probability of detection (POD) characteristics of the inspection method. For example, in the case of ultrasonic inspection, the likelihood of non-detection is related to the POD curve, reflecting the probability that a defect of a given size remains undetected. When no defects are observed during inspection, the posterior distribution is updated to favour smaller defect sizes, leading to a reduction in both the expected damage level and associated uncertainty [47].

Repeated inspections further refine the posterior distribution, progressively reducing uncertainty and improving confidence in the estimated structural state. In practical applications, this updating process may be implemented using analytical formulations for simple cases or numerical techniques such as Markov Chain Monte Carlo (MCMC) methods when dealing with complex, multi-parameter systems [110].

This probabilistic updating framework enables inspection data to directly influence predictions of degradation evolution and failure probability. As illustrated in Figure 5, the updated structural state feeds into model calibration and decision-making processes, supporting adaptive inspection planning and maintenance strategies. In this way, inspection is transformed from a periodic verification activity into an integral component of predictive structural integrity assessment.

7.3. Reliability-Based Maintenance Strategies

Maintenance strategies in marine renewable systems are increasingly transitioning from deterministic, schedule-based approaches towards reliability- and risk-informed frameworks that explicitly account for uncertainty in degradation processes. Within the closed-loop paradigm illustrated in Figure 5, inspection data, model updating, and decision-making are tightly coupled to enable adaptive lifecycle management.

Risk-based inspection (RBI):

Inspection planning is prioritised based on quantified risk, defined as the product of failure probability (P_f) and consequence (C_f):

$$\text{Risk} = P_f \times C_f$$

Components are ranked according to their risk contribution, enabling targeted allocation of inspection resources to critical locations [116]. For example, structural hotspots such as monopile mudlines and jacket joints typically exhibit higher risk due to combined fatigue loading and environmental exposure, whereas lower-risk components are inspected less frequently [110]. This prioritisation ensures that inspection effort is aligned with structural criticality and reliability targets.

Predictive and condition-based maintenance:

Traditional time-based inspection intervals are increasingly replaced by condition-based strategies informed by monitoring data [111]. Damage indicators (DI) derived from structural health monitoring (SHM), such as cumulative fatigue damage:

$$DI = \sum \left(\frac{n_i}{N_i}\right)$$

are used to trigger inspections when predefined thresholds are exceeded. Maintenance decisions are further conditioned on reliability metrics, for example when $DI > 0.7$ and the reliability index βapproaches target limits. Such approaches have been shown to reduce inspection frequency while improving early detection of anomalous degradation, resulting in both risk reduction and operational cost savings [111].

Remaining useful life (RUL) prediction:

RUL estimation integrates inspection data with physics-based degradation models and probabilistic updating frameworks [47]. A typical formulation expresses RUL as:

$$RUL = \frac{a_{\text{critical}} - a_{\text{current}}}{(da/dt)_{\text{effective}}}$$

where the effective crack growth rate is obtained from calibrated fracture mechanics models incorporating measured loading histories, environmental effects, and uncertainty in material parameters. Bayesian updating enables continuous refinement of model parameters as new inspection data becomes available, resulting in probabilistic RUL estimates with associated confidence bounds [110].

In practical applications, such as offshore jacket joints with detected subcritical cracks, this approach enables estimation of remaining service life and supports informed decisions on inspection intervals, repair, or replacement. Importantly, the probabilistic nature of RUL predictions allows explicit consideration of uncertainty, which is essential for risk-informed decision-making.

Overall, the integration of inspection data, probabilistic modelling, and physics-based degradation laws establishes a robust framework for adaptive maintenance. As illustrated in Figure 5, this closed-loop approach enables continuous updating of structural integrity assessments, facilitating a transition towards digital twin-enabled lifecycle management in marine renewable energy systems.

8. Qualification and Design Standards: Current Gaps

Qualification and design standards provide the foundation for structural integrity assessment in marine renewable energy systems, defining accepted methodologies for design, material selection, inspection, and lifecycle management. However, these frameworks have largely evolved from offshore oil and gas practices and remain predominantly empirical in nature, relying on historical datasets, simplified damage models, and conservative safety factors.

As highlighted in preceding sections, degradation in marine renewable systems is governed by complex, interacting mechanisms spanning multiple length and time scales, including microstructure-sensitive fatigue, corrosion–fatigue coupling, hydrogen-assisted cracking, and manufacturing-induced variability. While advanced modelling approaches (Section 5) and inspection-informed updating frameworks (Section 7) offer the capability to capture these mechanisms, their integration into current standards remains limited.

This disconnect becomes increasingly critical as marine renewable systems grow in scale, operate under more severe cyclic loading, and incorporate advanced materials and manufacturing processes. Consequently, existing qualification approaches may introduce excessive conservatism in some cases while failing to capture critical degradation mechanisms in others.

These limitations highlight the need for a transition from purely empirical design frameworks towards mechanism-informed, data-integrated qualification methodologies that combine physics-based modelling, probabilistic assessment, and inspection-driven updating. The following sections critically examine current standards, identify key limitations, and outline pathways toward next-generation qualification frameworks.

8.1. Existing Offshore and Marine Standards

Offshore renewable energy design frameworks are largely derived from established oil and gas industry standards, adapted to account for wind- and wave-induced loading conditions. These standards provide comprehensive guidance for structural design, material qualification, and inspection planning, forming the basis of current engineering practice.

Structural design is primarily governed by standards such as DNV-ST-0126, which provides design requirements for offshore wind turbine support structures, including both fixed and floating configurations. Fatigue design is typically addressed using recommended practices such as DNV-RP-C203, which defines S–N curves and fatigue assessment procedures, while ISO 19902 provides broader guidance for fixed offshore steel structures. In parallel, IEC 61400-3-1 establishes design requirements specific to offshore wind energy systems, integrating environmental loading and turbine–structure interaction considerations [57,116,121,122].

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Material qualification and fabrication are addressed through standards such as DNV-ST-C502 for offshore concrete structures [123] and AWS D1.1 for structural welding [124], which define testing procedures, acceptance criteria, and welding qualification requirements. Supporting guidelines, including DNVGL-CG-0129 [125], provide material property data and fatigue design parameters derived from experimental databases.

Inspection and integrity management are guided by probabilistic frameworks such as DNV-RP-C210 [126], which supports risk-based inspection planning for fatigue-critical components. More recently, standards such as DNVGL-RP-0001 [127] have begun to address emerging technologies, including the qualification and assurance of digital twins, reflecting the increasing role of data-driven approaches in structural integrity assessment.

While these standards provide a robust and widely accepted foundation for design and lifecycle management, they are predominantly based on empirical relationships and historical datasets. As a result, their ability to capture emerging materials, complex multiphysics degradation mechanisms, and manufacturing-induced variability remains limited, particularly in the context of next-generation marine renewable energy systems.

8.2. Limitations of Current Qualification Approaches

Despite their widespread adoption, current qualification approaches exhibit fundamental limitations in their ability to represent the underlying physics governing degradation and structural performance. These limitations arise primarily from the reliance on empirical formulations that do not fully capture the multiscale and multiphysics nature of damage evolution in marine environments.

A key limitation lies in the treatment of materials as homogeneous continua within fatigue design methodologies. Conventional S–N curve approaches neglect microstructural effects such as grain size, crystallographic texture, phase distribution, and local heterogeneity within heat-affected zones (HAZ) [42]. As discussed in Sections 4 and 5, these features play a critical role in crack initiation and early damage evolution. Their omission necessitates the use of conservative safety factors, typically on the order of 1.5–3.0, which may penalise advanced materials and restrict design optimisation.

A second limitation is the lack of mechanistic coupling between interacting degradation processes. While standards account for environmental effects through empirical reduction factors, for example, applying fatigue life reduction factors for seawater exposure, they do not explicitly model the interaction between electrochemical processes, cyclic loading, and hydrogen effects [56]. Consequently, key phenomena such as corrosion–fatigue interaction, hydrogen-assisted cracking, and coating degradation are treated in a simplified and decoupled manner, limiting predictive capability under realistic service conditions.

Manufacturing-induced variability represents a further source of discrepancy between qualification and in-service performance. Current qualification procedures, particularly for welded structures, rely on limited testing of procedure qualification records (PQR), often based on a small number of specimens under controlled conditions [39]. These tests do not adequately capture the statistical variability associated with production-scale welding, including residual stress distributions, defect populations, and geometric variability. As a result, the influence of manufacturing on structural performance is only partially represented.

These challenges are further amplified for emerging manufacturing technologies such as additive manufacturing, where variability in microstructure, defect distribution, and mechanical properties remain significantly higher than in conventional processes [82]. The absence of standardised qualification methodologies, coupled with limited long-term performance data, introduces substantial uncertainty in the structural reliability of additively manufactured components.

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Collectively, these limitations indicate that current qualification frameworks remain largely disconnected from the physical mechanisms governing material degradation and failure. Their reliance on conservative empirical factors can lead either to over-conservative designs or, in some cases, insufficient representation of critical degradation processes. This highlights the need for a transition towards mechanism-informed qualification approaches that integrate multiscale modelling, multiphysics coupling, and inspection-driven updating.

8.3. Need for Mechanism-Resolved Qualification Frameworks

Addressing the limitations identified above requires a fundamental shift towards mechanism-resolved qualification frameworks, in which material behaviour, degradation processes, and structural response are explicitly linked through multiscale modelling and inspection-informed updating. Rather than relying solely on empirical testing and historical datasets, future qualification approaches must integrate validated physics-based models with targeted experimental evidence.

A central requirement is the explicit incorporation of microstructure–property relationships. Advanced modelling approaches, such as crystal plasticity and phase-field methods, calibrated using micromechanical testing and microstructural characterisation (e.g. nanoindentation, micropillar testing, and EBSD), enable prediction of fatigue behaviour and damage initiation based on material microstructure [42]. This provides a pathway for evaluating material performance beyond conventional S–N curve representations.

In parallel, manufacturing processes must be explicitly incorporated into qualification through process–structure modelling. Thermal–metallurgical–mechanical simulations enable prediction of residual stress fields, microstructural evolution, and defect distributions, providing realistic as-manufactured material states as input to structural analyses [78]. This represents a departure from traditional approaches that assume nominal material properties.

A further requirement is the integration of coupled multiphysics degradation models. As discussed in earlier sections, degradation mechanisms in marine environments arise from interactions between electrochemical processes, mechanical loading, hydrogen diffusion, and environmental exposure. Finite element frameworks capable of capturing these coupled phenomena are essential for realistic prediction of damage evolution under service conditions [56].

Equally important is the incorporation of inspection-informed updating within the qualification process. Bayesian frameworks enable continuous refinement of degradation predictions as inspection data becomes available, allowing qualification to evolve over the structure's lifetime rather than remaining fixed at the design stage [47]. This capability is further enhanced through integration with digital twin architectures, where real-time sensor data and operational information are assimilated into predictive models to provide asset-specific structural integrity assessment [111].

Collectively, these elements establish a mechanism-resolved approach that reduces reliance on extensive empirical testing, enables qualification of novel materials and manufacturing routes, and provides transparent safety margins grounded in physical understanding rather than historical precedent. Such frameworks support a transition from static, design-stage qualification towards dynamic, lifecycle-based assessment, in which structural integrity is continuously evaluated and updated.

Table 6 summarises the key differences between current empirical approaches and mechanism-based qualification frameworks. Overall, while existing standards provide a necessary baseline for structural design, they lack the capability to fully capture the complex, coupled degradation processes present in marine renewable systems. Bridging this gap requires integration of multiscale modelling, manufacturing-aware analysis, and inspection-informed updating within unified qualification frameworks. The following section builds upon these concepts to present an integrated mechanism-resolved design and qualification framework.

Table 6. Comparison between conventional empirical qualification approaches and mechanism-resolved frameworks for marine renewable structures.

Aspect	Current Standards	Mechanism-Based Approach
Material model	Homogeneous	Microstructure-informed
Fatigue	S-N curves	Mechanism-based
Degradation	Reduction factors	Multiphysics coupling
Manufacturing	Implicit	Explicit modelling
Inspection	Periodic	Adaptive & data-driven

9. Future Framework: Mechanism-Resolved Reliability Design

Building on the limitations identified in current qualification approaches (Section 8), this section presents an integrated mechanism-resolved reliability framework for marine renewable energy systems. The proposed framework synthesises advances in multiscale modelling (Section 5), manufacturing-aware analysis (Section 6), and inspection-informed updating (Section 7) into a unified design and qualification methodology.

In contrast to conventional approaches, which rely on empirical relationships, static safety factors, and decoupled analyses, the proposed framework explicitly links material behaviour, degradation mechanisms, and structural response across scales. This integration enables a physically consistent representation of damage initiation, propagation, and failure under realistic service conditions.

A key feature of the framework is the transition from static, design-stage qualification to dynamic, lifecycle-based structural integrity assessment. By incorporating manufacturing variability, environmental interactions, and continuously updated inspection data, the framework supports adaptive prediction of structural performance and reliability over time.

This mechanism-resolved approach provides a pathway for reducing design conservatism while maintaining safety, enabling qualification of advanced materials and manufacturing processes, and supporting digital twin-based asset management. The following subsections outline the key components of the framework and their integration into a closed-loop reliability design methodology.

9.1. Proposed Integrated Design Framework

The proposed framework is structured around four interconnected pillars that collectively enable mechanism-resolved structural integrity assessment across the full lifecycle of marine renewable energy systems. As illustrated in Figure 6, these pillars form a closed-loop reliability framework, in which information continuously circulates between multiscale modelling, manufacturing qualification, digital twin integration, and adaptive inspection and maintenance. Unlike conventional approaches, this framework explicitly links material behaviour, as-manufactured state, operational data, and decision-making within a unified and continuously evolving system.

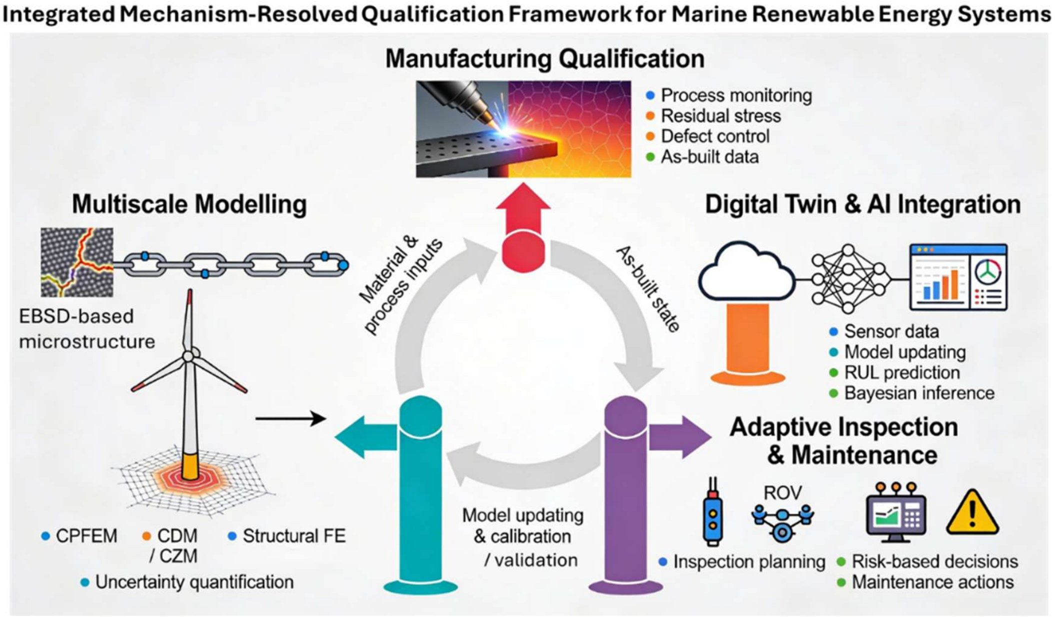

Figure 6. Integrated mechanism-resolved qualification framework for marine renewable energy systems. The framework combines multiscale modelling, manufacturing qualification, digital twin integration, and adaptive inspection and maintenance within a closed-loop system. Information flows across scales through parameter transfer and upscaling, while operational data enable continuous model updating, calibration, and validation. This integrated approach links material behaviour, as-manufactured state, and structural performance to support adaptive, data-informed lifecycle reliability assessment.

Pillar 1: Multiscale Modelling

The first pillar establishes a hierarchical modelling chain linking processing → structure → properties → performance [118]. At the microscale, material behaviour is represented using synthetic microstructure generation techniques (e.g., Voronoi tessellation, phase-field methods) or direct EBSD-based inputs capturing grain morphology, crystallographic texture, and phase distribution. Crystal plasticity finite element modelling (CPFEM) is employed to resolve stress–strain heterogeneity and identify damage initiation indicators such as fatigue indicator parameters (FIPs).

At the mesoscale, statistically representative volume element (RVE) homogenization provides effective constitutive laws for continuum-scale modelling, while damage evolution is captured using continuum damage mechanics (CDM) and cohesive zone models (CZM). These models are subsequently integrated into macroscale finite element (FE) simulations to predict structural response, fatigue life, and reliability under realistic loading conditions.

Uncertainty quantification, typically through Monte Carlo sampling across microstructural realizations, provides statistical bounds on performance [42]. Importantly, this pillar enables upscaling and parameter transfer across length scales, while also allowing feedback from higher-scale observations to refine lower-scale models. These outputs provide the foundational material behaviour and uncertainty bounds required for manufacturing qualification and structural analysis.

Pillar 2: Manufacturing Qualification

The second pillar captures the as-manufactured state, which plays a critical role in determining structural performance. Process monitoring and control are achieved through in-situ sensing techniques, such as weld thermal imaging and additive manufacturing melt pool monitoring, providing real-time indicators of fabrication quality. These measurements are coupled with process–structure models to predict microstructural evolution, residual stress distributions, and defect populations based on thermal histories [78].

Statistical process control frameworks track key manufacturing indicators (e.g., heat input variability, defect occurrence rates), enabling early detection of deviations and corrective action. Additionally, comprehensive as-built documentation, including geometry, residual stress measurements, and process histories, is generated for each component.

This pillar transforms manufacturing from a deterministic assumption into a data-rich input, where the resulting as-built state feeds directly into digital twin initialization and subsequent structural integrity assessment.

Pillar 3: Digital Twin Integration

The third pillar introduces a cyber-physical system that maintains a continuously updated digital representation of the physical asset [113]. The digital twin is initialized using calibrated FE models that incorporate as-manufactured properties, including measured residual stresses, geometry deviations, and material heterogeneity.

During operation, real-time data from structural health monitoring (SHM) systems—such as strain, acceleration, tilt, and temperature—are assimilated alongside environmental inputs (wind, waves) using filtering techniques (e.g., Kalman filtering) to continuously update the structural state.

Physics-based degradation models are then applied to predict damage evolution and estimate remaining useful life (RUL) with associated uncertainty bounds.

Crucially, this pillar enables data-driven model updating and parameter calibration, ensuring that predictions remain consistent with observed structural behaviour. The updated state information forms the basis for decision-making and maintenance planning.

Pillar 4: Adaptive Inspection and Maintenance

The fourth pillar closes the loop by linking model predictions to inspection and maintenance strategies. Initial inspection plans are derived from design-stage reliability assessments, typically using risk-based methodologies. As inspection data become available—such as crack detection or measured defect sizes—Bayesian updating techniques are used to refine probabilistic descriptions of damage states and structural reliability [110].

This updated information enables re-optimization of inspection intervals, selection of appropriate inspection techniques, and prioritization of critical components. Maintenance actions are triggered based on predicted reliability thresholds and RUL estimates, transitioning from fixed schedules to condition-based and predictive maintenance strategies.

Importantly, inspection outcomes and operational data are fed back into both the digital twin and multiscale modelling frameworks, enabling continuous improvement of predictive capability and informing future design practices.

Framework Integration and Closed-Loop Operation

Collectively, these four pillars establish a closed-loop, mechanism-resolved framework that links material-scale behaviour to system-level performance while continuously incorporating real-world data. The interaction between pillars, material and manufacturing inputs, as-built state transfer, data-driven model updating, and feedback to modelling, ensures that structural integrity assessment evolves throughout the lifecycle of the asset.

This integrated approach represents a shift from static, design-stage qualification toward adaptive, data-informed lifecycle management, enabling reduced uncertainty, improved reliability prediction, and more efficient inspection and maintenance strategies.

9.2. Integration with Materials 4.0 and Industry 5.0

Emerging paradigms such as Materials 4.0 and Industry 5.0 provide enabling capabilities for the implementation of mechanism-resolved reliability frameworks, supporting the integration of data-driven methodologies, physics-based modelling, and lifecycle management.

Materials 4.0 represents a data-centric approach to materials development, combining high-throughput experimentation, computational modelling, and machine learning to accelerate material discovery and qualification [128,129]. In this context, large-scale datasets generated through combinatorial synthesis and automated testing enable the development of surrogate models—such as Gaussian process regression and neural networks—that interpolate material behaviour across composition and processing spaces. Active learning strategies further enhance efficiency by iteratively selecting experiments that maximise information gain, thereby reducing the experimental effort required for model calibration [130].

Within marine renewable energy applications, these approaches offer the potential to accelerate the development and qualification of advanced materials, including corrosion-resistant high-strength steels (e.g. S550–S750) and novel alloy systems. Data-driven optimisation of composition and processing parameters can reduce development timelines while enabling targeted improvement of fatigue, corrosion, and hydrogen resistance [131]. Importantly, when integrated with the multiscale modelling framework described in Section 9.1, Materials 4.0 enables direct linkage between material design and structural performance.

Industry 5.0 extends this paradigm by emphasising human-centric, sustainable, and resilient manufacturing systems that integrate digital technologies with expert knowledge [128]. In the context of structural integrity assessment, this enables collaborative qualification approaches in which domain expertise from metallurgists, inspectors, and operators is combined with AI-assisted predictions to support informed decision-making. Furthermore, Industry 5.0 introduces sustainability considerations into the design process, incorporating lifecycle environmental impact, material recyclability, and repair-versus-replacement strategies into qualification frameworks.

In addition, distributed and flexible manufacturing approaches, such as additive manufacturing and modular fabrication, enhance supply chain resilience and enable localised production of critical components [132]. However, these approaches also introduce variability that must be explicitly accounted for within mechanism-based qualification methodologies.

The integration of Materials 4.0 and Industry 5.0 concepts within the proposed framework enhances its scalability, adaptability, and predictive capability. By combining data-driven materials design, physics-based modelling, and inspection-informed updating, the framework supports reduced design conservatism, improved qualification of emerging materials and manufacturing processes, and more efficient lifecycle management through adaptive inspection and maintenance strategies.

9.3. Research Priorities and Emerging Technologies

The practical implementation of mechanism-resolved qualification frameworks requires addressing several critical research challenges that currently limit their scalability, validation, and industrial adoption. These challenges span multiscale modelling, manufacturing variability, and data-driven decision systems, and must be resolved to enable reliable, deployable engineering solutions.

A key priority is the development of robust corrosion–fatigue multiphysics models. Although individual corrosion and fatigue mechanisms are relatively well understood, validated coupled formulations that simultaneously capture electrochemical kinetics, mechanical loading, and damage evolution remain limited. Progress in this area requires benchmark experimental datasets obtained under controlled conditions, incorporating simultaneous electrochemical and mechanical measurements, alongside the development of constitutive laws capable of representing coupled degradation processes across scales [56].

Another major challenge lies in quantifying variability in additively manufactured materials. Compared to conventional manufacturing, AM components exhibit greater scatter in mechanical properties and defect populations, necessitating statistically rigorous characterisation. This includes large-sample experimental studies, detailed defect mapping through destructive and non-destructive techniques, and systematic evaluation of the transferability of coupon-scale data to structural components [82]. Without such datasets, reliable integration of AM materials into structural integrity frameworks remains constrained.

The credibility and validation of digital twins represent a further research priority. While digital twin technologies offer significant potential for real-time structural assessment, standardised validation methodologies are still emerging. Key requirements include quantitative metrics for model fidelity—such as prediction–measurement residuals and uncertainty coverage—as well as evaluation of decision-making performance, including false-positive and false-negative rates in maintenance actions [111,113]. Establishing such validation protocols is essential to ensure confidence in digital twin-assisted integrity management.

In addition, the qualification of hybrid renewable systems introduces new interdisciplinary challenges. The integration of offshore structures with process equipment, such as electrolyzers and hydrogen handling systems, requires reconciliation between traditionally separate design frameworks, including offshore structural standards and pressure equipment codes. This necessitates consideration of hydrogen–material interactions, process safety methodologies (e.g. HAZOP), and their integration within structural integrity assessment [58,133].

Alongside these research challenges, several emerging technologies offer significant potential to support mechanism-resolved qualification frameworks. Self-sensing materials, incorporating embedded sensing capabilities such as piezoelectric fibres or magneto-elastic coatings, may enable distributed structural monitoring without reliance on external sensor networks [134]. Autonomous inspection systems, including underwater robotic platforms equipped with onboard artificial intelligence, provide opportunities for more frequent, consistent, and cost-effective inspection, reducing dependence on human operators and improving data quality [135].

Advances in corrosion-resistant materials, including alloy design strategies for enhanced durability in marine environments, may reduce reliance on conventional protection systems such as cathodic protection, thereby simplifying maintenance requirements [37]. In parallel, the development of offshore edge computing technologies enables localised data processing and real-time analytics, reducing communication demands and enhancing the robustness of monitoring systems under limited connectivity conditions [113].

Collectively, addressing these research priorities and leveraging emerging technologies are essential steps toward transitioning mechanism-resolved frameworks from conceptual models to practical engineering tools. By integrating advances in materials science, multiscale modelling, and digital technologies, the proposed framework provides a pathway toward next-generation structural integrity assessment, in which design, monitoring, and maintenance are unified within a continuously evolving, data-informed system. This approach has the potential to reduce uncertainty, enhance reliability, and optimise lifecycle performance, thereby supporting the large-scale deployment of marine renewable energy infrastructure.

10. Key Research Gaps and Open Challenges

Despite advances in modelling and materials, several critical challenges limit the practical implementation of mechanism-resolved structural integrity frameworks:

1. Lack of validated multiphysics corrosion–fatigue models; existing models typically treat corrosion and fatigue independently, whereas real systems exhibit strongly coupled behaviour.
2. Manufacturing-induced variability not fully quantified; residual stresses, defects, and microstructural gradients significantly influence fatigue life but are not systematically incorporated into design models.
3. Digital twin validation remains immature; robust validation methodologies and performance metrics are lacking, limiting industrial confidence.
4. Microstructure effects are absent in design standards; current standards assume homogeneous materials, neglecting microstructure-sensitive behaviour.
5. Data scarcity for emerging materials; advanced alloys and AM components lack long-term field data required for reliable qualification.

Addressing these gaps is essential for transitioning from empirical design approaches to predictive, mechanism-based frameworks.

11. Conclusions

This review has examined the degradation, modelling, and qualification challenges governing structural integrity in marine renewable energy systems, with emphasis on offshore wind, tidal, wave, and emerging hybrid offshore energy platforms. A central conclusion is that reliability remains the dominant barrier to cost-effective deployment, not only because of high offshore operations and maintenance costs, but because degradation in these systems is governed by coupled physical mechanisms that are insufficiently represented in current qualification practice. Corrosion–fatigue, hydrogen-assisted cracking, variable-amplitude loading, tribological damage, and manufacturing-induced variability act across multiple length scales and often interact non-linearly, making purely empirical design approaches increasingly inadequate.

The review further shows that structural performance cannot be understood solely at the continuum scale. Microstructure-sensitive deformation, phase interaction, void nucleation, residual stresses, and defect populations all influence crack initiation and early damage evolution. These effects are particularly important in advanced materials, welded joints, and additively manufactured components, where the as-manufactured condition strongly affects in-service behaviour. Multiscale and multiphysics modelling approaches, including CPFEM, CZM/CDM, fracture mechanics, and inspection-informed Bayesian updating, provide the tools needed to bridge this gap between material behaviour and structural reliability.

A further key conclusion is that qualification methodologies must evolve from static, design-stage verification towards adaptive, lifecycle-based integrity management. Inspection and monitoring are not merely diagnostic activities; when integrated with probabilistic updating, digital twins, and physics-based degradation models, they become central to predictive structural integrity assessment. This enables continuous refinement of remaining useful life estimates, risk-based maintenance, and more transparent management of uncertainty during service.

Current standards provide a necessary and robust baseline for offshore structural design, but they remain largely empirical and are only partially aligned with the degradation complexity of marine renewable systems. Their limited treatment of microstructural effects, manufacturing variability, and coupled degradation processes highlights the need for more physically informed qualification strategies. The integrated mechanism-resolved reliability framework proposed in this review addresses this gap by linking four core pillars: multiscale modelling, manufacturing qualification, digital twin integration, and adaptive inspection and maintenance.

Looking forward, the development of reliable and scalable marine renewable energy infrastructure will depend on coordinated advances in experimental validation, process-aware modelling, probabilistic qualification, and digital engineering. In particular, research priorities should focus on validated multiphysics corrosion–fatigue models, robust quantification of additive manufacturing variability, digital twin credibility assessment, and qualification of hybrid offshore energy systems involving hydrogen infrastructure. By integrating materials science, structural mechanics, manufacturing knowledge, and operational data within unified frameworks, the sector can move beyond conservative empirical design towards predictive, mechanism-informed lifecycle management. This transition is likely to be essential for reducing uncertainty, improving reliability, and supporting the large-scale deployment of marine renewable energy systems over the coming decades.

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