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Review

Failure analysis of tidal turbine blades: understanding erosion mechanisms and their impact on structural integrity

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ABSTRACT

Tidal energy presents a promising renewable resource; however, the reliability of turbine systems remains a critical challenge. Erosion of turbine blades, driven by mechanisms such as cavitation, abrasion, and suspended sediment impact, compromises both structural integrity and hydrodynamic performance over extended operational periods. Horizontal-axis tidal turbines equipped with composite blades have emerged as a leading technology that demands long-term durability in marine environments.

Polymer composites offer favourable strength-to-weight characteristics, yet their susceptibility to moisture, dynamic loading, and surface degradation must be carefully managed. Predicting and mitigating erosion remains complex due to the diverse range of contributing factors, including flow friction, cavitation-induced microjets, and abrasive particles. The severity and localisation of erosion are strongly influenced by site-specific operational and environmental conditions, progressing from micro-scale pitting to material loss and surface roughening.

Accurate metrology techniques and controlled experimental studies, when coupled with multiphysics simulations, can support the design of erosion-resistant materials and blade geometries. Leading-edge erosion is of particular concern, as it disrupts flow separation and stall characteristics, resulting in reduced lift and long-term power loss. Validated numerical models enable insight into these effects beyond the scope of physical testing.

This review promotes an integrated framework that links materials research, erosion monitoring, and predictive modelling to inform the development of durable turbine blades. Advancements in these areas are essential for extending maintenance intervals, improving operational efficiency, and unlocking the full potential of tidal energy conversion technologies in challenging offshore environments.

1. Introduction

1.1. Background

The climate crisis and the finite nature of fossil fuel resources have driven growing interest in low-carbon renewable energy sources

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[1,2]. In 2007, fossil fuels accounted for 88 % of global energy consumption. In response, the Intergovernmental Panel on Climate Change called for a 50 to 85 per cent reduction in greenhouse gas (GHG) emissions by 2050 to mitigate the impacts of severe global warming and climate change [3]. Their recommendation highlights the urgency of transitioning from fossil fuels to reliable and economically viable renewable energy sources such as hydroelectricity, solar, and wind, which are among the leading renewable technologies capable of sustainably meeting energy demands. Solar and wind power expanded rapidly, supplying approximately 850 TWh and 250 TWh of electricity worldwide in 2015, respectively. Hydroelectric generation has grown steadily, increasing fourfold between 1965 and 2015 as more countries adopted this renewable resource [4]. However, current hydroelectric output represents only a fraction of the global potential of this technology. Although geographical limitations restrict further hydroelectric expansion, oceans cover over 70 per cent of the Earth's surface, representing a vast and largely untapped source of renewable energy. This energy can be harnessed from offshore winds, waves, tidal currents, ocean thermal and salinity gradients [5]. The kinetic energy from tidal currents and offshore winds are particularly promising ocean renewable resources for conversion into electricity [1].

Ocean currents are primarily driven by wind patterns and surface heat fluxes, circulating large volumes of water across the globe. These currents represent a substantial indirect solar energy resource, with flow velocities reaching up to 2.5 m per second in narrow channels near islands and coastal cliffs [6]. Tidal Energy Converters (TECs) can harness localised high-velocity currents at these chokepoints to generate electricity. Given their advantages over offshore wind turbines, there are compelling reasons to advance the development and study of TECs. The density of water is approximately 850 times greater than that of air, resulting in significantly higher thrust and power generation potential for tidal turbines with capacities equivalent to wind turbines. In addition, the buoyant force can counterbalance the weight of components in horizontal-axis (h-axis) tidal turbines, which is essential for their structural stability [5]. However, tidal turbines experience torque loads that are approximately 50 per cent higher than those in wind turbines, requiring more robust structural designs to endure lifetimes of 20 to 25 years in harsh marine environments [7]. Blade materials and components must withstand corrosion, cavitation, and continuous load reversals. While these performance advantages are well established in principle, the practical deployment of TECs remains constrained by high uncertainty regarding long-term structural reliability and limited availability of field data. The extended development timeline for energy converters such as tidal and wind turbines is largely driven by the need for reliable and efficient systems capable of withstanding extreme operational conditions [8]. Maintaining functionality throughout operational lifetimes in remote offshore locations continues to present a significant technical challenge.

Despite the advantages of TECs, commercialisation remains constrained by high initial capital costs [2]. In addition, tidal energy projects require extensive reference data on site-specific environmental interactions to inform zoning, permitting, and device placement. Establishing baseline environmental impact data is essential for evaluating and managing risks associated with full-scale deployment. However, the collection of long-term ecological and hydrodynamic data at prospective tidal energy sites presents logistical and financial challenges. The difficulty of conducting continuous monitoring in remote offshore environments further limits the ability to validate model predictions or generalise findings across different locations. As a result, many of the assumptions used in tidal energy feasibility studies remain unverified at commercial scale. Addressing these technical and economic uncertainties is essential for unlocking the full potential of tidal energy.

Several technologies have been developed to harness the considerable potential of tidal energy. The two principal approaches

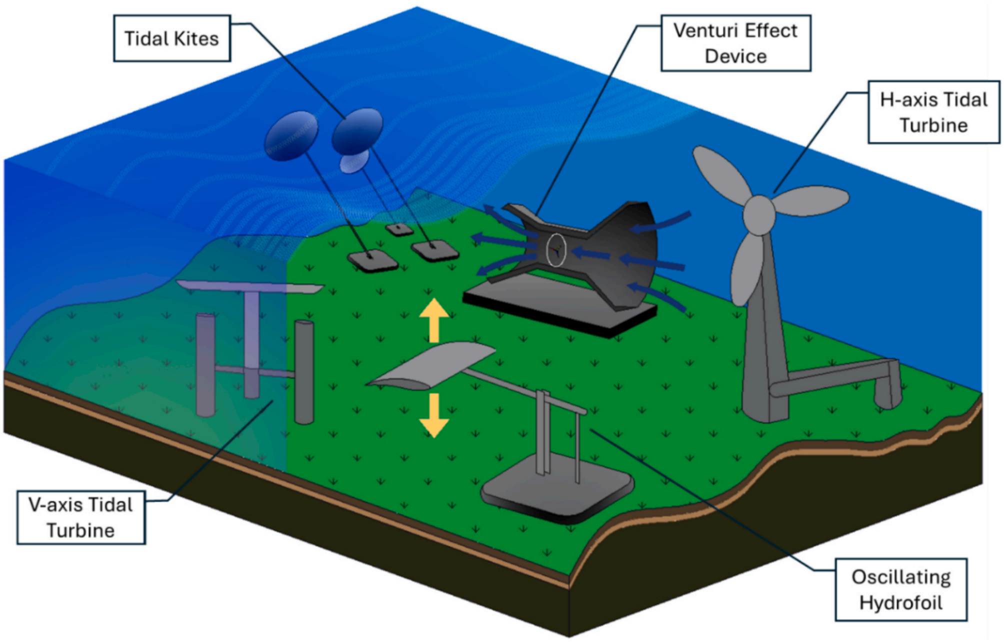

Fig. 1. Types of tidal energy converters.

include tidal barrages or lagoons, which trap water behind dams, and tidal current converters, which extract kinetic energy from free-flowing currents. Tidal barrages operate based on the tidal range, defined as the difference between high and low tide levels. These systems use low-head hydropower turbines to generate electricity during ebb and flood conditions as water moves through gated structures [9]. Although the concept is technically mature and well understood, its implementation remains rare. Tidal barrages require substantial capital investment and are frequently associated with concerns over ecological disruption, sediment displacement, and long-term impacts on estuarine biodiversity. These factors have limited the global adoption of barrage schemes. To date, only a small number of projects have been constructed, including La Rance in France and Sihwa Lake in South Korea, both of which serve more as test beds or demonstration sites than scalable commercial models [10].

In contrast, tidal current converters extract kinetic energy directly from marine currents while aiming to minimise environmental impacts. Tidal currents follow bidirectional cycles, driven by gravitational interactions between the Earth, Moon, and Sun [11]. A variety of conversion technologies have been proposed, including horizontal-axis turbines, vertical-axis turbines, oscillating hydrofoils, venturi-effect devices, and tethered tidal kites [12]. Fig. 1 illustrates several representative concepts. Among these, horizontal-axis tidal turbines are considered the most technologically advanced, owing to their structural similarity to wind turbines and their relatively higher level of system integration and prototyping to date [13]. However, it is important to note that most other converter types remain at low Technology Readiness Levels and are subject to unresolved uncertainties regarding efficiency, reliability, and cost-effectiveness in real marine environments. For example, vertical-axis turbines offer simpler designs but have demonstrated lower hydrodynamic performance and remain underexplored at commercial scale [14]. Oscillating hydrofoils and venturi-based devices have shown potential in simulations and small-scale testing, but their scalability and long-term durability remain largely unvalidated. Tidal kites offer theoretical performance benefits but pose significant challenges in terms of control, anchoring, and survivability.

Tidal current converters offer the advantage of precise predictability due to the astronomical nature of tidal cycles, which sets them apart from intermittent wind and solar resources [14]. This predictability supports long-term planning and grid integration, although it remains dependent on site-specific flow modelling and bathymetric data accuracy. TECs are often described as having minimal environmental impacts when compared with other marine energy systems or with conventional marine propellers [15]. However, these conclusions are largely drawn from theoretical analyses or limited pilot deployments, and long-term ecological effects, particularly those related to sediment transport, benthic disturbance, and species interactions, remain insufficiently characterised. Energy extraction is typically limited to 10 to 15 per cent of the available kinetic energy at a site in order to preserve local flow dynamics and minimise disruption to sediment patterns. Although relatively low tip speeds (typically less than 12 m per second) and moderate energy absorption densities (around 4 kW per square metre) are believed to reduce collision risks to marine life, this assumption requires further empirical support across varied habitats. Conflicts with maritime navigation are generally considered low, and tidal technologies do not produce direct emissions [16]. The long-term commercial viability of TECs will rely not only on selecting suitable high-velocity current sites and minimising ecological disturbance, but also on improving cost efficiency, device resilience, and the development of regulatory frameworks that support scaled deployment. Although tidal energy remains a promising low-carbon resource, substantial uncertainties persist regarding its full-scale implementation.

This review begins with a broad overview of tidal energy systems and blade configurations in order to establish the technical and operational context necessary for understanding degradation mechanisms. The discussion then narrows progressively toward the evaluation of structural failure modes, with particular attention given to erosion and its interplay with fatigue, corrosion, ageing, and impact. The review aims not only to synthesise findings from the existing literature, but also to critically examine the limitations of current models, the maturity of proposed mitigation strategies, and the scarcity of field-validated data. By structuring the manuscript in this manner, the analysis maps areas where the field has reached technological consolidation while also highlighting unresolved questions in material performance, erosion prediction, and hydrodynamic response. This structure supports future research on the structural integrity of tidal turbine blades and informs the development of more targeted erosion-resilient design frameworks.

1.2. Methodology

This review adopts a structured and descriptive approach to examine failure mechanisms in tidal turbine blades, with a particular focus on erosion and its implications for structural integrity and hydrodynamic performance. The manuscript is deliberately structured to begin with a broad overview of tidal energy systems, blade configurations, and material selection, before progressively narrowing toward specific degradation mechanisms. These include erosion, fatigue, corrosion, ageing, and impact-related damage, all of which are considered in relation to their structural consequences and potential interactions.

Rather than presenting quantitative models or statistical evaluations, the manuscript offers a qualitative and conceptual synthesis of published literature. This approach is suited to the current state of the field, where empirical data on real-world tidal blade failures and long-term operational performance remain limited. The review draws on both well-established and emerging studies to assess the maturity of existing knowledge, highlight inconsistencies or limitations where present, and identify unresolved questions. The intention is to provide a consolidated and critical framework that supports future investigations into the durability of tidal turbine blades and the modelling of erosion-related degradation.

Relevant literature was identified through targeted searches conducted using Google Scholar and the University of Strathclyde Library research portal, which provides access to academic databases including Scopus, Web of Science, ScienceDirect, and SpringerLink. Search queries combined keywords such as tidal turbine, composite blade, erosion, fatigue, biofouling, hydrodynamic degradation, failure mechanisms, marine composites, and structural integrity. The review focused on literature published between 2005 and 2025, with particular emphasis on the most recent decade in order to reflect current developments. Earlier works were retained when they provided foundational insights into erosion processes or composite material behaviour.

Studies were selected based on the following criteria: (a) direct relevance to degradation mechanisms affecting tidal turbine blades or comparable marine composite structures; (b) the presence of technical content supported by experimental, computational, or field-based investigation; and (c) relevance to structural integrity or hydrodynamic performance. Publications were excluded if they lacked technical depth, focused on unrelated systems, or presented insufficient methodological detail for critical evaluation.

The reviewed literature is categorised and analysed according to a mechanism-centred structure, designed to reflect how various degradation processes influence blade performance over time. Thematic groupings are based on failure mechanisms such as erosion, fatigue, and ageing; material systems such as glass or carbon fibre composites and coatings; and performance responses such as hydrodynamic degradation. This structure enables a multidisciplinary view of the interconnections between structural failure modes and their environmental, material, and operational drivers.

A key motivation for the chosen structure is the recognition that structural failures, particularly erosion, cannot be evaluated in isolation from their hydrodynamic consequences. Surface degradation due to erosion alters blade geometry and roughness, which directly affects local flow patterns, pressure distribution, and overall turbine efficiency. For this reason, the review draws upon both structural assessment studies and fluid–structure interaction research to examine how degradation mechanisms impair energy capture and mechanical reliability. This coupling of material degradation and hydrodynamic response underpins the review's multidisciplinary scope and informs the classification and discussion of the literature throughout the manuscript.

2. Tidal turbines

Horizontal-axis tidal turbines (HATTs) have emerged as the most technically and commercially viable form of tidal energy conversion technology. HATTs share structural similarities with wind turbines and benefit from decades of accumulated experience in the wind energy sector. They represent the predominant tidal turbine configuration currently being engineered and tested worldwide [17]. HATTs position their rotors perpendicular to the incoming current, thereby exposing the full rotor area to maximise kinetic energy capture and benefit from the blockage effect [13]. The rotor, typically comprising two or three blades, is mounted on a horizontal drivetrain connected to an electrical generator that is usually enclosed within a streamlined nacelle. The nacelle is positioned on a tower and foundation that are mounted to the seabed or riverbed [18]. Design tools include blade element momentum (BEM) theory for hydrodynamic modelling, computational fluid dynamics (CFD) simulations, structural dynamics analysis, and control systems adapted from wind energy applications. Although the fundamental physics of harnessing tidal currents parallels that of wind energy extraction, the marine environment presents a significantly more demanding operating regime [19]. HATTs must endure bidirectional flow conditions, cavitation, corrosion, biofouling, and impacts caused by debris and marine organisms [20]. These conditions contribute to increased fatigue loading, surface damage, and material degradation. The high cost of maintenance in offshore environments further highlights the importance of system reliability and structural resilience [7]. Despite the progress made through simulation and prototyping, long-term validation of HATT performance under real tidal conditions remains limited.

2.1. Vertical and horizontal axis tidal turbines

Vertical-axis tidal turbines (VATTs) have been investigated as potential alternatives to horizontal-axis tidal turbines (HATTs). A primary advantage of VATTs is their omnidirectional design, which permits energy extraction regardless of the flow direction. Certain configurations enable the drivetrain and generator to be located above the waterline, facilitating easier access for maintenance tasks [21]. However, their swept area interacts with unsteady flow from all directions, including reversing tidal currents, which subjects the

Table 1
Comparison between h- and v-axis tidal turbines' features.

Feature	H-Axis Turbines	V-Axis Turbine
Design [1,9,21]	Less straightforward (−)	More straightforward (+)
Fixation [9,21]	More difficult to fix/mount (−)	Easier to fix/mount (+)
Installation [9,21]	More challenging (−)	Simpler (+)
Starting Torque [24]	Higher (+)	Lower (−)
Mechanical Noise [9]	Higher (−)	Lower (+)
Hydrodynamic Behaviour [9]	More Stable (+)	Less Stable (−)
Control System [1]	Simpler (+)	More complex (−)
Blockage Effect [13,21,25]	Increased performance due to blockage effect individually and in a farm (+)	Increased performance due to blockage effect only in a farm (−)
Output Torque [24]	Steady/Constant (+)	Fluctuating (−)
Efficiency [1,9,21,23]	Higher (+)	Lower (−)
Power Production [1,9]	More consistent (+)	Less Consistent (−)
Type [1,26,27]	Seabed or riverbed mounted (+), Circular rotor with positive effects both individually and array scale (+)	Mostly floating or near-surface (−), Rectangular rotor with better performance only in twin (array) VAT system (−)
Applications [9,28]	Suited for non-ducted, but can use ducts, and current velocity of 2.5 m/s (−)	Best for ducted applications, and current velocity of 1.5 m/s (+)
Previous Experience [9]	Leverages wind turbine Experience (+)	No long-term experience (−)
Price [9,21]	Higher (−)	Lower (+)

system to complex cyclic loading and increases the risk of fatigue. Consequently, their structural design typically requires more careful reinforcement than that of HATTs [22].

The relatively higher energy conversion efficiency, consistent power output, and technological parallels with wind turbines make HATTs more attractive for most tidal power applications [23]. While VATTs may be better suited for ducted installations, HATTs can also be integrated with ring-shaped ducts to enhance flow acceleration. Most VATT systems are based on floating or near-surface fixed platforms, which must counter large overturning moments due to current forces acting on vertically aligned rotors. This necessitates substantial anchoring infrastructure. In contrast, HATTs are often deployed using bottom-fixed foundations. Although such foundations are more demanding to design and install, the extensive expertise gained from offshore wind and oil industries, along with lower exposure to surface wave motion, enhances their appeal for long-term deployments [9].

HATT designs incorporate either fixed-pitch or variable-pitch blades. Fixed-pitch configurations are structurally simpler and cost-effective but cannot adjust blade orientation during operation. As a result, power regulation relies on stall-based control using carefully profiled foils to prevent over-speeding. Variable-pitch turbines, by contrast, can actively adjust blade angles to modulate output power, limit structural loads, and enhance startup or braking responses across a range of tidal flow conditions [1].

HATTs have emerged as the dominant technology in tidal energy development owing to their higher power capture efficiency, established design foundation inherited from wind turbine research, and demonstrated advantages over VATT alternatives, as summarised in Table 1. Continued innovation is expected to improve reliability, operational performance, and economic competitiveness. However, the current maturity of HATTs positions them as the most commercially viable option for large-scale tidal energy deployment. Achieving sustained operation under long-term marine exposure will require the development of damage-resistant blade materials, protective surface treatments, and structural designs capable of enduring decades of cyclic hydrodynamic and mechanical loading in seawater environments.

2.2. H-axis tidal turbine sections

HATTs incorporate both enclosed mechanical systems and externally exposed tribological components that are directly subjected to marine environmental conditions. Internally, key mechanical elements include the drivetrain gearbox, shaft, generator, control units, and the associated power and data cables. Externally, the most exposed and critical components are the rotor assembly, nacelle, tower, and supporting foundation. These external structures must withstand continuous exposure to saltwater, mechanical stress, and dynamic flow conditions. The rotor system, which includes the hub and blades, is particularly vulnerable to both mechanical and hydrodynamic degradation. Fig. 2 illustrates the major structural elements of a representative HATT configuration.

The nacelle and tower shape turbine flow dynamics, as depicted in Fig. 3. The tower partially obstructs lateral current flow, while the nacelle disrupts vertical flow paths. Under upstream flow conditions, this interaction results in static pressure buildup in front of the rotor, enhancing power output via the blockage effect. When flow approaches from the downstream side, the presence of these structures leads to vortex generation due to wake shedding, known as the shadow effect. This effect increases turbulence intensity in the rotor's wake, especially during ebb conditions. While these phenomena improve energy capture, they also intensify dynamic pressure loading on the rotor and support structures. These fluctuating loads may induce vibrations and initiate fatigue damage. Streamlining the tower geometry can mitigate such disturbances and reduce the formation of vortex streets [25,29].

Tidal turbine foundations must resist hydrodynamic forces, sediment shifts, and corrosion throughout a typical service life of 20 to 25 years [4,30]. These foundations support and stabilise the rotor system under varying tidal and wave conditions. Common designs include gravity bases, monopiles, tripod or jacket structures, and floating platforms. Foundation design must account for load-bearing

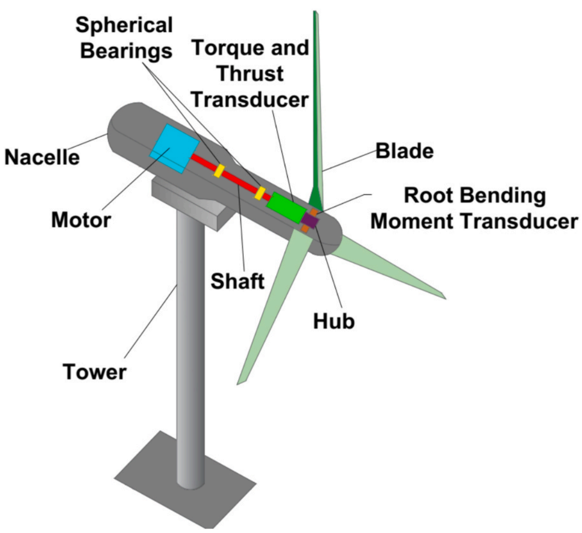

Fig. 2. Tidal turbine model sections.

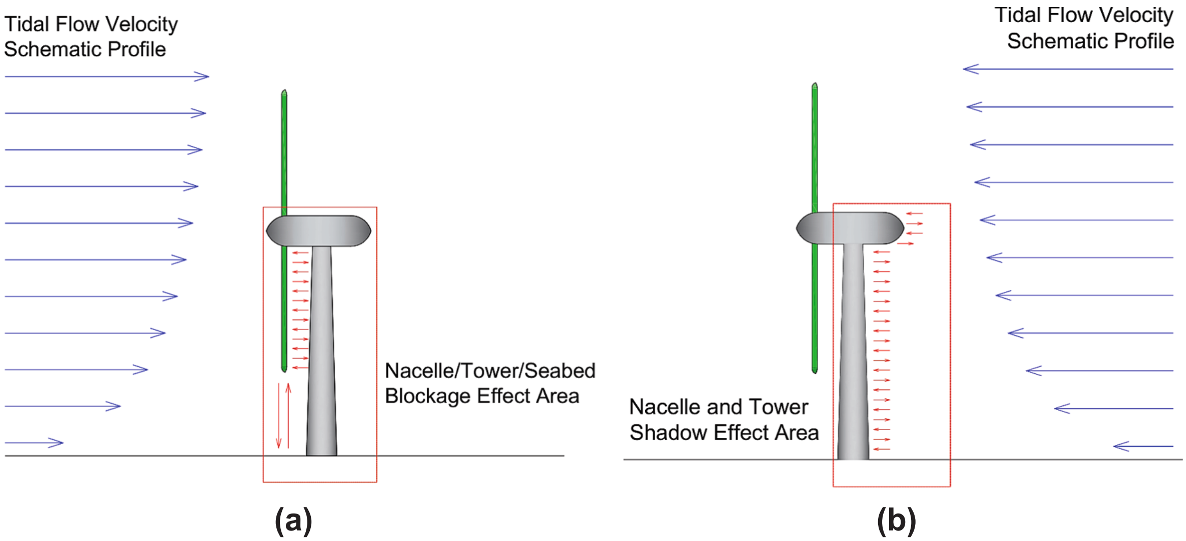

Fig. 3. Schematic area of (a) Local Blockage effect and (b) Shadow effect for h-axis tidal turbines.

stability, marine current velocities, seabed composition, and cyclic loading arising from tidal oscillations [22].

Rotor blades represent the most performance-critical elements of a HATT, experiencing the highest combination of structural and hydrodynamic loads. These blades govern the efficiency, power output, and operational lifespan of the turbine. Their slender geometry makes them highly susceptible to flow-induced vibration and cyclic fatigue, particularly in turbulent and wave-affected flows [31]. Preserving blade condition is essential to avoiding costly underwater maintenance. Blade degradation is commonly initiated by erosion, cavitation, corrosion, and biofouling, often acting synergistically. The severity and progression of damage are influenced by the selected material system, surface treatment, flow characteristics, and the physical properties of the surrounding marine environment. Ensuring blade integrity is vital for the long-term operational stability and energy output of tidal turbines [30].

3. Tidal turbine blades

3.1. Tidal turbine blade materials

Material selection for tidal turbine blades is a critical factor in ensuring long-term durability under harsh marine conditions. The high density of seawater contributes to both hydrostatic pressure and hydrodynamic loading, while cyclic loading associated with tidal flow variations introduces mechanical fatigue. Concurrently, the corrosive nature of the marine environment accelerates surface degradation through chemical attack and material loss [32,33]. Blade materials must therefore demonstrate a reliable balance of strength, stiffness, and resistance to fatigue, erosion, and corrosion in order to endure these combined stressors. Appropriate material selection remains essential for ensuring the mechanical reliability and extended service life of tidal turbine systems operating in offshore environments [30,33,34].

Tidal turbine blades are commonly manufactured from metallic alloys or polymer matrix composites. Steel alloys provide considerable strength and offer resistance to corrosion; however, their high density increases the overall blade mass, which necessitates the use of more robust support structures [35,36]. In contrast, composite materials composed of high-strength fibres embedded within a polymer matrix deliver improved strength-to-weight and stiffness-to-weight ratios. These properties are essential for large-scale blades, where minimising weight reduces structural demands and enhances efficiency [33,37]. Liu et al. observed that plastic blades fabricated from polyamide exhibit suboptimal hydrodynamic performance due to their excessive flexibility. This results in blade deformation and a reduction in the effective angle of attack [38]. Therefore, composite blades must maintain adequate rigidity to preserve optimal hydrodynamic geometry. Rigorous alignment of reinforcing fibres along principal load paths maximises their structural contribution, especially under complex loading conditions. Quasi-isotropic laminate configurations are often used to distribute stresses uniformly across the blade structure. This design approach improves the blade's ability to accommodate multidirectional loads while maintaining hydrodynamic performance [31,38,39].

Glass Fibre-Reinforced Polymer (GFRP) and Carbon Fibre-Reinforced Polymer (CFRP) represent the two primary composite systems currently used in the fabrication of tidal turbine blades [33,40]. The fibres, either glass or carbon, serve to provide strength and stiffness, while the surrounding polymer matrix enables load transfer and geometric stability [41]. Although epoxy resins are more costly than vinyl esters, they are preferred due to their superior fatigue resistance. GFRP offers a favourable combination of mechanical properties, reduced weight, and economic efficiency, making it well suited for many blade applications. In contrast, CFRP provides higher stiffness and strength, which is advantageous for large-scale turbines where these properties enhance structural performance and justify the additional cost [30,33,40]. As turbine dimensions continue to scale up, the mechanical benefits of CFRP become increasingly relevant, making it a more suitable material for high-load, long-span blade configurations [30,38].

Recent advances in nanostructured reinforcements have identified graphene-based composites as promising materials for enhancing the durability of tidal turbine blades. Graphene nanoplatelets (GNPs) exhibit high intrinsic strength, surface hardness, and excellent barrier properties. These characteristics help reduce the initiation and growth of cracks, prevent moisture penetration, and improve resistance to surface abrasion. Experimental studies report that GNP-reinforced glass fibre/epoxy laminates can achieve up to an 80 per cent improvement in impact resistance following seawater exposure. These modified laminates also retain greater mechanical integrity under saltwater ageing when compared to their unmodified counterparts [42]. The dispersion of graphene within the epoxy matrix introduces a tortuous diffusion path that restricts water absorption and improves the long-term durability of the composite [43,44]. Although most findings to date are based on general marine applications, the evidence suggests significant potential for extending these material benefits to tidal blade systems operating under erosion-intensive conditions.

In summary, composite blades offer several advantages over metallic blades, including (a) higher strength-to-weight and stiffness-to-weight ratios, (b) lower overall blade mass, (c) improved fatigue tolerance, (d) increased durability, (e) greater design flexibility, (f) reduced manufacturing and maintenance costs, (g) enhanced resistance to corrosion and erosion, (h) superior vibration damping, and (i) lower noise emission. One major limitation of polymer composites, compared to metals, is their tendency to absorb water in marine environments [30,34,45]. GFRP can absorb as much as 5 per cent of its weight in water, resulting in tensile strength reductions of more than 25 per cent [46]. CFRP performs more reliably, especially in high-stress areas such as spar caps and trailing edges. Under similar loading, CFRP spar caps exhibit lower maximum strain than their GFRP counterparts. However, the cost of carbon fibres is typically 10 to 20 times higher than that of glass fibres [47]. As a result, GFRP remains an attractive solution in regions of the blade where performance demands are moderate [33,40]. A practical alternative involves hybrid blades, which apply CFRP in high-stress regions and GFRP elsewhere. This configuration achieves a balance between mechanical performance and affordability [48]. Several other criteria influence material selection, including:

- Impact resistance and damage tolerance [49,50];
- Durability under seawater, humidity, and temperature exposure [51];
- Compatibility with large-scale manufacturing methods [41];
- Repeatability and quality control in production [52];
- Potential for recycling or reuse at end-of-life [41].

Much of the available materials research relies on coupon-scale testing and simplified exposures that do not reproduce the combined erosive, cyclic, biological, and corrosive loading typical of tidal operation. Reported gains for graphene-modified laminates, for instance, are drawn mainly from short-term laboratory studies in generic marine conditions; tidal-specific data on long-term water uptake, interfacial degradation, and erosion synergy remain unavailable. The readiness of coatings or nano-reinforced composites for leading-edge applications therefore, cannot yet be confirmed without validation under slurry erosion and saltwater ageing, with realistic duty cycles and span-wise stresses. Equally, large-scale manufacturing variability—such as void content, fibre alignment, and cure quality—is rarely quantified in relation to erosion resistance, yet it is likely a key source of scatter in performance outcomes. These gaps need to be acknowledged when weighing GFRP, CFRP, or hybrid configurations and when interpreting cost–performance trade-offs.

3.2. Failure modes in tidal turbine blade

Although this review places particular emphasis on erosion and its structural implications, it is necessary to consider the broader set of failure mechanisms that compromise tidal turbine blades. These mechanisms include fatigue, corrosion, ageing, impact-induced damage, and biofouling. They often operate simultaneously and may be intensified by early-stage erosion. A combined perspective is therefore important for understanding the complex degradation processes that develop under marine operating conditions. This section outlines the most common structural failure modes observed in tidal environments and establishes a foundation for the erosion-specific discussion presented later.

Tidal turbine blades share some similarities with ship propellers and wind turbine blades, but they are subject to a unique combination of challenges, including high current loads, sand erosion, impacts from marine mammals, chemical interactions, ageing, and biofouling. Given the limited maintenance opportunities in underwater environments, understanding the mechanisms of structural failure is essential for the optimal design of tidal turbine blades [8]. The primary structural failure modes encountered in marine environments include:

- Fatigue, defined as progressive material degradation caused by repeated hydrostatic pressure, flow loading, and vibration.
- Corrosion, resulting from electrochemical reactions with seawater, which lead to surface damage and weakening of the material.
- Erosion, driven by cavitation and particulate impact, which gradually removes material from the blade surface.
- Ageing, which involves the slow alteration of material properties due to water ingress, temperature cycles, and ultraviolet exposure.
- Biofouling, the biological accumulation of marine organisms that increases drag, alters flow patterns, and adds uneven weight.
- Impact-induced damage, caused by collisions with marine life or debris, often leading to cracking, fibre breakage, or delamination.

These structural failures not only compromise the integrity of the blade but also alter its surface characteristics, which in turn affect local flow behaviour and turbine efficiency. As illustrated in Figs. 4 and 5, surface degradation can modify pressure distributions, induce premature flow separation, and increase turbulence in the wake. Conversely, unstable flow conditions also affect load distributions on the blade surface, accelerating material fatigue and erosion. This two-way interaction highlights the need for integrated models that account for both structural and hydrodynamic behaviour.

While many studies have examined individual failure mechanisms in isolation, there remains a lack of validated frameworks that can simulate their combined effects in tidal operating conditions. Current structural analysis methods often fail to link degradation progression with performance decline. The development of performance-based failure models is therefore critical to improving the reliability and lifetime assessment of tidal turbine blades.

3.2.1. *Structural failures*

Durability and operational lifespan are fundamental design priorities for tidal energy systems. The blades experience some of the most demanding loads, making them especially vulnerable to structural degradation. Enhancing structural endurance is therefore central to improving cost-effectiveness, as the long-term viability of tidal installations depends on reducing repair frequency and

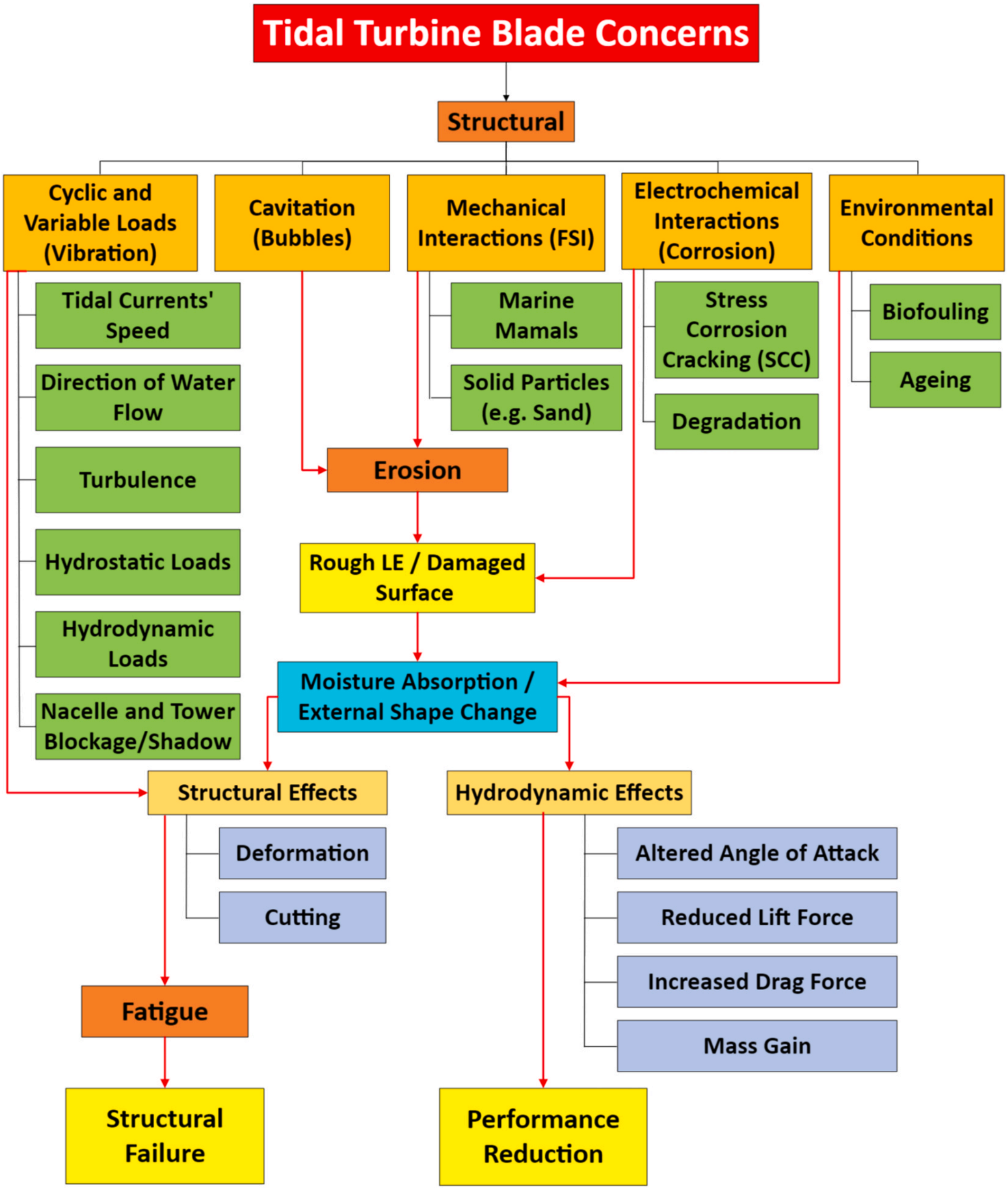

Fig. 4. Key concerns affecting tidal turbine blades leading to structural and hydrodynamic degradation.

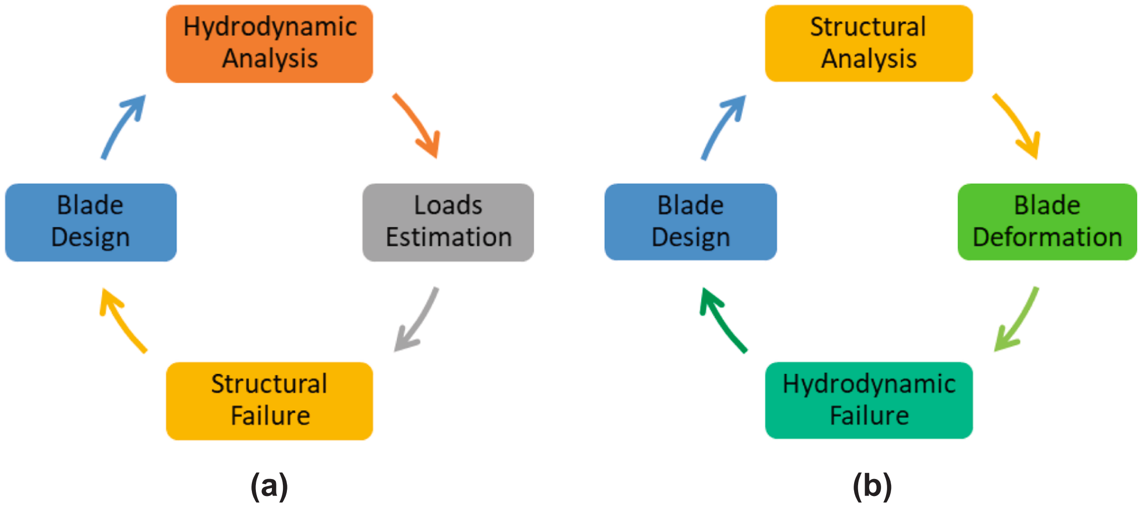

Fig. 5. Blade failure analysis framework for design optimisation based on a) Structural Performance, b) Hydrodynamic Performance.

extending component service life. Fibre-reinforced polymer composites have emerged as the most suitable materials for tidal turbine blades because of their resistance to the types of structural failure common in marine environments [53–55]. The failure mechanisms most relevant to tidal turbine operation are summarised in Fig. 6.

The type and severity of failure modes depend on several factors, including the blade's sectional geometry, the materials and laminates used, the choice and condition of surface coatings, operating loads, and environmental exposure [8,56–59]. To mitigate the risk of failure, designers and operators must consider a range of strategies, such as:

- Material selection: Composites with high fatigue resistance, fracture toughness, and low water permeability are preferred. Hybrid materials can help balance mechanical performance with affordability [60].
- Structural design: Blade performance is improved through optimised shape, layup orientation, and thickness distribution [60].
- Protective coatings: Surfaces may be treated with erosion- and corrosion-resistant coatings. These may require periodic renewal to maintain protection [61].
- Condition monitoring: Sensors for strain, vibration, and crack detection support early identification of structural problems. Recent advances include offshore digital twin platforms that integrate machine learning and SCADA (Supervisory Control and Data Acquisition) data to deliver real-time condition tracking [60,62,63].
- Maintenance planning: Scheduled inspection and repair routines are essential to prevent failure accumulation and support reliable operation [60,62].
- Impact protection: Local reinforcement systems or bumper designs may be used to absorb impact loads and minimise localised structural damage [61,62].

(a) Fatigue

Fatigue is among the most critical failure modes influencing the durability and service life of tidal turbine blades. These blades are

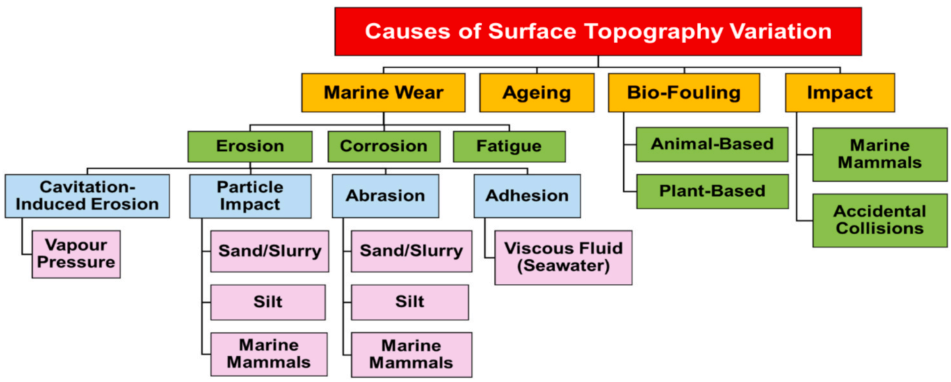

Fig. 6. Factors contributing to blade surface degradation in marine conditions.

subjected to a combination of cyclic hydrostatic and hydrodynamic loads, which can induce vibrations and result in cumulative structural damage over time [16,31]. As illustrated in Fig. 7, oscillatory loads arise from multiple sources [64,65] including: (a) fluctuating hydrodynamic forces and associated bending moments induced by tidal currents, (b) unsteady turbulent flow from wave-induced disturbances acting on the blade from varying directions, (c) vortex shedding, (d) periodic changes in the blade's angle of attack during rotation, (e) the influence of wakes produced by adjacent blades, and, (f) cyclic loading introduced by start-up and shut-down operations.

Tidal turbine blades are subjected to cyclic loading, which leads to progressive fatigue damage over time. As turbine sizes increase, mitigating fatigue becomes increasingly critical, particularly in drivetrain components. The blade root endures the highest fatigue loads, as it is exposed to the largest cyclic bending moments. Research indicates that more than 80 per cent of a composite blade's fatigue life is consumed during the damage propagation phase originating at the root [50]. However, most existing fatigue datasets are derived from constant-amplitude laboratory testing, which does not capture the spectrum of variable-amplitude, multi-axial loading seen in real tidal environments. This limits the reliability of direct extrapolation from coupon-level data to full-scale blades.

Key fatigue failure modes in composite tidal blades include matrix cracking, delamination, fibre breakage, and fibre–matrix debonding. Among these, delamination is particularly detrimental, as it permits water ingress, which accelerates internal damage. Both flapwise and edgewise load components contribute to fatigue progression, with edgewise fluctuations often reaching magnitudes up to twice those of flapwise loading [65]. Although numerous modelling frameworks attempt to capture these behaviours, most reported studies rely on short-duration laboratory fatigue tests or scaled specimens. The absence of full-scale, long-term validation limits confidence in transferring laboratory-derived S–N curves directly to operational turbines. Furthermore, inconsistencies in loading protocols and environmental conditions across studies hinder direct comparison and highlight the need for standardised testing approaches. Estimating the fatigue lifespan of tidal turbine blades requires an integrated approach involving CFD, finite element analysis (FEA), and coupling between BEM theory and FEA models. These numerical methods must be supported by validation through testing under realistic operating conditions. As tidal turbine scale increases, effective fatigue management becomes increasingly critical to ensure both reliability and cost-efficiency. The interaction between fatigue and erosion, including how each accelerates the other, is discussed in greater detail in Section 4.3.4.

(b) Corrosion

Corrosion represents a significant failure mode for tidal turbine blades, particularly those constructed from metallic materials. The marine environment is inherently corrosive and, without adequate protection, can progressively degrade blade integrity. Common corrosion mechanisms affecting metallic components in marine environments include general corrosion, crevice corrosion, pitting, galvanic corrosion, and microbiologically influenced corrosion (MIC).

Corrosion tends to develop most severely near the blade root and at structural joints, where crevices promote localised fluid retention and oxygen depletion. Several strategies are employed to mitigate corrosion in such systems:

- Protective coatings such as epoxy, polyurethane, and fluoropolymer layers serve as physical barriers that enhance resistance to environmental exposure.
- Cathodic protection systems, based on either sacrificial anodes or impressed current, are used to prevent electrochemical reactions at the metal surface.
- Alloy selection focuses on materials such as stainless steel and nickel-based alloys, which form stable passive oxide layers that suppress corrosion. Although these alloys offer improved durability, they also increase material costs.
- Design considerations aim to reduce the presence of crevices and lap joints and to promote effective drainage in areas where fluid accumulation would otherwise accelerate degradation.

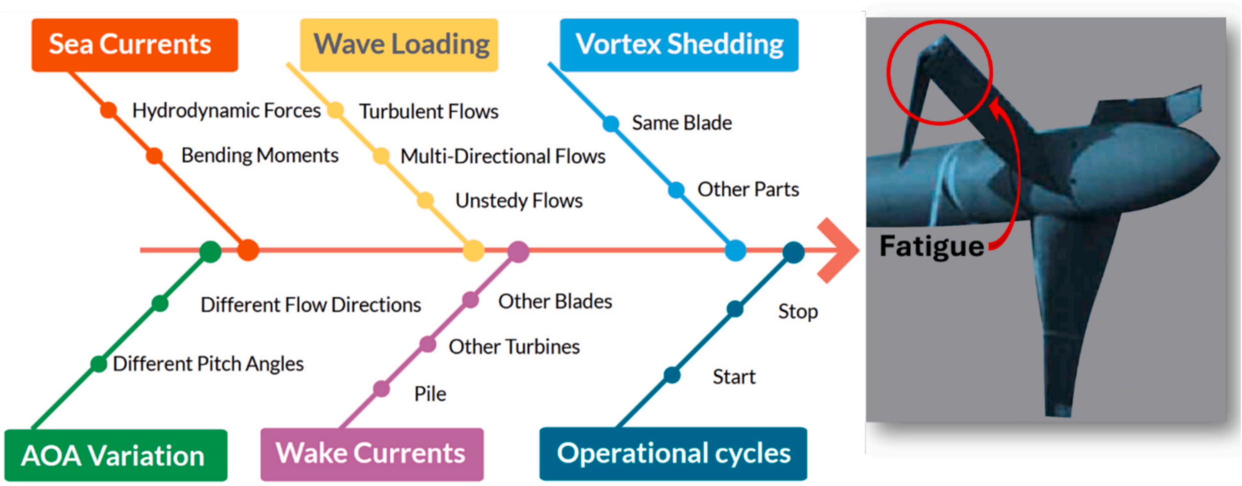

Fig. 7. Causes of Fatigue in Underwater Tidal Turbine Blade Structure.

- Maintenance routines involve scheduled inspection and recoating, along with timely localised repairs to preserve structural integrity.

Despite the wide range of protection strategies, there is limited consensus on their long-term performance under tidal operating conditions. Much of the supporting evidence is drawn from offshore oil, gas, or naval applications, where loading and exposure regimes differ from those of tidal turbines. Reported durability of coatings, for example, varies considerably between laboratory immersion tests and field deployments, making it difficult to establish reliable service-life predictions. This lack of standardised, tidal-specific validation creates uncertainty in selecting the most effective protection strategy for blades in service.

In the case of composite tidal blades, the reinforcing fibres are inherently resistant to corrosion. However, the surrounding polymer matrix may absorb moisture and undergo hydrolysis in humid, aqueous environments. This degradation process can result in swelling, plasticisation, and gradual loss of mechanical strength. The use of low-permeability matrices such as vinyl ester resins can significantly reduce water ingress and improve long-term durability.

Corrosion protection must be incorporated during the early design stages, including material selection, surface treatments, and joint configuration. It is also essential to validate accelerated corrosion testing methods so that they accurately reflect the exposure conditions of tidal operating environments. Monitoring tools such as visual inspection, ultrasonic testing, X-ray imaging, and tap testing support early fault detection and enable pre-emptive maintenance interventions to limit structural degradation and prevent critical failure. While corrosion and its prevention strategies are relatively well documented for offshore structures, the combined action of corrosion with erosive wear introduces additional complexity. The implications of this interaction for tidal turbine blades are discussed further in Section 4.3.2.

(c) Erosion

Erosion is a major contributor to surface damage and performance deterioration in marine energy systems. The principal erosion mechanisms include:

- **Suspended particle erosion**: Sand, silt, and other sediments suspended in tidal currents strike and abrade blade surfaces, particularly in seabed-mounted turbines [61,66–68].
- **Friction erosion**: Shear interactions between seawater flow and the blade surface cause progressive material removal. The leading edge is especially vulnerable, and erosion severity strongly depends on the impact angle [69].
- **Cavitation erosion**: The collapse of vapour cavities during cavitation produces high-energy microjets and shockwaves that erode the blade surface, typically on the suction side of the leading edge [70,71].

Erosion damage begins at the microscopic level and progressively evolves into pits, gouges, and substantial material loss, as illustrated in Fig. 8. These surface changes disrupt blade geometry and reduce hydrodynamic performance. The erosion rate is governed by several factors [61,71] including: (a) operational conditions such as flow velocity, turbulence intensity, angle of attack, and the presence of cavitation; (b) fluid properties such as density, viscosity, pH, salinity, and temperature; (c) erodent characteristics such as particle size, hardness, shape, and concentration; (d) target material properties such as hardness, toughness, ductility, and microstructure; (e) surface conditions such as roughness, residual stress, and the use or absence of protective coatings.

To mitigate erosion in tidal turbine blades, several strategies may be employed [30,61], including: (a) shape optimisation, in which

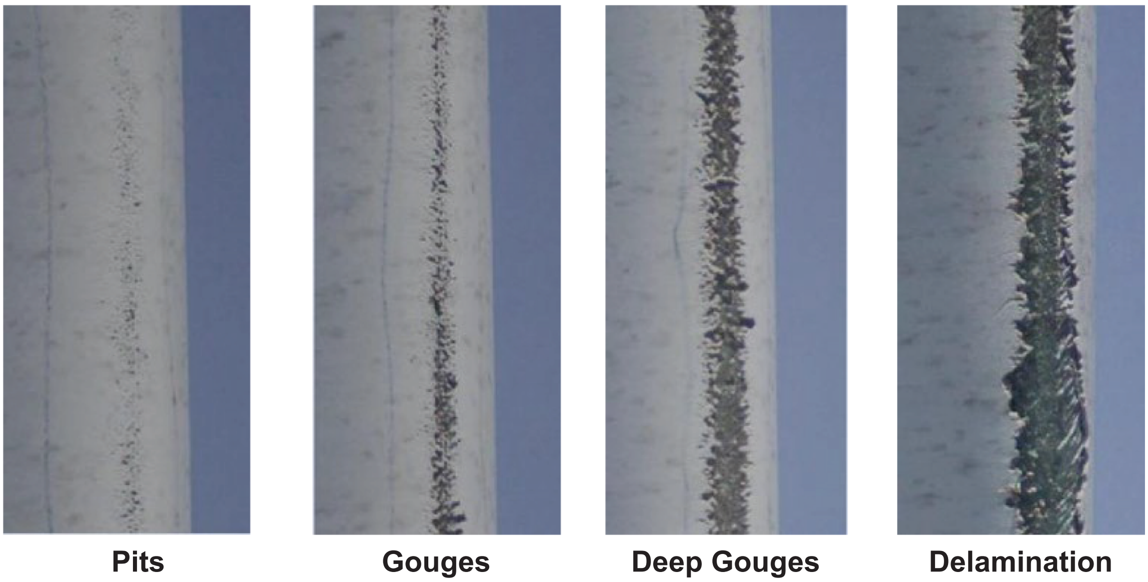

Fig. 8. Erosion damage on the blade at different scale levels [72].

streamlined geometries and smooth curvature transitions reduce pressure concentrations and flow separation; (b) material and manufacturing process selection that improves resistance to erosion through enhanced surface and bulk properties; (c) protective coatings, where dense, erosion-resistant polymer films such as polyurethanes, polyesters, and fluoropolymers shield the blade surface; (d) condition monitoring techniques that detect early-stage surface roughness changes and guide predictive maintenance; (e) maintenance and repair strategies such as recoating, repolishing, or blade replacement, which restore surface quality and preserve turbine efficiency.

Fig. 9 summarises the design-stage, material-level, and operational factors that contribute to improved erosion resistance throughout the turbine's lifecycle.

These mechanisms illustrate the multifaceted nature of erosion in tidal environments. A more detailed examination of erosion phenomena, including material-level interactions, performance impacts, and current research challenges, is presented in Section 4.

In light of ongoing research into tidal turbine blades, further investigation is required in several key areas, including (a) validated predictive models for erosion rates based on operating conditions and material properties; (b) novel nanocomposite coatings with improved toughness and self-healing capabilities; (c) real-time erosion monitoring techniques based on vibration signatures, surface temperature, or other indirect indicators; and (d) erosion testing protocols tailored to tidal-specific flow conditions, velocities, and particulate characteristics [30,61,71].

(d) Ageing

Prolonged immersion in seawater alters the material properties of tidal turbine blades, particularly those constructed from polymer composites. Moisture absorption over time is a key ageing concern in these materials [48,73–75]. When exposed to humid marine environments, polymer composites are affected by several degradation mechanisms [34,45]:

- Plasticisation: Water molecules diffuse into the polymer matrix, soften the material, and reduce the glass transition temperature, leading to lower stiffness.
- Hydrolysis: Chemical reactions between water and polymer chains cause chain scission, reduce molecular weight, and embrittle the material.
- Swelling: Moisture absorption induces expansion stresses, which may cause void growth, matrix cracking, or interfacial damage.
- Delamination: Water accumulation at ply interfaces weakens interlaminar bonding, promoting delamination and laminate expansion.

In tidal turbine blades, the effects of ageing include [76]: (a) increased weight due to water uptake, which changes balance and load distribution; (b) reductions in strength, stiffness, fatigue resistance, and fracture toughness; (c) increased fatigue crack growth rates; (d) surface roughness changes and microcrack formation, along with the possible onset of galvanic corrosion in moisture-affected regions.

As moisture diffuses into the structure, it further facilitates damage progression and accelerates mechanical degradation. Composite materials exhibit different levels of moisture uptake, as shown in Fig. 10, depending on their matrix chemistry and laminate quality.

[57]. One critical mitigation strategy is to minimise void formation during manufacturing, since voids provide sites for water accumulation and accelerate degradation [34].

Water absorption exceeding 1 % by weight in fibre-reinforced composites leads to increased mass, alters hydrodynamic behaviour, and reduces tensile strength. These changes are particularly relevant for tidal turbine blades, where structural balance and surface geometry are essential for maintaining efficient energy capture. The long-term effects of ageing have been studied using both experimental and analytical approaches. Accelerated ageing methods, such as hygrothermal conditioning, are widely used to replicate the combined effects of temperature and moisture on composite properties [75]. While these tests offer practical insights within shorter timeframes, they may not fully reflect the mechanical fatigue and flow-induced stresses present in operational tidal environments.

Kennedy et al. [76] evaluated the impact of seawater absorption on blade lifespan in pitch-regulated and stall-regulated tidal turbines. They reported that after 20 years of immersion, stall-regulated blades showed a lifespan reduction of approximately three

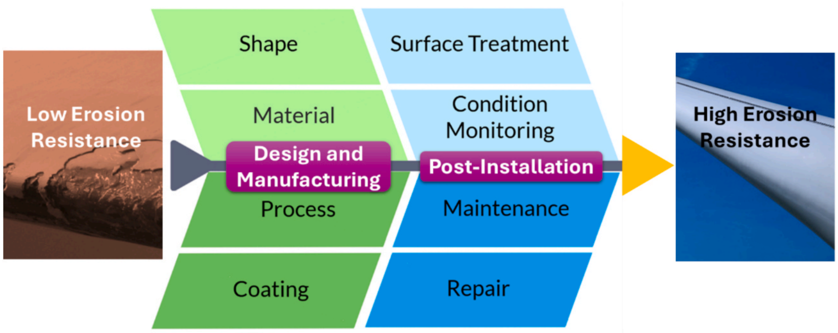

Fig. 9. Parameters enhancing turbine blade erosion resistance.

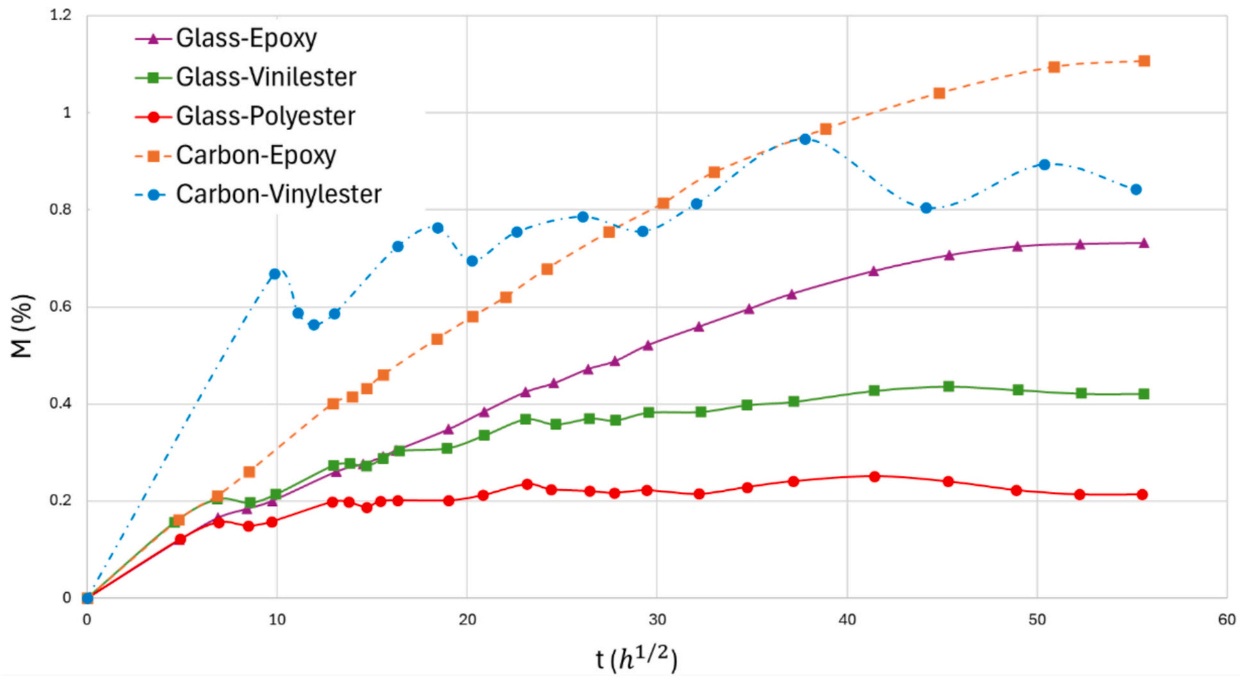

Fig. 10. Water absorption curves of different fibre-reinforced composites.

years, while pitch-regulated blades were affected to a lesser extent. This effect could be mitigated by increasing laminate thickness. Although the study highlights the structural benefit of pitch control and lamination strategies, it assumes a simplified ageing process and does not account for concurrent degradation from erosion or biofouling.

Alam et al. [45] investigated hygrothermal ageing in carbon fibre-reinforced polymer (CFRP) composites, showing that moisture ingress reduced impact resistance and increased the likelihood of erosion-induced microcracking. While this work demonstrates the coupling between ageing and erosion, it is limited to lab-scale testing conditions and does not incorporate variable flow or dynamic loading, which are common in tidal deployment scenarios.

Despite these limitations, such studies provide essential information on degradation pathways in polymer composites. However, translating accelerated laboratory results into accurate long-term predictions for field conditions remains an unresolved challenge. Identifying and mitigating ageing effects is crucial for optimising tidal blade reliability and performance [77,78]. The wider implications of ageing, particularly its interaction with erosion and long-term durability in tidal environments, are examined further in Section 4.3.5.

(e) Biofouling

Biofouling refers to the accumulation of microorganisms, plants, and animals on submerged surfaces such as tidal turbine blades [8,71,77]. The primary fouling organisms include:

- Algae: Including diatoms and green or brown algae, which form slimy surface coatings.
- Barnacles: Hard-shelled organisms that attach firmly to submerged surfaces.
- Tubeworms: Marine worms that inhabit calcareous tubes fixed to structures.
- Mussels: Bivalves that adhere strongly to surfaces using byssal threads.
- Bryozoans: Colonial animals embedded within gelatinous or calcareous matrices.

The accumulation of these organisms increases surface roughness and reduces turbine efficiency. Fouling increases the mass and surface drag of the blades while reducing lift force, thereby degrading the lift-to-drag ratio and overall hydrodynamic performance. Over time, these effects contribute to increased energy losses, shorter maintenance intervals, and higher Levelised Cost of Electricity (LCOE) [7].

Additionally, biological deposits can trap moisture and promote localised erosion or corrosion beneath the fouled regions. In severe cases, fouling may obstruct moving parts or degrade the accuracy of sensors and monitoring equipment.

Fig. 11 presents a tidal turbine that exhibited extensive biofouling after six months of operation. Fouling tends to concentrate around the hub and blade root, where flow velocities are lower and rotational cleaning effects are minimal [8]. While the rotation of the blades inhibits biofouling to some degree, static or low-speed regions remain highly susceptible. Biofouling is typically more manageable on fully submerged surfaces. However, splash zones that undergo frequent wet–dry cycling often show higher fouling persistence and present greater cleaning challenges.

Antifouling strategies commonly rely on coatings containing biocides, along with mechanical removal methods such as brushing, high-pressure water jets, and robotic cleaning systems.

[30]. While these methods are effective, their long-term impact on surface integrity and local marine ecosystems is not always well understood. Monitoring metrics such as rotor torque variation and water turbidity have been proposed to detect fouling accumulation, although their sensitivity and reliability vary under field conditions.

Future progress in this area requires greater attention to several open research questions, including (a) the development of non-toxic, low-drag coatings that reduce adhesion without environmental harm; (b) the ecological impact of biocide leaching and accumulation in sensitive marine habitats; (c) the optimisation of cleaning intervals and techniques to reduce downtime and minimise surface wear; (d) the potential of bioinspired surface geometries that passively deter fouling through texture or patterning; (e) the integration of real-time fouling detection systems into blade monitoring frameworks; and (f) the determination of critical rotational velocities that inhibit the initial attachment of fouling organisms.

Although biofouling is often considered secondary to other failure modes, its cumulative effects can significantly reduce turbine output and increase operational costs. The broader implications of biofouling for erosion processes are discussed in Section 4.3.3.

(f) Impact-Induced damage

Impact-induced damage is a significant risk for tidal turbine blades, particularly in marine environments with high vessel activity or dense ecological populations. Collisions may occur with industrial equipment, floating or submerged debris, or marine animals such as seals, dolphins, and whales. These events can result in surface cracking, delamination, fibre fracture, or permanent deformation, all of which compromise the structural integrity of the blade.

The severity of impact depends on several parameters, including the mass, velocity, shape, and angle of the object involved. For example, a bottlenose dolphin weighing between 300 and 500 kg and travelling at five metres per second may impose a force ranging from 7.5 to 12.5 kilonewtons. In contrast, a humpback whale weighing between 25,000 and 40,000 kg at a velocity of three metres per second may exert forces in the range of 75 to 120 kilonewtons. These localised and dynamic loads produce complex transient stress responses that are difficult to capture using conventional structural design frameworks. The location and orientation of such impacts are typically unpredictable, which adds considerable uncertainty to structural modelling. While hydrodynamic loads can be estimated from turbine configuration and flow conditions, impact loading is much harder to define using deterministic approaches. Although probability models based on habitat data and marine animal movement patterns have been proposed, their accuracy in estimating realistic impact scenarios remains limited.

Laboratory-scale impact tests and full-scale prototype blade trials, in combination with non-destructive evaluation methods such as ultrasonic inspection and X-ray computed tomography, have supported improvements in material selection and structural design [14,79]. Nonetheless, many of these tests are conducted under controlled or idealised conditions and may not reflect the full complexity of real-world impact behaviour in marine environments. Increasing the composite skin thickness, adding reinforcement patches, and incorporating internal stiffening elements have all been shown to improve resistance to impact damage, although these modifications may lead to higher weight and cost penalties.

Designing blades to withstand possible collisions with marine mammals requires conservative safety factors, comprehensive experimental testing, and detailed modelling of energy transfer during impact. However, current regulatory standards do not

Fig. 11. Fouled tidal turbine six months after commissioning [7].

consistently define permissible impact thresholds or required material qualification procedures, which complicates the establishment of consistent design practices.

Risk mitigation strategies have included environmental impact assessments, marine mammal monitoring schemes, and the implementation of time- or location-based restrictions on turbine operation during migration periods or in sensitive habitats. Acoustic deterrent technologies have also been trialled to redirect marine animals away from active turbines [14,80,81]. While some of these measures have shown promise, their effectiveness depends heavily on local ecological conditions and species behaviour. Their long-term ecological consequences are not yet fully understood. Balancing structural protection requirements with ecological responsibility remains a complex challenge that requires further collaborative research across engineering and marine biology disciplines. The implications of such impacts for erosion processes are examined further in Section 4.3.1.

3.2.2. Hydrodynamic failure

A decline in hydrodynamic performance is expected over the 25-year operational lifespan of a tidal turbine blade. Blade design must achieve a careful balance between structural durability, economic viability, and the ability to maintain efficient flow interaction. Hydrodynamic performance governs the power extraction capability of the system, yet it is progressively compromised by structural degradation mechanisms such as erosion, corrosion, fatigue, and biofouling. These mechanisms alter the blade surface and geometry, increasing surface roughness and degrading the finish, which leads to performance deterioration. Maintenance interventions, including cleaning, polishing, and recoating, can partially restore the surface condition, but degradation inevitably accumulates between interventions. In severe cases, performance loss can become irreversible, leading to functional hydrodynamic failure. Understanding how structural failures influence lift, drag, and stall behaviour is therefore essential for preventing such outcomes and for designing resilient blades.

Performance losses arise from changes in flow interaction, geometric distortion, and surface condition. As illustrated in Fig. 12, structural damage alters local flow patterns. Failures such as erosion, corrosion, and biofouling increase surface roughness, which enhances turbulence, increases drag, and reduces lift, thereby lowering energy conversion efficiency [82]. Fig. 13, adapted from the work of Song et al., shows that surface roughness caused by biofouling reduces torque while increasing shear torque. This phenomenon lowers the overall power coefficient of the turbine. However, the study's assumptions of uniform roughness distribution and fixed operational conditions may restrict the general applicability of its findings to diverse real-world environments.

The interaction between structural degradation and site-specific flow conditions adds complexity that challenges standard design and modelling methods. Localised defects can modify pressure distribution and boundary layer development, affecting both the aerodynamic and hydrodynamic response of the blade. Minimising these failures is essential for preserving turbine performance throughout service life. Computational fluid dynamics (CFD) modelling can simulate the effects of surface irregularities such as roughness and waviness on flow behaviour. While these models provide valuable insights, their predictive accuracy depends on the validity of input parameters and their ability to capture the irregular and evolving nature of real surfaces. This highlights the importance of experimental validation. Laboratory testing enables evaluation of how specific damage modes influence performance and informs the optimisation of blade shapes, materials, and protective coatings. In-situ monitoring methods, including underwater imaging and strain measurement, facilitate early detection of deterioration, while power output tracking supports correlation between damage progression and performance decline. Establishing a ranked assessment of the severity and impact of different failure types can guide design priorities and maintenance scheduling.

Improving hydrodynamic resilience requires the integration of optimised materials, surface treatments, and blade geometries. Operational data from installed turbines can inform the development of models linking structural degradation to hydrodynamic performance trends, enabling evidence-based design and maintenance strategies.

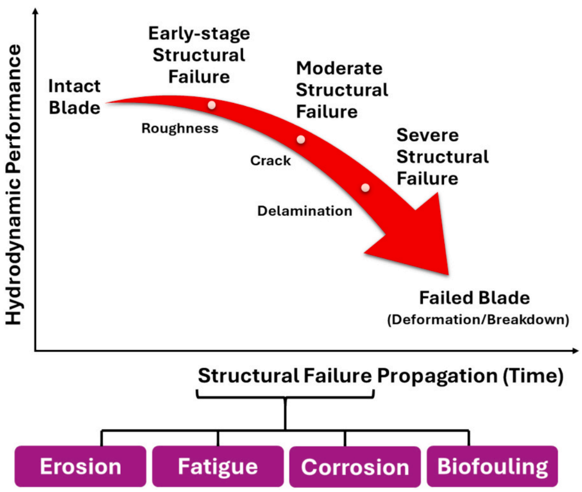

Fig. 12. Qualitative behaviour of hydrodynamic performance of a turbine blade under structural failure progression.

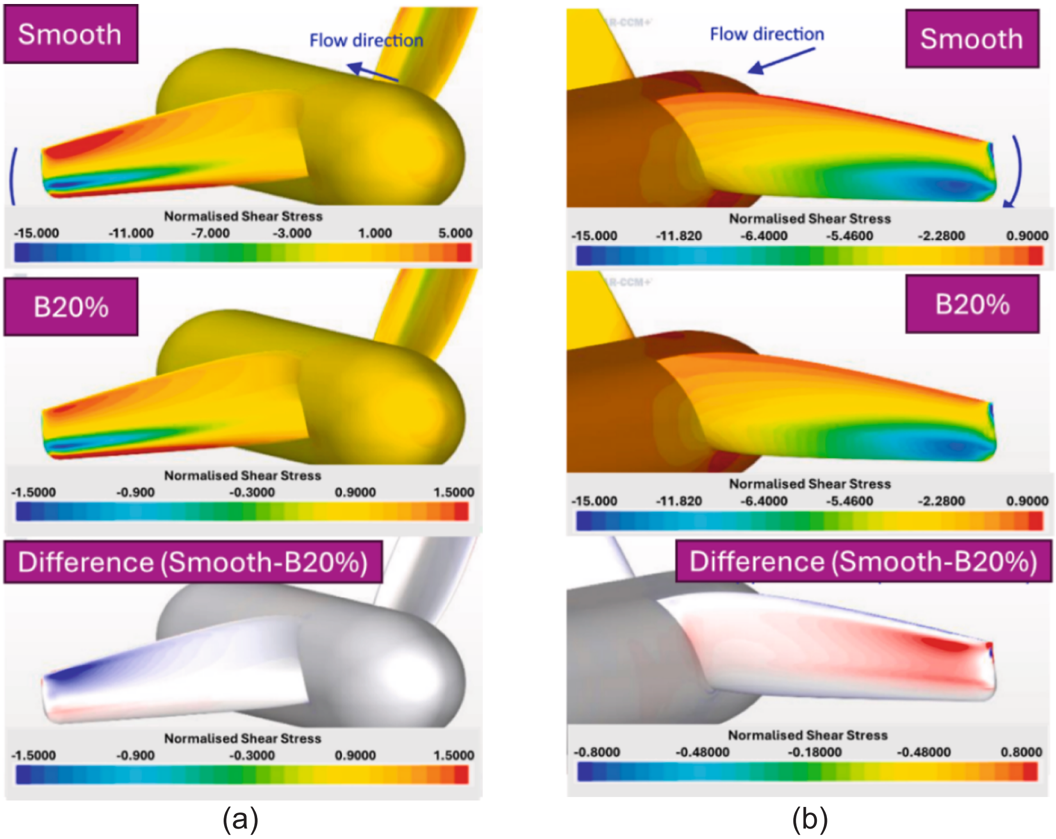

Fig. 13. Pressure distribution on smooth and severely fouled (B20%) tidal turbine blades and comparison between the face side (a) and back-side (b) of the blade, along with shear stress distribution across the turbine surface, at a tip-speed ratio (TSR) of 4 [7].

Extensive literature exists on the hydrodynamic and structural performance of wind turbines, ship propellers, and hydro turbines, with research addressing blade geometry [83–85], material properties [86], and failure mechanisms [85,87]. Comparable studies for tidal turbines include simulation-based performance analysis [88–90], blade design and manufacturing [91], reliability assessment [89,92,93], and maintenance approaches [94]. Additional investigations address blockage effects [95], cavitation [96], and surface roughness [97], alongside more recent work on fatigue life [98], hydrodynamic performance evaluation methods [99–101], and condition monitoring systems [63,102]. While these studies have advanced understanding, many remain dependent on laboratory environments or numerical predictions, which may not fully represent operational realities.

Although this section outlines the relationship between structural degradation and hydrodynamic response, much current understanding remains grounded in simulations and controlled testing. Field data on long-term blade degradation and associated performance decline are extremely limited, leaving significant uncertainty in predicting how small-scale defects accumulate into functional losses. This uncertainty not only constrains the validation of existing models but also limits the ability to anticipate coupled effects with other failure mechanisms, such as fatigue and erosion. A more detailed discussion of performance deterioration arising from erosion is presented in Section 4.4.

4. Erosion in tidal turbine blade

Erosion is a major structural failure mode in tidal turbine blades, progressively reducing performance through material loss and surface roughening. Understanding the mechanisms of erosion is essential for ensuring blade longevity and sustaining energy productivity, particularly as tidal power deployment expands. In marine environments, erosion arises from several sources:

1. Suspended sand particles acting as abrasives.
2. Seawater flow inducing adhesive wear on polymer surfaces.
3. Cavitation bubbles producing localised material erosion.

These mechanisms can act individually or synergistically, accelerating material removal and resulting in roughening, pitting, and defect formation. Such changes increase drag and reduce lift, leading to diminished blade efficiency. While erosion resistance is a critical design requirement, materials and coatings that enhance durability may introduce additional weight and increase manufacturing complexity. Addressing this challenge requires collaboration between materials scientists, fluid dynamics specialists, design engineers, and field researchers.

Several factors should be considered when addressing erosion in tidal turbine blades, including: (a) predominant erosion mechanisms and associated damage morphologies, (b) condition monitoring techniques and methods for evaluating erosion severity, (c) metrology approaches for characterising surface topography, and (d) the dependence of erosion rate on blade materials, coating systems, and loading conditions [103–105].

Given the high costs associated with tidal turbine downtime, mitigating erosion is a priority. Research in this area aims to improve both longevity and efficiency under harsh marine conditions. Future work should focus on:

- Developing multiscale erosion models that link short-term wear processes with long-term degradation trends
- Implementing online erosion monitoring systems for early detection of material loss
- Designing advanced nanocomposite coatings with enhanced resistance to abrasive and cavitation wear
- Refining multiphase computational fluid dynamics (CFD) models to improve prediction of particle–surface interactions
- Investigating how surface condition changes affect boundary layer behaviour and hydrodynamic performance

Progress in these areas will be essential for improving the economic viability and operational reliability of tidal energy systems [17,106,107].

4.1. Introduction to the erosion parameters

Erosion, defined as the progressive loss of material caused by repeated deformation and cutting actions, is governed by several interrelated factors [108]:

- Operational conditions, such as flow or impingement velocity and angle, exposure duration, and fluid temperature.
- Erodent characteristics, including cavitation properties, particle size, shape, hardness, and concentration.
- Target material properties, such as substrate composition, surface hardness and morphology, and the method and material of applied coatings.

The erosion mechanism identifier assists in the accurate prediction of erosion behaviour by accounting for the combined influence of the three previously mentioned factors [109]. In composite blades, erosion generally progresses from microscopic surface roughness to cracking and delamination, eventually leading to macroscopic scooping and reduced service life [56,110,111]. Fig. 14 illustrates these stages for composite blades, showing the progression of damage from initial pitting to severe material loss over the operational life of the blade [111]. Over time, erosion interacts with other failure modes, including fatigue, corrosion, biofouling, and water-ingress-induced ageing, by initiating, accelerating, or amplifying these structural mechanisms through complex and often synergistic processes. The location and extent of erosion are influenced by blade geometry, structural configuration, operating conditions, and environmental exposure, with affected regions including the suction face, pressure face, leading edge, and trailing edge. Predicting and quantifying erosion remains a complex, multi-parameter challenge. Although laboratory and numerical studies have improved

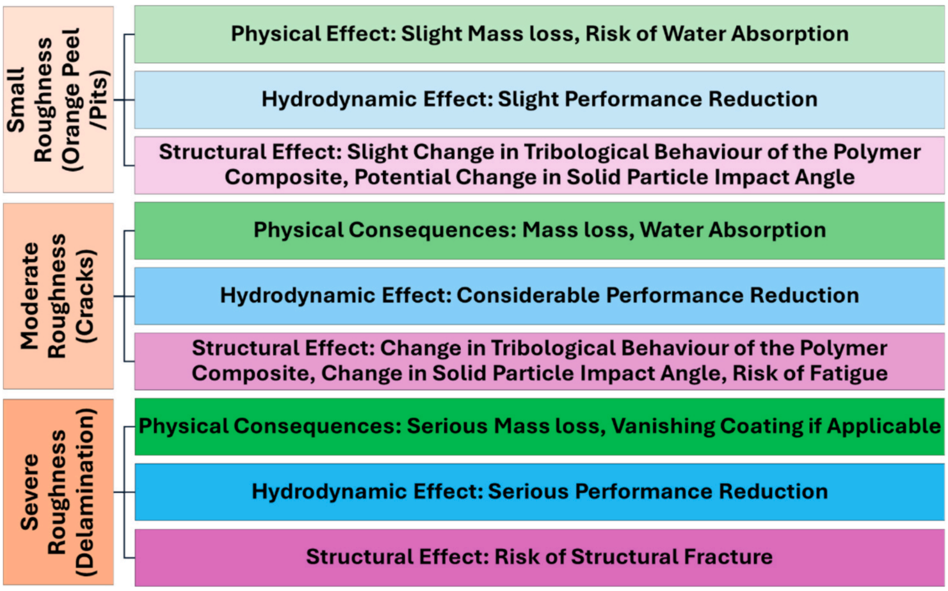

Fig. 14. Surface roughness effects on composite blades [111,112].

understanding, these approaches often rely on controlled conditions and simplified assumptions, which may not fully capture real-world variability. This underlines the need for continued experimental and numerical investigation supported by long-term field data.

4.2. Tidal turbine Blade's erosion causes

4.2.1. Solid particles impingement

Solid particle impingement is a major contributor to erosion damage in hydro and tidal turbine blades. Suspended sediments transported by seawater currents cause abrasive wear through repeated impacts, progressively altering blade geometry and reducing both performance and reliability, as illustrated in Fig. 15.

As noted in the previous section, erosion caused by solid particle impingement depends not only on the blade material but also on several additional factors:

- Particle characteristics: Size, shape, hardness, and concentration influence the severity of abrasive wear. Higher particle concentrations typically increase the frequency of impacts, although excessive particle–particle interaction can reduce kinetic energy transfer [61].
- Operational conditions: Impingement angle and velocity have a strong influence on erosion rate. Ductile materials typically experience maximum erosion at low angles (around 20°), whereas brittle materials show peak wear at normal incidence (90°) [33]. Higher velocities increase kinetic energy transfer, and factors such as tidal current speed and seabed geology affect slurry composition and behaviour. Erosion is often intensified in regions where the flow accelerates [114].

The leading edge, particularly near the blade tip, is most susceptible to severe particle impingement because of higher local velocities. In ductile materials, impacts result in ploughing and cutting, whereas brittle materials tend to exhibit microcracking and grain ejection. Prolonged exposure causes cumulative surface erosion and a gradual reduction in structural integrity. The dimensionless erosion efficiency (η) is used to estimate erosion severity and to support material selection and design optimisation:

$$\eta = V_{removed}/V_{impacting}$$

Where $V_{removed}$ represents the volume of material removed from the blade surface, and $V_{impacting}$ denotes the volume of the erosive particles. Lower values of η correspond to higher erosion resistance [37,67,106,109,115,116]. While this metric is widely used, many reported values are derived from controlled laboratory testing, which may not fully replicate the complexity of in-service marine environments. The scarcity of long-term field data continues to limit the validation of erosion models and highlights the need for datasets reflecting actual operational conditions.

4.2.2. Friction

Structural frictional interactions between seawater and tidal turbine blades arise from viscous fluid–structure interaction (FSI), progressively wearing blade materials over time. As seawater flows across the blade surface, a thin boundary layer forms and adheres due to viscosity, enforcing a no-slip condition. Shear stress is greatest where the boundary layer remains thinnest, particularly at the leading edge, and diminishes downstream as the boundary layer thickens. In turbulent boundary layers, additional shear develops from eddy shedding.

At the microscale, adhesive junctions form between seawater molecules and surface asperities. These junctions break under shear loading, producing adhesive wear that removes aggregated molecules and microparticles. Polymers and composite resins used in tidal blades are particularly vulnerable to this process. Friction acting parallel to the blade surface is driven by both fluid viscosity and the

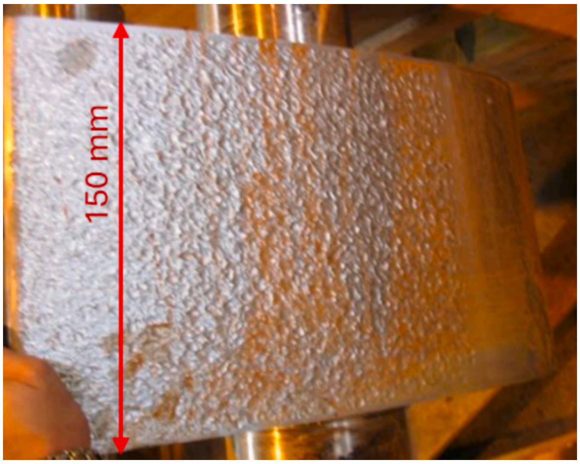

Fig. 15. Erosion on the suction side of a hydrofoil caused by solid particle impingement [113].

velocity difference between the slower boundary layer and the faster external flow, resulting in cumulative material loss over prolonged service [82,117].

Friction-induced erosion increases blade surface roughness, reducing hydrodynamic efficiency as discussed in Section 3.2.2. This reduction occurs through its influence on boundary layer transition from laminar to turbulent flow, as well as through changes in lift and drag. Additionally, friction-generated heat can alter the thermal and mechanical properties of the blade's polymer matrix. Although these mechanisms are recognised in laboratory-scale studies, there remains a lack of in situ measurements quantifying the long-term role of friction in overall erosion for tidal turbine blades. This knowledge gap limits the accuracy of predictive models and highlights the need for extended field monitoring to verify laboratory-based assumptions.

4.2.3. Cavitation

Cavitation refers to the formation and collapse of microscopic vapour bubbles when local static pressure drops below the vapour pressure of water. This phenomenon causes material loss due to the high temperatures and pressures generated during bubble collapse. It can also produce micro-jets and shockwaves that plastically deform the surface and form shallow pits. As shown in Fig. 16, this process gradually increases surface roughness and contributes to a decline in blade efficiency, as previously discussed in Section 3.2.2. In addition, elevated temperatures associated with cavitation may degrade the mechanical and thermal properties of polymer materials.

Tidal turbine blades are particularly vulnerable to cavitation in certain operating conditions, with the most severe effects typically occurring on the suction side and near the trailing edge of blade sections. To fully understand the initiation and consequences of cavitation-induced erosion on blade surfaces, three additional factors must be considered alongside the inherent properties of the target material:

- Cavity collapse energy: More energetic bubble collapses generate higher erosive forces and accelerate material damage.
- Exposure duration: Prolonged operation in cavitating conditions causes cumulative surface degradation.
- Standoff distance: Shorter distances between collapsing cavities and the blade surface increase impact intensity and localised erosion.

Under typical operating conditions, tidal turbine blades are designed with tip-speed ratios ranging from 4 to 6, which are lower than the 7 to 11 range commonly used for wind turbines. At these relatively low velocities, cavitation is generally unlikely during normal operation. However, increasing the tip-speed ratio to enhance power output introduces a greater risk of cavitation, which must be mitigated. Furthermore, under high blockage conditions, as discussed in Section 2.2, rotors are subjected to elevated loads and pronounced suction peaks, making cavitation erosion more likely and more critical to manage.

The significance of cavitation in tidal turbine blades, particularly its potential impact on structural integrity and hydrodynamic performance, highlights the need for targeted mitigation strategies through design optimisation and operational control. These strategies include:

- Slower tip speed: This reduces cavitation risk, although it may compromise power performance [71].
- Optimised blade geometry: This alters local pressure distribution and influences cavitation behaviour [112].
- Passive blade pitch control systems: These alleviate hydrodynamic loads during cavitation without active control mechanisms [119].
- Cavitation-resistant coatings: These provide an additional protective barrier to reduce surface damage [120].

Although these measures have been widely examined in ship propellers and hydroturbines, the extent to which they apply to tidal turbine blades remains uncertain. The lower rotational speeds typical of tidal devices may prevent cavitation from occurring, or at least limit its severity. However, this assumption has not been comprehensively validated. Most available studies on cavitation mechanisms,

Fig. 16. Cavitation-induced erosion on the trailing edge of a blade [118].

mitigation, and material performance have been conducted under operational and environmental conditions that do not match those of tidal turbines. There is therefore a clear need for dedicated research that evaluates cavitation risk and consequences in tidal-specific contexts, ensuring that mitigation strategies are both relevant and effective for these systems.

4.3. Tidal turbine Blade's erosion Stimuluses and influences

This section provides a qualitative perspective on the interaction between erosion and other degradation mechanisms affecting tidal turbine blades. Instead of presenting quantitative analysis, it draws on conceptual relationships reported in the literature to examine how erosion may influence or be influenced by structural processes such as fatigue, corrosion, impact loading, biofouling, and ageing. The intention is to emphasise that erosion should not be viewed as an isolated phenomenon, but as one component of a broader degradation environment that shapes blade integrity under prolonged marine exposure.

Erosion can both initiate and be triggered by other mechanisms in the marine environment. In addition to its direct causes, various interacting factors, illustrated in Fig. 17, can accelerate or slow its progression, and may themselves be affected in return. Although these relationships are often acknowledged, a detailed understanding remains limited, as many proposed mechanisms are based on controlled laboratory studies or simulations that may not fully represent operational tidal conditions.

To further illustrate the cumulative nature of these processes, Fig. 18 presents a schematic timeline of degradation mechanisms under marine operating conditions. This chart is not intended to provide a quantitative prediction of damage but rather to emphasise how different mechanisms may initiate, overlap, and interact across a turbine's lifetime. The relative contributions and timings are deliberately shown schematically, since no comprehensive data exist in the current literature to define them for tidal applications. The site-dependent variability of sediment composition, flow regimes, and loading conditions adds further complexity. For these reasons, Fig. 18 should be read as a conceptual framework that underscores the importance of deeper investigation. Its main purpose is to signal the need for field-based monitoring and multiphysics modelling to refine such timelines into accurate, real-world representations.

While many mitigation strategies reported in the literature originate from wind turbine research, transferring these approaches to tidal environments presents additional challenges. Full submersion, biofouling, high sediment loading, and restricted maintenance access create conditions that differ significantly from those faced by wind turbines. This underlines the need for innovations in materials, coatings, and sensor technologies that are specifically designed for tidal applications, supported by validation under realistic operational environments.

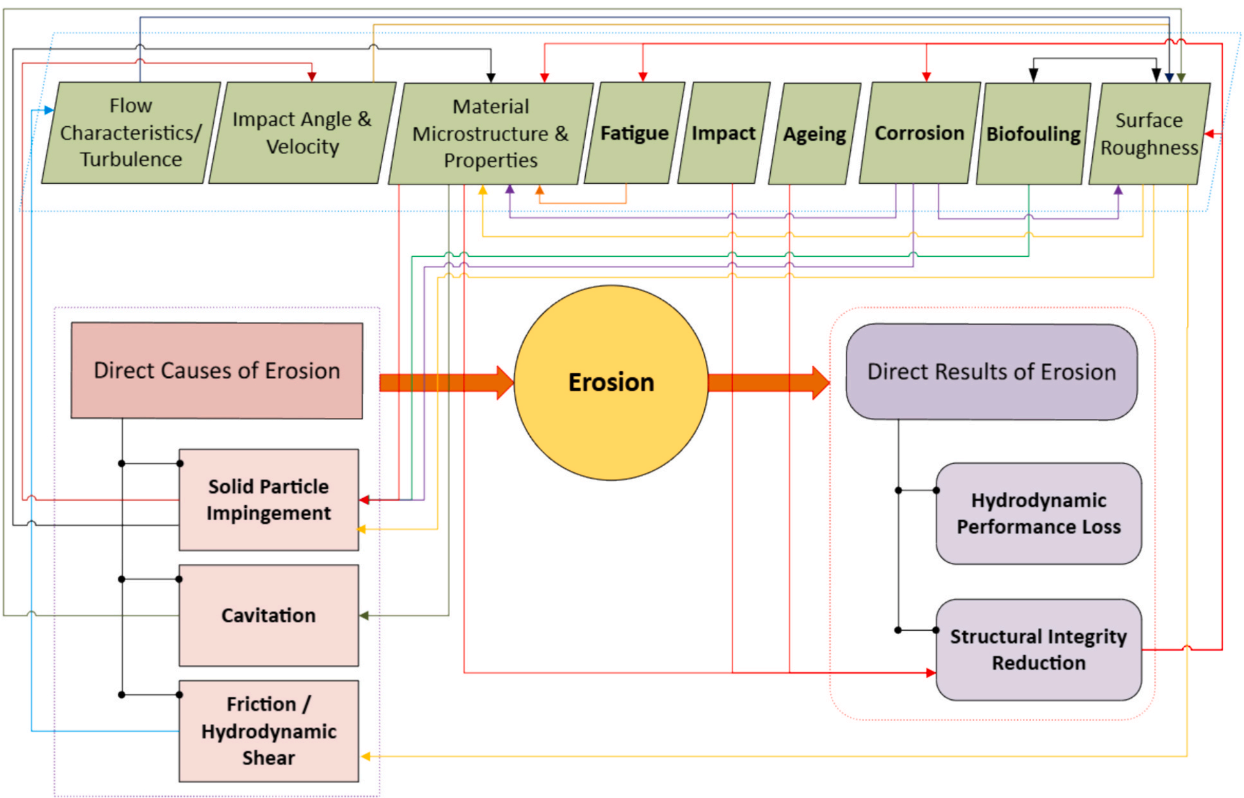

Fig. 17. Conceptual schematic of tidal blade erosion: causes, influencing factors, feedback loops, and results.

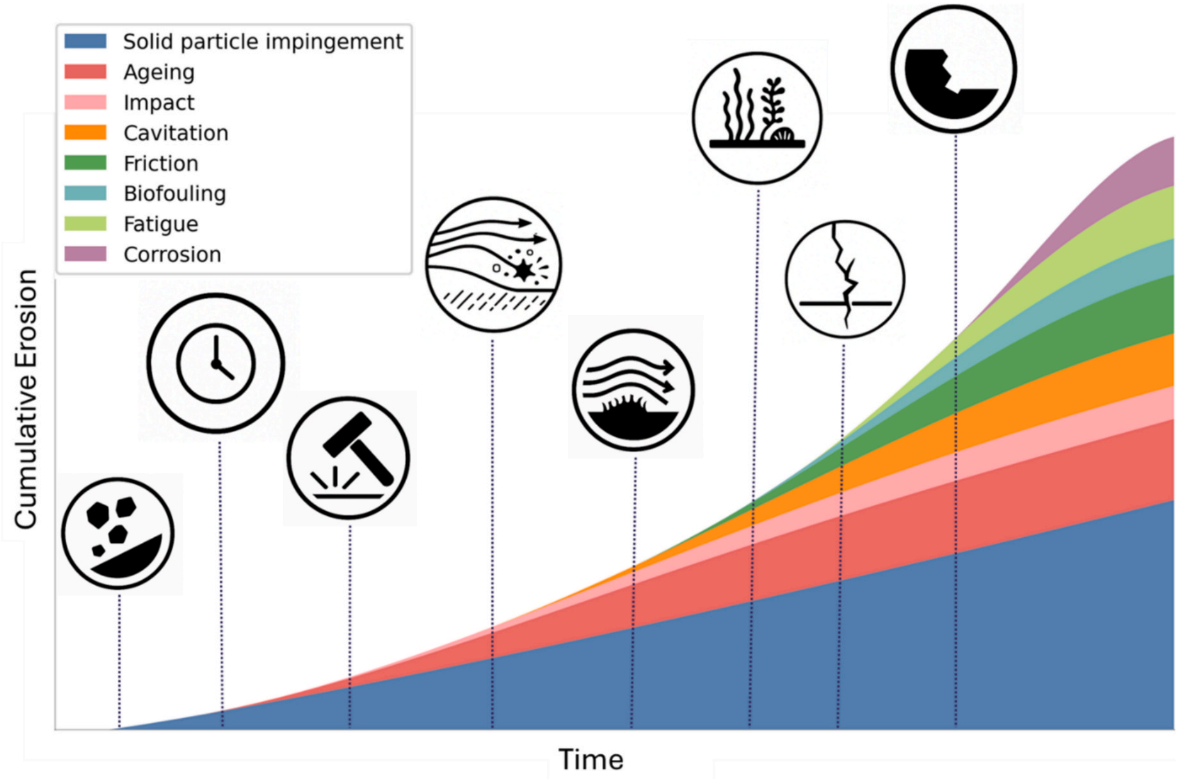

Fig. 18. Schematic accumulation of erosion-related degradation mechanisms over time under marine operating conditions.

4.3.1. Impact

Collisions with external objects, ranging from small debris to large marine animals, can significantly accelerate erosion on tidal turbine blades [41,90]. As discussed in Sections 3.2.1 and 4.2.1, such impacts damage the blade surface directly through high-velocity contact, initiating pits, cracks, delamination, and deformation that alter the external geometry, as illustrated in Fig. 19. Impacts can also contribute indirectly by weakening structural integrity and creating heat-affected zones that are more vulnerable to degradation. Erosion itself reduces the structural resilience of blade materials, making them more susceptible to further damage from subsequent impacts, whether minor or severe.

As outlined in Section 3.2.1(f), impacts can arise from wildlife, debris, vessels, and equipment. In the context of erosion, these events not only damage the surface directly but also accelerate material removal through secondary mechanisms.

The unpredictable nature of collision events in tidal environments makes numerical modelling and prediction challenging. While physical testing using strain gauges and accelerometers provides valuable data on impact forces and stress distributions, replicating realistic high-energy collisions under controlled conditions remains difficult. Moreover, much of the available experimental evidence

Fig. 19. Erosion on hydro turbine metal components caused by impact-induced damage [113].

comes from impact scenarios unrelated to tidal turbines, limiting the direct transferability of results. Underwater inspection constraints and the sporadic occurrence of such events further complicates long-term monitoring.

Mitigation strategies include the following [33,37]:

- Selecting composite materials with high fracture toughness and impact resistance.
- Reinforcing critical areas, particularly along the leading edge.
- Applying compliant bumper coatings to absorb and dissipate impact energy.
- Temporarily halting blade rotation during high-risk operational conditions.
- Employing sensor systems to trigger automated shutdowns when high-energy impacts are detected.
- Repairing damaged surfaces to restore protection and erosion resistance.

Ongoing research integrating modelling, field monitoring, and targeted testing is necessary to improve the management of impact-related erosion. In particular, future studies should focus on generating data under tidal-specific operating conditions, as current understanding relies heavily on extrapolation from other marine and hydrodynamic applications.

4.3.2. Corrosion

Erosion–corrosion, a form of tribocorrosion, can significantly affect tidal turbine blades constructed from metals and certain composites. This synergistic degradation mechanism combines mechanical wear with electrochemical reactions, often leading to severe material loss under conditions involving turbulent flow, cavitation, or particle impingement [121]. Corrosion degrades surface finish by generating pits and increasing roughness, which in turn accelerates erosion. In polymer composite blades, although the fibres are generally corrosion-resistant, the matrix can absorb moisture and undergo hydrolysis, producing swelling stresses and micro-cracking. These defects act as initiation sites for intensified erosion and accelerated fatigue cracking.

Erosion can also strip away protective corrosion films, exposing sensitive materials to renewed chemical attack. This interaction is especially damaging in environments where abrasive suspended sediments in turbulent flow coincide with active corrosion processes. While mitigation measures such as protective coatings, cathodic protection, and material selection have been outlined in Section 3.2.1, much of the evidence supporting these strategies originates from applications such as hydroturbines, ship propellers, or offshore structural components. The specific behaviour of tidal turbine blades under prolonged combined erosion–corrosion loading remains poorly characterised, limiting the predictive accuracy of current models.

Targeted field measurements and tidal-specific laboratory simulations are needed to clarify how operational parameters, sediment characteristics, and marine chemistry interact to drive erosion–corrosion in these systems. Without such data, design optimisation and maintenance planning will continue to rely heavily on assumptions from related but non-identical marine environments.

4.3.3. Biofouling

Biofouling, defined as the accumulation of microorganisms, plants, and animals on tidal turbine blade surfaces, has a significant influence on the progression of erosion. It begins immediately after submersion, starting with the formation of a thin biofilm composed of bacteria and microalgae, and followed by the attachment of larger macrofouling organisms such as barnacles and mussels.

Biofouling can accelerate erosion through several mechanisms:

- Increasing surface roughness: This disrupts local flow, generating turbulence and vortices that intensify shear stress and particle impingement forces.
- Enhancing boundary layer turbulence: This promotes an earlier transition from laminar to turbulent flow, increasing skin friction and adhesive wear.
- Releasing secret substances: Certain biofouling organisms secrete acidic or enzymatic substances that degrade protective coatings and expose the underlying substrate to more severe erosion.

Some studies have suggested that moderate levels of biofouling may offer partial shielding against erosion; however, this effect remains poorly understood, and available data are often context-specific to other marine systems rather than tidal turbines. Surface erosion can also create conditions that promote further biofouling, illustrating the bidirectional relationship between the two phenomena.

Preventive measures and cleaning strategies for biofouling have already been outlined in Section 3.2.1; the focus here is on its interaction with erosion. More tidal turbine-specific research, combining experimental testing, high-resolution surface metrology, and multiphysics modelling, is required to quantify these reciprocal effects under realistic marine operating conditions.

4.3.4. Fatigue

Structural fatigue damage and erosion progression in tidal turbine blades are closely interrelated and mutually reinforcing. Fatigue-induced cracks accelerate erosion, while erosion promotes fatigue cracking, creating a self-reinforcing cycle of structural deterioration. Fatigue failure ruptures protective gel coats, exposing the substrate to moisture ingress and abrasive flow conditions.

The presence of cracks also disrupts local flow behaviour, advancing the transition to turbulence and increasing shear stresses. This intensifies erosion through adhesive wear mechanisms, as described in Section 3.2.2. Experimental studies have reported erosion rates up to fifteen times higher in regions with pre-existing damage. Fatigue damage also facilitates biofouling accumulation, which further disturbs flow and exacerbates erosion [48].

Conversely, erosion influences fatigue by roughening the surface and creating microscopic pits, cracks, and gouges. These eroded features act as stress risers and serve as initiation sites for fatigue cracking, accelerating crack propagation due to localised stress concentration, disrupted surface geometry, and structural weakening. This process also promotes moisture ingress, which compromises structural integrity and reduces the overall fatigue resistance of the blade.

Mitigation strategies for managing the coupled fatigue–erosion process include.

- Applying erosion-resistant coatings to prevent surface damage associated with fatigue crack development.
- Using self-healing composite materials to repair early-stage fatigue defects.
- Implementing operational controls to reduce fatigue loading during periods of intensified erosion.

Further research is needed to improve understanding and modelling of this interaction. Advancing knowledge in this area will support the optimisation of blade designs, the development of adaptive material systems, and the formulation of targeted maintenance strategies. Interrupting the recursive link between fatigue and erosion through advanced materials, improved structural design, and effective operational planning is key to extending blade service life.

4.3.5. Ageing

Long-term marine exposure leads to ageing in tidal turbine blades, a process that can significantly accelerate erosion. This is particularly relevant for polymer composites commonly used in blade construction. Over time, these materials absorb moisture, resulting in internal stresses and chemical changes through mechanisms such as hydrolysis and plasticisation. These changes reduce resistance to erosion by softening the composite, making the surface more susceptible to deformation under water flow and particle impacts. At the microstructural level, ageing promotes the formation of microcracks and weakens the fibre–matrix bond, which reduces the blade's ability to withstand even minor impacts.

Fig. 20 presents the findings of Idrisi and Mourad, who investigated the strength degradation of GFRP materials over an 11-year period in seawater, providing valuable insights into the long-term performance of materials used in tidal turbine blades [122]. Aged materials can erode considerably faster than new ones, in some cases by several orders of magnitude.

The effects of ageing on erosion are multifaceted:

- Moisture uptake leading to swelling and microcrack formation.
- Degradation of fibre–matrix bonding, reducing structural integrity.
- Softening of the composite matrix, increasing susceptibility to abrasive wear.
- Reduced ability to resist hydrodynamic loading and particle impacts.

Mitigation strategies include:

- Selecting water-resistant materials with low moisture absorption.
- Refining manufacturing processes to minimise internal defects and weak points.
- Developing self-healing and water-repellent composite systems.

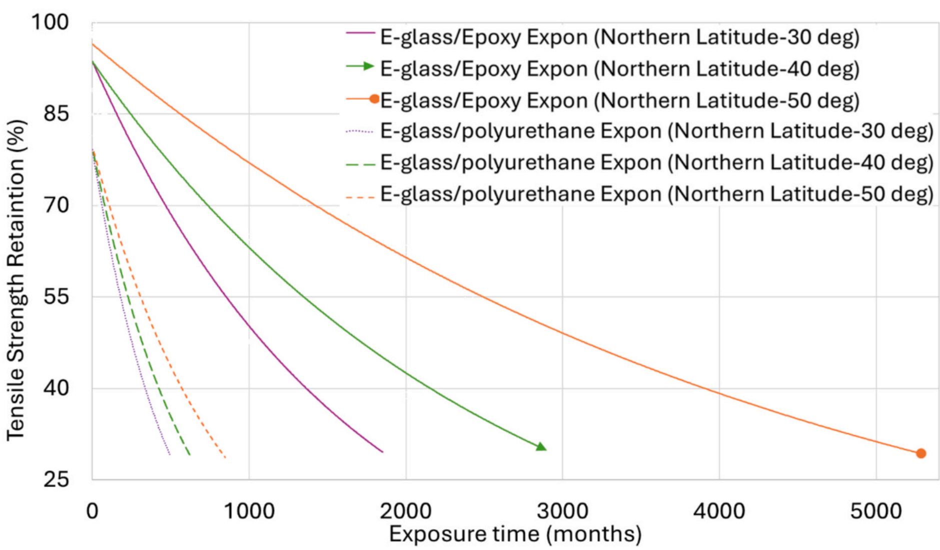

Fig. 20. Predicted tensile strength degradation of E-glass/epoxy and E-glass/polyurethane composites over long-term seawater exposure.

- Applying robust protective coatings to limit water ingress.

Conversely, erosion can initiate or accelerate ageing by damaging protective layers and increasing permeability, creating a feedback loop in which both processes reinforce one another. Although laboratory-based accelerated ageing tests are used to predict long-term degradation before deployment, the validity of these tests for tidal-specific conditions remains uncertain. This underscores the need for further long-term field data collection and improved modelling to quantify the coupled effects of ageing and erosion in operational tidal energy systems.

4.4. Effects of erosion on tidal turbine blade performance

Erosion-induced roughness, pitting, and material loss on tidal turbine blades significantly influence hydrodynamic performance by altering lift, drag, and stall characteristics. Fig. 21 presents a schematic representation of how erosion interacts with blade hydrodynamics, illustrating the bidirectional relationship between structural changes and fluid behaviour.

Roughened surfaces disrupt pressure distribution and increase the boundary layer Reynolds number, intensifying local turbulence. As illustrated in Fig. 22, such disturbances reduce lift and lead to a decline in energy conversion efficiency. Increased turbulence accelerates the transition from laminar to turbulent flow and delays boundary layer separation. Although delayed separation may postpone stall onset, it also increases drag, further reducing performance [82].

Localised roughness along the blade span determines the location of boundary layer separation, the spread of stall, and variations in lift and drag. These effects create distinct hydrodynamic behaviours from root to tip. Surface metrology of eroded regions allows damage quantification and correlation of severity with performance changes. Baseline experiments are used to validate numerical models that predict hydrodynamic degradation over time [124]. Both experimental and numerical approaches are therefore essential to capture fluid–structure interaction (FSI) between erodent particles, blade surfaces, and the surrounding flow. Such understanding supports the development of improved materials, coatings, and blade geometries that can minimise surface degradation while sustaining efficiency throughout the operational lifespan of tidal turbines in harsh marine environments.

Although there is an established body of research quantifying the effects of surface roughness on flow behaviour in marine propellers, including the example shown in Fig. 22, these studies are not based on tidal turbine blades and therefore do not account for tidal-specific operational conditions or geometries. At present, there is no validated empirical or computational framework that directly relates erosion severity, defined by parameters such as depth, roughness, or mass loss, to hydrodynamic power loss in tidal turbines. Likewise, no operational guidelines exist to determine maintenance intervals based on erosion progression.

A recent study by Habibi et al. [125,126] established the first correlation between erosion-induced roughness and mass loss for GFRP composites under controlled laboratory testing. While this provides a measurable foundation for future model development, it does not yet form a comprehensive predictive framework. Addressing these limitations will require integrated, evidence-based erosion–performance models developed specifically for tidal turbine applications. Such models should incorporate site-specific sediment characteristics, blade material properties, and flow conditions, ultimately enabling more accurate performance prediction and condition-based maintenance planning.

Addressing the uncertainty surrounding leading-edge erosion is therefore central to performance prediction and maintenance

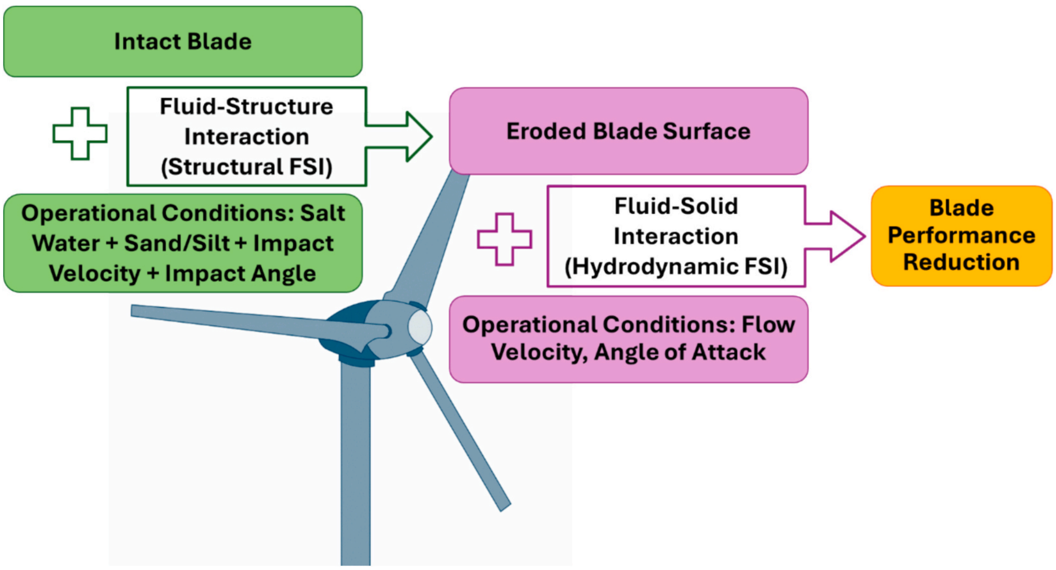

Fig. 21. Schematic representation of fluid–structure interaction (FSI): the bidirectional relationship between hydrodynamic forces and structural responses in a coupled system.

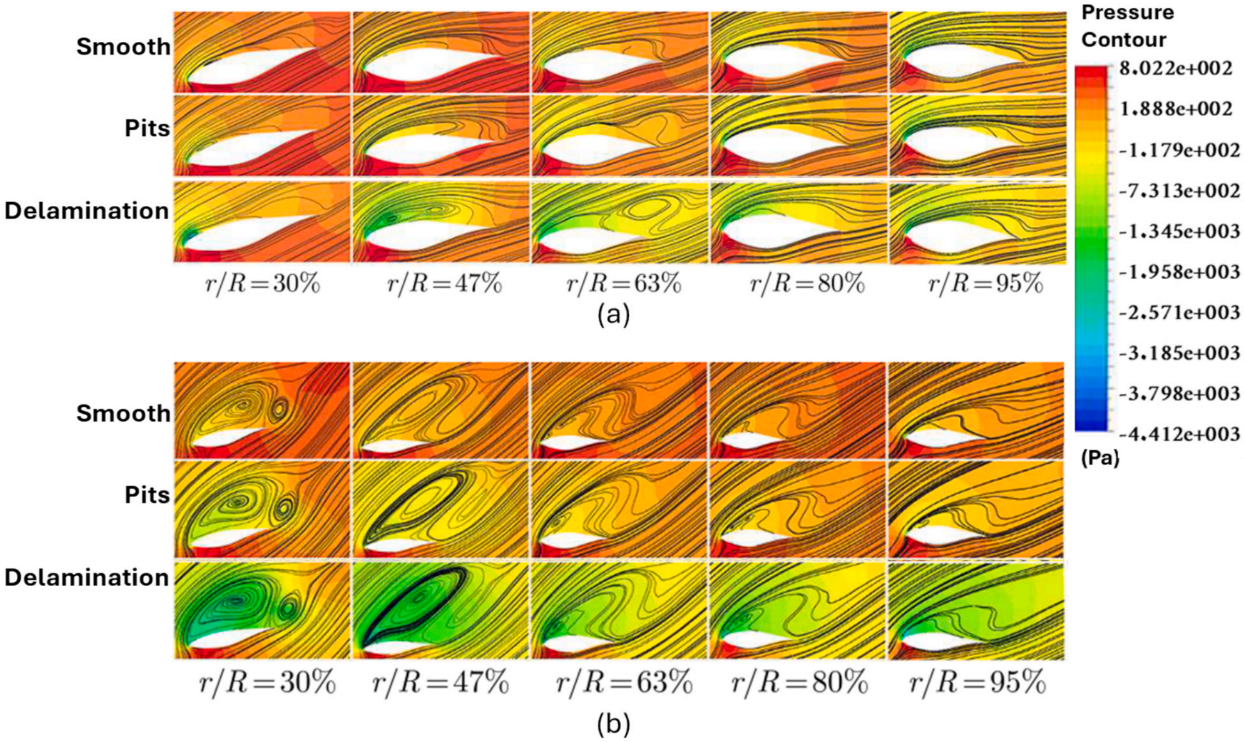

Fig. 22. Flow behaviour around blade sections at flow speeds of (a) 7 m/s and (b) 20 m/s in different roughness severities [123].

planning. Without tidal-specific data to quantify its effects, long-term reliability assessments will remain highly uncertain.

Despite the clear performance implications outlined above, publicly available case studies of operational tidal turbine blade failures remain scarce and, in many cases, proprietary. This scarcity limits the ability to validate laboratory findings against real-world data and hampers the development of reliable erosion–performance models. Addressing this gap through transparent field reporting and systematic post-deployment assessments would provide a stronger empirical foundation for linking erosion to hydrodynamic and structural performance losses.

5. Consideration of the leading-edge erosion

This review identifies a critical gap in tidal turbine research: the lack of quantitative studies directly linking leading-edge erosion to hydrodynamic performance and structural reliability. Although erosion at the blade's leading edge is widely recognised as the most severe form of material loss in marine energy systems, no tidal-specific investigations currently exist on the roles of cavitation, impact angle distributions, or protective coatings. Insights from related sectors, such as wind turbines and hydraulic machinery, demonstrate the importance of these factors, but their transferability to tidal conditions remains untested. This absence of data prevents the development of robust predictive models and underlines the novelty of LEE as a focus of this review.

By framing LEE in this way, we aim not only to summarise current understanding but also to highlight the research gaps that most urgently need to be addressed. Progress in this area will depend on dedicated tidal-specific studies, including field measurements, span-wise erosion mapping, and coupled CFD–metrology validation, which are not yet available in the literature.

The leading edge of tidal turbine blades warrants particular attention in erosion research. Surface roughness caused by leading-edge erosion has a pronounced influence on lift and drag, leading to measurable reductions in efficiency. Understanding this relationship is therefore essential for accurate performance prediction and effective maintenance planning.

Several factors complicate the study of leading-edge erosion:

- Variability in environmental conditions, including particle concentrations, velocities, and impact angles in tidal flows.
- Challenges in isolating erosion effects from other concurrent degradation mechanisms.
- Limited accessibility for inspection, which restricts regular monitoring of erosion progression.

Addressing these challenges requires a coordinated and multidisciplinary approach, including:

1. Advanced materials research to develop erosion-resistant composites and protective coatings.
2. Controlled laboratory testing to simulate long-term erosion and validate material performance.

3. High-fidelity multiphysics modelling to predict erosion patterns and quantify hydrodynamic impacts.
4. Field monitoring of operational turbines to validate model predictions and inform maintenance schedules.

Detailed flow measurements around eroded blade sections, supported by computational simulations, can help establish roughness thresholds that trigger significant performance losses. Advanced numerical models, incorporating variables such as erosion severity and spatial distribution, can predict the influence of leading-edge degradation on lift, drag, and overall efficiency under varying tidal conditions.

The outcomes of this integrated approach will inform the development of optimised erosion-resistant materials, improved blade geometries, advanced coating technologies, and condition-based maintenance strategies. In conclusion, quantifying the effects of progressive leading-edge erosion demands a comprehensive strategy that combines materials science, experimental validation, computational modelling, and in-situ monitoring. This integration will support the creation of more durable blade designs, refined operational controls, and predictive maintenance frameworks tailored to the unique demands of tidal energy systems.

6. Conclusion

- Tidal turbine blades are critical components that require sustained research into failure mechanisms, particularly erosion, which has a major influence on durability and hydrodynamic performance.
- Although fatigue and cavitation-induced damage can often be mitigated through structural design and hydrodynamic optimisation, erosion remains a complex and unpredictable phenomenon.
- Erosion mechanisms such as particle impingement, cavitation, and friction progressively alter blade shape and surface finish, thereby affecting lift, drag, and stall characteristics, and leading to long-term reductions in power output.
- Sand particle impacts are especially problematic for seabed-mounted turbines, as they incrementally increase surface roughness from the microscopic to the macroscopic scale.
- Multiphysics modelling is essential for capturing the complex interaction between evolving erosion patterns, operating conditions, and hydrodynamic behaviour.
- Controlled laboratory testing is vital for quantifying the relationship between surface roughness and aerodynamic changes such as increased drag and reduced lift, providing validation for numerical models.
- High-resolution flow measurements around eroded blades, combined with surface metrology, can help identify roughness thresholds beyond which hydrodynamic performance is noticeably degraded.
- Advanced numerical simulations can support the optimisation of erosion resistance by accounting for material selection, coating strategies, blade geometry, and maintenance scheduling to preserve power output throughout the turbine's operational life.
- Online condition monitoring and adaptive control methods offer promising pathways to mitigate progressive erosion through real-time load adjustments and timely maintenance interventions.
- Performance-led blade design presents a complex multiphysics optimisation challenge, requiring reliable model validation supported by experimental data.
- Further integrated research across materials development, multiphysics simulation, laboratory experimentation, and in-situ condition monitoring is necessary to achieve long-term performance gains as global tidal energy capacity continues to expand.

Maintaining efficient tidal blade performance over time requires a multidisciplinary and coordinated approach. Integrating expertise in hydrodynamics, materials degradation, and system monitoring will support the development of blade systems capable of withstanding harsh marine conditions throughout their operational lifespan.

CRediT authorship contribution statement

Payvand Habibi: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Farhad Abad:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Saishuai Dai:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Ali Mehmanparast:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Saeid Lotfian:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] P. Qian, B. Feng, H. Liu, X. Tian, Y. Si, D. Zhang, Review on configuration and control methods of tidal current turbines, Renew. Sustain. Energy Rev. 108 (2019) 125–139.
[2] S.J. Sangiuliano, Turning of the tides: Assessing the international implementation of tidal current turbines, Renew. Sust. Energ. Rev. 80 (2017) 971–989.
[3] R.K. Pachauri, A. Reisinger, Climate change 2007: Synthesis report. Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change, Climate Change 2007. Working Groups I, II and III to the Fourth Assessment (2007).
[4] C.E. Clark, B. DuPont, Reliability-based design optimization in offshore renewable energy systems, Renew. Sustain. Energy Rev. 97 (2018) 390–400.
[5] F.-M. Jing, W.-J. Ma, L. Zhang, S.-Q. Wang, X.-H. Wang, Experimental study of hydrodynamic performance of full-scale horizontal axis tidal current turbine, Journal of Hydrodynamics, Ser. B 29 (1) (2017) 109–117.
[6] C.W. Finkl, R. Charlier, Electrical power generation from ocean currents in the Straits of Florida: some environmental considerations, Renew. Sustain. Energy Rev. 13 (9) (2009) 2597–2604.
[7] S. Song, Y.K. Demirel, M. Atlar, W. Shi, Prediction of the fouling penalty on the tidal turbine performance and development of its mitigation measures, Appl. Energy 276 (2020) 115498.
[8] R.J.K. Wood, A.S. Bahaj, S.R. Turnock, L. Wang, M. Evans, Tribological design constraints of marine renewable energy systems, Proc. r. Soc. A 368 (1929) (2010) 4807–4827.
[9] M.J. Khan, G. Bhuyan, M.T. Iqbal, J.E. Quaicoe, Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: a technology status review, Appl. Energy 86 (10) (2009) 1823–1835.
[10] T.A. Adcock, S. Draper, T. Nishino, Tidal power generation–a review of hydrodynamic modelling, Proceedings of the Institution of Mechanical Engineers, Part a: Journal of Power and Energy 229 (7) (2015) 755–771.
[11] H. Izadi Gonabadi, Performance of low cost composites for tidal turbine applications, Newcastle University, 2019.
[12] S.P. Neill, Fundamentals of ocean renewable energy : generating electricity from the sea, [internet Resource] (2018).
[13] F.Z.d. Arcos, Hydrodynamics of highly-loaded axial flow tidal rotors, Oxford, 2021.
[14] Z. Zhou, M. Benbouzid, J.-F. Charpentier, F. Scuiller, T. Tang, Developments in large marine current turbine technologies – a review, Renew. Sustain. Energy Rev. 71 (2017) 852–858.
[15] A.S. Bahaj, L.E. Myers, Fundamentals applicable to the utilisation of marine current turbines for energy production, Renew. Energy 28 (14) (2003) 2205–2211.
[16] P. Fraenkel, Marine current turbines: pioneering the development of marine kinetic energy converters, Proceedings of the Institution of Mechanical Engineers, Part a: Journal of Power and Energy 221 (2) (2007) 159–169.
[17] S. Walker, P.R. Thies, A review of component and system reliability in tidal turbine deployments, Renew. Sustain. Energy Rev. 151 (2021) 111495.
[18] G.S. Payne, T. Stallard, R. Martinez, Design and manufacture of a bed supported tidal turbine model for blade and shaft load measurement in turbulent flow and waves, Renew. Energy 107 (2017) 312–326.
[19] W. Finnegan, R. Allen, C. Glennon, J. Maguire, M. Flanagan, T. Flanagan, Manufacture of high-performance tidal turbine blades using advanced composite manufacturing technologies, Appl. Compos. Mater. (2021) 1–26.
[20] T. Xie, T. Wang, Q. He, D. Diallo, C. Claramunt, A review of current issues of marine current turbine blade fault detection, Ocean Eng. 218 (2020) 108194.
[21] S. Zanforlin, Advantages of vertical axis tidal turbines set in close proximity: a comparative CFD investigation in the English Channel, Ocean Eng. 156 (2018) 358–372.
[22] L. Chen, W.-H. Lam, A review of survivability and remedial actions of tidal current turbines, Renew. Sustain. Energy Rev. 43 (2015) 891–900.
[23] P. Ouro, P. Dené, P. Garcia-Novo, T. Stallard, Y. Kyozuda, P. Stansby, Power density capacity of tidal stream turbine arrays with horizontal and vertical axis turbines, Journal of Ocean Engineering and Marine Energy 9 (2) (2023) 203–218.
[24] F.O. Rourke, F. Boyle, A. Reynolds, Marine current energy devices: current status and possible future applications in Ireland, RENEW SUST ENERG REV 14 (3) (2010) 1026–1036.
[25] C. Santoni, K. Carrasquillo, I. Arenas-Navarro, S. Leonardi, Effect of tower and nacelle on the flow past a wind turbine, Wind Energy 20 (12) (2017) 1927–1939.
[26] A. Hunt, C. Stringer, B. Polagye, Effect of aspect ratio on cross-flow turbine performance, J. Renewable Sustainable Energy 12 (5) (2020).
[27] S. Müller, V. Muhawenimana, C.A. Wilson, P. Ouro, Experimental investigation of the wake characteristics behind twin vertical axis turbines, Energ. Conver. Manage. 247 (2021) 114768.
[28] S.P. Neill, K.A. Haas, J. Thiébot, Z. Yang, A review of tidal energy—Resource, feedbacks, and environmental interactions, J. Renewable Sustainable Energy 13 (6) (2021).
[29] F.A.M. Zahle, Helge ; Sørensen, Niels N. , Evaluation of tower shadow effects on various wind turbine concepts, Danmarks Tekniske Universitet, Risø Nationallaboratoriet for Bæredygtig Energi2009.
[30] P. Harper, S. Hallett, A. Fleming, M. Dawson, 9 - Advanced fibre-reinforced composites for marine renewable energy devices, in: J. Graham-Jones, J. Summerscales (Eds.), Marine Applications of Advanced Fibre-Reinforced Composites, Woodhead Publishing, 2016, pp. 217–232.
[31] M. Fal, R. Hussein, K. Chandrashekhara, A. Abutunis, V. Menta, Experimental and numerical failure analysis of horizontal axis water turbine carbon fiber-reinforced composite blade, J. Renewable Sustainable Energy 13 (1) (2021) 014501.
[32] H. Gonabadi, A. Oila, A. Yadav, S. Bull, Structural performance of composite tidal turbine blades, Compos. Struct. 278 (2021) 114679.
[33] D.M. Grogan, S.B. Leen, C.R. Kennedy, C.M.Ó. Brádaigh, Design of composite tidal turbine blades, Renew. Energy 57 (2013) 151–162.
[34] V. Jaksic, C.R. Kennedy, D.M. Grogan, S.B. Leen, C.M. Brádaigh, Influence of composite fatigue properties on marine tidal turbine blade design, Durability of Composites in a Marine, Environ. 2 (2018) 195–223.
[35] Y. Abdulwahhab, Investigations of Corrosion Effects at High Temperatures and High pressure Conditions, Curtin University, 2020.
[36] G. Marsh, Tidal turbines harness the power of the sea, Reinf. Plast. 48 (6) (2004) 44–47.
[37] P.W. Harper, S.R. Hallett, Advanced numerical modelling techniques for the structural design of composite tidal turbine blades, Ocean Eng. 96 (2015) 272–283.
[38] P. Liu, N. Bose, R. Frost, G. Macfarlane, T. Lilienthal, I. Penesis, Model testing and performance comparison of plastic and metal tidal turbine rotors, Appl. Ocean Res. 53 (2015) 116–124.
[39] R.B. Barber, M.R. Motley, Cavitating response of passively controlled tidal turbines, J. Fluids Struct. 66 (2016) 462–475.
[40] C.R. Kennedy, S.B. Leen, C.M. Brádaigh, A preliminary design methodology for fatigue life prediction of polymer composites for tidal turbine blades, Proceedings of the Institution of Mechanical Engineers, Part l: Journal of Materials: Design and Applications 226 (3) (2012) 203–218.
[41] I.O. Oladele, T.F. Omotosho, A.A. Adediran, Polymer-based composites: an indispensable material for present and future applications, International Journal of Polymer Science 2020 (2020) 1–12.
[42] S. Thiru, M. Megahed, A. Seif, D. Hegazy, A.S. Sakr, A.-H.-S.-S. Said, A. Sadoun, M.A. Alazwari, W.M. Abdelfattah, I. Najjar, Enhancing Marine Composite Performance: the Role of Cu, Al, and Graphene Nanofillers in Seawater-Aged Glass Fiber Epoxy Composites, J. Mater. Res. Technol. (2025).
[43] S.J. Lee, S.J. Yoon, I.-Y. Jeon, Graphene/polymer nanocomposites: Preparation, mechanical properties, and application, Polymers 14 (21) (2022) 4733.
[44] T. Shahnaz, G. Hayder, M.A. Shah, M.Z. Ramli, N. Ismail, C.K. Hua, N.M. Zahari, N.H. Mardi, F.E. Selamat, N. Kabilmiharbi, H.A. Aziz, Graphene-based nanoarchitecture as a potent cushioning/filler in polymer composites and their applications, J. Mater. Res. Technol. 28 (2024) 2671–2698.

[45] P. Alam, C. Robert, C.M.Ó. Brádaigh, Tidal turbine blade composites - a review on the effects of hygrothermal aging on the properties of CFRP, Compos. B Eng. 149 (2018) 248–259.
[46] N.B. Baba, A.S. Suhaimi, M.A. Mohd Amin, A. Mohd, Study on mechanical and physical behaviour of hybrid GFRP, Adv. Mater. Sci. Eng. (2015 (2015).).
[47] M. Nachtane, M. Tarfaoui, D. Saifaoui, A. El Moumen, O.H. Hassoon, H. Benyahia, Evaluation of durability of composite materials applied to renewable marine energy: Case of ducted tidal turbine, Energy Rep. 4 (2018) 31–40.
[48] H. Gonabadi, A. Oila, A. Yadav, S. Bull, Fatigue life prediction of composite tidal turbine blades, Ocean Eng. 260 (2022) 111903.
[49] Y.L. Young, Fluid–structure interaction analysis of flexible composite marine propellers, J. Fluids Struct. 24 (6) (2008) 799–818.
[50] M. Nachtane, M. Tarfaoui, A. El Moumen, D. Saifaoui, Damage prediction of horizontal axis marine current turbines under hydrodynamic, hydrostatic and impacts loads, Compos. Struct. 170 (2017) 146–157.
[51] N. Zhuang, Y. Zhou, Y. Ma, Y. Liao, D. Chen, Corrosion activity on CFRP-strengthened RC piles of high-pile wharf in a simulated marine environment, Adv. Mater. Sci. Eng. 2017 (2017).
[52] F. Rubino, A. Nisticò, F. Tucci, P. Carlone, Marine application of fiber reinforced composites: a review, Journal of Marine Science and Engineering 8 (1) (2020) 26.
[53] M.C. Tanzi, S. Farè, G. Candiani, Chapter 5 - Sterilization and Degradation, in: M.C. Tanzi, S. Farè, G. Candiani (Eds.), Foundations of Biomaterials Engineering, Academic Press, 2019, pp. 289–328.
[54] A.S. Pouzada, Chapter 5 - Basic data required for designing plastic parts, in: A.S. Pouzada (Ed.), Design and Manufacturing of Plastics Products, William Andrew Publishing2021, pp. 141-199.
[55] M. Nachtane, M. Tarfaoui, M. Ait Mohammed, D. Saifaoui, A., El Moumen, Effects of environmental exposure on the mechanical properties of composite tidal current turbine, Renew. Energy 156 (2020) 1132–1145.
[56] M.K. Padhy, R.P. Saini, A review on silt erosion in hydro turbines, Renew. Sustain. Energy Rev. 12 (7) (2008) 1974–1987.
[57] E. José-Trujillo, C. Rubio-González, J.A. Rodríguez-González, Seawater ageing effect on the mechanical properties of composites with different fiber and matrix types, J. Compos. Mater. 53 (23) (2018) 3229–3241.
[58] G. Vizentin, G. Vukelic, L. Murawski, N. Recho, J. Orovic, Marine propulsion system failures—a review, Journal of Marine Science and Engineering 8 (9) (2020) 1–14.
[59] R.J.K. Wood, Marine wear and tribocorrosion, Wear 376-377(PB) (2017) 893-910.
[60] P. Harper, S. Hallett, A. Fleming, M. Dawson, Advanced fibre-reinforced composites for marine renewable energy devices, Elsevier, Marine Applications of Advanced Fibre-Reinforced Composites, 2016, pp. 217–232.
[61] G. Rasool, M.M. Stack, Some views on the Mapping of erosion of Coated Composites In Tidal Turbine simulated Conditions, Tribol. Trans. 62 (3) (2019) 512–523.
[62] D.M. Faris Elasha, J.A. Teixeira, Condition monitoring philosophy for tidal turbines, International Journal of Performability, Engineering 10 (5) (2014) 521.
[63] E. Marino, M. Gkantou, A. Malekjafarian, S. Bali, C. Baniotopoulos, J. van Beeck, R.P. Borg, N. Bruschi, P. Cardiff, E. Chatzi, Offshore renewable energies: a review towards floating Modular Energy Islands—Monitoring, Loads, Modelling and Control, Ocean Engineering 313 (2024) 119251.
[64] P. Liu, B. Veitch, Design and optimization for strength and integrity of tidal turbine rotor blades, Energy (oxford) 46 (1) (2012) 393–404.
[65] G. Bai, G. Li, Y. Ye, T. Gao, Numerical analysis of the hydrodynamic performance and wake field of a horizontal axis tidal current turbine using an actuator surface model, Ocean Eng. 94 (2015) 1–9.
[66] R.A.R. Ahamed, C.M. Johnstone, M.M. Stack, Impact Angle Effects on erosion Maps of GFRP: applications to Tidal Turbines, J Bio Tribo Corros 2 (2) (2016) 1–11.
[67] G. Rasool, S. Sharifi, C. Johnstone, M.M. Stack, Mapping Synergy of erosion Mechanisms of Tidal Turbine Composite Materials in Sea Water Conditions, J Bio Tribo Corros 2 (2) (2016) 1–15.
[68] E. Hassan, I. Zekos, P. Jannson, T. Pecor, C. Floreani, C. Robert, C.M. Ó Brádaigh, M.M. Stack, Erosion mapping of through-thickness toughened powder epoxy gradient glass-fiber-reinforced polymer (GFRP) plates for tidal turbine blades, (2021).
[69] G. Stachowiak, A.W. Batchelor, Engineering tribology, Butterworth-heinemann2013.
[70] S. Sharifi, C. Johnstone, M.M. Stack, Tribological challenges of scaling up tidal turbine blades, (2015).
[71] W. Li, H. Zhou, H. Liu, Y. Lin, Q. Xu, Review on the blade design technologies of tidal current turbine, Renew. Sustain. Energy Rev. 63 (2016) 414–422.
[72] D. Eisenberg, S. Laustsen, J. Stege, Wind turbine blade coating leading edge rain erosion model: Development and validation, Wind Energy 21 (10) (2018) 942–951.
[73] C.-H. Shen, G.S. Springer, Effects of moisture and temperature on the tensile strength of composite materials, J. Compos. Mater. 11 (1) (1977) 2–16.
[74] I. Kafodya, G. Xian, H. Li, Durability study of pultruded CFRP plates immersed in water and seawater under sustained bending: Water uptake and effects on the mechanical properties, Compos. B Eng. 70 (2015) 138–148.
[75] N. Tual, N. Carrere, P. Davies, T. Bonnemains, E. Lolive, Characterization of sea water ageing effects on mechanical properties of carbon/epoxy composites for tidal turbine blades, Compos. A Appl. Sci. Manuf. 78 (2015) 380–389.
[76] C.R. Kennedy, V. Jaksic, S.B. Leen, C.M. Brádaigh, Fatigue life of pitch-and stall-regulated composite tidal turbine blades, Renew. Energy 121 (2018) 688–699.
[77] A. Wolfson, G. Van Blaricom, N. Davis, G. Lewbel, The marine life of an offshore oil platform, Mar. Ecol. Prog. Ser. 1 (1979) 81–89.
[78] A. Wimshurst, C. Vogel, R. Willden, Cavitation limits on tidal turbine performance, Ocean Eng. 152 (2018) 223–233.
[79] A. Copping, M. Grear, R. Jepsen, C. Chartrand, A. Gorton, Understanding the potential risk to marine mammals from collision with tidal turbines, Int. J. Mar. Energy 19 (2017) 110–123.
[80] C. Sparling, M. Lonergan, B. McConnell, Harbour seals (Phoca vitulina) around an operational tidal turbine in Strangford Narrows: No barrier effect but small changes in transit behaviour, Aquat. Conserv. Mar. Freshwat. Ecosyst. 28 (1) (2018) 194–204.
[81] M.D. Esteban, J.-S. López-Gutiérrez, V. Negro, Gravity-based foundations in the offshore wind sector, Journal of Marine Science and Engineering 7 (3) (2019) 64.
[82] H. Schlichting, Boundary-layer theory / [internet resource], Ninth edition. ed.,, Springer, Berlin, 2016.
[83] A. Bahaj, W. Batten, G. McCann, Experimental verifications of numerical predictions for the hydrodynamic performance of horizontal axis marine current turbines, Renew. Energy 32 (15) (2007) 2479–2490.
[84] A. Arredondo-Galeana, G. Olbert, W. Shi, F. Brennan, Near wake hydrodynamics and structural design of a single foil cycloidal rotor in regular waves, Renew. Energy 206 (2023) 1020–1035.
[85] F. Hummel, M. Lötzerich, P. Cardamone, L. Fottner, Surface roughness effects on turbine blade aerodynamics, J. Turbomach. 127 (3) (2005) 453–461.
[86] E.M. Fagan, C.R. Kennedy, S.B. Leen, J. Goggins, Damage mechanics based design methodology for tidal current turbine composite blades, Renew. Energy 97 (2016) 358–372.
[87] U. Dorji, R. Ghomashchi, Hydro turbine failure mechanisms: an overview, Eng. Fail. Anal. 44 (2014) 136–147.
[88] M. Benbouzid, J.-A. Astolfi, S. Bacha, J.-F. Charpentier, M. Machmoum, T. Maître, D. Roye, Concepts, modeling and control of tidal turbines, John Wiley & Sons, 2012.
[89] S.A. Kinnas, W. Xu, Y.-H. Yu, L. He, Computational methods for the design and prediction of performance of tidal turbines, J. Offshore Mech. Arct. Eng. 134 (1) (2012).
[90] S. Draycott, B. Sellar, T. Davey, D.R. Noble, V. Venugopal, D.M. Ingram, Capture and simulation of the ocean environment for offshore renewable energy, Renew. Sustain. Energy Rev. 104 (2019) 15–29.
[91] M.R. Ahmed, Blade sections for wind turbine and tidal current turbine applications–current status and future challenges, Int. J. Energy Res. 36 (7) (2012) 829–844.
[92] Z. Hu, X. Du, Reliability analysis for hydrokinetic turbine blades, Renew. Energy 48 (2012) 251–262.
[93] D.V. Val, L. Chernin, D.V. Yurchenko, Reliability analysis of rotor blades of tidal stream turbines, Reliab. Eng. Syst. Saf. 121 (2014) 26–33.

[94] B.F. De Cal, Application of vibration monitoring to the detection of early misalignment and rub failures in a tidal turbine, Technol. Econ. Smart Grids Sustainable Energy 4 (1) (2019) 9.
[95] J.I. Whelan, J.M.R. Graham, J. PeirÓ, A free-surface and blockage correction for tidal turbines, J. Fluid Mech. 624 (2009) 281–291.
[96] L. Chernin, D.V. Val, Probabilistic prediction of cavitation on rotor blades of tidal stream turbines, Renew. Energy 113 (2017) 688–696.
[97] S. Sezen, Marine propeller hydrodynamic and hydroacoustic performance with roughness effects, (2022).
[98] D.H. Zeiner-Gundersen, Turbine design and field development concepts for tidal, ocean, and river applications, Energy Sci. Eng. 3 (1) (2015) 27–42.
[99] R. Murray, Passively adaptive tidal turbine blades: Design methodology and experimental testing, (2016).
[100] J. Seo, J.-H. Yi, J.-S. Park, K.-S. Lee, Review of tidal characteristics of Uldolmok Strait and optimal design of blade shape for horizontal axis tidal current turbines, Renew. Sustain. Energy Rev. 113 (2019) 109273.
[101] M.M. Nunes, A.C.P. Brasil Junior, T.F. Oliveira, Systematic review of diffuser-augmented horizontal-axis turbines, Renew. Sustain. Energy Rev. 133 (2020) 110075.
[102] T. Blackmore, L.E. Myers, A.S. Bahaj, Effects of turbulence on tidal turbines: Implications to performance, blade loads, and condition monitoring, Int. J. Mar. Energy 14 (2016) 1–26.
[103] G.V. Messa, S. Malavasi, A CFD-based method for slurry erosion prediction, Wear 398–399 (2018) 127–145.
[104] Y. Gao, H. Liu, Y. Lin, Y. Gu, S. Wang, Numerical investigation of the erosion behavior in blades of tidal current turbine, J. Renewable Sustainable Energy 14 (4) (2022).
[105] P. Kumar, S. Singal, P.P. Gohil, A technical review on combined effect of cavitation and silt erosion on Francis turbine, Renew. Sustain. Energy Rev. 190 (2024) 114096.
[106] J.M. Walker, K.A. Flack, E.E. Lust, M.P. Schultz, L. Luznik, Experimental and numerical studies of blade roughness and fouling on marine current turbine performance, Renew. Energy 66 (2014) 257–267.
[107] X. Chen, J.W. Hutchinson, Particle impact on metal substrates with application to foreign object damage to aircraft engines, J. Mech. Phys. Solids 50 (12) (2002) 2669–2690.
[108] S. Groucott, K. Pugh, I. Zekos, M.M. Stack, A study of raindrop impacts on a wind turbine material: Velocity and impact angle effects on erosion maps at various exposure times, Lubricants 9 (6) (2021) 60.
[109] H. Grewal, A. Agrawal, H. Singh, Identifying erosion mechanism: a novel approach, Tribol. Lett. 51 (2013) 1–7.
[110] A. Harsha, A.A. Thakre, Investigation on solid particle erosion behaviour of polyetherimide and its composites, Wear 262 (7–8) (2007) 807–818.
[111] A. Sareen, C.A. Sapre, M.S. Selig, Effects of leading edge erosion on wind turbine blade performance, Wind Energy 17 (10) (2014) 1531–1542.
[112] J. Carlton, Marine propellers and propulsion, Butterworth-Heinemann2018.
[113] H.P. Neopane, Sediment erosion in hydro turbines, Norwegian University of Science and Technology (NTNU), 2010.
[114] B. Gaurier, P. Davies, A. Deuff, G. Germain, Flume tank characterization of marine current turbine blade behaviour under current and wave loading, Renew. Energy 59 (2013) 1–12.
[115] J. Wang, J. Gao, Y. Zhang, H. Cui, Analysis of the sand erosion effect and Wear Mechanism of Wind Turbine Blade Coating, Energies 17 (2) (2024) 413.
[116] H. Meng, K. Ludema, Wear models and predictive equations: their form and content, Wear 181 (1995) 443–457.
[117] J. Dutta Majumdar, I. Manna, 21 - Laser surface engineering of titanium and its alloys for improved wear, corrosion and high-temperature oxidation resistance, in: J. Lawrence, D.G. Waugh (Eds.), Laser Surface Engineering, Woodhead Publishing, 2015, pp. 483–521.
[118] W. Pfitsch, S. Gowing, D.J. Fry, M.J. Donnelly, S.D. Jessup, Development of Measurement Techniques for Studying Propeller Erosion Damage in Severe Wake Fields, 2009.
[119] H. Amarendra, G. Chaudhari, S. Nath, Synergy of cavitation and slurry erosion in the slurry pot tester, Wear 290 (2012) 25–31.
[120] S. Feih, E. Boiocchi, E. Kandare, Z. Mathys, A. Gibson, A. Mouritz, Strength degradation of glass and carbon fibres under high temperature, International Committee on Composite Materials Proceedings; Edinburgh, UK (2009) 27-31.
[121] R.J.K. Wood, Erosion–corrosion interactions and their effect on marine and offshore materials, Wear 261 (9) (2006) 1012–1023.
[122] A.H. Idrisi, A.-H.-I. Mourad, Fiber reinforced polymer composites sustainability under prolonged exposure to hot seawater: Experimental and prediction study, Mater. Lett. 304 (2021) 130689.
[123] Y. Wang, L. Wang, C. Duan, J. Zheng, Z. Liu, G. Ma, CFD simulation on wind turbine blades with leading edge erosion, J. Theor. Appl. Mech. 59 (4) (2021) 579–593.
[124] H. Arabnejad, A. Mansouri, S.A. Shirazi, B.S. McLaury, Abrasion erosion modeling in particulate flow, Wear 376–377 (2017) 1194–1199.
[125] P. Habibi, T.F. Algaddaime, F. Abad, M.M. Stack, A. Mehmanparast, F. Brennan, S. Lotfian, Structural integrity evolution of composite tidal turbine materials: Correlating surface roughness with progressive erosive damage, Theor. Appl. Fract. Mech. 139 (2025) 105076.
[126] P. Habibi, S. Lotfian, Calibration and validation of slurry erosion models for glass fibre composites in marine energy systems, J. Mar. Sci. Eng. 13 (9) (2025) 1602.