An Evaluation of Blade Repair Techniques and Applicability for Tidal Turbines

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The number of tidal stream energy installations is set to rise rapidly as countries deploy increased renewable energy capacity to meet net zero targets. The year 2023 was a pivotal year for the tidal stream industry in the UK, with 11 Contracts for Difference being awarded to tidal stream projects in Allocation Round 5. This will grow UK deployed capacity to nearly 100MW by 2028. In wind energy, an estimated 3800 incidents of blade damage occurred for 700,000 installed turbines in 2020 [1]. This has resulted in significant attention on optimisation of repair procedures to minimise operational downtime. As a result, this is now supported by a skilled and experienced repair industry with developed practices. Wind and tidal blades share significant similarities in composite material construction and design, and as tidal energy scales, similar attention to blade repair will likely be required to ensure that tidal turbine blades can be kept in service with minimal downtime. This study reviews and contrasts the observed and expected damage experienced by in-service composite wind and tidal turbine blades to establish a baseline for transfer of existing techniques between the industries. The tidal-specific repair requirements and impacts of blade design and operating conditions are assessed, enabling assessment of the applicability and suitability of developed wind industry procedures, techniques, and tools for tidal blade repair. The challenges surrounding the unique design features of tidal blades such as thick sections, ply tapering, and large curvature are assessed to identify areas requiring novel repair approaches. The study acts as a primer to allow tidal stream project developers and operators to anticipate blade maintenance requirements and better understand the transferability of existing wind repair practices to bolster future growth in the tidal stream industry.

Keywords—**Repair, Composite Blade, Operations and Maintenance.**

I. INTRODUCTION

Tidal stream energy shows promise to become an increasingly significant part of the future energy mix due to its predictability and high energy density. Tidal stream energy is still an emerging technology, with 18MW currently installed within the UK [2]. Tidal turbines have been developed in a range of topologies, yet mainstream, high-capacity turbines are approaching technological convergence towards horizontal axis turbine designs [3]. Figure 1 and Figure 2 show examples of major floating and bottom-mounted tidal stream turbines.

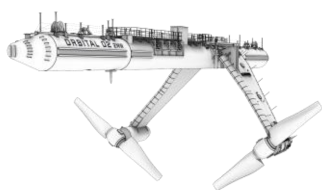

Figure 1: Orbital Marine Power O2 2MW Tidal turbine [4]

Figure 2: SIMEC Atlantis 1.5MW Tidal turbine [5]

These horizontal axis tidal turbines operate on similar principles of extracting energy from a moving fluid to horizontal axis wind turbines [6]. However, tidal turbines operate under very different conditions. The key

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difference is in the working fluid, since the density of water is 1025kg.m^{-3}, 837 times denser than air (1.225kg.m^{-3}). A tidal turbine with equivalent rated power to that of a wind turbine, extracting energy from fluid flow of the same velocity, would have a radius 29 times smaller than that of the wind turbine. Tidal sites typically feature velocities of ca. 2.5m/s compared to ca. 11m/s wind speeds. Due to the difference in flow velocity, tidal blades are approximately three times shorter than equivalent power wind turbine blades [7]. Additionally, tidal turbine rotors are subjected to a highly turbulent environment with wave loading.

The Government of the United Kingdom has shown support for tidal energy by guaranteeing a set price for tidal electricity through the Contracts for Difference (CfD) scheme. It is anticipated that 6GW of tidal stream energy will be deployed to meet net-zero commitments by 2050, which could result in an estimated £2.45bn gross value added to the UK economy [8]. Within the UK, the latest round of CfD allocations, Allocation Round 5, amounted to 53.14MW [9] of tidal projects with expected delivery in 2027/28, in addition to the previous round of 40.82MW expected to be delivered between 2025 and 2027 [10]. If this growth continues, a significant supply chain will be required to support tidal projects.

The blades of tidal turbines share some commonality in design features to wind turbine blades, while requiring an increased stiffness due to the high forces from hydrodynamic loading. Composite materials are the dominant material for large wind turbine blades primarily due to their high strength and stiffness to weight ratios which enable lightweight structures. In addition, composites can be designed to have excellent corrosion and fatigue resistance [11]. For this reason, composites are also utilised for tidal turbine blades, typically comprising glass and carbon fibre reinforcements with thermoset resins such as epoxy, polyester, and vinyl-ester.

High rates of failure of composite wind turbine blades have resulted in significant turbine downtime and high cost of rectification within the wind industry. A notable example occurred when Danish energy company Ørsted had to repair a total of 2,000 blades in 2018 [12]. More recently, in 2023, wind turbine manufacturer Siemens Gamesa reported issues with quality control of certain components, including their blades, which led to a $5 billion net loss for the company [13]. Despite advancements in design, it is evident that maintenance will continue to be a major consideration, resulting in the growth of blade repair technologies and a specialised composite blade maintenance industry.

Information on failure mechanisms for blades is commonly determined through analysis of failed blades, full-scale testing, incident reports, and computational modelling [14]. In a review of 350 offshore wind turbine failures, blades were the fifth largest cause of failure [15]. On average, each blade required 0.485 minor repairs and 0.01 major repairs per year. Over a 25-year design lifespan this is equivalent to each blade requiring 12 minor repairs and 0.25 major repairs. In a survey of wind blade failures in India, lightning strikes and leading edge erosion due to ice and rain were the most observed damage mechanisms [16]. Due to tidal power's relative immaturity, there is little equivalent operational data on blade failure rates to compare. A 2021 review of tidal turbine component reliability showed blade failure occurred in 4 out of 58 device deployments. At 6.9% this was the most prevalent failure mode across the deployments analysed [17].

Offshore wind operations and maintenance (O&M) is expected to be valued at £9 billion per year in the UK by 2030 [18]. As the first generation of offshore wind farms leave their manufacturer warranty period, typically 2-5 years, an already established repair industry for wind turbine blades will grow. Similarly, as the number of tidal stream devices deployed increases, it can be expected that a significant proportion of composite tidal blades will require repair. By examining publicly available information for developers with recently awarded CfDs, it is possible to estimate that 300 additional tidal turbine blades will be in operation by 2028 [19], [20], [21], [22], [23].

It is likely that existing processes and supply chains from the wind industry will be adopted for composite tidal blade maintenance. However, the philosophy behind blade design, economics, and tidal operating conditions present unique challenges for tidal stream projects. The impact of these factors on blade repair is an area of little investigation. This paper provides an introduction of the composite tidal turbine blade repair market, highlighting key challenges and opportunities for leveraging the established expertise and techniques from the wind turbine blade repair industry.

II. Location of Blade Repair

The wind industry has achieved significant decreases in the levelized cost of energy (LCoE) by increasing rotor diameter, which in turn has created very long blades; the world's largest wind turbine blade, unveiled in 2024, has a length of 131 metres [24]. As a result, specialised heavy-lift vessels are used to lift blades to nacelle height during wind farm construction. The cost and availability of these vessels is very high, hence their use for operations and maintenance purposes is minimised. This makes it impractical to substitute a new wind turbine blade while a damaged blade is repaired at a factory or workshop. Therefore, significant effort in the wind industry has been put towards developing in-situ repair practices, which can be effectively performed by rope access technicians, or, increasingly, unmanned devices.

In contrast, the tidal industry has not reached such a consensus regarding increasing blade length as a primary design objective. Some tidal developers focus on increasing power output through distributed small turbines in tidal farms. Figure 5 shows the blade diameters used in 19 tidal deployments.

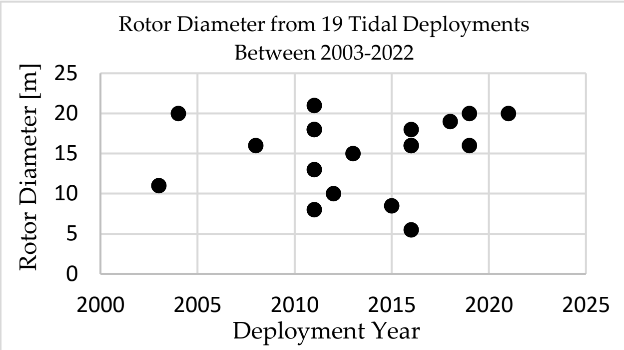

Figure 3: Rotor diameter of 19 tidal deployments from 2003-2022. Plot produced using data from [25]

Across historical deployments, there is no clear convergence on a tidal rotor diameter across this sample. Nevertheless, research by the Tidal Stream Industry Energiser project (TIGER) has shown that increasing rotor diameter will offer the greatest potential for LCoE reduction in tidal stream [26]. The MAXBlade project plans to produce the industry's longest tidal turbine blades, with a 26m diameter swept area [27]. Based on the conclusions of the TIGER report, convergence towards larger blade diameters may be expected in future turbines.

When considering repair strategies for a tidal blade, the cost of blade replacement plays a key role. The approximate cost of a wind turbine blade increases with the cube of the increase of blade length [28]. Under the assumption that tidal blades follow a similar trend, it is intuitive to understand that complex repairs become more economical for larger blades, whereas smaller tidal turbine blades are more easily replaced. This demonstrates that rotor diameter, and hence blade length, is of relevance to understanding decisions around maintenance practices.

Tidal turbine technologies also differ based on foundation type. The rotor foundation can be set on the seabed or it can be integrated in a floating device. Seabed-mounted turbines are sheltered from energetic wave zones, produce no visual impact, and allow tighter array spacing. However, the reliability and cost of accessing seabed mounted turbines has a significant effect on LCoE. Hence, floating turbines are being developed to decrease operations and maintenance cost. The most recent UK Government Energy Innovation Needs Assessment estimates O&M at 17% and 43% of total project cost for floating and fixed devices respectively [29]. Figure 6 shows the configuration of 19 recent tidal turbine deployments, in which 28% of devices had blades accessible for maintenance.

Figure 4: Sabella seabed-fixed turbine being installed [30]

Figure 5: Orbital O2 floating turbine maintenance [31]

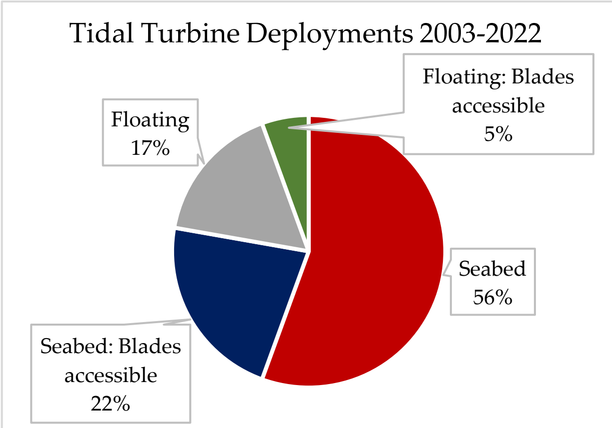

Figure 6: Tidal turbine foundation types of 19 tidal deployments from 2003-2022. Plot produced using data from [25].

Large-scale seabed mounted turbines often require large heavy-lift vessels which are expensive and have a long lead time to charter. Even with the limited number of tidal turbines which have blades accessible for maintenance at sea, performing complex blade maintenance in energetic tidal sites is neither practical nor economic. As tidal blades are smaller and easier to handle than wind blades, it is likely most companies will opt for a 'strategic spares' approach where significantly damaged blades can be swapped for spares either on site or quayside. The damaged blades may then be repaired in a workshop to become new spares. Performing repairs in a workshop allows for more controlled processes, strategic maintenance planning, and many more options for on-land repair contractors.

III. Tidal vs Wind Turbine Blade Design

Most tidal turbine blades follow similar designs to wind turbine blades, where a hydrodynamic shell efficiently converts flow into torque and an internal structure bears the bending moments. However, while a comparison to wind turbine blades is useful for intuitive understanding, tidal blades are subject to very different operating conditions. The environmental operating conditions for a typical 1MW tidal turbine and equivalent 1MW wind turbine were evaluated in a study by Winter [7]. These are summarised in Table 1

Table 1: Theoretical comparison of 1MW wind and tidal blade operating characteristics. Collated results from [7].

	Wind	Tidal
Diameter [m]	56	18
Flow Speed [ms-1]	12.0	2.6
Tip Speed [ms^{-1}]	60.1	12.5
RPM	20.5	13.3
Rotor Inertia [$kgm^2 x10^3$]	1,128	30
Thrust [kN]	146	675
Torque [kNm]	546	837

The structural requirements for tidal turbine blades tend to lead to thicker laminate sections [32]. Tidal blades utilise a higher proportion of carbon fibre in their root sections than wind turbine blades, due to carbon's increased strength in comparison to glass. Figure 7 shows an example cross section which is typical to wind and tidal blades.

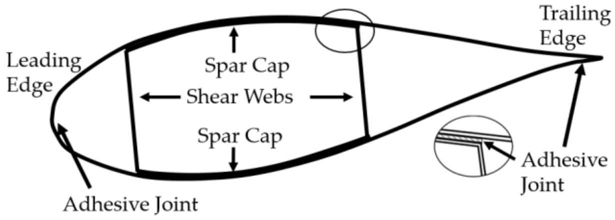

Figure 7: Example wind and tidal blade cross section.

A blade must feature certain key structural elements: spar caps bear primary bending stresses, while shear webs transfer shear forces along the blade. Construction approaches for blades differ depending on manufacturer. Often blades will be manufactured in separate parts before being assembled using structural adhesive [33]. Wind turbine blades must be lightweight, hence cross sections typically use core materials between laminate skins to reduce skin thickness. Due to the higher loads imposed on tidal blades, significantly higher monolithic skin thicknesses are used. This increased skin thickness is a key consideration when designing repair techniques.

IV. Environmental Degradation

The organic nature of resins makes them vulnerable to physical and chemical changes in adverse external environments. One such process is plasticisation, a significant softening of the polymer caused by chemical degradation, and laminate swelling, both of which can occur due to water penetration into the matrix. This degradation of materials due to moisture and temperature is called hygrothermal aging [34].

It has been shown that epoxy composites can lose between 20-40% of their tensile strength in tension as a result of seawater aging [35]. Tests on materials within a tidal turbine blade showed that seawater had significant negative impacts on blade strength and stiffness [36]. It has been found that fatigue damage accumulation due to mechanical load is exacerbated by seawater aging [37].

The effect of seawater aging is an understood parameter in tidal turbine design which is often accounted for through "knock-down" factors. Material screening test campaigns for tidal blades usually include experiments to quantify aging. For composite materials, the rate of water absorption can be modelled using Fick's second law of diffusion. Equation (1) expresses moisture uptake D and Equation (2) expresses theoretical change in mass M:

$$D = \pi \left(\frac{h^2}{4M_\infty} \right)^2 \left(\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}} \right)^2 \left(1 + \frac{h}{L} + \frac{h}{w} \right)^{-2} \quad (1)$$

$$\mathrm{M} = \left[1 - \frac{8}{\pi^2} e^{\left(-\pi^2 \frac{Dt}{h^2} \right)} \right] M_\infty \quad (2)$$

Here, M_1 and M_2 are the moisture contents of the CFRP at times t_1 and t_2, respectively, h is the composite thickness, L is the composite length, w is the composite width, t is time and M_∞ is the maximum change in mass. [34].

Fick's law of diffusion shows that mass absorption is highest during initial immersion due to the exponential decay term. The impact of material degradation due to hygrothermal aging is therefore an important consideration for assessing the strength and suitability of different repair materials and techniques.

V. Biofouling Degradation and Protection

Biofouling is the process whereby organic organisms colonise structures to produce a measurable build-up of living material [38]. The change in hydrodynamic properties of a tidal turbine blade with moderate biofouling can result in a ca. 13% decrease in power coefficient C_P at rated power [39]. A full scale experiment found that severe fouling can reduce power performance of a tidal turbine by 47% [40].

To protect against biofouling, the exterior surfaces of tidal turbine blades are often coated with anti-fouling paints or coatings. There are a wide range of coatings which have been developed for the marine industry. There exist two main types of antifoul: biocide release which uses biocides to inhibit marine fouling settlement, and fouling release coatings which utilise low surface energy to weaken the surface bonds of marine organisms and allow removal by water shear forces [41]. Biocide release coatings release toxins into the water, hence their use is being phased out [42]. Fouling release coatings are well-suited to blades due to the abundant shear forces available for removing organism growth. The performance of a given antifoul coating depends on the local conditions [43]. The ReDAPT project analysed the performance of a range of antifoul coatings in the Falls of Warness tidal site. The results of ReDAPT predicted the antifouling coatings to remain effective for the 25 year service life of a tidal turbine, notwithstanding exposure to mechanical damage [44].

An effective coating for tidal blades will serve a dual purpose: 1) to prevent the build-up of organic fouling, and 2) to protect from damage due to solid particle and cavitation erosion.

VI. TIDAL BLADE DAMAGE REGIONS AND REPAIR

The various defect types within blades can be classified depending on their severity as follows.

1. **Surface defects** (no fibre penetration) which often require no immediate action as propagation into structural defects is unlikely or slow.
2. **Non-structural defects** (e.g. fibre penetration/matrix debonding in non-critical structures) which require simple corrective action to prevent propagation into structural defects.
3. **Structural defects** (significant fibre breakage or delamination) that require immediate and significant intervention to restore load bearing capability.

Different approaches are used to repair each defect, varying in cost, time and complexity [45]. There are several regions of the blade which are likely to undergo degradation. In reporting from the wind industry, the areas which have been found to experience the most damage are the root region (30-35% of length from the root), tip region (70% length from blade root), root connection, maximum chord, upper spar cap, and trailing edge on the high pressure side [14].

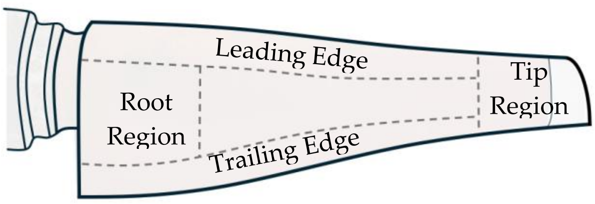

Figure 8: Diagram showing regions of tidal blade damage.

1) *Root Region*

The root region is where the blade transitions from a hydrofoil to a connection to the hub of the turbine. For large tidal blades, the rate of change of profile, and hence curvature, can be significantly higher than that of a wind turbine blade. The root section also bears the total bending moment of the blade. Due to this, laminate thicknesses can reach more than 100mm [46]. Moving from the root region to the blade tip, the number of plies in the laminate decreases. These ply drops introduce local stress concentrations due to geometric discontinuities and shear lag [47]. The increased presence of large ply drops in the root region can lead to ply delamination at low strains under fatigue loading [48]. The root region also includes the root connection device. A typical configuration for the root connection is a T-bolted connection, which features a barrel nut inserted into a drilled hole in the root laminate. The root connection device introduces stress concentrations through which cracks can propagate. Blade root sections are highly loaded critical areas of primary structure, which also feature elements prone to damage. Damage and defects within the root section are a key concern which will likely require structural repair to rectify.

2) *Leading edge*

Erosion caused by the high relative velocity impact of rain droplets on the leading edge is the most observed damage mechanism for wind blades [16]. In contrast, tidal turbines are most likely to experience leading edge erosion due to sediment and cavitation erosion [49]. Due to the smaller rotor diameters of tidal turbines compared with wind turbines, tidal turbine blade tips experience tip speeds over four times lower than those of wind turbine blades.

Sediment erosion of marine composites is a known damage mechanism and a field of significant study [50]. Damage due to physical abrasion has been observed in tidal turbine deployments near estuaries [51]. Tidal turbines are purposefully located in energetic flow zones which are likely to have more sand and debris. In an evaluation of the mechanism of sand and salt erosion of tidal turbine composites, it was found that materials with absorbed salt water offered lower abrasion resistance [52]. The damage caused by solid particle erosion on a tidal turbine blade can be closely compared to leading edge erosion on a wind turbine blade. The pitting damage begins as a surface level defect, causing reduced hydrodynamic performance. The defect requires prompt discovery and rectification to prevent propagation. Composite surfaces can be protected from solid particle erosion through the application of protective coatings [53]. These coatings must be maintained, especially as aged composites are also more susceptible to surface erosion damage [34]. The leading edge of a tidal turbine blade may also be subject to collisions with debris. The extent of this damage is hard to quantify, yet these collisions could result in significant blade damage.

The extent of the issue of leading edge erosion on tidal blades is currently unknown. It can be expected that some degree of protection from erosion will be required. Tidal blade leading edges should be designed to mitigate the damage caused by significant leading edge impact due to collision. Extensive leading edge damage should also be anticipated in the development of repair strategies.

3) *Trailing Edge*

The trailing edge of a wind turbine blade is likely to fail due to peeling stresses and buckling of the surface, brought on due to edgewise moments and influenced by flap wise bending and torsion [54]. In comparison, the higher thickness of a tidal turbine hydrofoil is likely to provide some additional resistance to buckling, which may reduce the likelihood of trailing edge failure. Failed adhesive joints at blade trailing edges due to bending stresses are likely to require adhesive injection repairs which reinstate failed adhesive bonds [45].

4) Blade Tip

Cavitation occurs when the hydrostatic pressure on the blade surface drops to or below the vapour pressure of the fluid. The pressure drop results in the formation of bubbles which implode on the blade surface, causing cyclic surface fatigue loading. Tidal turbine blades are designed to minimise the occurrence of cavitation [55]. This is assisted by the introduction of reactive pitch control systems. However, due to the complexity of wave current interaction it is likely some cavitation will persist.

The risk of cavitation increases with the speed of the fluid flowing over the blade. Numerical analysis has shown that risk of cavitation on tidal blades increases with tip speeds over 12ms^{-1} [56]. Cavitation is likely to produce surface defects due to the repeated fatigue loading on the hydrodynamic surface.

5) Adhesive/Bond lines

It is likely that many composite tidal blades will contain adhesive joints. Adhesive joints allow for simplified manufacture though open-mould processes. Assuming similarity to wind blade internals, joints are typically located at the leading and trailing edges, shell and main spar, shear webs, and internal stiffeners. Adhesive joints are critical load bearing features and therefore disbond can lead to total blade failure. In closed tidal turbine blade structures, adhesive joints are difficult to inspect, and failures often propagate from manufacturing defects. When the origins of adhesive failure are identified early there are options for repair strategies, including adhesive injection to restore the bond between surfaces.

VII. Damage Assessment

The three primary methods of inspecting blades are visual inspection (VI), non-destructive inspection (NDI), and structural health monitoring (SHM) [45].

VI is a straightforward technique for detecting surface damage and can be performed by eye or though cameras.

NDI techniques have been developed for inspecting the sub-surface of composite blade structures. Examples from the wind industry vary in complexity, including tap hammer testing, ultrasonic testing, digital shearography, and thermography [45]. Tap hammer testing involves an experienced operator listening for changes in acoustic response of a structure when struck by an object, indicating a void or disbond. Ultrasonic techniques are based on time-of-flight for reflected high frequency waves which can identify the exact depth and size of defects in laminate. Ultrasonic techniques are less effective on thick composite laminates such as tidal blades [57].

SHM systems continuously provide information on component condition to operators. This information assists with identification of blade damage, allowing operators to plan maintenance activities more efficiently. SHM techniques include measurement of material strain, vibration, acoustic emission, and automatic VI [58]. Stator current-based analysis techniques have been proposed for monitoring the build-up of biofouling on tidal blades [59]. Due to the inaccessibility of tidal blades for inspection, SHM systems can reduce operations and maintenance costs as early defect detection allows minor damage to be rectified before propagation into more serious damage.

VIII. Repair Procedure

1) Surface Repair

The objective of surface level repairs is to restore the hydrodynamic surface and prevent propagation of any surface level defects. Typical surface repairs can include repairs to anti-fouling coatings or filling and fairing of erosion damage such as pitting. Significant effort has been put into developing procedures and products for repairing erosion in wind blades.

Erosion repair will involve cleaning marine growth from the area before preparing erosion pits to remove loose debris and damaged material. Filling products are then used to return the surface to its original form and anti-fouling protection is replaced. There is a limited amount of operational data to predict the prevalence of erosion on tidal blades. If erosion is widely observed, it may be necessary to install coatings or leading edge-protection covers on tidal blades as have already been implemented on wind turbine blades [60].

2) Adhesive Injection

Adhesive injection can be used to rectify disbonding of adhesive joints to restore their original strength. Resin injection repairs are also used to rectify cases of local matrix cracking. Repairing matrix cracks is important to prevent further crack growth which may evolve into a delamination or structural defect. Matrix cracking also accelerates penetration of seawater into the composite structure.

The typical procedure for injection repair is to drill holes into the cracked substrate to reach the delaminated level. A minimum of two holes are required to allow the air to be displaced through a vent hole and resin to be injected into the other. Adhesive or resin is then injected until it flows out of the vent hole. The adhesive is then cured as required with heat and time.

The blind injection of adhesive is simple to perform; however, for repairs when the adhesive flow path is not visible, it is not easy to verify whether the adhesive has covered the entire repair area. With tidal blades, which are immersed in water, contamination of the matrix crack becomes a significant issue. For cracks which have propagated from surface level, seawater will have entered the crack. Before injection repairs are undertaken, the crack must be fully drained and dried. Where cracks have been present for some time, it is likely that some marine growth will have taken place. The development of blind surface preparation techniques prior to repair will be required to ensure effective injection repairs can be performed. Otherwise, matrix cracking occurrences at critical stress areas may escalate and require future structural repair.

3) Structural Repair

Structural repairs are undertaken when load-bearing elements, such as spar caps, are damaged. In these cases, both the matrix and fibres have been damaged such that they can no longer handle the loads imposed.

For wind blades, structural repair techniques have been developed which work under the assumption that access to only one side is possible. If tidal blades are removed prior to repair in a workshop environment, there may be opportunity to deploy novel techniques, since access to both sides may be possible.

Two types of structural repairs are employed on blades: a) doubler, and b) scarf (flush) repairs. Doubler repairs are where material is built up on top of the blade skin to reinforce damaged areas. This approach requires significantly less preparation effort than flush repairs; however, these raised patches affect hydrodynamic performance and are unlikely to be applicable to tidal blades due to the thickness of additional laminate.

Scarf joints are more commonly employed within the wind industry. They involve removing a chamfered section of material and rebuilding it with new material to produce a repair that is flush with the hydrofoil skin. The purpose of scarf joint repairs is to rebuild the blade as close as possible to the original design, retaining original load paths. Scarf repairs are used in strength-critical applications [61].

The patches used in both doubler and scarf repairs can either be assembled on the blade in-situ (soft) or pre-manufactured and bonded to the repair using adhesive (hard). Soft patches are formed of individual plies, which means plies must be held in place as they are laid up. Resin is typically introduced to the plies either by hand wet lay-up, wet lay-up with vacuum bagging, or by direct resin infusion of the repair area. Vacuum bagging and resin infusion are only possible when a vacuum seal is achievable on the blade skin. In the case of tidal turbine blades, the presence of thicker sections with no core material means a soft patch could contain over 100 plies. The lay-up process is likely impractical to perform on vertical surfaces and be labour intensive. The preparation of a soft patch is also unlikely to be practical for field repair. Once a patch has been applied, its full strength is not achieved until post-cure at an elevated temperature.

Hard patches are pre-manufactured plugs, which enable the use of a wider range of manufacturing techniques in controlled environments. Hard patches are much more suitable for field repairs, as adhesives can be chosen with preferable cure cycles. However, a challenge with hard patch approaches is accurately matching the patch to the prepared scarf. Conversely, soft patches allow a degree of flexibility as they mould into the cut scarf. Hard patches must be manufactured to the exact scarf dimensions to avoid large adhesive bond lines. Scarf preparation is a generally manual process performed by technicians with hand power tools.

When evaluating scarf repair on tidal blades, hygrothermal aging effects should be considered. Studies of hygrothermal aging of adhesives used in hard patch scarf repair have shown that bulk adhesive mechanical properties decrease with moisture content [62]. In the few available reports on the aging of adhesive scarf joints, it was found that the reduction in the strength of the joint between the patch and the scarf due to hygrothermal aging did not exceed that of the bulk adhesive [63],[64],[65].

The hygrothermal challenge that exists in scarf joints in tidal turbine blades is that of differential moisture content. An in-service tidal turbine blade will have moisture content closely related to its duration of submersion. This means the bonding surfaces, on which a scarf joint is applied, may be completely or partially seawater aged. The effect of secondary adhesive bonding to pre-aged surfaces has received little attention in literature. If this is found to have a significant effect on initial adhesion, the bonding area may require drying prior to adhesion. Once a scarf repair has been applied, there may exist a discontinuity between the degree of aging of the existing laminate and the replacement laminate. If hygrothermal aging affects the mechanical properties of composites, then this may lead to repair interfaces unintentionally introducing stress concentrations, potentially reducing the life of the repair.

IX. Discussion

Surface repair, adhesive injection, and structural repair are three techniques found in the wind industry which show likely applicability to composite tidal turbines. Table 2 presents an indication of the suitability of the three techniques discussed to repair common damage types.

TABLE 2: INDICATIVE REPAIR TECHNIQUE SELECTION. MOST LIKELY (++) TO MOST UNLIKELY (--)

	Surface Repair	Adhesive Injection	Structural Repair
Matrix cracking	--	++	+
Adhesive de-bond	--	++	+
Minor impact damage	++	-	+
Major impact damage	+	--	++
Surface erosion	+	--	--
Fibre breakage	--	-	++

Selecting a repair technique depends on many factors including defect location, residual load paths, defect type, and access. Once a defect is identified, the immediate risk to the blade structure determines whether the blade can remain in-service and how urgently repairs must be undertaken. The lifetime of the defect influences repair choice as damage often exposes un-protected material to bio-contamination. Surface repair and non-structural injection repairs can follow standard procedures and require the least amount of technical investigation. Structural repairs require bespoke investigation to ensure that repairs are practical to perform and can restore critical structure.

The field of wind turbine blade repair has laid the groundwork for developing robust repair strategies for tidal blades. The challenge of assessing tidal blade repair lies in the expected variation in tidal blade design. Due to their smaller size and lack of requirement for lightweighting, tidal blades are more likely to show greater variation in terms of materials and structural design than wind blades. As a result, commonalities in repair methods between tidal turbine blade types are less likely to appear. A lack of convergence in tidal blade design may result in specialised repair strategies being required. This introduces complexity for third-party supply chain repairers, both in terms of the skills and proprietary processes required to service tidal operators. The tidal blade repair market will be limited in size compared to wind blades; however, the specialisation in more complex repair techniques offers a high-value service to operators.

Blade repair overtakes blade replacement as the most economical option when considering larger diameter rotors, yet the opposite may be true for shorter blades. Compared to wind blades, there is also less imperative to repair tidal blades on-site as they are more transportable. Instead, a likely strategy for tidal power operators may be to allow damaged blades to be replaced in a low-cost operation. The damaged blades can then be repaired in a controlled workshop environment. This opportunity granted by the shorter length of tidal blades, combined with the impracticality of submerged maintenance both from an access and composite bonding perspective, makes a strong case for replacement over repair. This change in strategy will be the most significant consideration when transferring maintenance approaches and knowledge from the wind industry into tidal stream projects.

X. Conclusion

This paper has presented an overview of the composite tidal blade repair problem, introduced some of the challenges of tidal blade repair, and discussed key techniques which are applicable for transfer from the wind sector. The size of tidal blades offers alternative repair approaches compared to wind turbines, such as utilising a "swap and repair" strategy which also allows for increased O&M flexibility and control. The field of composite repair has developed through a range of industries including wind energy. It can be concluded that some techniques of wind blade repair will be applicable to tidal turbines. Despite this, tidal blades operate in very different conditions than wind turbine blades. The environmental degradation of composites in seawater is a phenomenon which can significantly affect material properties. Seawater degradation must therefore be considered in all repair options. Biofouling of bonding surfaces has the potential to weaken repair areas which are exposed to seawater prior to repair. An understanding of how to maintain and protect composite materials underwater can be transferred from marine-based industries such as shipbuilding and offshore energy installations.

The understanding of degradation mechanisms of wind blades has evolved through observation of operational turbines. As tidal energy installations increase in size, device operators must similarly collect operational data on observed damage and deterioration of tidal turbine blades to enable improvements in blade design and maintenance.

XI. Key Recommendations

- Materials used in tidal blade repair must be characterised for seawater degradation.
- Adhesive and resin injection repairs require consideration of contamination due to seawater ingress.
- Surface coatings for tidal blades should provide resistance to surface erosion in addition to providing anti-fouling protection.
- Relatively low transportation costs allow tidal blades to be repaired in locations further from installation sites.
- A non-convergence in tidal blade design and size reduces the applicability of "universal" repair solutions.
- Structural health monitoring systems for blades allow defect identification without blade access leading to lower operations and maintenance cost.
- Tidal blade designers should anticipate repair requirements at the design stage.

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