Advancements in Structural Testing and Life Predictions of Tidal Turbine Blades

Tenis Ranjan Munaweera Thanthirige, Micheal Flanagan, Ciaran Kennedy, Jamie Goggins, and William Finnegan

Abstract— **The research explores advancements in structural testing and their outcomes to identify strategies for predicting the lifespan of tidal turbine blades with greater reliability, efficiency, and accuracy. In this context, as a case study, this research examines the structural testing results of a 5m-long crossflow helical tidal turbine foil. The advanced instrumentation, unbalanced rotating mass, and post inspection analysis used in the testing program improved data accuracy and result reliability, ensuring a more precise assessment of the turbine blade's structural performance. Moreover, validating the experimental results through FE modelling opens new avenues for utilising FE simulations as a viable alternative to traditional structural testing programs, which are often time consuming, expensive, and complex. Furthermore, this study identifies critical gap in structural testing of composite tidal turbine blades, particularly the limitation in assessing the impact of water absorption on composite materials under operational marine conditions. To address this challenge, the research proposes two FE modelling approaches to predict tidal turbine blades' lifespan. Approach 1 integrates accelerated aged fatigue test data, while Approach 2 simulates water diffusion for material degradation. Validating these methods can improve sustainability of the tidal energy sector for clean and affordable energy solutions in the future.**

Keywords— **Structural testing, advancements in structural testing, tidal energy, water diffusion, material degradation, marine renewable energy, finite element modelling.**

I. INTRODUCTION

Tidal Stream Energy has become an increasingly significant component of the global renewable energy portfolio due to its reliability, predictability, and potential to contribute to clean energy transitions. Unlike other renewable energy sources such as wind and solar, which are subject to weather variability, tidal energy leverages the consistent and predictable movement of ocean currents [1]. This consistency makes it a valuable resource for energy diversification and provides a dependable means of reducing greenhouse gas emissions. Tidal turbines, particularly their blades, play a critical role in converting the kinetic energy of water into mechanical energy, which is then converted into electricity. However, the success of tidal energy systems relies heavily on the structural reliability and durability of turbine blades [1], [2], [3], [4], [5], [6], [7], [8], [9]. These components are subjected to cyclic loading, environmental stresses, and exposure to harsh marine conditions, all of which can compromise their integrity over time. Ensuring the structural reliability of turbine blades is crucial for optimising their lifespan, minimising maintenance costs, and managing the economic viability of tidal energy projects [2], [8], [10]. In this context, the industry is following DNV-ST-0164 and IEC DTS 62600-3:2020 standards to perform structural testing to de-risk the full-scale prototype tidal turbine blades [11], [12].

The DNV-ST-0164 standard outlines requirements for tidal turbine design, construction, and operation, focusing on structural integrity under operational stresses [12]. Similarly, IEC DTS 62600-3:2020 provides methodologies

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for assessing tidal energy converters (TECs) performance through mechanical load measurements [11]. However, the conventional methods of performing structural testing are time consuming while challenging to report the data precisely and reliably due to the technical limitations of some of the instrumentations used to monitor the performance of the tidal turbine blades during the testing process [13]. Employing state-of-the-art instrumentation and innovative methodologies to perform structural testing can provide a more realistic assessment of blade performance under operational conditions [14]. Advanced tools such as fibre Bragg grating (FBG) sensors, laser scanning vibrometers (LSVs), digital inclinometers, acoustic emission sensors, infrared thermal imaging cameras (IRTICs), and digital image correlation (DIC) systems can be employed to enhance the accuracy and reliability of data collection and reporting [14], [15], [16], [17], [18], [19], [20], [21], [22]. These tools enable precise measurement of strain, displacement, dynamic performance, and temperature changes during testing, offering a comprehensive understanding of blade behaviour under idealised loading conditions. The integration of advanced instrumentation enhances the accuracy and representation of post-processing results, establishing a new benchmark for structural testing in the tidal energy industry. Additionally, incorporating modern testing methodologies can expedite the structural testing process of tidal turbine blades. Among these methods, the use of rotating pendulum mechanisms commonly employed in wind turbine blade testing emerges as one of the most promising techniques for applying fatigue loading to tidal turbine blades [13], [23].

While these standards provide a comprehensive foundation for testing and validation, current methodologies often fall short in replicating the complexities of real-world operating conditions. Structural testing of turbine blades is typically conducted under controlled dry laboratory conditions, which simplifies experimentation and reduce costs. However, such conditions fail to account for the critical effects of seawater exposure, particularly the phenomenon of water diffusion into composite materials. This represents a significant gap in conventional testing practices, as water diffusion can have profound implications for the structural integrity of turbine blades.

Water diffusion into composite materials can deteriorate their mechanical properties, leading to swelling, delamination, plasticisation, and weakening of the fiber-matrix interface. This degradation reduces their resistance to cyclic loads and increases the risk of crack propagation and delamination, particularly in submerged environments [24], [25], [26]. These degradation mechanisms not only compromise the reliability of turbine blades but also shorten their operational lifespan, increasing the frequency of maintenance and replacement [27], [28]. As a result, the economic benefits of tidal energy projects may be undermined. Despite these risks, the effects of water diffusion are often overlooked in standard dry testing procedures, leaving a critical gap in the assessment of turbine blade performance. Addressing this limitation is crucial for developing more accurate and reliable performances analysing methodologies that better reflect the actual environmental and operational stresses experienced by tidal turbine blades.

Enhancing structural testing processes and performance assessment methodologies for composite materials in marine environments can improve the reliability of tidal turbine blades, reduce operational risks, and optimise the levelised cost of energy. These advancements contribute to the development of more robust and cost-effective tidal energy systems, accelerating the shift toward affordable and sustainable energy solutions. As a result, they strengthen the role of tidal energy in the global renewable energy mix, fostering a cleaner and more resilient energy future. Additionally, this progress aligns with the UN's Sustainable Development Goal 7, which aims to ensure access to affordable and clean energy for all.

II. METHODOLOGY

The primary aim of this study is to provide a concise discussion on potential opportunities for advancing structural testing processes for tidal turbine blades and to explore the feasibility of developing a lifespan prediction mechanism for these blades. To support this aim, this paper presents the following objectives:

1) Study the structural testing results of a 5m-long crossflow tidal turbine blade and discuss the suitability of new approaches in structural testing.
2) Investigate fatigue and material degradation and its impact on tidal turbine blade lifespan.
3) Utilise the validation of finite element (FE) model results against experimental data to suggest an integrated approach that incorporates material degradation, enabling more accurate lifespan prediction of tidal turbine blades.

The research follows a structured four steps approach shown in Fig. 1 aimed at discussing the advancements in structural testing and improving the lifespan prediction of tidal turbine blades. The first step involves discussing the modern methods and technologies that enhance the current structural testing processes. This includes exploring advanced instrumentation, testing techniques, and computational models that could provide more accurate and reliable data. In the second step, the results of a case study conducted at the University of Galway’s in-house Large Structures Testing Laboratory on a structural testing program for a tidal turbine blade using modern tools are studied to identify opportunities for applying these findings in predicting the lifespan of tidal turbine blades. This analysis highlights both the advantages and limitations of the applied methodologies, providing insights into their effectiveness in assessing long-term performance. This phase will also involve identifying any advancements that can be made to improve the testing process and increase its efficiency while highlighting the importance of FE model validations against the structural testing results. In here, the research only highlights main research findings of employing advanced tools and testing methodologies as more comprehensive discussions related to this case study are already published by the University of Galway [13], [14], [21], [29].

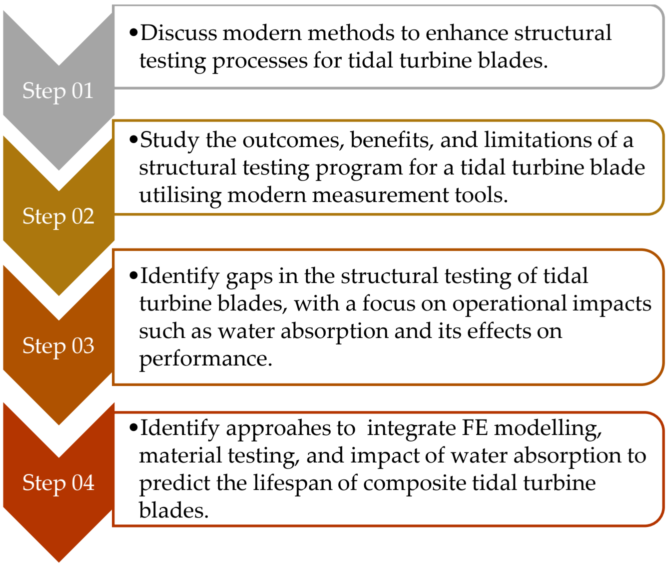


Fig. 1. Methodology of the research

The third step focuses on addressing the gaps in current structural testing practices, particularly concerning operational impacts such as water absorption and its influence on blade performance. This includes investigating how water absorption affects the material properties and the long-term durability of the turbine blades. Finally, the research will explore approaches to integrate FE modelling, material testing results with the impact of water absorption to develop a predictive framework for estimating the lifespan of composite tidal turbine blades. By combining these insights, the research aims to provide a more comprehensive understanding of blade performance and offer methods for improving their reliability and longevity.

The approaches highlighted in Fig. 1 aim to bridge the gap between conventional laboratory tests and real-world operational challenges, providing deeper insights into blade performance. By focusing on a holistic examination of structural integrity, the study addresses critical factors influencing the durability and reliability of tidal turbine blades. methodologies under controlled dry laboratory conditions. In this context, a case study showcases the structural testing of a 5m long crossflow tidal turbine blade, selected from a set of three blades comprising a 1.8-meter rotor diameter turbine, as shown in Fig. 2. Due to the helical shape, this tidal turbine blade is often referred to as tidal turbine foil. The foils are manufactured using carbon fibre prepreg composite materials, and this study highlights the application of innovative testing methodologies under controlled dry laboratory conditions.

Fig. 2. Prototype turbine developed for towing tank and sea trails, image courtesy- ORPC

III. Instrumentation and Test Matrix.

A range of advanced instrumentation was utilised to monitor performance throughout the selected case study structural testing program. This included dynamic testing (before and after each fatigue test), static testing (at the initial and final stages with idealised loading conditions), fatigue testing (conducted at five intervals, each consisting of 250,000 fatigue cycles), and residual strength testing (performed after each fatigue interval using idealised loading conditions from the initial static tests). The configuration relevant to the modern tools and different testing methods utilised for structural testing are shown in the Fig. 4.

FBG sensors and strain gauges were used for precise strain measurements, offering superior resolution and sensitivity. LSV provided detailed analyses of the blade's dynamic performance, capturing intricate vibrational behaviour under operational loads. DIC systems enabled non-contact measurement of surface deformations and strain distribution, while laser displacement sensors accurately tracked displacement during loading cycles. IRTIC was employed to monitor temperature fluctuations at the cantilever fixed end of the turbine foil, preventing any temperature increase that could alter the damage mechanism or degradation pattern of the tidal turbine foil.

Two servo hydraulic actuators with 500 kN and 250 kN capacities were employed to apply the static loading on the foil. At the same time, unbalanced rotating mass (URM) system was utilised to apply the fatigue loading on the tidal turbine foil as a new approach for tidal turbine structural testing. Due to the use of the URM system for fatigue testing, two dynamic test configurations were considered: one with the URM system and one without it.

Post-test inspections and analyses were conducted to gain insights into damage mechanisms and material degradation. Damaged sections from the final stage of static testing were closely examined to identify the damage mechanisms affecting the tidal turbine foil. In parallel, test specimens were extracted from undamaged regions of the foil and subjected to tensile testing in accordance with the ASTM 3039D standard to further investigate material degradation. The results were integrated into a FE model to compare the strain distributions observed during the initial static tests. This process allowed for validation of the experimental results against material properties obtained from the materials suppliers and derived from the extracted test specimens. Abaqus 2023 software version was used to conduct the FE simulations for the foil [30]. The Abaqus generated FE model is shown in the Fig. 3. Moreover, the FE model comprised 26,787 nodes and 26,756 elements, incorporating both 3-node triangular general-purpose shell elements and 4-node quadrilateral shell elements throughout the mesh.

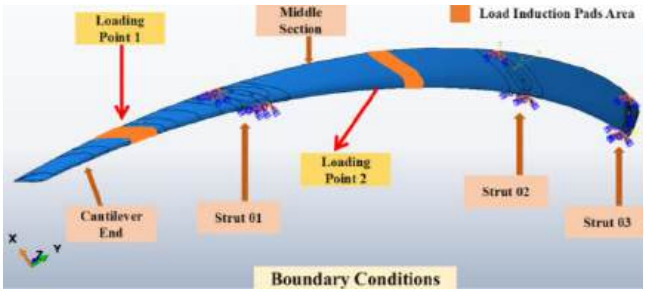


Fig. 3. FE mesh model generated in Abaqus 2023 version

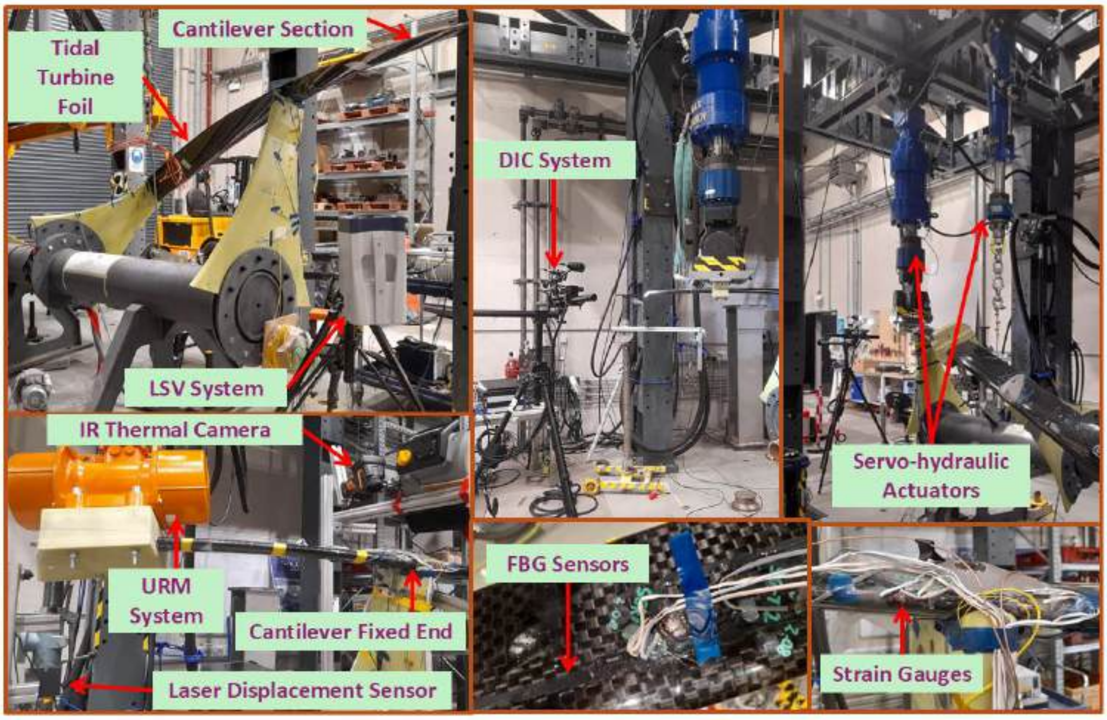


Fig. 4. Instrumentation arrangements for the structural testing

IV. STRUCTURAL TESTING RESULTS

The integration of state-of-the-art tools significantly enhanced the reliability of data collection, the precision of post-processing, and the clarity of result representation, setting a new benchmark for structural testing methodologies in structural testing of tidal turbine blades. A comprehensive discussion regarding the utilisation of these instruments and their findings has been published in the Journal of *Measurement: Sensors* [14]. Additionally, detailed results from the structural testing program of the tidal turbine foil examined in this study are available in the Journal of *Engineering Structures* [13].

Fig. 5 presents a summary of key findings generated from the LSV, DIC, and IRTIC. Specifically, Fig. 5 (a) and (b) depict the changes in natural frequencies observed before the initial static testing stage (23.88 Hz, 37.50 Hz, 62.75 Hz) and after the final static testing stage (24.50 Hz, 30.00 Hz, 31.00 Hz, 61.25 Hz) for the dynamic test setup without the URM system. These results clearly demonstrate a shift in natural frequencies due to structural stiffness alterations caused by the applied fatigue loading and the damage incurred at the final static testing stage. A thorough investigation of the foil's dynamic performance was conducted before and after all scheduled static, fatigue, and residual strength tests.

Fig. 5 (c) and (d) illustrate the displacement readings at the tip end of the tidal turbine foil obtained during static testing using the DIC system. The laser displacement sensor recorded a displacement of 57 mm, while the DIC system measured 57.8 mm, revealing a deviation of only 1.4%. This close agreement highlights the reliability of both the DIC system and the laser displacement sensors for displacement measurements.

Fig. 5 (e) through (f) present the IRTIC readings taken before the initiation of fatigue testing, after approximately 1,000 fatigue cycles, and after cooling the cantilever fixed end with a fan followed by another 1,000 fatigue cycles. Moreover, temperature at the cantilever fixed end was randomly monitored throughout the fatigue testing process to ensure proper thermal control. FBG sensors and strain gauges recorded the strain distribution on the turbine foil during all structural testing stages. For comparing experimentally obtained results with those derived from FE modelling, the initial static testing stage under 30% of the idealised loading condition was selected and Fig. 6 illustrates this comparison.

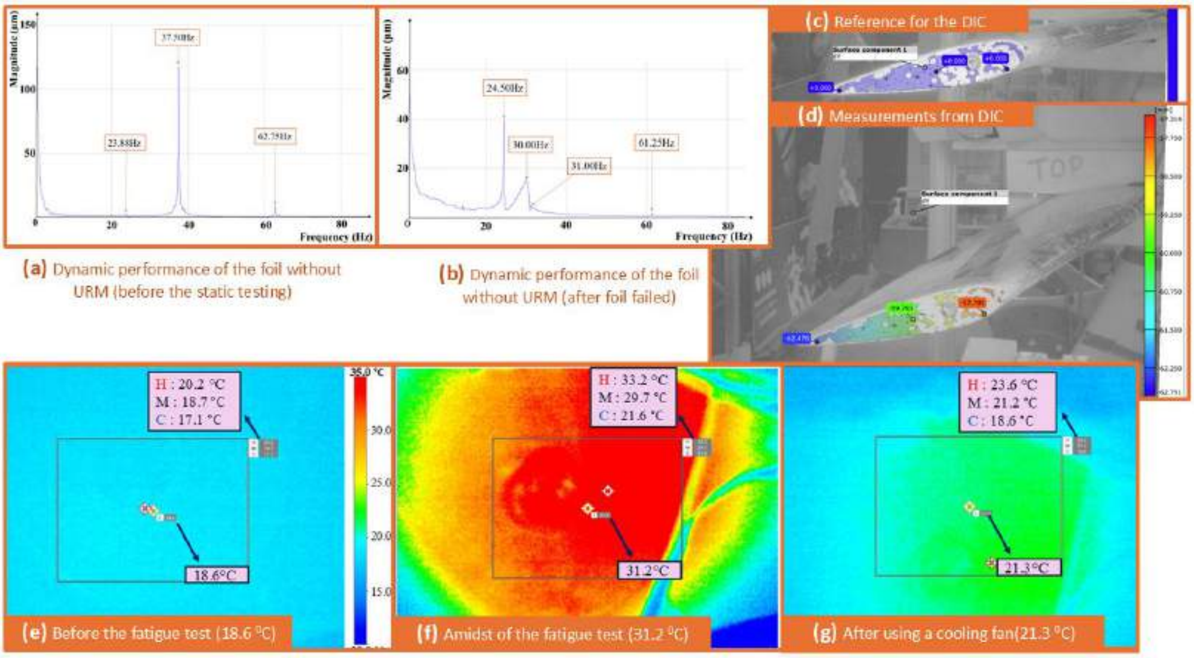


Fig. 5. Instrumentation arrangements for the structural testing

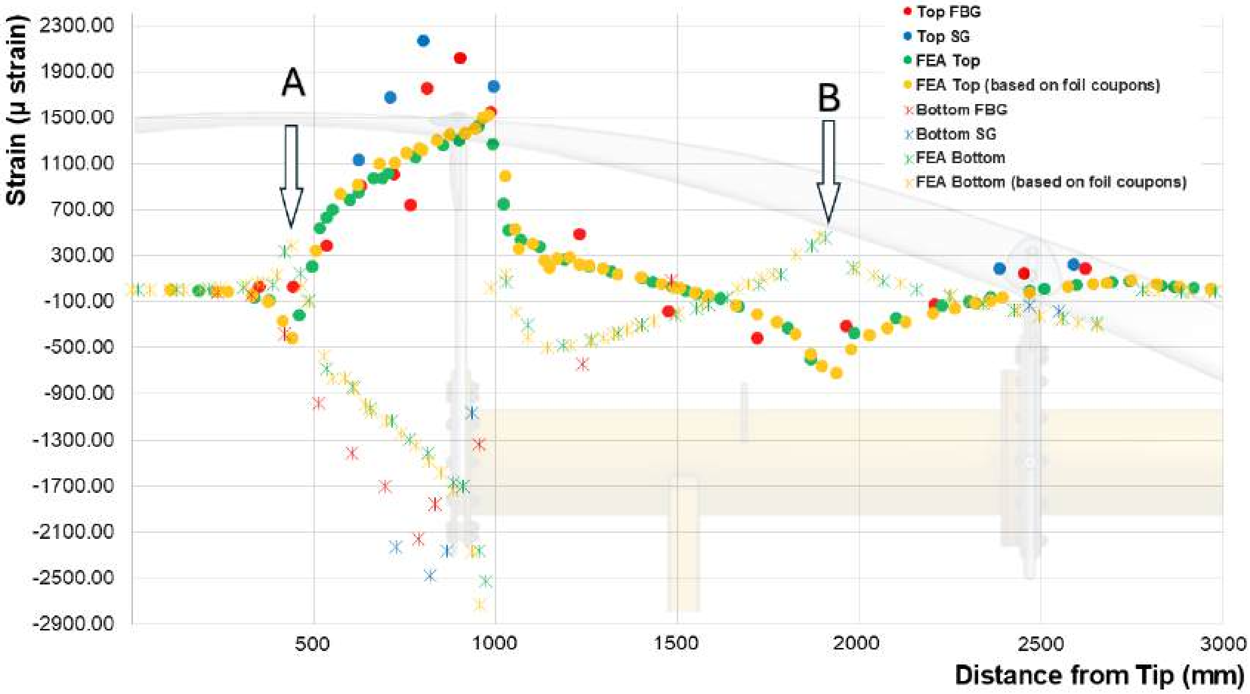


Fig. 6. Strain distribution comparison at initial static testing [13]

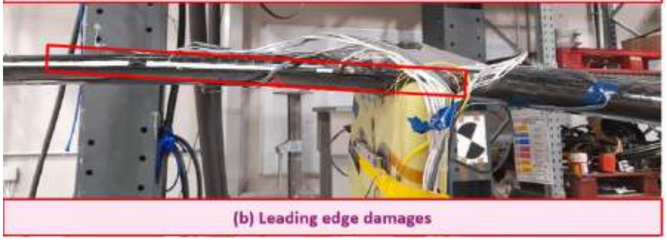
Fig. 6 results from the FBG sensors and strain gauges showed higher strain values than the FE model predictions, which were based on material data provided by the supplier as well as material properties derived from the damaged tidal turbine foil at the final testing stage. However, the overall strain distribution patterns were consistent between experimental data and FE model results. Additionally, the FE model using experimentally derived material properties exhibited a slight increase in strain distribution compared to the virgin material data. Although the same idealised loading conditions were applied for both experimental and FE modelling approaches, this discrepancy indicates material degradation in the final-stage foil compared to the virgin material used for manufacturing. Additionally, it can be observed that loading points "A" and "B" exhibit variations in compression and tension values when compared to the FBG and strain gauge results versus the FE model results. Furthermore, FBGs and strain gauges recorded higher strain values at the cantilever's fixed end compared to the FE model. These discrepancies can be attributed to parasitic effects from the loading pads and the boundary conditions defined in the FE models [31]. Despite these differences, the FE model results, and experimental data demonstrate a reasonable level of correlation. This underscores the potential of using FE modelling for future design validation and lifespan prediction of tidal turbine blades.

Furthermore, the research employed an innovative fatigue loading mechanism using an URM to conduct fatigue testing. This approach achieved a milestone of 1.3 million fatigue cycles, representing a significant advancement in fatigue testing techniques for tidal turbine blades. Compared to traditional servo-hydraulic actuators, this method proved more efficient, reducing testing durations 20 to 25 times without compromising accuracy or reliability. The ability to perform fatigue loads more effectively accelerates the development and validation of turbine blade designs, contributing to the broader goal of improving their performance and extending their operational lifespan. However, the URM system demonstrated certain limitations when applied to fatigue testing, such as its unsuitability for highly rigid tidal turbine blades and the lack of a mechanism to measure the excitation load on the foil. These shortcomings represent the primary constraints of using the URM system for fatigue testing of tidal turbine blades. Consequently, incorporating an accurate mechanism to monitor excitation loads on the blades could facilitate the effective use of the URM system for testing small-scale, less rigid tidal turbine blades. Overall, the integration of cutting-edge instrumentation and innovative methods sets a new standard, improving the reliability and durability of tidal energy systems.

V. Post-Test Damage Assessment.

The final stage damage assessments of the tidal turbine foil revealed significant structural failures, including shear fractures in the matrix materials, bond failures at the matrix-fibre interface, delamination, and fibre breakage along both the leading and trailing edges of the turbine foil as illustrated in Fig. 7. However, this process does not highlight crack initiation and propagation before the final stage of failure. These phenomena can accelerate water diffusion, further weakening the structure, yet they are not extensively studied by researchers worldwide at present.

(a) Trailing edge damages



(b) Leading edge damages

Fig. 7. Leading and trailing edge damages [13]

These findings underscore the complex interactions between operational loading conditions and material behaviour, offering valuable data for improving tidal turbine blades design and manufacturing processes while highlighting the importance of conducting comprehensive studies at operation stage in marine environments.

VI. Operational Impacts and Water Absorption in Structural Testing

Loading conditions, design and manufacturing factors, material degradation, and unexpected circumstances are key elements influencing the lifespan predictions of tidal turbine blades. Comprehensive studies of these factors are essential when de-risking new design strategies for tidal stream turbine systems through structural testing programs [1]. In this situation, this study focuses on addressing critical gaps in current structural testing methodologies by aiming at the often-overlooked operational impacts encountered by tidal turbine blades in real-world environments. Current laboratory testing conditions, while offering controlled and repeatable scenarios, fail to capture the complex effects of environmental factors such as water absorption, corrosion, and erosion that contribute to the degradation of tidal turbine blades. These factors are known to significantly influence the performance, durability, reliability, and operational life of tidal turbine blades.

The effects of corrosion and erosion on tidal turbine blades depend heavily on the characteristics of the flow of the stream and the tribological parameters of the water, such as particulate content, velocity, and salinity [32]. Although these factors are important, their overall impact on blade degradation is minimal compared to the influence of water absorption. Addressing corrosion and erosion impacts require more rigorous and environment-specific testing approaches. However, given their relatively smaller contribution, these factors were not the primary focus of this study.

Water diffusion in composite materials deteriorates mechanical properties, leading to swelling, delamination, plasticisation, and fiber-matrix interface weakening. Therefore, it emerged as a significant factor affecting the structural performance of tidal turbine blades [26], [33]. Moreover, water absorption primarily impacts the matrix-fiber interface, worsening microcracking and reducing the overall structural integrity of the blade [9], [26], [34]. This degradation mechanism highlights the urgent need to integrate the effects of water absorption with fatigue loading to better understand the material property changes induced by operational stresses.

Therefore, the study investigates the relationship between water absorption and material degradation, focusing on developing approaches to predict the lifespan of tidal turbine blades in operational stage. The proposed methodology of this study involves accelerated aging, FE modelling, and material testing of accelerated aged coupons to replicate the degradation processes observed in operational conditions. These tests provide fundamental data for predictive modelling of blade lifespan. By integrating laboratory-based fatigue testing with water diffusion studies and the FE model validation process from the case study, this research proposes a framework for assessing the evolution of material property degradation over time, driven by the combined effects of fatigue and water absorption in tidal turbine blades. This integrated approach can offer a more comprehensive understanding of blade behaviour, enabling the development of predictive models that enhance the lifecycle management and design of tidal energy systems.

Based on these facts and a thorough review of the literature and experimental findings, this study identifies two approaches for generating vulnerability curves as life predicting tools for tidal turbine blades. These curves aim to forecast the lifespan of blades during their operational period, taking into account deployment site characteristics, fatigue loading, material properties, and water diffusion effects. The conceptual frameworks for developing these vulnerability curves are illustrated in Fig. 8.

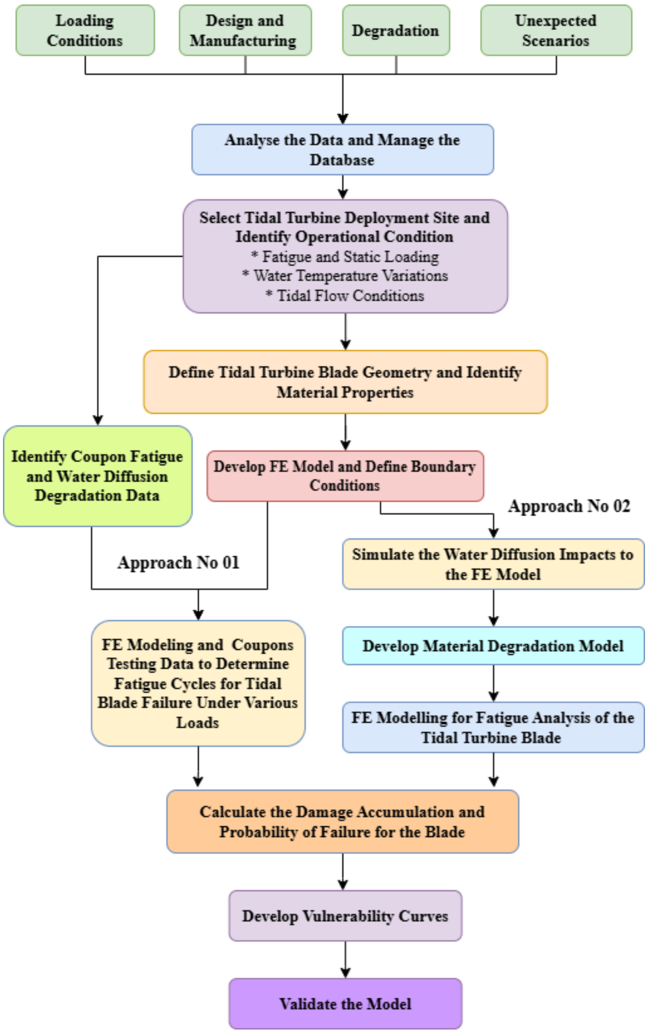


Fig. 8. Proposing approach to develop vulnerability curves

These predictive frameworks combine insights from material degradation under fatigue loading and water absorption to offer practical tools for estimating blade failure. Approach 1 combines experimental fatigue data from coupon testing with FE modeling to predict the fatigue life of tidal turbine blades under various loading conditions. In contrast, Approach 2 simulates water diffusion effects within the FE model to develop a material degradation model, providing insights into structural weakening over time. These two approaches can bridge the gap between laboratory testing and real-world operational conditions, advancing the structural integrity analysis and reliability of tidal turbine systems. However, it is essential to fully validate these two approaches for developing vulnerability curves for tidal turbine blades in the future. In this context, future research will focus on validating and refining the proposed methodology while conducting comprehensive studies about water absorption effects of composite materials used in tidal turbine blades manufacturing.

VII. CONCLUSION

The study focuses on discussing the advancements of structural testing process of tidal turbine blades based on a case study completed at University of Galway and potential strategies to develop life predicting tools for the tidal turbine blades. The integration of advanced measurement tools including laser scanning vibrometers, digital image correlation systems, infrared thermal cameras, laser displacement sensors, and fibre Bragg grating sensors improve the accuracy, reliability, and efficiency of performing structural testing process of tidal turbine blades. The approach to use the unbalanced rotating mass system for accelerated fatigue testing further represents a significant advancement in structural testing of tidal turbine blades. This method reduces testing durations by 20 to 25 times compared to traditional approaches while ensuring reliable fatigue data, making it a valuable tool for validating tidal turbine blade designs. The FE model was employed to validate the experimental results from the initial static testing process, revealing similar patterns in the strain distribution along the foil's span-wise direction. However, some discrepancies were noted between the strain results obtained from FBG sensors, strain gauges, and the FE model using both supplier-provided and extracted material properties of the foil. Furthermore, post-test inspections included detailed characterisation of damage mechanisms, such as delamination, fiber breakage, and matrix-fiber bond failures. These findings are crucial for improving blade design and manufacturing processes. Moreover, it underscores the need for comprehensive studies on water absorption degradation in composite materials during damage initiation and propagation, a critical gap for future life prediction tools. This study evaluates operational impacts, particularly water absorption, which affects material degradation and fatigue life in life predictions of tidal turbine blades. Based on these evaluations, two novel approaches are proposed to develop vulnerability curves for lifespan estimation, considering site-specific characteristics and operational factors. While these approaches require validation and refinement through future testing, the suggestions and recommendations highlighted in this paper contribute substantially to enhancing the reliability, efficiency, and sustainability of tidal energy systems. This work lays the foundation for improved lifecycle management and the development of more resilient tidal turbine designs.

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