# A methodology for developing a prediction model for the remaining fatigue life and residual strength of tidal turbine blades

Tenis Ranjan Munaweera Thanthirige, Jamie Goggins, and William Finnegan

*Abstract*— **As tidal energy nears commercial viability; the reliability and safety of a tidal energy device becomes more prevalent. A key aspect for determining their reliability and safety, along with reducing risk during operational deployment, is the structural integrity of tidal turbine blades. Therefore, a validated model for predicting the structural integrity of tidal turbine blades will aid in de-risking tidal energy technologies. In this study, a three-phase approach was used to formulate a strategy to predict the remaining fatigue life and residual strength of tidal turbine blades, over their operational lifespan. In Phase 1, the parameters influencing the structural properties of tidal turbine blades were identified based on the literature review, and the expertise in the field. Then, parameters were extensively studied and classified into four main impact groups, which include load conditions, design and manufacturing, degradation, and unexpected situations. In Phase 2, a data management strategy was formulated related to identified four impact categories and investigated the possible methods of analysing the data. In this context, finite element analysis of composite tidal turbine blades was identified as the most appropriate tool to comprehensively examine collected data, prior to comparing the results to the field and laboratory-based test data. In Phase 3, with the information gathered, as well as knowledge and experience in the field, a method for estimating the residual strength and remaining fatigue life of tidal turbines at each stage of their operation was formulated. The model will be validated using experimental testing datasets and used to develop vulnerability curves related to the remaining structural life of tidal turbine blades in the future.**

*Keywords*—**Fatigue life, residual strength, tidal energy, structural integrity, structural testing.**

## I. INTRODUCTION

TIDAL energy is estimated to be available in shallow waters in the amount of 1000 GW, but no more than 1% of it has been harnessed to date [1], [2]. These untapped tidal energy sources can therefore make a significant contribution to meeting future electricity demands with minimum environmental impact [3]. On the other hand, tidal energy generates a vast amount of predictable and reliable electricity compared to other renewable energy sources [4]. However, the development of tidal energy has been relatively slow, with only a handful of commercial-scale tidal power plants in operation around the world. The largest tidal deployments can be identified as a 240 MW plant installed in France in 1966 and a 254 MW plant deployed in the Republic of Korea in 2011, with the "MeyGen" project in Scotland being one of the largest projects in the pipeline[2]. Technology readiness of the industry and the limited number of locations with sufficiently strong tidal currents to generate significant amounts of power can be recognized as main reasons behind this slow progress of the tidal energy sector [5]. Although, the development of the tidal energy industry has been slow in recent decades, due to various constraints, it is starting to gain more attention as countries around the world explore strategies to reduce their reliance on fossil fuels and increase their use of renewable energy sources [6]. In addition, the world's energy sector is targeting to deploying large scale tidal energy projects to generate affordable and clean energy that contributes to achieving the United Nations' sustainable development goals [7]. In this regard, the European marine energy sector is planning to deploy 100GW of ocean energy generation projects by 2050 [8]. Consequently, tidal energy has the potential to be a



Sponsor and financial support acknowledgement: This work has been funded through the TIDAL-GES project of the University of Galway Global Challenges Programme. The research is also supported by Science Foundation Ireland (SFI) through MaREI Research Centre for Energy, Climate and Marine (Grant no.12/RC/2302_2) and the Sustainable Energy Authority of Ireland (Grant no. 22/RDD/783).

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Digital Object Identifier: https://doi.org/10.36688/ewtec-2023-285

significant contributor to the global energy mix, but there are still challenges to be overcome, including the high costs of building tidal energy facilities, difficulties in monitoring the structural properties and maintenance requirements, and the potential impacts on marine life [9], [10].

Recent developments in materials science and construction are driving down the cost of constructing tidal power plants and opening up opportunities even for small and medium-sized energy companies to invest in tidal power [11]. At the same time, developers have come up with new generation design concepts and modifications which are more sustainable, efficient, and reliable compared to traditional tidal energy converters. This includes floating tidal turbine systems, tidal arrays with different layouts, multi rotor tidal turbine systems and hubless tidal systems with multi-blades as shown in Fig. 1 [12]–[17].

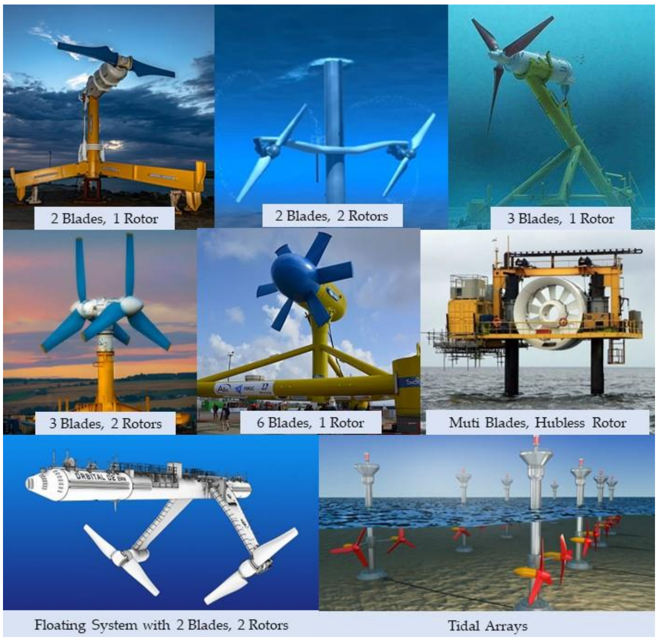


Fig. 1. New generation tidal systems

In this context, the deployments of tidal and wave energy devices make significant impact to the marine life and it has limited the access to the ocean energy sources [18]–[21]. To address this critical issue, frameworks are in place to assess the environmental impacts of marine energy generation equipment and ensure environmental sustainability [19], [22], [23]. In this particular scenario, the lack of monitoring mechanisms to identify the structural integrity of tidal turbine blades throughout their operational lifetime will be the one of the main reasons for the sector's slow progress now [9]. Therefore, it requires to identify short- and long-term strategies to improve the reliability and safety of the tidal systems, which are at operating stage. Currently, prominent research institutes are engaged in conducting structural tests on tidal turbine blades to verify their structural integrity based on the DNVGL-ST-0164 and IEC DTS 62600-3 standards. The University of Galway stands out among these institutes for its extensive involvement in multiple structural testing programs for different types of tidal turbine blades. In 2022, the university conducted tests on an 8m long full-scale axial flow tidal turbine blade, as depicted in Fig. 2 [24]. This particular blade holds the remarkable distinction of being the largest reported tidal turbine blade ever tested worldwide.

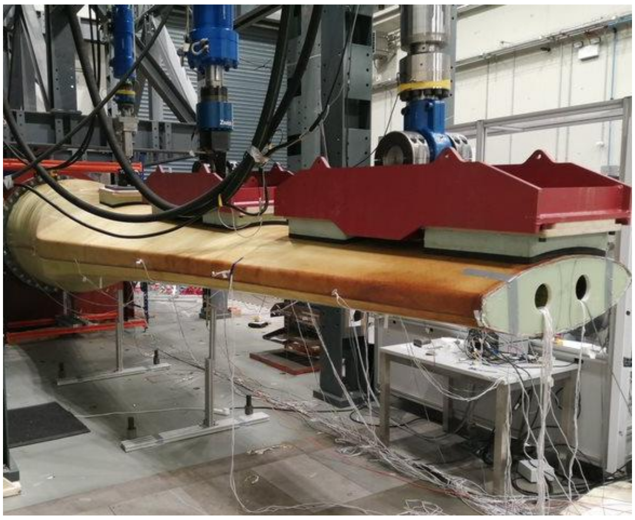

Fig. 2. Structural testing of tidal turbine blade [12]

However, performing finite element analysis (FEA) and comparing it to structural testing data can be identified as a costly, short-term approach to de-risking the tidal power industry and is not a sustainable solution as it requires more people, time, and laboratory resources. At the same time, this method does not support the identification of operational-stage structural properties of blades, which are critical for monitoring the structural health of tidal systems to ensure their safety and reliability. In this context, formulating a strategy to predict the structural properties of tidal turbine blades until their end-of-life can be identified as a long-term strategy to accelerate the number of tidal energy deployment projects in the future.

## II. Methodology

The main aim of this study is to identify a strategy to predict the remaining fatigue life and residual strength of the tidal turbines until the end of their operational lifespan. To support this aim, this paper presents the following objectives:

1) To identify the parameter which decide the structural integrity of tidal turbine blades in active power generation.
2) To study the scale of impact of the identified parameters on lifetime of the tidal turbine blades.
3) To identify the approaches of developing mathematical models to estimate the material properties of the composite materials in marine environments.

Therefore, a three-phase approach was implemented to explore a method of developing the predicting model for the tidal turbine blades, as illustrated in Fig. 3. The identification of all relevant parameters to predict the remaining fatigue life and residual strength of tidal turbine blades was completed in Phase 1 and a database managing plan was developed in Phase 2. Following this, the identified parameters were studied in detail, and it was found that the mutual connections between them served to explore a new methodology to predict the structural properties of tidal turbine blades, during their operational lifetime in Phase 3.


Fig. 3. Methodology of the research

## III. Predicting Model and Discussion

The operational lifespan of the tidal turbine blades is a critical aspect in the efficient operation of a tidal energy device, where designers are expecting 20 + years of service life from tidal turbine blades [12]. To ensure uninterrupted power generation over this period, the turbine system must be safely operated and maintained. In this context, for taking the operational stage decisions, it is necessary to accurately predict the remaining fatigue life and residual strength of tidal turbine blades. Therefore, the following seven parameters, which mainly affect the useful operational life of the tidal system, have been identified:

*1) Fluid structure interactions:*

The load and stress on a tidal turbine blade can directly affect their lifespan. Blades that are subjected to high loads and stresses may experience more wear and tear, leading to a shorter lifespan [25]–[27]. Therefore, it becomes critically important to predict the loading conditions accurately at design stage considering all aspects affecting the hydrodynamic loads on the blade such as climate conditions, geographical changes at the deployment site, and unexpected scenarios.

*2) Manufacturing process:*

The manufacturing process of the blade should be undertaken according to the industry standards and practices otherwise, they may have defects that cause them to fail prematurely [28]. Delamination, ply waviness, void formation, adhesive failure, and thickness variations can be identified as a few manufacturing stage damages of composite materials [29]. Therefore, it is required to optimize the layup of the turbine blade structure based on the composite design guidelines while following the proper manufacturing process to minimize the defects formation.

*3) Maintenance:*

Proper maintenance and regular inspections can help extend the lifespan of tidal turbine blades. Neglecting maintenance or failing to identify and repair problems can lead to blade failure [30]. However, since tidal turbine systems are underwater structures, frequent monitoring is problematic. Therefore, preventive and scheduled maintenance should be carried out accordingly to ensure continuous power generation. Structural health monitoring systems can be integrated to detect possibilities of failures and malfunctions in tidal turbine systems, but this can result in significant operational costs.

*4) Properties of materials:*

The material used to manufacture the blades can also impact their lifespan. Blades made from more durable materials in marine environments, such as composite materials, may have a longer lifespan than those made from less durable materials [31]–[33]. In current context, the tidal energy industry uses composite materials to manufacture structural components of the tidal system due to remarkable advantages of them. The properties of the composite materials are depending on the type of fibre and matrix materials, type of the fabric structure, and permeability of the fabric. Therefore, it is required to select the most suitable materials while satisfying the financial constraints.

*5) Blade design:*

The design of the blade can also affect its lifespan. Blades that are designed to be more efficient and have less drag may last longer than those with more complex or inefficient designs. To minimize drag in tidal turbines, engineers employ several design techniques. These techniques include optimizing the shape and profile of turbine blades, reducing surface roughness, and utilizing advanced materials with low friction coefficients specifically for the surfaces exposed to seawater. Similarly, composite design and manufacturing guidelines must be carefully followed, taking into account the thermal responses involved in the structural curing process [34]. In addition, bonding and joining process of the structural components should be undertaken based on the industry standards. It is also evident that the blade design makes considerable impact on wear and tear of the blade [13], [28]. Therefore, designers should incorporate design strategies to minimise erosion of the blade. Designing a turbine blade that can withstand erosion can require a lot of prototyping testing and numerical modelling works. At the same time, the number of blades on the turbine rotor may also decide the cost of manufacturing, structural dynamics, installation and maintenance complexities, and performance of the tidal turbine system. Therefore, the designers should decide the number of blades on the rotor according to the standards and numerical analysis.

*6) Operating conditions:*

The operating conditions of the turbine, such as the characteristics of water flow, tribological properties of the water and temperature of the surrounding can significantly affect the lifespan of the blades. Blades that operate in high-stress environments may experience more wear and tear and may have a shorter lifespan than those in more moderate conditions [13], [35], [36]. Moreover, the operating conditions should be predicted at the design stage of the blade to avoid permanent failure during the operation. For example, a 12 bladed hubless tidal turbine deployed by OpenHydro in 2009 failed due to unexpected sea currents, highlighting the importance of correctly predicting the loading conditions that act on the tidal blades during structural testing. [37]. In this context, the fluctuations of fluid flow velocities, wake characteristic, tribological phenomena, and temperature fluctuations should be studied very closely in order to estimate the hydrodynamic loading and degradation of the blade in seawater [38], [39].

*7) Erosion and corrosion:*

The tidal blades may also be affected by solid particle erosion and cavitation erosion due to aggressive marine conditions. This can lead to major tribological problems for composites blades in tidal environments, which includes matrix cutting and reinforcement fracture [40]. Therefore, the process of measuring or modelling of tribological conditions in the vicinity of the tidal turbine system support to predict the impact of erosion on tidal turbine blade performance. Similarly, the tidal turbine systems are subjected to corrosion, especially if they are made of materials that are prone to rust or other forms of corrosion. This can also shorten the lifespan of the structural components of the system such as supporting frames [36].

Based on the studies undertaken, the

Fig. 4 summarizes these seven parameters affecting the life of tidal turbine blades into four main impact categories named (C-1) loading conditions, (C-2) design and manufacturing, (C-3) degradation, and (C-4) unexpected situations. Loading conditions of the blade are directly linked to hydrodynamic forces, maintenance, operating conditions, and erosion and corrosion effects. The design and manufacturing category mainly represents the mechanical properties of composite materials, the geometry of the blade, and manufacturing process parameters. Therefore, adequate attention should be given for the material selection of the tidal turbine blades. The designing process of composite materials are critical for the structural integrity of the turbine blades.

Similar to the other structures, tidal turbine blades are subject to deterioration during their service life, which significantly compromises the structural integrity of the blade. This results to weakening the composite structure and increased temperature is accelerating the aging process of the turbine blade [39]. Therefore, aging is a critical component to consider when evaluating the fatigue life and residual strength of turbine blades. In addition, tidal power systems can experience unexpected situations, and turbines may have a significant impact from collisions with marine objects or animals such as mammals.

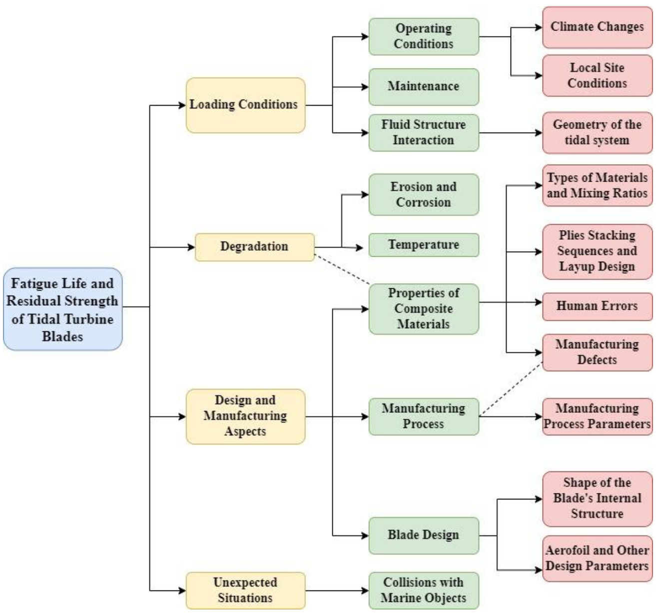


Fig. 4. Parameters linked with fatigue life and residual strength of tidal turbine blades.

Overall, all these parameters must be considered when formulating a mechanism to predict the remaining fatigue life and residual strength of in-service tidal turbine blades, and it is a complex task that helps ensure the safety and reliability of the tidal turbine system. The approaches that can be used to make these predictions, and the specific methodology used will depend on the specific characteristics of the blades, the operating conditions they are subjected to, and the use of appropriate analytical tools and techniques.

Based on the literature information, knowledge, and experience of the authors, the main four impact categories identified related to the prediction of the remaining fatigue life and residual strength of tidal turbine blades are summarised in Fig. 5 and are discussed in the following sections.

*a). Managing the database*

Fig. 4 provides detailed information about the four data categories to be considered for managing a database. A comprehensive site monitoring mechanism is required to identify the operating conditions of the blades, including loads, stresses, and fatigue cycles. However, these parameters are subjected to change based on climate conditions and site topography variations over the time. With reference to the designing and manufacturing processes of the tidal turbine blade, the required material data and geometry of the blade can be obtained, and data is reported by the tidal turbine blade's manufacturer. At the same time, it is required to undertake a comprehensive literature review for identifying the degradation over the service life of tidal turbine blades and record the useful information to predict how the material properties of the blade structures change over. In addition, unexpected disasters or collisions with marine objects and sea mammals can occur to the tidal turbine system at the deployed site and it may create adverse effects on the systems. Therefore, it is beneficial to study the similar and possible situations reported to date in order to minimise the future damages due to these unexpected scenarios. At the same time, it is vital to study the presence of sea mammals in the vicinity of the tidal deployment site at the beginning of the designing stage in order to make required precautions.

*b). Analyse the collected data*

The analysis of the four data categories depicted in

Fig. 4 emphasizes the essential parameters that need to be monitored to ensure continuous operations throughout the entire lifespan of the tidal turbines. Loading conditions and degradation data are subjected to change over the time and it is required to use most updated data for the analysis. In addition, the degradation process is also associated with cavitation erosion, which results in the formation of microcracks on the surface, which has a significant impact on the performance of tidal turbine blades, and relevant data should be investigated [41]. Design and manufacturing data is unique for the tidal turbine system while the data relevant to the unexpected situations can also be estimated approximately based on the past incidents taken place in marine environments. However, the reported unexpected tidal turbine system failures are limited.

*c). Conduct FEA for unused tidal turbine blade*

Based on the data analysis, the input data can be identified for the numerical modelling, and it is required to conduct dynamic, static and fatigue numerical simulations. The results of the numerical simulations can be used to estimate the stress and strain distribution, fatigue life and displacements of the blade. The material properties should be obtained from the material supplier's data sheets and degradation can be neglected for the unused tidal blades.

*d). Compare the FEA results with structural testing outcomes*

It is required to compare the FEA results with field and/or laboratory testing data to validate the numerical modelling. If there were significant deviations, the numerical model should be modified accordingly to corelate the numerical and experimental results or testing data analysing process should be examined thoroughly. This process becomes very critical for the validation method of this research and extra attention must be given for the modifications to the numerical model.

*e). Predict composite material property changes*

Sea water aging and operational characteristic cause to change the material properties of the tidal turbine blades drastically. Temperature fluctuations of the sea water accelerate the degradation of composite blades which results to weaken the structure [39], [42]. At the same time, the residual stresses present on the turbine blade may contribute to the fractures or fatigue failures. In this context, material properties of the tidal turbine blade should be predicted more accurately, in order to identify the structural integrity of the blade using numerical simulations. Therefore, it is required to formulate a mathematical model to forecast the material properties of the tidal turbine blades throughout their lifespan become significant.

*f). Conduct FEA for predicted material properties and compare the results to field and/or laboratory testing data*

Similar to the step (c), numerical simulations should be undertaken for the tidal turbine blade and compared the results to field and/or laboratory testing data for identifying the possible modifications to the mathematical model used to predict the material properties. This process should be continued until both FEA and structural or field data corelating satisfactorily. Incorporating a structural condition monitoring system can add further benefits to the process of monitoring the structural properties of rotor blades during operation.

*g). Develop the model to predict fatigue remaining fatigue life and residual strength of tidal turbine blades*

After successful completion of steps (a)to (f), it is required to formulate the predicting model to estimate the fatigue life and residual strength of tidal turbine blades until their end of service life as represented in Fig. 5

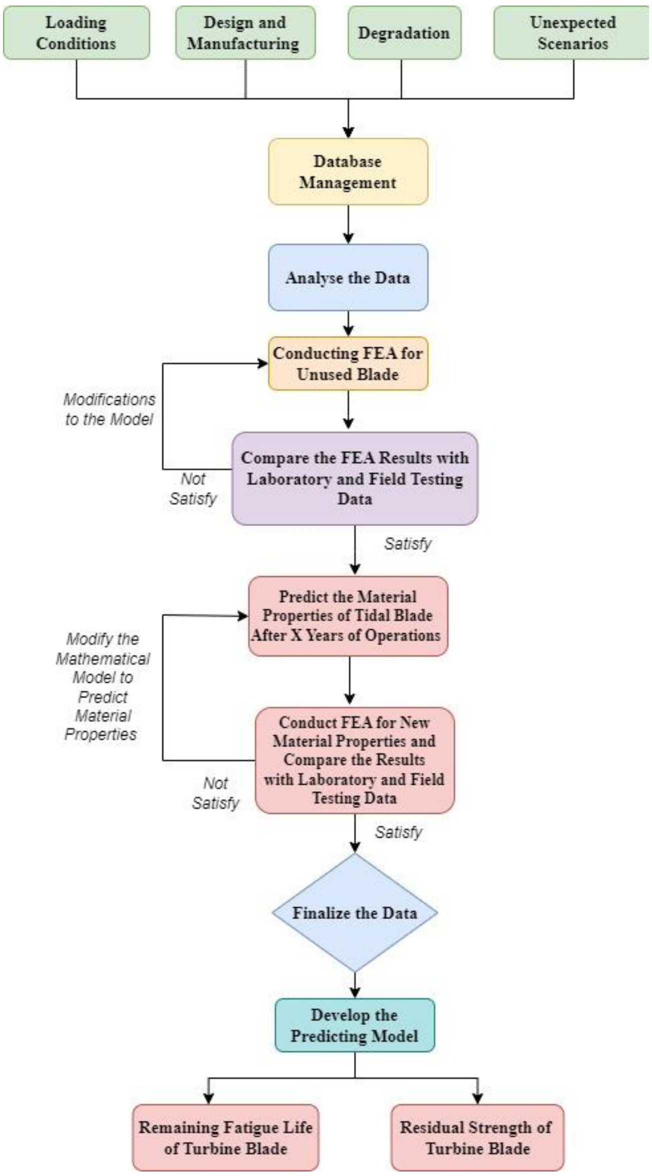


Fig. 5. Proposed strategy for the prediction model development

## IV. CONCLUSION

This study focuses on developing a methodology for predicting the remaining fatigue life and residual strength of tidal turbine blades, during their operational lifespan. Consequently, four main impact categories which decide the life of tidal turbine blades were identified, and the possibility of developing a database to be used with FEA was explored. The database will comprise the data relevant to loading conditions, design and manufacturing, degradation, and unexpected situations of tidal turbine blades. A validation process was then proposed to compare the FEA results with the field and laboratory test data in different stages of the tidal turbine blade. Finally, with the literature information, experience, and knowledge in the field, a strategy was identified to forecast the structural properties of tidal turbine blades throughout their service life. The next stage of the research is the prediction model, which will be developed based on the strategy presented in this paper.

This prediction model will help to reduce the risk associated with tidal energy devices in operation, as it provides a better indication of the remaining structural life of the tidal turbine blades, using improved vulnerability curves. The knock-on effects of de-risking the tidal turbine blades is expected to see more investment in the tidal energy sector, while improving the efficiency of the technology making it less costly, and, ultimately, reducing the levelised cost of tidal energy.

## ACKNOWLEDGEMENT

This work has been funded through the TIDAL-GES project of the University of Galway Global Challenges Programme. The research is also supported by Science Foundation Ireland (SFI) through MaREI Research Centre for Energy, Climate and Marine (Grant no.12/RC/2302_2) and the Sustainable Energy Authority of Ireland (Grant no. 22/RDD/783).

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