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De-risking the next generation of tidal turbine blades through advanced full-scale structural testing

William Finnegan, Yadong Jiang, Patrick Meier, Le Chi Hung, Conor Glennon and Jamie Goggins

Abstract—Renewable energy is now viewed as being the preferred alternative to electricity generation from fossil fuels. In recent years, tidal energy has shown promise as it is a more reliable source of renewable energy, compared to wind and solar, where 15 GWh of electricity from tidal energy was generated in 2019. As tidal technologies move closer to commercial viability, key components will now need to be certified. One such key component that will need to be type-certified for tidal energy is the turbine blades. Structural testing of these blades will be a central aspect in this certification. Therefore, in this paper, methodology for de-risking the next generation of tidal turbine blades through structural testing in line with international standards is presented. This methodology has been applied to a number of tidal turbine blade testing programmes at the Large Structures Research Laboratory at NUI Galway, where three case studies of three different turbine blades have been presented in this paper: (1) a large blade for a 1MW rotor; (2) a small blade for a 70kW rotor; and (3) a helix foil for a novel 50kW marine turbine. A discussion on each test, along with selected static test results, has been included in the paper, along with a final conclusion on the impact of structural testing on the development of tidal energy.

Keywords—Blades, Fibre reinforced composites, Structural testing, Tidal energy.

I. INTRODUCTION

As the world shifts its reliance from fossil fuels to renewable energy, a reliable, predictable and

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dependable source of energy is vital; tidal energy provides such a solution. In 2019, the installed capacity of tidal stream energy in Europe reached 27.7 MW [1], which is almost four times as much as the rest of the world. The increase in the cumulative installed capacity of tidal stream energy in Europe from 2010-2019 is shown in Fig. 1. While the total electricity produced in Europe from tidal energy increased by 15 GWh to a total to date of 49 GWh [1]. The tidal turbine blades convert the energy in the tidal current to useful mechanical energy that can be converted to electricity. Therefore, the reliability of the blades is paramount to the success for the turbine.

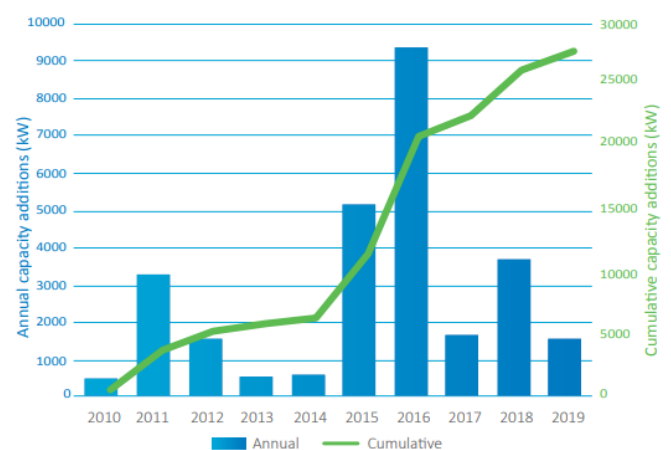


Fig. 1 Annual and cumulative tidal stream capacity (in kW) in Europe 2010-2019 [1].

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In recent years, as tidal energy reaches commercial viability, there has been an increase in this rigorous structural testing of blades in order to de-risk them in advance of their operational deployment. The Large Structures Research Laboratory, which is operated by the Sustainable & Resilient Structures Research Group (<https://www.nuigalway.ie/structures/>) in the SFI MaREI Research Centre at NUI Galway, is the World's leading facility for the structural testing of tidal turbine blades having completed tests for Orbital Marine Power, ORPC, Openhydro, Siemens and Schottel. The first major tidal component testing was conducted for a 3/8th scale blade and rotor subsection for the OpenHydro prototype tidal turbine [2]. In 2020, a static and fatigue testing programme was completed on a helical foil for the ORPC device [3] and an advanced structural testing programme was completed on a full-scale blade for the Orbital Marine Power tidal turbine, where fatigue cycles for the equivalent of 25 years operation were completed on the blade. During the static testing of the latter, the largest load ever reported on a tidal energy turbine blade was applied, which was in excess of 1,000kN [4]. In 2021, a fatigue testing programme was completed on a prototype Schottel blade for a 70kW tidal turbine, where the blade underwent fatigue loading that was equivalent to 20 years of operation. In parallel to building their testing capacities, the Research Group in the SFI MaREI Centre has also developed a range of advanced computational design methodologies for tidal turbine blades [5-8], which are based on finite-element analysis and computational fluid dynamics, along with an in-house composites design optimisation software, BladeComp [9].

In this paper, the methodology used for advanced structural testing to de-risk full-scale tidal turbine blades, along with the relevant testing standards and specifications, is presented. A number of case study examples of testing programmes, which were performed at the Large Structures Research Laboratory at the NUI Galway, have been used to illustrate the discussions. These full-scale tidal turbine blades have been tested at the facility using a novel multi-actuator load introduction system, which is mounted on a modular testing frame that is anchored to a strong floor. A discussion on each test has been included in the paper, along with a final conclusion on the impact of structural testing on the development of tidal energy.

II. MATERIALS AND METHODS

A. Aim and objectives

The overall aim of this study is to present a robust methodology to de-risk the next generation of tidal turbine blades through a series of structural testing. This testing is essential to ensure that blades, in particular their design and manufacture, are resilient enough to survive their design life, which is typically in excess of 20 years. However, in order to achieve the aim of the study, a number of objectives must be achieved:

- To develop a rigorous and repeatable testing procedure in line with technical standards and specifications.
- To validate the testing procedure through static, dynamic and fatigue **mechanical testing**.
- To de-risk the strength of the blade under extreme load conditions through static **mechanical testing**.
- To de-risk its structural integrity over the design life of the blade through **fatigue mechanical testing**.

B. Methodology

This paper presents a high-level overview of the requirements for the structural testing of tidal turbine blades. In order to illustrate this, along with the versatility of the testing facilities, three case studies are presented for three different turbine systems:

- A large blade for a 1MW rotor
- A small blade for a 70kW rotor
- A helix foil for a novel 50kW marine turbine

These three case studies are shown in Fig. 2, Fig. 4 and Fig. 6, respectively, which shows the blade installed for testing at the Large Structures Research Laboratory.

The structural testing is performed in line with the DNV-GL and IEC standards, which is discussed in the next section, where the main stages are broadly as follows:

- Dynamic testing – evaluates the natural frequencies, stiffness and associated damping of the blade.
- Static testing – determines the strength (and strength distribution) of the blade.
- Fatigue testing – establishes if the blade can withstand the operational loads over its design life (typically >20 years for tidal blades).
- Residual strength testing – quantifies the remaining strength in the blade after fatigue testing, as well as the change in stiffness.

In advanced of each testing programme, a detailed bespoke test procedure for performing the structural testing is designed, in line with the DNVGL-ST-0164 standard, in conjunction with the blade developer, along with the necessary safety documentation for the test. This is to ensure the efficient and accurate transfer of information during the testing programme.

For case studies detailed in this paper, only results from the static testing programmes are presented, for brevity.

C. Technical standards and specifications

In order to ensure that the research is performed to the highest of standards by the Sustainable & Resilient Structures Research Group, the physical testing performed by the group is done in accordance with the relevant technical standards, which are set out by ISO, IEC, DNV GL and ASTM. For structural testing for renewable energy applications, the relevant standards set out by DNV GL and IEC are adhered to in the testing laboratory. Therefore, the **mechanical static and fatigue testing** of tidal turbine blades are performed in accordance to DNVGL-ST-0164

‘Tidal turbines – Rules and standards’ [10] and IEC 62600-3:2020 ‘Marine energy – Part 3 Measurement of mechanical loads’ [11].

D. Testing facilities

The testing facilities described in this paper is the Large Structures Research Laboratory, which is the world-leading tidal turbine structural testing laboratory. The facility at NUI Galway consists of a 375 m² state-of-the-art high-bay laboratory, with a novel multi-actuator load introduction system, which is mounted on a modular testing frame that is anchored to a strong floor (with anchor points at 500-1000 mm centres each having a capacity of 500 kN), which are well represented in the image in Fig. 2. This modular setup within the laboratory allows for flexible testing of small to large structural and mechanical elements and materials. Some of the key testing technologies in the laboratory include:

- servo-hydraulic testing machines with capacities ranging from 10 kN to 750 kN,
- hydraulic ring main with a maximum pressure of 207 bar, with a flow capacity of 180 lpm,
- an advanced data acquisition systems and sensors for measurement of load, deformation, strain and acceleration,
- advanced videometric and optical metric measuring systems, including 3D digital image correlation system, 3D laser scanner and laser scanning vibrometer.

III. RESULTS: CASE STUDIES

Three case studies are described briefly in this section in order to demonstrate the structural testing methodology developed at the Large Structures Research Laboratory.

E. Structural testing of a large tidal blade

The first case study involves the structural testing of a blade designed for the Orbital Marine Power O2-2000 tidal turbine [12]. The O2-2000 tidal turbine is being deployed in the Fall of Warness at the European Marine Energy Centre (EMEC) in 2021, where tidal speeds can exceed 3m/s. It will be connected to the local electricity grid and will help power the communities of Orkney cleanly and sustainably from the waters that flow past their islands. The previous generation of this device achieved a world record delivery of over 3.2 GWh of tidal stream power to the UK grid.

In this study, a blade designed for the O2-2000, which is approximately 8 metres in length with a mass of approximately 4.5 tonnes, underwent a rigorous static and fatigue testing programme in order to validate a 20-year design life for the blade design, resulting in more reliable blades that will lead to reduced maintenance and increased productivity and revenue.

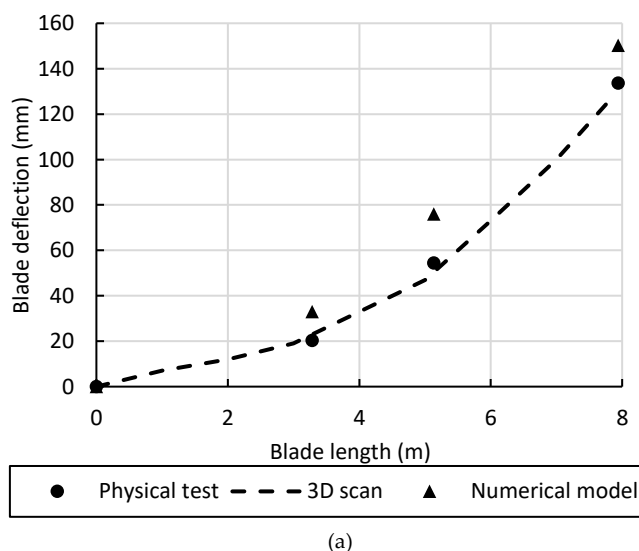
For this testing programme, 3 actuators were used in conjunction with 5 contact pads to impose the loading vertically downward on the blade, which can be seen in

Fig. 2. The blade was integrated into the testing laboratory using a large support frame to attach the root to the strong floor.



Fig. 2 A large tidal blade installed at the Large Structures Testing Laboratory undergoing structural testing using the multi actuator load introduction system.

Initially, dynamic testing was performed on the blade to determine its flapwise, edgewise and torsional natural frequencies, along with the associated blade damping. Following this, a static testing programme was completed on the blade to ensure it had the strength required to withstand the maximum loads envisaged. During the static testing campaign, the maximum load imparted on the blade was 1,008 kN, which is the largest load ever reported on a tidal blade in the world – a milestone for the tidal energy sector. The blade deflection and strains along the spar caps measured under this maximum static load is presented, where the tip deflection was 133 mm, which includes any movement of the support frame, and the maximum strain observed was approximately $\pm 1.97 \times 10^{-3}$.



(a)

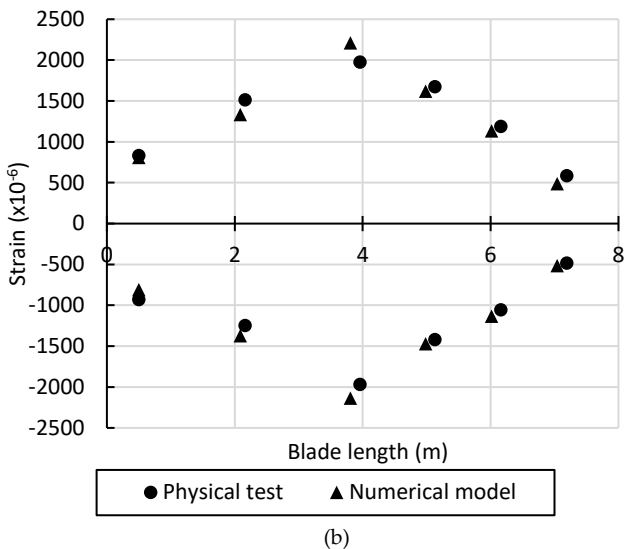


Fig. 3 Selected testing results from the structural testing of a large tidal blade under the maximum static load, showing (a) the blade deflection and (b) the strain at the outer surface along the spar caps along the length of the blade.

Following the completion of the static testing programme, a fatigue testing programme of over 300,000 cycles was completed on the blade, which is the equivalent of over 20 years operation for the blade. A residual strength test was performed that showed that there was no significant change due to the fatigue loading, when compared to the results from the initial static tests. Thus, proving the resilience of the blade, along with its design and manufacture, over its design life. This blade is the largest blade ever tested in to its full fatigue design life.

F. Structural testing of a small tidal blade

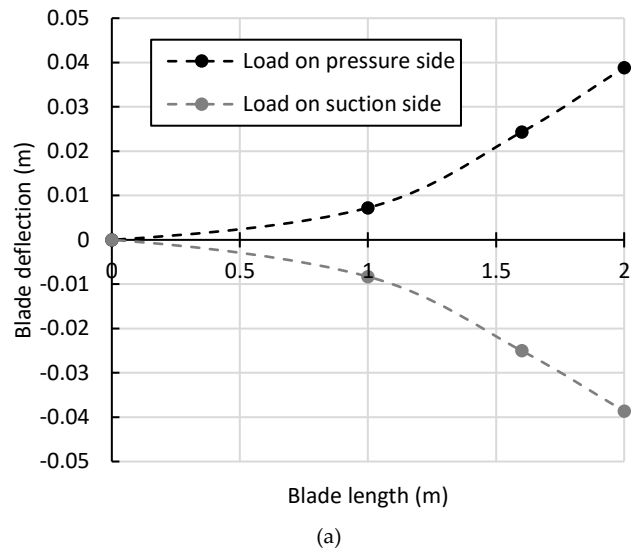
The second case study explores the structural testing of a small tidal blade using a single actuator. For this case study, one of the prototype Schottel blades for a 70kW tidal turbine is examined, which is shown in Fig. 4. For this test, the blade was mounted on its hub, along with 2 dummy blade roots, and attached to the strong floor of the testing laboratory with a strong base fixture. A single actuator was mounted at a 11° angle near the tip of the 2 metre blade (at a distance of 1.6m from the centre of the hub) to impart loads on the suction side and pressure sides of the blade.

The main aim of this study was to investigate if the blade had the capacity to withstand equivalent mechanical loading that represented its 20 year design life. Therefore, the fatigue testing programme was of main concern to the developer.



Fig. 4 A small tidal blade installed at the Large Structures Testing Laboratory undergoing structural testing using a single actuator.

Similar to the first case study, a dynamic testing was performed on the blade to determine its flapwise and torsional natural frequencies, along with the flapwise damping of the blade. In order to obtain the baseline strength and stiffness for blade, initial static tests were performed. The blade deflection and strains at the monitoring points on the blade when it is loaded on the pressure and suction sides, respectively, are shown in Fig. 5. The blade performed very similar in both directions, which is evident from the tip deflection at the maximum load of approximately ±39mm.



(a)

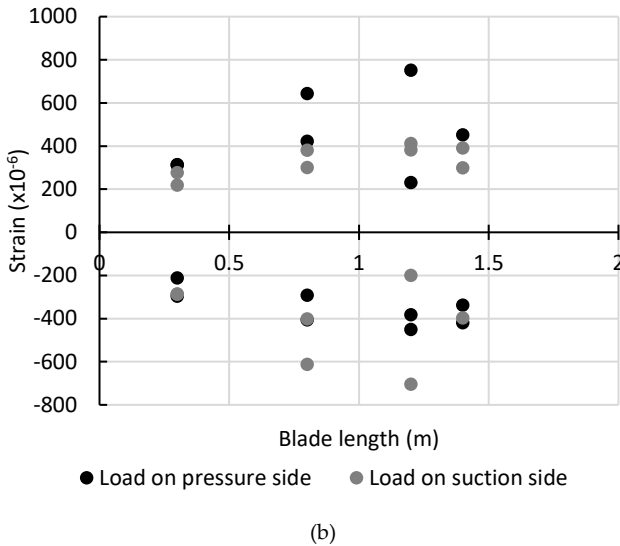


Fig. 5 Selected testing results from the structural testing of a small tidal blade when loaded on the pressure side and suction side, showing (a) the blade deflection and (b) the strain at the outer surface along the length of the blade for the two test conditions.

Following this, a fatigue testing programme, which consisted of 150,000 cycles, was completed on the blade that proved its structural integrity over the equivalent of 20 years operation. A residual strength test was performed to ensure that there was no significant change in the blade stiffness due to the fatigue loading, when compared to the initial static tests.

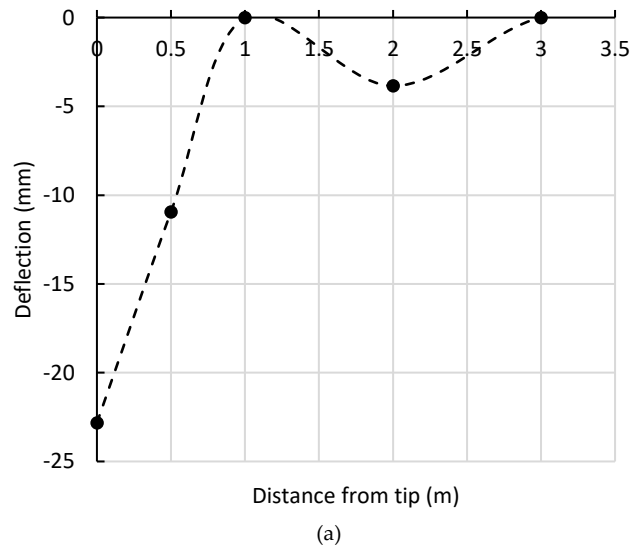
G. Structural testing of a helical foil for a tidal turbine

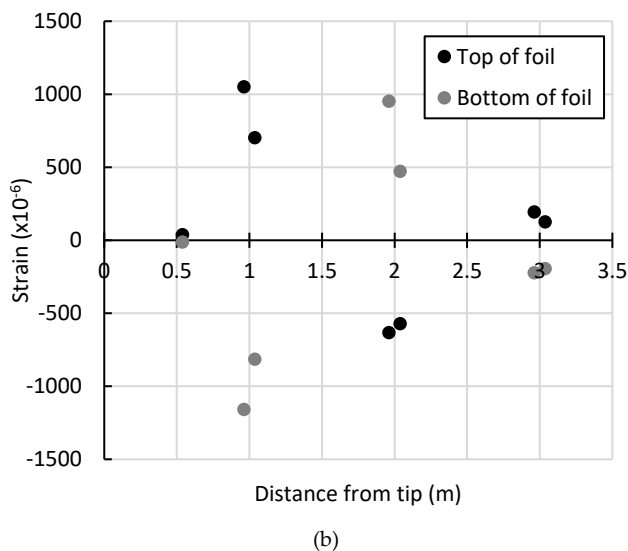
The third case study investigates the structural testing of a helical foil for a novel 50kW marine turbine, which is a power system that generates emission-free electricity from river currents and connects directly into existing remote community grids using smart grid technology. The structural testing programme for a single prototype helical foil was performed using two vertical actuators, as shown in Fig. 6. The actuator at the cantilever section was attached directly to the foil, while the actuator at the mid-span section used a wire rope connection to load the foil towards the centre of rotation. A comprehensive set of static tests, along with low-cycle fatigue testing, was performed. The full details of the results from this testing programme for the device are given in [3].



Fig. 6 A helical foil installed at the Large Structures Testing Laboratory undergoing structural testing using two actuators.

A comprehensive static testing programme was first completed on the helical foil, where the deflection and strain along the foil under the maximum static load profile is given in Fig. 7. The maximum deflection is at the cantilever tip of the blade of 23 mm, where the mid-span deflection was approximately 4 mm. The maximum strain on the foil is approximately -1.2×10^{-3} in compression and approximately 1.05×10^{-3} in tension. These strains aligned well with the predictions used in the foil design and were lower than the conservative strains given in the DNVGL-ST-0164 standard.





(b)
Fig. 7 Selected testing results from the structural testing of a helical foil under the maximum static load, showing (a) the foil deflection and (b) the strain at the top and bottom outer surfaces along the length of the foil.

In addition to the static testing programme, a low-cycle fatigue test was performed on the foil for 35,000 cycles, which ensured that the blade had the structural resilience to withstand the operational trials period. Once the testing on the foil was complete, the turbine went into production and has since been deployed at a location that provides power to the remote Alaskan village of Igiugig.

IV. CONCLUSION

In this paper, the methodology used for advanced structural testing to de-risk full-scale tidal turbine blades, along with the relevant testing standards and specifications, was presented. Three case study examples of testing programmes for three different tidal turbines, which were performed at the Large Structures Research Laboratory at the NUI Galway, were used to illustrate the methodology, where a discussion on each test was included. For each of these tests, a static testing programme was completed to ensure the strength and stiffness of the blades were sufficient to withstand the maximum expected loading, along with a fatigue testing programme to ensure the blade structure can resist the operational loading for the design life in excess of 20 years. A key achievement to date is the static load of 1,008 kN, which is the largest load ever reported on a tidal blade in the world – a milestone for the tidal energy sector.

The de-risking of tidal turbine blades through structural testing will result in more reliable blades that will lead to reduced maintenance and increased productivity and revenue, in turn reducing the commercial risks associated with tidal energy. The overall impact will be a reduced levelized cost of tidal energy for the European citizen as we move to a more sustainable way of living.

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