Observations from structural testing of full-scale tidal turbine blades

William Finnegan, Yadong Jiang, Conor Glennon, Michael Flanagan and Jamie Goggins

Abstract—**In recent years, tidal energy has emerged as a potential key player in future energy security, as it provides a reliable, predictable and dependable source of renewable energy, where, in 2022, the cumulative installed capacity of tidal stream energy in Europe, since 2010, reached 30.2 MW. As tidal energy strives towards commercial viability, optimisation of structural components, along with their de-risking through structural testing, has become more prevalent. Full-scale structural testing of tidal turbine blades provides a mechanism to ensure the blades can withstand the high operational loads when deployed, in a controlled laboratory environment. In recent years, this type of testing has been used to de-risk prototype blades in advance of operational trials. However, a limited number of these tests have been performed globally. Therefore, in this paper, observations during the structural (static, dynamic and fatigue) testing of 5 full-scale tidal turbine blades are presented and discussed. The length of these blades range from 2-8 metres, for devices of 70kW to 2MW. A case study of a large blade from a 2MW floating tidal turbine has been used to illustrate some of the results obtained from the structural testing. The experience gained from these structural testing programmes highlighted a number of best practices that could be introduced to the next revision of both the IEC 62600-3:2020 test specification and the DNV-ST-0164 standard.**

Keywords— **Fatigue, Fibre Reinforced Composite, Static, Structural Testing, Tidal Energy.**

I. INTRODUCTION

As the world shifts its reliance from fossil fuels to renewable energy, a reliable, predictable and dependable source of energy is vital; tidal energy provides such a solution. In 2022, the cumulative installed capacity of tidal stream energy in Europe, since 2010, reached 30.2 MW [1], which is roughly three times as much as the rest of the world. The total electricity produced in Europe from tidal energy increased by 8 GWh to a total of 68 GWh to date [1]. In recent years, a number of large multi-MW tidal installation have taken place, demonstrating that the tidal energy sector is nearing commercial viability. Orbital Marine Power deployed world largest two rotor 2MW floating tidal turbine in 2021 [2] and SIMEC Atlantis Energy Limited deployed world's largest 2 MW single rotor tidal turbine in 2022, where the "MeyGen" project recorded 50 GWh generation in 2022 [3].

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. Structural testing of composite tidal turbine blades is performed to ensure the design and manufacturing processes [4] produce a reliable component that performs for its design life span. In recent years, a number of structural testing programmes have been performed on full-scale tidal turbine blades, as the sector strives for commercial viability. Although the

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methods used to test the tidal turbine blades are similar to those used for wind turbine blades, in recent years, tidal turbine blades standards (DNV-GL-ST-0164 and IEC TS 62600-3:2020) have been developed to test them as differing challenges exist, due to the higher loadings on stiffer tidal turbine blades compared to their wind energy counterparts.

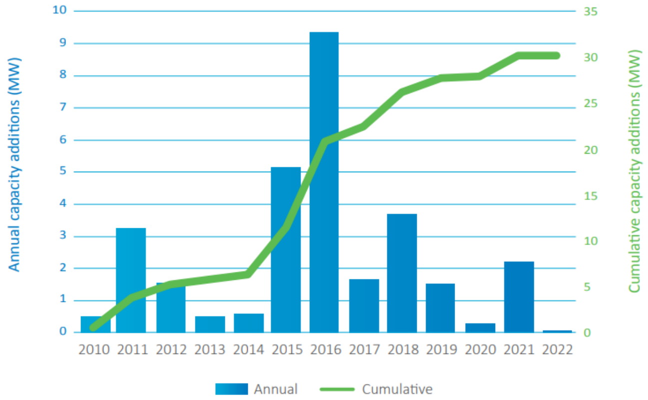


Fig. 1 Overview of the annual and cumulative tidal stream capacity in Europe [1]

In this paper, observations during the structural (static, dynamic and fatigue) testing of full-scale tidal turbine blades are presented and discussed. These observations have been made from 5 testing campaigns on full-scale tidal turbine blades at the Large Structures Testing Laboratory in the SFI MaREI centre in the University of Galway. The length of these blades range from 2-8 metres, for devices of 70kW to 2MW, where they are summarised in Table I. A case study of a large blade from a 2MW floating tidal turbine has been used to illustrate some of the results obtained from the structural testing. The experience gained from these structural testing programmes highlighted a number of best practices that could be introduced to the next revision of both the IEC 62600-3:2020 test specification and the DNV-ST-0164 standard, which are discussed in Section IV of this paper.

II. MATERIALS AND METHODS

A. *Aim and objectives*

The overall aim of this study is to discuss the main observations made during the structural testing of full-scale tidal turbine blades. These observations have been made from 5 testing campaigns on full-scale tidal turbine blades, which included static, dynamic and fatigue testing programmes. A brief overview of these testing campaigns are presented in Table I. However, in order to achieve this aim, the following objectives need to be completed:

- To present an overview for the 5 testing campaigns
- To analyse the data collected from each of these campaigns, where key results from one of the testing is presented in Section III, as a case study.
- To critically discuss the main observations made across a range of aspects of the testing programme

TABLE I
SUMMARY OF THE TIDAL TURBINE BLADE/FOIL TESTING CAMPAIGNS REFERENCED IN THIS PAPER

Type	Company	Length
Prototype full-scale RivGen foil	ORPC Ireland	5 metres
Prototype full-scale blade	Orbital Marine Power	8 metres
Full-scale blade	Schottel HYDRO	2 metres
Vertical axis foil	GKinetic	3 metres
Next generation tidal foil	ORPC Ireland	5 metres

B. *Structural testing overview*

Structural testing of tidal turbine blades is performed in line with the DNV-GL-ST-0164 standard [5] and IEC TS 62600-3:2020 test specifications [6], where the main stages can be broadly categorised into the following tests:

- Dynamic testing – this test is performed using accelerometers to evaluate the natural frequencies, stiffness and associated damping of the blade.
- Static testing – applied the maximum static design load to determine the strength (and strength distribution) of the blade.
- Fatigue testing – performed where a cyclical load is applied to the blade to establish if it can withstand the operational loads over its design life (typically in excess of 20 years for most of the current generation of tidal turbines).
- Residual strength testing – this is performed to quantify the remaining strength in the blade after fatigue testing, as well as the change in stiffness, by applying a static load.

In advance of testing programme, a test procedure is specified in line with DNV-GL-ST-0164 and IEC TS 62600-3:2020 and agreed with all parties. This procedure also includes all of the H&S documentation specific to the test, along with templates for record-keeping during the testing.

C. *Case study*

In order to present an insight into the results obtained from structural testing of full-scale tidal turbine blades, a single case study has been selected. The case study selected involves the static, dynamic and fatigue testing of a blade designed for the Orbital Marine Power O2-2000 tidal turbine [2].

The O2-2000 tidal turbine was deployed in the Fall of Warness at the European Marine Energy Centre (EMEC) in 2021, where it is said to be the “most powerful tidal turbine in the world”. The tidal speeds can exceed 3m/s at EMEC and the device is connected to the local electricity grid, where it will help power the communities of Orkney, moving to a more sustainable energy source that takes advantage of 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 [2].

The blade, itself, was approximately 8 metres in length with a mass of approximately 4.5 tonnes and it was designed with the aid of numerical model, developed using the BladeComp software [7], in order to optimise the composite make-up. Only the structural parts of the blade, i.e. the spar caps, webs, root section and skin, were tested and a flared trailing edge and aerodynamic tip section would be added when in operation.

The testing programme used a multi-actuator load introduction system, which consisted of 3 actuators that spread the load over 5 contact pads, to impose the desired loading vertically downward on the blade. The load, which was derived from the previous operational trials, has been distributed over the length of the blade to replicate what it will experience when in operation. This system can be seen in Fig. 2.

The blade was integrated into the large structures testing laboratory using a large steel support frame to attach the root to the strong floor, which was designed to withstand a moment at the blade root in excess of 6,000 kNm.

The test loads on the blade were defined by the tidal turbine developer, which were determined through a combination of computational fluid dynamics modelling of the turbine, previously laboratory-scale testing and through observations from a previous generation of the tidal turbine, which had undergone operational trials for a one year period. For the static test, the maximum design load was imparted onto the blade, while, for the fatigue testing, a 'typical' operational load and a scaled version was used to demonstrate the performance of the blade over its 20-year operational design life.

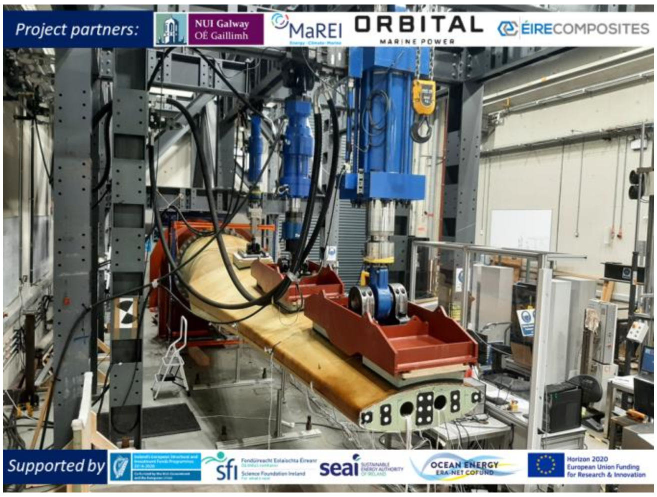
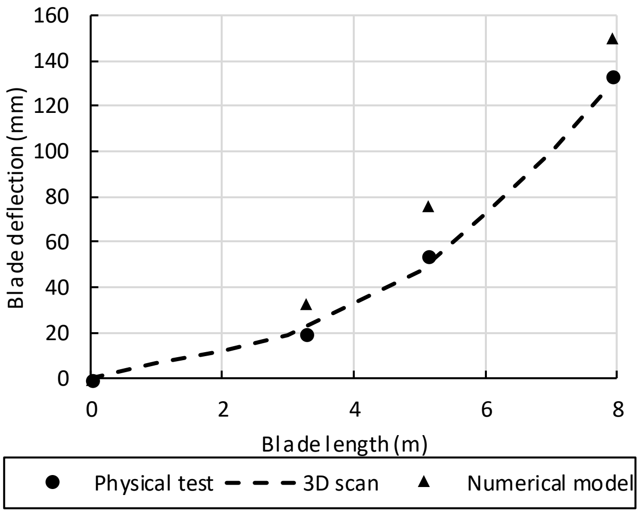


Fig. 2 A large tidal blade installed at the Large Structures Testing Laboratory undergoing structural testing using the multi actuator load introduction system.

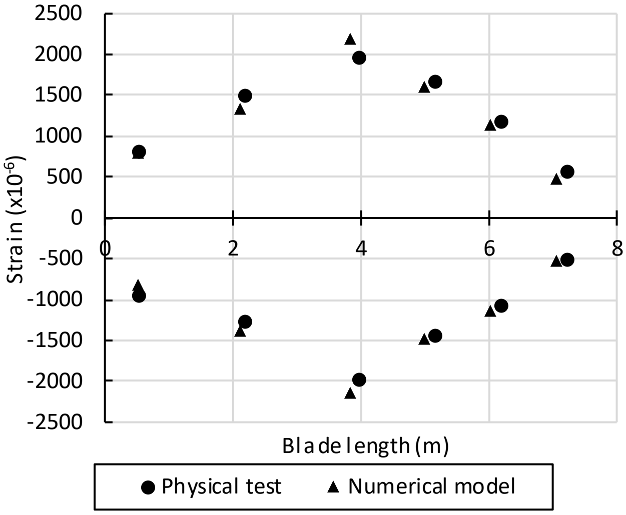
III. TESTING RESULTS

Selected results from the structural testing of the case study tidal turbine blade are presented in this section to illustrate a sample of the results obtained from the static testing of a full-scale tidal turbine blade. These results help to inform the observations made in Section IV.

Initially, dynamic testing was performed on the blade to determine it's 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 in Fig. 3, where the tip deflection was 133 mm, which includes any movement of the support frame, and the maximum strain observed was approximately ±1.97x10^{-3}. The results from the experimental testing programme has been compared to the predictions from the numerical model, which was used in the blade design, where these are in good agreement. Therefore, the results from this testing programme validate the accuracy of the BladeComp software, giving greater confidence when designing large composite structures in the future. Further details on the model that was developed using BladeComp for this tidal turbine blade can be found in Jiang et al. [8].



(a)



(b)

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, in line with the design life of the tidal turbine. A residual strength test was then performed, where the 100% static load was applied to the tidal turbine blade, along with a dynamic check to detect if there was any change in the natural frequencies of the blade. The results of the residual strength test 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 it design and manufacture, over its design life. This blade is the largest blade ever tested in to its full fatigue design life.

IV. DISCUSSION AND OBSERVATIONS

The experience gained from the structural testing programmes, summarised in Table I, highlighted a number of best practices that could be introduced to the next revision of both the IEC 62600-3:2020 test specification and the DNV-ST-0164 standard, which are discussed in this section.

D. Test setup

Restricting movement and rotations at the blade support point is a significant challenge during the test setup. Therefore, it is essential to monitor any displacements that may occur during testing to ensure that all movements may be captured when post-processing the response of the blade. This may be performed using displacement sensors (such as linear variable differential transformers (LVDTs) or string potentiometers) and/or a digital image correlation system.

E. Combined flapwise-edgewise loading

Depending on the loading requirements for the test, a combined flapwise-edgewise loading for static and fatigue testing may be preferable. For tidal turbine blades, the critical loading direction is the flapwise direction. The DNVGL-ST-0164 standard allows for edgewise loading to be omitted if not critical and the IEC 62600-3:2020 test specification specifies testing the static blade root edgewise bending moment as "Recommended". The main advantage of using the combined loading is a reduced requirement on laboratory test time, due to complexity of installation and test set-up, where only a single installation would be required. However, the use of the combined loading would need to be assessed depending on the test, in particular the significance of the edgewise loading.

F. Test load distribution

In operation, there is a distributed load on the blade. Therefore, this should be replicated, where both the bending moment and shear force profiles along the length of the blade are matched during testing. This may be achieved using a multi-actuator system to impart the hydraulic load on the blade that uses series actuators. The load could be transferred over more locations through contact pads, where the load from a single actuator is split across two or more locations, as can be seen in Fig. 2. For example, on the 8-metre tidal blade test, 3 actuators were used that imparted the load through 5 contact pads. However, for shorter blade lengths, a single loading point or rotating mass system may only be possible. During the test design, the shear force diagrams are compared between the desired test load and the actual test load in order to determine the number of contact points required to limit shear loads.

G. Static test duration

The DNVGL-ST-0164 standard states a minimum duration of 10 seconds and the IEC 62600-3:2020 test specification states a minimum duration of 30 seconds. However, it also states "for TECs the recommended minimum duration of the test load is 6 hours". The design loads have short durations so 30 seconds is acceptable. However, a 6-hour test was performed (detailed in Finnegan et al. [9]) and found that no significant changes occur over this duration.

H. Fatigue testing

Depending on the loading requirement, a rotating mass may be suitable. If there are large loads on longer blades, then actuators are more suitable. The main limitation is the large number of cycles that may be required. For example, at 0.25 Hz, it would take approximately 12 weeks to complete 1,000,000 fatigue testing cycles, allowing for daily checks and running the testing from Monday to Friday. Therefore, the average operational load is scaled using the S-N curve for the blade material, which is derived from material testing, so that a reasonable number of cycles can be defined.

I. *Design strain limits*

As part of the tidal turbine blade design (Section 7.8.2.4) in the DNVGL-ST-0164 standard, it is advised that a conservative estimate for the maximum strain on glass-fibre reinforced epoxy laminates is a tensile strain of ≤ 0.35% and a compressive strain of ≤ |0.25%|. Based on the observations within 8-metre tidal blade test programme, these conservative limits are in good agreement with the values observed at the maximum design static loads on the blade.

V. CONCLUSION

This paper presents the observations made during the structural (static, dynamic and fatigue) testing of 5 full-scale tidal turbine blades, where the length of these blades range from 2-8 metres, for devices of 70kW to 2MW. A case study of a large blade from a 2MW floating tidal turbine has been used to illustrate some of the results obtained from the structural testing.

Full-scale structural testing of tidal turbine blades is essential for de-risking new design iterations in advance of deployment, in order to ensure the blades have the required structural integrity (through static testing) and can withstand operational loading over their design life (through fatigue testing). In addition, the connection of roots and struts to the blades and foils can also be de-risked during these testing campaigns. These testing programmes are completed in order to improve the reliability of tidal blades, allowing developers to deploy their devices for operational trials. This, in turn, will lead to reduced maintenance and increased productivity and revenue, as it helps to de-risk tidal energy technology aiding in lowering the levelised cost of tidal energy.

In addition, the experience gained from the structural testing programmes, discussed in this paper, highlights a number of best practices that could be introduced to the next revision of both the IEC 62600-3:2020 test specification and the DNV-ST-0164 standard, which benefits all of the tidal energy sector.

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