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Review

A State-of-the-Art Review of Structural Testing of Tidal Turbine Blades

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Abstract: Over the last two decades, the tidal energy industry has laid the groundwork for creating commercially viable tidal power generation projects to strengthen sustainable energy policies around the world. At the end of 2021, the cumulative installation of tidal stream technology that has been deployed in Europe reached 30.2 MW, where the majority of the installations are by small and medium-sized companies. Due to a growing demand among investors related to the global tidal energy industry, the reliability and safety of operational-stage tidal energy systems' components are becoming increasingly important. In this context, companies, universities and research institutes are focusing on conducting large- and small-scale tests of tidal turbine elements to validate their projected design life, and major attention is being given to assessing the structural integrity of turbine blades. This review paper focuses on structural tests that have been reported for axial flow tidal turbine blades manufactured using composite materials around the world, highlighting the testing standards, equipment and instrumentation required. Overall, this review article discusses the state of the art in the structural testing of tidal turbine blades. In addition, it highlights the global concerns and research gaps to ensure the long-term sustainability of axial flow tidal turbine blades. In addition, the information contained in this article will be useful for formulating a smooth and reliable mechanism to enhance the evaluation process of the structural properties of tidal turbine blades in the future.

Keywords: structural testing; tidal energy; structural integrity; full-scale testing

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1. Introduction

The total potential of tidal energy is predicted to be 3000 GW, and nearly 1000 GW is available in shallow waters [1]. As of the end of 2021, the cumulative installation of tidal stream technology that has been deployed in Europe since 2010 has reached 30.2 MW [2]. Figure 1 illustrates regions with relatively high tidal energy potentials around the globe [3]. Since tidal energy can be predicted more accurately than some other renewable energy sources, tidal energy industries are expected to invest in large-scale projects to enhance sustainable electricity generation. To motivate the industry, several demonstration projects have been carried out to illustrate the feasibility of capturing the energy from the tides generated by sea currents. This includes a few breakthroughs that have been achieved with the successful commissioning of several MW tidal turbine projects in the world. In line with these successful stories, in 2021 Orbital Marine Power (formerly Scotrenewables) deployed the world's largest two-rotor 2 MW floating tidal turbine, "Orbital O2", while in 2019 SIMEC Atlantis Energy Limited deployed the world's largest 2 MW single-rotor tidal turbine, "AR 2000" [4–7]. In addition, the "MeyGen" tidal project, which is operated by SIMEC Atlantis, recorded 50 GWh generation in 2022, and it can be identified as a remarkable achievement by the European tidal energy sector [5]. Moreover, Figure 2 illustrates the number of tidal energy converter (TEC) deployment projects per year from 2003 to 2020 [8]. Throughout this period, there have been fluctuations in the deployment patterns of tidal turbines, with nine reported deployments in 2018. The scattered distribution of these deployments can be attributed to multiple factors, such as the absence of sufficient technological advancements to accommodate different capacities and adapt to varying site topographies, economic considerations, environmental regulations, challenges related to grid infrastructure and interconnection, and the limited availability of viable tidal resources [9,10]. Moreover, the strategy of tidal energy companies prioritizing large-scale projects while reducing the number of small deployments could also be considered a significant factor contributing to this varied deployment [6,11]. On the other hand, these large-scale projects highlight that the development of TECs is backed by commercial interests with the support of extensive modelling and testing programs carried out by several world-leading research organizations.

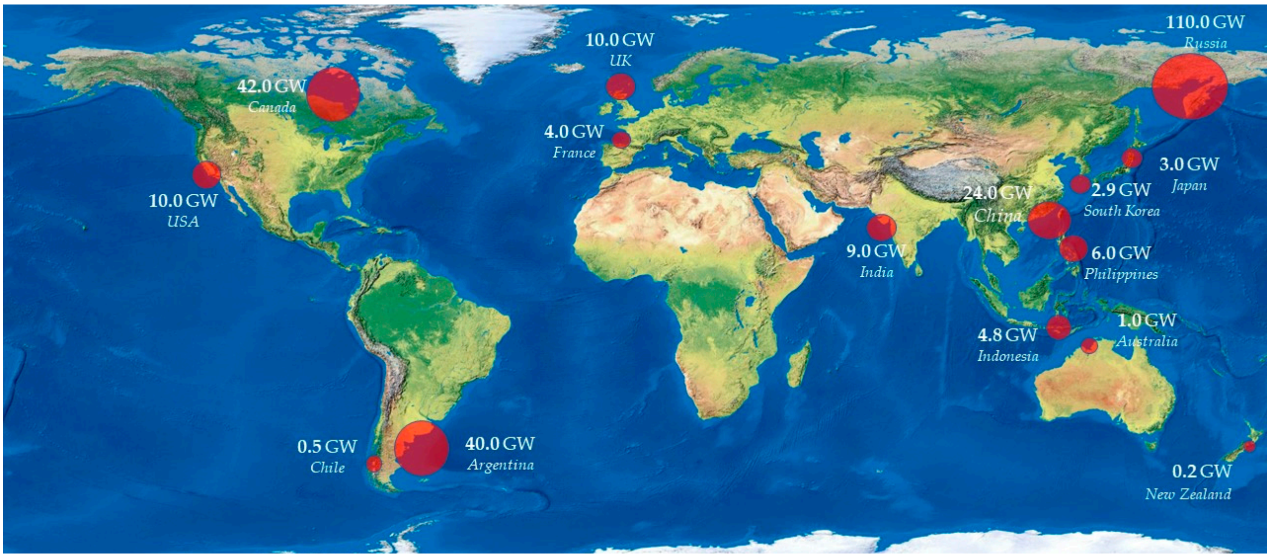

Figure 1. Tidal energy potential in the world. Note that size of red dots indicates magnitude of tidal energy potential at that location. Adapted from: [3].

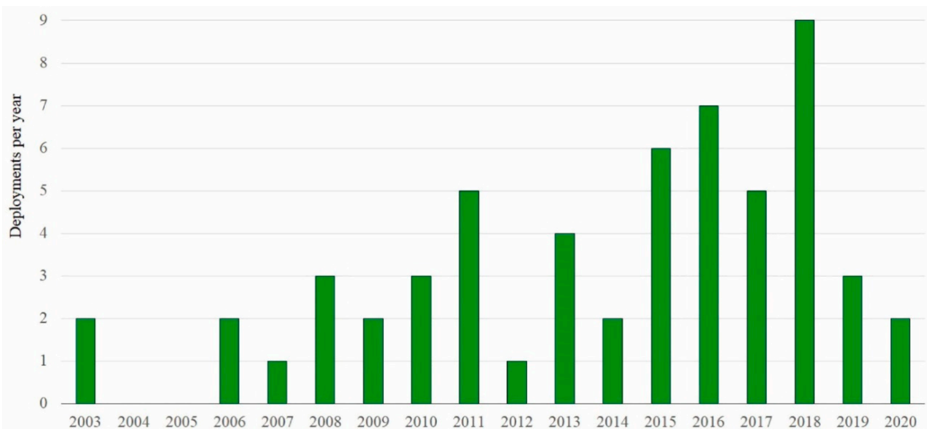

Figure 2. Deployments per year of tidal energy projects around the globe. Obtained from: [8].

In this context, the tidal sector has made remarkable progress throughout the last two decades, and Figure 3 summarizes the size and capacity evaluation of tidal turbine deployments from 2003 to 2021. In addition to the increase in size, developers have come up with different design approaches to capture tidal energy, and these include new-generation floating and hubless tidal turbine systems. At the same time, developers have improved the efficiency of the tidal turbine systems without making significant changes to the rotor diameters. For instance, "HS 1000", with a rotor diameter of 21 m, had a rated power of 1 MW in 2012, while "AR2000", with a rotor diameter of 20 m, was capable of generating 2 MW in 2019 [12,13].

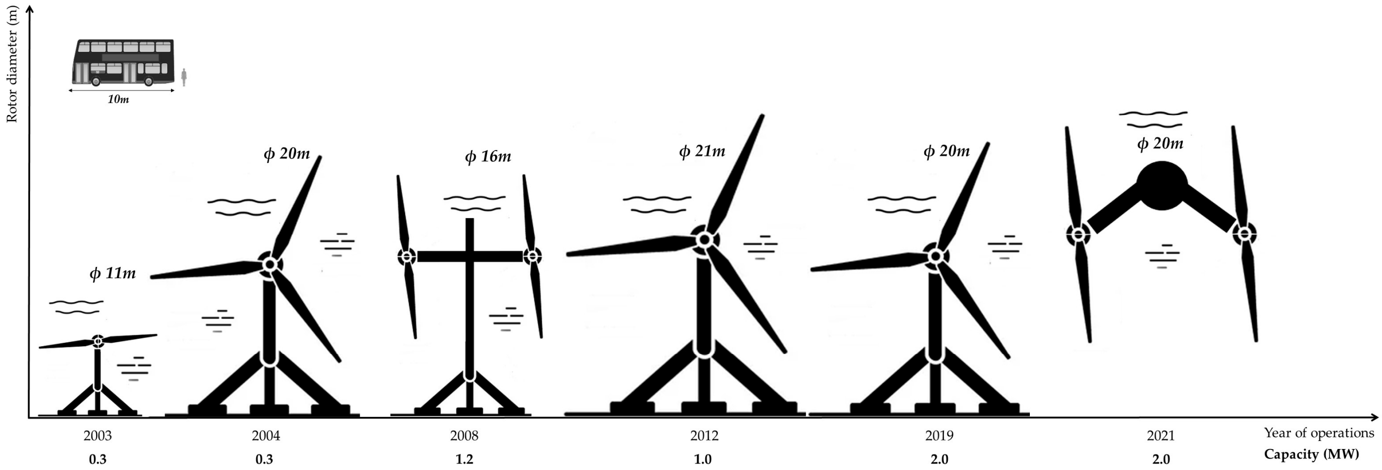

Figure 3. Size and capacity evaluation of tidal turbines.

Currently, advanced composite materials are employed by almost all manufacturers to fabricate turbine blades due to their numerous advantages, such as a high strength-to-weight ratio, durability, corrosion resistance and fatigue resistance, which enable them to withstand the severe and rigorous marine environment [14–16]. Moreover, the flexibility of composites provides designers with the ability to construct blades of complicated shapes and geometries, thereby optimizing the efficiency of the diverse types of TEC. Of the different types of TEC, horizontal-axis (axial flow) tidal turbines have achieved a technology readiness level of 8, signaling the maturity of the axial flow tidal energy sector around the world [17]. It justifies the deployment of 86% of axial flow tidal turbine projects around the world compared to the other types of TEC [8]. Table 1 summarizes the major axial flow tidal turbine deployments around the world in the last two decades, including their main design features. These horizontal-axis tidal turbine blades are exposed to harsh environmental conditions and high hydrodynamic loading on the blades in the operating phase, and their designed life expectancy of up to 25 years is questionable [18,19]. Subsequently, in order to assure safe operation of the structural components of the tidal turbine system, the turbine blades take precedence. The static loads acting on the tidal turbine blades are much higher than the equivalent-length wind turbine blades, and the spar caps should be strengthened, as they are crucial members to bear most of the loadings of the turbine [19]. Therefore, designing a horizontal-axis tidal turbine is a challenging task for designers, and they need to consider several factors during the design process. This causes overdesigning of the tidal turbine systems, leading to higher-cost drivers at the manufacturing and installation phases. High costs can limit investments in the tidal energy industry. Furthermore, some critical failures of the tidal turbine systems also slow down the development of the industry. For instance, a 12-bladed hubless tidal turbine, which was deployed by OpenHydro, failed due to the unexpected sea currents in 2009, and this emphasizes the importance of accurately predicting the loading conditions that act on the tidal blades during structural testing [20]. Therefore, structural testing to reduce uncertainties and risk is required to improve the reliability of tidal turbine blades so that investors can make their decisions effectively. In addition, the structural testing program should validate the structural integrity and ensure economic sustainability in the manufacturing and operational phases of tidal turbine systems.

Table 1. Major axial flow tidal turbine deployments in the last two decades (2003–2022).

No	Year	Project Name	Location	Number of Rotors	Number of Blades per Rotor	Rotor Diameter (m)	Capacity per Rotor (kW)	Remarks
1	2003	Seaflow	Lynmouth in Devon	1	2	11.00	300	The world's first "full-size" tidal turbine. The turbine is installed to a structure fixed to the seabed [21]
2	2004	HS300	Kvalsund, Finnmark, Norway	1	3	20.00	300	A tidal prototype connected to the grid for the first time in the world. The turbine is fixed to the seabed [12,13]
3	2008	SeaGen	Strangford Narrows in Northern Ireland	2	2	16.00	600	A system to generate 1.2 MW of rated power. The turbines are attached to a structure fixed to the seabed (the world's first commercial-scale tidal energy project) [22]
4	2011	SR250	European Marine Energy Centre (EMEC) tidal test site in the Fall of Warness	2	2	8.00	125	A system to generate 250 kW of rated power (the SR250 has become the world's first floating tidal turbine) [23]
5	2011	AK-1000	European Marine Energy Centre (EMEC) tidal test site in the Fall of Warness	2	3	18.00	500	The tidal turbines are attached to the same hub connection, which is fixed to the seabed and generates 1 MW rated power [24]
6	2011	AR1000	European Marine Energy Centre (EMEC) tidal test site in the Fall of Warness	1	3	18.00	1000	The turbine is fixed to the seabed [25]
7	2012	HS1000	European Marine Energy Centre (EMEC) tidal test site in the Fall of Warness	1	3	21.00	1000	The turbine is fixed to the seabed [12,13]
8	2013	HyTide 1000	European Marine Energy Centre (EMEC) tidal test site in the Fall of Warness	1	3	13.00	1000	The turbine is fixed to the seabed [13,26,27]
9	2015	Sabella	Ushant island, Brittany (France)	1	6	10.00	1000	The turbine is attached to the seabed using a four-leg structure [13,27,28]
10	2015	Delta Stream	Placed on the seabed in Ramsey Sound off the Pembrokeshire coast	3	3	15.00	400	A tidal turbine system attached to a triangular steel base placed on the seabed to generate 1.2 MW rated power [29]
11	2016	Nova M100	Bluemull Sound, Shetland, off the far-northeast coast of mainland UK	6	2	8.50	100	The world's first offshore tidal array to generate rated capacity of 300 kW. Another three rotors were added at later stages. The turbines are fixed to the seabed [30,31]
12	2016	OpenHydro Turbines	Paimpol Bréhat, Brittany (France)	2	10	16.00	500	Each turbine is installed to a two-column structure fixed to the seabed. Has 1.0 MW of rated power [32,33]
13	2016	Tocardo T-2 Tidal Turbines	Eastern Scheldt barrier, Zeeland (The Netherlands)	5	2	5.50	240	Turbines are attached to a single structure to form the world's largest commercial tidal array. System has 1.2 MW of rated power [32,34]
14	2016	AR1500	Site in Pentland Firth, Scotland	1	3	18.00	1500	An active-pitch, full-yawing tidal turbine system fixed to the seabed [35–37]

Table 1. *Cont.*

No	Year	Project Name	Location	Number of Rotors	Number of Blades per Rotor	Rotor Diameter (m)	Capacity per Rotor (kW)	Remarks
15	2016	SR2000	Orkney Islands, Scotland	2	2	16.00	1000	A floating tidal turbine system with 2 MW of rated power [38]
16	2018	Atir marine current turbine	Ria of Vigo (Northwest of Spain)	2	3	19.00	750	The tidal turbines are attached to the same hub connection and generate 1.5 MW of rated power. It is a floating system [39]
17	2019	OpenHydro Turbines	Naru Strait (Japan)	1	10	16.00	2000	Turbine is installed to a two-column structure fixed to the seabed [32]
18	2019	AR2000	Scotland	1	3	20.00	2000	An active-pitch, full-yawing turbine attached to seabed [6,7]
19	2021	Orbital O2	Orkney Islands, Scotland	2	2	20.00	1000	2.0 MW of rated power floating tidal turbine system [40]

In this context, this study reviews the standards for structural testing of tidal turbines blades, effective methods of using the equipment and instrumentation, the scope and results of the tests performed and possible future developments in order to improve the testing mechanism of tidal turbine blades to de-risk the tidal energy sector. In addition, this paper formulates stepwise testing procedures for dynamic, static and fatigue testing in line with the testing standards. Furthermore, the working principles of the equipment and instruments used for the testing are highlighted to provide better awareness of the structural testing of tidal turbine blades.

2. Methodology

To explicitly define the methodology of the review, the aim and objectives of the study, along with the reviewing approach, are outlined in this section.

2.1. Aim and Objectives

This review paper aims to investigate the state of the art in structural testing of tidal turbine blades made from fibre-reinforced composite materials and make recommendations to improve existing testing practices to support the deployment of new-generation axial flow tidal turbines in the future. In this context, the review expects to cover the following objectives:

- To critically evaluate the testing standards of tidal turbine blades and articulate a step-by-step approach for each standard test to be conducted;
- To discuss the effective use of equipment and instrumentations for structural testing of tidal turbine blades;
- To review reported structural tests of tidal turbine blades and their results;
- To identify and explain possible developments to enhance the structural testing process of tidal turbine blades in the future.

2.2. Review Methodology

In order to compile this review, the authors studied scholarly journal articles, test reports and industry guidelines, as well as reliable government and private websites in different countries, to incorporate information relevant to the structural testing of axial flow tidal turbine blades.

After the scope definition of the review paper, the information-searching strategy was formulated, as outlined in Figure 4. The selected keywords were employed to conduct a comprehensive survey to identify the background and the status of the research literature to align with the scope and the review questions [41]. A three-phase filtering mechanism, illustrated in Figure 5, was employed to disregard the irrelevant/unreliable literature documents, which meant that there were only 12 relevant publications available for this review. In addition to the selected reliable and relevant research documents, a few websites, reports, and scholarly journal articles were studied in order to capture up-to-date information and other minor technical details required for the review.

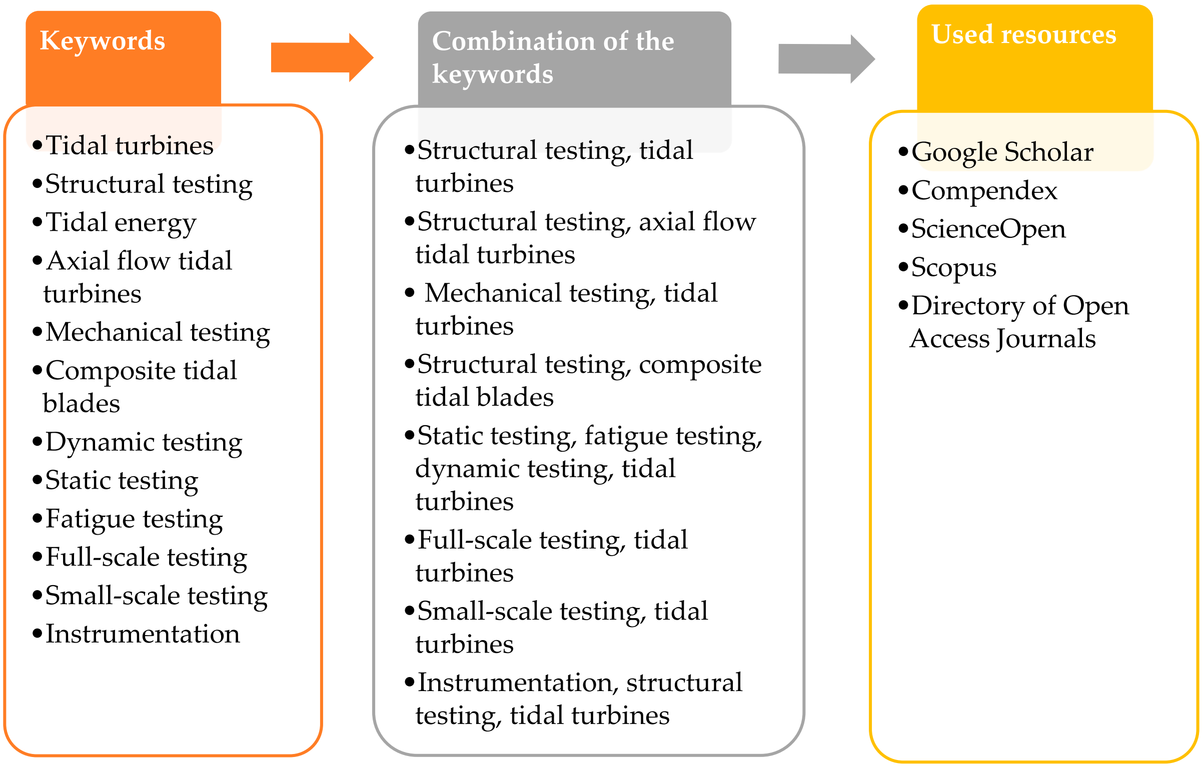

Figure 4. Searching strategy of the review.

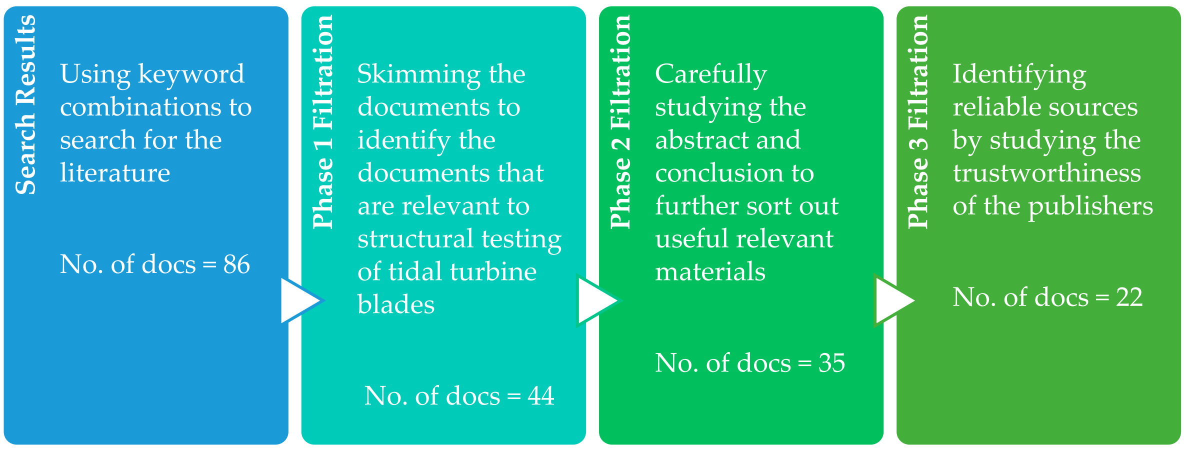

Figure 5. Literature resource-filtering mechanism for structural testing of tidal turbine blades.

3. Structural Testing Procedure

In operation, horizontal-axis tidal turbine blades are loaded throughout their span, while being supported at their roots during rotation. Therefore, the most suitable approach to studying the structural behaviour of blades is to consider one blade as a cantilevered section loaded in bending [42]. Blades for tidal turbines are generally shorter and stiffer than blades for an equivalent-capacity wind turbine. Furthermore, multiple loading points are required to closely replicate the shear force and bending moment distributions experienced along the length of tidal turbine blades while in service. These loads are typically applied in the mechanical/structural testing of tidal turbine blades in the laboratory through multiple hydraulic actuators applying loads simultaneously. In this context, it requires a substantial capital investment to build a large structural testing facility capable of undertaking the full-scale structural testing of tidal turbine blades. This has resulted in a limited number of facilities being available around the world. University of Galway, The University of Edinburgh, National Renewable Energy Laboratory (NREL), French Institute for Ocean Science (IFREMER—Institut Français de Recherche pour l'Exploitation de la Mer), BLAEST in Demark and Technical University of Denmark have been identified as some of the leading institutions that have large enough structural testing facilities to conduct full-scale tidal turbine blades for testing [11,43–45]. An image of the schematic facility at University of Galway, including the test bed, test frame, load introduction fixtures and some of the equipment used, is shown in Figure 6.

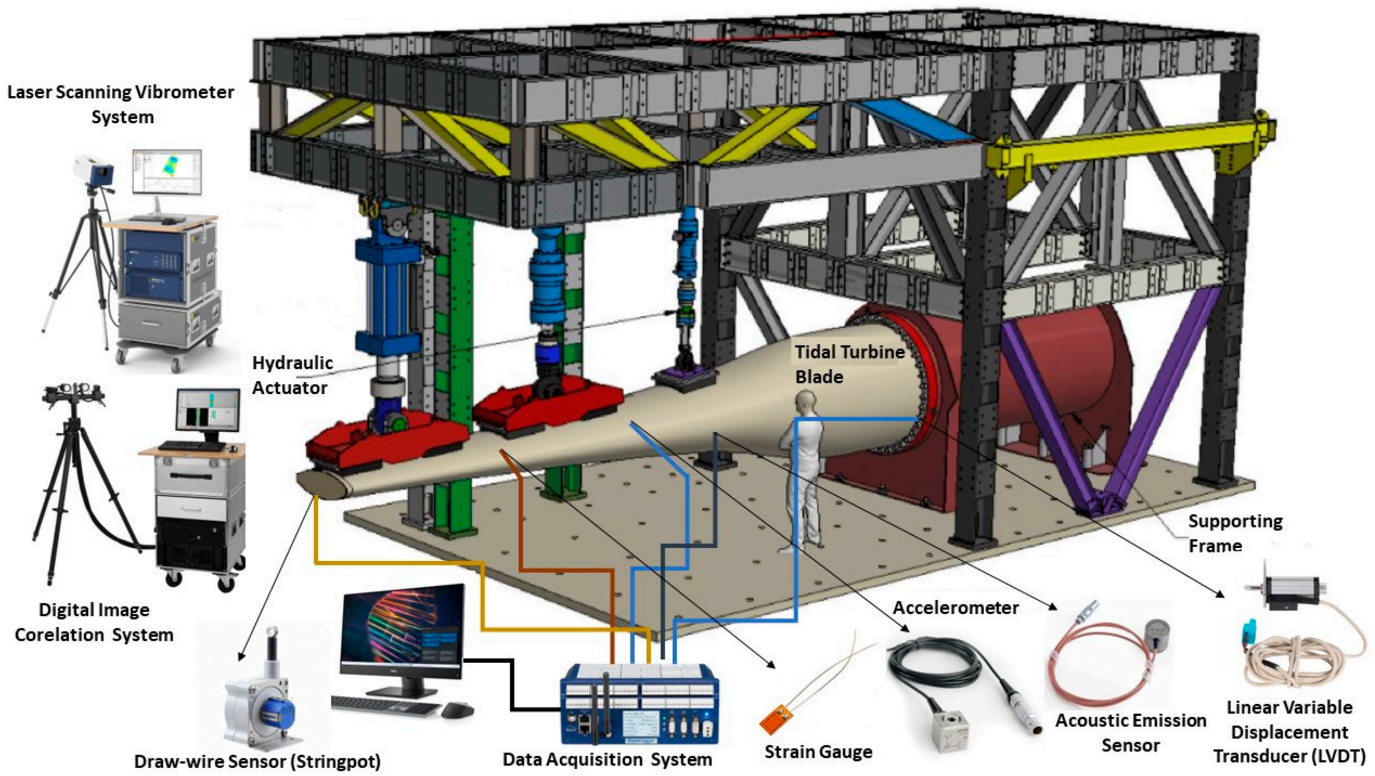

Figure 6. Structural testing facility at the University of Galway for tidal turbine blades. Adapted from [11].

The structural testing procedure of TECs should be aligned with DNVGL-ST-0164 and IEC DTS 62600–3 standard procedures to meet the regulations and safety standards. Therefore, the cantilevered blade, as shown in Figure 6, is subjected to dynamic, static, fatigue and residual strength testing to identify the structural integrity and reliability of tidal turbine blades. In addition, the mass and the center of gravity of the blade should also be measured as part of the testing procedure. In this context, the procedures, equipment and instrumentations used for these tests are vital in ensuring that the requirements mentioned in the standards are met.

Under the testing procedure, all critical regions of the blade should be tested in accordance with predetermined loading conditions. To estimate the testing loads, hydrodynamic loadings and environmental conditions at the chosen deployment site must be considered. During testing, particular attention should be given to the parts that have the lowest safety factors applied in their design against buckling, fatigue life and strength. Similarly, the blade's sections attached to hydrodynamic braking systems, local reinforcements or any other special design features should be tested to identify their structural integrity.

These critical sections of the blade and safety factors can be identified based on the design calculations and should be tested accordingly [46,47].

3.1. Blade Set-Up and Installation

Ensuring that the blade is loaded correctly is critical to carrying out successful testing. To represent the operating conditions of the turbine, all targeted regions should be substantially loaded [46,47]. To achieve this, the blade must be attached to the test bed and the load must be applied along the length of the blade. Therefore, a support frame to connect the blade to the test bed and load introduction fixtures (loading saddles/pads) should be designed and fabricated accordingly. Figure 6 shows the custom support frame and load introduction saddles required for testing a tidal blade. The cost of design and fabrication of these fixtures must be accounted for in the test budget. The features of the loading mechanism depend on the loading points of the blade, and estimated flapwise and edgewise loading requirements of both static and fatigue testing. In addition, the process of attaching the blade to the test rig and defining the test procedure is very important for the structural testing of tidal turbine blades. The features of the loading mechanism depend on the loading points of the blade and the estimated flapwise and edgewise loading requirements of both static and fatigue testing. In addition, the process of attaching the blade to the test rig and defining the test procedure is very important for the structural testing of tidal turbine blades.

During testing, forces, deflections, strains and accelerations may be recorded, since they are all key parameters that must be understood in any structural test program. The acceleration of the blade after impact is used to identify the natural frequency of the blade, which is also a fundamental property that should be measured in every test program. Some of the equipment and instrumentations that can be used to conduct and monitor the structural testing of tidal turbine blades have been highlighted in Figure 6. Each actuator contains a load and deflection sensor to monitor the loading at each location along the blade. Strain gauges are used to measure the strains at predefined locations along the blade and they may also be used on the test frame to measure its deflection. Draw-wire sensors ("stringpots"), and linear variable displacement transducers (LVDTs) measure the deflections at key locations. Laser scanning vibrometers (LSVs) and accelerometers may be used to measure the acceleration of the blade at various locations. A digital image correlation (DIC) system may be used to monitor strain during testing. A DIC system measures full field strain and displacement of a surface (as opposed to a strain gauge, which gives strain at a single location). It should be noted that the DIC is generally not used to test the whole surface of the blade due to limitations to the maximum measurement area and surface curvature. However, it can be used to effectively measure deformations of the critical areas of the turbine blades. A 3D laser scanner can be used to scan the blade and test set-up before and during testing, so a full as-built 3D geometry can be captured, as well as a 3D point cloud of the blade under loading conditions. Acoustic emission sensors are used to record sounds that might indicate damage occurring during the testing. In addition, Table 2 discusses the working principles of the instruments used for structural testing in brief. These sensors should be connected to the data acquisition (DAQ) system before starting the testing, and system checking must be undertaken to ensure the responses of the transducers. The positions of the strain gauges, accelerometers, stringpots, acoustic emission sensors and LVDTs are decided based on the testing requirements and the experience of the testing technicians.

Table 2. Working principles of the equipment and transducers used for the structural testing of tidal turbine blades.

Equipment/Transducer	Working Principles
LSV System	This noncontact velocity transducer system works based on the Doppler effect. The system measures the frequency shift of the laser-scattered beam from the vibrating surface relating to the reference beam, as shown in Figure 7 [48].
DIC System	The system compares the digital images of a part or a test piece at different stages of deformation and compares these images to produce strain and deflection measurements. Measurements are limited to the area seen by the DIC cameras [49].
Accelerometer	The piezoelectric materials in accelerometers generate electrical charge due to the change of motion or vibration. Then, they measure the variation of the electric charge generated as it is proportional to the acceleration of the object [50].
Strain Gauge	The resistance of the strain gauge varies depending on the applied force to it, as a result of movement of the surface it is adhered to. Therefore, the change in electrical resistance is measured to identify the strain of the testing object [51].
Draw-Wire Sensor	It uses a highly flexible steel wire to measure the linear movements of the objects.
LVDT	It measures displacement based on the mutual induction of primary and secondary windings, as represented in Figure 8. The movement of the core creates a different electromagnetic field (EMF) in both windings, and the difference is used to measure displacement [52].
3D Laser Scanner	It can be used to obtain a point cloud survey that captures the as-built geometry of the tidal blade, test fixtures and fittings, as well as full 3D geometry of the deformed blade under loading conditions.
Acoustic Emission Sensor	It converts high-frequency stress waves into voltage. Then, the voltages are amplified to process the acoustic emission signal data to identify defects [53].

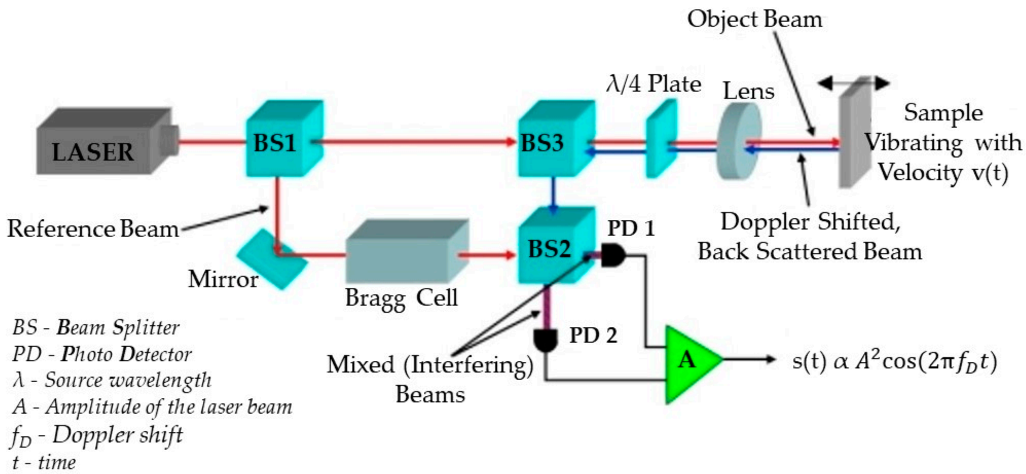

Figure 7. Working principles of LSV. Adapted from [54].

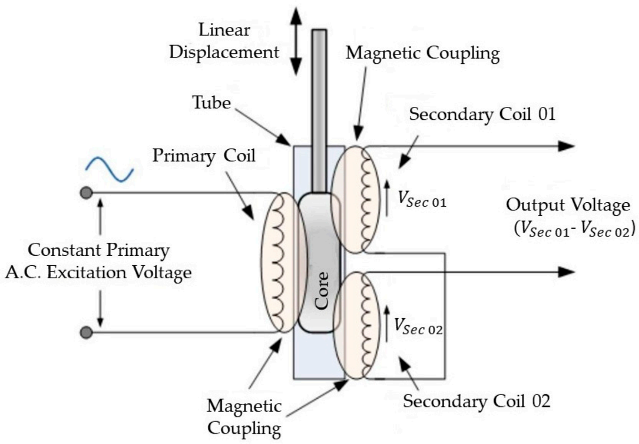

Figure 8. Working principles of LVDT. Obtained from [55].

3.2. Dynamic Testing

Dynamic testing is carried out to determine the relevant natural frequencies, mode shapes and damping ratios of the blade. For this test, the blade should be connected to the test bed, but it should not have other equipment such as load introduction fixtures attached. For that, piezoelectric accelerometers or LSV may be utilized with an impulse hammer under free-damped vibration to monitor the acceleration responses in different locations of the blade. Then, responses are analysed based on the fast Fourier transform (FFT) algorithm to obtain the dynamic properties of the blade. Figure 9 summarizes the steps used to perform dynamic testing using accelerometers and LSV relevant to the DNVGL-ST-0164 and IEC 62600–3 standards. According to the DNVGL-ST0164 standard, it is not required to estimate the second-order flapwise mode shape, since the hydrodynamic damping acting on the tidal turbine is much higher compared to the aerodynamic damping on wind turbine blades [47]. The dynamic behaviour of the blade is important, as the measured value can be compared to the value predicted by the design to validate the design. Furthermore, changes in dynamic behaviour over the course of testing indicate that a change in the structural response of the blade has occurred due to damage or a change in the boundary conditions of the blade.

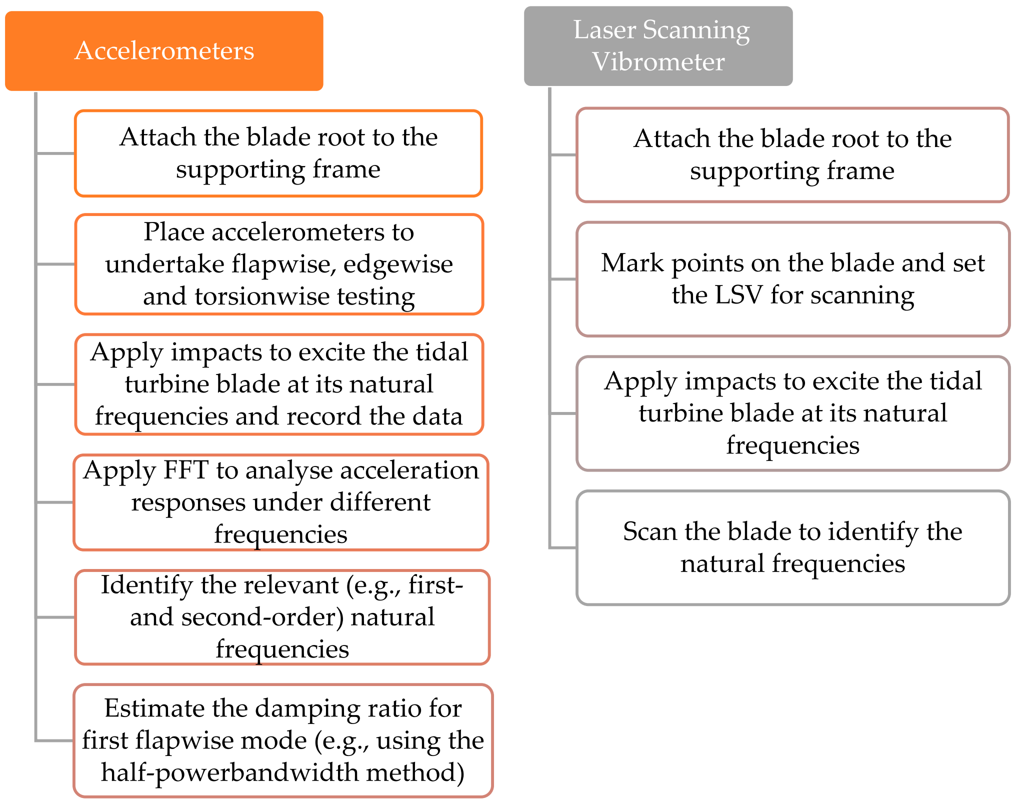

Figure 9. Steps for evaluating dynamic properties of tidal turbine blade [46,47,56].

3.3. Static Testing

A static test procedure for tidal turbine blades, which is in accordance with [46,47], is given in Figure 10. The target test loads in this procedure should represent extreme loading conditions in the following orientations:

- Flapwise direction from pressure side to suction side;
- Flapwise direction from suction side to pressure side;
- Edgewise direction from trailing edge towards leading edge;
- Edgewise direction from leading edge towards trailing edge;
- Torsion-only stiffness distribution (this can be neglected if the torsional extreme loadings are not critical for the blade design.) [47].

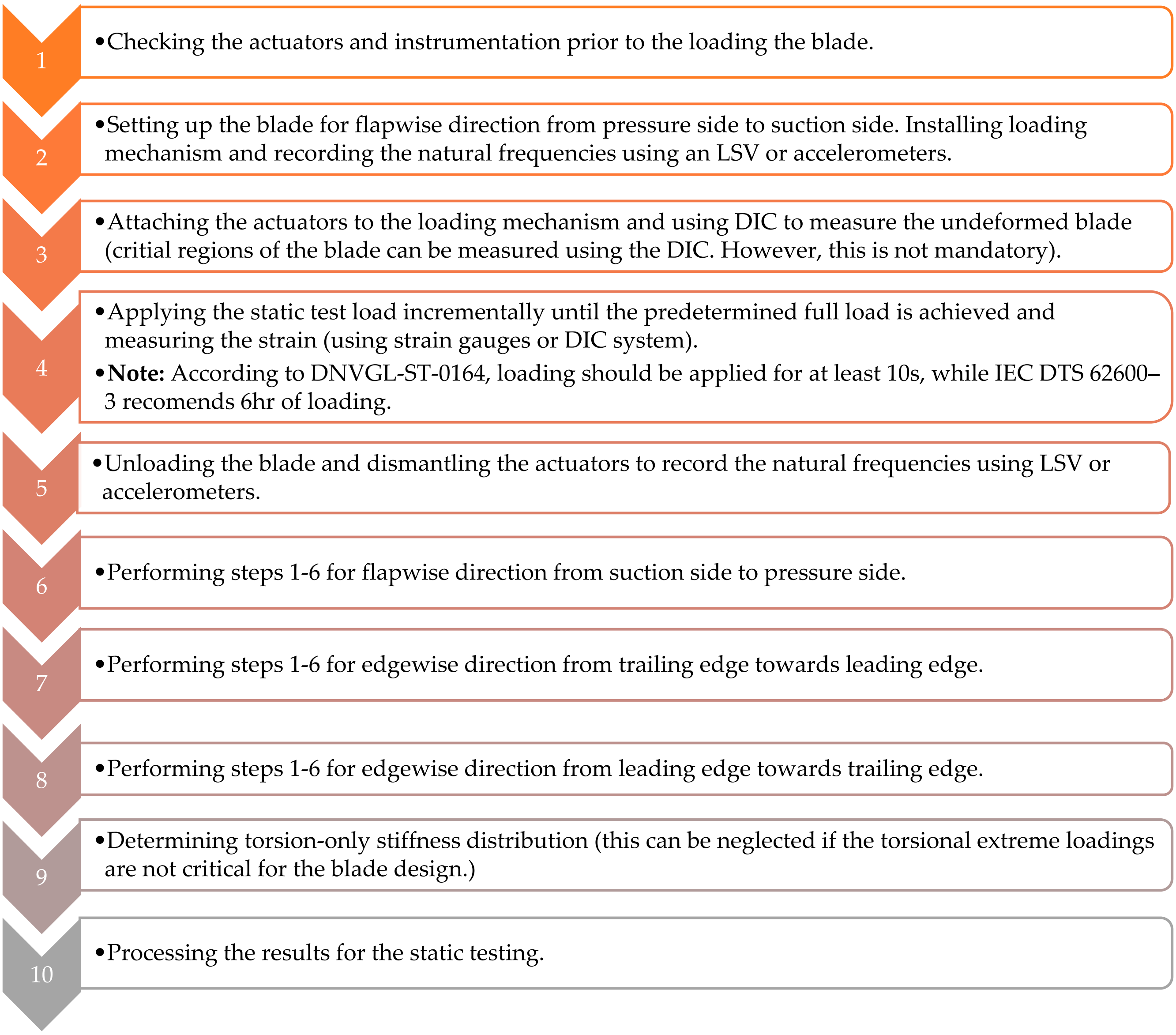

Figure 10. Static testing procedure for tidal turbine blades [46,47].

The edgewise extreme loading conditions can be omitted if they are not critical for the blade design. Dynamic testing will be carried out before and after all static and fatigue tests. The dynamic tests should be carried out without the actuators connected and with and without the load introduction saddles connected. Subsequently, the tests should be performed intermittently during testing to ensure no damage has occurred to the blade. In addition, the use of acoustic emission sensors enables the detection of fibre breaks, cracking and delamination in their early stages. Consequently, it can provide a platform to observe damage propagation of the tidal turbine blade during testing [46,47].

3.4. Fatigue Testing

Hydraulic actuators and unbalanced rotating mass mechanisms can be used to conduct fatigue testing for the tidal turbine blades. Figure 11 represents the testing procedure for both hydraulic actuators and unbalanced rotating mass systems.

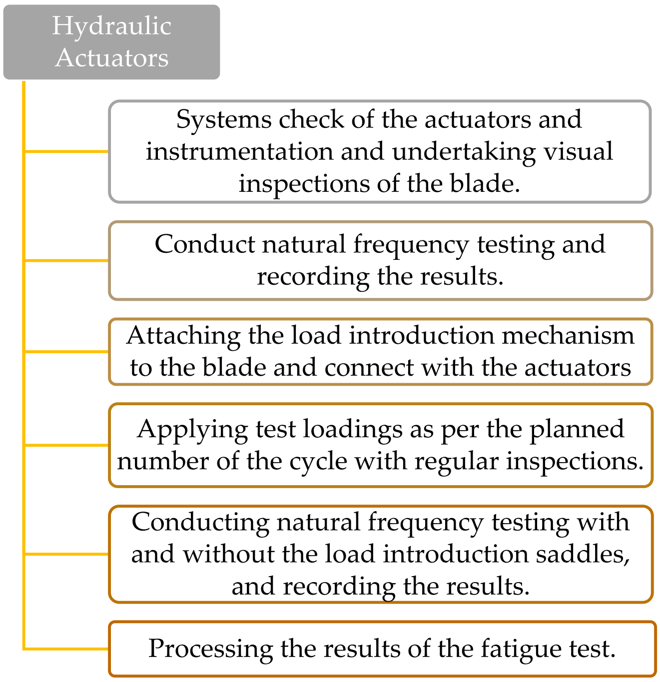

Figure 11. Standard fatigue testing procedure for tidal turbine blades [46,47].

3.5. Residual Strength Testing

Both dynamic and static test results are used to undertake the residual strength testing of the tidal turbine blades. Therefore, static and dynamic testing should be undertaken again, according to the steps mentioned in Figures 8 and 9, respectively. During the testing programme, some regions of the blade may experience damage, and this damage should be assessed to identify any influence on the structural performance of the blade [46,47].

4. Testing Programmes Undertaken

The tidal energy sector expects to undertake more extensive structural testing programmes to ensure the structural integrity of the composite tidal turbine blades for a service life of circa 25 years. However, there are currently a very limited number of completed structural tests of tidal turbine blades. Details of testing reported in the literature are given in Table 3. As shown in Table 3, the University of Galway has conducted several structural testing programs for full-scale axial flow and hubless tidal turbine blades using the large structural testing facility developed at the University of Galway. In 2022, the University of Galway, in collaboration with Orbital Marine Power and EireComposites, conducted comprehensive structural testing (static, dynamic, fatigue, and residual strength testing) for a full-scale 8 m long axial flow tidal turbine blade. The load of 1008 kN applied to the blade during static testing was the highest load ever reported on a tidal turbine blade. Furthermore, it was the first time a large composite tidal blade underwent structural fatigue testing at full-scale to its equivalent design life of 20+ years [11]. The University of Galway also undertook static and fatigue testing for a novel small-scale 3 m long hubless tidal turbine blade in collaboration with OpenHydro in 2018 [57,58]. Moreover, the university has undertaken static and fatigue testing for a full-scale 5 m long helical river turbine in 2020 [59].

Simultaneously, the partners of the RealTide project (BureauVeritas, 1-Tech, EnerOcean, Ingeteam, Sabella, University of Edinburgh and IFREMER) conducted full-scale static testing for a 5 m long axial flow tidal turbine blade in 2022 [45]. Additionally, the National Renewable Energy Laboratory (NREL) [60], Newcastle University [61] and Dalhousie University [42] have conducted structural testing for 2.275 m (full-scale), 1 m (small-scale), and 0.36 m (small-scale) long axial flow tidal turbines, respectively.

Table 3. Details of the structural testing of tidal turbine blades undertaken.

No *	Specifications of the Tested Tidal Turbine Blade	University/Organization	Details of the Tests Performed	Data Acquisition and Instrumentation	Remarks
1	8 m long full-scale axial flow tidal turbine blade test (1 MW tidal turbine) [11]	University of Galway (2022) Orbital Marine Power, UK EireComposites Teo, Ireland	• Dynamic testing • Static testing • Fatigue testing • Residual strength testing	12 linear strain gauges, 18 rosette strain gauges, 7 displacement sensors, 7 accelerometers, 3 servohydraulic actuators with 5 loading points, 3 load cells, LSV and DIC systems.	• DNVGL-ST-0164 and IEC DTS 62600–3:2020 standards were employed. • 1008 kN of the highest load ever applied on a tidal turbine blade. • Conducting a full-lifetime fatigue testing program (equal to 20+ years). • Validated the results of the numerical finite element (FE) model using structural testing.
2	5 m long full-scale axial flow tidal turbine blade test [45]	Bureau Veritas, 1- Tech, EnerOcean, Ingeteam, Sabella, University of Edinburgh and IFREMER (2022)	• Static testing	46 rosette strain gauges, 10 wire displacement transducers, 2 acoustic emission transducers, 2 optical fibres and a novel ultrasonic wave propagation monitoring network developed by EnerOcean, with 27 EnerOcean gages, 9 ultrasonic transducers and 2 hydraulic cylinders applying the loads through three loading points.	• Results of numerical simulations and real full-scale test data were compared to establish confidence in FE modelling. • IEC/TS 62600-200:2013 standard was referred to. • Acoustic emission sensors were employed to identify the damage initiations.
3	3 m long full-scale axial flow tidal turbine blade test [57]	University of Galway (2021) SCHOTTEL Hydro, Germany	• Dynamic testing • Static testing • Fatigue testing • Residual strength testing	12 linear strain gauges, 5 rosette strain gauges, 6 displacement sensors (4 LVDTs and 3 stringpots), 2 servohydraulic actuators, 2 load cells and LSV.	• DNVGL-ST-0164 and IEC 62600–3:2020 standards were employed. • The passive-adaptive design was used.
4	3 m long small-scale hub less tidal turbine blade test (3/8 scaled 10-blade turbines with a diameter of 16 m) [62]	University of Galway (2018) OpenHydro, Ireland	• Static testing • Fatigue testing	33 strain gauges, 8 LVDTs, 5 stringpots, 3 crack opening sensors, DIC system and 1 servohydraulic actuator.	• Testing was conducted for a novel hubless tidal turbine blade. • Validated the FE model results using the structural testing results.
5	2.275 m long full-scale axial flow tidal turbine blade test [60]	National Renewable Energy Laboratory (NREL), (2012)	• Static testing • Fatigue testing	29 strain gauges, 8 acoustic emission sensors, 1 servohydraulic actuator, 1 thermal imaging camera	• Only flapwise loads were applied to the blade. • IEC 61400-23 technical specification for testing of wind turbine blades was followed. • All possible practical issues during structural testing were highlighted, with feasible solutions to minimize their impact on the results.

Table 3. *Cont.*

No *	Specifications of the Tested Tidal Turbine Blade	University/Organization	Details of the Tests Performed	Data Acquisition and Instrumentation	Remarks
6	2 m long full-scale axial flow tidal turbine blade test [57]	University of Galway (2021) SCHOTTEL Hydro, Germany	• Dynamic testing • Static testing • Fatigue testing • Residual strength testing	11 linear strain gauges, 4 rosette strain gauges, 7 displacement sensors (4 LVDTs and 3 stringpots), 3 accelerometers, 1 servohydraulic actuator and 1 load cell.	• DNVGL-ST-0164 and IEC 62600–3:2020 standards were employed. • The passive-adaptive design was used.
7	1 m long small-scale axial flow tidal turbine blade test [61]	Newcastle University, UK (2021)	• Static testing	DIC system	It was focused on finding the correlation between FE model analysis and mechanical testing of the small-scaled tidal turbine blade.
8	0.36 m long small-scale axial flow tidal turbine blade test [42]	Dalhousie University (2016)	• Static testing	1 load cell and 1 optical displacement tracking system	• To compare the load vs. displacement and load vs. twisting of tidal turbine blade experimentally and numerically. • A damaged blade was repaired and tested, and a 1.2% reduction in deflection of the repaired blade at a load of 25 N was observed.

* Table 3 represents all published structural testing details of tidal turbine blades. However, it is acknowledged that it is likely that there are unpublished test results that are not reported here.

5. Observations from the Testing Programmes

The increasing number of tidal turbine deployments has accelerated testing programs taking place in the world to ensure the structural integrity of TECs. As a result, leading research institutes such as the University of Galway, the University of Edinburgh, NREL, IFREMER and the University of Newcastle (UK) have undertaken full-scale and small-scale structural testing programs for tidal turbine blades and published their significant results. Some of the key findings of these testing programs are highlighted in Table 4. In addition, the University of Galway and partners [11] applied the largest load ever reported on a tidal turbine blade for a 1 MW nacelle, and then tested the same full-scale blade to its equivalent design life of 20+ years. However, it should be noted that none of the structural testing programs outlined in Table 4 have focused on the remaining fatigue strength or residual strength of tidal turbine blades during their operational life.

Table 4. Summarized outcomes of tidal turbine blade testing.

Publication Details	Finding	Remarks
[11,45,61,62]	Validated the FE model results with the structural testing.	Tidal energy developers will be able to conduct comprehensive FE analysis and ensure the structural integrity of tidal turbine blades in the future (with the support of further validation programs).
[45]	The internal damage mechanism of the blade was established by analysing the cut sections of the blade.	Manufacturers will be able to minimize the internal damage of the tidal turbine blades in the future.
[11]	It is not necessary to statically load the blades for 6 h during the static test program, as this does not affect the static test results.	The 6 h loading requirement of the IEC DTS 626003 standards can be neglected. Holding the load for a duration of 30 s during static testing should suffice.
[62]	Demonstration of a unique approach to testing new-generation TECs with different designs.	The research methodology used for novel hubless tidal turbine blades is crucial for conducting structural tests for novel TEC designs in the future.
[57]	A linear relationship between static loading and tip deflection of the tidal turbine blades.	Based on this research observation, the designers can roughly estimate the deflections of the tidal turbine blades at the design stage. However, the tip deflection depends on several factors, including the environmental conditions, material properties of the turbine, structural design and geometrical parameters of the turbine.
[61]	Conducted composite material testing, FE analysis and small-scale structural testing to assess industrial-level tidal turbine blades.	It demonstrates the possibility of undertaking structural testing for small-scale tidal turbine blades to predict the performance of full-scale blades. However, there are constraints to be considered.
[42]	Performed static tests on damaged and repaired tidal turbine blades and found that the deflection responses of the damaged and repaired blades were less than 1.2% for a 25 N static load.	This approach will be important for the future development of the tidal energy sector, as it needs to focus on the damage repair strategies of tidal turbine blades to achieve sustainability goals. However, the result of this exercise is highly dependent on the location, size and repair strategy of the damage. Therefore, a more detailed research study is necessary to validate the reliability of repaired blades to be reused in tidal power generation.

6. Suggestions for Future Developments

Based on the information gathered, this paper highlights nine suggestions, where there are research gaps that need to be addressed to derisk blade manufacture in the TEC manufacturing industry, which are detailed as follows:

1. Developing a monitoring system to study the fatigue strength and residual strength of tidal turbine blades in service throughout their lifespan;
2. Developing vulnerability curves to predict the remaining life of tidal turbine blades throughout their operational life;

3. Identifying new testing approaches to replicate the current costly and time-consuming testing procedures more accurately and efficiently;
4. Building a mechanism to distribute the predicted hydrodynamic loading across the tidal turbine blade test surface to mimic both the test shear force and bending moment distributions [11];
5. A mechanism to correlate the macromechanics of composite structures and structural testing results of tidal turbine blades [61];
6. Considering the harsh environmental conditions and heat-induced aging factors in seawater for structural testing [63];
7. A mechanism to compare structural testing data with structural health monitoring system data to identify the gaps in laboratory testing in order to introduce safety limits for the test results;
8. Developing a mechanism for repairing damaged tidal turbine blades and reinstallation for operation;
9. Developing a model for selecting the most suitable internal configurations for spar caps (internal web arrangement) of tidal turbine blades and promoting the development of strong and economical tidal turbine blades.

The tidal energy industry is close to reaching technological maturity, so the design and installation process of TECs should be accelerated to build large power generation facilities. However, the structural testing and validation process is significantly slowing the development of the industry down. In this context, suggestions (1)–(3) were made to bypass the complex and costly structural testing requirements of the new tidal turbine blade profiles. A validated monitoring mechanism with vulnerability curves for identifying the residual life of the blade will reduce the requirements of conducting structural testing. In addition, a new testing strategy to reduce the number of testing orientations defined in the standards, as mentioned in suggestion (3), would speed up the testing process, since it would minimize data processing and testing times. Suggestion (4) is formulated to enhance the reliability and accuracy of structural testing, as the results can be integrated with the monitoring mechanism mentioned in suggestion (1). At the same time, it is required to study the fluid behaviour in the vicinity of the proposed locations of the TEC for accurate estimations of hydrodynamic loading. The composite materials' properties are vital for the structural integrity of the tidal turbine blades. Therefore, the macromechanics of the composite structures must be integrated into the testing process to develop the monitoring mechanism mentioned in suggestion (1). In this context, suggestion (5) will minimize the damage initiations on the TEC. Due to harsh environmental conditions, the life of the TEC can drastically reduce. Consequently, it is required to model the future environmental conditions integrate them into the testing process, as mentioned in suggestion (6). In addition, structural testing is conducted in air, even though the actual tidal system operates in water; therefore, it is possible that the test data is not fully representative of real-world operation, and it is required to introduce safety factors for the testing data. Suggestion (7) will correlate the test data and actual operating conditions to formulate safety margins for the structural testing results. Due to uncertainties, a few tidal turbine blades can be damaged before their end of the lifespan; therefore, suggestion (8) highlights the necessity of developing a damage-repairing mechanism to reuse the damaged tidal turbine blades (repairable blades). The spar cap of the blade is the strongest structural component, and blade life is highly dependent on it. Therefore, it is necessary to develop a strategy to select the most appropriate internal spar cap configuration based on the design requirements. This requirement is highlighted in suggestion (9). Altogether, nine of these proposals will improve the structural integrity of tidal turbines by encouraging the commercial tidal power industry to meet global sustainability goals.

7. Conclusions

This review paper presents the reported information from universities and research institutions that have undertaken full-scale and small-scale structural testing of tidal turbine blades over the last two decades. To ensure the reliability of the test results, the testing programs were aligned with DNVGL-ST-0164 and IEC 62600–3 testing standards. On the other hand, most of the testing programs have been limited to static and fatigue testing, based on the scope of the testing programmes. The University of Galway has undertaken a number of comprehensive full-scale axial flow tidal turbine tests, compared to the other universities and research institutes, but the University of Edinburgh has recently commissioned a purpose-built tidal turbine blade testing facility, where a number of blade tests are planned in the coming years. Based on a comprehensive analysis of test programs conducted, it becomes evident that there are significant research gaps in the structural testing of tidal turbine blades. These gaps primarily revolve around the need for strategies to predict real-time performance, ensure structural integrity, assess damage propagation and develop effective repair approaches. These gaps, if addressed, hold the potential to propel the tidal energy sector towards achieving a fully mature commercial level.

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Abbreviations

DAQ	Data Acquisition
DIC	Digital Image Correlation
EMEC	European Marine Energy Centre
EMF	Electromagnetic Field
FE	Finite Element
FFT	Fast Fourier Transform
IFREMER	Institut Français de Recherche pour l’Exploitation de la Mer
LSV	Laser Scanning Vibrometer
LVDT	Linear Variable Displacement Transducer
NREL	National Renewable Energy Laboratory
TEC	Tidal Energy Converters

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