ABSTRACT: Renewable energy is now viewed as being the preferred alternative to energy generation from fossil fuels. Wind energy has been established as a leading form of renewable energy, with tidal energy showing promise in recent years as 15 GWh was generated in 2019. However, with the advancements in these sectors, new engineering challenges within key components are presented. The turbine blades, which convert the energy in the resource to useful mechanical energy, are a key component that is being developed to improve operational performance. The Sustainable & Resilient Structures Research Group provide design and structural testing solutions for the development of wind and tidal turbine blades. In this paper, the capabilities and facilities of the group are presented that includes expertise in numerical modelling and large-scale structural testing, which uses a state-of-the-art multi-actuator load introduction system. Case study examples of wind and tidal turbine blades that have been tested by the group have been detailed in this paper, along with details of the in-house structural modelling software BladeComp and other numerical models that have been developed by the group. Further details are available at: http://www.nuigalway.ie/structures/

KEY WORDS: Finite element method; Numerical modelling; Renewable energy; Structural testing; Tidal; Wind.

1 INTRODUCTION
In recent years wind energy has been established as a leading source of renewable energy and, now, tidal energy is nearing commercial viability. There is 192 GW (170 GW onshore and 22 GW offshore) of installed wind energy in Europe, where electricity generated from wind accounted for 15% of the electricity demand of the EU-28 in 2019 [1]. In 2019, electricity generated from wind energy in Ireland account for 33% of its overall demand [1]. In 2019, the installed capacity of tidal stream energy in Europe reached 27.7 MW [2], which is almost four times as much as the rest of the world. While the total electricity produced in Europe from tidal energy in 2019 increased by 15 GWh to a total of 49 GWh [2]. For these systems to operate up to, and beyond, their design life spans, the reliability and longevity of certain key components of both wind and tidal energy converters is paramount. The blades of these turbines are such key components. The turbine blades convert the energy of the resource into mechanical energy, encountering high variations in loading. In order to ensure that wind and tidal turbine blades have the required structural capacity, mechanical static and fatigue testing of the blades is performed.

In this paper, the research activities of the Sustainable & Resilient Structures Research Group at NUI Galway in relation to wind and tidal turbine blade testing have been detailed. This world-leading research work supports the growth of the renewable energy sector during the development of device concepts and individual components, as they move through the Technology Readiness Levels. The capabilities and facilities available to the group, including their expertise in numerical modelling and large-scale structural testing, are presented. This includes a state-of-the-art multi-actuator load introduction system, which is used to impart the operational loads on the blades during the physical testing. These capabilities are also demonstrated through case study examples of wind and tidal turbine blades that have been tested by the group, along with details of the in-house structural modelling software BladeComp and other numerical models been developed by the group.

2 METHODOLOGY

2.1 Aim and objectives
The overarching aim of this paper is to showcase the capabilities of the Sustainable & Resilient Structures Research Group for testing the structural capacity of wind and tidal turbine blades. Therefore, in order to demonstrate these capabilities, the following aspects will be discussed in this paper:

- Numerical modelling, in particular the development of computational fluid dynamics models and the in-house structural analysis software BladeComp
- Structural testing (mechanical static and fatigue testing) at the Large structures Testing Laboratory, which uses a state-of-the-art multi-actuator load introduction system
- Research and development experience of the Sustainable & Resilient Structures Research Group

2.2 Testing standards
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 to the relevant technical standards, which are set out by ISO, IEC, DNV GL and ASTM. However, as the main focus of the research group revolves around the structural testing of wind and tidal turbine blades, the relevant standards set out by DNV GL and IEC are adhered to in the testing.
laboratory. The mechanical static and fatigue testing of wind turbine blades are performed in accordance to:

- DNVGL-ST-0376: Rotor blades for wind turbines
- IEC 61400-23 Wind turbines – Part 23 Full-scale structural testing of rotor blades

Tidal turbine blades are performed in accordance to:

- DNVGL-ST-0164 Tidal turbines – Rules and standards
- IEC 61400-23 Marine energy – Part 3 Measurement of mechanical loads

2.3 Laboratory facilities

The laboratory testing facility at NUI Galway for full-scale testing consists of a 375 m² state-of-the-art high-bay Large Structures Testing Laboratory. The laboratory specialises in accelerated design life testing of wind and tidal turbine blades and components, achieved through mechanical fatigue testing of the full-scale blade within the Large Structures Test Cell at NUI Galway, which can be seen in Figure 1. The components of the laboratory relevant to wind and tidal turbine blade testing include:

- Flexible testing spaces that allow for testing small to large structural and mechanical elements and materials.
- A large reconfigurable test frame with 4 hydraulic actuators with advanced actuator control system that allows for a wide variety of load or displacement sequences across multiple actuators.
- Servo-hydraulic testing machines with capacities ranging from 10 kN to 750 kN.
- Hydraulic ring main that allows convenient, efficient test setup, operation, and maintenance of individual test systems without disturbing other systems (working pressure of existing hydraulic ring main is max 207 bar and with a flow capacity of 180 lpm).
- Data acquisition of up to 136 independent high-speed channels can be carried out simultaneously; displacement, force, acceleration, strain and other types of sensor are available to configure the test
- 3D laser scanning, digital image correlation (DIC) and laser doppler velocimetry (LDV) for advanced non-contact measurement.

2.4 Key testing campaigns and projects

The key testing campaigns and projects completed, to date, by the Sustainable & Resilient Structures Research Group are:

- H2020 MaRINET2 - Marine Renewables Infrastructure Network for Enhancing Energy Technologies, Part 2, where components for GKinetic, Schottel and Orbital Marine Power have been tested
- LEAPWind – Leading Edge Advanced Protection using novel thermoplastic materials and processes for offshore Wind turbine blades, being completed in collaboration with ÊtreComposites and Suzlon Energy Blades
- H2020 FLOTec - Floating Tidal Energy Commercialisation project, where NUI Galway collaborated on the blade design using BladeComp with Orbital Marine Power
- SEABLADE - Systematic Evaluation and Analysis of BLADEs for a 2MW floating Tidal Energy Converter, being completed in collaboration with ÊtreComposites and Orbital Marine Power
- ACCORD - Advanced Composite design for Commercial ORPC RivGen Device, which involved testing a full-scale foil for ORPC
- OpenHydro blade fatigue testing campaign, which was completed by the group in 2017

Figure 1. Overview of facilities and capabilities of the Large Structures Testing laboratory, which is operated by the Sustainable & Resilient Structures Research Group
3 NUMERICAL MODELLING

Along with their testing capabilities, the Sustainable & Resilient Structures Research Group at NUI Galway have developed numerical models using a range of commercial software packages, including ABAQUS, ANSYS, MATLAB and ANSYS CFX. This includes the development of BladeComp, which is an in-house software that is used to develop optimum design solutions for wind and tidal turbine blades and complete advanced finite element modelling that is discussed in Section 3.1. In addition, the research team at NUI Galway have developed computational fluid dynamics models of marine renewable energy systems, which is discussed in Section 3.2.

3.1 BladeComp

BladeComp is an in-house developed software package aiming for the design and optimisation of wind and tidal turbine blades. BladeComp comprises advanced Finite Element (FE) analysis techniques and design optimisation strategies for efficient, robust and rapid design of turbine blades. The methodology utilized by BladeComp can produce blade models for a range of input properties, such as aerodynamic profiles, composite materials, layup distributions and loads. Since the composite wind turbine blade can be considered as thin-wall structure, shell elements are utilised by BladeComp to construct the skins and webs of wind/tidal turbine blade models. The generated blade FE models are meshed with a combination of triangular and quadrilateral composite shell elements with a smart interpolation algorithm. The algorithm controls the local major axis of the element to be in line with the blade fibre direction, which ensures the multidirectional laminates are in the correct orientation. BladeComp is a pre-processing tool and can interact with ABAQUS and Ansys Mechanical APDL as its solver. In terms of the blade optimisation, BladeComp involves genetic algorithm (GA) [3] to generate high-quality solutions to composite laminate optimisation under multiple design objectives. To satisfy different design goals, a wide range of blade attributes can be adopted as the optimisation objectives.

These attributes include, manufacturing cost, blade mass, blade stiffness and ultimate stress/strain. Figure 3 displays the concepts utilised by BladeComp, where all the optimisation procedures, namely the creation of blade FE models, the analysis of FE models and the GA-based evolutions, are automated. A user-friendly Graphical User Interface, which can be seen in Figure 2, is developed for BladeComp to generate and manage blade models easily and directly. The reliability and effectiveness of BladeComp were verified in several research projects which covered both wind and tidal blades [4-8]. According to the case study performed by Fagan et al. [6], the application of BladeComp can result in a 23% of mass saving as well as a 15.5% of manufacturing costs saving in the structural design of a 13 m wind turbine blade. The structural design of a 15 kW wind turbine blade was optimised by BladeComp [5]. Based on the static testing results, the tip deflection of the blade reduced by 15.8% without increasing the total material usage.

Figure 3. Design methodology employed by the BladeComp

Figure 2. A 1 MW tidal turbine blade created by the BladeComp
3.2 Computational fluid dynamics

Advanced computational fluid dynamics models have been developed for wave energy (single and arrays of point absorber wave energy converters (WECs)) and tidal energy (horizontal-axis tidal turbines) systems. These models have been developed using the commercial software, ANSYS CFX, where its solver is based on the finite volume technique [9].

Initially, a methodology for developing a linear numerical wave tank was developed [10], which was subsequently expanded to allow for linear irregular waves [11], similar to what is observed in the ocean. These models have been applied to a number of applications, including shape optimisation of a WEC [12], structural health monitoring of WECs [13] and to modelling the motions of the CECO WEC [14]. The numerical wave tank model has been coupled with a SWAN model to investigate the effect of WEC arrays on the waters in the nearshore wave climate off the West coast of Ireland [15].

Numerical models of tidal flow on horizontal-axis tidal turbines have also been developed [16]. These models have been used to estimate the forces on the tidal turbine blades during operation. In particular, the operational fatigue loadings induced on tidal turbine blades have been investigated, where two factors were considered - the presence of a support structure and varying vertical velocity profile of the tidal current.

4 EXPERIMENTAL TESTING CASE STUDIES

In order to demonstrate the testing capabilities of the Sustainable & Resilient Structures Research Group, two case studies are presented - a number of tidal turbine blades being tested, through various funded project, and a wind turbine blade, which is being tested as part of the LEAPWind project.

4.1 Tidal turbine blades

As tidal energy nears commercial viability, it is essential for developers to use innovation design and manufacturing techniques in order to produce highly efficient blades. Within the Sustainable & Resilient Structures Research Group, design capabilities are offered through their modelling capabilities, such as BladeComp, and de-risking these new techniques through large-scale structural testing of tidal turbine blades.

During the structural testing campaigns of the tidal turbine blades, a comprehensive instrumentation strategy is implemented in order to monitor the blade during the testing, using a data acquisition system. The force at each of the load introduction points using load cells, the displacement of the blade, in order to model its reaction to the loadings, and the strains on the blade surface at strategic locations are also monitored. This allows for in-depth data to be generated to inform the tidal device developers.

Three examples of tidal turbine blades being tested in the Large Structures Testing Laboratory are shown in Figure 4. Figure 4 (a) shows a single blade and connection of a 10-blade hubless turbine, which was developed by OpenHydro, where a fatigue testing campaign with approximately 1,000,000 cycles was completed. Figure 4 (b) shows a single blade of a 3-blade horizontal axis tidal turbine using a single loading point. Figure 4 (c) shows a foil of a helical tidal turbine with a load introduction system that uses a multi-actuator system, where further details of the test is given in Meier et al. [17].

Figure 4. Various tidal turbine blades installed for structural testing, where (a) and (b) use a single actuator and (c) uses the multi-actuator load introduction system
4.2 Wind turbine blade

The second case study being detailed in this paper is the structural testing of a full-scale wind turbine blade, which is currently ongoing at the Large Structures Testing Laboratory, NUI Galway as part of the LEAPWind project [18, 19]. In this project, a novel protection system against leading edge erosion (LEP) is being developed, which is being tested on a full-scale wind turbine blade undergoing fatigue loading.

The full-scale wind turbine blade is a 13-metre long blade from a 225 kW wind turbine, which has a mass of 674 kg. The blade is manufactured from glass-fibre reinforced powder epoxy composite material using a novel “one-shot” manufacturing process, which cures the different parts of a wind turbine blade (i.e. skin sections, spar caps web and root) in one single process to avoid the need for gluing. Steel inserts in the root of the blade provide a connection to the steel test fixture during testing. The steel test fixture has been designed and manufactured, where the details are provided in Kazemi Vanhari et al. [20], along with the loading profiles used during the testing campaign.

To date, the dynamic testing campaign has been completed on the blade, where the results and findings, along with a comparison to the numerical model of the blade, are given in Jiang et al. [21]. The next stage of testing will be the static testing campaign, followed by fatigue testing. The results from a previous flapwise static testing campaign [6] are compared to the results from the numerical model of the blade, with and without the LEP attached.

Figure 6. Comparison of the deflections from the FEA model of the full-scale wind turbine blade under the defined loading along the length of the blade with and without the LEP bonded and the experimental results [6]

5 CONCLUSION

In this paper, the research activities of the Sustainable & Resilient Structures Research Group at NUI Galway in relation to wind and tidal turbine blade testing have been detailed. This world-leading research work supports the growth of the renewable energy sector during the development of device concepts and individual components, as they move through the Technology Readiness Levels. The capabilities and facilities available to the group, including their expertise in numerical modelling and large-scale structural testing, have presented, along with case study examples of wind and tidal turbine blades that have been tested by the group, along with details of the in-house structural modelling software BladeComp and other numerical models been developed by the group.

The results from testing campaigns that are carried out by the Sustainable & Resilient Structures Research Group give developers confidence in their designs as they can examine the performance of their blades under design loads in a controlled environment. The ultimate load of the blade can also be determined and the results can be used to validate the numerical models used to design the blades. Fatigue testing of the blades gives an insight into their operational life span as it is performed using the cyclic loads that the blades would see in operation and can also be used to validate the material damage models included in the blade design. This will allow developers to improve the efficiency of their blade and, ultimately, aid in lower the levelized cost of energy, making their turbines more competitive with the more traditional methods of energy generation (i.e. fossil fuels).
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