Parasitic effects of load introduction points in full-scale composite tidal turbine blade tests

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Abstract. This research studied the optimization of load introduction points in full-scale composite tidal stream turbine (TST) blade tests with strain gauges and Digital Image Correlation (DIC) during a blade clamping procedure. The induced effects of saddles on TST blades were analysed, as current blade certification standards are based on wind turbine blades, which do not consider TST blades operation conditions. The experiments were conducted on a 5.25m composite blade at FastBlade, the world's first full-scale regenerative tidal blade fatigue test facility. The results show significant strain values at the interaction surface every time a bolt is tightened, which can be higher than those outside the disturbed area and could cause failure.

Introduction

The UK has a significant opportunity to increase its energy security by incorporating various green technologies, including tidal energy. Tidal energy is attractive as it is a predictable and reliable energy source. If fully harnessed, tidal energy could provide up to 50 TWh/year or 16% of the UK's total electricity consumption. However, the annual energy production of tidal generators in the UK has varied due to several prototype trials, peaking at 14 GWh in 2019 and decreasing to 4 GWh in 2021 [1]. Since the first tidal stream turbine (TST) device documented test in 1994, the industry has increased its development, requiring dedicated facilities to achieve affordable fatigue testing. Initially, the design and test methodology for TST blades has been adapted from wind energy. However, the loads and environmental conditions in which TST operates and their mechanical properties differ. The implications of these early assumptions can be seen in the current standards for tidal turbine certification, such as the DNVGL-ST-0164, where most sections refer to other standards mainly based on wind turbines. Regardless of the method used to load the blades in test rigs, the IEC 61400-23 standard obliges to exclude all the values inside the area covered by one blade chord length to each side of the load introduction point [2]. As the chord-to-span ratio is relatively high in tidal blades, applying the one-chord length criterion often leaves the test with no usable area for analysis along the blade. In that sense, this research aims to understand and minimise the induced effects of load introduction points in full-scale composite TST blade tests with the help of strain gauge measurements and Digital Image Correlation (DIC). Several load introduction methods have been explored on wind blades [3]. However, there has typically been more focus on improving the correlation between the test and the real moment distribution along the blade, neglecting the area surrounding the load introduction points, even though blades could fail exactly underneath the saddles [4]. Recently, DIC implementation has shown accurate strain fields on a full-scale wind turbine blade [5]. For full-scale tidal blade tests, a few studies [6] explored onshore testing with DIC implemented but focused on other aspects of the tests. To the author's knowledge, no studies focused on the damage induced by load introduction points on a TST blade prior to static and fatigue tests.

Materials and Methods

All the experiments and data collection was performed at FastBlade, the first full-scale regenerative tidal blade fatigue test facility that uses a Digital Displacement® hydraulic system [7].

Blade. The specimen is a 5.25m composite blade fixed to an 80-tonne test frame. It was part of a 500kW tidal turbine called DeepGen. It was designed by Tidal Generation Ltd and manufactured by Aviation Enterprises Ltd. The skin comprises an 8mm thick glass fibre with +/-45º unidirectional (UD) prepreg. The blade also has 6mm UD prepreg ribs along the span of the blade and carbon fibre prepreg spar caps and shear webs with variable thicknesses. Finally, a two-part iron casting is bonded to the spar at the blade root for fitting purposes.

Load Introduction Method. Medium-density fibreboard (MDF) saddles were fitted at 2.275, 3.56, and 4.477 metres from the blade's root. A steel frame surrounded the MDF at both sides, and six 20mm bolts were used to clamp the saddle to the blade. During the process, no significant changes in temperature were registered (less than 1 ^{o}C), ensuring reliable strain measurements.

Instrumentation. The DIC setup consisted of two pairs of cameras facing the pressure side of the blade. FLIR BFS-U3-88S6M-C cameras were used, all with a focal length of 12mm. The software package used to capture and process the images was MatchID® [8]. A set of 14 accelerometers, 60 strain gauges, and 3 extensometers were also used for correlation purposes. Strain gauges were placed in both linear and rosette modes.

Methodology. The pressure side of the blade between the root and the first saddle was selected as the region of interest. The DIC was calibrated in pairs, the first set was aligned with the y-axis and the second with the x-axis, as seen in Figure 1a. For calibration, 215 images were taken at 1Hz with 9,000μs exposure on all cameras. An average stereo error of 0.0192 pixels was calculated for both sets. After DIC calibration was evaluated, the bolts on both sides of the saddle were loosened until a 1mm gap could be observed between the MDF and the blade. Tightening started at 27.1Nm for all six bolts on both sides of the saddle and was increased to 81.4Nm in 13.6Nm increments. During the experiment, images were collected at 1Hz. Moreover, a finite element analysis (FEA) correlated the structural response of the blade at the interaction surface and showed the creation of a second-order moment when the actuator does not follow the blade's bending angle.

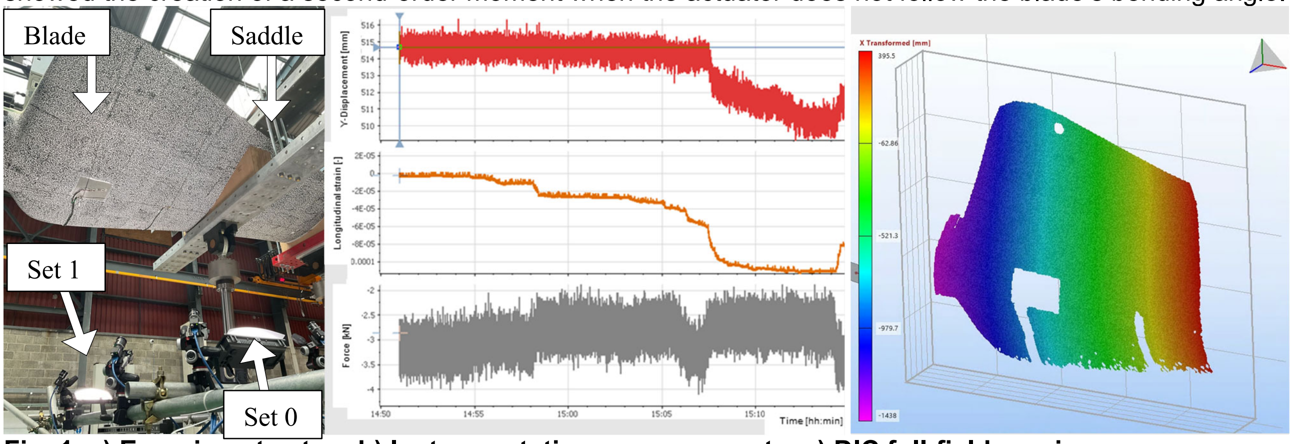

Fig. 1. a) Experiment setup, b) Instrumentation measurements, c) DIC full-field preview.

Results and Discussion

Initial results from the measuring instruments show the structural response of the blade every time a bolt is tightened. Strain gauges placed at 0.2m from the saddle experienced as much as 100με, and the load cell recorded a change in the force of 2kN (see Fig. 1b). Strain gauges located at 0.7m from the saddle experienced little to no change after reaching 81.4Nm of torque in all six bolts. The extensometer located near the saddle was able to detect a maximum displacement of 5mm, which given the mechanism of the ram, indicates that most of the displacement happened at the bottom side of the blade. The region of interest selected in the DIC (Fig. 1c) processing module shows a correlation with the strain gauge data, and maximum strain values of 1000με can be observed close to the contact. The blade's response also appears to be influenced by its internal structure, increasing the stress and strain values on its surface close to stiff components like the shear webs or the composite ribs. An analysis of the strain along the chord length at 0.2m from the saddle shows an increasing pressure gradient towards the leading edge, with the skin surface reacting more than the trailing edge skin. The regions close to the edges of the blade were not processed with DIC as they were positioned in a very distorted field of view. In that sense, the FEA shows high-stress concentrations in the blade edges that might be worsened by the narrow circular hole in the MDF profile, which could be minimised by chamfering and shifting the centre of pressure of the saddle with different torques applied to the bolts.

Conclusion

A test was run to quantify the impact of load introduction points during a tidal turbine composite blade on a test rig. During a clamping procedure, a 5.25m composite blade was equipped with stain gauges, temperature sensors, accelerometers, and a DIC system. The structural response of the blade was then recorded and processed. The clamping force of the saddle could result in longitudinal strain values up to two times higher than those outside the disturbed area, which can cause failure near the saddle or at the exact point of contact during static or fatigue tests. An FEA showed that a second-order moment could be created, damaging the blade much faster at the contact edge closer to the root as the load introduction points do not follow the blade's rotation angle as it moves upwards. A complete study during static and fatigue tests could find a methodology to determine the minimum torque needed to avoid slip from the saddles and thus minimise the disturbances in the area surrounding the load introduction points.

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