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DEVELOPMENT OF NOVEL MANUFACTURING TECHNIQUES FOR COMPOSITE TIDAL TURBINE BLADES

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ABSTRACT

As the global tidal stream energy moves closer to commercial viability, additional challenges are presented as developers strive to lower the levelised cost of energy in order to challenge the low cost associated with generating energy from fossil fuels. This paper details a number of novel techniques that have been developed in order to manufacture the next generation of tidal turbine blades from composite materials. The main challenges that are overcome include the manufacture of thick section laminates, an integrated design approach for a robust root connection, and a quantification of the effect of saltwater immersion on the glass fibre composite. In order to prove the resilience of the proposed solutions, physical testing has been performed and some of the results are presented in this paper, particularly in relation to the effect of saltwater immersion on the composite material and the manufacture of thick section laminates. These advances will give tidal turbine blades the best chance of surviving the harsh environment presented, along with maintaining a design life of 20+ years.

1 INTRODUCTION

After many years of delay, tidal stream energy is now becoming a commercial reality. The MeyGen project is set to become the first 4-turbine, 6MW tidal array [1], and in 2017, Scotrenewables Tidal Power's SR2000 tidal current turbine (Figure 1) generated 1.2 GWh of electricity over a 5-month period [2]. At the same time, EDF [3] is committed to projects in France using the OpenHydro/DCNS tidal device and projects are also being considered in the Bay of Fundy in Canada and elsewhere. A number of market assessments for tidal stream energy have been independently developed and as with any early stage technology sector there is a wide degree of variation between projections. The

Figure 1: Scotrenewables Tidal Power's SR2000 tidal current turbine being deployed

International Energy Agency’s ‘Blue Map’ medium growth scenario predicts 13GW of installed tidal capacity by 2050 [4], with a high growth scenario of 52GW over the same period.

However, if the tidal energy sector is to build on these achievements and reach a state of commercial viability, further advances in both design and production of devices and their cost effectiveness need to be developed. A key measure of this is the Levelized Cost of Energy (LCoE), which needs to be competitive with fossil fuels and is currently estimated to be between 54 and 71 cent/kWh for tidal arrays [5]. Similar to the wind energy sector, tidal energy converters are beginning to converge to a principle design, the horizontal axis tidal turbine. An EU report by Corsatea and Magagna [6] indicates that 76 % of research and development efforts in the tidal energy sector are related to horizontal axis tidal turbine technologies. The key enabling technology within these tidal turbines are the turbine blades that convert the tidal energy into useful mechanical energy.

In this paper, several challenges for the composites industry in the manufacture of large (>8 metres length) tidal turbine blades and proposed manufacture solutions are presented. These challenges are not applicable to wind turbine blade manufacture as they are the result of the magnitude of the forces on the blades in an underwater environment. The main aspects that are investigated include the manufacture of thick section laminates, design of a robust root connection, and the effect of saltwater immersion on the glass fibre composite. In this paper, the development of novel manufacturing and design methods to produce an efficient composite tidal turbine blade, in terms of manufacturability, repeatability, and cost-effectiveness, are described. Detailed discussions on the advanced design, prototype testing, and their practical implementation have been provided.

2 MATERIALS & METHODS

2.1 Objectives

The aim of this study is to develop novel manufacturing techniques in order to produce cost-effective and efficient tidal turbine blades. However, to achieve this, a number of objectives had to be met, which are:

- to explore the effect of saltwater immersion on the mechanical properties of epoxy glass fibre composite,
- to successfully manufacture thick section laminates, and
- to develop and test a robust root connection.

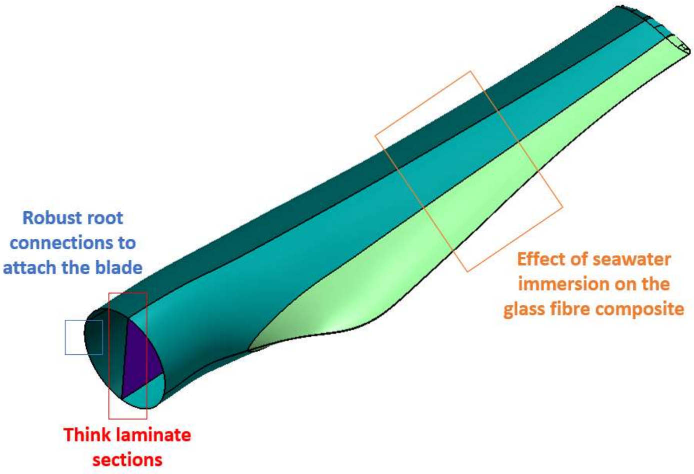


Figure 2: Novel aspects for the manufacture of tidal turbine blades

A schematic summarising these aspects, along with their relevance to the manufacture of tidal turbine blades is given in Figure 2. Materials were made in a hand layup process from UD and biaxial glass fibre fabric impregnated with a powder epoxy matrix. Test laminates and demonstrators were oven cured under vacuum pressure in an out-of-autoclave cure process. The manufacturing process has been described extensively by Maguire et al. [8, 9]

2.2 Effect of saltwater immersion on glass fibre composite

In order to investigate the effect of saltwater immersion on the glass fibre composite material, two sets of test specimens were placed in a saltwater conditioning tank at 50°C. Test specimens were conditioned at 50°C to aggressively increase the rate of ageing of the material over the test period. The first set was left immersed for a period of 60 days and the second set was immersed for 180 days. Concurrently, separate batches of unconditioned specimens were tested as a control or baseline to accurately assess the knockdown resulting from the saltwater immersion. The mechanical tests performed on these specimens, include 0° & 90° static tension tests to ISO527-5, 0° & 90° static compression tests to ASTM D6641, in-plane shear tests to ISO 14129 and tensile fatigue testing at $R = 0.1$. Water absorption of the test specimens was monitored using traveller specimens of 1 mm and 2 mm thickness that were also immersed in the saltwater conditioning tank and weighed regularly using a high precision weighing scales. After conditioning, test batches were wrapped in a saltwater soaked cloth and stored in plastic bags at room temperature. However, during testing there was no attempt made to keep the specimens surrounded by saltwater.

2.3 Manufacture of thick section laminates

As the loadings on tidal turbines are much larger than for wind turbines blades of the same length, the sections, particularly close to the root, are much thicker. Therefore, advanced manufacturing techniques to produce these thick section laminates were required. Thick section laminates with thickness ranging from 50 – 120 mm were processed in order to understand the behaviour of the material at multi-ply level. Initially, a 100 mm test laminate was produced to observe the thermal behaviour of the material during the cure, where 14 thermocouples were embedded in the laminate layup to record the temperature during processing. Additionally, trials for manufacturing the root end section using an end plate (with an end plate perpendicular to 0° fibres) were performed. These included investigating the use of end plates of differing heights, the distance of laminate from end plate and the use a caul plate to ensure constant thickness of the processed laminate section. In order to prove this manufacturing techniques at large scale, a full-scale half root section was produced. See Figure 7 for further details.

2.4 Robust root connections

As the reaction shear force and bending moment on the blade are largest in the root, it is necessary to design robust root connections, which are steel connections embedded in the composite for this design. This approach allows for a high strength connection that avoids post-manufacture re-working and does not require an adhesive. The turned steel inserts are installed in the layup during manufacture and remain in place during cure, creating a glass fibre epoxy-steel bond at the interface. Initially, trials were performed with a plain section 20 mm steel bar co-cured in a composite block in order to establish the maximum stress the bond could withstand, which resulted in a peak mean shear stress (MSS) on the composite-epoxy bond of 30 MPa. Therefore, to ensure static tensile (or pull-out) testing was within the capacity of the testing machine, ⅜ scale demonstrators were used to assess the performance of this novel root insert design. A programme of fatigue testing was also conducted on the ⅜ scale demonstrators

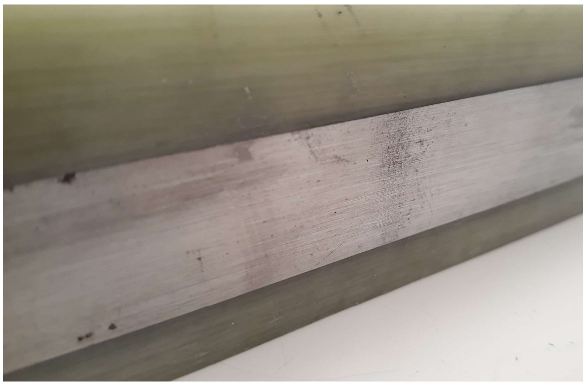


Figure 3: Steel insert embedded in glass fibre-epoxy composite – no adhesive

For certification of tidal turbine blades, DNVGL-ST-0164 [7] mandates full-scale testing of blade root connections and, therefore, testing of a full-scale root connection is planned to verify the results found heretofore.

3 RESULTS & DISCUSSIONS

3.1 Effect of saltwater immersion on glass fibre composite

For the operational life of the tidal turbine blades, they will be immersed in saltwater. Therefore, an investigation into the performance of the material when immersed in saltwater for different periods of time has been conducted. The change in tensile and in-plane shear strength and modulus after 60 days and 180 days is presented in Figure 4. For each of the tests a knockdown in both strength and modulus was observed. The most significant change was observed in the 0° tensile strength, which reduced by approximately 35% after 6 months. This is also the most critical orientation of the layup as the majority of the load will be transmitted in this direction. The knockdown in tensile strength and modulus was much lower for the 90° tensile test, where they were both reduced by approximately 9% after 6 months. On the other hand, there was negligible change when the specimens were tested for in-plane shear.

These knockdowns in both strength and modulus, compared to the initial baseline tests, should be incorporated in the design stage, where they may be accounted for within the imposed safety factors.

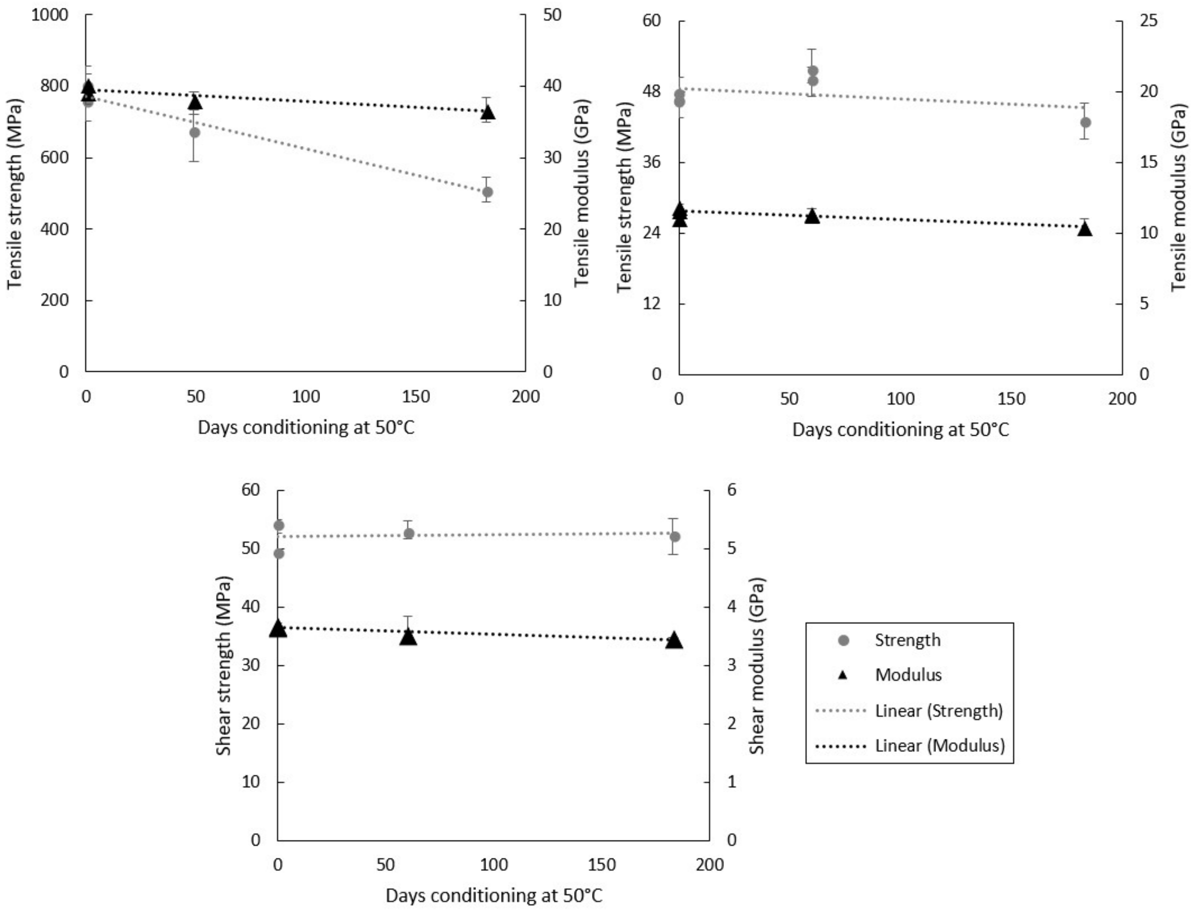


Figure 4: Strength and modulus of UD glass fibre composites after 0, 60, and 180 days conditioning at 50°C for (top left) 0° tensile ISO527-5, (top right) 90° tensile ISO 527-5 and (bottom) in-plane shear ISO 14129

Two 50 mm x 50 mm plates of 1 mm and 2 mm thickness were also placed in the saltwater conditioning tank at 50°C in order to investigate their water absorption by monitoring their change in mass over the test period. This experiment is for a worst-case scenario as, in operation, the composite material would be far thicker and would have a coating applied to it that would have a level of resistance for water uptake. The change in mass of the test specimens over time is plotted in Figure 5, where both the specimens reached a level of saturation of approximately 0.7% by the end of the period.

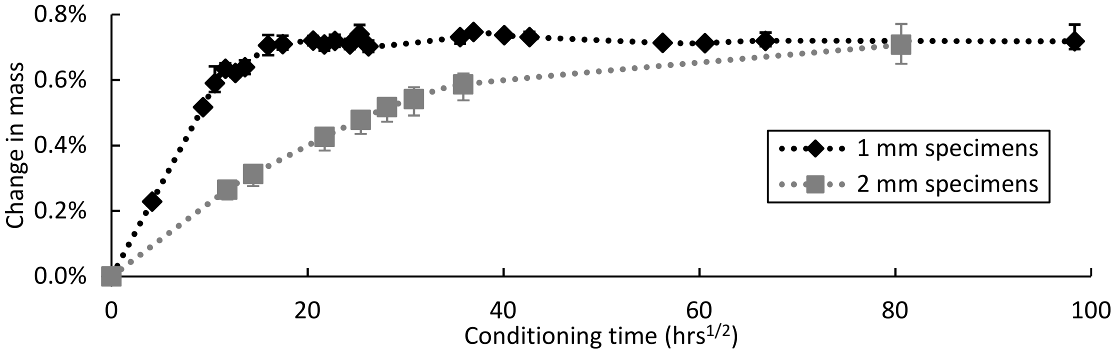


Figure 5: Change in mass due to water absorption of 50 mm x 50 mm UD composite specimens with a thickness of 1 mm and 2 mm

3.2 Manufacture of thick section laminates

In general the manufacture of thick section composite laminates is susceptible to problems in ply consolidation, voiding, non-uniform cure, and difficulties in transferring exothermic heat out of the laminate. The critical issue of whether the section reaches the required temperatures during the consolidation and curing stages of the process was investigated. Figure 6 displays the output from thermocouples that were embedded in a 100 mm thick section during processing. The variation in temperature of the top, middle and bottom ply, along with the oven temperature, is illustrated and shows that the temperature of the section approaches the desired level by the end of each stage. This analysis allows for the efficient design of the processing, including the length of stages, while ensuring that the section is cured throughout. An analysis of the laminate produced showed excellent consolidation of the with no voiding visible. Processing of thick section composite laminates using the powder-epoxy composites has also been investigated and modelled by Maguire et. al [8, 9].

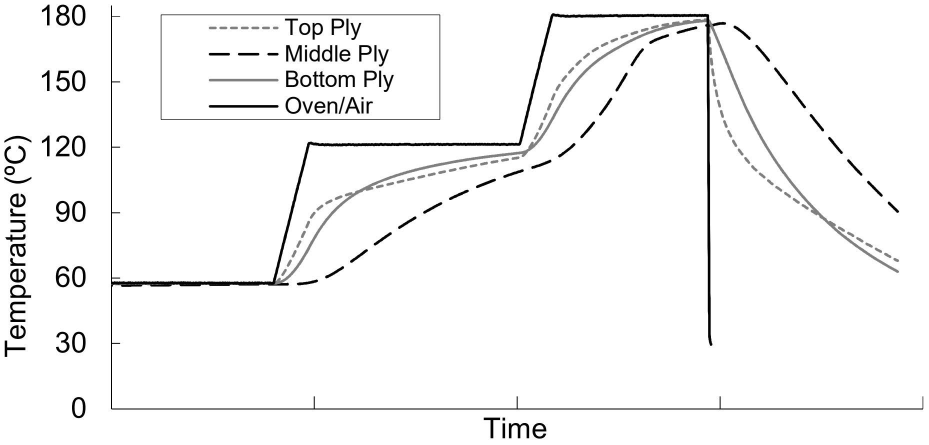


Figure 6: Variation in temperature of the top, middle and bottom ply in a thick section composite laminate during processing

In manufacturing the thick sections, the production of an evenly distributed, level laminate is a particular challenge. The most successful trial is shown in Figure 7 (a), where the end plate is the same height as the cured laminate thickness, which is in contact with layup, and a caul plate is on top of laminate. This method will be developed further to de-risk the technique, so it can be used in the production of tidal turbine blades.

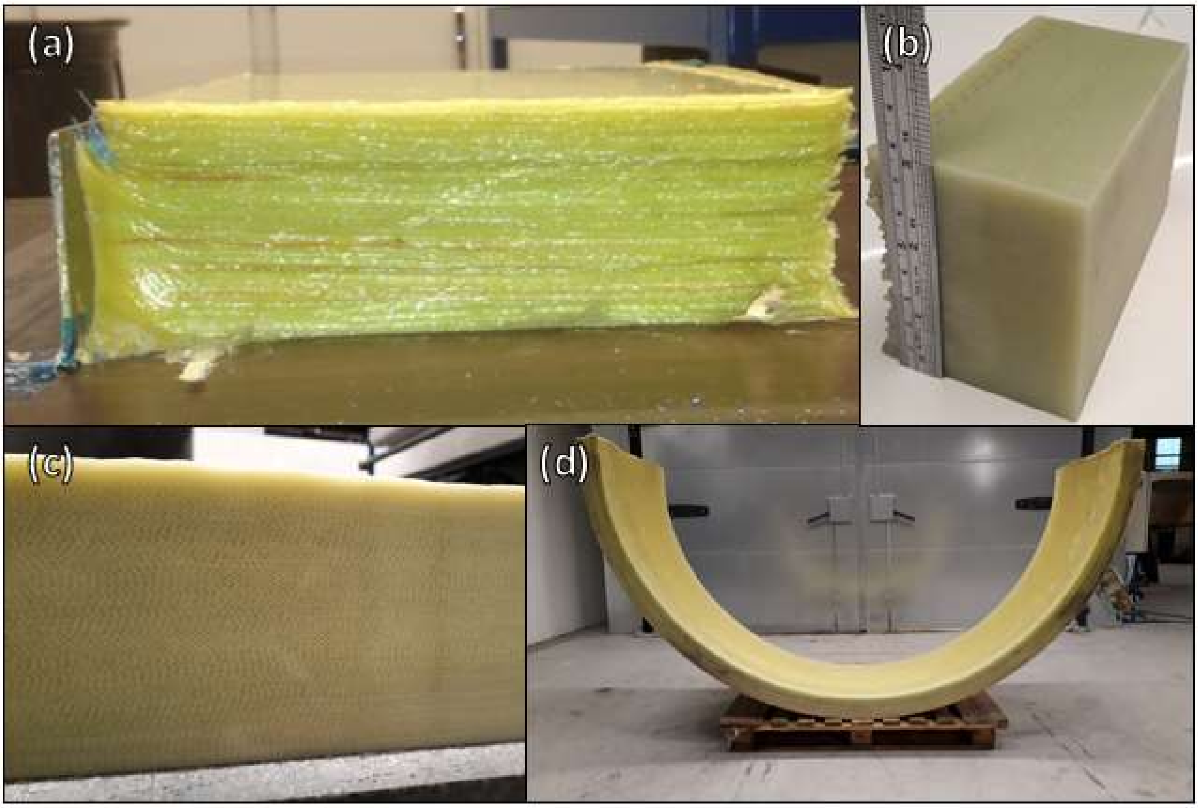


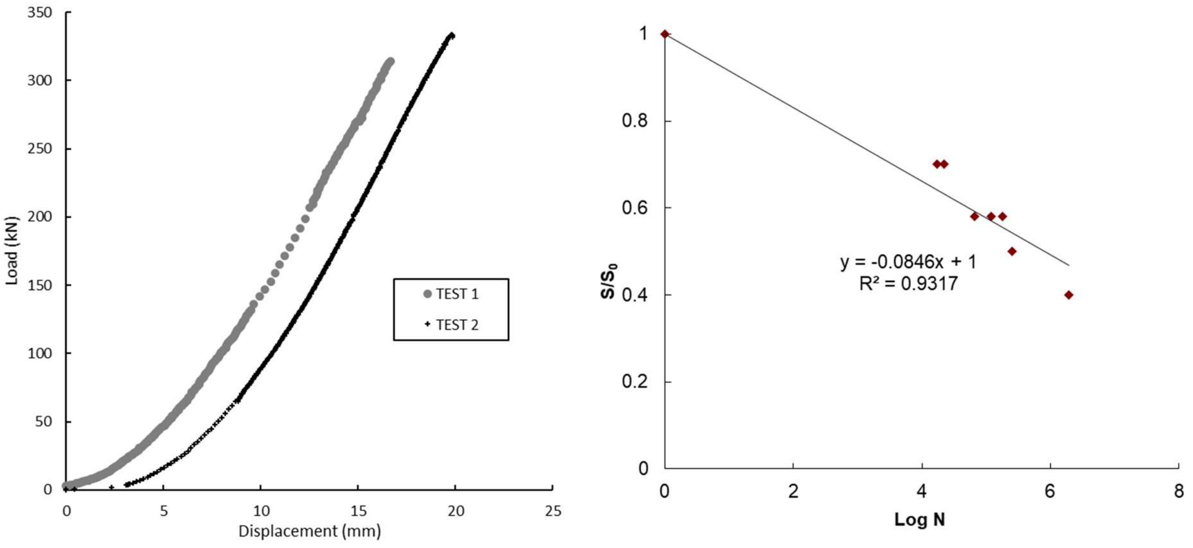
Figure 7: Trial thick section laminates for the manufacture of the root section of tidal turbine blades (a) level laminate demonstrator ~70 mm thickness (b) 75 mm thick section trial (c) 100 mm/96-ply laminate cross section (d) 100 mm thickness root section demonstrator

3.3 Robust root connections

Two steel inserts at ⅜ scale were tested in static tension and failed at loads of 315 kN and 334 kN, which represents a mean shear stress at failure of 23 MPa and 24 MPa respectively. Design features incorporated to resist other load cases have been attributed to the drop off in mean-shear stress at failure from the test discussed in Section 2.4

Figure 8 (a) shows the load-displacement plot for the two pull-out tests. The large displacement over the course of the test can be attributed to the wedge-action grips which ‘bedded in’ on the steel inserts throughout. An LVDT was mounted on the second test specimen to record the displacement of the insert with respect to the composite which showed a total test displacement of <0.25 mm.

The failure mode in each case was the sudden failure of the steel-epoxy bond. The demonstrators exhibited considerable residual pull-out resistance after failure due to friction between the two surfaces.



(a) **(b)**

Figure 8: Physical testing results of root insert demonstrators for (a) static pull-out testing and (b) fatigue testing

The results of fatigue testing conducted on root insert demonstrators are shown in Figure 8 (b). test specimens were tested at $R = 0.1$ and at various max loads (S/S_0). Max loads in fatigue testing were calculated as a proportion of the average static pull-out load where $S/S_0 = 1$ is the average static failure load. Cycles to failure were expressed in log form to produce the plot shown. The inverse of the slope of the linear fit (the slope parameter) describes the behaviour of the material. The slope parameter calculated from this testing is 11.8.

3.4 General discussion

The research conducted here has considered challenges in large composite manufacture from manufacturing limitations, to the effect of the operating environment, to the interface of the composite with other machine components. In overcoming these three obstacles the path is now clear to manufacture even larger composite structures and thus contribute to the increased adoption of tidal energy devices.

4 CONCLUSION

As tidal energy becomes commercially viable, innovative manufacturing techniques like those detailed in this paper will be vital in order to lower the Levelised Cost of Energy. The effect of saltwater immersion on the composite materials needs to be incorporated into the early stage design as the tensile strength of the material is shown here to be reduced by up to 35%. However, further testing on larger demonstrators or full-scale blades, immersed in saltwater during testing, should be performed in order to assess the true impact. A critical issue in the manufacture of thick sections is to ensure the section is cured throughout. Therefore, through the use of thermocouples during processing, the manufacturing process for these sections has been optimised, particularly in terms of the time for each stage.

Currently, ÉireComposites is in the process of manufacturing next generation tidal turbine blades for ScotRenewables. These techniques described in this paper, along with previous experiences in manufacturing wind turbine blades using epoxy-glass fibre composites, will be used in order to produce as efficient a blade as possible. Additionally, the manufacturing techniques described in this paper have further applications in the blue economy, including floating offshore wind and boats.

5 ACKNOWLEDGEMENTS

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