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Powder Epoxy Based UD-CFRP Manufacturing Routes For Turbine Blade Application

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POWDER EPOXY BASED UD-CFRP MANUFACTURING ROUTES FOR WIND AND TIDAL TURBINE BLADES

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ABSTRACT

The potential of ocean renewable energy is tremendous. However, further development of tidal turbine blades is required due to the harsh marine environment, large cyclic forces and high cost of installation. Carbon fibre reinforced polymers are promising materials for marine applications; hence, it is vital to understand fully their material properties and failure mechanisms. The tidal turbine blade processing conditions need to be perfected to ensure a robust and cost-effective design. In this study, a novel powder-based epoxy process, with low resin viscosity and low exotherm, is described. Two manufacturing routes were investigated. Initially, a hand lay-up process, which used a custom tensioning apparatus, was adopted to keep the carbon fibres straight during the thermal cure cycle. Additionally, a powder-epoxy-fed tapeline was developed as a first step to automation. Mechanical properties from both techniques were examined, with specimens from both processes exhibiting autoclave-like properties, which highlights the advantages of the powder epoxy based materials. Hygrothermal ageing of the composites in seawater conditions was also performed. At water saturation (1.23 wt.%), an 11.5% reduction of the failure stress was reported but stiffness was retained. Finally, fatigue testing was carried out to predict the durability of the structure.

1. INTRODUCTION

As the requirements of the wind energy market evolve, the length of wind turbine blades are increasing to increase the power harvested and to reduce the cost of electricity generated, so that typical turbines are now 100-metre-range superstructures weighing over 60 tons [1]. In this context, achieving high blade quality via well controlled manufacturing is essential. However, current vacuum infusion processes are limited by thermal runaway, insufficient fibre wetting and solvent release, which all compromise ultimate blade quality.

In addition, the developing tidal energy market, [2] is attempting to provide a stable, renewable and reliable source of energy. However, as water density is 800 times higher than that of air, the surface area required to achieve the equivalent energetic output as a wind blade is greatly reduced. This indicates that, in contrast to much larger wind structures, tidal turbine systems should ultimately incur lower manufacturing and logistic costs for an equivalent energy yield [3, 4, 5]. Yet, it is well known that composite mechanical properties deteriorate in water [4], and the challenges of designing a turbine blade for the highly variable load states in a marine water column mean that turbine blades are typically over-designed to account for increased risk of fatigue failure. The much thicker sections required (100 mm) are more vulnerable to exothermic events during processing and curing of the sections. The use of a powder epoxy resin, which has reduced risk of exotherm during cure, is hereby proposed for use in such tidal blade sections. Another major advantage of power-based epoxies is the absence of solvent, for safer and more ecologically-friendly processing. Finally, the ability to consolidate preforms prior to curing them together in a single step, giving a superior cohesion and removing a usually time-consuming bonding step, is a key argument in favor of the use of powder-based epoxies for industrial purpose.

In this study, a novel powder-epoxy manufacturing route will be investigated as an alternative method to vacuum infusion processing for both tidal and wind turbine blade processing.

2. EXPERIMENTATION

2.1 Material

The same powder epoxy system [6] and carbon fibre reinforcements [7] were used in both CFRP processing methods for comparison. The powder epoxy resin (EC-CEP-0016), supplied by ÉireComposites Teo (density 1.22 g/cm3), requires a heat activated catalytic process where the curing agent requires a temperature of 120°C for reaction initiation, as described by Maguire et al. [8] and Mamalis et al. [9].

Composite plates and coupons were manufactured using continuous tow carbon fibres T700S-24K-50C (1% sizing agent), T700S-24K-F0E (0.7% sizing agent) and T700S-24K-60E (0.3% sizing agent) from TORAYCA® (Toray Industries, Inc.) [7].

2.2 Processing routes

Two processing routes were studied in this paper: 1) an initial hand layup technique to demonstrate the processing feasibility of the powder epoxy based-CFRFP and investigate its mechanical properties; 2) a tapeline system developed in parallel and as a first step to automation of the powder-epoxy based CFRP manufacturing process.

2.2.1 Manual plate layup

Unidirectional carbon fibre powder epoxy composite (CFRP) plates with dimensions of 450 × 250 mm (length × width) and thicknesses of ~1 mm (5-plies) were fabricated. A hand lay-up process was used that included a specially designed tensioning apparatus to maintain fibre straightness and a steady fibre-tow formation and shape. Firstly, carbon fibre tows were cut to the desired length and laid side by side on a flat surface. Then, the fibre tows were combed by hand to align any loose fibres and smooth the appearance of the tows. Then, the taped fibres (plies) were loaded in the tensioning apparatus and clamped at both ends. The next step was to apply uniform tension using a torque wrench on the fibres in order to align them. The limit of fibre tension was detected when fibres started sliding at both clamped ends. Note that the applied tension on the carbon fibre plies was estimated by using a newton-meter. A mass of ~300kg was applied uniformly on the fibre plies which equalled ~ 3000N according to the tension readings. Furthermore, the powder-epoxy was distributed evenly on each ply to achieve a 60:40 (carbon: epoxy) final weight ratio of the laminate. The thickness of a single ply was approximately 0.2 mm.

The time/temperature cycle used was the same as that for layup of industrial parts [9]; drying from room temperature to 50°C in 1 hour followed by 16 hours isothermal-hold at 50°C, a second melting from 50°C to 120°C in 1 hour followed by 2 hours isothermal-hold at 130°C, and a third curing stage from 120°C to 180°C in 1 hour followed by 2.5 hours isothermal-hold at 180°C, followed by cooling to room temperature. The fabrication process was performed under vacuum conditions for consolidation. Breather cloth was employed to remove the air bubbles and volatiles. The test coupons of all T700S/epoxy composite laminates were cut using a diamond saw (wet) technique to produce high quality smooth edges avoiding any defects/imperfections that might affect the final mechanical performance.

2.2.2 Tapeline manufacturing

Tow-preg coupons were prepared using a custom-built tapeline employing carbon fibre tows (50C sizing) mounted initially on two bobbins (Figure 1) which were subsequently pulled through a closed chamber wherein powder was deposited onto the fibres via an electrostatic spray gun. The powder deposition unit is shown in Figure 2. The tows coated with powder-epoxy were then heated to melt the powder-epoxy onto the carbon fibre surfaces, creating a towpreg stable at ambient temperature. Figure 3 shows a schematic of the manufacturing unit including; the electrostatic powder deposition gun, the heating zone and the tow winding.

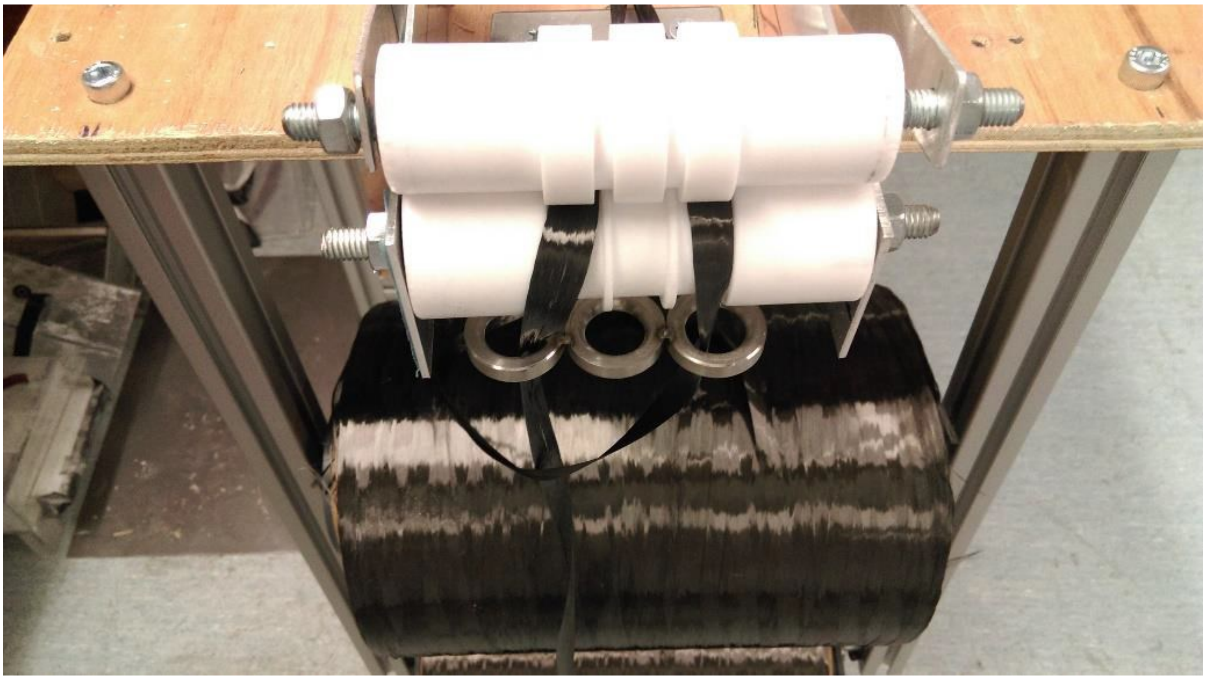

Figure 1: Tows being pulled from bobbins into the towpreg manufacturing unit.

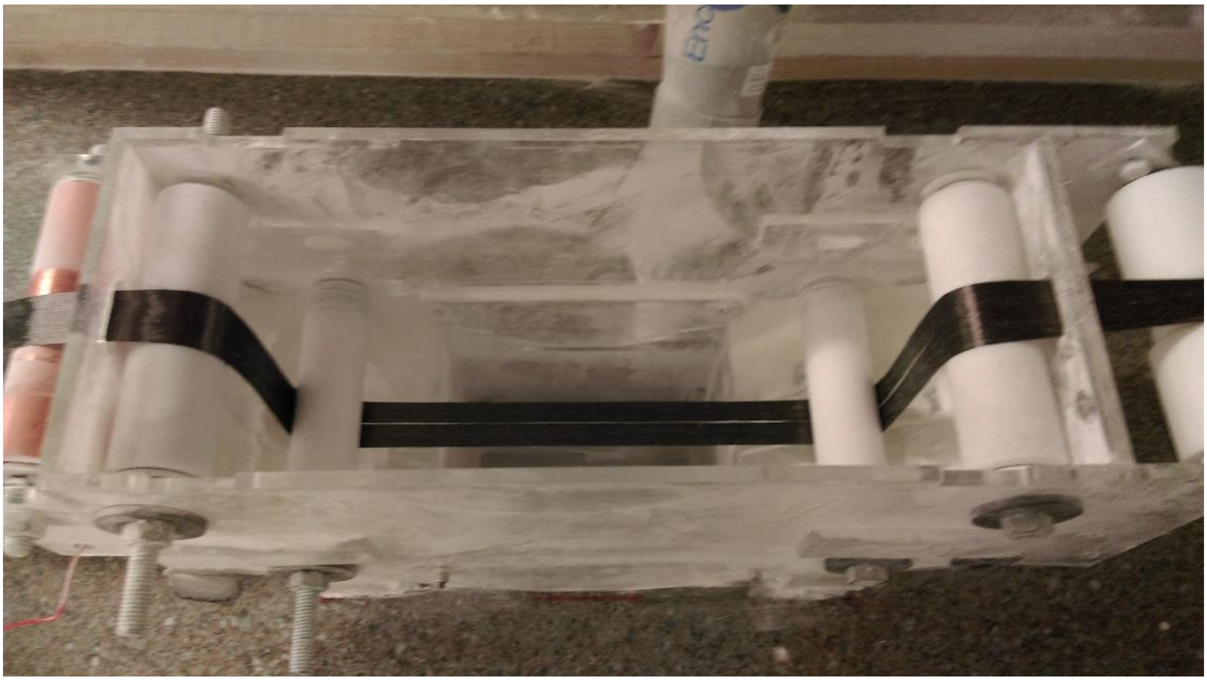

Figure 2: A plan view of the powder deposition unit.

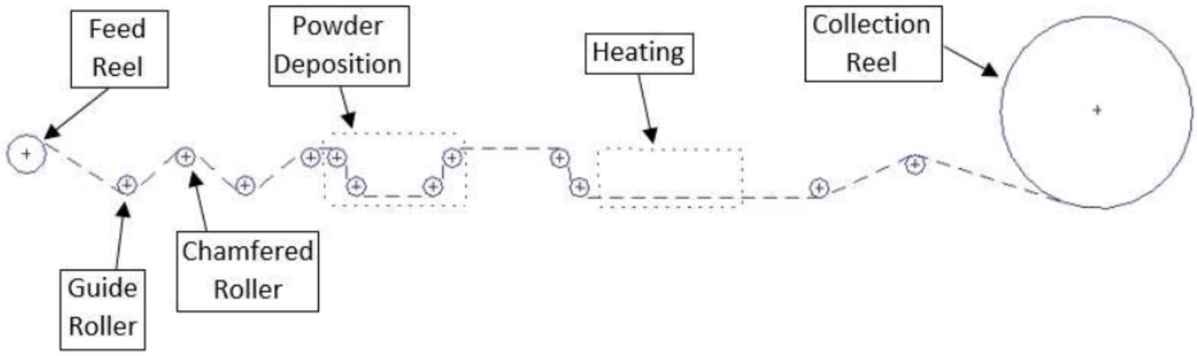

Figure 3: Schematic of Towpreg manufacturing unit showing positions of the electrostatic powder deposition gun, the fibre heating zone and the tow winding.

CFRP coupons were manufactured using a custom-made aluminium mould, Figure 4, with a manufacturing capacity of 10 coupons, each of which was milled to the standard ISO 527-5 dimensions for UD-CFRP testing. Once cured, CFRP coupons were end-tabbed with GFRP glued on using slow-setting epoxy resin (2 part Araldite standard).

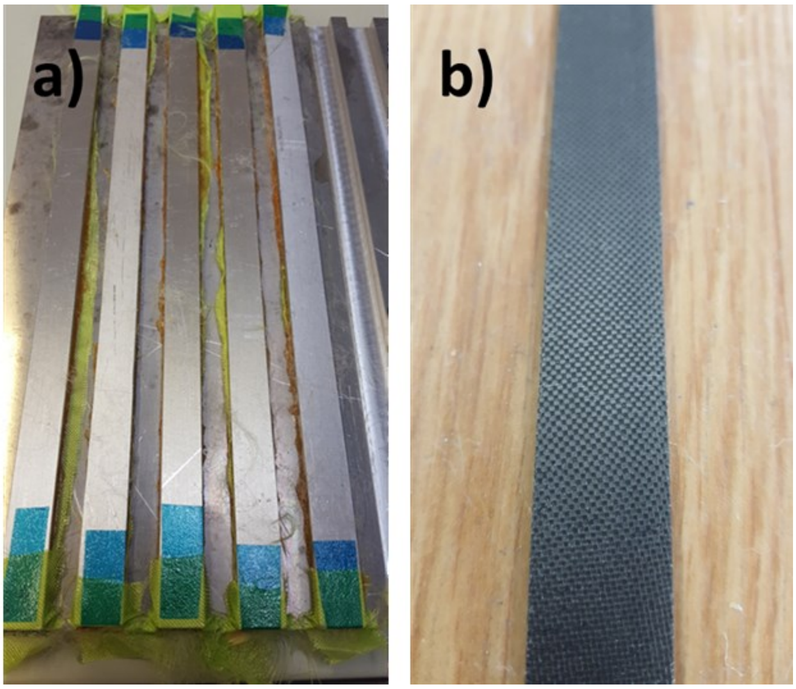

Figure 4: a) Aluminium mould used to manufacture tensile test coupons from UD-CFRP towpreg , an example of which is shown in b).

2.3 Water ageing

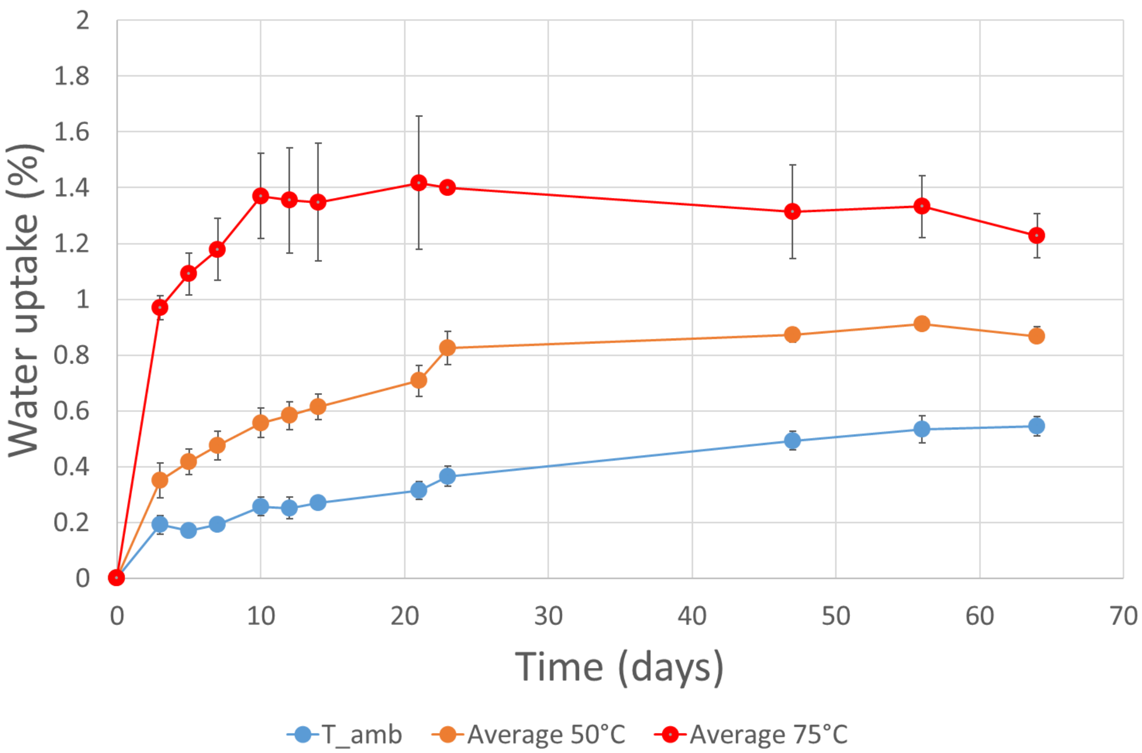

Figure 5: Water uptake by composites at T_{amb}, 50˚C and 75˚C plotted as a function of time

The samples were hygrothermally aged at ambient temperature (T_{amb}), 50˚C and 75˚C for 2 months in sea water sourced from the Edinburgh coastline. The immersion temperature was controlled using a 6 loop PID controller system from Omega. Travellers (samples kept specifically to check water intake) were weighed regularly to discern the extent of water uptake under each condition over the course of the 2 months (Figure 5). Control samples, not immersed in water, were labelled 'dry samples'. In this figure, specimens ageing at 75˚C can be seen to absorb water at a faster rate than specimens ageing at 50˚C, which in turn absorb water at a faster rate than specimens ageing at T_{amb} (around 21°C).

2.4 Testing

In the case of the hand laid up specimens, quasi-static tensile tests were carried out in accordance with BS EN 2561 using a minimum of 15 specimens (dimensions: 250 length x 25 width x 1 mm thickness) for each fibre sizing system, i.e., 50C, F0E and 60E, under tensioning conditions. Tensile tests of composite specimens were performed in a universal testing machine Zwick/Roell, model Z250 (250 kN load cell), with hydraulic grips and an MTS 632.85F-14 extensometer, at constant cross-speed between 2 mm/min. A minimum of 5 specimens were machined from each carbon fibre epoxy composite plate and subsequently tested.

Regarding Towpreg specimen, quasi-static tensile tests were performed in conformity with the ISO standard 527-5 on UD-CFRP coupons with an MTS Criterion Model 45 with a load cell capacity of 333 kN in static mode and gripped at a pressure of 100 bar. Both longitudinal and transverse strains were recorded using a digital imaging correlation system from Imetrum set to log data into the MTS elite software. 8 samples were usually used per sample set. Once the ultimate tensile strength (UTS) was determined, fatigue testing was performed on Instron 8801 with a load cell capacity of 250 kN in dynamic mode. After an initial fatigue investigation, the maximum load applied was set at 80%, 75% and 70% of the UTS. The R ratio used was 0.1 and the frequency was set at 5 Hz.

2.5 Fibre volume fraction (FVF) investigation

As the linear mass of the carbon tow was known, the FVF of each individual towpreg coupon was determined by weight measurement. The coupons were then classified depending on their FVF range. However, the resin bled out on the peel plies during the curing procedure, significantly increasing the FVF of UD-CFRP cured coupons (on average by 10% when working with 51% FVF towpreg, resulting in a final cured samples FVF of 61%).

FVF characterisation of the cured coupons was performed by a furnace burn-off technique, in compliance with the ASTM D3171 standard. As the burning time-temperature procedure wasn't specified (McDonough et al. [10]), TGA analysis was used to determine the most suitable furnace temperature program. A 30 minute ramp from ambient temperature to 600°C, followed by a 45 min isotherm, was performed to fully burn off the resin while retaining the carbon fibres intact. Samples were weighed on a precision scale (Ohaus adventurer) before and after burnoff.

3. RESULTS AND DISCUSSION

3.1 Fibres sizing influence on mechanical properties for hand layup specimens

Results of the tensile tests for the three tensioned composite cases (FVFs around 59%) are listed in Table 1. The average 0° tensile strength value of the UD composites reinforced with 50C fibres (~2650 MPa) was higher (~11% and ~13%) compared to the F0E (~2350 MPa) and 60E (~2210 MPa) composite cases, respectively, as seen in Table 1. Similarly, the (0°) tensile modulus of the composites reinforced with the 50C fibres (~134 GPa) was slightly higher; +7%

and +10%, than those of F0E (~127 GPa) and 60E (~121 GPa) laminates, respectively. Since the composite properties using all the T700S fibre sizing systems are the same [7], it might be expected that the composites (with equivalent FVFs) would exhibit similar tensile behaviour. However, the obtained tensile strength and modulus values for the three different composites, were different. This difference is attributed to the different amounts of sizing agent on the carbon fibre surfaces, which in turn could result in different fibre-matrix interfacial bonding strength and strain-to-failure. It is worth noting that the degree of the UD character, represented by the fibre straightness, for each composite most likely played an important role in the final tensile performance of the composites as reported by Mamalis et al. [9]. Thus, the varying degree of fibre straightness in connection with the sizing amount presented on the CF surface altered the tensile behaviour of the composites. Overall, the 50C-sized composite with the highest amount of sizing agent and the highest degree of fibre straightness [9], gave the best performance. Hence, this carbon fibre type was chosen as the optimum material for the investigation of the tapeline application.

Table 1: Tensile properties of the three type of CFRPs, under tensioning conditions. The tensile values are averages and they were calculated from ~6 tests for each composite case. Note that the tensile results of the fabricated composites were normalised at ~59% FVF for means of comparison.

Composite	Strength (MPa)	Modulus (GPa)
50C CF/epoxy	2650±120	134±4.1
F0E CF/epoxy	2350±100	127±2.8
60E CF/epoxy	2210±105	121±3.1

3.2 Influence of FVF on UD-CFRP mechanical properties

An initial investigation of quasi-static mechanical properties results depending on fibre volume fraction (FVF) was first undertaken to determine the optimal mechanical properties of dry UD-CFRP samples in tension. Figure 6 exhibits the ultimate tensile stress UTS of dry UD-CFRP measured within four FVF coupons towpreg ranges, from 46% to 65%. The samples were tested to breakage in quasi-static mode, in compliance with ISO527-5. The UTS increases as the FVF increases, reaching a peak at 56-60% FVF range. This result is expected as the fibres have a higher strength than the resin. However, above a FVF of 60% (as shown in Fig. 6), the UTS decreases. From these results, we deduce that the FVF is sufficiently high that fibres are not completely wetted by epoxy, and are consequently unable to bear as much load as fully-wetted fibre composites.

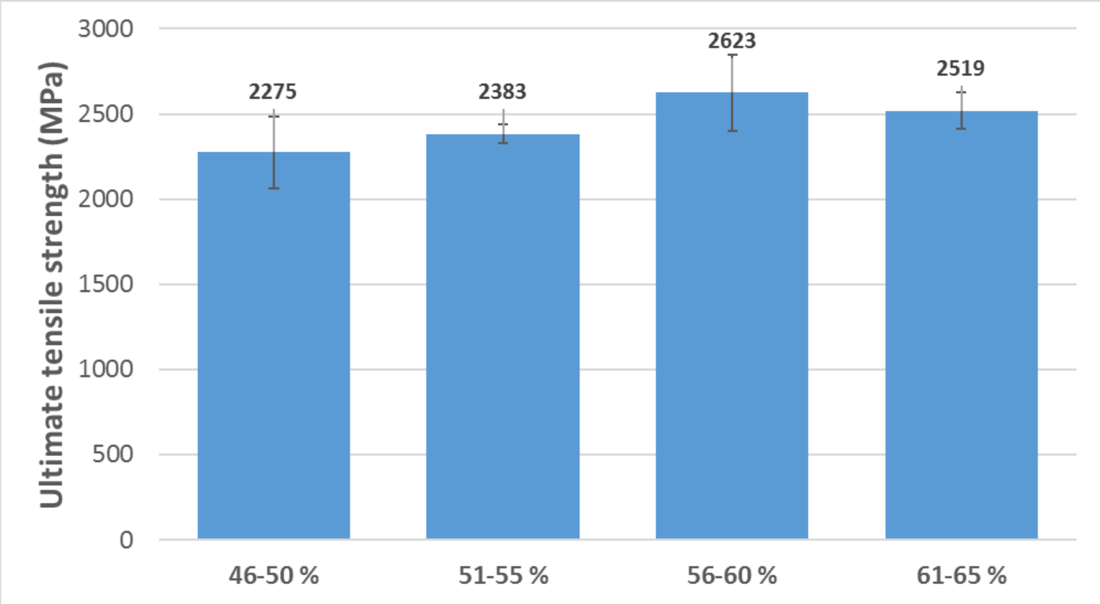

Figure 6: Ultimate tensile strength of UD-CFRP composites at 46-50%, 51-55%, 56-60% and 61-65% FVF. Error bars indicate the standard deviations in each sample set.

As the bleeding out behaviour was pronounced and the scatter started to increase in the 56-60 % towpreg coupons FVF, we therefore decided to continue the study working with the 51% to 55% towpreg coupons FVF range in order to reduce the scatter obtained with fatigue testing. Out of 200 samples prepared for the following investigation, the average FVF of the towpreg coupons was 51.40 +- 0.91 %, rising to 60.89 +-2.55 % once properly cured and consolidated.

3.3 Influence of water ingress on UD CFRP mechanical properties

As samples were aged in water at different temperatures, the rate of water absorption differs (Figure 5). All UD-CFRP sets (Dry, T_{amb}, 50°C and 75°C) were tested in quasi-static tension, and both the modulus and the stress at break were plotted against the final water content, as shown in Figure 7. There is a linear trend of mechanical properties decreasing with increasing water content and a slight decrease of the Young Modulus (1.62% loss per percent increase in water content). However, the stress at break is clearly more affected (8.79% loss per percent increase in water content). This study shows that the composite modulus is less affected by moisture ingress than the ultimate strength, which is significantly affected by water ageing, in agreement with the study of Tual et al. on CFRP seawater accelerated ageing [11].

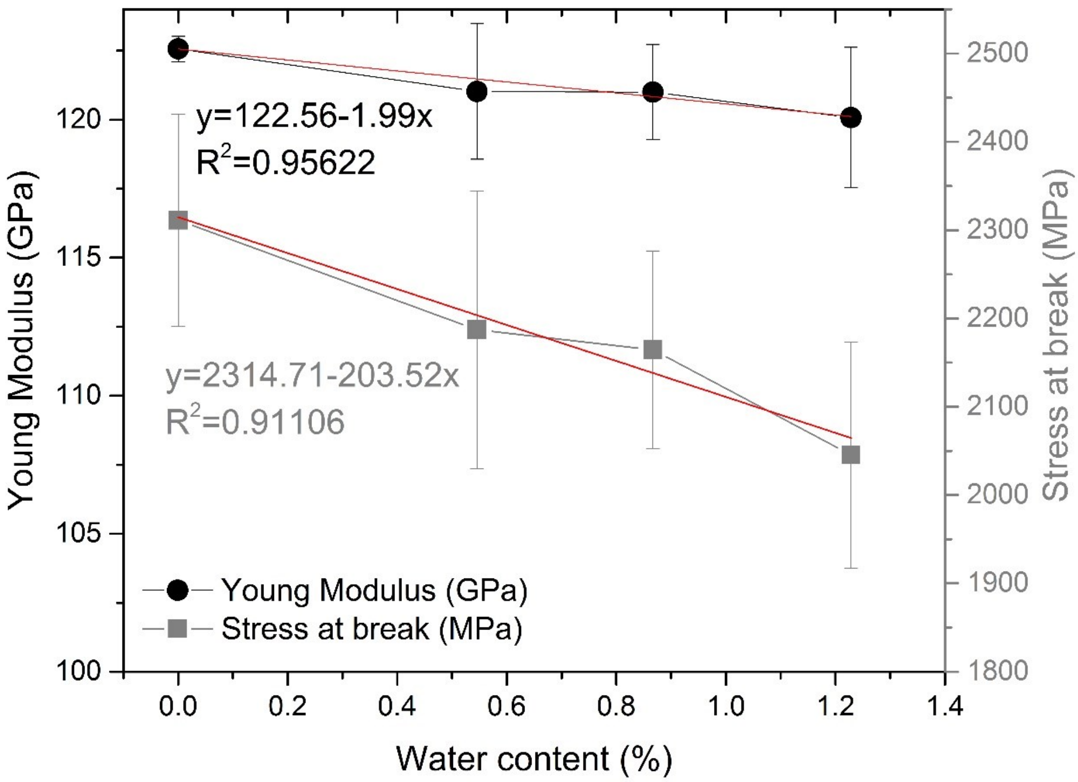

Figure 7: Quasi-static mechanical properties of UD-CFRP depending on their water content.

Water ingress in composites is a well-known phenomenon [12], usually governed by Fickian diffusion [13, 14], and is characterised by filling of voids within the matrix bulk [15], and wicking at the fibre-matrix interfaces [16]. The volume of water that will enter a CFRP laminate will depend significantly on the type of matrix polymer that is used. Epoxy matrix CFRPs tend to gain more weight through moisture absorption than vinyl ester- and urethane-acrylate-based CFRPs [17] since epoxies have molecular structures with larger numbers of hydrogen bonding sites per unit volume than esters and acrylates.

A CFRP laminate will swell when water enters its structure, in a similar manner to heat-induced swelling, and the extent of swelling will determine the level of damage caused to the fibre-matrix interface through both shear [18, 19] and compression [20]. The logical consequence of water ingress, swelling, internal localisation of stress, and the loss of interfacial shear strength, is that the ultimate stress of CFRP is detrimentally affected.

3.4 Fatigue properties of UD-CFRP tapeline samples

Figure 8 represents the dry UD-CFRP S-N curves obtained at loadings of 70%, 75%, and 80% of the UTS. The scatter in the fatigue data is typical of that for FRPs in general [21-26]. A

Weibull probability distribution function has been demonstrated previously for the analysis of high-scatter results obtained in S-N curves [24].

Allowing for scatter, the average cycle number values depending on stress applied of UD-CFRP S-N exhibit a definite trend as the average number of cycles to failure is smaller at 80% UTS than that at 75%, which is itself smaller than that at 70% UTS. Note that the testing was stopped after 1 to 2 million cycles, artificially reducing the cycle to breakage average number value obtained at 70% UTS. Although the general trend is steep, the results conform to those in the literature [27, 28, 29].

Every sample was manufactured separately from each other, and therefore were all unique. This could explain the large scatter in the results obtained. This tool needs to be replaced by a more versatile solution, to help reduce the scatter and allow more versatile configurations.

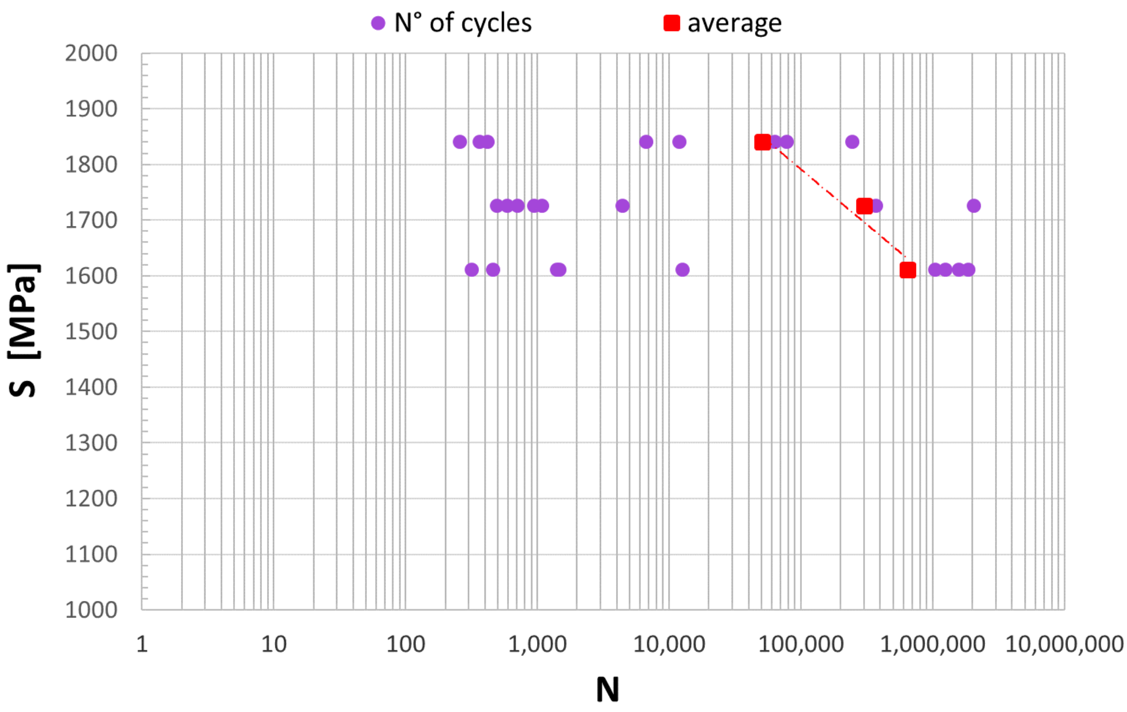

Figure 8: Dry UD-CFRP S-N curves (separated by imposed stress). The average values for each group within each batch are shown in red.

4. CONCLUSIONS

Tidal and wind renewable energy turbines present new challenges to composite designers and manufacturers: as key parts are becoming larger (e.g. blades), new processing technologies need to be developed to ensure the feasibility and reliability of the superstructures involved. In addition, improved understanding of the effect of water ingress on composite mechanical properties is critical. In this study, a new powder-epoxy based system (low viscosity, low exotherm) and new processing routes were developed to meet these new expectations. An initial hand layup processing investigation of the influence of sizing agent of T700S carbon fibre on the mechanical properties of a powder-epoxy CFRP laminate was performed. The process was then automated to demonstrate the potential application of this process to large structure manufacturing needs. The influence of fibre volume fraction on mechanical properties was determined, evidencing an optimal fibre volume fraction of 61%. The powder-epoxy system exhibited good mechanical properties under water ageing: at water saturation (1.23 wt.%), an 11.5% reduction in the CFRP failure stress was reported with minimal decrease in stiffness (2.0% loss). The dry samples were further tested in fatigue. Although the samples' fatigue test results revealed a high scatter, they generally agreed with results found in the literature, and the number of cycles to failure increased with decreasing applied stress.

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