Evaluation of the durability of composite tidal turbine blades

Peter Davies\textsuperscript{1}, Grégoire Germain\textsuperscript{2}, Benoît Gaurier\textsuperscript{2}, Amélie Boisseau\textsuperscript{1} and Dominique Perreux\textsuperscript{3}

\textsuperscript{1}Materials and Structures Group, IFREMER Brest Centre, 29280 Plouzané, France
\textsuperscript{2}Hydrodynamic and MetOcean Service, IFREMER, 62321 Boulogne/Mer, France
\textsuperscript{3}MaHyTec, 210 Avenue de Verdun, 39100 Dole, France

The long-term reliability of tidal turbines is critical if these structures are to be cost effective. Optimized design requires a combination of material durability models and structural analyses. Composites are a natural choice for turbine blades, but there are few data available to predict material behaviour under coupled environmental and cycling loading. The present study addresses this problem, by introducing a multi-level framework for turbine blade qualification. At the material scale, static and cyclic tests have been performed, both in air and in sea water. The influence of ageing in sea water on fatigue performance is then quantified, and much lower fatigue lives are measured after ageing. At a higher level, flume tank tests have been performed on three-blade tidal turbines. Strain gauging of blades has provided data to compare with numerical models.

1. Introduction

In order to develop cost-effective tidal energy conversion systems, the reliability of turbine blades must be as high as possible. Ideally, the development of an optimized composite tidal turbine blade would involve several iterations between material characterization (cyclic loading in sea water), structural analysis and fluid/structure interaction modelling, small-scale flume tank tests and instrumented prototype projects. This process can be represented as a test pyramid, similar to those applied in aeronautical developments, figure 1, with testing and modelling at each level. At this
stage in the development of tidal turbines, data from prototype demonstrators are largely confidential, but considerable information can be gained from the other steps in the process. This study will present a series of such results.

First, results from fatigue tests in sea water of glass and carbon-fibre-reinforced composite materials will be discussed. Both new specimens and specimens aged for up to 9 months at 60°C in natural sea water were tested. Weight gain measurements at different temperatures for over a year have enabled diffusion kinetics to be established, so that the transition from material data to structural behaviour can be modelled. Water ingress modifies the material response, and may also affect fatigue properties. Changes are not simple, as failure modes can also vary as ageing progresses, so a thorough understanding of the influence of water on the kinetics of failure mechanisms is essential if expensive accidents are to be avoided. A recently completed 4 year study in collaboration with glass fibre and resin suppliers focused on this point [1,2], and a brief summary of the main results will be given here. Additional results from a study on carbon fibre composites will also be given.

Results from flume tank tests, in which three sets of blades instrumented with strain gauges were subjected to a range of test conditions, will then be presented. These tests have provided valuable data at the small structure scale and, in particular, provide indications on how current speed and current/wave interactions can affect turbine blade response.

Next, the development of a coupled fluid/structure analysis for a three-blade tidal turbine rotating at a fixed speed in a constant velocity flow field will be briefly described. The blade models were initially checked by comparing with the response during static loading tests. The implications of these results, both in terms of testing to qualify materials and in the modelling of long-term durability, will be discussed.

Finally, the importance of manufacturing and process control in the development of reliable turbines will be illustrated by an example involving the manufacture of a multi-blade prototype composite turbine. Composite quality depends on manufacturing, and even if materials are optimized, their long-term durability will not be achieved if manufacturing conditions are not optimal.

2. Marine experience of composites

There is extensive experience of composites in marine structures, from pleasure boats to offshore structures [3–5]. The influence of water on composite properties has been studied for many years and is now reasonably well understood [6–8]. Studies of ageing in sea water are less frequent, but some data are available [9–13]. Many marine structures are not highly loaded however, so
there has been little interest in cyclic loading during immersion, nor of the influence of wet ageing on fatigue performance. An exception is for composite propellers, though these are not yet widely used.

3. Materials

A natural starting point for a study of tidal turbines is the composite materials used today for wind turbines. Short wind turbine blades are manufactured using glass-reinforced thermosetting resins, and infusion is widely used. Longer blades are increasingly using carbon fibre reinforcement to achieve the required stiffness, but the dimensions of most tidal turbine blades are less than 10 m long. Wind blades have shown good resistance to fatigue loads, and have been studied in various large projects that have generated significant amounts of fatigue data [14–16]. However, it is recognized that the loading of tidal turbine blades is quite different from that of those used to generate wind energy, principally due to load variations in the water column (seabed boundary layer, turbulence intensity level and/or wave–current interaction effects) and cavitation. An infused glass/epoxy composite currently used for wind blades was selected as the baseline material for tests. A similar glass-reinforced composite material was used for the OpenHydro tidal turbine prototype immersed in the Bay of Fundy, which was recovered in 2010 with all the blades missing [17]. Few construction details are available for prototype tidal turbines. The 11 m diameter Seaflow composite rotor featured a 65 mm thick carbon-fibre-reinforced spar bonded to fibreglass ribs and sheathed with a fibreglass-reinforced skin, all using a marine-quality epoxy resin matrix. The spar was made using proprietary prepreg, vacuum bagged and cured in an oven at 75°C [18]. The subsequent 16 m diameter SeaGen rotor blades comprise a hollow carbon fibre composite box spar as the main load-bearing member, along with carbon ribs, and a glass-fibre composite envelope bonded to this skeleton. Prepreg was used for both carbon and glass elements [19]. The wet fatigue of carbon composites is therefore also of interest; so materials based on carbon-reinforced epoxy prepreg were also tested in this study.

4. Material characterization

The different materials studied were first subjected to a range of mechanical and physico-chemical analyses using standard equipment. Only the tests developed specially to study durability will be detailed here. Some tensile tests have been performed in sea water in a specially designed fixture, figure 2a, but specimen preparation is time consuming; each specimen requires bonded end tabs, and the sealing system that holds the water vessel is an elastomer that must be cast onto the specimen. The loads are also high, so large-capacity fatigue machines with special gripping systems are required, and thus this approach is not well suited to generating fatigue data.

The main test used to characterize the different materials was therefore four-point flexure. This has the advantage of introducing tensile, compressive and shear loads in the same test and is more easily adapted to immersion testing than standard tensile or compression configurations. Small-capacity test machines such as those shown in figure 2b can also be used, making it easier and cheaper to multiply test stations. Unfortunately, the main disadvantage of this test when it is performed on parallel-sided glass-reinforced specimens is a tendency for premature failure to occur owing to indentation below the loading points. For this reason, a dog-bone specimen was developed, which allows central span failures to be obtained in either tension or compression.

It should also be emphasized that this is a test that is very sensitive to environmental effects, as the most highly loaded parts of the specimen are in contact with water; so a diffusion model is essential if results are to be transposed to other geometries.

5. Influence of wet ageing

The natural sea water ageing facility at Institut Français de Recherche sur l’Exploitation de la Mer (IFREMER) in Brest, figure 3, was used to determine diffusion kinetics and to condition specimens
before testing. Conditioning tanks are maintained at different temperatures (4°C, 20°C, 40°C, 60°C, 80°C), and the water, natural sea water from the Brest Estuary, is continuously renewed.

**Figure 4** shows examples of weight gains for immersions at 20°C and 60°C for 400 days of two materials, an infused quasi-unidirectional E-glass/epoxy (90% 0° plus 10% mat and 90° fibres), **figure 4a**, and a unidirectional (UD) carbon/epoxy from prepreg (**figure 4b**). The resins used are both based on epoxy chemistry, but the formulations (infusion grade and prepreg) are quite different. Nevertheless, the weight gains are similar for both, reaching a level of around 1 per cent after a year at 60°C. The unreinforced infusion resin used here (**figure 4b**) saturates at 60°C in sea water at 2.5 per cent, but other epoxy resin weight gains at saturation vary in the range from 1 to 5 per cent, so much larger differences than those measured here can be observed.
Figure 4. Weight gains in seawater. (a) Infused E-glass. (b) Carbon/epoxy prepreg. (a,b) Squares, 60°C; circles, 20°C.

Figure 5. Influence of wet ageing (sea water 60°C) on quasi-static flexural behaviour of E-glass/epoxy composites.

The absorbed water will affect both quasi-static and fatigue behaviour. The modulus remains reasonably constant after ageing, but figure 5 shows an example of the loss in E-glass/epoxy properties under quasi-static loading. It is interesting to note the change in flexural failure mode after a certain ageing duration. Initially compressive (C), the failure became tensile (T) after about 8 weeks in sea water at 60°C.

Figure 6 shows how ageing at 60°C in sea water affects fatigue performance of flexural glass (figure 6a) and carbon composite (figure 6b) samples.

All specimens were kept in water between removal from ageing tanks and testing in continuously renewed sea water at 20°C ($F_{\text{max}}/F_{\text{min}} = 0.1$, where $F_{\text{max}}$ and $F_{\text{min}}$ are the maximum and minimum applied loads, test frequency 2 Hz, upper span 60 mm, lower span 120 mm). The glass/epoxy showed a very large reduction in fatigue life after ageing. Once again, there was a failure mode change, new samples fail in compression, whereas aged samples failed in tension, suggesting there may be a stress corrosion mechanism acting [20,21]. The carbon/epoxy material was tested using both dog-bone and parallel-sided specimens. The parallel-sided specimen results shown here correspond to interlaminar shear failures, not fibre failures. This is of interest as large interlaminar shear stresses may be generated at the connection between turbine blades and the central hub [22].

It is clear that extended ageing can result in significant property losses. The extent of these is directly determined by the matrix resin formulation. Tests have been performed on alternative resin systems, and this reduced these losses considerably. Fibre sizing (coatings added to improve
handling and matrix adhesion) can also play a role; the results shown above were for fibres with sizings optimized for the epoxy resin, but non-optimized fibre sizings were also tested in the project and resulted in lower fatigue lives. These results emphasize the need for very careful composite selection for this application.

6. Tests on small structures

In order to examine the behaviour of a small structure, both mechanically and in the flume tank, a three-bladed model turbine, with three different series of instrumented blades was manufactured. These used a sandwich construction, with a polyurethane casting giving the blade its form, stiffness was then increased by adding a single external layer of composite reinforcement, either chopped strand mat, to provide an isotropic layer, or quasi-unidirectional (90% UD) glass to give an orthotropic reinforcement. Both were impregnated with epoxy resin. Static cantilever bending tests enabled the stiffness of the three series of blades to be measured on a standard test machine. The blades were rigidly clamped at the hub end, and a controlled displacement up to 5 mm was applied vertically to the tip. The resulting load was recorded providing force–displacement plots for each of the nine blades. Figure 7 shows three examples that indicate a quite linear response for these small displacements. The use of a single layer of 300 g m$^{-2}$ glass mat reinforcement more than doubles the bending stiffness, whereas a layer of 1250 g m$^{-2}$ UD E-glass composite increases it by a factor of 6. These tests also enabled the strain gauges to be checked, and provided data to compare with blade model calculations.

At a higher level on the pyramid in figure 1, flume tank testing can provide valuable information on the response of small-scale tidal turbines under controlled conditions [23–30]. Figure 8 shows one of the models tested here, a 1/30th scale model (dimensions 1/30th of those of the full size turbine) of a three-bladed turbine prototype. The blades were a modified version of the National Advisory Committee for Aeronautics (NACA) 63418 blade, 305 mm long with a 90 mm chord.

A specially designed autonomous data logger recorded the strain gauge responses during all tests, at an acquisition frequency of 100 Hz. In addition, measurements of the thrust forces and moments acting on the model were made with a custom-built three-dimensional load cell from six axes (load capacity 1000 N, maximum moment 800 Nm).

The flume tank at the IFREMER Centre in Boulogne-sur-Mer allows models to be subjected to both current profiles and waves (figure 9). The dimensions of the flume tank are 18 m long by 4 m wide and 2 m deep. The flow turbulence can be adjusted between three discrete conditions: 5, 8 and 25% (though it could be extended to other conditions between 5 and 25% with modifications.
to the inlet honeycomb if needed). The flow velocity range is 0.1–2.2 m s\(^{-1}\). The wave generator is composed of eight independent displacement paddles 0.5 m wide and 500 mm deep. It can be easily moved between an upstream or a downstream surface position in order to create waves propagating with or against the current. Without current, the capabilities of the wave generator enable the production of regular waves with a period range between 0.5 and 2 s and a maximum peak-trough height of 280 mm. Measurements revealed that the resulting reflection coefficient was less than 12 per cent for all the usual periods and amplitudes.

Tests were performed with varying imposed turbine rotation speeds, from 0 to 140 r.p.m., at different current velocities, from 0.4 to 1 m s\(^{-1}\). A series of tests were also performed with a constant current speed and superposed waves, with an amplitude of 50–120 mm and frequency of 0.5–0.75 Hz. Blade pitch angle was varied for some test conditions.

Two test campaigns, performed in 2009 and 2010, generated very large amounts of data. There is insufficient space here to provide full details, but some examples of the results are shown below.

**Figure 10a** shows an example of the mean strain measurements from gauges on two blades without composite reinforcement at different current flow speeds. The gauges were placed at two-thirds of the length of the blade from the hub. Strains were quite high, reaching 0.15 per cent at the highest flow speed. Error bars indicate the minimum–maximum strain range measured. The loads on the blade increase with the square of the flow speed, which explains the form of the strain increase.

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**Figure 7.** Static flexural stiffness of blades.

**Figure 8.** Model turbine with strain-gauged composite blades before flume tank immersion. (Online version in colour.)
Figure 9. Flume tank, IFREMER Boulogne Centre, showing wave generator. (Online version in colour.)

Figure 10. Tensile strains on polyurethane blades at 100 r.p.m. (a) Strains for different flow speeds. (b) Detail at 0.6 m s\(^{-1}\).

Figure 11. Strains and drag force measured on glass mat-reinforced blade versus TSR. (a) Strains for different flow speeds. (b) Drag force under wave and current.

Figure 10b shows a detailed recording of the strain variations in two blades during each cycle for a 0.6 m s\(^{-1}\) flow speed. This reveals a significant variation in strain during each cycle, with a phase difference between the two recordings. These plots suggest that a small cyclic loading owing to rotation is superposed on the flow-induced bending strain.
Figure 11a shows an example of the mean strains measured on a glass mat/epoxy composite-reinforced blade. Error bars show standard deviations. The strains are significantly lower than those measured on the polyurethane blade (figure 10a), but for a given rotation speed, the increasing trend with increasing flow speed is similar. An increase in 1.5 of the flow speed at a tip speed ratio TSR = 6 produces an increase of the blade strain by a factor of nearly 3.

Figure 11b shows the drag force measured with the load cell during tests with waves and current. The two different curves correspond to the two cases: waves in the current direction and waves against the current. The wave was the regular one at 0.60 Hz frequency and 120 mm amplitude, and the current speed was 0.4 m s$^{-1}$.

On this figure, no significant difference is apparent between the two configurations, except for the amplitudes of the standard deviations (error bars). For the case of waves in the current direction, the fluctuations were 1.6 times larger, with about 80 per cent of the mean value, compared with the case of waves against current for which they reach 50 per cent. These fluctuations are larger than the ones usually observed without waves, between 10 and 20 per cent depending on the turbulence intensity [31].
A part of the time evolution of the drag force (figure 12a) and the strains (figure 12b) are shown in figure 12, with their corresponding fast Fourier transforms. On both these spectra, the wave frequency at 0.60 Hz is clearly visible. This confirms that the force fluctuations are related to the flow fluctuations, coming mainly from the waves. There is no other visible frequency on the force spectrum, whereas the rotation frequency (≃1.4 Hz) and its harmonics are identified on the strain spectrum (figure 12b) with wide peaks (≃2.8 and 4.2 Hz).

The other peaks on figure 12b are difficult to identify owing to a lot of different possible sources such as waves, flow turbulence, revolution speed or interactions between waves, current and the model.

It should be emphasized that these were the first tests performed that combined both waves and currents, and the results are included to show the potential of the test facility. A more extensive test programme will be performed to clarify the contributions of waves, current and rotation speed.

7. Numerical modelling

Various numerical models have been developed in order to link the material testing to the structural application. COMSOL MULTIPHYSICS software was used throughout, as it is well suited to coupled modelling problems, both at a material level (water diffusion coupled with mechanical loading) and at a structural level (fluid/structure interactions). For example, at a specimen level, the dog-bone geometry was modelled, and a coupled model with strength versus weight gain input data enabled a flexural failure mode transition from compression to tension to be predicted [13].

A three-dimensional geometrical model of the turbine blades was generated by laser scan, figure 13, which enabled the correct geometry to be imported directly into the finite-element, software, figure 14a.

This numerical model could then be loaded both mechanically and by a fluid, as shown in figure 14b, using the coupled fluid dynamics and structural mechanics software modules.

Such models offer the potential for numerical studies of the influence of material parameters and blade shapes, but they must first be validated with respect to experimental data. The validation should include both comparisons between experimental and numerical flow fields (using results such as those shown in figure 15), and correlations between predicted and measured mechanical behaviour of the turbine (performance, loads, strains). Detailed results will not be
shown here, as the development of the models and the programme of validation tests are currently still in progress. This mechanical model should provide a useful tool, complementary to other numerical methods [32,33] more dedicated to flow studies.

8. Manufacturing

In order to make the transition from small-scale models to prototypes and industrial structures, the top of the pyramid in figure 1, careful consideration must be given to manufacturing. Indeed,
the influence of manufacturing quality on long-term durability should not be underestimated. Figure 16 shows one example to illustrate this point. Two series of specimens based on nominally the same materials (same epoxy resin, optimal sizing, Advantex glass fibres, infused at 35°C, post-cured for 10 h at 70°C), but different manufacturing batches, were tested in sea water under the same four-point flexure cyclic test conditions. Quality control checks, including interlaminar shear revealed lower quality for series A, and this is clearly revealed in poorer
fatigue performance compared with specimens of good quality (B). The failure mechanisms were the same for both series (failure in compression of the upper face), and earlier damage at the fibre/matrix interface is believed to account for the lower fatigue lifetimes of series A.

MaHyTec (http://www.mahytec.com/home.html?id_lang=2) has developed a marine current turbine prototype to study manufacturing procedures (figure 17). This is being used both to optimize the manufacture, with an outer shroud housing in glass/epoxy and carbon/epoxy blades, but also to perform fatigue tests on blade materials. The turbine is loaded by water jets and rotates so the response of the blades to cyclic loading can be evaluated. Different materials (fibres and resins), stacking sequences and blade geometries can be studied. The use of composite materials for blades and other structural parts of marine current turbines offers the possibility to reinforce the structure in the more highly stressed directions by choosing appropriate fibre orientations. Composites can also combine extension and twist of blades owing to the coupling coefficient, which can be observed in the stiffness tensor of laminated materials. This last point can be especially useful for hydrodynamic performance where changes in rotation speed can induce a change of blade profile. Composite materials can thus provide a way to produce passive smart blades to improve the efficiency. This has been studied recently [34,35], and could provide a significant additional benefit, provided the service loads are well known.

9. Conclusions

Ensuring the long-term durability of ocean energy structures is a key element in the development of cost-effective industrial systems such as tidal current turbines. The combined experience of composite boats and composite wind turbine blades has led to a common belief that composites can be used in tidal turbine blades without further development. However, coupling between sea water diffusion, ageing processes and high mechanical loads can result in very severe loading conditions, which must be fully investigated if costly failures at sea are to be avoided. The integration of durability evaluation in a testing and modelling pyramid similar to those used in the aerospace industry allows a systematic framework for material qualification. This study provides some examples from such a pyramid applied to composite tidal turbine blades. Material characterization, small-scale structural tests, flume tank trials and manufacturing studies are briefly described. However, the development of a complete validated model is complex and must also include sea trials on larger structures, as these are required to define loading conditions more accurately than tank tests. Data from large-scale blade instrumentation during sea trials should become available shortly, to improve the analysis.

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