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Evaluation of the durability of composite tidal turbine blades

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Abstract:

The long term reliability of tidal turbines is critical if these structures are to be cost-effective. Optimised 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. This paper 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 seawater. The influence of ageing in seawater 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.

Keywords: Composite ; Fatigue ; Ageing ; Tidal Turbine ; Flume tank ; FE model

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 optimised 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, Fig. 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 paper will present a series of such results.

First, results from fatigue tests in seawater 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 seawater 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

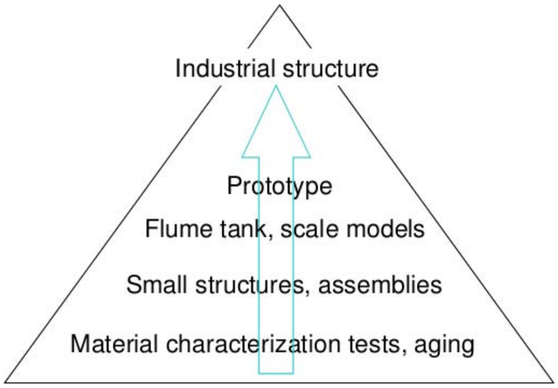


Figure 1: Tidal turbine test pyramid

if expensive accidents are to be avoided. A recently completed 4-year study in collaboration with glass fibre and resin suppliers focussed on this point [3, 6] 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 optimised 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 [32, 7, 31]. The influence of water on composite properties has been studied for many years and is now reasonably well understood [33, 21, 35]. Studies of ageing in seawater are less frequent, but some data are available [10, 15, 8, 23, 4]. 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 metres long. Wind blades have shown good resistance to fatigue loads, and have been studied in various large projects which have generated significant amounts of fatigue data e.g. [19, 27, 28]. However, it is recognized that the loading of tidal turbine blades is quite different to 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 [30]. Few construction details are available for prototype tidal turbines. The 11 metre 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 [20]. The subsequent 16 metre 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 [9]. 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

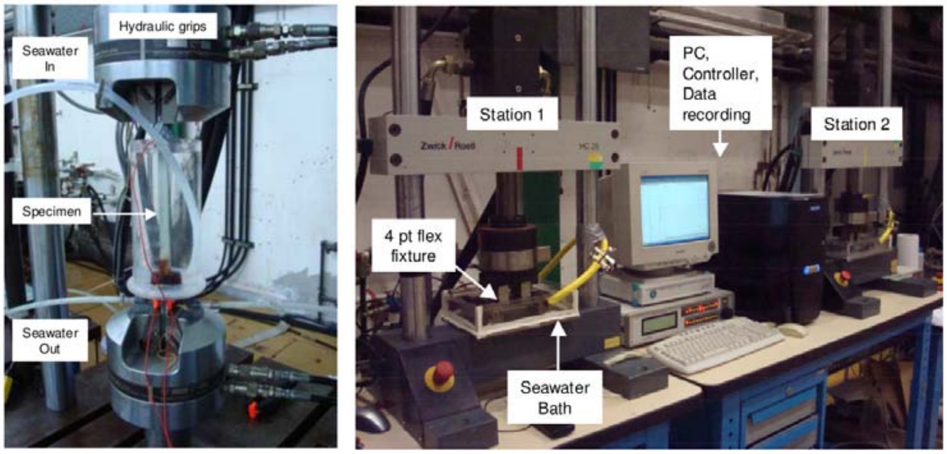
The different materials studied were first subjected to a range of mechanical and physicochemical analyses using standard equipment. Only the tests developed specially to study durability will be detailed here. Some tensile tests have been performed in seawater in a specially designed fixture, Fig. 2a,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

The main test used to characterise 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 Fig. 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 due 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 which 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 seawater ageing facility at IFREMER in Brest, Fig. 3, was used to determine diffusion kinetics and to condition specimens before testing. Conditioning tanks are maintained at



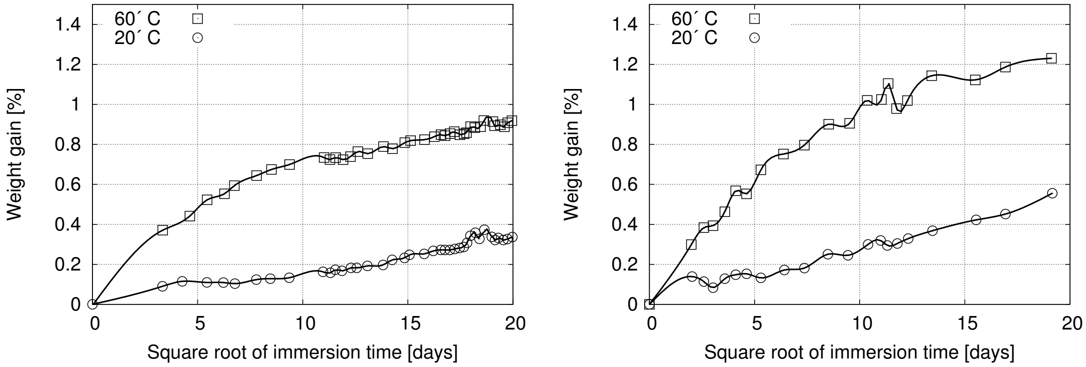
(a) Tensile test set-up (b) Flexural test set-up

Figure 2: Test set-up for static cyclic tests in seawater

Figure 3: Natural seawater ageing facility

different temperatures (4, 20, 40, 60, 80°C) and the water, natural seawater from the Brest Estuary, is continuously renewed.

Fig. 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), Fig. 4a, and a unidirectional (UD) carbon/epoxy from prepreg, Fig. 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 % after a year at 60°C. The unreinforced infusion resin used here (Fig. 4b) saturates at 60°C in sea water at 2.5 %, but other epoxy resin weight gains at saturation vary in the range from 1 to 5 % so much larger differences than those measured here can be observed.



(a) Infused E-glass

(b) Carbon/epoxy prepreg

Figure 4: Weight gains in seawater

The absorbed water will affect both quasi-static and fatigue behaviour. Modulus remains reasonably constant after ageing but Fig. 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 seawater at 60°C.

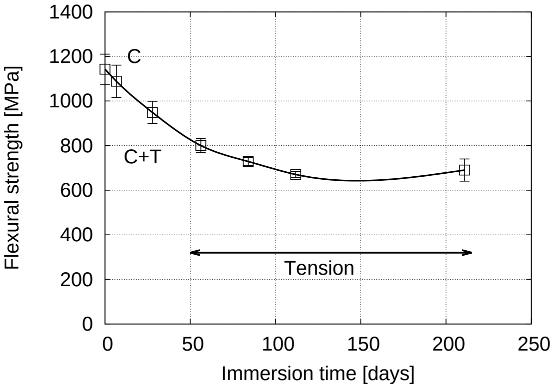
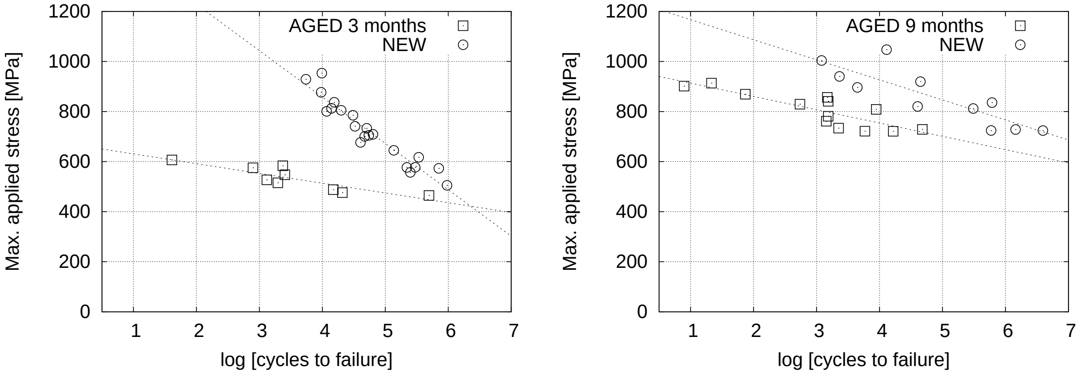


Figure 5: Influence of wet ageing (seawater 60°C) on quasi-static flexural behaviour of E glass/epoxy composites

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

All specimens were kept in water between removal from ageing tanks and testing in continuously renewed seawater at 20°C ($F_{max}/F_{min} = 0.1$, where F_{max} and F_{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, aged samples failed in tension suggesting there may be a stress corrosion



(a) Glass/Epoxy, Quasi-UD, Wet fatigue, 2 Hz, R=0.1, Dogbone specimens

(b) Carbon/epoxy UD, Wet fatigue, 2 Hz, R=0.1, Parallel specimens

Figure 6: Influence of wet ageing (seawater 60°C) on fatigue behaviour

mechanism acting [5, 29]. 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 [34].

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 optimised for the epoxy resin, but non-optimized fibre sizings were also tested in the project and resulted in lower fatigue lives. These results emphasise 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. Fig. 7 shows three examples, which 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, while 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.

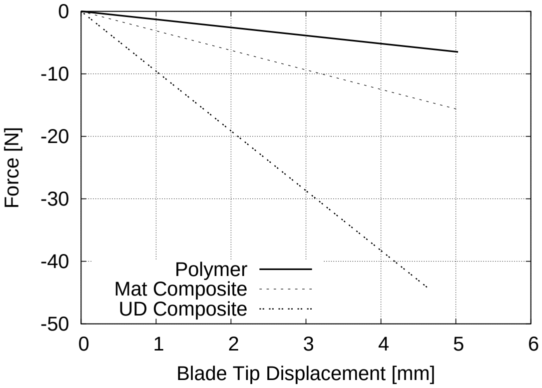


Figure 7: Static flexural stiffness of blades

At a higher level on the pyramid in Fig. 1, flume tank testing can provide valuable information on the response of small scale tidal turbines under controlled conditions [11, 12, 13, 22, 24, 25, 1, 2]. Fig. 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 NACA63418 blade, 305 mm long with a 90 mm chord.

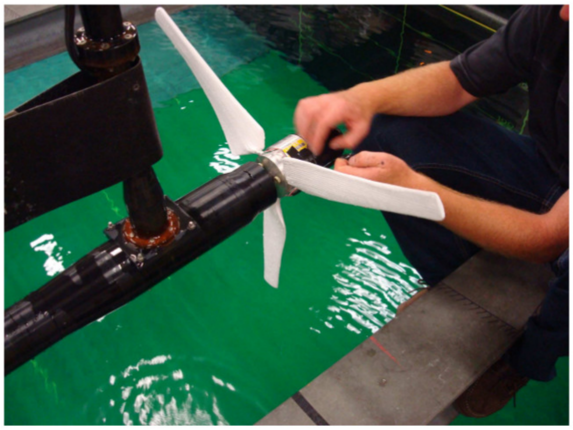


Figure 8: Model turbine with strain gauged composite blades before flume tank immersion

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, Fig. 9. The dimensions of the flume tank are 18 m length by 4 m wide and 2 m deep. The flow turbulence can be adjusted between 3 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 to 2.2 m/s. The wave generator is composed of 8 independent displacement paddles of 0.5 m width 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 to 2 seconds and a maximum peak-trough height of 280 mm. Measurements revealed that the resulting reflection coefficient was less than 12 % for all the usual periods and amplitudes.

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

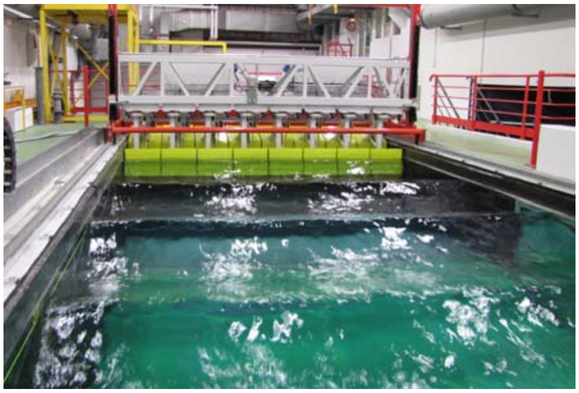


Figure 9: Flume tank, IFREMER Boulogne Centre, showing wave generator

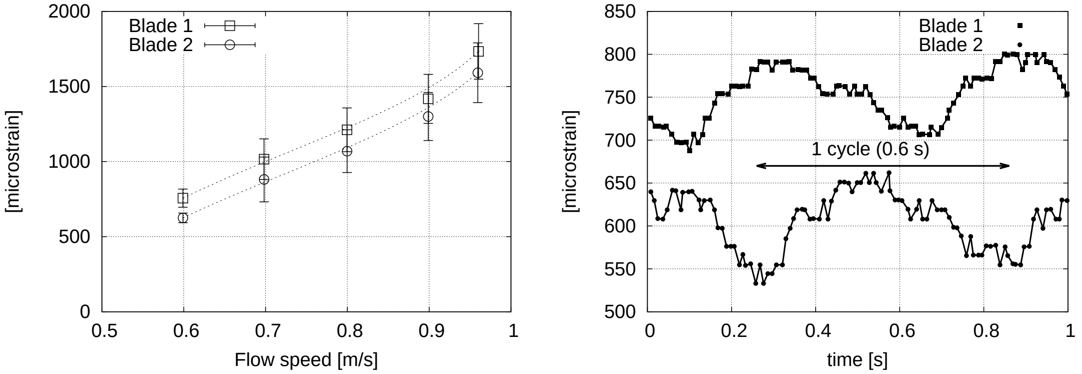
Two test campaigns, performed in 2009 and 2010, generated very large amounts of data. There is insufficient space here to provide full details, but some examples of the results are shown below.

Fig. 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 % 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.

Fig. 10b shows a detailed recording of the strain variations in two blades during each cycle for a 0.6 m/s 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 due to rotation is superposed on the flow induced bending strain.

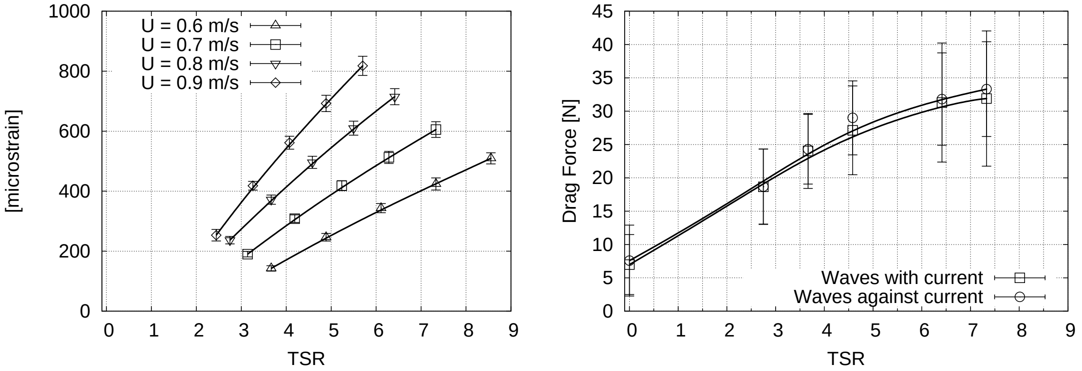
Fig. 11a shows an example of the mean strains measured on a glass mat/epoxy composite reinforced blade. Error bars show standard deviations. The strains are significantly lower than those measured on the PU blade (Fig. 10a) but for a given rotation speed the increasing trend with increasing flow speed is similar. An increase of 1.5 of the flow speed at Tip Speed Ratio (TSR) = 6 produces an increase of the blade strain by a factor of nearly 3.

Fig. 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



(a) Strains for different flow speeds (b) Detail at 0.6 m/s

Figure 10: Tensile strains on PU blades at 100 RPM



(a) Strains for different flow speeds (b) Drag force under wave and current

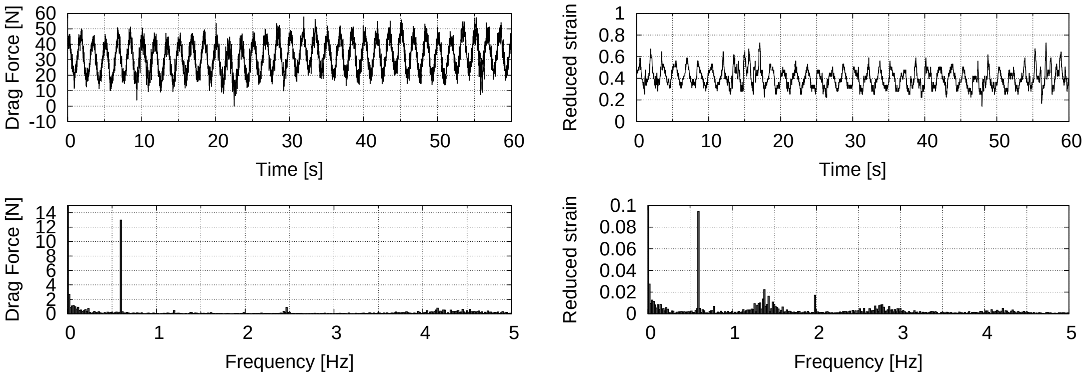
Figure 11: Strains and drag force measured on glass mat reinforced blade versus TSR

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.

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 % of the mean value, compared to the case of waves against current for which they reach 50 %. These fluctuations are larger than the ones usually observed without waves, between 10 and 20 % depending on the turbulence intensity [17].

A part of the time evolution of the drag force (Fig. 12a) and the strains (Fig. 12b) are shown below, 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 ($\simeq$ 1.4 Hz) and its harmonics are identified on the strain spectrum (Fig. 12b) with wide peaks ($\simeq$ 2.8



(a) Drag force

(b) Reduced strain

Figure 12: Drag force and reduced strain evolution with time and FFT

and 4.2 Hz).

The other peaks on Fig. 12b are difficult to identify due 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 which 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 [4].

A 3-D geometrical model of the turbine blades was generated by laser scan, Fig. 13, which enabled the correct geometry to be imported directly into the FE software, Fig. 14a.

This numerical model could then be loaded both mechanically and by a fluid, as shown in Fig. 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 Fig. 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 [16, 14] more dedicated to flow studies.

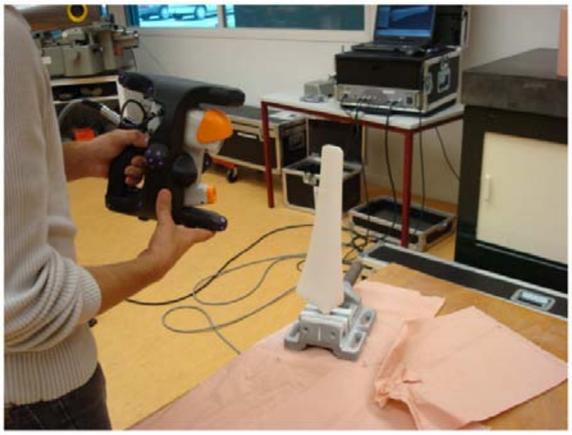
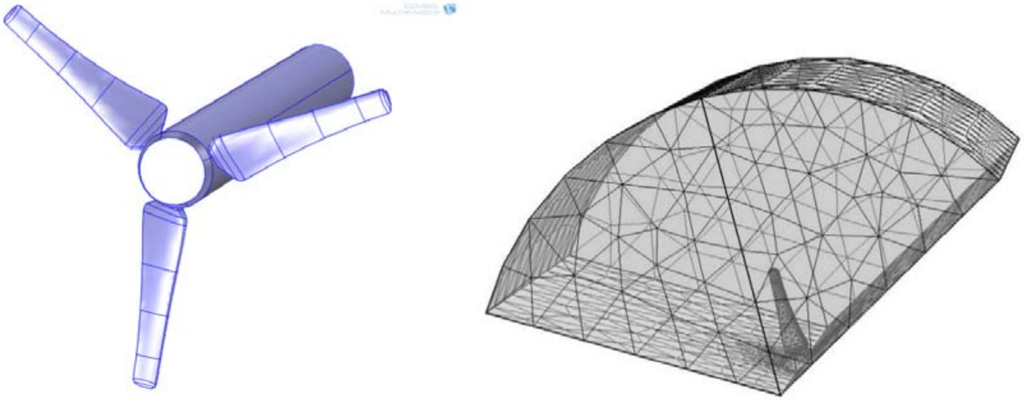


Figure 13: Construction of digital model of blade using laser scanner



(a) Blade profile model and rotor

(b) Representation of one third of turbine

Figure 14: Numerical model

8. Manufacturing

In order to make the transition from small scale models to prototypes and industrial structures, the top of the pyramid in Fig. 1, careful consideration must be given to manufacturing. Indeed, the influence of manufacturing quality on long term durability should not be underestimated. Fig. 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 hours at 70°C) but different manufacturing batches, were tested in seawater 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 to 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

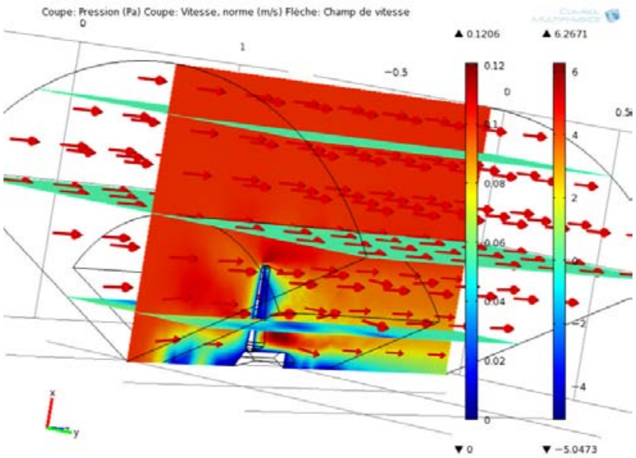


Figure 15: Example of model result showing velocity (in m/s) and pressure (in Pa) fields around turbine blade (current flow 0.1 m/s)

account for the lower fatigue lifetimes of series A.

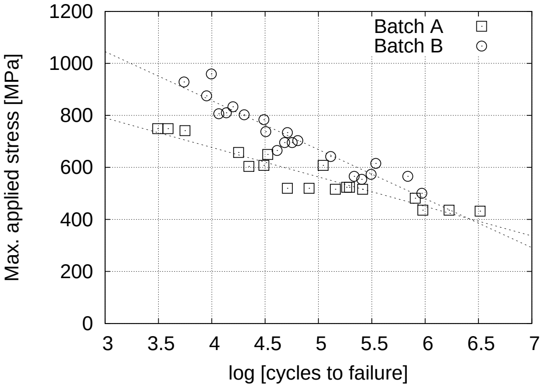


Figure 16: Influence of manufacturing quality on fatigue performance

MaHyTec [18] has developed a marine current turbine prototype to study manufacturing procedures, Fig. 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 due 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 [36, 26], and could provide a significant additional benefit, provided the service loads are well known.

Figure 17: Current turbine prototype, for manufacturing study and cyclic tests

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 paper 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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