CHARACTERIZATION OF SEA WATER AGEING EFFECTS ON MECHANICAL PROPERTIES OF CARBON/EPOXY COMPOSITES FOR TIDAL TURBINE BLADES

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Abstract

The renewable marine energies represent a major economic and political development. Among these new sources of energy, tidal turbines offer considerable potential. Most of the tidal turbine blades developed by industry so far are manufactured using thick carbon fibre composites. To ensure the life of the blades, it is necessary to develop a damage model taking into account the water absorption and its effects on behavior. Moreover, the multi-scale nature of these materials leads to complex, coupled failure mechanisms, whose thresholds and evolution are dependent on the layup and ply thickness. The purpose of this paper is to propose an experimental approach to characterize the long term behavior of different carbon/epoxy composites for tidal turbine blades.

1. Introduction

Over the last 50 years composite materials have found many applications in the maritime domain, particularly in the yachting and offshore energy industries. Composite materials are used in many offshore structures and new applications are being developed such as tidal turbine blades. The reliability of these components, in a very severe environment, is crucial to the profitability of tidal current energy systems.
These structures are subject to many forces such as ocean tides, waves, storms but also to various marine aggressions, such as sea water and corrosion. The mechanical loads on marine energy converters are cyclic (due to the motion of the waves for wave energy converters or the action of tides on tidal turbines). A thorough understanding of the fatigue behavior of the moving parts (example: turbine blades) is therefore essential. A previous study [1,2], has highlighted the material sensitivity of durability to the choice of components (fiber, resin, surface treatment of fibers). That work was carried out on thin composites reinforced by glass fibres. However, the majority of tidal turbine developers (MCT SeaGen, Alstom/TGL, Atlantis, Sabella…) have preferred carbon blades and the composite thicknesses are very

large, especially in the area of connection between blade and hub. Under these conditions the lifetime will be dominated by the interlaminar or out-of- plane response of the composite.
The purpose of this paper is to characterize the long term behavior of thick composite carbon/epoxy for tidal turbines blades. This characterization is based on standardized tests at different sea water ageing times.

2. Materials and methods

In order to qualify the influence of sea water ageing on composite materials for marine energy structures, static, quasi-static and cyclic tests were performed on different specimens.

2.1. Materials

Tidal turbine blades can be manufactured in different ways using different processes and materials. For example, Gurit manufactured blades for the HS1000 [3]. They feature a spar cap molded with unidirectional carbon prepreg and glass prepreg. The shells are all glass prepreg and all components are oven-cured, Figure 1. In another approach Norco has successfully manufactured three very large tidal turbine blades for The Atlantis Resources Corporation [4], which have now been in service for some time. Each individual laminate stack was impregnated using vacuum infused epoxy resin processing.

Figure 1. On left, the Gurit tidal turbine blade for the HS1000, on right the Atlantis blades manufactured by Norco, sources: Gurit and Norco

In this study three processes and materials have been chosen to produce samples for tests, before and after sea water ageing:

- A carbon epoxy pre-preg manufactured in an autoclave (used in blade spar)
- A carbon epoxy made by resin transfer molding (used in blade body and blade spar),
- A carbon epoxy manufactured by vacuum infusion (used for blade body).

This choice of material reflects the different current possibilities for manufacturing tidal turbine blades. It also allows the impact of fiber, matrix, and interface on the ageing mechanisms to be studied.

2.2. Quality control

All composites panels were checked using DSC (Differential Scanning Calorimetry) to verify the state of cure before putting the materials in circulating natural sea water temperature baths. Table 1. shows the results.

Materials	Curing process	Tg
Infused	16h@65°C	75°C
RTM	12h@65°C	76°C
Pre-preg*	2h@180°C	195°C

Pre-preg cured with 7 bar autoclave pressure

Table 1. Curing process and glass transition temperature resulting for each material.

To check the density of each type of material, density measurements were performed with a helium pycnometer, Table 2. shows the results.

Materials	Density (kg/m^3)	Fibre rate (%)
Infused UD	1.492 (0.002)	56.33
RTM UD	1.493(0.001)	52.76
Prepreg UD	1.571 (0.003)	58.26

Table 2. Density measurements on studied materials.

Interlaminar shear strength (ILSS) tests were performed to check that materials are well impregnated, an acceptance criterion of 45MPa was defined, above that value we can consider that the material is well impregnated. Results are shown in Table 3.

Materials	ILSS (MPa)
Infused UD	55.9 (0.2)
RTM UD	67.5 (0.9)
Prepreg UD	93.3 (2.7)

Table 3. ILSS test results on composite materials (EN ISO 14130)

The Figure2. shows some pictures taken with an optical microscope to check composites quality. Those pictures will also be used as a reference to check the evolution of ageing.

Figure 2. Optical microscope observation on UD samples Infused, RTM and Pre-preg material (left to right)

2.3. Gravimetric analysis

Water uptake has a particularly severe effect on the static characteristics, changes in toughness properties are initially due to matrix plasticization, which increases failure strain, followed by reductions due to matrix and/or fibre/matrix interface changes. It is important to follow the evolution of the rate of water entry into the composite material in order to develop predictive models of property changes through the laminate as a function of diffusion kinetics, e.g. [5].

In this way, sea water ageing was performed on each material at different temperatures. Twelve specimens of each material for different thickness and material orientation were cut from composite plates by water jet cutting in the following dimensions, (50 x 50 x thickness mm^{3}). Then those samples were measured and weighed and finally distributed in four natural circulating sea water tanks at different temperatures: 25, 40, 60 and 80°C, Figure 3. based on weight measurements made during ageing the water uptake was determined as a percentage of the initial weights of specimens.

Figure 3. Ifremer facilities, sea water ageing baths with natural water pumped from the sea.

2.4. Mechanical tests

The characterization of the elastic properties is performed using tensile tests on 90° and 0° laminates before and during different steps of sea water ageing. For the determination of toughness, DCB specimens (Double Cantilever Beam) for mode I and MMB specimens (Mixed Mode Bending) for mixed mode were used.

Mode I tests were performed according to ISO 15024. The MMB tests were made according to ASTM D 6671. Image analysis was used for measuring crack length under mode I and mixed mode conditions.

Another mode of damage studied is inter-fiber tensile cracking in tensile mode [6]. UD laminates (infused composite with a layup having some plies at 90° were prepared [0,0,90,90]s). Monitoring of the cracking was performed using two high definition cameras, Figure 4.

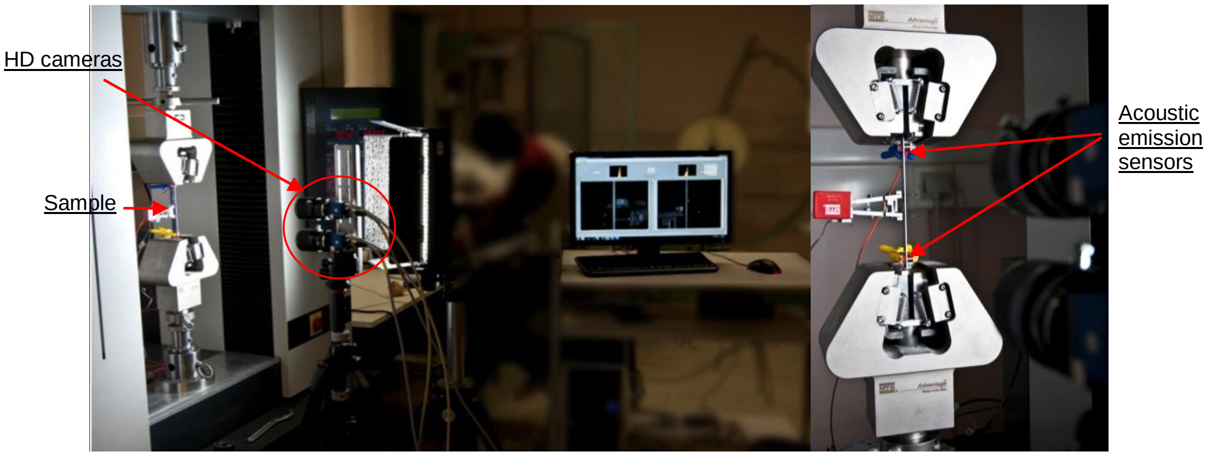

Figure 4. Test set-up to measure inter-fiber tensile cracking

Coupled with this visual analysis, acoustic emission was also used. Images of the two cameras were then assembled to obtain the complete surface of the specimen. The images were processed to subtract the noise. The cracks were then counted automatically using Matlab ™ by differentiating levels of grey.

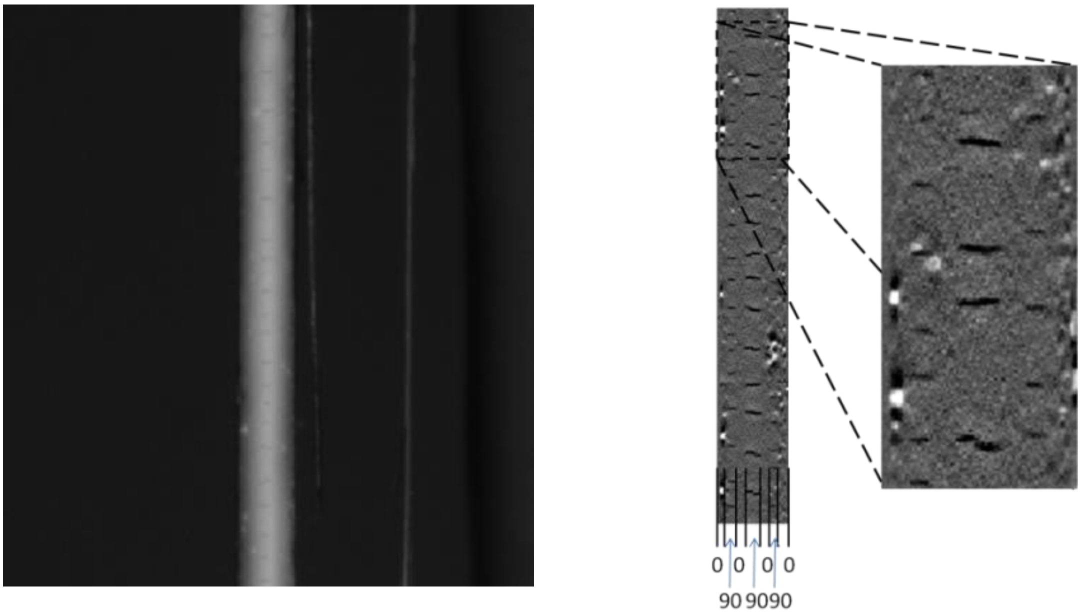

Figure 5. Visualization of cracks before (left) and after (right) Matlab ™ processing.

3. Results

3.1. Diffusion of water

The three types of material were measured and weighed periodically. For each material different thicknesses and material orientations were used. The weight gains have been plotted versus the root square of immersion time at 25°C, 40°C, 60°C and 80°C. Those materials have been immersed for 1200 and 5000 hours. The diffusion kinetics of the materials can be fitted to a Fickian law. For each material, a stable weight gain is noted, after about 650 hours at 60°C for infused material and 900 hours at 80°C for pre-preg, Figure. 6.

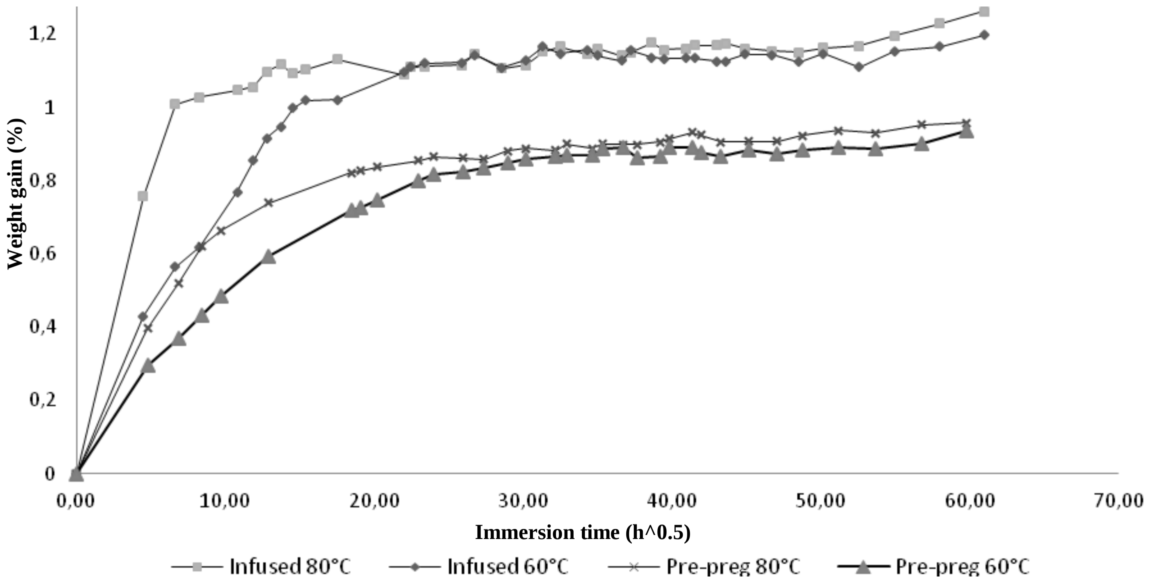

Figure 6. *Plots of experimental weight gain for infused and pre-preg composites*

3.2. Effect of sea water ageing on material properties

For the infused carbon/epoxy materials characterization of the mechanical properties was performed with tensile tests on 90° and 0° after 900 hours at 60°C in natural sea water. Results in Table 4. show an important reduction of longitudinal and transversal strengths.

Properties	**Dry**	**Aged 900h@60°C**
E_{11} (GPa)	136.9 (1.79)	141.26 (1.76)
Xt (GPa)	2.12 (0.10)	1.68 (0.11)
E_{22} (GPa)	7.38 (0.36)	6.09 (0.01)
Yt (MPa)	43.2 (2.4)	25.8 (1.7)
ILSS* (MPa)	55.9 (0.2)	37.7 (1.2)
Tg	75°C	51°C

**Interlaminar Shear Strength*

Table 4. Comparison of infused composite mechanical properties before and after sea water ageing.

3.3. Evolution of crack density

The evolution of damage was studied by inter-fiber tensile cracking in tensile mode on infused composites in the dry state and after 900 hours at 60°C. The crack density is the relation between the number of cracks and observation length and 90° plies thickness. In Figure 7. the effect of sea water ageing does not modify the crack density but significantly affects the damage threshold.

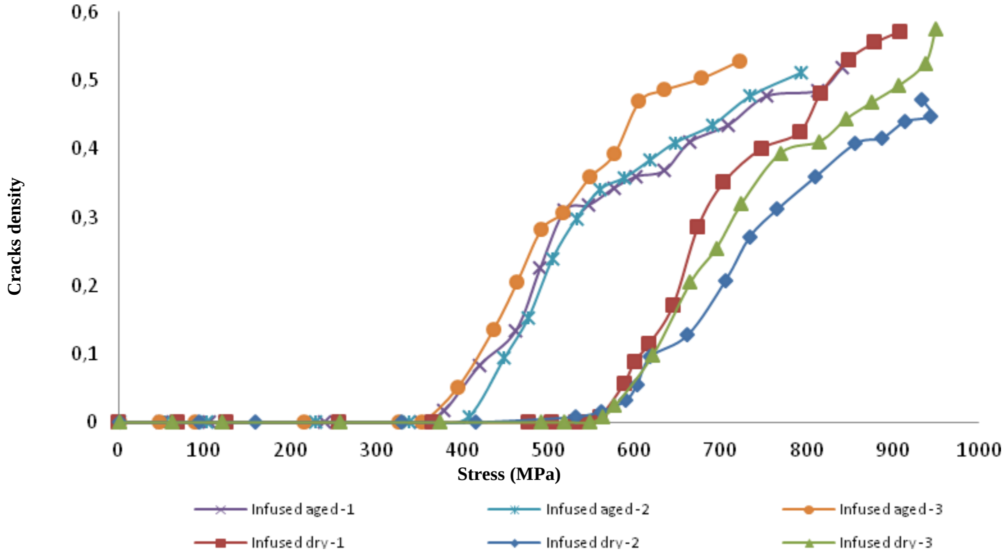

Figure 7. *Evolution of crack density for infused composite [0,0,90,90]s before and after ageing (3 specimens per condition)*

3.4. Fatigue

Sea water aging also affects the response to cyclic loading. Figure 6 shows an example, for a pre-preg composite, cycled in 4-point flexure in 20°C seawater (R=0.1, cycling frequency 2 Hz). Samples were tested both unaged, and after saturation in seawater at 60°C.

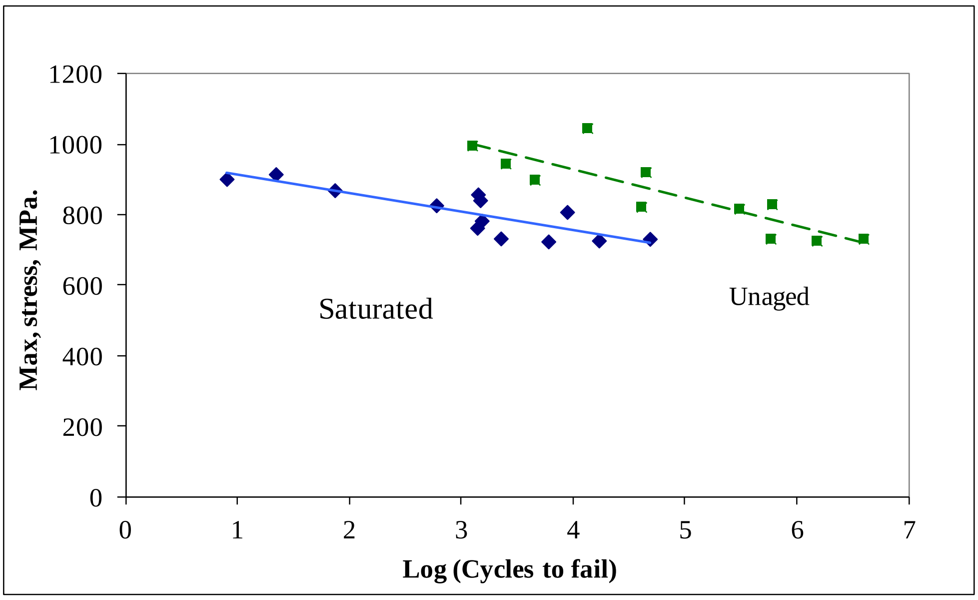

Figure 8. *Fatigue response of UD prepreg composite unaged and after saturation in seawater at 60°C.*

In this case there is a small shift to lower lifetimes after saturation. Other specimen orientations, particularly those with 90° plies, can show larger effects of aging depending on matrix choice and interface integrity.

4. Conclusion

Water uptake has a particularly severe effect on the static characteristics of certain carbon/epoxy composites proposed for tidal turbine blades. The evolution of the rate of water entry into different composite materials has been followed, in order to develop predictive models of property changes through the laminate as a function of diffusion kinetics. Using standardized tests on composites with different orientations, the effect of sea water ageing was evaluated, and after the first aging period (900 hours at 60°C) a decrease of 20% to 40% in failure strengths but minimal changes in elastic moduli were observed. These aging tests are continuing in order to evaluate long term behavior of materials of different thicknesses under static and cyclic conditions.

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