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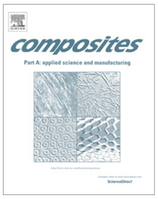

Characterization of sea water ageing effects on mechanical properties of carbon/epoxy composites for tidal turbine blades

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ABSTRACT

In recent years, many tidal turbine projects have been developed using composites blades. Tidal turbine blades are subject to ocean forces and sea water aggressions, and the reliability of these components is crucial to the profitability of ocean energy recovery systems. The majority of tidal turbine developers have preferred carbon/epoxy blades, so there is a need to understand how prolonged immersion in the ocean affects these composites. In this study the long term behaviour of different carbon/epoxy composites has been studied using accelerated ageing tests. A significant reduction of composite strengths has been observed after saturation of water in the material. For longer immersions only small further changes in these properties occur. No significant changes have been observed for moduli nor for composite toughness. The effect of sea water ageing on damage thresholds and kinetics has been studied and modelled. After saturation, the damage threshold is modified while kinetics of damage development remain the same.

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 [1–4]. Composite materials are used in many offshore structures and new applications are being developed such as tidal turbine blades. Tidal turbines offer an exciting opportunity to exploit ocean current flows to generate energy. The interest in the use of composite materials for tidal energy convertor structures is based on the potential improvements in hydrodynamic and structural performance. In addition to the advantages of high strength-to-weight and strength-to stiffness ratios, the anisotropy of the composites can be designed to allow three dimensional tailoring of the blade deformation [5]. 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. It was estimated [6] for a 1 MW turbine operating in a 4.5 knot tide that 900 tons/s of water pass through the turbine rotor. Structures for tidal energy must also be designed to withstand transient forces caused by turbulence and passing surface waves. As a consequence, 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 behaviour of the moving parts (example: turbine blades) is therefore essential. A previous study [7,8], has highlighted the sensitivity of durability to the choice of components (fibre, resin, surface treatment of fibres). That work was carried out on thin composites reinforced by glass fibres. However, the majority of tidal turbine developers (MCT Sea-Gen, 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, sea water can induce changes in carbon/epoxy composite materials [9,10]. The absorption of water molecules in polymer composites is known to have important effects on their final performance [11,12], especially in their long-term exploitation [13,14]. By the organic nature of the matrix resin, often an epoxy, long immersion in sea water can induce both physical and chemical changes [15]. Plasticization and swelling are the main physical consequences of water absorption on polymer structures [16,17]. The plasticization corresponds to a modification of the structure of the polymer and results in a decrease of the glass transition temperature [18,19]. It

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also induces loss of mechanical properties with a reduction in moduli and failure stress. Swelling of the matrix is caused by the penetration of water into polymers, as a consequence volume changes will occur. At the composite scale, swelling can create interfacial cracks and fibre/matrix debonding [20]. Transverse cracking (intra-laminar) is the principal damage mechanism in uni-directional composite laminates loaded off-axis. A transverse crack is often followed by debonding at the plies interface. This micro-debonding can have a major influence on both transverse cracking saturation [21] and on the composite out-of-plane-strength [22]. As a result, the lifetime of composites will be dominated by their interlaminar or out-of- plane response. When composites are immersed at sea, water is first absorbed at the surface and then diffuses into the material. Some analogies between heat transfer and mass diffusion were established by Fick [23] in order to determine the kinetics of water entry into composites. Experimentally it is also possible to follow water concentration in polymer and composite materials. There are various experimental methods but the simplest and definitely the most popular is based on sample weight measurements dry (w_0) then in wet (w) conditions throughout the immersion time of the samples. It is then possible to determine the water mass fraction: $m = (w - w_0)/w_0$ and quantify the diffusion behaviour of water in a composite material [15]. The kinetics of diffusion can change during the service life of composites in operation, damage due to the diversity of mechanical loads may impact and accelerate the diffusion of water inside the composite structures, as damage can create new pathways for water entry [24,25].

Sea water ageing in the tidal turbine environment, at ocean temperature, will generate a slow process of degradation and damage in composites. Therefore there is a need to develop a procedure to accelerate ageing in order to assess the long term in-service behaviour of composites to be used in the marine environment. Accelerated testing is also a valuable tool for rapid comparison of different material options. As a 25-year lifetime requirement is commonly specified in the renewable marine energy industry, the accelerated test protocol must aim to reproduce the effects of 25 years exposure in a few months [26].

The purpose of this paper is to characterize and model the long term behaviour of different carbon/epoxy composites for tidal turbine blade applications. First, the characterization of the carbon/epoxy composites will be presented using standardized tests after different sea water ageing times. For this characterization, the sea water ageing process has been accelerated through immersion at higher temperature than ocean conditions. Second, a damage model taking into account the crack development in composite materials will be discussed. Finally, methods to identify and validate the model during the accelerated ageing will be presented.

2. Materials and methods

In order to evaluate the influence of sea water ageing on composite materials for tidal turbine blades, static, quasi-static and cyclic tests have been performed on different candidate materials. Some cyclic test results will be presented subsequently, but a preliminary investigation has already been described [27], here only results from static and quasi-static tests will be discussed.

2.1. Materials

Tidal turbine blades can be manufactured using different processes and materials. For example, Gurit manufactured blades for the HS1000 turbine [28] based on a spar cap moulded with unidirectional carbon prepreg and glass prepreg. The outer shells are all glass prepreg and all components were oven-cured. In another approach, Norco has successfully manufactured three very large tidal turbine blades for The Atlantis Resources Corporation [29], which have now been in service for some time, using vacuum infused epoxy resin processing. Airborne Marine has produced blades for Tocardo and Nautricity using Resin Transfer Moulding (RTM), [30].

In this study three processes and materials have been chosen to produce samples for tests:

(i) A carbon reinforced epoxy pre-preg manufactured using the autoclave process, this pre-preg could be used in blade spars. The samples were produced by FMC Composites in Brest. The UD pre-preg layers are composed of HexPly® M21 matrix and UD HexTow® IMA (UD194 12 K) carbon fibres. Pre-preg curing conditions were respected following product data specifications. Full vacuum was applied on composites, then a 7 bar autoclave pressure at 180 °C for 120 min.
(ii) A carbon reinforced epoxy made by resin transfer moulding (RTM), provided by Airborne Marine. The RTM material could be used in blade body and blade spar elements. Airborne has already used the RTM process to manufacture one shot tidal turbine blades. The fibre is a standard carbon one and the matrix is a marine optimised epoxy resin. Information and details about Airborne material are protected by industrial confidentiality.
(iii) A carbon reinforced epoxy manufactured by vacuum infusion, this material could be used to manufacture the blade body. This carbon epoxy was manufactured in the LBMS Laboratory, using Tenax-E IMS65 E23 24 K carbon and the same epoxy resin as the RTM material. The samples were made on a glass plate, with a vacuum of 0.95 bars for the infusion process. All the plates have been cured at 65 °C for 16 h.

This choice of material reflects the different current possibilities for manufacturing tidal turbine blades. It also allows the impact of fibre, matrix, and interface on the ageing mechanisms to be studied. Some details about the material composition are presented in Table 1. For this study, materials were produced with different orientations and thicknesses.

As the specimen cutting method can affect composite mechanical and diffusion properties, all specimens tested were cut using the same high pressure water jet cutting method.

2.2. Quality control

An initial series of quality tests was performed, both to check the quality of each material and to obtain reference values for mechanical properties before ageing.

Thus 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. A TA Instruments Q200 DSC was used with a heating rate of 10 °C/minute. The glass transition temperature (Tg) is useful to determine the maximum sea water ageing temperature for accelerated conditions. Table 2, shows the results. As sea water ageing

Table 1
Materials, process, resin and fibre compositions.

Materials	Process	Resin	Fibre
Infused	Infusion	Infusion/RTM resin	Tenax-E IMS[a]
RTM	RTM low pressure	Infusion/RTM resin	Standard carbon fibre[b]
Pre-preg	Autoclave 7 bar	Hexcel M21	IMA

[a] IMS: intermediate modulus.
[b] Reference protected by industrial confidentiality.