ENVIRONMENTAL EFFECTS ON THE BENDING FATIGUE OF LAMINATED COMPOSITES: EXPERIMENTAL AND MODELLING APPROACHES

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Abstract
This paper investigates the effects of sea water immersion on the fatigue failure of CFRP composites. Dry and wet specimens were tested in a variety of bending conditions following the ISO standard [1], and the failure mechanisms revealed by the authors' previous study [2-4] were then recalled to understand the fatigue behaviour. A 2D FEA model was developed to simulate the fatigue crack propagation in bending, while a 3D FEA model was developed to examine the mechanisms of fatigue crack initiation and propagation when the terms of free edge effect and water ingress were introduced. The study shows that the bending fatigue failure was due to the so called buckling driven delamination, and the fatigue life was reduced significantly owing to the combination of edge effect and capillary effect. Therefore, a 4-step fatigue failure theory was proposed to account for the environmental effects on the crack propagation of bending fatigue.

1. Introduction

The early introduction of the FRP composites to marine structures started at the end of the second World War when the US navy was seeking to build ship hulls based on the potential for reducing maintenance and production costs [5]. Compared with the aerospace industry, where high strength and stiffness to weight is essential, the use of marine composites was driven by their superior performance of environmental resistance and fatigue life. The growth of the shipment of marine composites has benefited from the development of marine renewable energy and the offshore platforms. Since FRP composites can be moulded to very complex shapes, FRP composites have been used for critical marine structures, such as propellers [6], ship hulls [7], shafts [8], pipes & tanks [9, 10].

The challenges for composite materials used in marine environment include the long exposure time to moisture, temperature, numerous ionic species as well as microorganisms. Recently, Summerscales [11] gave a general review on the marine environmental effects on the durability of FRP composites. The loss in the mechanical properties of composite materials is mainly attributed to the plasticisation of polymeric matrix. However, previous investigations of the long-term performance of current commercial FRP composites in the marine environment mainly considered moisture diffusion and are often based on accelerated laboratory studies due to the slow processes involved.

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The determination of the resistance to combined states of cyclic stress is a fundamental problem concerning the engineering uses of FRP composites. The fatigue failure of FRP composites is much more complicated than isotropic materials such as metals because the predominant state of stress within composites with orthotropic/anisotropic properties is multi-dimensional. The failures in FRP composites include fibre breakage, matrix cracking, interfacial debonding and delamination [12]. In view of the complexity of microstructural damage accumulation during fatigue cycling, there is little hope for resolving such problems particularly fatigue cracks development by micromechanics methods even when the applied stresses are smaller than the material strength. One has to extract the complex stress fields, the inherent anisotropic and nonlinear behaviour to understand the nature of fatigue, as fatigue can cause extensive damage throughout the specimen volume combined with a variety of failure modes instead of a single crack.

Composite structures served in marine environment are subjected to many aspects in which this paper pursues the effects of water ingress on the fatigue failure. The hygrothermal expansion can be developed by the change of moisture content after water immersion, which not only affects the stress distribution in FRP composites but also degrades the interface of fibre/matrix. On the other hand, the typical rate of capillary climb in polymeric composites is approximate 7 cm/min [13], which is nearly one million times faster comparing with the moisture diffusivity, thus the capillary climbing also plays an important role on the fatigue behaviour while immersed. As the fatigue failure is a process of the accumulation of structural fracture, the research scope of this study will cover the failure mechanisms of the CFRP composites, from static failure to fatigue crack propagation.

Considerable research had been carried out to investigate the marine environmental effects on either mechanical property, e.g. uniaxial tensile strength/modulus or chemical properties, e.g. moisture diffusion of FRP composites. However there is still a lack of knowledge on the fracture mechanics of FRP composites when water ingress is considered which is essential to fatigue failure since the water ingress is also a very slow process. The study is closely linked to the application of carbon fibre reinforced plastic (CFRP) composites in marine renewable energy devices. An accelerated testing method, which includes moisture diffusion and environmental fatigue, was developed to investigate the interaction between composite fatigue and marine environmental effects. CFRP coupons with specific stacking sequences were designed and manufactured in autoclave, and then immersed in both fresh and seawater until moisture saturation. Quasi-static test and cyclic test were carried out in both air and simulated marine environment, and the failure mechanisms were investigated using visual and microscopic methods. Additionally, a robust 2D Finite Element Analysis (FEA) model was developed to simulate the fatigue crack propagation based on virtual crack closure technique, while a 3D FEA model was developed to investigate the edge effects on the fatigue crack evolution.

2. Research approaches

2.1. Experiment setup

High strength carbon fibre/epoxy pre-preg (product code: Cytec 977-2-12kHTS-34-300), provided by Cytec Industries Incorporated, was used in this study. This is a high temperature (180°C) curing toughened epoxy resin with 212°C glass transition temperature (Tg) which is formulated for autoclave moulding. Unidirectional (UD, $[0]_{16}$) and cross-ply (CP, $[90/0]_{4s}$) laminates were investigated for the fatigue test. The composite plates were sliced into 100 mm in length by 15 mm in width for the bending fatigue test in accordance with the ISO standard [1]. The composite laminates were visually inspected by a microscope before being fatigue tested, and no void was found in both two layups. However, resin rich regions were found between the interface of two abjacent plies, which made the apparent thickness of UD laminate thicker than CP laminate. Indeed, the actual thickness of the UD and CP laminates were measured as 2.06 mm and 1.95 mm respectively. Figure 1 shows a typical

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microscopic image of a UD laminate, in which the resin rich region between two abjacent plies are observed.

The coupons were first tested in quasi-static bending to estimate the flexural properties as well as the failure mechanisms, and the results have been reported previously [2]. Secondly, the coupons were submerged into sea water until moisture saturation, and the results have been reported previously [3]. After that, the coupons were tested in cyclic bending on a universal fatigue testing machine (INSTRON E3000). For the comparison, some coupons were immersed into fresh water (tap water) before being fatigue tested. In order to simulate the marine environment exposure, the wet coupons were covered by a wet sponge during the fatigue test.

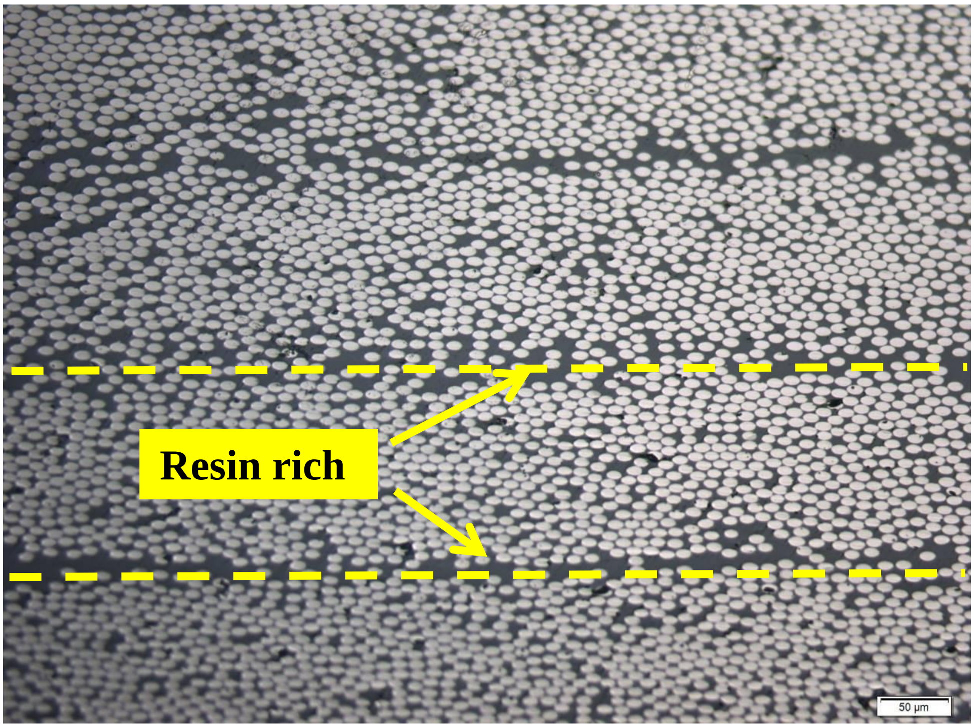

Figure 1. The microscopic image of a UD laminate

The ISO standard provides a guidance for the choice of stress level in fatigue test: 40%, 55%, 65% and 80% UFS (ultimate flexural strength). A pre-test for the dry coupon was run prior to the test of wet coupons in order to estimate the approximate fatigue life of this kind of composite, and it was found that the dry coupon survived at 80% UFS till 5×10^6 cycles without obvious stiffness reduction. Therefore only the highest stress levels, 80% UFS was chosen for the study. For the comparison, some coupons were tested at 90% UFS. Table 1 gives an over view of the condition of the fatigue test.

Table 1. Flexural properties of the dry coupons and stress levels for fatigue test.

Specimen Type	Flexural strength σ_f (MPa)	Flexural modulus E_f (GPa)	65% UFS (MPa)	80% UFS (MPa)	90% UFS (MPa)
UD ($[0]_{16}$)	1598	120	1038	1278	1438
CP ($[90/0]_{4s}$)	1416	55	921	1133	1274

2.2. FEA simulation

A comprehensive study of bending fatigue was conducted using commercial FEA code

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(ABAQUS/STANDARD). Because both the UD and CP laminates are symmetric in geometry, material properties and the boundary condition, it is sufficient to simplify the model half geometry in order to reduce the computational resource. For the 3D case, the geometry was simplied to a quarter model, as shown in Figure 2. The mesh at critical regions, such as the edge and contact region, were refined.

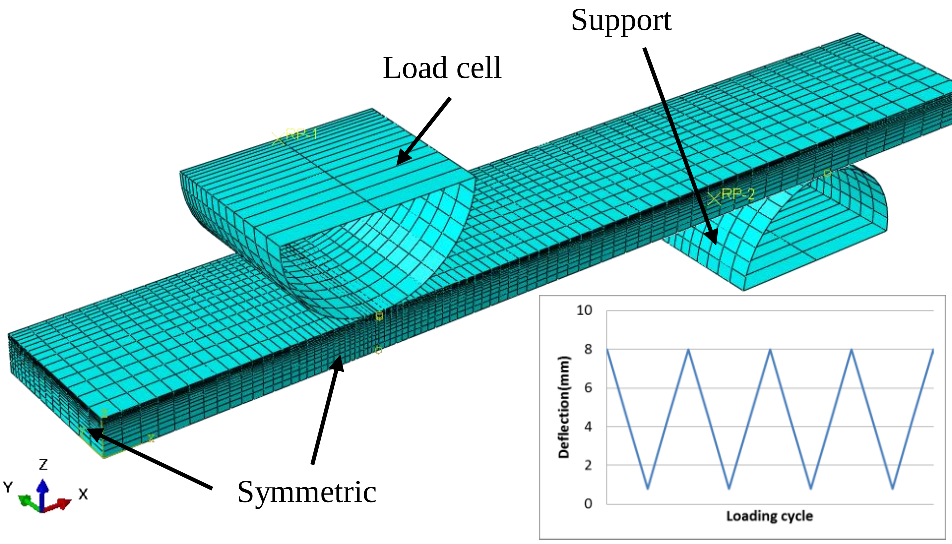

Figure 2. Mesh plot of the 3D FEA model and the loading history. A initial crack (0.2mm) was embedded at the interface between ply15 and ply16 under the load cell.

The onset and fatigue crack propogation are characterized by using the Paris law, which relates crack growth rate da/dN to the relative strain energy release rate [14],

$$\frac{N}{c_1 \Delta G^{c_2}} \geq 1 \qquad (1)$$

$$\Delta G = G_{\max} - G_{\min}$$

$$\frac{da}{dN} = c_3 \Delta G^{c_4} \qquad (2)$$

where N is fatigue cycle; a is the crack length; c_1, c_2, c_3, c_4 are material constants; G_{max} and G_{min} correspond to the strain energy release rates when the structure is loaded up to F_{max} and F_{min} respectively.

The crack tips will not grow unless the equation (1) is satisfied; and then the crack propagates at an exponential rate governed by equation (2); after that the crack will grow catastrophically when the G_{max} is higher than the strain energy release rate upper limit. Table 2 gives the material properties including elastic and fracture properties. In accordance with the apparent thickness of the laminate, the ply thickness of UD laminate was defined as 0.13 mm (laminate thickness 2.08 mm) while the ply thickness of CP laminate was define as 0.12 mm (laminate thickness 1.92 mm).

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Table 2. Material properties for the FEA simulation [2, 14].

Elastic properties		Fracture properties	
E_1(GPa)	139	G_{IC}(J/m^2)	1500
E_2(GPa)	8.8	G_{IIC}(J/m^2)	1500
E_3(GPa)	8.8	G_{IIIC}(J/m^2)	1500
ν_{12}	0.26	η	1.75
ν_{23}	0.48	c_1	0.5
ν_{13}	0.26	c_2	-0.1
G_{12}(GPa)	4.7	c_3	4.88E-06
G_{23}(GPa)	3	c_4	1.15
G_{13}(GPa)	4.7		

3. Results and discussion

Figure 3-4 show the fatigue test results of the two layups, plotting as SN graph. There are three fatigue test conditions shown in Figure 3-4: (a) specimen without immersion (Dry); (b) immersed specimen covered by wet sponge (Wet1); and (c) immersed specimen without the cover of wet sponge (Wet2).

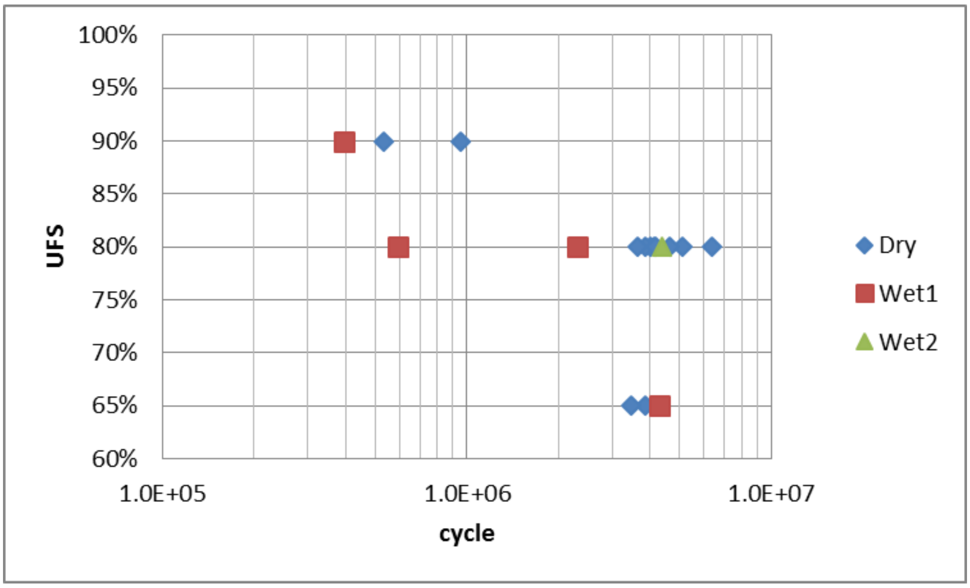

Figure 3. The fatigue life of CP laminate

At the highest stress level, 90% UFS, all of the specimens failed at no more than 1×10^6 cycles. The immersed specimen showed relatively lower cycle count than those specimens without water immersion. At the intermediate stress level, 80% UFS, all the dry specimens presented more than 3×10^6 cycles, in contrast, all of the immersed specimens broke although one specimen still showed a relatively high level of fatigue cycle count (more than 2×10^6). The fatigue cycle counts for the dry specimens distribute at 80% UFS stress level with a scatter in the figures because the tests were stopped manually when it was found that the fatigue cycle count had exceeded three million and such a specimen was labelled as having an infinite fatigue life. It is interesting to note that the immersed specimen which was tested in dry did not break at this stress level, indicating that the fatigue behaviour was also affected by the testing environment. At the lowest stress level, 65% UFS, all of the CP specimens survived regardless of the laminate pre-conditions and testing environments.

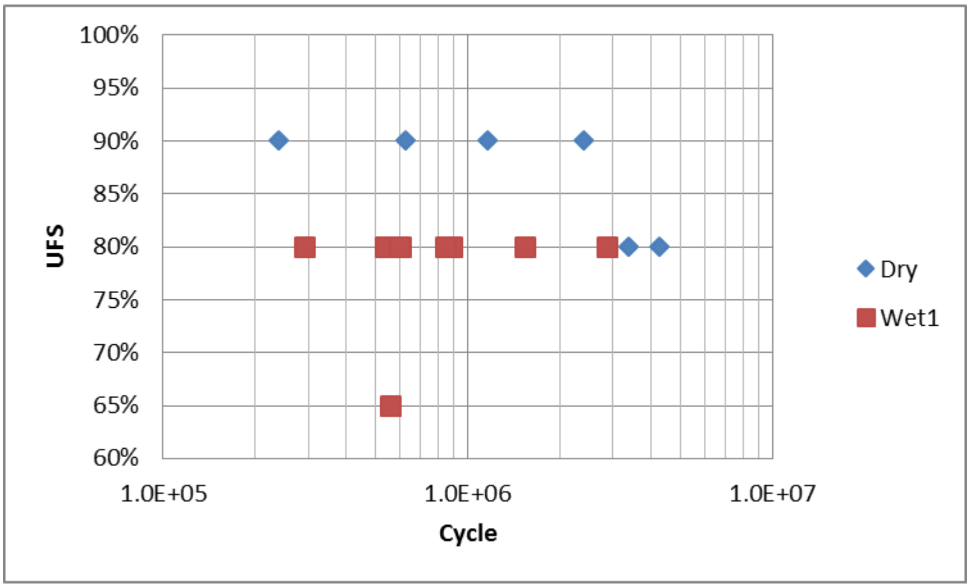

Figure 4. The fatigue life of UD laminate

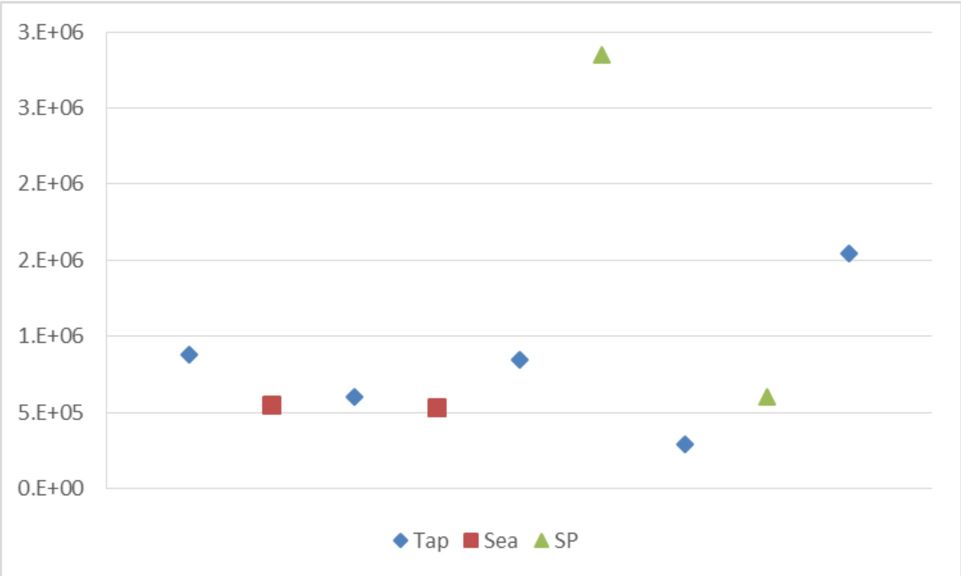

Figure 5. Comparison of the fatigue life of UD laminate under three submersion conditions. Tap: tap water immersion; Sea: sea water immersion; SP: sea water immersion with 70 bars hydrostatic pressure.

For the UD laminate, the dry specimen survived while all the immersed specimens broke at the 80% UFS. More specifically, as shown in Figure 5, the effects of the three kinds of water immersions showed such a large scatter that there was no evidence to identify the difference of the three kinds of water immersions. As discussed in the SEM analysis in previous report [3], the sea water immersed specimens presented a larger number of bare fibres than the tap water condition, meaning that the sea water degradation was more severe than tap water. One possible explanation for this phenomenon is that the period of water immersion was not long enough to see the obvious difference of the effects on the fatigue behaviour.

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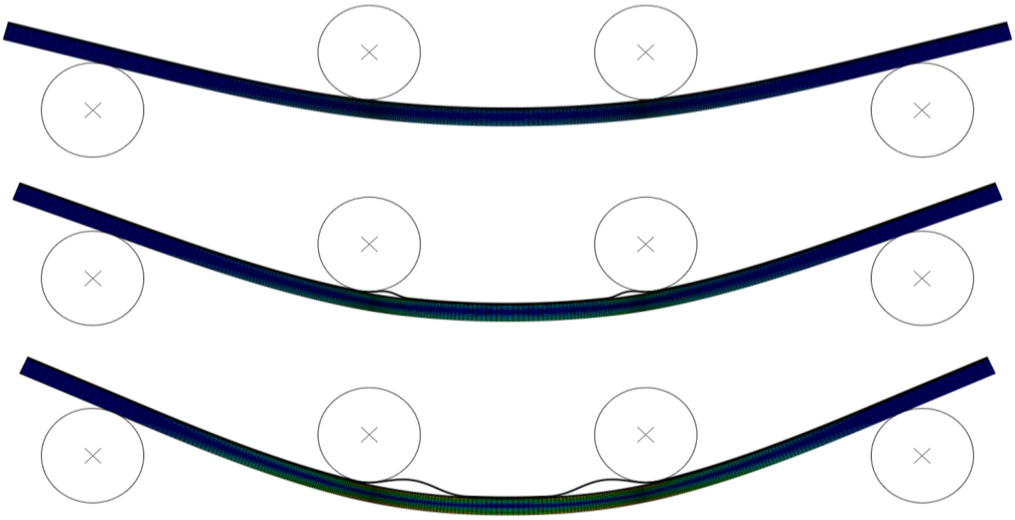

Figure 6. Fatigue crack growth in bending

Figure 6 presents the development of delamination in bending fatigue. Ply 16 withstand the maximum compressive stress, and the delamination between ply 15 and 16 is called buckling driven delamination in this study, which formed as four steps: (a) the edge cracks were induced underneath the load cell; (b) the edge cracks penetrated inside the laminate to form the initial crack (which was embedded in the FEA model); (c) the edge cracks lead the foregoing fracture during fatigue; until (d) the crack length met the criterion of buckling and then the buckling drove a catastrophic delamination. After the first compressive ply (top surface) failed by the buckling-driven delamination, the second ply repeated the same process, and then the third ply…until the whole specimen failed.

Considering those specimens fatigue tested in the wet environment, liquid water is in contact with the specimen during testing so that the foregoing mass of water is preserved during the loading cycle. As a consequence, the water prevented the crack closure when the specimen was unloaded, and then the crack propagation was accelerated, leading to a much shorter fatigue life.

4. Conclusions

This paper performed the fatigue study of dry specimens in dry environment, and moisture saturated specimens (tap water immersion, sea water immersion, and sea water immersion with 70bar hydrostatic pressure) in both dry and wet environments. Bending fatigue was carried out at three stress levels to investigate the fatigue performance of the UD and CP laminates. FEA models, based on VCCT, were conducted to investigate the fatigue crack propagation as well as the fatigue failure mechanisms.

The experimental study showed that water ingress during the fatigue significantly accelerated the crack initiation and fatigue crack propagation, therefore a short fatigue life was expected. However, no evidence was found to identify the effects of the three different immersions on the fatigue performance. The use of the traditional S-N curve was inappropriate to predict the fatigue of CFRP composites and the fatigue analysis must be associated with the practical conditions.

Both the UD and CP laminates failed by the so-called buckling-driven delamination in the bending fatigue. FEA based on VCCT performed the buckling-driven delamination in both 2D and 3D. The FEA modelling unveiled the development of the 4-step buckling-driven delamination, in which the edge effect played its important role in the fatigue crack propagation. Besides, the water ingress due to the capillary phenomenon significantly accelerated the progress of crack initiation and propagation.

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