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# Moisture effects on the bending fatigue of laminated composites

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ABSTRACT

This paper investigated the effect of moisture ingress on the bending fatigue of laminated composites. An accelerated testing method was developed to investigate the correlation between composite fatigue and moisture diffusion effects. Unidirectional and cross-ply laminated CFRP composites were manufactured in autoclave, and then submerged in both fresh and seawater for various periods until moisture saturation. Quasi-static and cyclic tests were carried out in both air and wet environment, and the failure mechanisms were investigated using visual and microscopic methods. Additionally, a robust 2D Finite Element model (FEA) was developed to simulate the fatigue crack propagation based on virtual crack closure technique (VCCT), while a 3D FEA model was developed to investigate the edge effect on fatigue crack propagation. The experimental observations gave a good agreement with the FEA models. The study showed 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. The fatigue test indicated that the fatigue resistance was degraded one stress level due to the water ingress, e.g. from 80% ultimate flexural strength (UFS) to 65% UFS. Therefore, a 4-step fatigue failure theory was proposed to explain the moisture effects on the crack propagation under bending fatigue.

## 1. Introduction

Due to the high ratio of strength to weight, superior performance of environmental resistance and fatigue life, FRP composites have been widely used in aerospace and marine industries. Since the FRP composites can be moulded to complex shape, these materials have been successfully introduced to construct the blades of tidal or underwater turbines [1–3]. The challenges for composite materials used in marine environment include the long exposure time to moisture, temperature, numerous ionic species as well as the microorganisms. Recently, a multiscale study of CFRP composite has been demonstrated that the marine environment exposure not only affects the stress distribution in composite laminates but also degrades the interface of the fibre and matrix [4,5]. In the marine environment, the mechanical structure is designed to have a service life of several decades so that the determination of the resistance to the state of cyclic stress is a fundamental problem in the marine applications of FRP composites. Therefore environmental fatigue is the main concern of engineers in the design of marine structures in order to minimise the cost of maintenance.

The fatigue of FRP composites in ambient environment had been investigated extensively, in which some of them developed theories to predict composite fatigue [6–8]. Meanwhile, the marine environmental effects on the durability of FRP composites had been investigated by correlating the decrease of tensile strength with exposure time [9], fibre/matrix interfacial strength [10], transverse and shear strengths [11,12]. In view of the complexity of the environmental effects and the damage accumulation during fatigue cycling, there is little hope for including fibre breakage, matrix cracking, interfacial debonding and delamination in a single formula. On the other hand, most of the previous works focused on the uniform axial loads, which neglect some stress components such as out-of-plane stresses. Due to the nature of bending, laminates are subjected to tension, compression and shear, which is fundamentally different from uniaxial loads [13]. However, there are few reports related to the environmental effects on bending fatigue.

Many mathematical techniques have been developed to predict the crack growth, in which some of the most popular methods used for the delamination of composites are extended finite element method (XFEM) [14–16], cohesive element method (CZM) [17,18] and virtual crack closure technique (VCCT) [19–21]. The XFEM which predicts the onset of the crack by maximum principal stress/strain, is commonly combined with other methods to model the crack initiation and propagation. However, the fracture

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criterion of XFEM is based on tensile strength which is unlikely to predict the onset of the crack in bending correctly where the composite is subject to compressive delamination.

The present work was intended to investigate the bending fatigue behaviour of laminated composites correlated with water ingress. Unidirectional ($[0]_{16}$) and cross-ply ($[90/0]_{4s}$) laminates were manufactured and tested in bending fatigue in accordance with ISO standards [22,23] to perform the flexural behaviour and ASTM standards [24] to simulate marine exposure. A robust 2D FEA model based on VCCT was then developed to examine the buckling-driven delamination in bending fatigue, while a 3D FEA model was developed to investigate the free edge effects and the effects of water ingress. The mode I and mode II strain energy release rates in critical areas of the laminated composites were examined and correlated with the observation of the fatigue crack propagation in experiments.

## 2. Experimental methods

### 2.1. Material preparation

Unidirectional (UD) and cross-ply (CP) laminates made from pre-preg CFRP composites (Cycom HTS/977-2) were used for the 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. The pre-preg CFRP composite plates were autoclave-manufactured and sliced into the required dimensions (*length* × *width* = 100 mm × 15 mm) following the ISO standards [22,23].

The coupons were divided into two sets: (a) the as-received (dry) coupons were tested in quasi-static 3-point bending in the normal environment following the ISO standard [22], and the apparent flexural strength was recorded to define the loading level for the bending fatigue tests. Some of the as-received coupons were saved for the fatigue test; (b) the second set of coupons were submerged in three chambers which contained fresh water, sea water and sea water with 70 bar hydrostatic pressure respectively. In order to accelerate the diffusion process, all the three chambers were placed in an oven at a constant temperature of 50 °C. The coupons were saturated after soaking for three months, and then the flexural strength was measured in quasi-static 3-point bending in ambient condition and was compared with that of un-soaked coupons. After moisture saturation, some of the immersed coupons were saved for the fatigue test. The quasi-static bending test results of both as-received and immersed coupons are shown in Table 1.

### 2.2. Bending fatigue setup

The bending fatigue, conducted in accordance with ISO standard [23], was carried out on a universal fatigue testing machine (INSTRON E3000) which created a sinusoidal cyclic load. The R ratio (minimum load to maximum load) was fixed at 0.1 and the load control method (constant maximum and minimum forces for each cycle) was applied. The main consideration in the choice of frequency was the heat generation and the thermal conductivity (associated with heat dispersion) of the specimen. Since the carbon fibres present much higher value of thermal conductivity than other kinds of fibres, a relatively higher frequency can be applied to a CFRP specimen. Many researchers employed 5 Hz for GFRP composite and 10 Hz for CFRP composites; however 30 Hz for CFRP composites was reported in some cases [25]. According to the FEA simulation (ANSYS Workbench), the first order of resonance frequency of the unidirectional and cross-ply laminates are in the order of 600 Hz and 900 Hz respectively, therefore the resonance effect can be neglected when the loading frequency is in the range of 5–30 Hz. In the present work, most of the specimens were tested at a frequency of 10 Hz though a few were at 15 Hz for comparison.

The ISO standard [23] provides a guidance for the choice of loading level in fatigue test: 40%, 55%, 65% and 80% UFS. A pre-test for the dry coupon was run prior to the wet coupons in order to estimate the approximate fatigue life, and it was found that the dry coupon survived at 80% UFS till $5 \times 10^6$ cycles without significant stiffness reduction. Therefore specimens were mainly tested at 80% UFS, and a few specimens were tested at 65% UFS and 90% UFS for comparison. Considering the time consumption and the difficulty to maintain the wet environment for the wet coupons, 3–5 coupons were tested at each condition (dry or wet) at the primary loading level (80% UFS) while 2–3 coupons were tested at 90% and 65% UFS for comparison. The ultimate flexural strengths of the unidirectional and cross-ply laminates were taken from the quasi-static bending tests shown in Table 1. The mean value and amplitude are necessary for machine setup, which are calculated by,

$$\begin{aligned} F_{mean} &= \frac{F_{\max}(1+R)}{2} \\ F_{amp} &= \frac{F_{\max}(1-R)}{2} \end{aligned} \qquad (1)$$

with R = 0.1. Table 1 has shown that the flexural strengths of the dry and wet specimens were very close to each other; therefore the loading levels for both dry and wet specimens with the same layup were the same in the fatigue tests. Table 2 shows the loading levels corresponding to the mean value and amplitude.

In order to simulate the condition of water immersion, the specimen was covered by a wet sponge which was regularly replenished with water by a tube during the fatigue test, using sea water or tap water. Fig. 1 shows the three test conditions:

**Table 1**
Apparent flexural strength and their standard deviations (SDs) in quasi-static bending.

| | Immersion* | $\sigma_x^{app}$ (MPa)** | |
|---|---|---|---|
| | | Dry | Saturation |
| UD($[0]_{16}$) | Sea | 1598 ± 56 | 1696 ± 41 |
| | SP | | 1780 ± 122 |
| | Tap | | 1688 ± 137 |
| CP($[90/0]_{4s}$) | Sea | 1416 ± 53 | 1441 ± 40 |
| | SP | | 1398 ± 88 |
| | Tap | | 1400 ± 74 |

[*] ‘Sea’: sea water immersion; ‘Tap’: tap water immersion; ‘SP’: sea water immersion with 70 bar hydrostatic pressure.

[**] The apparent flexural strength was calculated with the ‘large-deflection correction’ provided by ISO standard [13].

**Table 2**
Loading levels of the UD and CP laminates for the fatigue test. The level ‘100%’ represents the ultimate flexural strength which was measured in quasi-static bending. The apparent flexural stresses corresponding to the loading levels are also shown in the table.

| | Bending | Level | $F_{mean}$ (N) | $F_{amp}$ (N) | $\sigma_{max}$ (MPa) |
|---|---|---|---|---|---|
| UD $[0]_{16}$ | 3-Point | 65%UFS | 305 | 250 | 1039 |
| | | 80%UFS | 375 | 307 | 1278 |
| | | 90%UFS | 422 | 345 | 1438 |
| | | 100%UFS | 853 | – | 1598 |
| | 4-Point | 65%UFS | 458 | 374 | 1039 |
| | | 80%UFS | 563 | 461 | 1278 |
| | | 90%UFS | 634 | 518 | 1438 |
| | | 100%UFS | 1280 | – | 1598 |
| CP $[90/0]_{4s}$ | 3-Point | 65%UFS | 225 | 184 | 924 |
| | | 80%UFS | 277 | 227 | 1137 |
| | | 90%UFS | 312 | 255 | 1279 |
| | | 100%UFS | 630 | – | 1421 |
| | 4-Point | 65%UFS | 338 | 276 | 924 |
| | | 80%UFS | 416 | 340 | 1137 |
| | | 90%UFS | 468 | 383 | 1279 |
| | | 100%UFS | 945 | – | 1421 |