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Quantification of flexural fatigue life and 3D damage in carbon fibre reinforced polymer laminates

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ABSTRACT

Carbon fibre reinforced polymer (CFRP) laminated composites have become attractive in the application of wind turbine blade structures. The cyclic load in the blades necessitates the investigation on the flexural fatigue behaviour of CFRP laminates. In this study, the flexural fatigue life of the $[+45/-45/0]_{2s}$ CFRP laminates was determined and then analysed statistically. X-ray microtomography was conducted to quantitatively characterise the 3D fatigue damage. It was found that the fatigue life data can be well represented by the two-parameter Weibull distribution; the life can be reliably predicted as a function of applied deflections by the combined Weibull and Sigmodal models. The delamination at the interfaces in the 1st ply group is the major failure mode for the flexural fatigue damage in the CFRP laminate. The calculated delamination area is larger at the interfaces adjacent to the 0 ply. The delamination propagation mechanism is primarily matrix/fibre debonding and secondarily matrix cracking.

1. Introduction

Fibre reinforced polymer (FRP) laminated composites have been widely used in wind turbine blade structures due to their good strength-to-weight ratio, corrosion resistance and excellent fatigue properties [1–3]. Glass fibres are currently the most common reinforcements in the laminate for wind turbine blades; however, there is an increasing interest in carbon fibres as a result of their decreasing cost and better properties. Wind turbine blades in service are subjected to highly variable loads such as aerodynamic, gravitational and inertial forces. The aerodynamic and gravitational forces bring about the cyclic stress in the blade structures, making the flexural fatigue one of the important failure modes in the blades [4,5]. It is thus necessary to investigate the flexural fatigue behaviour of carbon fibre reinforced polymer (CFRP) laminates in order to predict the service life of the turbine blades subjected to cyclic loading.

The fatigue damage in FRP laminated composites is usually associated with the degradation of stiffness. The stiffness is an indicator for the laminate's resistance to fatigue loads. Note that in force-controlled fatigue, the load bearing capacity of laminates can also be used to describe the fatigue failure when it declines to the level of the applied stress in the fatigue cycle [6]. However, the failure in displacement-controlled fatigue is often specified when the stiffness degrades to a defined level. The stiffness degradation process is influenced by the laminate constituents, layup sequences, and fatigue loading conditions (such as the load type and level) [7]. Philippidis and Vassilopoulos [8] reported that the reduction of stiffness up to the failure in glass fibre reinforced polymer laminates ranges from less than 7% to 50% for different layup sequences. There seems no general agreement on the stiffness degradation level at which the fatigue failure is defined [8–10]. Jessen and Plumtree [9] considered the occurrence of failure in the tension–tension fatigue tests of pultruded glass composites when the stiffness reduces by 20%. Jones et al. [10] proposed that a 15% reduction in stiffness of [0/90] epoxy-based laminates serves as the criterion for the flexural fatigue failure. The ISO 13003 standards suggested the stiffness reduction between 5% and 20% for the fatigue failure in FRP composites. Therefore, it is worthwhile to analyse the stiffness degradation behaviour in CFRP laminated composites subjected to flexural fatigue loads for the prediction of fatigue life.

The fatigue life of FRP laminates is usually scattered even under carefully controlled testing conditions because of the inhomogeneous microstructure and anisotropic properties. Various statistical methods have been developed to analyse the distribution of fatigue life data [11–13]. Among these methods, the Weibull distribution function has been well-established to characterise the fatigue life of laminated composites [11]. However, to design laminate components requires statistically predicting the fatigue life as a function of cyclic loading levels.

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The fatigue failure mechanism of FRP composites are generally complicated and in the forms of matrix cracks, fibre failure, matrix/fibre debonding and delamination [14]. However, one of these failure modes can be the dominant mechanism responsible for the fatigue damage in the composite depending on the material and loading conditions [15,16]. It is thus essential to examine the damage in the laminate during and after the fatigue test and to determine how the damage leads to the degradation of properties. X-ray microtomography (μXT) has recently become a powerful non-destructive testing technique to characterise the full 3D material damage under various loads [17–20]. In particular, the failure mechanisms of FRP composites subjected to various loads have been reliably investigated using the μXT technique [14,21–23]. Nevertheless, a quantitative analysis of the 3D damage has been rarely reported on CFRP composites [21].

The aim of this study was to investigate the stiffness degradation, fatigue life prediction and 3D damage of CFRP laminates with the symmetric layup sequence $[+45/-45/0]_{2s}$ subjected to flexural fatigue loads. Static three-point bending flexural tests were conducted to measure the elastic modulus and failure strength/deflection of the laminate. Displacement-controlled flexural fatigue tests in the three-point bending fixture were performed on the laminate specimens at different cyclic deflection levels to determine the stiffness degradation process and the fatigue life. The two-parameter Weibull distribution model was employed to analyse and predict the fatigue life. Finally, the 3D damage in the laminate after a specific fatigue cycle was characterised in the μXT, and the interlaminar facture surfaces after the fatigue tests were examined in the scanning electron microscope (SEM). The statistical method and the μXT technique provided the insights into the flexural fatigue life and 3D damage in the CFRP laminate.

2. Experimental procedure

2.1. Materials and specimens

The carbon fibre reinforced polymer laminates with the symmetric layup sequence $[+45/-45/0]_{2s}$ were fabricated using the L-930HT (Cytec Solvay Group, USA) flame retardant epoxy carbon prepregs in the unidirectional form. The cured ply thickness of the prepreg is 0.178 mm as provided by the prepreg manufacturer. The $[+45/-45/0]_{2s}$ laminates are extensively used in some components in the wind turbine blade, especially those subjected to multiaxial stresses, such as the skin and the root [1,2,14].

The prepreg laminates were cured in the autoclave at 127 °C for 60 min under the vacuum pressure of −0.069 MPa (i.e., 0.069 MPa lower than the atmospheric pressure). The pressure in the chamber was maintained at 0.41 MPa during the entire curing process. The laminates after curing were approximately 2.13 mm in depth (thickness). The rectangular specimens (150 × 12 mm) for the flexural tests were machined from the cured CFRP laminates using the waterjet cutter. The transverse cross section of the laminate was ground and polished for the optical microscopic examination to inspect any manufacturing defects and determine the fibre volume fraction. Fig. 1 illustrates very few small pores in the +45 ply, suggesting the negligible effect on the flexural fatigue behaviour [24,25]. The fibre volume fraction was (57.8 ± 2.7)% as measured from the optical images on various locations in the transverse cross section.

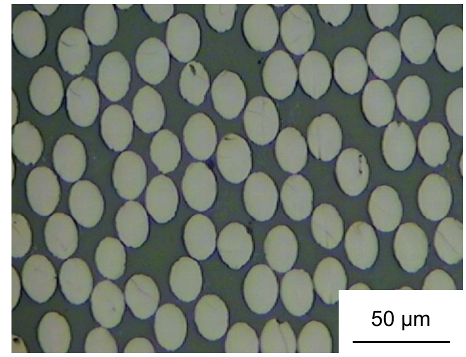

Fig. 1. Optical image of the polished transverse cross section of the +45 ply in the $[+45/-45/0]_{2s}$ CFRP laminate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Static and fatigue flexural tests

The flexural experiments with the support span length 75 mm were conducted in an in-house three-point bending fixture which was clamped to the MTS 810 (MTS Systems Corp., USA) servo-hydraulic universal testing machine by the wedge grips. A relatively high span-to-depth ratio of approximately 35 was employed because (1) the high ratio specimen is recommended for the flexural test of highly anisotropic laminated composites and (2) the shear stress effect on the failure behaviour becomes insignificant with the increased span length [25]. Note that the 0 ply in the laminate was directed along the span in the flexural tests.

Four specimens were subjected to the static flexural tests (ASTM D790) with the crosshead velocity 2 mm min^{-1} to determine the flexural properties. After the failure, the crosshead returned to the initial position, and reloading was then applied to the same specimens to characterise the residual properties. Displacement-controlled flexural fatigue tests with the sinusoidal waveform (ASTM D7774) were performed under five different cyclic deflection levels (CDL). The CDL normalised by the static failure deflection (SFD) was γ_c = CDL/SFD = 0.58, 0.65, 0.71, 0.84 and 0.91. Eight specimens were repeated in the flexural fatigue tests under each CDL. The ratio of the minimum and maximum displacement was constant at $R = 0.1$ for all the fatigue experiments. The frequency was limited to 2 Hz given the large midspan deflection. The stiffness was measured and monitored in the fatigue tests.

2.3. X-ray microtomographic and fractographic characterisation

To characterise the damage, the flexural fatigue test on a CFRP laminate specimen subjected to the normalised CDL $\gamma_c = 0.84$ was interrupted after the specific cycle. The midspan portion of the specimen was then scanned in the X-ray microtomography at 55 kV and 46 μA [17,18,26]. A set of 720 projections were recorded as the specimen was rotated through 360°. The 3D image was reconstructed from the projections using an in-house algorithm that enhances the reconstruction quality of planar objects [27,28]. The internal damage including the fibre failure, matrix cracking and delamination was visualised in the AVIZO/FIRE software. The ImageJ software was used to quantify the projected area of the delamination in the specimen.

After fatigue testing under each CDL, the interlaminar fracture surfaces of the laminate specimens were examined in the SEM to explore the fatigue failure mechanism.

3. Results and discussion

3.1. Static flexural behaviour

The static flexural response of the CFRP laminate was quantitatively characterised by the measured histories of both the bending load P and the midspan deflection D. As the deflection of the specimen exceeds 10% of the support span, the flexural stress at the