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A phenomenological fatigue life prediction model of glass fiber reinforced polymer composites

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ABSTRACT

In this paper, a macro phenomenological fatigue model is developed for the off-axis fatigue behavior of glass fiber reinforced polymer (GFRP) composite laminates. The residual stiffness method and strain failure criterion are used to characterize the brittle nature of fatigue damage evolution. This allows one to obtain a practical form of multiaxial fatigue model that takes into account of the non-linear effects of fiber orientation dependence, stress ratio dependence as well as the effect of loading frequency on the fatigue behavior of composite laminates. Parameters of the model are fitted out according to relative fatigue experiment data with specific lay-up under certain stress ratio and loading frequency. Fatigue life predictions are verified by different stress ratios and loading frequencies, and the results of the model show a good agreement with experimental data.

1. Introduction

Glass fiber reinforced composite materials, as an alternative to traditional materials like metals, now have been widely used for aerospace components, sporting goods, structural applications in automobiles, ships, aircraft, etc., in view of their beneficial characteristics, such as stability, high specific strength, stiffness and good chemical resistance. In fact, structural components are usually subjected to complex fatigue loadings, which is one of the main forms of failure in mechanic and structural catastrophe [1,2]. Thus, it is important to investigate and determine the fatigue characteristics of GFRP composites for application as the primary structural member in various fields.

Many studies on the fatigue damage growth behavior of GFRP composite laminates have been conducted. It is known that mechanical properties and the fatigue life of composite materials are concerned with many factors including the fiber/matrix material, volume fractions, orientation of fiber arrangement, moisture content, porosity, temperature, frequency of loading, applied stress, strain rate, and stress amplitude. The fatigue behavior of composites has been shown to be highly dependent on the stress ratio R and the frequency of applied cyclic load f [3–9]. Elyn [10] and Mandell [11] have discussed the effects of stress ratio on the fatigue life of composites and have shown that for a given maximum stress in a tension–tension scenario, the fatigue life of the composite increases with increasing magnitude of R. In compression–compression loading, increasing the magnitude of R reduces the fatigue life of composite. Rosenfeld and Huang [12] investigated the effect of the compressive loading on the fatigue behavior of graphite/epoxy laminates for $R = 0$, $-\infty$ and -1. They concluded that a significant life reduction occurs for both $R = -\infty$ and $R = -1$. Rotem and Nelson [13] studied the fatigue behavior of graphite/epoxy laminates and indicated that tension–compression fatigue behavior was more important than tension–tension or compression–compression fatigue. Also Saff [14], Sun and Chan [15] have shown that when the frequency f increases, the fatigue crack propagation rate decreases and the fatigue life of the polymer increases correspondingly, provided that the temperature is assumed to be constant. It is likely to be considered when evaluating the fatigue life of small composite wind turbine blades as they are subject to relatively high frequency loading in an "air-cooled" environment.

Fatigue analysis of GFRP composite materials is difficult due to several basic characteristics of the composite materials. However, many attempts have been made for fatigue modeling and life prediction. Various fatigue theories have been proposed for correlating constant amplitude fatigue behavior of anisotropic composite laminates. Degrieck and Van Paepegem [16] divided existing fatigue models into several categories: macroscopic fatigue life model (S–N curves), residual strength/stiffness model, and progressive damage model.

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In this paper, a phenomenological fatigue life prediction model was proposed on the basis of residual stiffness method to describe the strength degradation and to predict the fatigue life of glass fiber reinforced polyester composite materials. In order to establish a more comprehensive and feasible model for fatigue life prediction, a strain failure criterion is introduced to substitute the failure stiffness. The effects of stress ratio, loading frequency and fiber orientation on fatigue life are taken into account as well. It is assumed that the temperature of the specimen is constant during the test.

2. Experimental method

A systematic experimental investigation was undertaken, consisting of static and fatigue tests of straight edge coupons cut at various directions from a multidirectional laminate. Coupons were cut by a diamond saw wheel at 0° on-axis, 45° and 90° off-axis orientations.

The specimens were prepared according to ASTM: 3039 standard, and aluminum tabs were glued at their ends. Coupon edges were trimmed with fine sandpaper. The coupons were 230 mm long and had a width of 25 mm. Their nominal thickness was 3 mm. The length of the tabs, with a thickness of 2 mm, was 45 mm leaving a gauge length of 160 mm.

Static tests were performed in tension and compression in an MTS of 250 kN capacity, under displacement control at a speed of 1 mm/min. Coupons loaded in compression had a gauge length of 30 mm to avoid buckling.

Fatigue tests were performed with the same machine applying a constant amplitude sinusoidal force at room temperature (*RT*, about 23 °C). Under different stress ratios, $R = 0.1$, $R = 0.5$ (T–T), $R = -1$ (T–C) and $R = 2$, $R = 10$ (C–C), *S–N* curves were determined experimentally. The number of cycles to failure and stress applied to each coupon are recorded with a frequency of 10 Hz. Most specimens were fatigue tested for up to 10^6 cycles. For some cases, the fatigue tests continued up to 10^7 cycles.

3. Modelling

The fatigue damage of composite laminates has been known to cause changes of material properties. It is feasible to obtain a measure of damage by measuring the changes in material properties such as the residual strength, stiffness and life. The residual stiffness is a parameter monitored nondestructively, easily measured and interpreted. Therefore, a stiffness degradation model [17] is proposed with the assumptions that the residual stiffness is related to the fatigue life by the following relationship

$$\frac{dE(n)}{dn} = -E(0)Q\upsilon n^{\upsilon-1} \tag{1}$$

where $E(0)$ is initial stiffness, n is the number of loading cycles. Q and υ are parameters dependent on the applied stress, stress ratio, frequency, which can be approximated as $Q = a_1 + a_2\upsilon$, a_1 and a_2 are material constants.

Integrating Eq. (1) and applying the boundary conditions, the stiffness degradation expression can be written as

$$1 - \frac{E(N)}{E(0)} = \frac{a_1 + a_2\upsilon}{f^\upsilon}(N^\upsilon - 1) \tag{2}$$

As the failure stiffness $E(N)$ cannot be determined until the failure of specimen occurs, a strain failure criterion is introduced to substitute the failure stiffness, which assumes that failure occurs when the strain reaches the tensile ultimate strain. The failure criterion is based on the following assumptions: (i) For the case where the stress strain response remains linear to failure, the stiffness of the undamaged specimen can be determined as $E(0) = \sigma_u/\varepsilon_u$, where σ_u is the ultimate strength and ε_u is the static ultimate strain. (ii) If the stress strain response remains linear during fatigue cycling, then the stiffness as failure can be defined as $E(N) = \sigma_{\max}/\varepsilon_f$, where $\sigma_{\max}$ is the maximum applied stress and ε_f is the strain at fatigue failure. It is assumed that failure occurs when the strain at fatigue failure is equal to the ultimate strain ($\varepsilon_f = \varepsilon_u$), thus the relationship between the failure stiffness $E(N)$ and the applied stress $\sigma_{\max}$ is obtained and modified to account for non-linear effects as [18]

$$\frac{\sigma_{\max}}{\sigma_u} = b_1\left[\frac{E(N)}{E(0)}\right]^{b_2} \tag{3}$$

where b_1 and b_2 are constants determined by experiments, $\sigma_{\max}$ is maximum applied stress and σ_u is the ultimate stress.

After applying the strain failure criterion to Eq. (2), the following stress-life relationship is obtained as

$$1 - \left(\frac{\sigma_{\max}}{b_1\sigma_u}\right)^{1/b_2} = \frac{a_1 + a_2\upsilon}{f^\upsilon}(N^\upsilon - 1) \tag{4}$$

Eq. (4) is applied to evaluate and predict the average fatigue life for fiber-reinforced composite materials, where the parameters υ is related to maximum applied stress $\sigma_{\max}$, stress ratio R, frequency f. The porosity and temperature are considered as constant. Consequently, υ is defined as

$$\upsilon = A_1 \cdot H(R, \sigma_{\max}, \sigma_u) \tag{5}$$

where A_1 is assumed to be a constant.

The stress ratio R, stress σ_u and $\sigma_{\max}$ are the controlling parameters in fatigue failure mechanism of composites. Many researchers have shown that the effect of R and $\sigma_{\max}$ on the fatigue life of composites is non-linear and discontinuous. Here the deterministic model developed by Sendeckyj [19] and Hertzberg [20] were used to postulate the following formulation

$$H(R, \sigma_{\max}, \sigma_u) = \sigma_u^{1-\alpha}\sigma_{\max}^{\alpha}(1 - R)^{\alpha} \tag{6}$$

where α is a constant. To account for the fatigue life dependence on fiber angle, α is established as $\alpha = 1.6 - \psi\sin\theta$, θ is the smallest angle between fiber and loading direction. In the absence of any 0° fibers, ψ is defined as: $\psi = R$ for $-\infty < R < 1$ (tension–tension and reverse loading), $\psi = 1/R$ for $1 < R < \infty$ (compression–compression loading).

Substituting Eq. (6) into Eq. (5) yields

$$\upsilon = A_1 \cdot \sigma_u\left(\frac{\sigma_{\max}}{\sigma_u}(1 - R)\right)^{1.6-\psi|\sin\theta|} \tag{7}$$

For a specific composite material, ultimate stress σ_u, the smallest angle θ between the direction of fiber and loading, stress ratio R as well as ψ are all determined. As a result, υ is a function of maximum applied stress $\sigma_{\max}$. The expression of fatigue life could be written in the form of logarithm as

$$\mathrm{Log}N = \frac{1}{\upsilon}\log\left\{\frac{1 - (\sigma_{\max}/b_1\sigma_u)^{1/b_2}}{a_1 + a_2\upsilon}\cdot f^\upsilon + 1\right\} \tag{8}$$

where $\upsilon = A_1\sigma_u\left(\frac{1-R}{\sigma_u}\right)^{1.6-\psi|\sin\theta|}\cdot(\sigma_{\max})^{1.6-\psi|\sin\theta|}$

There are five parameters a_1, a_2, b_1, b_2 and A_1 in this model, which can be determined by experiment data. Furthermore, only a few straightforward fatigue tests are required at one stress ratio for a number of stress levels to calculate.

4. Result and discussion

In this section, the parameters in Eq. (8) are acquired according to the experiment data of literature [21,22], which contains a wide