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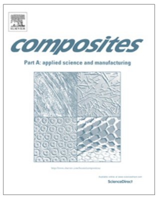

Off-axis tensile fatigue assessment based on residual strength for the unidirectional 45° carbon fiber-reinforced composite at room temperature

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ABSTRACT

The tensile fatigue behavior of unidirectional carbon fiber-reinforced thermoplastic and thermosetting laminates was examined at room temperature. Tension-tension cyclic fatigue tests were conducted under load control at a sinusoidal frequency of 10 Hz to obtain stress-fracture cycles (*S-N*) relationship. The fatigue limits of carbon fiber-reinforced thermoplastic laminates (CF/PA6) and thermosetting laminates (CF/Epoxy) were found to be 28.0 MPa (48% of the tensile strength) and 56.2 MPa (63% of the tensile strength), respectively. Two types (in constant and incremental loading way) of loading-unloading low cycle fatigue tests were employed to investigate the modulus history of fatigue process for announcing the fatigue mechanism. The residual tensile strength of specimens that survived fatigue loading maintained with the increase of fatigue cycles and applied stress. Examination of the fatigue-loaded specimens revealed that the more flexible/ductile trend of resins and the formation of micro-cracks at the interface between fiber and matrix was facilitated during high fatigue loading (⩾fatigue limit stress), while no interfacial/matrix damage in resins was detected during low fatigue loading (<fatigue limit stress), which was consider to be the governing mechanism of strength maintain during fatigue loading.

1. Introduction

Advanced composites reinforced with inorganic fibers, such as carbon, glass and basalt, are expected to be used in various applications including aerospace and aircraft structure, yachts, vehicles as well as wind generator blades and other products on the account of their outstanding and designable mechanical properties, lightweight, thermostability, longer service life and good damage-resistant safety [1–7]. Long fiber composites are heterogeneous and, unlike more traditional isotropic materials, have different material properties in different directions, which results in crack growth in preferred directions. In the past two decades, research studies on the various mechanical properties of fiber-reinforced composites have been performed [1–13]; however, the results of these studies were still insufficient to establish the design criteria for load-bearing structures. In particular, the fatigue behavior of carbon fiber-reinforced composites is not well understood. Therefore, the usage of carbon fiber-reinforced composites is still limited to heat resistant components of spacecraft, rocket nozzles and nuclear reactors, etc. [1,4].

Laminated composites are generally composed of a series of thin unidirectional plies arranged in definite orientations that form cross-plies and quasi-isotropic laminates. Thus, studies on the fatigue of composites have concentrated mainly on multi-ply lay-ups [14–20] where delamination between the plies plays a vital role [14,15]. However, it is important to understand how damage evolves in an individual ply in order to form a basis for cyclic damage evolution in a multidirectional laminate. In an off-axis unidirectional composite, progressive matrix cracking and debonding can be studied without the complication of delamination. Varvani-Farahani and coworkers [16–20] have studied damage progress in FRP composites in three stages of (I) matrix cracking, (II) fiber-matrix interface cracking and (III) fiber fracture over life cycles. They mapped these stages and formulated for various off-axis loading conditions. Testing an off-axis unidirectional composite has the additional advantage of experiencing little non-progressive fiber damage [21].

It is currently understood that (1) fatigue limit of laminated composites is 80–90% of the static tensile strength [22–25], (2)

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residual tensile strength remains almost unchanged during the fatigue test until the number of cycles reaches a critical value where the residual stress undergoes a sudden drop [26,27]. On the other hand, some researchers reported that the residual tensile strength of composites after fatigue loading is not degraded from original static value, and is sometimes improved [22,23]. The mechanism responsible for the above behavior have not yet been clarified owing to the limited amount of experimental results and the lack of information regarding changes in the microstructures induced by fatigue loading [22,28–32]. Previous study on the static tensile properties of fiber-reinforced composites was strongly affected by the interfacial bonding strength between fibers and matrices [33–35]. Interfacial issues are also critical when looking at recyclability and life cycle characteristics of composites. It could be inferred that the residual strength of composites might also be related to interfacial mechanical properties according to the previous studies [22,35,36]. The off-axis fatigue failure of unidirectional fiber-reinforced composites is governed by the fatigue strengths of matrix and fiber-matrix interface/interphase, which is one of the best ways.

Off-axis fatigue behavior of different types of unidirectional composites has been investigated in the following series of literature [37–42]. In reference [37] reported by Kawai et al., the off-axis tension-tension fatigue behavior of unidirectional carbon fiber-reinforced composites at room temperature, and at 100 °C was investigated. The tensile strength and fatigue life for specimens with a fiber orientation θ° of 0°, 5°, 10°, 15°, 20°, 30°, 45° and 90° were determined. A very good fit between the experimental results and predicted results using the Tsai-Hill criterion was found. According to the tension-tension fatigue tests, they also concluded that the off-axis fatigue life curves plotted on a linear-logarithmic scale are approximately described by linear relationship (straight line), irrespective of the fiber orientation. The various curves all fell within a narrow scatter band after normalizing the fatigue life curves using the corresponding off-axis static strength. In references [38–42], similarly behaviors of unidirectional composites were found and predictions of associated failure envelopes were carried out based on the corresponding model. The (0/90) layup configurations of FRP composites were discussed and formulated through involvement of each composite laminate and were found in good agreement with experimental data [19].

In the present study, attention was focused on the residual strength behavior of unidirectional carbon fiber-reinforced composites after off-axis (45°) fatigue loading. The residual strength, elastic modulus and ultimate strain after fatigue loading at various numbers of cycles and loads were determined in order to discuss the mechanism that maintains the residual tensile strength. Two types (constant and incremental loading way) of loading-unloading low cycle fatigue tests were employed to investigate the modulus history of fatigue process for announcing the fatigue mechanism. The fracture surfaces and cross sections of the fatigued and un-fatigued carbon fiber-reinforced composites were observed in order to identify the micro-damage induced during fatigue loading. Finally, the mechanisms responsible for the strength maintaining after fatigue and the higher resistance of the carbon fiber-reinforced composites are discussed based on the present experimental evidence.

2. Stiffness degradation and damage of unidirectional FRP composites under fatigue cycles [16–20]

The stiffness degradation of composites after cycles of fatigue were general reported in Refs. [16–20]. Varvani-Farahani and coworkers [16–20] have studied damage progress in UD FRP composites in three stages of (I) matrix cracking, (II) fiber-matrix interface cracking and (III) fiber fracture over life cycles as shown in Fig. 1. Matrix cracks are formed as an initial stage of micro-damage process (Region I), which affects the residual strength and the life of a given laminate. Matrix damage accumulation continues a more cracks integrate until they encounter a fiber, leading to matrix-fiber phase (Region II). Damage progress at this stage may cause matrix-fiber debonding and more reduction in stiffness of composite laminates. The later stage of damage developments is typified by increasing rate of progression of all damage modes resulting in catastrophic fiber failure (Region III). The concept of damage accumulation may be used a more suitable approach to predict the fatigue life of composite materials. A damage fatigue index (D) is often used to evaluate the fatigue damage due to cyclic loading as shown in Eq. (1).

$$D = 1 - \frac{E}{E_0} \tag{1}$$

where D is the accumulated fatigue damage index ranging between 0 and 1, E_0 is the Young's modulus of the un-fatigued composites, and E is the Young's modulus of fatigued composites. Thus, the extent of damage can be quantified by measuring the Young's modulus. Varvani-Farahani and co-workers [16–20] proposed a fatigue damage model taking into the account the effects of cyclic stress magnitude, mean stress, off-axis angles and interfacial bonding stress as the strength of unidirectional FRP composites degrades under fatigue cycles. The proposed fatigue damage model is defined as:

$$D = 1 - \frac{E}{E_c} = \{E_{m\theta}[\alpha + f(\gamma - \alpha)] + E_{f\theta}R^{*}\lambda\} \tag{2}$$

Term f is the representative of the fiber-matrix interfacial shear strength and varies from zero (weak bonding) to unity (strong bonding). Terms $E_{m\theta}$ and $E_{f\theta}$ take into account the effect of off-axis angles and are defined as:

$$E_{m\theta} = 1 - \frac{E_f V_f}{E_c} \tag{3}$$

$$E_{f\theta} = \frac{\mathrm{E_f V_f} \cos\theta}{\mathrm{E_c}} \tag{4}$$

Meanwhile, terms α, γ, and λ are functions of the number of cycles to failure N_f and progressing fatigue cycles N and can be described as:

$$\alpha = \frac{\ln(\mathrm{N}+1)}{\ln(\mathrm{N}_f/\mathrm{n})} \tag{5-1}$$

$$\gamma = \frac{\mathrm{N}}{\mathrm{N_f}/\mathrm{n}} \tag{5-2}$$

$$\lambda = \frac{\ln(1 - \mathrm{Nn}/\mathrm{N_f})}{\ln(\mathrm{n}/\mathrm{N_f})} \tag{5-3}$$

where n is the percentage of drop in stiffness recorded for a fatigue test.

3. Experimental

3.1. Specimen preparation

The carbon fiber-reinforced composites used in this study were fabricated from a unidirectional reinforced prepreg made of reinforcing carbon fiber grade T700SC 12 K brought from Toray Industries, Inc. and polyamide 6 (PA6, Type: MXD-PA) and epoxy (Type: MCP939) supplied from Mitsubishi Gas Chemical Company and Maruhachi Corporation, respectively. Mechanical properties of