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A hysteresis dissipated energy-based parameter for damage monitoring of carbon fiber-reinforced ceramic–matrix composites under fatigue loading

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ABSTRACT

Under fatigue loading of fiber-reinforced ceramic–matrix composites (CMCs), the stress – strain hysteresis loops appear as fiber slipping relative to matrix in the interface debonded region. The area of hysteresis loops, i.e., the hysteresis dissipated energy, changes with the increase of cycle number, which can reveal the fatigue damage mechanisms, i.e., matrix multicracking, fiber/matrix interface debonding, interface slipping and interface wear. Based on the fatigue hysteresis theories, the relationships between hysteresis dissipated energy, hysteresis dissipated energy-based damage parameter, stress – strain hysteresis loops, and fatigue damage mechanisms have been established. The effects of fiber volume content, fatigue peak stress, fatigue stress ratio and matrix crack spacing on the evolution of the hysteresis dissipated energy and hysteresis dissipated energy-based damage parameter as a function of cycle number have been analyzed. The experimental hysteresis dissipated energy and hysteresis dissipated energy-based damage parameter of unidirectional CMCs corresponding to different fatigue peak stresses and cycle numbers have been predicted using the present analysis. It was found that the hysteresis energy-based parameter can be used to monitor the fatigue damage evolution and predict the fatigue life of fiber-reinforced CMCs.

1. Introduction

Ceramic materials possess high strength and modulus at elevated temperatures. But their use as structural components is severely limited because of their brittleness. The continuous fiber-reinforced ceramic–matrix composites (CMCs), by incorporating fibers in ceramic matrices, however, not only exploit their attractive high-temperature strength but also reduce the propensity for catastrophic failure. These materials have already been implemented on some aero engines' components [1]. The CMC flaps for exhaust nozzles of SNECMA M53 and M88 aero engines have been used for more than one decade [2]. The CMC turbine vanes have been designed and tested in the aero engine environment under the implementation of Ultra Efficient Engine Technology (UEET) program [3]. A CMC turbine blade has been tested for 4 h by General Electric in a modified GE F414 engine, which represents the first application of the CMC material in a rotating engine component. Incorporating the CMC turbine blades on a GE90-sized engine, the overall weight can be reduced by 455 kg, which represents approximately 6% of dry weight of a full sized GE90-115 [4]. The CMC combustion chamber floating wall tiles have also been tested in the aero engine environment for 30 min, with the temperature range of 1047–1227 °C and the pressure of 2 MPa [5].

Under fatigue loading of fiber-reinforced CMCs, matrix multicracking and fiber/matrix interface debonding would occur first [6], the open and closure of matrix cracking upon each cycle are the basic fatigue damage mechanisms [7]. The stress–strain hysteresis loops appear as fiber slipping relative to matrix in the interface debonded region upon unloading and subsequent reloading [8]. The hysteresis loop area, i.e., the hysteresis dissipated energy, can be used as an effective tool to monitor the damage evolution of fiber-reinforced CMCs under fatigue loading. Many researchers investigated the evolution characteristics of hysteresis dissipated energy under cyclic loading at room and elevated temperatures. Holmes and Cho [9] investigated the hysteresis loops evolution characteristic in unidirectional SiC/CAS-II composite under fatigue loading at room temperature. At the initial stage, the hysteresis modulus decreases rapidly and the hysteresis dissipated energy increases, due to matrix multicracking, fiber/matrix interface debonding and interface wear. When the cycle number approaches a critical value, the hysteresis modulus remains constant. However, the hysteresis dissipated energy continually decreases with the increase of cycle number. Upon approaching fatigue fracture, the hysteresis dissipated energy increases rapidly. Li [10] investigated the fatigue hysteresis dissipated energy

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evolution of cross-ply C/SiC composite at room and elevated temperature of 800 °C in air atmosphere. The hysteresis dissipated energy decreases with the increase of cycle number. Reynaud [11] investigated the evolution characteristics of the hysteresis dissipated energy corresponding to two different types of CMCs at elevated temperatures of 600 °C, 800 °C and 1000 °C in inert atmosphere. First, the hysteresis dissipated energy of 2D SiC/SiC composite increases with the increase of cycle number due to interface radial thermal residual compressive stress. The second ceramic composite, $[0/90]_s$ SiC/MAS-L, the hysteresis dissipated energy decreases with the increase of cycle number due to interface radial thermal residual tensile stress. Fantozzi and Reynaud [12] investigated the hysteresis dissipated energy evolution of 2.5D SiC/[Si–B–C] and 2.5D C/[Si–B–C] composites at an elevated temperature of 1200 °C in air atmosphere. The hysteresis dissipated energy of 2.5D SiC/[Si–B–C] composite decreases with the increase of cycle number due to interface wear; the hysteresis dissipated energy of 2.5D C/[Si–B–C] composite decreases significantly after 144 h static loading attributed to PyC interface recession by oxidation or by a beginning of carbon fibers recession. The objective of this paper is to develop a hysteresis dissipated energy-based parameter to effectively monitor the damage evolution in fiber-reinforced CMCs under fatigue loading.

Under fatigue loading, the hysteresis dissipated energy, which results from the interface frictional slip between fiber and matrix in the interface debonded region, can be employed to provide a quantitative damage assessment for fiber-reinforced CMCs. Based on the fatigue hysteresis theories [13], the hysteresis dissipated energy and a hysteresis dissipated energy-based damage parameter changing with the increase of cycle number, considering the fatigue damage mechanisms of matrix multicracking, interface debonding, interface slipping and interface wear, have been investigated. The relationships between hysteresis dissipated energy, hysteresis dissipated energy-based damage parameter, stress–strain hysteresis loops and fatigue damage mechanisms, have been analyzed. The effects of fiber volume content, fatigue peak stress, fatigue stress ratio and matrix crack spacing on the evolution of hysteresis dissipated energy and hysteresis dissipated energy-based damage parameter versus cycle number, have been analyzed. The experimental stress–strain hysteresis loops, hysteresis dissipated energy and hysteresis dissipated energy-based damage parameter as functions of cycle number of unidirectional CMCs have been predicted using the present analysis.

2. Hysteresis theories

If matrix multicracking and fiber/matrix interface debonding are present upon first loading, the stress–strain hysteresis loops would develop as a result of energy dissipation through the frictional slip between fiber and matrix upon unloading and subsequent reloading. Upon unloading, the counter slip between fiber and matrix occurs in the interface debonded region. The interface debonded region can be divided into two regions, i.e., interface counter slip region and interface slip region, as shown in Fig. 1(a). The unloading interface counter slip length is denoted to be y. Upon reloading, the new slip between fiber and matrix occurs in the interface debonded region. The interface debonded region can be divided into three regions, i.e., interface new slip region, interface counter slip region and interface slip region, as shown in Fig. 1(b). The reloading interface new slip region is denoted to be z.

Based on the fatigue damage mechanism of interface slip between fiber and matrix upon unloading and subsequent reloading, the stress–strain hysteresis loops of fiber-reinforced CMCs can be classified into four different interface slip cases, i.e., (1) the interface partially debonds, and fiber completely slips relative to matrix; (2) the interface partially debonds, and fiber partially slips relative to matrix; (3) the interface completely debonds, and fiber partially slips relative to matrix; and (4) the interface completely debonds, and fiber completely slips relative to matrix in the interface debonded region upon unloading and subsequent reloading.

2.1. Case 1: the interface partially debonds and fiber completely slips relative to matrix

Upon unloading, the unit cell of the half matrix crack spacing can be divided into two regions, i.e., interface debonded region and interface bonded region. The interface debonded region can be divided into two regions, i.e., interface counter slip region ($x \in [0, y]$) and interface slip region ($x \in [y, L_d]$). In the interface counter slip and slip regions, the interface shear stress is equal in magnitude but opposite in direction. Upon unloading to the applied stress of σ_{tr_pu} ($\sigma_{tr\_pu} > \sigma_{min}$), the unloading interface counter slip length y approaches the interface debonded length L_d, i.e., $y(\sigma=\sigma_{tr\_pu})=L_d$. Upon continually unloading, the interface counter slip length would not change, i.e., $y(\sigma_{min})=y(\sigma_{tr\_pu})$. The unloading interface counter slip length y is determined by the fracture mechanics approach.

$$y=\frac{1}{2}\left\{L_d(\sigma_{max})-\left[\frac{r_f}{2}\left(\frac{V_m E_m \sigma}{V_f E_c \tau_i}-\frac{1}{\rho}\right)-\sqrt{\left(\frac{r_f}{2\rho}\right)^2+\frac{r_f V_m E_m E_f}{E_c \tau_i^2}\zeta_d}\right]\right\} \tag{1}$$

where V_f and V_m denote the fiber and matrix volume content, respectively; E_f, E_m and E_c denote the elastic modulus of fiber, matrix and composite, respectively; r_f denotes the fiber radius; ρ denotes the shear-lag model parameter; τ_i denotes the interface shear stress; ζ_d denotes the interface debonded energy.

The unloading stress–strain relationship is determined by Eq. (2) and is divided into two regions, i.e., (1) when the applied stress is $\sigma > \sigma_{tr\_pu}$, the unloading strain is determined by Eq. (2); and (2) when the applied stress is $\sigma < \sigma_{tr\_pu}$, the unloading strain is determined by Eq. (2) by setting $y=L_d$.

$$\varepsilon_{c\_pu}=\frac{\sigma}{V_f E_f}+4\frac{\tau_i}{E_f}\frac{y^2}{r_f L}-2\frac{\tau_i}{E_f}\frac{(2y-L_d)(2y+L_d-L)}{r_f L}-(\alpha_c-\alpha_f)\Delta T \tag{2}$$

where L denotes the matrix crack spacing; α_f and α_c denote the fiber and composite thermal expansion coefficient, respectively; ΔT denotes the temperature difference between fabricated temperature T_0 and room temperature T_1 ($\Delta T=T_1-T_0$).

Upon reloading, the interface slip again occurs near the matrix cracking plane over a distance of z, which is denoted to be the interface new slip region. The interface debonded region can be divided into three regions, i.e., interface new slip region ($x \in [0, z]$), interface counter slip region ($x \in [z, y]$) and interface slip region ($x \in [y, L_d]$). In the interface new slip and counter slip regions, the interface shear stress is equal in magnitude but opposite in direction. Upon reloading to the applied stress of σ_{tr_pr} ($\sigma_{tr\_pr} < \sigma_{max}$), the interface new slip length z approaches the interface debonded length L_d, i.e., $z(\sigma=\sigma_{tr\_pr})=L_d$. Upon continually reloading, the interface new slip length would not change, i.e., $z(\sigma_{max})=z(\sigma_{tr\_pr})$. The reloading interface new slip length is determined by the fracture mechanics approach.

$$z=y(\sigma_{min})-\frac{1}{2}\left\{L_d-\left[\frac{r_f}{2}\left(\frac{V_m E_m \sigma}{V_f E_c \tau_i}-\frac{1}{\rho}\right)-\sqrt{\left(\frac{r_f}{2\rho}\right)^2+\frac{r_f V_m E_m E_f}{E_c \tau_i^2}\zeta_d}\right]\right\} \tag{3}$$

The reloading stress–strain relationship is determined by Eq. (4) and is divided into two regions, i.e., (1) when the applied stress is $\sigma < \sigma_{tr\_pr}$, the reloading strain is determined by Eq. (4); and (2) when the applied stress is $\sigma > \sigma_{tr\_pr}$, the reloading strain is