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Synergistic effect of arbitrary loading sequence and interface wear on the fatigue hysteresis loops of carbon fiber-reinforced ceramic-matrix composites

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ABSTRACT

This study investigates the synergistic effect of arbitrary loading sequence and interface wear on the fatigue hysteresis loops of fiber-reinforced ceramic-matrix composites (CMCs). Based on the fatigue damage mechanism of fiber slipping relative to matrix in the interface debonded region, the interface debonded length, unloading interface counter-slip length and reloading interface new-slip length are determined by fracture mechanics approach. The effects of peak stress, material properties, interface wear and arbitrary loading stress levels on the interface slip and fatigue hysteresis loops have been analyzed.

1. Introduction

Ceramic materials possess high strength and modulus at elevated temperature. But their use as structural components is severely limited because of their brittleness. The fiber-reinforced ceramic-matrix composites (CMCs), by incorporating fibers in the ceramic matrix, are designed to overcome the brittleness of monolithic ceramic materials while maintaining their advantageous high temperature stability, high specific strength and stiffness. The carbon fiber-reinforced silicon carbide ceramic-matrix composites (C/SiC CMCs) are one of the most promising candidates for many high-temperature applications, particularly as aerospace and aircraft thermostructural components [1]. Some of the individual applications include flaps for exhaust nozzles of SNECMA M53 and M88 aero engines, combustors, thrust chambers, turbine vanes, turbine blade and integrally bladed disks [2–5].

Under fatigue loading of fiber-reinforced CMCs, matrix multicracking and fiber/matrix interface debonding would occur first, the open and closure of matrix cracking upon each cycle are the basic fatigue damage mechanisms [6]. The stress–strain hysteresis loops develop due to the frictional slip occurred along any interface debonded region upon unloading and subsequent reloading [7,8]. The shape, location and area of the hysteresis loops can be used as an effective tool to monitor the damage evolution of fiber-reinfroced CMCs under fatigue loading [9]. Many researchers investigated the fatigue hysteresis loops models of fiber-reinforced CMCs [10–15]. Li et al. investigated the effect of interface debonding [16], fiber Poisson contraction [17], fibers fracture [18,19], matrix multicracking [20,21] and matrix cracking modes [22,23] on the cyclic loading/unloading and fatigue hysteresis loops of unidirectional, cross-ply and 2.5D woven CMCs under single fatigue stress level. Li [24] investigated the effect of single/multiple loading stress levels and different loading sequences on the hysteresis

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Nomenclature

E	Young's modulus
F	fiber load at the matrix crack plane
l_c	matrix crack spacing
l_d	interface debonded length
G_m	matrix shear modulus
r_f	fiber radius
R	matrix radius
V	volume fraction
v	relative displacement between the fiber and the matrix
w	axial displacement
y	unloading interface counter-slip length
z	reloading interface new-slip length
α	coefficient of linear thermal expansion
ΔT	temperature change from 'stress-free' temperature
ξ	interface wear region length
ζ_d	fiber/matrix interface debonded energy
ρ	shear-lag model parameter
σ	stress
$\sigma_{\max}$	fatigue peak stress
σ_{fo}	fiber axial stress in the interface bonded region
σ_{mo}	matrix axial stress in the interface bonded region
τ_i	fiber/matrix interface shear stress in the interface debonded region
τ_f	fiber/matrix interface shear stress in the interface wear region
ε	strain
$\varepsilon_c^{\text{unload}}$	unloading strain
$\varepsilon_c^{\text{reload}}$	reloading strain

Superscript and subscript

f	fiber
m	matrix
c	composite

loops of fiber-reinforced CMCs. During applications of ceramic composite structures on aircraft thermostructural components, there would exist synergistic effect of arbitrary loading stress level and interface wear mechanism on the fatigue performance, in which the interface shear stress in the interface wear region under low fatigue peak stress level is much lower than that in the new interface debonded region under high fatigue peak stress level. The difference of interface shear stress existing in the interface wear region and new interface debonded region would affect the interface slip lengths, i.e., the interface debonded length, interface counter-slip length and interface new-slip length, then affect the shape, location and area of the hysteresis loops, which can be used to monitor the internal damage evolution or life prediction of fiber-reinforced CMCs.

The objective of this paper is to investigate the synergistic effect of arbitrary loading sequence and interface wear on the fatigue hysteresis loops of fiber-reinforced CMCs. Based on the fatigue damage mechanism of fiber slipping relative to matrix upon unloading and subsequent reloading and considering the difference of interface shear stress existing in the new and original interface debonded region, the interface debonded length, unloading interface counter-slip length and reloading interface new-slip length are determined by fracture mechanics approach. The fatigue hysteresis loops models considering arbitrary loading stress levels and interface wear mechanism have been developed. The effects of fatigue peak stress, fiber volume fraction, matrix crack spacing, interface debonding and interface wear, and arbitrary loading stress levels on interface frictional slip and fatigue hysteresis loops have been analyzed.

2. Stress analysis

2.1. Initial loading

Upon first loading to the fatigue peak stress $\sigma_{\max}^1$, it is assumed that matrix multicracking and fiber/matrix interface debonding occur. After experiencing N cycles, fiber/matrix interface shear stress in the interface debonded region decreases from initial value τ_i to τ_f due to interface wear. When fatigue peak stress increases from $\sigma_{\max}^1$ to $\sigma_{\max}^2$, the crack propagates along fiber/matrix interface. To analyze the stress distributions in the fiber and matrix, a unit cell is extracted from the ceramic composite, as shown in Fig. 1. The unit cell contains a single fiber surrounded by a hollow cylinder of matrix. The fiber