Composites: Part B 56 (2014) 92–99

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Hysteresis loop model of unidirectional carbon fiber-reinforced ceramic matrix composites under an arbitrary cyclic load

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ARTICLE INFO

Article history:
Received 18 June 2013
Accepted 12 August 2013
Available online 21 August 2013

Keywords:
A. Ceramic–matrix composites (CMCs)
B. Fatigue
B. Microstructures
C. Micro-mechanics
C. Numerical analysis

ABSTRACT

The microstructure of unidirectional fiber-reinforced ceramic matrix composites is described by a cylindrical unit cell that is then discretized by a set of friction elements. Equilibrium equations resulting from the displacement increment balance between the fiber and matrix are constructed and solved, and the distributions of stress and displacement are obtained. Interfacial debonding, fiber fracture and matrix cracking are considered to simulate the hysteresis loops. Finally, the method developed in this paper is employed to study the interfacial sliding and hysteresis loops of a SiC/CAS composite subjected to arbitrary cyclic load. The results are discussed and compared with experimental data.

1. Introduction

The application of ceramic materials with superior thermal properties, chemical stabilities and wear resistances is restricted due to their internal brittleness. The incorporation of a continuous fiber reinforcement phase into a brittle ceramic matrix improves its strength and toughness. Therefore, continuous fiber-reinforced ceramic matrix composites (CMCs) have become one of the most promising materials for space-related applications.

During their actual use, these materials are usually subjected to random or arbitrary cyclic loads and are prone to fatigue fracture. Due to the combined effects of microstructural damages such as matrix cracking, interfacial friction and wear of fiber, ceramic matrix composites (CMCs) exhibit a notable hysteresis phenomenon before fatigue fracture. The hysteresis loops of CMCs reveal the details of microstructural damages; therefore, the loops are critical for understanding the mechanism of fatigue failure.

Many researchers have attempted to describe this hysteresis phenomenon with mathematical and mechanical models. In the study by Cho et al. [1], the sliding of the fiber/matrix interface is treated as the primary factor that causes hysteresis the fatigue process. The authors first introduced the concepts of completely and partially debonded interfaces and obtained the hysteresis energy dissipation rates of the two situations. Pryce and Smith [2] simulated the hysteresis loops for a partially debonded interface by assuming a constant interface shear stress within the debonded zone. Ahn and Curtin [3] used a statistical method to simulate the progression of matrix cracking and study the effect of matrix crack on the hysteresis loops. Solti et al. [4] extended the model of Pryce and Smith [2] to the case of the chemically bonded fiber/matrix interface. The debonding length of frictional sliding along the fiber/matrix interface was determined by the maximum shear stress criterion. Based on the fiber pull-out model of Hutchinson–Jensen [5], the chemically bonded fiber/matrix interface was also considered by Vagaggin, Domergue and Evans [6,7]. They used the model to simulate the hysteresis loops, and their results indicated that interfacial debonding energy has a significant effect on the interfacial debonding and sliding of CMCs subjected to fatigue loading. In recent years, Li, Longbiao and Song, Yingdong used the shear-lag method to estimate both the effect of fiber failure on the fatigue hysteresis loops of CMCs [8] and the interfacial frictional coefficient of CMCs from hysteresis loops [9].

However, all the models mentioned above can be used only for a regular tension–tension cyclic load but not for an arbitrary load. The main factor limiting those models to regular tension–tension cyclic loads is the assumption about the location and range of interface slip zones. As mentioned by Cho et al. [1], the hysteresis response of CMCs is mainly caused by interfacial friction. In fact, interfacial friction is a strong non-linear phenomenon that is difficult to model. Thus, all the works [1–9] mentioned above needed a series of assumptions about the locations and ranges of slip zones to reduce the difficulty of the mathematical analysis of the hysteresis loop model. These assumptions include the following: (1) The cyclic loading process is composed of initial loading and repeatable unloading and reloading processes; (2) during initial loading, the

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http://dx.doi.org/10.1016/j.compositesb.2013.08.063

fiber slips out from the matrix. A forward slip zone forms near the crack plane and expands along the interface; (3) during unloading, the pull-out fiber slips back into the matrix. A reverse slip zone forms near the crack plane and expands along the interface. Meanwhile, part of the forward slip zone is covered by the reverse slip zone during the process of complete unloading; (4) during the subsequent reloading, a new forward slip zone initiates near the crack plane and expands to cover the previous reverse slip zone. When reloading to the maximum value, the reverse slip zone has been entirely covered by the expanding forward slip zone caused by reloading, and a new forward slip zone occurs that is the same as the one caused by initial loading and (5) the residual cycles repeat processes 3 and 4. These assumptions may be appropriate in the case of regular tension–tension load; however, they are not correct in the case of arbitrary load, in which unloading may occur before loading to the maximum value, and the load spectrum may contain compressive load.

To develop a hysteresis model of CMCs under arbitrary load, an interfacial friction model based on fundamental friction laws is established in this paper. This model is quite different from the shear-lag model used in previous work [1–9]. The assumptions about the locations and ranges of interface slip zones are replaced by more general assumptions about friction. The microstructure of unidirectional fiber-reinforced ceramic matrix composites is described by a cylindrical unit cell that is then discretized by a set of frictional elements. The “equilibrium status” and “incremental status” are proposed to depict the interfacial friction. Furthermore, the effects of interfacial debonding, fiber fracture, matrix cracking and crack closure are considered within the model.

2. Stress analysis

2.1. Unit cell model

Assuming the fibers embedded in the matrix were uniform, the microstructure of unidirectional fiber-reinforced CMCs can be described using the unit cell model illustrated in Fig. 1. For the cell shown, L is its length, equal to the average crack spacing; r_f is the fiber radius and r_m is the radius of the matrix; v_f and d represent the volume fractions of the fiber and debonding length, respectively. When σ is applied at the end near the crack plane, $\tau(x)$ represents the variation of shear stress along the interface.

2.2. Interfacial friction model

For the differential volume elements shown in Fig. 1, the equilibrium equation of forces can be written as

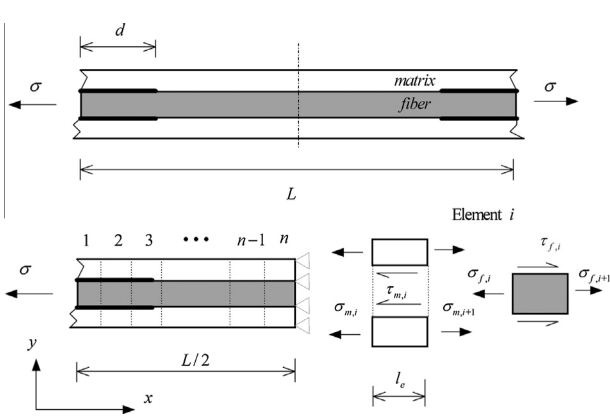

Fig. 1. Unit cell model and discretized unit cell model for unidirectional fiber-reinforced CMCs.

$$\frac{d\sigma_f}{dx} = \frac{2}{r_f}\tau(x)\frac{d\sigma_m}{dx} = \frac{2v_f}{r_f(1-v_f)}\tau(x) \tag{1}$$

In the bonded zone, the displacements of both fiber and matrix are equivalent, that is,

$$u_f(x) = u_m(x) \tag{2}$$

In the debonded zone, if no interfacial sliding occurred, the increments of the displacements of both fiber and matrix are equivalent, that is,

$$du_f(x) = du_m(x) \tag{3}$$

If interfacial sliding occurred in the debonded zone, however, interface shear stress is equal to the maximum friction shear stress:

$$\tau(x) = \tau_i \tag{4}$$

The basic equations of the shear-lag model are equivalent with Eqs. (1)–(4). To resolve the equations in the shear-lag model, the characteristics and distributions of slip zones must be presumed according to the loading state. To avoid this assumption, the system is regarded as being in equilibrium at every moment during the assumed quasi-static loading procedure in the present study. The state in which the increments of displacements of both fiber and matrix are equivalent along the interface is called the “equilibrium status”. As applied load is incrementally increased, the distribution of stress along the interface varies, and sliding occurs in the region where Eq. (4) is satisfied. The increment of displacement in the region without sliding is governed by Eq. (3), where a new “equilibrium status” is satisfied. The transition state between the two “equilibrium statuses” is called the “incremental status”.

To resolve the mechanical quantities of the equilibrium and incremental statuses, the fiber and matrix are each discretized into n cylindrical elements along the fiber axial direction (as shown in Fig. 1).

The relationships between the element interface shear force f_i and interface shear stress $\tau_{x,i}$; the normal force of fiber element $F_{f,i}$ and normal stress of fiber $\sigma_{f,i}$; and the normal force of matrix element $F_{m,i}$ and normal stress of matrix $\sigma_{m,i}$, can be written as

$$\begin{aligned} f_i &= 2\pi \cdot r_f \cdot l \cdot \tau_{x,i} \\ F_{f,i} &= \pi \cdot r_f^2 \cdot \sigma_{f,i} \\ F_{m,i} &= \pi \cdot (r_m^2 - r_f^2) \cdot \sigma_{m,i} \end{aligned} \tag{5}$$

where l is the length of the element.

At the equilibrium status, the equilibrium of forces acting on the fiber and matrix elements is satisfied, that is

$$\begin{aligned} F_{f,i} &= f_i + F_{f,i+1} \\ F_{m,i} &= -f_i + F_{m,i+1} \end{aligned} \tag{6}$$

At the incremental status, an increment ΔF is added to the applied force F; the end and interface shear forces of both fiber and matrix elements will vary with this increment. The increments follow these equilibrium relationships:

$$\begin{aligned} \Delta F_{f,i} &= \Delta f_i + \Delta F_{f,i+1} \\ \Delta F_{m,i} &= -\Delta f_i + \Delta F_{m,i+1} \end{aligned} \tag{7}$$

Assuming the increments of the displacements of both fiber and matrix are equivalent at the incremental status, the following relationship is yielded, using Eq. (3):

$$\Delta u_{f,i} = \Delta u_{m,i} i = 1, 2, \ldots, n \tag{8}$$

where