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A multi-scale stochastic fracture model for characterizing the tensile behavior of 2D woven composites

LiChuan Zhou, MingWei Chen, Chuang Liu, HengAn Wu*

CAS Key Laboratory of Mechanical Behavior and Design of Materials, Department of Modern Mechanics, CAS Center for Excellence in Complex System Mechanics, University of Science and Technology of China, Hefei 230027, China

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ABSTRACT

In this paper, a multi-scale stochastic fracture model is presented to study the nonlinear mechanical behaviors of two-dimensional (2D) woven C/SiC composites under uniaxial tension. This model considers the randomly distributed intrinsic flaws and the complex braided structure of composites. In the model, the micro-scale representative volume element (RVE) is developed to compute the effective properties of yarns, which are then used in the meso-scale RVE to capture the macroscopic stress response of woven composites. Weibull distribution law is applied to the material elements to reflect the random flaws. The failure mechanism of composites is identified by analyzing the damage rates and the fracture morphologies of fiber, matrix, and interface. The effects of fiber volume fraction and temperature on fracture strength are predicted and the results demonstrate that the failure location varies as the temperature increase due to the relief of thermal residual stress. The presented model provides an efficient tool for evaluating the mechanical properties of textile composites.

1. Introduction

Fiber reinforced ceramic matrix composites (FCMCs) have been extensively applied in the aerospace field including thermal protection systems, propulsion devices and hot structures for hypersonic vehicles due to its high specific stiffness and strength, low density, satisfactory durability as well as environmental stability [1–3]. The FCMCs overcome the intrinsic brittleness and low toughness of monolithic ceramics [4]. The carbon fiber reinforced silicon carbide matrix composites (C/SiC) possess enhanced oxidation resistance and broader sustainability at elevated temperatures [5]. Among several typical braided structures, the two-dimensional plain weave is the most commonly used textiles in industries [6], which not only inherits the high-temperature performance of ceramic composites but also exhibits the tremendous interlaminar shear strength and impact resistance [7,8]. Nevertheless, on account of the complex microstructure and constitutive properties, it is challenging to study the mechanical response of 2D woven C/SiC composites.

Over the years, many efforts have been made to research the damage behavior of FCMCs, including theoretical analyses and finite element methods combined with experiments. Aveston, Cooper and Kelly [9] first analyzed the critical stress of matrix cracking using the energy balance approach and the approach was extended by the model of Budiansky, Hutchinson, Evans [10], which is applied to predict the shear stress during debonding process based on the shear-lag theory. Curtin [11] investigated the evolution of multiple matrix cracking in unidirectional composites by assuming the stochastic distribution of initial matrix flaws. In order to establish an accurate finite element model, the internal geometry of plain weave fabrics was measured by Barbero et al. [12] based on the microphotograph. The continuum damage model (CDM) has been widely used to study the material nonlinear behavior, which can estimate not only the ultimate strength but also the failure process during the load history. A stiffness reduction model was developed by Barbero [13] to analyze the progressive damage process of ceramic composites under uniaxial tension using the energy equivalence principles and empirical hardening equations. Based on the Murakami–Ohno damage theory, Zako et al. [14] established an anisotropic damage model of woven composite. That model was later generalized by Zhou et al. [15] and Wang et al. [16] to investigate the progressive failure behaviors through multi-scale finite element analysis, which provides a framework to obtain the effective properties of material on various length scales. The link between the micro and meso scales of model was presented by Dinh et al. [17], which employed the digital element method to capture the nonlinear mechanical response of the coated fabrics. The bridge from laminates to woven composites was established by Obert et al. [18] using an enhanced damage model through cracks kinetics simulation. To predict the crack initiation, Faes et al. [19] proposed a 2D modeling approach

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* Corresponding author.
E-mail address: wuha@ustc.edu.cn (H. Wu).

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and found that the inhomogeneous distribution of transverse yarns would lead to a shift of stress towards the crimp regions. As a potential material for aerospace applications, it is necessary to research the composite properties in the extreme environment. In order to predict the strength of ceramic composites at elevated temperatures, several temperature-dependent fracture models were proposed which combines the effects of temperature, phase composition and oxidation reaction [20–22]. Borkowski et al. [23] investigated the progressive damage behavior of woven composites under thermal and mechanical loading conditions using a model considering the effect of manufacturing induced damage. Yu et al. [24,25] developed a detailed three-dimensional finite element model to predict the through-thickness thermal conductivity of woven composites and compared the results with a two-component system, which found that the model overestimates the effective conductivity at relatively low fiber volume fraction and underestimates it at very high fiber volume fraction.

Obviously, it is difficult to theoretically predict the stress distribution of 2D woven composites due to the complex braiding structure. Although the CDM approach has been implemented successfully to study the tensile behavior, the constituent elements are treated as a homogeneous material, which is lack of consideration for the microscopic flaws inside composites. For ceramic composites, the damage is usually caused by the extension of original flaws in the form of void defects and micro-cracks, which are usually inhomogeneous, anisotropic, and irregular. The stiffness degradation of components is only the macro representation of damage evolution. Hence, the CDM results are unable to reflect the localized failure mode of fiber and matrix. In addition, the CDM model sometimes does not correlate with the failure theory in micromechanics and some formulas are defined with the phenomenological parameters. Therefore, it is necessary to establish a model considering the evolution of intrinsic flaws.

The overall objective of this paper is to propose a stochastic fracture model for characterizing the tensile behavior of 2D woven C/SiC composites. In consideration of the randomly distributed flaws inside composites, the fiber and matrix components are defined with the inhomogeneous strength properties by the Weibull distribution. The finite element analysis is employed to study the nonlinear tensile behavior of composites. The computational framework is fully introduced in Section 2, including the material properties and multi-scale modeling approach. The simulation results are presented and discussed in Section 3. The effective properties and failure mechanisms of composites are revealed by combining the stress–strain curve with damage rates and fracture morphologies of constituent materials. The effects of fiber volume fraction and temperature on fracture strength are predicted to evaluate the composite properties in various environments. Finally, the main conclusions and perspectives are summarized in Section 4.

2. Multi-scale finite element modeling

Finite element method (FEM) is adopted to study the mechanical response of 2D woven composites. In consideration of the complex constitutive relationships and braided structure of composites, the simulation is divided into various length scales. Fig. 1 schematically demonstrates the framework of each length scale in the analysis. First, the material element properties need to be calculated through the experimental data and empirical formulas. Next, the micro-scale RVE is developed to compute the equivalent homogeneous properties of yarns which are composed of fiber, matrix, and interface. Then the effective properties of micro-scale RVE are used to investigate the macroscopic stress response of woven composites in meso-scale RVE. The meso-scale RVE consists of matrix and yarns in two directions. The proposed model is implemented in the finite element software ABAQUS.

2.1. Material properties and failure criteria

The composite simulated in this study is 2D woven C/SiC composite fabricated by the chemical vapor infiltration (CVI) technique. The constituent materials consist of carbon fibers and silicon carbide (SiC) matrix. The fiber used in this paper is the high-strength PAN-based T300 carbon fiber. The total fiber volume fraction V_f in woven composites is about 40%. During the CVI-process, the carbon fibers are wrapped with the pyrolytic carbon (PyC) coatings before the deposition of SiC matrix. The major properties of the carbon fiber and SiC matrix in composites are listed in Table 1 and all the parameters are taken from the literature [26–34].

2.1.1. Fiber breaking

The mechanical property of fiber is commonly described by the two-parameter Weibull distribution. The strength of single fibers is varied due to the existence of manufacturing flaws which are unevenly distributed inside the fibers. The cumulative failure probability P_f of the fiber with length L under the external stress σ is given by:

$$P_f = 1-\exp\left[-\frac{L}{L_0}\left(\frac{\sigma}{\sigma_0}\right)^{m_f}\right] \tag{1}$$

where L_0 is the gauge length, σ_0 is the characteristic strength (Weibull scale parameter) relative to L_0, m_f is the Weibull modulus (Weibull shape parameter). For a particular type of carbon fiber, its Weibull parameter can be measured by the experiment [30].

The single carbon fiber is brittle material. Therefore, the applied stress σ_f and strain ε_f on a single fiber satisfy the following relationships when subjected to the tensile load only:

$$\sigma_f = E_f \varepsilon_f \tag{2}$$

where E_f is the axial Young's modulus of fiber.

For a fiber bundle consisting of N_0 fibers under strain ε, the intact fiber number N is:

$$N = N_0(1-P_f) \tag{3}$$

Based on Eqs. (1)–(3), the fiber average stress $\bar{\sigma}$ under strain ε can be calculated by:

$$\bar{\sigma} = \frac{N}{N_0}E_f\varepsilon = E_f\varepsilon\exp\left[-\frac{L}{L_0}\left(\frac{\varepsilon}{\varepsilon_0}\right)^{m_f}\right] \tag{4}$$

where ε_0 is the scale parameter for strain. Thus, the maximum average stress $\bar{\sigma}_{max}$ and the corresponding maximum average strain $\bar{\varepsilon}_{max}$ are:

$$\bar{\sigma}_{\max} = E_f\varepsilon_0\left(\frac{L_0}{Lm_f e}\right)^{1/m_f} \tag{5}$$

$$\bar{\varepsilon}_{\max} = \varepsilon_0\left(\frac{L_0}{Lm_f}\right)^{1/m_f} \tag{6}$$

In order to avoid the error caused by the fiber length differences, the length of composite model simulated in this study is set to be equal to the fiber gauge length (25 mm). In the modeling process, the fiber is divided into uniform elements with volume V_e. A modified strength distribution is assigned to the fiber elements [35]:

$$P_f^* = 1-\exp\left[-\left(\frac{V_e}{V_0}\right)^{\gamma}\left(\frac{\sigma}{\sigma_0}\right)^{m_f}\right] \tag{7}$$

where V_0 is the reference volume of the test fiber. The exponent $\gamma \in [0, 1]$ is a volume sensitivity parameter which depends on the mesh density. For a specific mesh, the value of γ can be determined by the uniaxial tensile simulation. First, each fiber in the bundle should be meshed with the same density. The next step is to obtain the stress–-strain curve of the single fiber with a hypothetical γ value. The value of γ needs to be adjusted until the simulated maximum average strain of fiber is equal to $\bar{\varepsilon}_{max}$ calculated by Eqs. (1)–(6). It is worth mentioning that iterative simulations are required due to the stochasticity of strength distribution. When the element size is a constant, Eq. (7) can