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A coupled elastic-plastic damage model for the mechanical behavior of three-dimensional (3D) braided composites

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ABSTRACT

A coupled elastic-plastic damage model is developed to describe the non-linear mechanical behavior of three-dimensional (3D) braided composites. In this model, the fiber breakage, inter-fiber fracture and matrix fracture are considered in the level of the fiber bundle and matrix. The onset and propagation of fiber bundle failure mechanisms are elastic and brittle, which is accounted for elastic damage model, and the elastic-plastic damage model used to describe the degradation of matrix is non-linear with progressive damage and inelastic strains. A set of internal variables are introduced to characterize the damage states of the fiber bundle and matrix and as a subsequence the degradation of the material stiffness. The damage initiation and propagation criteria are based on the Hashin criteria for the fiber bundle and the von Mises yield criterion for the matrix. The proposed damage model is implemented in the non-linear finite element analysis code ABAQUS using a user-subroutine UMAT to determine the response behavior of 3D braided composites under quasi-static loading, and the numerical predictions are compared with experimental data. The results predicted by the proposed model agree well with the experiment.

1. Introduction

The three-dimensional (3D) braided composites have a wide application in aerospace and other fields because of their excellent mechanical properties [1,2]. Thus an accurate evaluation of the mechanical characteristics becomes very important. The meso-structure and stiffness properties of the 3D braided composites have been extensively studied in recent decades [3–7], and the satisfactory results have now been obtained. However, due to the complexity of meso-structure and the diversity of damage modes for constituent materials, it is difficult to reveal the damage mechanisms from the results of mechanical tests alone, and the numerical investigations on the damage and failure of 3D braided composites have not been sufficiently clarified yet. Therefore, there is a need to conduct reliable simulations and analytical evaluations for damage behavior of 3D braided composites.

It is known that after the resin is infused and the composite is cured, some internal defects (such as micro-cracks, voids, etc.) in material may be present. These defects of material make it more susceptible to damage when subjected to the external loading. An accurate damage model to degrade the mechanical properties of composites is necessary. Besides, because of the stress concentration in the vicinity of the defects, the constituent materials also undergo some plastic deformations during loading so that the damage model cannot be applied alone. Therefore, the mechanical behavior of 3D braided composites is determined by two factors: damage and plasticity. Many researchers have used the damage theory alone to characterize the degradation of material stiffness by a set of damage variables which act on the elastic behavior [8–11]. McGregor et al. [8] combined the experimental and numerical study to calibrate the parameters of a macro-mechanical damage model. Applying the Murakami-Ohno damage theory, Fang et al. [9] studied the non-linear response behavior of 3D braided composites and considered that the damage accumulation eventually led to the failure of the composites. Wehrkamp-Richter et al. [10] investigated the damage and failure of tri-axial braided composites under multi-

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axial stress states and conducted uni-axial tensile tests at different off-axis orientations. Ivanov et al. [11] discussed the damage and failure behavior of tri-axial braided composites under tensile loading and the Puck's criterion was applied for damage initiation of fiber bundle. However, these works failed to evaluate the effect of plasticity on non-linear response of matrix material which has been observed by SEM in Refs. [3,12]. On the other hand, some researchers have adopted plasticity theory alone to represent the mechanical behavior of braided composites [13,14]. Song et al. [14] studied the compressive damage behavior of tri-axial braided composites and taken into account the inelastic properties of the matrix. Fang et al. [13] analyzed the compressive mechanical properties of 3D braided composites using the J2 flow theory of plasticity for matrix. However, the stiffness degradation of matrix material due to micro-cracks was not considered in these works. It has to be noted that the non-linear mechanical behavior of material is controlled by both plasticity and damage, thus one cannot be considered without the other.

On the basis of the aforementioned argument, it is essential to establish a model that is able to consider the coupling between plastic deformations and damage. In this paper, a coupled elastic-plastic damage model is established to analyze the damage development of 3D braided composites and validated with the experimental data.

This research is organized as follows: the specific damage model including initiation and evolution of damage is proposed in Section 2. Section 3 describes the numerical implementation of UMAT. The experiments and the simulations based on the representative volume cell (RVC) are presented in Section 4. And then, in Section 5, the simulated results are compared to corresponding experimental data and the damage development process is analyzed. Finally, the conclusions are given in Section 6.

2. Coupled elastic-plastic damage model

The 3D braided composites have two constituents: the matrix and the fibers. The fibers are in the form of fiber bundle in braided composites. The fiber bundle and matrix are treated macroscopically as transversely isotropic and isotropic homogeneous bodies, respectively. In this paper, the damage models for fiber bundle and matrix are formulated within the framework of Continuum Damage Mechanics (CDM) using internal variables, and based on the assumption of small strains.

2.1. Damage variables and constitutive functions

After the initiation of damage, the progression of damage is characterized by material stiffness degradation. The damage variables as internal variables can be used to describe the damage process. In this paper, the damage tensor suggested by Matzenmiller et al. [15] is adopted to computer the stiffness degradation. Since the fiber bundle shows no significant plastic deformation before failure, the elastic damage model is developed to describe the damage of fiber bundle. The constitutive equation of the damaged fiber bundle is defined as follows:

$$\boldsymbol{\varepsilon}_f = \boldsymbol{S}_f\left(\boldsymbol{d}_f\right):\boldsymbol{\sigma}_f \tag{1}$$

where $\boldsymbol{\varepsilon}_f$ and $\boldsymbol{\sigma}_f$ are the strain tensor and nominal stress tensor of fiber bundle, and the $\boldsymbol{S}_f(\boldsymbol{d}_f)$ is damaged compliance matrix:

$$\boldsymbol{S}_f\left(\boldsymbol{d}_f\right) = \begin{bmatrix} \frac{1}{\left(1-d_{f,1}\right)E_{f,1}} & -\frac{\nu_{f,12}}{E_{f,1}} & -\frac{\nu_{f,13}}{E_{f,1}} & 0 & 0 & 0 \\ & \frac{1}{\left(1-d_{f,2}\right)E_{f,2}} & -\frac{\nu_{f,23}}{E_{f,2}} & 0 & 0 & 0 \\ & & \frac{1}{\left(1-d_{f,3}\right)E_{f,3}} & 0 & 0 & 0 \\ & \text{sym.} & & \frac{1}{\left(1-d_{f,4}\right)G_{f,12}} & 0 & 0 \\ & & & & \frac{1}{\left(1-d_{f,5}\right)G_{f,23}} & 0 \\ & & & & & \frac{1}{\left(1-d_{f,6}\right)G_{f,31}} \end{bmatrix} \tag{2}$$

where the subscript 1 denotes the longitudinal direction of the fiber bundle, and 2 and 3 denote the transverse directions. $E_{f,1}$, $E_{f,2}$, $E_{f,3}$, $G_{f,12}$, $G_{f,23}$ and $G_{f,31}$ are undamaged material moduli, and $\nu_{f,12}$, $\nu_{f,23}$ and $\nu_{f,13}$ are undamaged material Poisson's ratios. $d_{f,1}$ is the damage variable for fiber breakage, denoted by subscripts t and c for tension and compression, and $d_{f,2}$ and $d_{f,3}$ are the damage variables for inter-fiber fracture in the fiber bundle, denoted by subscripts t and c for tension and compression. $d_{f,4}$ and $d_{f,6}$ are the damage variables for fiber fracture and inter-fiber fracture, and $d_{f,5}$ is associated with inter-fiber fracture. In addition, it is postulated that the damage variables $d_{f,4}$, $d_{f,5}$ and $d_{f,6}$ are not independent, and can be expressed as a function of the remaining variables:

$$\begin{aligned} d_{f,4} &= 1-\left(1-d_{f,1}\right)\left(1-d_{f,2}\right) \\ d_{f,5} &= 1-\left(1-d_{f,2}\right)\left(1-d_{f,3}\right) \\ d_{f,6} &= 1-\left(1-d_{f,3}\right)\left(1-d_{f,1}\right) \end{aligned} \tag{3}$$

According to the hypothesis of strain equivalence, the effective stress tensor of fiber bundle is computed as: