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Progressive damage simulation of triaxially braided composite using a 3D meso-scale finite element model

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ABSTRACT

This article proposes a fully three-dimensional finite element model, developed at the meso-scale level, to predict the progressive damage behavior of a single-layer triaxially braided composite subjected to tensile loading conditions. An anisotropic damage model is established by Murakami–Ohno damage theory to predict damage initiation and progression in the fiber tows. A traction–separation law has been applied to predict theoretically the progressive damage of fiber tow interfaces. The proposed model correlates well with experiment on both global stress–strain responses and local strain distributions. According to the damage contours at different global strain levels, the damage development of fiber tows and interlaminar delamination damage of interface are obtained, explicitly analyzed and correlated with experimental observations. The comparison of model prediction and experimental observations indicate that the model can accurately simulate the damage development of this composite material, i.e. fiber bundle splitting, interaction of free-edge effect and delamination, and final failure of the specimen. This paper also discusses the role of material properties/parameters on the global responses through numerical parameter studies.

1. Introduction

Carbon composite materials are being widely used as structural components in aerospace, automotive, marine and sport-recreation products due to their outstanding physical, mechanical and thermal properties, especially their high stiffness and strength to weight ratio. The traditional laminated composite structures are used when in-plane properties are of primary importance. Textile composites are being developed to address many of the shortcomings of laminated composite systems, like damage tolerance and energy absorption. Another advantage of textile composites is that production of a large volume of textile preforms can be accomplished in a fast rate, thus reducing the manufacturing cost and fabrication time [1]. Woven, braided and textile polymer composites are being actively investigated for potential application in aerospace structures. In one recent application, new engine fan cases, which are required to contain the blade and fragments during engine blade out event, have been made by using two-dimensional triaxially braided composites [2].

A two-dimensional triaxial braided composite is made by three distinct sets of yarns, which are intertwined to form a single layer of fabrics. In a typical 0°/±60° braided composite architecture (shown in Fig. 1), bias fiber bundles undulate over and under each other alternatively, while the 0° yarns are straight and define the axial direction of the composite. The rectangle indicates the size of a unit cell: the length is the axial distance between center lines of two neighboring bias yarns, and the width is twice the transverse distance between the center lines of the two neighboring axial yarns. Due to this specific architecture, the composite is known to be quasi-isotropic, which can provide improved impact resistance because properties are balanced in all directions. Additionally, the triaxial braided architecture can resist crack propagation and braided composites are found to lose little stiffness and strength when suffering microcracking [3].

Due to the complicated braided architecture, the failure behaviors of triaxial braided composites are quite complicated and the modes of failure can vary under different loading conditions. NASA Glenn Research Center and The University of Akron conducted a series of small-scale specimen tests on several braided composite systems with different combinations of polymer matrices and

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carbon fiber [4,5]. Small-scale specimen tests of the braided composites provided a prior evaluation of damage initiation and fracture propagation under certain loading conditions. Free-edge damage in the form of shear-strain concentration and edge-initiated delamination were observed in both axial and transverse tensile tests; damage was especially significant in the transverse tension. The edge damage that occurred where bias fiber bundles terminated at free edges can influence the shape of stress–strain response producing nonlinearity. On the other hand, fiber-bundle splitting was also observed, but had relatively minor impact on the global failure of the specimens.

The macroscopic experiment, however, is not able to elucidate the damage evolution process of the interior components. Finite element methodology and numerical findings are very useful due to their capability of conducting virtual testing of composites and providing insights into local responses. Improved finite element analysis methods can help reduce the required number of expensive and time-consuming experiments. In the past decade, finite element (FE) modeling of damage and failure has been gaining popularity. The progressive damage simulations of textile composites have been studied by several scholars [6–11]. Zako et al. [12] gave a brief review of the damage analysis of woven composite materials, and proposed an anisotropic damage constitutive equation using the Murakami damage tensor. The most common way to realize damage evolution is through stiffness-reduction schemes. Fang et al. [6] predicted the failure modes of a 3D four-directional braided composite using a damage evolution model which is controlled by material fracture energy of composite constituents and equivalent displacements. McCarthy et al. [13] presented a 3D progressive-damage model for simulation of a multi-bolt composite joint. Huhne et al. [14] proposed two damage models with constant degradation and continuous degradation of engineering constants. It was shown that numerical results predicted by the continuous-degradation model correlates well with experiments. In the process of building the damage model, the reduction stiffness method should be correlated with local characteristic parameters of the composites, because the magnitude of reduction stiffness directly influences the progressive damage of material. In both McCarthy et al. [13] and Huhne et al.'s [14] work, the material properties were degraded to 10% of their original values after failure criteria are met.

To date, few attempts have been made to incorporate a progressive-damage model in the finite element simulation of triaxial braided composites. Schultz and Garnich [15] proposed a multicontinuum technology and successfully predicted the initial matrix failure of a 0°/±45° triaxially braided composite. Li and Binienda [16,17] developed a high fidelity meso-scale model with a cohesive zone for failure simulation of triaxially braided carbon/epoxy composites. The model was highly successful in quantifying the local damage propagation, failure of each constituent and interface delamination. Liu et al. [18] built a framework for a three-scale concurrent analysis of triaxially braided composites. The effective property of the Representative Volume Element (RVE) at each scale is determined from the generalized method of cells. The method

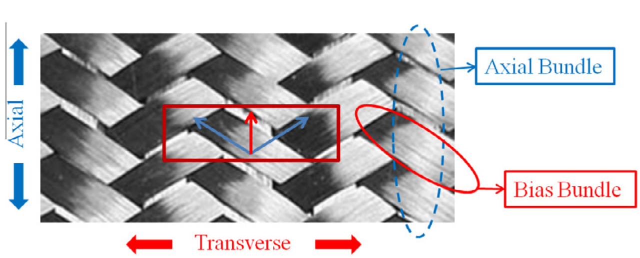

Fig. 1. Representative architecture of triaxially braided composite.

took into account the braided architecture, simulated the nonlinearity and failure, and obtained good correlation with experimental results. In our previous work, the free-edge effect was captured and analyzed using a two-dimensional meso-scale model through application of translation symmetrical boundary conditions [19]. However, none of the available models show the capability of predicting all the primary damage formations: fiber bundle splitting, the free-edge effect and delamination.

In this work, a fully three-dimensional finite element model of a single-layer triaxially braided composite is developed to further understand the local damage initiation, damage propagation and failure behaviors, as well as to investigate the relationship of the free-edge effect with delamination damage initiation. The single-layer material is chosen for this study because it is useful in highlighting the free-edge effect, due to the absence of suppressing effect from adjacent layers. Our experimental studies also identified that the single-layer specimen shows significant size-dependent mechanical performance. Numerical studies of the single-layer material provide insights into the intrinsic failure mechanisms, which are of great importance for developing more accurate macro-scale models and the design of more efficient test methods. Here, a progressive damage model is presented by implementing failure criteria and damage degradation model as a user-defined material model (VUMAT) in the commercial finite element program ABAQUS. A cohesive-zone model is used to model the interface delamination. This paper is organized as follows. The next section describes material models used to describe the progressive damage of the composite. The damage-evolution model of fiber bundles is based on fracture energy dissipated during the damage process, characteristic length of element and equivalent displacement. Hashin-type failure criteria are employed to determine damage initiation. A cohesive law is introduced to simulate interface failure. The third section presents experimental work and numerical simulation procedures. A unit cell model of this braided composite is described. The fourth section examines the capability of this model through correlation with experiments and shows the prediction results of local initiation and progression of damage. The main summary points and conclusions resulting from the present work are listed in Section 5.

2. Progressive damage model of braided composite

2.1. Progressive damage model of fiber bundles

The fiber bundle of textile composites is generally considered as a transversely isotropic unidirectional lamina in numerical simulation. The constitutive equation of an orthotropic material is implemented as follows:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \tag{1}$$

where σ_{ij}, C_{ijkl} and ε_{kl} (i, j, k and l = 1, 2, 3) are engineering stress, stiffness matrix and engineering strain components, respectively. Index 1, 2, 3 refers to the fiber axial direction, in-plane transverse direction and out-of-plane direction, respectively. E_{ij}, ν_{ij} and G_{ij} are the engineering constants of the material. If the material is transversely isotropic, then $G_{13} = G_{12}$, $\nu_{12} = \nu_{13}$, $E_{33} = E_{22}$. The material is assumed to be elastic before achieving one of the failure criterions.

2.1.1. Failure criteria

In the present work, a three-dimensional failure criterion for the fiber bundle is adopted based on Hashin's [20] and Hou's [21] criterions and is incorporated with continuum damage laws. A scalar factor is employed to better correlate with experimental results and accurately describe the failure behavior of the studied composite material.