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Multi-scale modelling of dynamic progressive failure in composite laminates subjected to low velocity impact

B.B. Liao[a],*, H.C. Tan[c], J.W. Zhou[d], L.Y. Jia[b],*

[a] *Institute of Process Equipment, Zhejiang University, Hangzhou 310027, China*
[b] *First Aircraft Institute of Aviation Industry Corporation, Xi'an 710089, China*
[c] *Jiangsu Province Key Laboratory of Aerospace Power System, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*
[d] *The Key Laboratory of Contemporary Design and Integrated Manufacturing Technology, Northwestern Polytechnical University, Xi'an 710072, China*

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ABSTRACT

This paper aims to investigate the structural mechanical responses and progressive damage behaviors of composite laminates subjected to low velocity impact. First, a three-dimensional multi-scale model based on micromechanics of failure (MMF) criterion with new damage evolution laws is introduced for intralaminar damage, which considers the different mechanical behaviors of the microscopic constituents for fiber and matrix. The macroscopic damage variables of the new damage evolution laws are directly evaluated by the degraded elastic parameters of the microscopic constituents calculated from representative volume elements (RVEs). Second, by using this multi-scale approach, the relationship between macroscopic stress and microscopic stress is established by stress amplification factors (SAFs) through the RVEs using ABAQUS-PYTHON scripting language. The proposed model is implemented by the user-defined material subroutine VUMAT built on ABAQUS/Explicit platform, and the bilinear cohesive model in ABAQUS is employed to capture the onset and progression of interlaminar delamination. Finally, impact numerical simulation for the impact force-time/central displacement curves and energy dissipation is performed on three composite laminates with different layup patterns. Relatively good agreements are achieved between the experimental and numerical results, which validates the effectiveness of the multi-scale model.

1. Introduction

Composite laminates have been widely used for aerospace, new energy automobile and wind turbine blade due to high strength- and stiffness-to-weight ratios and excellent fatigue performance by comparing to the traditional metal materials [1,2]. However, composites are usually subjected to impact loads during the manufacturing, appliance and maintenance processes [3], which leads to complicated failure mechanisms. In order to simulate impact responses of composite laminates better, developing theoretical and numerical models are particularly important. It is also beneficial to the structure design and safety assessment because of weaker load-carrying capability of laminates in the transverse direction than in the longitudinal direction [4,5].

During last decades, various failure theories for predicting damage initiation were developed for composites to recognize the complex damage mechanisms such as Hashin [6], Puck [7] and Phiho [8] criteria. These progressive damage theories [6–11] have been employed to predict the complicated composite damage behaviors under low velocity impact such as Gliszczynski [12], Faggiani and Falzon [13] and Liao and Liu [14]. However, in the numerical analysis for the composite laminates under low velocity above, almost all of them used macromechanics theories although they were capable to determine the damage modes by regarding composite as homogeneous material. However, these theories did not consider the influence of local stress difference caused by different mechanical performances of constituent fiber and matrix, which are related to the behaviors of composite materials at macroscale. Therefore, composite damage mechanisms subjected to low velocity impact need to study from a microscopic perspective in nature.

Some researchers proposed several multi-scale methods based on micromechanics-based failure theories for composite materials to understand different physical damage mechanisms of the microstructures. Tay et al. [15] introduced the strain invariant failure theory to identify fiber and matrix failures using the critical volumetric strain and critical equivalent strain invariants, respectively. Car et al. [16] solved the

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* Corresponding authors.
E-mail addresses: 1725777377@qq.com (B.B. Liao), taishanbuzuo@163.com (L.Y. Jia).

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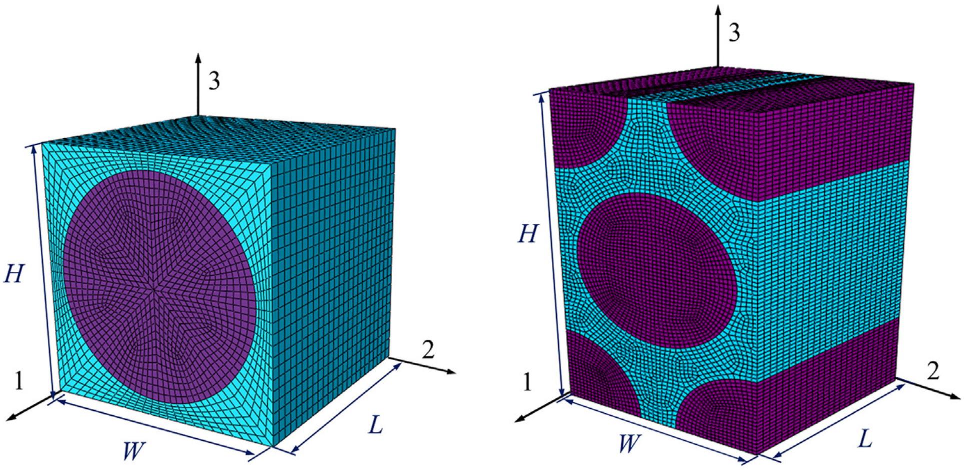

(a) Square model (b) Hexagonal model

Fig. 1. RVEs for micromechanical analysis: (a) Square model and (b) Hexagonal model.

problem at the microstructural scale using the macroscopic deformation gradient tensor to realize the multi-scale analysis. Huang and Zhou [17] also developed micromechanics-based failure theories by the bridging model. Recently, Ha et al. [18,19] proposed a new multi-scale method for composite materials based on micromechanics of failure (MMF) criterion, where the microscopic fiber and matrix failure were determined by maximum stress criterion and a modified von-Mises failure criterion, respectively. Besides, stress amplification factors are introduced by Ha et al. [18,19] to establish relationships between the microscopic and macroscopic levels. The multi-scale model proposed by Ha et al. [18,19] has been verified to be able to predict 12 test cases in the Second World Wide Failure Exercise (WWFE-II), which involves five composite laminates with different materials and multiple multi-axial loading cases including in the through-thickness direction [20,21]. It shows the MMF theory has good predictive capabilities among various failure theories in the WWFE-II [20,21].

However, the works by Ha et al. [18,19,22,23] and the follow-up researchers [24–26] basically explored the quasi-static loading cases. Besides, Ha et al. [18,19] used a complex method to calculate the macroscopic damage variables, which computed through the micromechanical RVEs. The macroscopic damage variables with respect to different damage statuses were stored in a table in advance, which calculated by microscopic damage variables and an averaging stress process. “stored in a table” means that storing damage variables in order of severity of damage statuses. If current damage statuses were not in the table, the required macroscopic damage variables were calculated using linear interpolation [18,19,22,23]. Thus, this method for calculating the macroscopic damage variables is time-consuming because of storing multiple damage statuses and increases the complexity of calculation by linear interpolation if current damage statuses were not stored in advance.

This paper further considers the influence of local stress difference caused by different mechanical performances of fiber and matrix. A three-dimensional multi-scale model based on micromechanics of failure (MMF) criterion with new damage evolution laws is first introduced for intralaminar damage. The macroscopic damage variables of current damage evolution laws are directly evaluated by the degraded elastic parameters of the microscopic constituents calculated from representative volume elements (RVEs). Then the relationship between macroscopic stress and microscopic stress is established by stress amplification factors (SAFs). In addition, the proposed model is implemented by the user-defined material subroutine VUMAT built on ABAQUS/Explicit platform, and the bilinear cohesive model in ABAQUS is employed to simulate the interlaminar delamination. Three composite specimens with different layup patterns subjected to low velocity impact are performed to validate the multi-scale model.

2. Progressive failure theories of the multi-scale model

2.1. Calculation of microscopic stresses in constituents

The behaviors of macroscopic composite plies are related to the properties of microscopic fiber and matrix constituents. In general, carbon fibers are linear elastic and brittle with transversely isotropic properties [18,23,24]. The matrix is assumed to be isotropic and ductile during progressive damage evolution [18,23,24]. Although the unidirectional ply is always regarded as homogeneous and transversely isotropic material, the local strain and stress distributions in the constituents at microscale are different because of the different mechanical performances of microscopic constituents. The microscopic stress $\boldsymbol{\sigma}$ for fiber and matrix is obtained by the stress amplification factors $\boldsymbol{M}_\sigma$ and the macroscopic stress $\bar{\boldsymbol{\sigma}}$ as follows [18,19,22,23]

$$\boldsymbol{\sigma} = \boldsymbol{M}_\sigma \bar{\boldsymbol{\sigma}} \tag{1}$$

$$\begin{cases} \boldsymbol{\sigma} = [\sigma_1 \;\; \sigma_2 \;\; \sigma_3 \;\; \sigma_{12} \;\; \sigma_{23} \;\; \sigma_{13}]^T \\ \bar{\boldsymbol{\sigma}} = [\bar{\sigma}_1 \;\; \bar{\sigma}_2 \;\; \bar{\sigma}_3 \;\; \bar{\sigma}_{12} \;\; \bar{\sigma}_{23} \;\; \bar{\sigma}_{13}]^T \end{cases} \tag{2}$$

$$\boldsymbol{M}_\sigma = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & M_{15} & 0 \\ M_{21} & M_{22} & M_{23} & 0 & M_{25} & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & M_{46} \\ M_{51} & M_{52} & M_{53} & 0 & M_{55} & 0 \\ 0 & 0 & 0 & M_{64} & 0 & M_{66} \end{bmatrix}_\sigma \tag{3}$$

The stress amplification factors (SAFs) $\boldsymbol{M}_\sigma$ in Eq. (3), which establish the relationship between the macroscopic and microscopic levels, can be calculated by representative volume elements (RVEs).

2.2. Extraction of stress amplification factors

The microscopic stress for fiber and matrix is extracted by SAFs through some reference points in the RVEs by application of the MMF criterion. Square model and hexagonal model are two typical RVEs that are often used as shown in Fig. 1 [24,25]. The geometry sizes for these two models are given unit values, i.e. $L = W = 1$ for both models but $H = 1$ and $H = \sqrt{3}$ for the square model and hexagonal model,