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A multi-scale modeling scheme for damage analysis of composite structures based on the High-Fidelity Generalized Method of Cells

Junjie Ye[a,*], Chenchen Chu[a], Heng Cai[a], Yongkun Wang[a], Xiaojun Qiao[b], Zhi Zhai[c], Xuefeng Chen[c]

[a] Research Center for Applied Mechanics, Key Laboratory of Ministry of Education for Electronic Equipment Structure Design, Xidian University, Xi'an 710071, China
[b] Taiyuan Heavy Industry Group Co., LTD Technology Center, Taiyuan 030024, China
[c] State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

This paper presents a description of a multi-scale method to investigate the failure behaviors and damage evolution of composite laminates reinforced with unidirectional fibers. The proposed approach is based on the microscopic mechanical theory and pre-processing function of the ANSYS/LS-DYNA software. At micro-scale, the High-Fidelity Generalized Method of Cells (HFGMC) is employed to establish the microscopic model, which can be used to acquire the microscopic stress distributions in the representative volume element (RVE). Moreover, a viscoplastic constitutive model is employed to describe the nonlinear behaviors of matrix materials. At macro-scale, each integration point in elements is employed to investigate the damage evolution for each lamina. In order to validate the proposed method, the numerical results of failure evolution path and stress-strain responses of the composite laminates are compared with experimental data. A good consistency between theoretical results and experimental data can be found. On this basis, the failure evolution path for each lamina is further investigated. The numerical results revealed that the crack firstly appeared in the 90° lamina. With the further increasing of external loading, the crack will accumulate along with the layer direction for −45° lamina, 45° lamina and 90° lamina.

1. Introduction

Due to their excellent performances, such as high strength, low weight, composite structures have been widely used in aerospace, automobile [1–8]. Moreover, the content of composites becomes one of the symbols, which evaluate the advances in airplane. For instance, composites in A350 made by European aircraft manufacturer Airbus, which are used to manufacture the fuselages and wings, weighed about 52%. The fuselage structures in B787 are composed of six composite components.

At microscopic scale, the microscopic structure of composite materials is a complex multiphase system. A serial of micromechanics, such as self-consistent model [9,10] and Mori-Tanaka method [11] are considered to be the effective methods to predict the mechanical responses and understand the underlying deformation behaviors of composite systems. Yang et al. [12] improved the self-consistent model by the Eshelby tensors to investigate the effective electrical conductivity of graphite composites. The key exponent of system was determined according to experimental results. This modified model was verified to be an effective method for designing and optimizing the composites. Tan et al. [13] employed the Mori-Tanaka method to account for interfacial debonding between reinforced particles and matrix. Meng et al. [14,15] proposed a micromechanical model to study the interfacial strength, failure mechanism of particle-reinforced composites, as well as the impact damage of composite laminates. As is well known, the macroscopic fracture or failure for composite structures is decided by the microscopic factors, such as fiber breakage [16–18], matrix crack [19–21], interphase debonding [22–25]. However, it is difficulty for the traditional macroscopic or microscopic mechanics to reveal failure mechanism of composite structures from microscopic damage to macroscopic fracture.

In recent years, a multi-scale theory has received a great attention for solving deformation and failure problems [26,27]. Meng et al. [28,29] developed a multi-scale crack-bridging model to investigate the fracture toughness of a mode-I crack in cellulose nanopaper. The theoretical results agree well with relevant experimental data. Wan [30] presented a finite element method from fiber/matrix scale to composite scale to investigate the compressive properties of three-dimensional

* Corresponding author.
E-mail address: ronkey6000@sina.com (J. Ye).

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(3D) braided composites subjected to quasi-static and high strain rate loadings. The method was verified by the experimental data. Romelt and Cunningham [31] developed a multi-scale finite element approach for a flat two-dimensional woven glass/epoxy laminate. Numerical results from the proposed approach were compared with experimental stress-strain data, which show a good agreement in the lower strain range. Ullah et al. [32] developed a three-dimensional multi-scale computational framework for predicting the nonlinear micro/macro-mechanical responses of the fiber-reinforced polymer (FRP) composites. Montesano [33] developed a multi-scale model, which implemented the laminate constitutive equations into ANSYS, to predict the durability of wind turbine blade structures. The study revealed a correlation with damage evolution, and provided the valuable insight for optimization of the blade designs. Based on finite element framework, McWilliams et al. [34] developed a multi-scale model to investigate the effectiveness of the microstructure on the tensile deformation behaviors, including progressive damage and failure of ceramic fiber and fabric reinforced composites. The results indicated that the interfacial debonding significantly contributes to the inelastic deformations. From the studies mentioned above, it can be easily found that most of the micromechanical-based approaches are done by using the finite element method to investigate the elastic and inelastic behaviors of composite materials. Although the proposed multi-scale methods mentioned above improve the computational efficiency in dealing with the mechanical problems for composites, few literatures refer to the crack failure path of each lamina for composite laminates are investigated.

As one of the heterogeneous materials, the macroscopic properties of composites (such as nonlinear stress-strain behaviors, damage evolutions) are closely dependent on microscopic characteristics, such as constituent materials, inclusion distributions, etc. Compared to finite element method (with progressive damage model) or microstructure-based numerical model, a multi-scale modeling can be employed to reveal the failure mechanisms of composites from constituent material damages to macroscopic structural fracture. To this end, this paper presents a new multi-scale modeling method for investigating the damage evolution of composite laminates. To this end, the HFGMC compiled by the FORTRAN language is implemented into ANSYS/LS-DYNA software, which is proposed to investigate the nonlinear deformations, progressive damage and failure for fiber-reinforced composite structures. For validating the presented method, the nonlinear stress-strain behaviors at specific regions are acquired by strain gauges, and the experimental data are compared with theoretical method. Moreover, the failure evolution paths for each lamina are predicted by employing the proposed multi-scale method. The article is organized as follows. Section 2 presents the microscopic image of glass/resin composites by the transmission electron microscopy. On this basis, a proper representative volume element is determined to solve the effective stiffness matrix by employing the HFGMC. Section 3 is concerned with the procedures of multi-scale damage modeling for composite laminates. Section 4 presents the validation of the multi-scale theory. On this basis, the stress distribution and damage evolution path are both investigated in Section 5. Conclusions are given in Section 6.

2. A multi-scale approach

In service, the macroscopic fractures of composite structures, which lead to disastrous accidents, are always due to the microscopic damages, such as fiber fracture, matrix crack or interfacial debonding. In order to reveal the failure mechanisms of composites, a multi-scale approach will be needed. In this section, the constituent properties and macro-scale problems are studied. Moreover, the relations between microscopic scale and macroscopic scale are considered.

2.1. The constituent properties of composite materials

As is well known, the mechanical behaviors and failure mechanisms for composite materials are closely dependent on microscopic structural parameters (such as inclusion arrangement, inclusion shape, etc.), and constituent properties [35,36]. Here, continuous glass-reinforced resin matrix composites are considered. The constituent material parameters are as follows [37,38]: elastic modulus $E_f = 71.42$GPa, Poisson's ratio $\nu_f = 0.2$, elastic modulus $E_m = 3.3$GPa, Poisson's ratio $\nu_m = 0.22$. The superscripts f and m indicate the reinforced fibers and matrix, respectively. Longitudinal tensile strength of reinforced fibers $X_T^f = 1617$ MPa. Longitudinal compressive strength of reinforced fibers $X_C^f = 421$ MPa. The tensile strength and compressive strength of matrix materials are $Y_T^m = 37$ MPa and $Y_C^m = 121$ MPa, respectively. Matrix shear strength is $S^m = 22$ MPa. Compared with the material pameters provided by Soden et al. [39], The parameters emloyed herein show a huge difference. It should be pointed out that the failure strength of glass fibers is related to fiber diameter, chemical composition, storage time, etc. The failure strength of glass fiber will be sharply decreased with the increasing of fiber diameter. In addition, due to the microscopic cracks, the measured strength of glass fiber is always lower than the theoretical strength. Here, the experimental results of failure strength provided by Zhai [38], are employed.

The glass fiber-reinforced composites are prepared through vacuum pumping technology. For further acquiring the microscopic structure, the proper dimension specimens are prepared. The microscopic image was acquired by the transmission electron microscopy (TEM, JEOL, JEM-2100F, Tokyo, Japan) as shown in Fig. 1. The Fig. 1(b) is the partial enlargement image of the Fig. 1(a). It can be concluded from the figure that the cross-section of the glass fibers has a circle shape, and a relatively uniform diameter of around $18\mu m$.

2.2. Macro-scale problem formulation

The finite element program LS-DYNA is proposed to describe the discrete system of macroscopic structure. The second order ordinary differential equation of the dynamic responses can be written as [40]:

$$M\ddot{u} + C\dot{u} + Ku = F \tag{1}$$

where M and C indicate the element mass matrix and the damping matrix, respectively. K and F indicate the element stiffness matrix and the external forces, respectively. The parameters u, $\dot{u}$ and $\ddot{u}$ are displacement, velocity and acceleration components at the Gauss points, respectively.

In the framework of Newmark method, velocity components $\dot{u}_{n+1}$ and displacement components u_{n+1} at the next global iterative step $n + 1$ can be expressed as:

$$\dot{u}_{n+1} = \dot{u}_n + [(1-\delta)\ddot{u}_n + \delta\ddot{u}_{n+1}]\Delta t \tag{2}$$

$$u_{n+1} = u_n + \dot{u}_n\Delta t + [(1/2-\alpha)\ddot{u}_n + \alpha\ddot{u}_{n+1}]\Delta t^2 \tag{3}$$

where the subscript n indicates the number of iterative step. Δt is the time increment. δ indicates a free parameter, which can be adjusted according to the requirements of accuracy and integration stability. It has been proved that the solution is unconditional stability when $\delta \geqslant 0.5$ and $\alpha \geqslant 0.25(0.5 + \delta)^2$.

Substituting Eqs. (2)–(3) into Eq. (1), the displacement component u_{n+1} will be obtained. Moreover, macroscopic strain increments $\Delta\bar{\varepsilon}_{ij}$ can be solved by employing the displacement gradient, that is

$$G_{ij} = \frac{\partial \Delta u_i}{\partial x_i} \tag{4}$$

$$\Delta\bar{\varepsilon}_{ij} = (G_{ij} + G_{ji})/2 \tag{5}$$

where Δu_i indicate the displacement increments and x_i are corresponding deformed coordinates.

2.3. Macro-micro scale transition

The Generalized Method of Cells (GMC), one of the