Composite Structures 128 (2015) 381–394

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Finite element prediction of the impact compressive properties of three-dimensional braided composites using multi-scale model

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ARTICLE INFO

Article history:
Available online 27 March 2015

Keywords:
3D braided composites
Impact compression
Finite element (FE)
Multi-scale structure

ABSTRACT

This paper presents a comprehensive study aimed at the compressive properties of three-dimensional (3D) braided composites subjected to quasi-static and high strain rate loadings using finite element method from fiber/matrix scale to composite scale. It focuses on a computationally efficient multi-scale methodology for prediction of the effective elastic properties and the failure strength of 3D braided composites. First, finite element models with strain rate sensitive elasto-plastic constitutive relationship and ductile and shear failure criterion were established to investigate the mechanical properties and failure mechanism. Second, the failure mechanism in micro-scale fiber/matrix was investigated. The mechanical properties of the interior unit cell, surface unit cell and corner unit cell were predicted and compared, which shows that the surface and corner region of braided preform play an important role during both quasi-static and high strain rate loading. The results obtained from the whole structure heterogeneous composite model and the homogeneous composite model were also analyzed and compared. Finally, the numerical results were verified by the experimental data and the results are encouraging. This method can provide an important guidance for evaluating the mechanical properties and selecting structural parameters for braided composites.

1. Introduction

Advanced textile composites are widely used in the fields of aeronautics, space, marine, automotive and sports recreation in recent years. As one of the classical textile composites, braided performs are particularly attractive due to their reduced part count, the ability to create nearnet-shapes as well as the presence of through-thickness reinforcement. Such kind of composites are usually applied to various occasions subjected to a wide range of loading rates from quasi-static strain rate to high velocity impact loading. Over the years, in order to use the braided composites efficiently, safely and reasonably, many attempts have been made to understand the mechanical behavior of these composite materials under various strain rates by various methods [1], such as experimental [2–4], analytical [5,6], systems methods [7], muti-scale methods [8], micro/meso-structure models [9,10], and representative unit cell (RUC) models [11–13].

Specifically, due to their complicated micro-geometry, earlier models used to predict the mechanical properties of 3D braided composites were mostly based on the homogenization method (multi-scale methods and RUC models, etc.). Indeed, multi-scale approaches, capable to efficiently transfer the material's behavior from micro- to macro-scale, offer a base tool for this demanding modeling task. Several studies have been reported on the modeling of braided composites. Ji et al. [8] developed a multi-scale braided structure to describe the change in elastic properties at different scales assisted by finite element (FE) approach. Yu and Cui [14] proposed a structure of braided composite materials with periodic configuration and predicted the stiffness and elastic strength parameters of 3D braided composites via the two-scale method. Moreover, the influence of the braiding angle and the fiber volume fraction on its strength was discussed. Tang et al. [15] reported a progressive damage model for stress analysis, failure analysis and material property degradation of braided composites employing a bottom-up multi-scale FE modeling approach. It sequentially considered three scales: fiber/matrix, tow architecture, and macro-scale. The effect of variation in braid parameters on the progressive failure behavior was given as well. Recently, the multi-scale analysis method was extensively applied to the prediction of the viscoelastic properties [16], on-axis and off-axis tensile properties [17] of braided composites. Deng et al. [18] presented

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http://dx.doi.org/10.1016/j.compstruct.2015.03.066
0263-8223/

a multi-scale correlating model, which not only concurrently obtains the stress/strain fields in multiple scales but also reveals local failure mode, failure sequence and the resulting failure progression of the composites.

However, most of these multi-scale methods are based on a representative unit cell homogenized using finite elements to derive the quasi-static mechanical properties of the braided composite materials. Few studies have considered high strain rate loading condition with failure initiation and progression in order to evaluate the dynamic mechanical response of the material. Representative works of this category are those of the unit-cell approach [19,20]. Due to the need for short computation time, the geometrical shape of the yarns within the braided composites is not considered in the homogenization model. In reality, however, the cross-sections of the yarns are quite complex due to the squeezing actions between yarns within such composites. The stress distribution of the yarns will become heterogeneous when subjected to external loadings. The damage and failure of braided composites may occur in certain local regions as well. Such factors can be taken into consideration in the heterogeneous model, also known as the meso-structure model.

In this paper, a multi-scale finite element model is established including the fiber/matrix on micro-scale, the meso-scale representative volume element of yarns, the meso-scale unit-cell model, the meso-scale full-size structure model as well as the homogeneous macro-scale model of 3D 4-step braided composites. Both the homogenization model and the in-homogenization model are adopted to analyze the impact compressive behavior of the braided composites. At the fiber/matrix and fiber tows levels, an elastic–plastic constitutive relationship considering the strain rate effect is developed. It is used to investigate the fiber/matrix interface failure and evaluate the effective mechanical properties of fiber tows. Then the mechanical behavior of both the meso-scale unit-cell model and the meso-scale full-size structure FE model is analyzed. A vectorized user-defined material (VUMAT) subroutine and a user-defined material (UMAT) subroutine are employed respectively to calculate the dynamic and quasi-static stress–strain curves of 3D braided composites at macro-scale. With this multi-scale model, the stress–strain curve, the stress distribution and the deformation of the 3D braided composites are obtained. The failure mechanism can also be predicted.

2. Framework of the multi-scale model

2.1. The geometric model

Fig. 1 presents the schematic of the multi-scale model for 3D 4-step braided composites. In the heterogeneous simulation, two levels (micro-scale fiber/matrix and meso-scale heterogeneous whole structure composite model) are included to calculate the compression behavior of the braided composites. In contrast to the heterogeneous simulation, the homogeneous simulation needs three levels to complete the prediction of compressive properties of the braided composites. A bottom-up homogenization procedure is employed that sequentially considers the micro-scale fiber/matrix, the meso-scale RUC and the macro-scale homogeneous composite. In both heterogeneous simulation and homogeneous simulation, analysis at the fiber/matrix scale is carried out for predicting the properties and mechanical responses of fiber tows in various strain rates using the elastic–plastic material model. The essential mechanical features of each constituent (fiber and matrix) are obtained from experimental data. Then, the mechanical behavior of the meso-scale heterogeneous whole structure composite model and the meso-scale RUC model are calculated based on the calculated mechanical properties of the fiber tows and matrix. Finally, the compressive behavior of the macro-scale homogeneous composite model are derived from the predicted properties of the three meso-scale RUCs. The detailed stress distribution and failure mechanism of the composite could be obtained by analyzing the meso-scale heterogeneous whole structure composite sample. Compared with the heterogeneous whole structure composite model, the macro-scale homogeneous composite model is used to predict the stress–strain curve and the stress distribution trend.

2.2. The material model

This section briefly introduces the constitutive and continuum damage models that are used to describe the deformation and damage response of the multi-scale models. The elasto-plastic theory was used as the constitutive relationship of all the multi-scale models. Damage initiation in all the multi-scale models were based on a ductile damage criterion in conjunction with shear damage criterion which allowed the removal of element from the mesh. In addition, the component material (fiber and matrix) and the macro-scale homogeneous composite model were modeled as strain-rate-dependent materials.

2.2.1. The constitutive relationship

For the textile reinforced composites under study, it is noticed that the experimental stress–strain curves of the polymer resin, the basalt fibers and the composite exhibit a yield region, where the strain increase is accompanied by a slow increase in stress. Due to plastic deformation, materials will not return to their original states when the external stress exceeding the yield values is removed. Before the stress reaches the maximum strength point, the total strain can be expressed as a sum of elastic (completely recoverable) and plastic (residual) strains:

$$\varepsilon_\Sigma = \varepsilon_e + \varepsilon_p \tag{1}$$

To define a work-hardening relationship, stress must be given as a function of the equivalent plastic strain [21]. The equivalent plastic strain is zero before the stress reaches the yield strength, after which the equivalent plastic strain increases due to plastic deformation as the loading proceeds.

The matrix in this study is assumed to obey the J2-isotropic hardening plasticity theory [22].

To define the yield properties of the fiber tows, Hill's anisotropic plasticity model is used [23]. Hill's potential function is a simple extension of the Mises function, which can be expressed in terms of rectangular Cartesian stress components as

$$f(\sigma)=\sqrt{F(\sigma_{22}-\sigma_{33})^2+G(\sigma_{33}-\sigma_{11})^2+H(\sigma_{11}-\sigma_{22})^2+2L\sigma_{23}^2+2M\sigma_{31}^2+2N\sigma_{12}^2} \tag{2}$$

where F, G, H, L, M, and N are constants that can be obtained by testing the material in different directions. They are defined as

$$\begin{cases} F=\frac{(\sigma^0)^2}{2}\left(\frac{1}{\bar{\sigma}_{22}^2}+\frac{1}{\bar{\sigma}_{33}^2}-\frac{1}{\bar{\sigma}_{11}^2}\right)=\frac{1}{2}\left(\frac{1}{R_{22}^2}+\frac{1}{R_{33}^2}-\frac{1}{R_{11}^2}\right) \\ G=\frac{(\sigma^0)^2}{2}\left(\frac{1}{\bar{\sigma}_{33}^2}+\frac{1}{\bar{\sigma}_{11}^2}-\frac{1}{\bar{\sigma}_{22}^2}\right)=\frac{1}{2}\left(\frac{1}{R_{33}^2}+\frac{1}{R_{11}^2}-\frac{1}{R_{22}^2}\right) \\ H=\frac{(\sigma^0)^2}{2}\left(\frac{1}{\bar{\sigma}_{11}^2}+\frac{1}{\bar{\sigma}_{22}^2}-\frac{1}{\bar{\sigma}_{33}^2}\right)=\frac{1}{2}\left(\frac{1}{R_{11}^2}+\frac{1}{R_{22}^2}-\frac{1}{R_{33}^2}\right) \\ L=\frac{3}{2}\left(\frac{\tau^0}{\bar{\sigma}_{23}}\right)^2=\frac{3}{2R_{23}^2} \\ M=\frac{3}{2}\left(\frac{\tau^0}{\bar{\sigma}_{13}}\right)^2=\frac{3}{2R_{13}^2} \\ N=\frac{3}{2}\left(\frac{\tau^0}{\bar{\sigma}_{12}}\right)^2=\frac{3}{2R_{12}^2} \end{cases} \tag{3}$$