Advances in Engineering Software 121 (2018) 206–222

Contents lists available at ScienceDirect

Advances in Engineering Software

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

Effect of micromechanical parameters of composites with wavy fibers on their effective response under large deformations

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ARTICLE INFO

Keywords:
Fibers
Mechanical properties
Finite element analysis (FEA)

ABSTRACT

The large deformation response of composites reinforced by continuous wavy fibers is investigated using three-dimensional Finite Element Analysis. The focus is placed on in-phase fibers with circular cross-sections following sinusoidal paths. The effects of the following micromechanical parameters are analyzed – relative fiber radius, fiber crimp ratio, fiber arrangement and matrix material compressibility. In addition, the responses predicted by three-dimensional and two-dimensional plane strain models are compared. The considered composite is modeled as a fully periodic wavy unit cell subjected to periodic boundary conditions and three load cases – elongations in the x_1 (longitudinal) and x_2 (transverse) directions, and simple shear in the x_1–x_2 plane. Both constituents of the composite, the fibers and the matrix, are modeled using an isotropic hyperelastic material formulation. The results are presented as plots of macroscopic Cauchy stress components versus applied stretch (or strain in the case of the shear loading) and of fiber undulation versus applied stretch for the longitudinal elongation.

1. Introduction

The fiber waviness present in some fiber-reinforced composites has a significant influence on the overall macroscopic responses of composite structures. Materials containing wavy fibers are encountered in man-made nanocomposite structures [1–4], composite laminates [5–7], and natural and artificial biological materials [8–10]. One of the important challenges in the analysis of these materials is predicting their macroscopic mechanical responses under large deformations [11–13]. Homogenization approaches proposed for estimating the overall large-deformation behavior of composites with wavy fibers can be grouped into two categories – analytical and numerical. Most analytical methods are based on mean-field homogenization techniques (e.g., Mori-Tanaka schemes) and numerical approaches are usually based on Finite Element Analysis (FEA).

Extensive research has been performed on composites reinforced by wavy carbon nanotubes (CNT). Fisher et al. [1] developed a finite element model of a unit cell to evaluate the contribution of a single wavy nanotube embedded in a large matrix volume and used the obtained results for micromechanical homogenization based on the Mori-Tanaka scheme to estimate the effective elastic moduli of CNT-reinforced polymers. It was shown that nanotube waviness can reduce the effective moduli of a material as predicted by micromechanical homogenization. Bradshaw et al. [2] extended the previous work and studied the influence of aligned and randomly oriented wavy fibers in a polymer matrix. They concluded that the CNT aspect ratio (ratio of the diameter to its length), amplitude-to-wavelength ratio, and mismatch in elastic moduli between the constituents play a significant role in the effective response of the composite structure. Anumandla and Gibson [14] proposed an approximate micromechanical model to estimate the effects of fiber waviness and the three-dimensional (3D) arrangement of CNTs on the effective elastic moduli of composites. Fiber waviness was again shown to have a significant influence on the effective moduli of the nanotube-reinforced composites. Abdin et al. [15] used a mean-field homogenization approach to predict the overall mechanical response of composites reinforced by curved (including sinusoidal) short fibers. They proposed to replace a curved fiber by an equivalent set of ellipsoids in order to estimate the overall response of the composite. Bhuiyan et al. [16] developed FEA simulations of representative volume elements of composites with wavy nanotubes to study the effects of the diameter, orientation, dispersion and waviness of CNTs on the tensile moduli of the composites. These authors used image analysis to obtain detailed probability distribution functions for the geometric parameters of the embedded CNTs. Matveeva et al. [3] assessed the effects of nanotube waviness and curliness on the macroscopic elastic behavior of CNT-reinforced polymers using FEA models with periodic boundary conditions and a Mori-Tanaka based micromechanical model. The results demonstrated a reduction of the longitudinal moduli of the

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https://doi.org/10.1016/j.advengsoft.2018.04.013
Received 11 October 2017; Received in revised form 26 April 2018; Accepted 29 April 2018
0965-9978/

composites affected by nanotube curvature. Taqa et al. [17] investigated numerically the influence of wavy CNTs embedded in cement paste on the overall elastic moduli of cementitious composites using 3D models. The parameters of the wavy fibers under consideration were volume fraction and fiber aspect ratio. They showed that waviness reduces the capabilities of the composite structures. Drach et al. [18] calculated the stiffness contribution tensor of a wavy fiber utilizing two approaches – numerical and analytical approximation, the latter being based on replacing the fiber with a set of spheroids having the same aspect ratio. The results showed a good agreement between FEA and analytical approximation.

The effective properties of composite laminates are also influenced by fiber waviness which might develop as a result of manufacturing imperfections. Lee et al. [19] proposed an analytical approach to model the influence of wavy patterns in laminates on the effective Young's moduli under tensile loading. In later research, Hsiao and Daniel [20] developed an analytical model to investigate the effects of different types of fiber waviness – uniform, graded, and localized – on stiffness and strength of unidirectional composites under compressive loading. The analytical model was validated by comparison with experimental investigations. It was concluded that waviness results in a significant reduction of strength and stiffness of the composites. These authors also investigated the influence of waviness on cross-ply carbon/epoxy composites [21]. Comprehensive numerical studies of the behavior of laminates with wavy fibers were performed by Garnich, Karami and collaborators [22–25], who developed linear elastic 3D FEA models of periodic sinusoidal unit cells to study the effects of amplitude-to-wavelength ratio and volume fraction of fibers on the volume-averaged stress and strain [22]. The results showed the importance of local stresses in failure predictions. It was also shown that material stiffness is strongly influenced by fiber waviness. In subsequent work, these authors conducted a comparison between localized stresses in wavy periodic unit cells with explicitly modeled fibers and straight homogeneous unit cells into which wavy fibers were introduced by prescribing material properties of the homogenized unidirectional composite with material orientation following wavy paths [23]. The results demonstrated the equivalence of the two models in the case of linear elastic analysis. In addition, they performed FEA on wavy periodic unit cells for a range of amplitude-to-wavelength ratios and volume fractions to investigate the thermoelastic responses of the composites [24]. It was shown that an increase in fiber waviness in carbon fiber reinforced polymers leads to an increase in the coefficient of thermal expansion (CTE) along the longitudinal direction and to a decrease in CTE in the transverse direction. Further work of this research group is related to the FEA analysis of a straight unit cell with localized fiber waviness modeled implicitly (via local material orientations) using FEA [25]. It was concluded that localized fiber waviness leads to a significant strength reduction of composite structures. Note that all of the publications discussed above focus only on the small-strain responses of composites. Large deformations are usually encountered in biological tissues as discussed below.

The homogenized mechanical behavior of biological and bio-inspired materials with wavy fibers has been studied by several research groups over the past decade. Khatam and Pindera [26] numerically investigated the effects of layer waviness, volume fraction and waveform shape (sinusoidal vs. corrugated) on the effective elastic moduli and CTEs of periodic multilayers composed of soft and stiff phases using the finite-volume direct averaging micromechanics (FVDAM) technique. It was shown that ply waviness affects the homogenized Young's modulus and CTE in both, transverse and longitudinal, directions. The analysis was limited to the investigation of two-dimensional (2D) unit cells with linear isotropic constituents that were subjected to small deformations. Khatam and Pindera [27] later extended their research to the numerical analysis of the influence of waviness in multilayered structures combining elastic and elastoplastic phases and studied the effect of the layers' thicknesses on the post-yield response. The authors concluded that the layer thickness influences the post-yield response of the composite structure, in contrast to a minimum impact to the elastic moduli. The same research group also investigated the effect of the amplitude-to-wavelength ratio, layer thickness, and mismatch of the phase moduli on the homogenized response of wavy composites with isotropic non-linear elastic properties undergoing finite deformations, see [28,29]. The results obtained with the FVDAM theory are in good agreement with experimental data. Note that the latter works are limited to the analysis of 2D unit cells. Karami et al. [30] modeled brain white matter as a fiber-reinforced composite with hyperelastic material properties undergoing large deformations. The influence of two geometrical parameters – fiber volume fraction and undulation – on the homogenized responses of periodic 3D unit cells was investigated. The volume fraction as well as undulation of fibers showed a significant impact on the overall stiffness of the composite and stress distributions. Pan et al. [31] developed a 3D micromechanical finite element model of white matter and investigated the effect of undulation on the local stress and strain fields at large deformations. The significant influence of waviness on the stress fields was also highlighted.

Despite the extensive published research, the influence of the following parameters on the homogenized response of composites reinforced by wavy fibers still requires additional consideration for various phase contrasts in 3D under large deformations: relative fiber radius, crimp ratio, fiber arrangement and compressibility of the matrix. In the current study, we determine the effects of these parameters on the overall response of fiber-reinforced composite structures containing continuous wavy fibers following sinusoidal paths. In addition, we investigate whether the mechanical response of such composites can be modeled accurately using 2D models.

The geometrical parameters of the considered wavy fibers are presented in Fig. 1a. There are two parameters, which describe each individual fiber – the crimp ratio CR and the relative radius $\tilde{r}$. The crimp ratio is defined as the ratio of the amplitude A to the wavelength λ of the fiber path:

$$CR = \frac{A}{\lambda} \tag{1.1}$$

The relative radius of a fiber is defined as the ratio of its radius, r, to the wavelength of the fiber path, λ:

$$\tilde{r} = \frac{r}{\lambda} \tag{1.2}$$

We perform numerical homogenization based on the smallest 3D repetitive volume element of the composite (unit cell, see Fig. 1b for the case of the square arrangement of fibers) via FEA.

This paper is organized as follows. In Section 2, we describe geometry generation and meshing of the wavy unit cell used in the FEA. In addition, a description of the FEA model preparation steps and processing of the numerical results is presented. In the same section, we provide a description of the hyperelastic material model considered in this work. Section 3 contains the numerical results for macroscopic stress components and fiber undulation as functions of applied deformation for unit cells with different micromechanical parameters. The conclusions of this research are presented in Section 4.

2. Finite element modeling approach

In this work we apply the FEA in order to evaluate the homogenized properties of composite structures reinforced with aligned wavy fibers undergoing finite deformations. The entire composite is represented as a collection of repeating periodic wavy unit cells mimicking the geometry of the fibers (see Fig. 1b). We focus our attention on three different fiber arrangements resulting in three types of unit cells: square, hexagonal, and random.