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Influence of fiber waviness on the effective properties of discontinuous fiber reinforced composites

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ABSTRACT

In this study, 3D Representative Volume Element (RVE) models are used to investigate the effect of fiber waviness not only on the Young's moduli but also on the shear moduli and Poisson's ratios of unidirectional discontinuous fiber reinforced (DFR) composites. In order to measure the sole influence of fiber waviness, properties of the RVE model with curved fibers are compared with those of the RVE model with corresponding straight fibers. This comparison shows that fiber waviness significantly affects E_{11} and moderately affects all the other effective properties. Variation in E_{22} due to fiber waviness is contrary to general expectations. It is observed that E_{22} initially decreases and then increases with the increase in fiber waviness. Influence of fiber volume fraction (V_f), fiber/matrix material property mismatch, fiber spatial distribution and fiber/matrix interphase region on the effective properties of DFR composite with curved fibers is also numerically investigated. It is found that V_f, material property mismatch and interphase region have strong influence whereas spatial distribution has weak influence on the effective properties of unidirectional DFR composite containing curved fibers.

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1. Introduction

Due to the advantages such as lesser weight, better fuel economy, lower number of assembly operations, higher damping, better corrosion resistance and higher cost savings, discontinuous fiber reinforced (DFR) composites are used in many automotive applications. Properties of these materials depend on their microstructure i.e. type of matrix, type of fiber, fiber size, fiber orientation, fiber spatial distribution, fiber/matrix interface properties and fiber waviness. Present study focuses on the influence of fiber waviness on the effective properties of DFR composites.

Many analytical methods to compute the effective properties of DFR composites with straight fibers are reported in the literature [1–6]. Kuo et al. [7] used analytical method to investigate the effect of fiber waviness on the Young's moduli in longitudinal and transverse directions of Unidirectional Continuous Fiber Reinforced (UCFR) composites. Influence of curved fiber arrangement on the effective properties of UCFR composites was also studied by considering iso-phase and random-phase models. Hsiao and Daniel [8,9] developed an analytical method to compute the effective properties of UCFR composites with uniform, graded and localized fiber waviness. Classical laminate theory was used to predict the strength of the unidirectional and cross-ply laminates. Monte-Carlo simulation method was used by Tsai et al. [10] to generate DFR composite microstructures with a given fiber waviness, fiber aspect ratio and fiber orientation distributions. Analytical methods were employed to compute the effective material properties of these microstructures.

Considerable amount of literature has been published on FE based computational micromechanical approach to compute the effective properties of DFR composites. Pan et al. [11,12] and Kari et al. [13] used Random Sequential Adsorption algorithm to generate RVE models of DFR composites with unidirectional as well as randomly oriented straight fibers. Effective elastic properties of these RVE models are then computed by using FE based computational micromechanics approach. Monte-Carlo procedure was used by Hine et al. [14] and Lusti et al. [15] to generate RVE models of short fiber reinforced composites with sphero-cylindrical shaped straight fibers. Experimentally measured fiber lengths and fiber orientations were used to generate microstructures that are similar to those seen in real composites. Brighenti and Scorza [16] used FE method to simulate the fracture behavior of brittle matrix material reinforced with unidirectional and randomly oriented fibers. Coupled Finite Element (FE) and Boundary Element (BE) method was used by Gorski [17] to numerically evaluate the effective properties of Carbon Nanotube (CNT) reinforced composites. Two

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dimensional Representative Volume Element (RVE) models with wavy CNTs were used to investigate the influence of reinforcement waviness on the effective properties. It was concluded that the waviness and shape of the CNT has a significant influence on the effective properties of CNT reinforced composites. Pantano and Cappello [18] investigated the influence of CNT waviness and interfacial bonding on the effective properties of CNT reinforced composites. RVE models with perfectly bonded and perfectly de-bonded CNTs were used in their numerical studies. In contrast to a perfectly bonded case, waviness in a perfectly de-bonded case increased the effective elastic stiffness of the CNT reinforced composites.

Combination of numerical and analytical methods was used by Bradshaw et al. [19] and Fisher et al. [20] to study the effect of fiber waviness on the effective properties of CNT reinforced composite materials. In this method, numerical model of an infinitely long sinusoidal fiber embedded in an infinite matrix was used to compute effective reinforcement modulus and dilute stain concentration tensor. These results were subsequently used in traditional analytical micromechanical models [1–6] to compute the effective properties of DFR composites. It was shown that a small waviness in CNT could lead to a significant decrease in effective modulus of the CNT composites.

Most of the studies in the literature did not report the influence of fiber waviness on the shear moduli and the Poisson's ratios of DFR composites. Also, in most of these studies, effective properties are normalized with respect to matrix material properties. To clearly understand the influence of fiber waviness, effective properties of the composites with curved fibers should be compared with those of the composites with straight fibers. In this paper, FE based computational micromechanics method is used to investigate the influence of fiber waviness on the effective elastic stiffness constants of unidirectional DFR composites. Curved fibers are assumed to have sinusoidal shape and they are characterized by their amplitude (A), wavelength (λ) and diameter (d). Various parameters such as waviness ratio (A/λ), wavelength ratio (λ/d) and fiber volume fraction V_f are systematically varied to create 3D RVE models of DFR composites with curved fibers. Boundary surfaces of these RVE models are subjected to Periodic Boundary Conditions (PBCs). Effective properties are then computed by performing numerical homogenization on the stress and strain distributions obtained through FE analysis of these RVE models. Validation of the FE based methodology is performed by comparing the predicted effective elastic material properties with those reported by Tsai et al. [10]. Results obtained illustrate the effect of waviness ratio, wavelength ratio and V_f on the effective properties of DFR composites. In addition, influence of fiber/matrix material property mismatch and fiber spatial distribution on the effective properties of DFR composite containing curved fibers is investigated. Finally, effect of interphase material on the effective properties of DFR composite with curved fiber is studied.

2. FE based computational micromechanics modeling

2.1. Characteristics of sinusoidal shaped curved fiber

In real composite materials, fiber waviness is a random phenomenon. However, in order to systematically study the influence of fiber waviness on effective properties of unidirectional DFR composites, fibers are assumed to have sinusoidal shape. This shape is represented by Eq. (1). Geometric parameters to characterize the sinusoidal shaped curved fiber are shown in Fig. 1. In this study, fiber waviness is restricted to xy plane. Longitudinal direction of the fiber is along the x-axis and in plane transverse direction is along the y-axis.

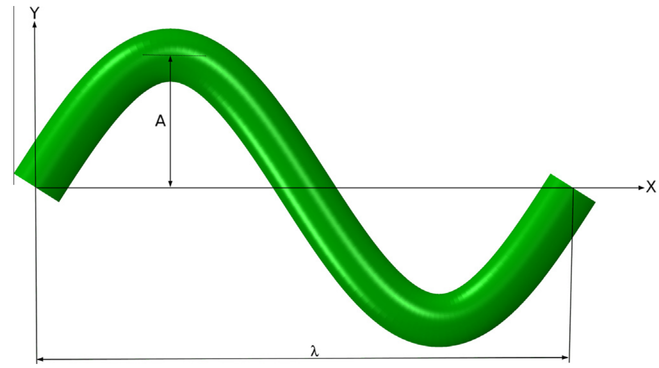

Fig. 1. Curved fiber with sinusoidal shape.

$$y = A \sin\left(\frac{2\pi x}{\lambda}\right) \tag{1}$$

2.2. Generation of 3D RVE models of unidirectional DFR composites

Three dimensional RVE models with curved fibers are generated by using ABAQUS/CAE [21]. These fibers are characterized by different values of A/λ, λ/d and V_f. RVE models with the straight fibers are also generated in similar fashion. It is ensured that the length of the straight fiber is equal to that of the corresponding curved fiber. Also, size of the RVE model with curved fibers is equal to that of the RVE model with corresponding straight; therefore, V_f of both RVEs is same. With these measures, it is now possible to compare the effective properties of both these RVEs to understand the sole influence of fiber waviness on the effective properties of DFR composites.

In order to investigate the influence of fiber/matrix material property mismatch on the effective properties of unidirectional DFR composite with curved fibers, two different composite materials are considered. Table 1 shows the properties of these materials [22,23]. Material property mismatch parameter is defined as the ratio of the Young's modulus of fiber to that of matrix. Material property mismatch of Al/Boron (Al/B) composite is 5.6 and that of Glass/Epoxy (GFRP) composite is 27.9.

RVE models with three different spatial distributions of curved fibers (Fig. 2): iso-phase, fixed-phase and random-phase are generated to investigate the influence of spatial distribution on the effective properties of DFR composite. Highlighted boxes in the Fig. 2 shows the typical RVE models used to compute the effective properties. Fibers in iso-phase distribution (Fig. 2a and b) are aligned with each other .i.e. the offset distance is zero. Fibers in fixed-phase distribution (Fig. 2c and d) are arranged in such a way that the offset distance is equal to $\lambda/4$. Random distribution of fibers in random-phase spatial distribution (Fig. 2e and f) is achieved by using a random number generator to assign the location of fibers. In order to capture the sole effect of waviness, corresponding RVE models with straight fibers and similar spatial distributions are also generated.

Table 1
Material properties of matrix and fiber in Al/B and epoxy/glass composites [22,23].

Material	E (GPa)	ν
Aluminum	68.3	0.3
Boron	379.3	0.1
Epoxy	2.6	0.4
E-glass	72.5	0.22

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