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A Numerical Investigation of Interface Properties on Damage Behavior of Fiber Reinforced Composites

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This paper investigates the micromechanical damage behavior of composite materials on the transverse tensile response of representative volume elements (RVEs) with various fiber volume fractions. A new algorithm is developed to generate the random distribution of fibers in the RVE, and it is possible to create a fiber distribution with high fiber volume fraction. The fibers and matrix are considered linear elastic and elastoplastic with Drucker–Prager's criterion, respectively. The fiber-matrix debonding is modeled by cohesive elements which lead to matrix cracking. To achieve a more realistic microstructure, the normal cohesive properties distribution is applied for interfaces between fibers and the matrix. To investigate the effect of the position of fibers with the weakest cohesive strength, sensitivity analysis concerning the different arrangements of specific normal cohesive properties on the RVE's strength are performed. Moreover, the effects of different damage parameters such as fiber random distributions and various cohesive strengths on the overall damage behavior of the RVE are described in detail. It is revealed that the application of a normal cohesive distribution strongly reduces the maximum strength of the RVE and shifts the strain of damage initiation point and crack propagation path.

***Keywords**: RVE-Fiber Matrix Debonding-Matrix Crack-Damage Mechanics-Composite Material*

Introduction

Composite materials have a significant role in the weight reduction of structures applied in the aerospace industry. The mechanical response of composite materials may be affected by several damage mechanisms in which the fiber-matrix debonding and matrix cracks are of primary damage modes. Although the initiation and propagation of these damage modes will not directly cause the collapse of the structure, they will instantly decrease the strength of the damaged layer to a certain limit. Finite element analyses become a practical approach for studying the complex failure behavior of composite materials in engineering applications. However, the execution of a structure with all the details required an excessive computational cost and was impractical most of the time. A more efficient approach for this purpose is to consider a micromechanical model with all their damage modes and apply the results to investigate the

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macroscopic mechanical behavior by numerical homogenization techniques. Experimental researches have confirmed that the primitive damage mechanism associated with transverse fiber direction is debonding occurring at the fiber-matrix interface [1,2]. Recently, however, numerous advanced micromechanics damage models have been advanced, such as those by Llorca et al. [3], which enable the prediction of microscopic damage progression and the final failure of carbon fiber-epoxy composites. These have been accomplished through the use of cohesive zone models at the fiber–matrix interface coupled with non-linear constitutive material models to represent the behavior of the constituent materials. Due to the damage behavior complexity, many micromechanical investigations have concentrated on transverse fracture behavior from the standpoint of damage initiation [4,5]. There are several different parameters affecting the fiber-matrix debonding damage mode such as fiber radius size, cohesive zone properties and random fiber distribution. The fiber radius is considered as one of the significant parameters affecting the behavior of the RVE. Although many previous kinds of research are based on the hypothesis of identical fiber radii [5-7], Vaughan and McCarthy [8] accentuated that the fiber radii are not identical and have a normal distribution by experimental imaging as shown in Fig. 1-A. Thus, the normal distribution of radii should be taken into account in the micromechanical analyses to obtain a more accurate conclusion. In the following, Ismail et al. [9] examined the elastic behavior of composites with the assumption of a normal distribution for the fiber radius and studied the effective elastic properties and the range of changes using an RVE with the random distribution of fibers. By applying normal fiber distribution, they predicted the effective properties closer to those measured from experiments, especially the predicted Poisson's ratios that have shown excellent agreement with the experimental data.

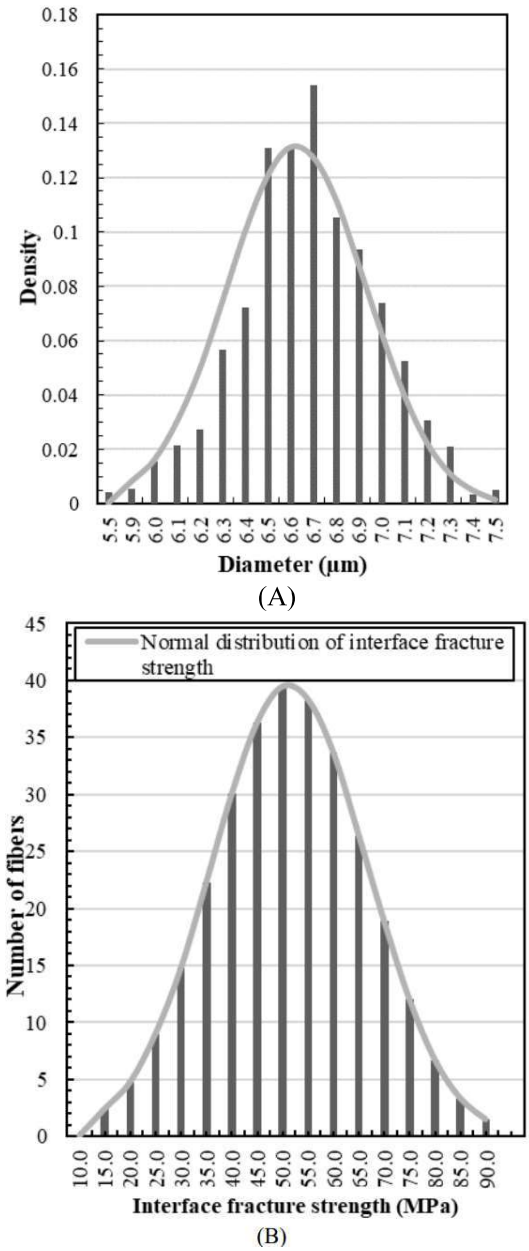


Fig 1. A) Normal distribution of fiber radii introduced by Vaughan and McCarthy [8], **B)** Normal cohesive properties distribution

Cohesive properties of fiber-matrix interfaces are the other parameters that affect the failure behavior of the RVE. Cohesive properties have been considered identical for all the fiber-matrix interfaces in most previous works [3-5,10]. However, in a real composite layer, the interfaces show various strength toward fiber-matrix debonding. Alfaro et al. [11] use discrete microscale fracture processes to create a mesoscale traction-separation law. The microscale fracture behavior

included both fiber-matrix debonding and matrix cracking. They demonstrated how the effective traction-separation response and the corresponding microscale fracture patterns under mesoscale tensile conditions depend on the RVE size, the fiber volume fraction, and the presence of imperfections. To investigate the effect of imperfections in fiber-matrix interfaces, various imperfection configurations were considered for one and two fibers for an RVE with a specific fiber volume fraction. They have shown that for all the imperfection configurations, the imperfection result in crack initiation and are included in the main crack which results in overall RVE fracture. Therefore, the imperfections can increase the length of the dominant failure crack (as compared to the crack length for an RVE without imperfections), and so would raise the effective fracture toughness of the RVE. Naderi et al. [12] examined the variation in properties of the cohesive zone and its effect on the overall behavior of the RVE. They assumed a normal distribution for cohesive material properties instead of constant material behavior. They showed that the assumption of cohesive constant properties would overestimate the fracture resistance of the RVE. Also, the initiation strain of damage and the growth of matrix cracks are highly dependent on the normal distribution of cohesive properties. The RVE size considered by Naderi et al. [12] was not large enough, so few fibers were modeled. Moreover, the random fiber distribution was predefined while this layout has a significant impact on the damage behavior of the RVE. Although many researchers have conducted valuable studies on the micromechanical damage analysis of composite material, the damage initiation and propagation mechanisms in microscale are still not well understood. However, computational micromechanics that take the influence of fiber volume fraction, normal distribution of radii for fibers, normal cohesive properties distribution of fiber-matrix interfacial, and fiber arrangement randomness into account are scarce in the literature. Therefore, the representative volume element consisting of fiber, matrix, and the interface was established for the simulation considering random fiber distribution. The two dominant damage mechanisms of fiber-reinforced composites, including fiber-matrix debonding and matrix cracking, were taken into account with the normal radii distribution hypothesis for fibers. Moreover, the effect of applying a normal cohesive properties distribution is investigated. The paper is organized into five sections. The second section provides details on the Finite element analysis features. The materials behavior and properties are presented in the third section. The discussion of results and conclusions are presented in the fourth and fifth sections, respectively.

Finite element analysis

Finite element (FE) analysis was implemented using ABAQUS. The two-dimensional 3-node and 4-node bilinear plane strain quadrilateral elements (CPE3, CPE4) were opted to mesh the fibers and the matrix. In addition, Python scripts have been written to generate and scatter fibers in the FE models of the RVEs. According to investigations carried out by Vaughan and McCarthy [8], the fiber radius in this study was considered as a normal distribution with a mean value of 6.6 and a standard deviation of 0.3106. The random fiber distribution algorithm is taking into account the minimum distance between fibers. The boundary conditions and the fiber distributions are considered periodic. In other words, the layouts of the fibers are such that the fibers on the opposite sides complement each other. This is a prerequisite for the creation of periodic boundary conditions, which is included in the placement of the fibers within the RVE. Another significant parameter is the dimension of the RVE. Trias et al. [13] pointed out that the minimum size of an RVE, which can investigate the behavior of the composite material with reasonable accuracy, is fifty times more than fiber radii in RVE with 50% fiber volume fraction. The dimensions of the RVEs in this study are modeled in the same way as the research [14,15], which is fifty times the radius of the fiber, a 165 x 165 square. The significance of periodic boundary conditions in the micromechanical analysis has been illustrated by several authors [16-18]. In this type of boundary condition, the displacement of the nodes in one edge is related to the displacement of the corresponding nodes on the opposite edge. RVE with random fiber distribution can represent a more realistic microstructure of fiber-matrix composites. Randomness can cause stress concentration where the fibers are near each other and will radically affect the plastic and damage behavior of the RVE. The program code is developed in MATLAB software and then the files are used to generate RVE with random fiber distribution in Abaqus. This algorithm has been developed to generate RVEs with high fiber volume fractions, with several

factors such as random fiber distributions, periodic distribution of fibers, minimum fiber neighboring distances and normal distribution of fiber radii.

Material behavior

As fiber fracture is unlikely to occur under transverse loadings, the carbon fibers are assumed to be linear elastic and no damage model has been implemented for the fibers. The mechanical properties used in the analysis were taken from [19] and are given in Table 1.

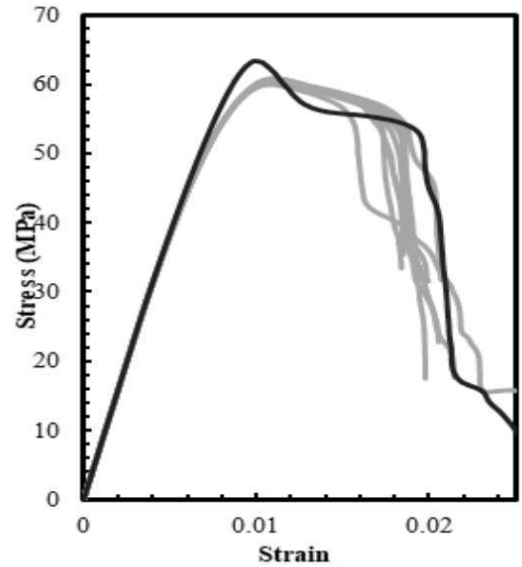
Table 1. Transverse mechanical properties of the carbon and epoxy resin

	Carbon fiber	Epoxy resin
Young's modulus (GPa)	13	3.8
Poisson ratio	0.47	0.35
Tensile strength (MPa)	-	95
Compressive strength (MPa)	-	125

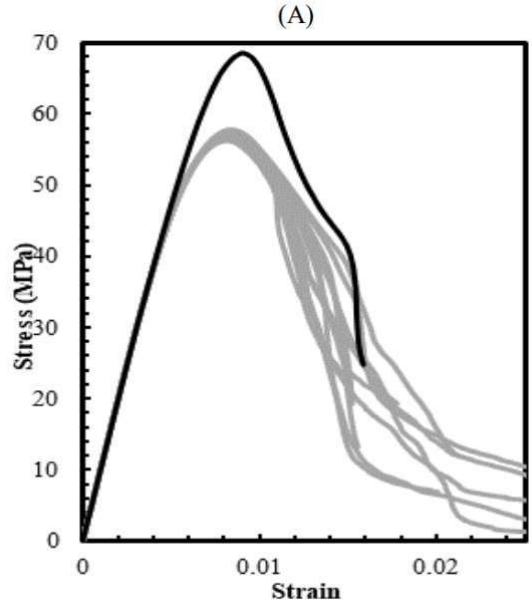
Several experimental studies have confirmed that fiber-matrix debonding and matrix cracks are the two dominant damage modes in micromechanical RVEs in composite materials under transverse loadings [20,21]. Consequently, the damage behavior of the epoxy and interface are considered, which is illustrated in detail in the following. As epoxy is sensitive to the hydrostatic stress [22,23], the matrix is assumed to behave as an isotropic, elastic–plastic solid with the Drager-Prager yield criterion. The matrix elastic constants are listed in Table 1 and the parameters of Drucker–Prager yield criterion are , and . Apart from the plastic criterion for the matrix, a criterion to predict the initiation and propagation of damage is also required. In this study, due to the investigation by Yang et al. [24], the equivalent plastic strains at damage initiation for uniaxial tension and compression are assumed as 0.025 and 0.25, respectively. After the initiation of matrix failure, the damage growth is introduced by a progressive failure procedure, based on energy criterion, with the fracture energy of the matrix defined as [24]. Fiber-matrix debonding is included in the simulation by the cohesive zone model in terms of a bi-linear traction–separation law. In this paper, the elastic stiffness is selected as and the B-K stress criterion is used to predict the damage initiation of the interface as . The fracture energy G for normal and shear traction–separation curves are considered as . Also, the B–K power law parameter is assumed as . Also, for normal cohesive properties distribution, the mean value for interface fracture strength is 50 MPa and ranges between 10 and 90 MPa. 4. Results In this section, the damage behavior of RVEs with different fiber volume fractions have been investigated. Also, the effects of applying normal cohesive properties and various random fiber distribution are discussed. Many researchers [3-7,10,11] have applied cohesive elements to analyze the behavior of fiber-matrix interfaces. However, unlike the real composite materials, they assumed that the mechanical properties of all fiber-matrix interfaces are identical. In this section, the damage behavior of the RVEs with the normal distribution of properties for the cohesive elements embedded between the fibers and the matrix is investigated. In this section, the failure behavior of the RVEs with different fiber volume fractions has been investigated. Several RVEs were analyzed and examined with the RVEs with identical interaction material properties to evaluate the effect of employing normal material properties distribution for interactions between the fibers and the matrix (Fig. 2). In the graphs shown in Fig. 2, the black graphs represent the RVEs with identical characteristics of the interfaces and the gray graphs indicate the damage behavior of the RVEs with different random fiber layouts and the normal distribution for the properties of the fiber-matrix interactions.

As presented in Fig. 2, the normal distribution of cohesive zone properties for RVEs with 20% fiber volume fraction can affect the maximum strength and damage initiation strain of the RVEs. In these RVEs, the maximum strength has dropped from 63.35 MPa to about 60 MPa (about 5% reduction). When the cohesive zone properties are considered constant for all the fiber-matrix interfaces, a large number of fibers simultaneously undergo fiber-matrix debonding in a particular strain, and the stress-strain diagram experiences a sudden drop. The strain of the initiation of fiber-matrix debonding is reduced by considering the normal distribution of properties for the bonding zones, from a strain of 0.009 to a strain of 0.007, and the RVEs show a drop-in strength in a lower strain. Due to the high-stress concentrations, the strain of matrix crack initiation would also decrease from 0.019 to 0.014. The fiber distribution layout also influences the overall damage behavior of the RVE. According to Fig. 2-A, there is a very high correlation between the results in the elastic region. This is while the variation in the maximum strength is about 0.7% with a mean of 60.37 MPa for different fiber distribution layouts. The study of the failure behavior of the RVEs with 40% fiber volume

fraction with a normal distribution of properties for fiber-matrix interfaces results in a decrease in the maximum strength value. Its value would be reduced by about 17% from 68.55 MPa to the average of 65.93 MPa (Fig. 2- b). The change in fiber distribution layouts can also fluctuate 1.3% at maximum strength in RVEs with 40% fiber volume fraction, which is approximately twice the tolerance in RVEs with 20% fiber volume fraction. In these RVEs, by applying the normal distribution for interaction properties, the strain of fiber-matrix debonding initiation would decrease from 0.008 to about 0.005. The same result has also occurred to matrix crack failure initiation, and its starting strain decreases from the 0.012 to about 0.011. In RVEs with 60% fiber volume fraction, a significant decrease in the maximum strength and damage initiation strain occurred (Fig. 2-C). In these RVEs, the maximum strength experienced a decrease from 66.79 to a mean of 57.79 MPa (about 13%) and the effect of different fiber distribution layouts within the RVE provided a variation of 0.7% for the maximum strength value. According to the results obtained for these three fiber volume fractions, it is concluded that up to 40% fiber volume fraction, by increasing the fiber volume fraction the maximum strength of the RVE would increase, and after that, due to the high fiber clustering and the high-stress concentration areas, the maximum strength of the RVE decreases. A notable point is that the effect of fiber distribution layouts in RVEs with 40% fiber volume fraction changes the overall maximum strength by about twice the RVEs with 20% and 60% fiber volume fractions. The strain reduction of the fiber-matrix debonding initiation is also greater in the RVEs with 40% fiber volume fraction (about 33%) than the other two types of RVEs.



(A)



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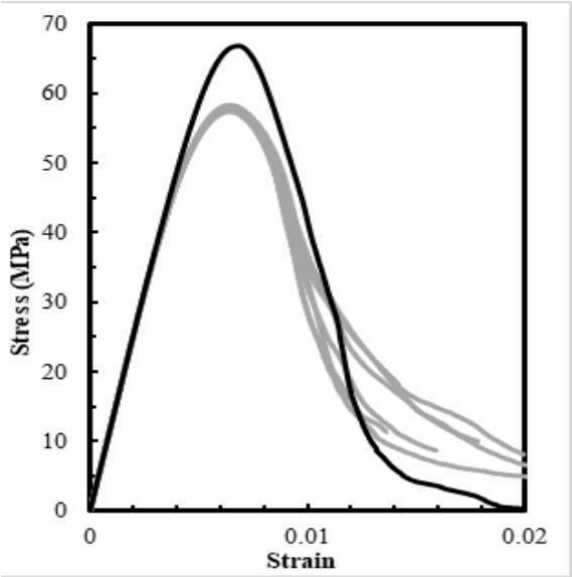

(C)

Fig. 2. The effect of normal cohesive properties distribution for fiber-matrix interfaces with different fiber volume fractions A)20%, B)40, and C)60

Concluding Remarks

In this paper, the damage behavior of composite materials in micromechanical scale under transverse tensile loading was studied. Different stages of the initiation and propagation of fiber-matrix debonding and matrix crack damage modes are discussed and the effect of different random fiber distribution layouts in the RVE and the application of normal distribution for cohesive interaction properties between fibers and the matrix was investigated. The layout of the cohesive properties distribution similar random fiber distributions can affect the damage behavior of the RVE. In RVEs with 20, 40 and 60 fiber volume fractions, the application of the normal distribution of cohesive properties will reduce the maximum strength value of the RVEs by a mean of 5, 17, and 13 percent, respectively. In RVEs with an identical cohesive property for all interfaces, fiber-matrix debonding occurs for a large number of fibers at once and the stress-strain graph will undergo a sudden drop. However, in RVEs with a normal distribution of cohesive properties, fiber-matrix debonding and strength reduction gradually occur. Apart from random fiber distribution in RVE, other parameters such as the layouts of a normal distribution of cohesive properties affect the damage behavior of RVE.

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