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A numerical method to evaluate the material properties degradation in composite RVEs due to fiber-matrix debonding and induced matrix cracking

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A R T I C L E I N F O

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A B S T R A C T

One of the most important issues about the behaviour of composite materials subjected different loading conditions is the initiation and propagation of various damage modes, which have significant effects on their application. In the present study, the cohesive zone model (CZM), as well as extended finite element method (XFEM) are used in the form of a new numerical method to study the effects of initiation and propagation of damage modes including fiber-matrix debonding and matrix cracking in different RVEs extracted from composite plies. To this end, some appropriate assumptions and boundary conditions are used to evaluate the reduced mechanical properties of RVEs. Firstly, CZM is used to model and study the fiber matrix debonding damage. Then by simulating the matrix cracking formation using XFEM, effects of fiber-matrix debonding as well as matrix cracking on the stiffness of composite are studied simultaneously. The precision of the numerical simulation on modelling of the mentioned damage modes is validated by the available numerical researches. The obtained results can be applied to provide the macroscopic constitutive behaviour according to computational homogenization techniques, which is undertaken by the authors.

1. Introduction

Recently, usage of composite materials has increased significantly due to the superior properties of these types of materials. However, in comparison with other materials, composites have their own deficiencies. One of the most obvious drawbacks, which come from their multiphase and heterogeneous structure, is different damage modes from micro to macro level. On the micro level, the most probable damage modes are fiber-matrix de-bonding and matrix microcracking. These modes consequently will cause other damage forms including transverse cracking and delamination in the macro level. There are many precise studies about the probable damage modes in micro level, which are useful for understanding these phenomena and finding ways to decrease their devastating effects [1,2]. However, simulation in micro scale usually contains modeling of constituents separately [3,4].

In the mesoscale, the equivalent properties of the composite lamina can be determined by using the computational micromechanics methods. Furthermore, computational micromechanics can be used to predict the overall response of the composites [5,6]. Bouhala et al. [7] determined the fracture parameters of composites by using a reversed method based on CZM and XFEM. The degradation of mechanical properties in Carbon fiber reinforced polymers have been studied based on a combined elastoplastic damage model by Zenia et al. [8]. Many studies have also investigated the effects of multiscale modeling on the behavior and properties of different materials including composite materials [9–11].

In the micro scale, the RVE based models often use a single fiber that is surrounded by matrix. The volume fraction of the fiber in the RVE is equal to the overall volume fraction of fibers in the lamina [12–14]. In general, empirical, semi-empirical, analytical and numerical approaches are known as major micromechanical models. In the recent decades and with respect to the fast progress in capabilities of computational instruments, usage of numerical and analytical methods has increased significantly. On the other hand, using empirical and semi-empirical models for micro level has some difficulties and limitations, which put them almost in a lower place of importance in comparison to the first two models. Nevertheless, a few experimental studies about initiation and propagation of de-bonding in single fiber specimens under transverse loading have been done by Zhang et. al. [15] and Martyniuk et al. [16].

Both numerical and analytical models have their own benefits and deficiencies that make them complementaries for each other to obtain a good understanding of the composite materials behavior at the micro level.

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The analytical models are restricted to RVEs with only one fiber in unidirectional loadings which are unable to define the final limit of crack propagation. Nevertheless, these models can be used to analyze the propagation of a crack in the matrix and prepare the prerequisites for studying the degradation of stiffness and other properties of composite materials.

Garcia et al. [17] studied the symmetry of debond onset at the fiber-matrix interface in single fiber specimens under transverse tension and by applying a coupled stress and energy criterion of the finite fracture mechanics. In their study, once an asymmetric configuration with only one single debonding and then a symmetric configuration with two debonds was taken into account. Based on their results, the coupled criterion predicts that an asymmetric post-failure configuration is originated by a lower critical remote tension than the symmetric one.

Carraro and Quaresimin [18] performed a parametric analysis to understand the influence of the main geometric and interface parameters on the critical debonding stress. Mantic [19] also developed a theoretical model based on stress criterion and incremental energy criterion to predict the crack onset at the interface between a stiff cylindrical inclusion and an unbounded matrix subjected to a remote uniaxial transverse tension.

On the other hand, many numerical studies have been carried out with the aim of understanding the micromechanical behavior of a RVE, which is extracted from a composite ply. Tavara et al. [20] have studied the onset and growth of debonds at fiber-matrix interfaces for a bundle of fibers under far field biaxial transverse loads. Danzi et al. [21] have studied the influence of fiber-matrix debonding on carbon-epoxy RVEs numerically. In their model, they used a 3D cell with only one single fiber with periodic boundary conditions and different loading cases to investigate the role of fiber-matrix debonding on the degradation of mechanical properties and in the onset of failure for this class of composite materials. Based on this finite element study, results are highly sensitive to the position of the interfacial decohesion especially for the transverse tension case. In another study, Lim et al. [22] presented a numerical scheme that can inversely evaluate the elastic properties of fibers in unidirectional composites. Some numerical procedures for the analysis of the crack evolution presented by Marfia and Sacco [23] based on CZM. In their study, Mode I fracture problems were investigated and the cohesive constitutive law adopted to model the process zone occurring at the crack tip in 2D models. In another attempts, Finite Element Method (FEM) codes have been used to model the fiber–matrix interface and study the onset and growth of debonding at their interface [24,25]. Boundary Element Method (BEM) also has been used to analyze the growth of partial de-bonding for fiber-matrix interfaces [26,27]. In general, numerical models can be used for studying the damage modes in different scales from micro to macro. This holds particularly in micro and meso-scales for studying different RVEs with one or more than one fibers. These models also can be used for studying multiaxial loadings; however, they only consider the effects of cracks at the interfaces and cannot evaluate the changes in the properties and stiffness of composite materials.

By reviewing the mentioned numerical researches, it can be found that the previously applied method for modeling damage in fibers and matrix interface uses the formulation based on FEM and interlayer elements with zero thickness. In this method, it is necessary to use structural relations in which the relative displacements and traction forces are related to each other by the interface. However, this will affect the results through the mounting mesh in a predefined path. As a result, the traditional methods to simulate a crack are not appropriate when the path of crack propagation is unknown. XFEM has overcome these restrictions, increased accuracy, decreased solving time and as the most important feature presented a tool for modeling cracks that is not dependent on meshing in every single step of crack propagation. Bouhala et al. [28] have used a combined XFEM and CZM to investigate the crack nucleation and growth in long fiber reinforced composites. Another model based on XFEM has been presented by Huynh and Belytschko [29] to investigate the fracture in composite materials. In their model, the treating fracture in a composite material with meshes that are independent of matrix/fiber interfaces and crack morphology described. They validated the results of their model with several 2D and 3D models and have shown that interface enrichment is sufficient to model the correct mechanics of an interface crack.

Fries [30] also presented a modification of the XFEM approximation in which the enrichment functions are modified such that they are zero in the standard elements, unchanged in the elements with all their nodes being enriched, and varying continuously in the blending elements, while all the nodes in the blending elements are enriched.

In the present study, a numerical method is presented that uses CZM and XFEM to study the effects of fiber-matrix debonding and matrix cracking, as two major preliminary damage modes, on the mechanical properties and behavior of composite materials.

By considering a multilayer composite in macro scale, which is under the effect of an external loading F, it would be possible to extract a unit cell from the layer 90° (Fig. 1).

To study the effects of fiber-matrix debonding and matrix cracking in the layer 90° and with considering the simplifying assumption of uniform

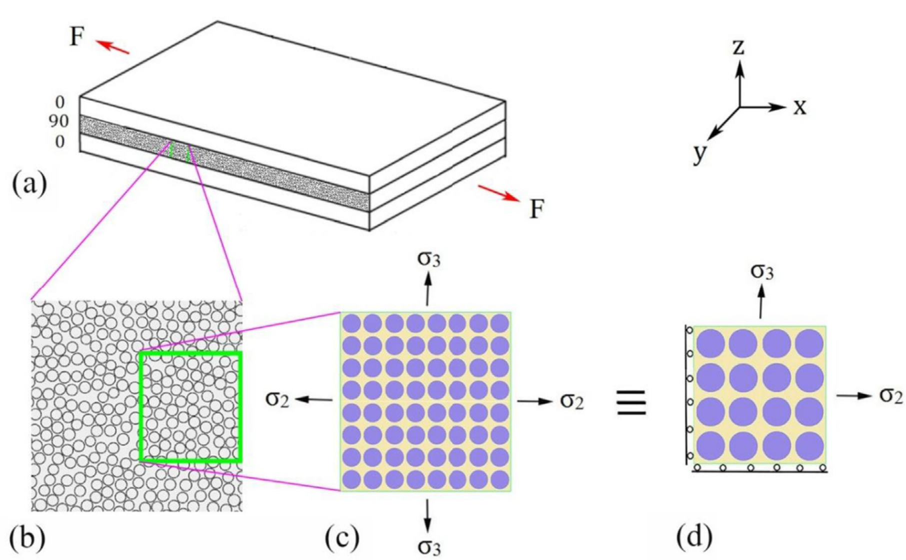

Fig. 1. A schematic representation of the study in which a RVE with 64 fibers has extracted from a multilayer composite.