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A computational micromechanics approach to evaluate elastic properties of composites with fiber-matrix interface damage

Néstor Darío Barulich [a,b], Luis Augusto Godoy [a,c,*], Patricia Mónica Dardati [b]

[a] Instituto de Estudios Avanzados en Ingeniería y Tecnología, IDIT UNC-CONICET, Ciudad Universitaria, Av. Vélez Sarsfield 1611, X5016GCA, Córdoba, Argentina
[b] Facultad Regional Córdoba, Universidad Tecnológica Nacional, Maestro M. López esq. Cruz Roja Argentina, X5016ZAA, Córdoba, Argentina
[c] Universidad Nacional de Córdoba, FCEFyN, Ciudad Universitaria, Avda. Vélez Sarsfield 1611, X5016GCA, Córdoba, Argentina

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ABSTRACT

Computational micro-mechanics is employed in this work to evaluate effects of fiber-matrix interface damage on the elastic properties of polymer matrix composites with continuous glass fibers. It is assumed that damage affects local zones along the fiber and a sector on the perimeter around the fiber. Elastic modulii are evaluated using Finite Element analysis, for a range of values in damage parameters considered. The occurrence of bi-modular behavior, with differences in Young's modulus under tension and compression, has been represented by contact without friction. Based on extensive parametric results, a Least Squares Method is employed to derive analytical expressions for each material property as a function of damage parameters. In most cases the elastic modulus has a nonlinear relation with the damage parameter in the length of the fiber, with the exception of the transverse elastic modulus under tension. The analytical expressions are used to couple micro and macro scales in an off-line scheme, without the need to perform in-time micro-scale computations.

1. Introduction

The analysis of fiber-reinforced composite materials has been traditionally performed using what is known as Classical Lamination Theory (CLT) (see for example Ref. [1]) or more refined higher order theories (such as in Ref. [2]), in which the heterogeneous fiber-matrix material is reduced to an equivalent homogeneous material for a lamina at the macro level. Thanks to increasing hardware and software capabilities, it is now possible to model this problem at the micro level to represent localized effects, such as defects and damage. However, to recover the complete picture it is necessary to couple the micro and macro levels, and this may be a costly procedure when both levels are modeled by means of Finite Elements in a non-linear analysis. This paper discusses an off-line procedure to couple the micro and macro levels, in which results of the micro level are previously computed.

The occurrence of damage at the fiber-matrix interface in glass fiber reinforced polymers (GFRP) has been identified for structures built in moisture and temperature environments. Evidence of such damage has been provided by laboratory testing [3] in which coupons were immersed in water at temperatures of 60–80 °C for several months, then were tested to evaluate their mechanical properties and damage was observed by scanning electron microscopy (SEM). The work reported by Kajorncheappunngam et al. [3] considered coupons at ambient and 60 °C temperatures in various water solutions for five months. These authors concluded that the elastic modulus in GFRP was not affected by hygro-thermal process, but significant reductions in strength were identified due to matrix cracking and fiber-matrix interface debonding. Interface damage was observed with the aid of SEM. In a study of resin and composite degradation in off-shore wind turbines, Faguaga et al. [4] found significant levels of matrix and interface degradation at 80 °C. For randomly oriented long fibers, some 20% reduction in modulus of elasticity was obtained, together with observations of fracture surfaces at the interface. For long, glass fibers in vinylester matrix, moisture absorption under short time exposure was studied by De la Osa et al. [5]. The influence of fiber orientation (either unidirectional, bidirectional, or randomly oriented) was investigated by means of bending tests on the material with hygro-thermal degradation.

Kotani et al. [6] tested a single fiber in matrix to measure consequences of hygro-thermal degradation in de-ionized water at 80 °C during 1000 h. The authors proposed a model and showed that there was a loss of strength arising from the degradation at

* Corresponding author at: Instituto de Estudios Avanzados en Ingeniería y Tecnología, IDIT UNC-CONICET, Córdoba, Argentina.
E-mail address: luis.godoy@unc.edu.ar (L.A. Godoy).

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the fiber-matrix interface. The elastic modulus did not change, most likely because testing was performed in the direction of the fiber.

More advanced experimental techniques have also been employed to identify damage at the micro level: X-ray Computed Tomography (XCT) was used in Refs. [7,8] to carry out a 3D scanning of the microstructure in short-fiber and 3D textiles composites, respectively. The XCT technique captures details such as fiber length and orientation.

Observations and testing such as those described above are not sufficient to describe the actual mechanisms leading to damage. The mechanisms may be dominated by physical or chemical sources, but no attempt has been made to model that part of the problem. Instead, damage models start from the assumption that damage has already occurred at the micro-structural level, and interest focuses on the changes occurred with respect to the undamaged configuration. Damage models of this kind were reported by Kamiński [9] as semi-circular voids at the interface, in which the radius and number of voids were variables of the model. A similar approach was carried out by Godoy et al. [10] to identify stress redistributions caused by interface damage at Unit Cell (UC) level.

Teng [11] evaluated axial and longitudinal shear modulus (G_{12} and G_{13}) of a composite having symmetric arrangements of cracks at the top and bottom of a fiber. The damage parameter in this case is the angle of debonding between matrix and fiber, with angle values ranging from 0 to 2π. The results show that there is a loss of the initial transverse isotropy of the material. The shear modulus in the axial direction in a fiber reinforced composite having interface debonding has been investigated in Ref. [12] using a statistical distribution of damage size and taking into account that fibers may or may not have interface damage. It was found that the largest reductions in elastic shear modulus occur for a fiber volume fraction of 80%.

Kim et al. [13] investigated a configuration with interface cracks having random size and orientation to evaluate the transverse modulus of elasticity and transverse shear modulus. For a 30% fiber volume fraction, a reduction in modulii higher than 50% was reported. Studies performed by Kushch et al. [14] at a UC level including interface damage allowed evaluation of the elastic constitutive tensor at macroscopic level. The results were based on a previous work by the authors [15] for a periodic composite having open cracks, but contact between surfaces was not taken into account.

For a unidirectional composite with metal matrix the influence of complete debonding on the transverse elastic properties was studied in Ref. [16]. By means of simplified analytical expressions, the authors evaluated tensile and compressive modulus; such materials having different properties in tension and compression are referred to as bimodular or bimodulus materials in the literature. The transverse modulus, transverse shear modulus, and transverse Poisson's ratio were modeled by Shan and Chou [17] for composites by accounting for separation and contact at the interface.

Teng [18] represented complete detachment at the interface in a fiber-reinforced composite at a Representative Volume Element (RVE) including 100 fibers in a square configuration. The number of fibers having damage was increased until all fibers exhibited interface damage, and tensile and compressive Young's modulus and Poisson's ratio were obtained in terms of fiber volume fraction.

Another way to model interface damage is by means of a layer surrounding the fiber, with properties based on assumed load-transfer mechanisms between matrix and fiber. This model is capable of representing strong or weak interfaces [19–21]; as a limit case it can account for complete interface separation but cannot represent a bimodular behavior.

Current needs in modeling a pre-existing damage (without explicit reference to the source of damage) require using micro-level parameters, such as phase fractions, size and position of damage, to obtain macro-level properties. The models reviewed above have features that are not observed in tests, such as continuous damage in the direction of the fiber (in a 2D representation) versus damage being limited to a sector along the fiber (in a 3D representation).

This paper focuses on the computational modeling of micromechanics in GFRP materials having localized damage at the fiber-matrix interface. Through the use of a 3D model, the aim is not only to understand the influence of damage on macro properties, but also to derive the elastic macroscopic properties of an orthotropic unidirectional lamina by means of analytical functions written in terms of damage parameters at the micro level. Interest in such analytical formulation arises because these expressions can be easily incorporated at the macro level by means of CLT or in a Finite Element discretization of the structure by means of an off-line scheme, i.e. without the need to perform calculations at the micro-level during the solution of the structural problem at the macro-level.

2. Methodology

The domain at the micro-level is modeled in this work by means of computational micromechanics, CMM [22,23], in which two scales are considered: microstructural details are taken into account at a UC (a part of the heterogeneous material that includes the necessary information to represent the macroscopic behavior of interest); at the macro-level the material properties are assumed to be homogeneous with a mechanical behavior which is equivalent to the material modeled at the microscale. The analysis is performed by imposing strains to the UC in order to obtain the macroscopic variables that represent the material at the macro level by means of a post-process. Notice that XFEM, the Extended Finite Element Method, is also capable of solving this RVE problem including internal cracks [24].

Periodic Boundary Conditions (PBC) were used in this work to represent a periodic composite under finite strains. PBC have been described in the literature on computational micro-mechanics, such as in Refs. [25–27], among others.

Evaluation of elastic properties at macro-level requires that non-linearity of the contact problem should be taken into account, i.e. stresses and strains at the macro level are evaluated by taking into account crack opening and eventual load transfer caused by contact between crack surfaces. With stress and strain at the macro level, elastic properties can be obtained from them. For example, the elastic modulus E_2 in the direction 2 results in

$$E_2 = \frac{\sigma_{22}}{\varepsilon_{22}} \quad (1)$$

and the shear modulus G_{13} is

$$G_{13} = \frac{\sigma_{13}}{2\varepsilon_{13}} \quad (2)$$

Poisson's coefficients are next computed as

$$v_{ij} = -\frac{\varepsilon_{jj}}{\varepsilon_{ii}} \quad (3)$$

where ε_{ii} is the imposed strain, and ε_{jj} is the resulting strain (Eq. (4.32) in Ref. [1]).

At the UC, contact without friction was assumed to model interface cracking, and it was implemented using a penalty approach. The surface of an interface crack is divided into a master surface and a slave surface, which are associated to fiber and matrix, respectively. The model employed to represent the behavior in