Composite Structures 155 (2016) 77–88

Contents lists available at ScienceDirect

Composite Structures

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

Micromechanical modeling of damage and load transfer in particulate composites with partially debonded interface

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ARTICLE INFO

Article history:
Received 26 April 2016
Accepted 29 June 2016
Available online 8 August 2016

Keywords:
Short-fiber composites
Debonding
Interface
Stress transfer
Cohesive zone

ABSTRACT

A new micromechanical damage model accounting for progressive interface debonding is developed for composite materials. It consists of an original evolution law of the damage at the interface and an appropriate load transfer law at the matrix-fiber interface integrated into a generalized incremental Mori–Tanaka homogenization scheme. The interface damage evolution is driven by the interfacial stress state while the load transfer is obtained from a new model inspired by the shear lag model. Specifically, such damage evolution is supported by experimental microscopic observations for short glass fiber reinforced polyamide-66.

The proposed model is validated based on numerical reference solutions provided from finite element analyses of a representative unit cell of a composite, where imperfect interfaces are represented using cohesive elements. A further comparison with experimental data proves that the proposed model is an alternative to micromechanical models involving weak interfaces in the case of spherical reinforcements. It is shown that the proposed model is able to accurately reproduce the non-linear effective response of composite materials for a broad range of reinforcement shapes, including spherical particles and matrix mechanical properties.

1. Introduction

Composite materials have received increasing attention in the past forty years thanks to their excellent weight to mechanical properties ratio. Specifically, short fiber reinforced composites (SFRC) have been considered as a good alternative to metals, especially in the automotive industry, to reduce gas emission through the reduction of automotive vehicle mass. Their high thermomechanical performance to density ratio allows for the design of lightweight structural parts. However, the microstructure of such materials, combined with the matrix sensitivity to environmental conditions, has a strong impact on their overall behavior and specifically on the apparition of damage. Damage in SFRC occurs at the microscopic level according to different physical degradation mechanisms, namely: interfacial decohesion, fiber breakage and matrix microcracks [1–5]. All these studies have shown that fiber/matrix interfacial debonding is the predominant damage mechanism and plays a crucial role in the progressive degradation of the effective behavior.

The development of predictive models for fatigue of composites requires proper descriptions of these phenomena, which depends on local mechanical fields. Micromechanics therefore appears to be an adapted approach to combine the required the knowledge of the local stress state in each phase constituting the particulate composite and the description of the effective behavior. This type of modeling approach remain a challenge, especially considering the non-linear behavior of the matrix combined with damage. Multiscale models have always been a key approach to approximate the macroscopic behaviour of microstructure-dependent particulate composite materials such as SFRC [6,7]. The evolution of the defects and void density are therefore computed as a function of the local stress state [8,9]. However, the integration of damage at the interface does not properly include the evolution of the load transfer between the reinforcements and the matrix, and has to be enhanced accordingly.

Damage at the interface in composite materials has received a lot of interest in the past two decades. One of the developed methods consists of using a dedicated fiber coating also called an interface [10]. The main drawback is that such a three phase model implies that the knowledge of coating properties, which is rarely available. Hashin introduced the imperfect interface approach which accounts for the displacement and stress jump at the fiber/matrix interface [11,12]. The aim was to replace the explicit three

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http://dx.doi.org/10.1016/j.compstruct.2016.06.075

phase problem consisting of two constituents and an interface by a two phase homogenization with one imperfect interface. Many authors have investigated the imperfectly bonded interface [13,14]. Zhong and Meguid developed a new solution for the eigenstrain problem, as defined by Eshelby [15], of a spherical inclusion with an imperfect interface [16]. In addition, the shear lag model (SLM) has been developed to model the behavior of fiber reinforced composites. This approach predicts the elastic behavior of a two phase composite, whose fibers are stiffer than the matrix. It specifically gives the stress state inside the fiber. This method was originally developed by [17]. One of the main assumption of this method is that no slip occurs on the fiber/matrix interface. Recently, Jain et al. [18] have developed an equivalent debonded inclusion model for Eshelby based approaches coupled with the Cox's predictions applied for six loading cases, namley three uniaxial tensile and three shear loads.

The presence of stiff fibers induces a stress and strain distribution within the composite while the fibers bear most of the macroscopic stress, the strain in the matrix is more significant. As a consequence, this leads to a shear stress at the fiber/matrix interface, which governs the load and stress transfer between the matrix and the fibers. The definition of this stress transfer depends on the properties of the two-phase composite. Key equations will be briefly recalled in this paper. The whole method is detailed in terms of mechanical and mathematical analyses by [19,20], which are considered among the reference works in this topic. Jiang and Gao have also studied the stress transfer from matrix to fiber in short carbon fiber aluminium-matrix composites at several different thermal conditions [21]. In particular, they have compared several theories including, the shear lag model, and have considered a wide range of fiber aspect ratios.

The approach developed in this paper combines the result of an interfacial damage law with a specific load transfer model inspired by the shear lag model. Indeed, the shear lag model is utilized to determine the stress distribution of a partially debonded fiber, considering a non-zero shear stress field only at the non-damaged interface. The determination of the evolution of debonded zones depends on an evolution equation for interfacial damage, based on a probabilistic criterion. Translated into a debonded area, a shear lag model approach allows for the determination of the stress state in the fiber to be compared with the non-damaged stress state. Thus, a load transfer ratio is obtained, which is integrated into an adapted micromechanical homogenization scheme using an appropriate computation of the concentration tensor in order to determine the stress fields of the different phases. The developed approach is therefore designed to suit an incremental multiscale model and can accurately capture the nonlinear behavior accounting for progressive interface degradation.

The organization of this work is as follows. Section 2 further describes the experimental observations of interfacial damage that led to the proposition of the present load transfer model. Section 3 presents the formulation of the damage evolution law based on a statistical local criterion and the load transfer model. The end of Section 3 is devoted to the integration of such formulation into a homogenization scheme, namely the modified Mori–Tanaka model applied for particulate composites [22,8]. A numerical validation of this new approach is performed in Section 4, based on a finite element solution for interface decohesion using an advanced cohesive element approach proposed by [23]. The comparison considers the case of a short fiber reinforced polyamide 66 composite. In Section 5, the limiting case of spherical inclusions is investigated and the developed model is then applied for three types of composite with spherical reinforcements and compared with several results from literature and reference solutions: experimental results of [24,25] and a model developed by [26] for slightly weakened interfaces. The influence of the fiber aspect ratio is briefly discussed. The last section of this paper provides a conclusion summarizing the main results.

2. Experimental observation of interface damage evolution

Interfacial damage mechanisms have been observed by several authors in many different systems. For the particular case of short glass fiber reinforced polyamide-66, in situ damage mechanisms' characterization under quasistatic monotonic loading were investigated by [1–3,5]. They reported that in most cases, interfacial damage starts at the fiber ends and further propagates along the fiber–matrix interface.

Following the analysis of Horst and Spoormaker [3], Arif et al. [4] have proposed a damage progression scenario where the dependance on the relative humidity (RH) is taken into account:

- The damage starts at the fiber ends, or in areas where local stress concentration is the highest, and at locations where fibers are close to each other (all studied RH contents), as shown in Fig. 1. Specifically, for RH = 0%, fiber breakage occurs in addition to the previous forms of mechanisms.
- Damage interface propagates along the fiber in the form of fiber/matrix interfacial debonding as observed by Arif et al. [4] for all studied RH contents. The interfacial decohesion is accompanied by fiber breakage occurrence for RH = 0% whereas it appears with a locally strained zone around the fiber for RH = 50% and 100%.
- Matrix microcracks develop and propagate in a brittle way for RH = 0% and in a ductile way for RH = 50% and 100%, accompanied with high matrix deformation bands for RH = 100%.
- The propagation of the matrix microcracks brings about damage accumulation leading to total failure.

Such interfacial decohesion appears in PA66-GF30 along the fiber interface, shown in Fig. 1, from [4]. Fig. 1a shows that the damage along the interface leads to a rather important interfacial decohesion. The stress distribution in the phases is then strongly impacted according to the creation of free surfaces in the material. Fig. 1b illustrates that fiber ends are a principal spot for the initiation of damage.

Such observations lead to the conclusion that micromechanical predictive models with damage should include the effect of interfacial debonding. Since damage evolution is driven by the local damage state for all mechanisms, it is crucial to determine the stress distribution in the different phases where interfacial debonding propagates. In particular, the stress transfer at the damaged interface requires thorough attention in order to determine the stress state of the fibers, which impacts the overall stress distribution.

The recent development of microcomputer tomography (microCT) has pushed forward the quantitative evolution of damage propagation in composite materials [27]. The specific case of damage evolution in PA66-GF30 fatigued samples has been studied by [1]. The main features of defects, such as volume, orientation and shape, have been obtained for several levels of overall damage, represented in terms of number of cycles relative to the number of cycles to failure. One of the main conclusion is that the orientation of defects follows the orientation of fibers, which indicate that interfacial debonding is the leading damage mechanism. Indeed, the volume of defects oriented in the fiber direction is increasing throughout the lifetime of the composite. Tt is difficult to directly relate those quantifications to an evolution law of the interface decohesion surface, however, this clearly shows that such an evolution equation drives the fatigue behavior of the composite.