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Crack propagation analysis in composite materials by using moving mesh and multiscale techniques

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ABSTRACT

A novel concurrent multiscale method for the crack propagation analysis in heterogeneous materials is proposed, based on a non-overlapping domain decomposition technique coupled with an adaptive zoom-in strategy. Both fiber/matrix interfacial debonding and matrix cracking are accounted for; the latter one is modeled by using an innovative shape optimization method coupling a moving mesh technique and a gradient-free optimization solver. Numerical applications are carried out with reference to the failure analysis of a single notched fiber-reinforced composite beam subjected to both mode-I and mixed-mode crack propagation conditions. The validity of the proposed method is assessed through original comparison models.

1. Introduction

Composite materials may be affected by different kinds of damage mechanisms, which are usually triggered by pre-existing manufacturing-induced defects. Fiber-reinforced composites, with reference to laminate configurations, experience both intralaminar mechanisms (such as matrix cracking, fiber splitting, and fiber/matrix interfacial debonding) and interlaminar mechanisms (such as delamination). Several studies have shown that delamination phenomena frequently start at free edges and/or at discontinuities arising from matrix cracking (see, for instance, [1]), by also involving bridging and dynamic effects (see [2,3], respectively), i.e. a strong interaction between different mechanisms may rise at multiple length scales. Indeed, such damage mechanisms, which initially take place at the microscopic level, strongly influence the overall structural behavior of composite materials, leading to a highly nonlinear structural response associated with a progressive loss in strength and stiffness (see, e.g., [4]), by also involving microscopic instabilities (see [5]), up to catastrophic failure events.

Therefore, a proper analysis of damage mechanisms in composites would require a complete description of their microstructural evolution, resulting in fully microscopic problems, whose numerical solution needs a huge computational effort; as a consequence, simplified models are preferred when performing failure analyses of composite materials.

Damage mechanics has been recognized as a powerful tool for studying brittle or quasi-brittle fracture in composite materials (see, e.g., the reviews by [6,7]). Damage models are established by performing the following steps: (i) a properly defined (scalar or tensorial) damage variable is introduced to represent the damage state at any material point of the composite material; (ii) a damage evolution equation is formulated in a thermodynamically consistent manner; (iii) a constitutive equation, describing the mechanical behavior of the damaged material, is obtained; and (iv) the macroscopic boundary value problem is solved by using the above-mentioned equations. However, differently from ductile damage, microcracking-induced damage has some distinct features, such as high anisotropy, dependence on the loading history and loading paths, non-associated damage rule due to the frictional sliding of microcracks under compression (see, for instance, [8]). Due to the difficulty to phenomenologically incorporate such effects into a unified macroscopic constitutive equation, microscopically-informed modeling of damage has attracted a special attention for quasi-brittle materials.

Within the theoretical framework of micromechanics, both analytical and numerical homogenization techniques have been extensively adopted to predict the overall mechanical response of composite materials on the basis of the properties of the various individual microconstituents, by establishing relationships between the microscopic stress and strain fields and the corresponding variables at the macroscopic level (see, for instance, [9–11]).

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However, classical homogenization methods, also referred to as first-order schemes, are effective when the microscopic stress and strain fields are rapidly varying with respect to their macroscopic counterparts, namely when the microscale and the macroscale are well separated. Such hypothesis ceases to hold when handling strain localization phenomena in locally periodic structures, which experience the loss of the initial macroscopic uniformity. Softening cannot be properly accounted for, because of the mesh dependence arising from the ill-posedness of the macroscopic boundary value problem, as shown in [12].

In order to overcome such drawbacks, more sophisticated homogenization approaches have been proposed in the literature, such as the higher-order homogenization and the continuous-discontinuous homogenization schemes. The first type of methods has been adopted in [13] for transferring higher-order kinematics from the microscale to the macroscale, by incorporating a length scale, corresponding to the size of the so-called representative volume element (RVE), into the macroscopic model. The latter type is based on the incorporation of a proper localization band at the macroscopic scale (see, for instance, the approach adopted in [14]). Both classes of approaches may be used within the more general framework of multiscale methods. According to [15], such methods can be grouped in three classes depending on the nature of the coupling between the microscale and the macroscale: hierarchical, semiconcurrent and concurrent methods.

In hierarchical methods, a "one-way" bottom-up coupling is established between the microscopic and macroscopic problems, i.e. during the "micro-to-macro" transition step the information is passed from lower to higher scales. In semiconcurrent methods, also referred to as computational homogenization approaches, a microscopic boundary value problem is associated with each integration point of the discretized microstructure, in order to obtain the local governing equation at the macroscale. This class of methods allows one to compute the fine-scale response required by the coarse-scale model for a specific input and passes the information to the coarser scale during the analysis; thus, a phenomenological constitutive model at the macroscale is not needed. On the other hand, concurrent multiscale methods abandon the concept of scale transition in favor of the concept of scale embedding, according to which models at different resolutions are defined in adjacent regions of the same domain. Such methods fall within the class of domain decomposition methods (DDMs), in which a strong two-way coupling between different scales is established.

In this work an innovative multiscale method capable to perform crack propagation analysis in fiber-reinforced composite materials is proposed, taking advantage of a non-overlapping domain decomposition method, combined with an adaptive technique able to continuously update the fine-resolution subdomain around a macroscopic crack evolving along non prescribed paths. Although the proposed method can be applied to general failure modes, transverse cracking mechanisms are considered in the present work, since such a mechanism, which includes both matrix cracking and fiber/matrix interfacial debonding is one of most observed in continuous fiber-reinforced laminates; this allows to perform numerical simulations in a 2D setting. The competition between fiber/matrix interface debonding and kinking phenomena from and towards the matrix is accounted for, as well the continuous matrix cracking, by incorporating in the model the ad hoc fracture criteria. Matrix cracking is simulated by using a novel shape optimization method based on the coupling between a moving mesh technique and a gradient-free optimization solver; such an ingredient makes the present approach different from existing concurrent multiscale methods, which usually adopt damage models or cohesive zone models to simulate damage propagation (see, for instance, [16]).

Numerical computations are performed for a single notched composite beam subjected to different loading conditions involving both mode-I and mixed-mode crack propagation. Comparisons with solutions obtained by direct numerical simulations and simplified homogenized solutions are presented, in order to assess the validity of the proposed multiscale approach.

The paper is based on preliminary results obtained by the authors in [17] and introduces two main aspects of novelty. The first corresponds to the introduction of a refined approach for managing crack kinking within the material interface; this aspect has not been discussed in our previous work, which was based on a simplified approach, as will be discussed in Section 2.2.2. The second is the presentation of innovative numerical applications and original approximate comparison models which allows a more general validation of the proposed multiscale method. These innovative numerical applications involve fiber-reinforced composite beams subjected to both mode I and mixed-mode loading conditions. In the context of approximate comparison models, an original purely homogenized model of the analyzed specimens have been developed capable to obtain a reasonable prediction of the peak load, by means of appropriate assumptions about the macroscopic fracture toughness.

2. Theoretical background

This section aims to present the main concepts used to develop the proposed numerical model, which will be described in Section 3. In the first part, a general framework of concurrent multiscale modeling is presented, by extending the multiscale version of the non-overlapping domain decomposition schemes (see, for instance, [18]) to the case of a damaging composite material; in the second part, attention is focused towards fracture modeling in composite materials, with special reference to the competition between different damage mechanisms involving both matrix and fiber/matrix interfaces.

2.1. A concurrent multiscale framework for damaging composite materials

Let us consider the elasticity problem in a quasistatic setting of a cracked heterogeneous structure, occupying the open set $\Omega \subset R^3$, as shown in Fig. 1a; its boundary $\partial\Omega$ is supposed to be Lipschitz continuous, such that $\partial_t\Omega \cup \partial_u\Omega = \partial\Omega$ and $\partial_t\Omega \cap \partial_u\Omega = \emptyset$, where $\partial_t\Omega$ and $\partial_u\Omega$ represent the portion subjected to Neumann and Dirichlet boundary conditions, respectively; moreover, the measure of $\partial_u\Omega$ is supposed to be greater than zero to avoid rigid-body motions. Such a heterogeneous body is made by a spatial array of periodically distributed unit cells, whose microstructure is the same as for a reference cell, denoted as repeating unit cell (or RUC in short). The given crack set K is represented by a set of physical surfaces, denoted by $\Gamma_c^{(i)}$ $(i = 1, \ldots, n)$, where displacement jumps are admitted. For microconstituents made of linearly hyperelastic material, under the assumptions of small deformation and absence of contact phenomena between the crack faces, such a problem can be mathematically stated via a classical elliptic PDE system with associated boundary conditions. The related weak form reads as:

$$\int_\Omega [\mathbf{C}(\mathbf{X})\nabla\mathbf{u}] \cdot \nabla\mathbf{v} \, d\Omega = \int_\Omega \bar{\mathbf{f}} \cdot \mathbf{v} \, d\Omega + \int_{\partial_t\Omega} \bar{\mathbf{t}} \cdot \mathbf{v} \, dS \quad \forall \mathbf{v} \in V(\Omega), \tag{1}$$

with $\mathbf{u} \in H^1(\Omega)$, $\mathbf{u} = \bar{\mathbf{u}}$ on $\partial_u\Omega$, $\mathbf{u}$ being is the (actual) unknown displacement field, $\bar{u}$ the prescribed displacement on $\partial_u\Omega$, and $H^1(\Omega)$ denoting the usual Hilbert space of order 1 on Ω; moreover