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Adaptive multiscale modeling of fiber-reinforced composite materials subjected to transverse microcracking

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ABSTRACT

In this work an innovative multiscale model able to perform complete failure analyses of fiber-reinforced composite materials subjected to transverse cracking is presented, taking advantage of an adaptive multilevel domain decomposition method in conjunction with a fracture criterion able to track the crack path. Competition between fiber/matrix interface debonding and kinking phenomena from and towards the matrix is accounted for, whereas continuous matrix cracking is modeled by using a novel shape optimization strategy. Numerical calculations are performed with reference to the complete failure analysis of a single-notched fiber-reinforced composite beam subjected to a three-point bending test. Comparisons with reference solutions obtained by means of a fully microscopic analysis are presented in order to validate the proposed multiscale approach.

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1. Introduction

In many practical applications, composite materials experience different kinds of failure during their manufacturing processes and/or in-services, especially for laminate configurations, where damage phenomena are rather complex, involving both intralaminar mechanisms, such as matrix cracking, fiber splitting and fiber/matrix interface debonding, and interlaminar mechanisms, such as delamination between plies (see [1–3] for instance). Continuously fiber-reinforced composites, whose mechanical properties in terms of overall strength and stiffness are lower in the transverse direction than in the fiber one, are most prone to failure under transverse tensile loads and, as a consequence, one of their most common damage mechanisms is transverse cracking, including both matrix cracking and interfacial debonding, as confirmed by experiments [4].

These damage mechanisms, which take place at the microscopic scale, strongly influence the macroscopic structural behavior of composites, leading to a highly nonlinear post-peak response associated with a gradual loss of stiffness prior to failure [5–7]. As a consequence, a proper failure analysis of a composite material subjected to such microstructural evolution should require a numerical model able to completely describe all its microscopic details; however fully microscopic models are not pursued in practice due to the large computational cost, and thus simplified models are commonly used to predict failure in composite materials.

In the context of continuum damage models, for instance, macroscopic nonlinear constitutive laws developed by using the thermodynamics of irreversible processes have been provided in terms of damage variables used in both scalar [8] and tensorial representations [9,10], the latter being more suitable when handling crack propagation in heterogeneous media. However the application of continuum damage models to fiber-reinforced composite materials leads to additional difficulties due to their anisotropic behavior, since the presence of fiber/matrix interfaces weaker than the surrounding materials induces some preferred patterns in the crack path involving interfacial debonding.

Two main approaches have been extensively used to define damage models for composite materials, i.e. mesoscopic models and homogenization models. Mesoscopic models treat the composite lamina or sub-laminate as a homogeneous material (see, for instance, [11,12]) and are suitable for large scale computation, especially when diffuse damage localizes in narrow bands leading to the nucleation of macrocracks. On the other hand, homogenization models aim to predict the overall mechanical response of composites on the basis of the properties of the different individual constituents at the microscopic level, by establishing relationships between the microstress and microstrain fields and the corresponding macrovariables. More general approaches include damage evolution effects into the macroscopic constitutive law by means of brittle interface models [13], or incorporate fracture mechanics based damage evolution laws.

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Homogenization models have increasingly gained in importance due to their better flexibility and accuracy with respect to mesoscopic models. Strictly speaking, homogenization denotes the mathematical techniques for the asymptotic analysis of physical media with periodic microstructure, developed by many authors (see, for instance, [14,15]). The classical homogenization approach, also referred to as first-order approach, however, is very effective when the macroscopic stress and stress fields are characterized by a small variation with respect to their microscopic counterparts, namely when the micro- and macro-scales are well separated. On the contrary, strong approximations can be introduced in the solution when this hypothesis is not adequately satisfied as in the case of locally periodic composites, or in presence of microscopic damage leading to the loss of periodicity and macroscopic uniformity assumptions. Moreover, more accurate analyses can be carried out by considering non-local interactions between inhomogeneities in presence of boundary and scale effects [16].

Therefore the classical homogenization schemes are not suited for studying strain localization phenomena which commonly affect the macroscopic behavior of composites; moreover, softening behaviors cannot be properly analyzed because of the mesh dependence at the macroscopic scale due to the ill-posedness of the macroscopic boundary value problem, as shown in [17]. On the other hand, when large deformations must be accounted, additional complexities arise since the size of the representative volume element (RVE) is not a priori known (see [18–20] for additional details).

In order to partially overcome such limitations, other homogenization approaches have been proposed in the literature, such as the higher-order homogenization and the continuous–discontinuous homogenization schemes. The first one has been adopted in [21] for transferring higher-order kinematics from the microscale to the macroscale, by incorporating a length scale, defined by the size of the representative volume element (RVE), into the model. The latter one essentially relies on the proper incorporation of a localization band at the macroscopic scale and it has been adopted by many authors (see, for instance, the approaches proposed in [22,23]). Both continuous and continuous–discontinuous homogenization models are usually adopted within the more general framework of multiscale methods. Following [24], such methods can be classified in three main groups depending on the type of coupling between the microscale and macroscale problems: hierarchical (or sequential), semiconcurrent and concurrent methods.

In hierarchical methods, a "one-way" bottom-up coupling is established between the microscopic and macroscopic problems since during the micro-to-macro transition step the information is passed from lower to higher scales. As a consequence, such methods are efficient in determining the macroscopic behavior of composites in terms of stiffness and strength, but may have a limited predictive capability for problems involving the above-mentioned damage phenomena (see, for instance, [25]). When dealing with microscopic nonlinear phenomena due to evolving defects whose spatial configuration is not known a priori, however, a "two-way" coupling between micro- and macrovariables is required. Semiconcurrent methods, also referred to as computational homogenization approaches, especially when implemented in a finite element setting [26–28], have been proved to be very efficient in such cases, also for only locally periodic composites [29]. The key idea of such approaches is to associate a microscopic boundary value problem with each integration point (or macroelement, as in [30]) of the macroscopic boundary value problem, after discretizing the underlying microstructure. By using the macrostrain as boundary data for each microscopic problem (localization step), the set of all microscale problems is then solved and the results are passed back to the macroscopic problem in terms of overall stress field and tangent operator (globalization step). Localization and globalization steps are carried out within an incremental–iterative nested solution scheme, thus the two-scale coupling remains of a weak type. Concurrent multiscale methods abandon the concept of scale transition in favor of the concept of scale embedding, according to which models at different scales coexist in adjacent regions of the domain. Such methods can be regarded as falling within the class of domain decomposition methods (DDMs); in fact, the numerical model describing the composite structure is decomposed into a fine- and coarse-scale sub-models, which are simultaneously solved, thus establishing a strong two-way coupling between different resolutions. Most of concurrent multiscale methods can be classified in overlapping and non-overlapping methods (see, for instance, [31,32], respectively). Overlapping methods seem to be more suitable for coupling continuum and discrete models, as in MAAD approach [33], whereas non-overlapping methods are preferred when dealing with purely continuum models.

Alternative multiscale approaches, which fall in the range between the hierarchical methods and the more advanced concurrent and computational homogenization techniques, have been proposed in the literature (see [34,35] for instance).

In this work an innovative concurrent multiscale model able to perform complete failure analyses of fiber-reinforced composite materials is presented, by using a non-overlapping domain decomposition method in a finite element tearing and interconnecting (FETI) framework in conjunction with an adaptive strategy able to continuously update the fine-scale subdomain around a propagating macroscopic crack.

Only transverse cracking is considered in the present paper, since such a mechanism, which includes both matrix cracking and fiber/matrix interfacial debonding, is one of the main damage modes observed in continuous fiber-reinforced laminates; this allows to perform numerical calculations in a 2D setting, which is frequently adopted in the literature due its relatively low computational cost.

Thus, in the proposed model, the competition between fiber/matrix interface debonding and kinking phenomena from and towards the matrix is accounted for, as well as the continuous matrix cracking, described by using a novel shape optimization method. Such a strategy, based on the coupling between a moving mesh framework and a gradient-free optimization solver, represents an innovative ingredient which makes the present multiscale approach different from the existing ones of concurrent type, which usually adopt damage models and/or cohesive zone models to simulate damage initiation and propagation, to the best authors' knowledge. The main advantages of the proposed model are the possibility to simulate the competition between different damage mechanisms during crack propagation in a standard finite element setting, and to capture also unstable equilibrium branches in a quasistatic setting by virtue of the adopted crack length control scheme.

The paper is organized as follows: in Section 2 a general framework of concurrent multiscale modeling is presented; in Section 3 the fracture models here adopted to account for the competition between damage mechanisms in fiber/matrix systems are illustrated; in Section 4 the proposed numerical strategy is described, including some implementation details; then Section 5 is devoted to some numerical results obtained via the proposed method and their validation by means of comparisons with direct numerical simulations (DNSs); finally Section 6 provides some concluding remarks.

2. Concurrent multiscale modeling of damaging composite materials

In this section, a general framework of concurrent multiscale modeling is presented, by extending the multiscale version of the non-overlapping domain decomposition scheme (see, for instance, [36,37]) to the case of a damaging composite material. Periodic

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