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A study of composite laminates failure using an anisotropic gradient-enhanced damage mean-field homogenization model

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ABSTRACT

The failure of carbon fiber reinforced epoxy laminates is studied using an anisotropic gradient-enhanced continuum damage model embedded in a mean-field homogenization scheme.

In each ply, a homogenized material law is used to capture the intra-laminar failure. The anisotropy of the homogenized material model results from the homogenization method and from the reformulation of the non-local continuum damage theory to account for the material anisotropy. As a result the damage propagation direction in each ply is predicted with accuracy as compared to the experimental results, while the problems of losing uniqueness and strain localization, which occur in classical finite element simulations when strain softening of materials is involved, can be avoided.

To model the delamination process, the hybrid discontinuous Galerkin/extrinsic cohesive law method is introduced at the ply interfaces. This hybrid method avoids the need to propagate topological changes in the mesh with the propagation of the delamination while it preserves the consistency and stability in the un-cracked interfaces.

As a demonstration, open-hole coupons with different stacking sequences are studied numerically and experimentally. Both the intra- and inter-laminar failure patterns are shown to be well captured by the computational framework.

1. Introduction

An efficient design using advanced composite materials relies on the development of accurate analytical and computational tools which are able to predict the response of composite structures under complex severe loading conditions. In particular, the modeling of the failure process of such structures becomes an important requirement to reduce the cost inherent to mechanical tests on large numbers of specimens.

Fracture mechanisms of composite materials are complex and require a multiscale approach: from the microscale within a ply to the laminate macroscale. Different solutions have been developed to address these particular topics, such as the damage-based micro-meso-macro approaches for composites [1–3], or purely numerical approaches as discussed by LLorca et al. [4]. However, since composite materials are aggregates of multiple phases, and as each phase has its own mechanical properties, the failure models require the material characterization of many parameters at the laminate level [2,3,5,6]. Moreover, the use of mesh-dependent characteristic sizes [5,6] or of time regularization [7] is common to simulate the failure of composite structures since the governing partial differential equations lose ellipticity at damage induced strain-softening onset, removing the uniqueness of the finite element solution, which becomes mesh-dependent. As a result, the finite-element solution does not converge with the mesh refinement. The use of cohesive zones within the plies using the extended finite element method, see *e.g.* [8], or the phantom node method [9] does not suffer from the loss of solution uniqueness.

An alternative to these approaches consists in using homogenized material properties at the macro-scale, in which case only the constituents need to be characterized. Indeed the macro or mesoscopic material responses of heterogeneous materials can

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be derived from the micro-structure constituents properties using analytical and/or numerical homogenization techniques. A comprehensive overview of different homogenization methods can be found in Refs. [10,11].

One semi-analytical efficient homogenization framework for the modeling of particle or fiber reinforced composite materials is the mean-field homogenization (MFH) approach [12]. MFH methods were first developed for linear elastic structures by extending the Eshelby single inclusion solution [13] to multiple inclusions interacting in an average way in the composite material. Most common extensions of the Eshelby solution are the Mori–Tanaka scheme [14,15] and the self-consistent scheme [16,17]. As the constituents of a composite material can exhibit an inelastic behavior such as plasticity, visco-elasticity, *etc.*, MFH methods were also developed in the non-linear range [18–26].

Although multiscale homogenization methods in general, and MFH schemes in particular, have achieved a high level of accuracy to capture the non-linear behavior of composite materials, accounting for material degradation, through damage or fracture models, remains highly challenging, see the reviews in [11,4]. Recently, Wu et al. [27,28] have proposed a non-local MFH method accounting for the damage evolution of the matrix phase of the composite material. In that formulation, an incremental-secant MFH approach was developed in order to account for the elastic unloading of one of the composite material phases during the strain softening of the other phase. When compared to a finite-element resolution of the micro-structure, the model was shown to predict accurately the softening response of the composite material, as well as the response of the different phases, even for volume ratios of inclusions around 60%, [28]. In order to avoid the strain/damage localization caused by the matrix material softening, an implicit non-local formulation [29–32] was adopted during the homogenization process.

Besides the intra-laminar damage, the inter-laminar failure is also of importance. The delamination process is usually modeled by recourse to cohesive interface elements inserted between the plies, which integrate an intrinsic cohesive law (ICL), see [33–38] among many others. In that case, the traction separation law of the cohesive element also models the elastic response prior to the delamination process, yielding mesh-dependent effects [37,38] due to the lack of consistency of the method (because of the lack of consistency, convergence is not achieved upon mesh-refinement). This mesh-dependent effect has motivated the use of extrinsic cohesive laws (ECL), which represent the fracturing response only, and for which cohesive elements are inserted at the fracture onset [39,40], requiring on-the-fly topological changes of the mesh. An energetically rigorous and computationally efficient way to integrate a cohesive zone model is to combine the extrinsic cohesive law with a discontinuous Galerkin (DG) approach [41–45]. With this hybrid method, interface elements are inserted between bulk elements at the beginning of the simulation, but the consistency and continuity during the pre-fracture stage are ensured by having recourse to the discontinuous interface terms, contrarily to a classical intrinsic cohesive zone model, thus avoiding the mesh-dependence effect and the need to propagate topological changes in the mesh with the propagation of the delamination. Efficient implementations of this method in open-source and commercial software are now available [46–48].

In this paper, the non-local damage-enhanced MFH model developed in [27,28] is applied to predict the failure of composite laminates such as coupon tests with a hole. To this end numerical models of the laminates are obtained by meshing each different ply separately. Within a ply, the material model follows the MFH to represent the damage process corresponding to the different fiber orientations. At the interface between plies, the hybrid discontinuous Galerkin/extrinsic cohesive law (DG/ECL) method is used to model the delamination process. This paper is organized in two main sections.

Section 2 presents the multi-scale numerical model of the composite laminate. First, in Section 2.1, the implicit non-local approach originally derived for isotropic materials [29–32] is extended to the case of anisotropic materials, such as UD-fiber reinforced epoxy ones. Indeed, in that case a single characteristic length l is not enough to characterize the interactions, of the non-local model, between material points in all the directions. In the transverse directions of UD-fiber reinforced epoxy composites, the fibers have the effect of blocking the material points interactions, and on the contrary, in the longitudinal direction, fibers prolong the interactions between material points [49,50]. In order to respect this anisotropic character of composite materials, the implicit non-local approach is derived in an anisotropic framework, and three characteristic lengths l^1, l^2 and l^3 are defined in the three principal directions of the material. The anisotropy of the homogenized material model results thus from the homogenization method and from the reformulation of the non-local continuum damage theory to account for the material anisotropy. Because of this anisotropic model, the damage propagates along the fiber directions, which is not necessarily the case with meso-scale continuum damage models [51]. As a result the damage propagation direction in each ply is predicted with accuracy as compared to the experimental results. Then, in Section 2.2, the finite-element discretization of the hybrid discontinuous Galerkin/extrinsic cohesive law method is presented in the particular case of laminated structures: within a ply a classical continuous Galerkin approximation is used while the hybrid DG/ECL method is used at ply interfaces, allowing the delamination to be captured by an adequate cohesive law. Third, the non-local incremental-secant MFH scheme, accounting for the damage evolution in the matrix [28], is recalled in Section 2.3 to define the material model of the bulk elements within the plies. Finally, as the delamination models are usually developed for intrinsic cohesive laws [33–38], their extrinsic version is proposed in Section 2.4.

Section 3 presents the numerical applications of the developed framework and its validation. The material parameters of the carbon fibers and of the epoxy matrix of prepreg Hexply M10.1/38%/UD300/ HS (R) are identified from the manufacturer data and the cohesive energy required for the delamination model is extracted from a Double Cantilever Beam (DCB) experiment in Section 3.1. The effect of the characteristic lengths of the non-local damage model is studied in Section 3.2, showing the necessity to consider an anisotropic non-local model for UD composite material. Eventually the predicted responses of open-hole laminate coupons are compared to experimental results. Tensile tests on open-hole laminate involve complex intra- and inter-laminar failure modes which depend on the geometrical dimensions, stacking sequence etc. For this reason such tests have been commonly used to validate composite laminate failure models as in [52] to assess the meso-scale continuum damage model [1], in [53] to validate the phantom-node method [53] combined to interface elements and fiber damage models, or in [54] to study the thickness size effect using the smeared crack model [5], as a non-exhaustive list. In the present work, experimental tests with two different stacking sequences are performed following the setup described in Section 3.3, and the results are compared to the developed model predictions in Section 3.4. It is found that the numerical model predicts the damage bands in locations and with orientations as observed in the experimental samples loaded up to 90% of the failure stress and inspected by X-ray computed tomography (XCT). Moreover, the fracture load is relatively well captured by the model as well as the delamination pattern.