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Validated progressive damage analysis of simple polymer matrix composite laminates exhibiting matrix microdamage: Comparing macromechanics and micromechanics

Evan J. Pineda*, Brett A. Bednarcyk, Steven M. Arnold

NASA Glenn Research Center, 21000 Brookpark Road, MS 49/7, Cleveland, OH 44135, USA

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ABSTRACT

The generalized method of cells micromechanics theory, employing the multi-axial mixed-mode continuum damage mechanics model for the matrix of the composite, is used to predict the evolution of matrix microdamage in un-notched (simple), unidirectional and laminated polymer matrix composites. Matrix microdamage is considered to be the evolution of subscale phenomena (including micro-crack, micro-fissure, micro-void, and shear band growth) that are responsible for all non-linearity in the composite up to the onset of more severe damage mechanisms, such transverse cracking, fiber breakage or delamination. Micromechanics is used to explicitly resolve the constituents of the composite at the microscale (fiber-matrix scale). The micromechanics model is validated against experimental data for numerous different laminate stacking sequences and a previously validated macroscale (e.g, lamina-scale), thermodynamically-based, work potential theory (Schapery theory). The inputs used in the continuum damage model, which was incorporated in the micromechanics theory, were calibrated against the same three experimental stress-strain curves utilized to calculate the inputs for the macroscale model. The agreeable predictions, obtained with the micromechanics model, establishes that both the macro- and micro-models are suitable for progressive damage analysis of laminated composites, considering only matrix microdamage. Moreover, the validated micromechanics theory is utilized to study the effect of fiber volume fraction on the matrix microdamage evolution in the various lay-ups. This demonstrates a key capability of the micromechanics approach that is lacking in the macromechanics method due to the macroscale assumption that the laminae are monolithic, anisotropic materials.

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1. Introduction

Virtual testing of composites is becoming more prevalent as computational power continues to increase and because of the potential cost savings for aerospace structure manufacturers and designers [1–3]. This is further evidenced by NASA's Advanced Composites Project and the recently completed Air Force Research Laboratory Tech Scout I project [4]. One aim of this project is to identify state-of-the-art progressive damage analysis (PDA) tools for polymer matrix composites (PMCs). While physical testing will never be (*nor should it be*) eliminated, implementation of judicious virtual testing strategies can significantly reduce the number of component and subcomponent experiments, as well as the associated costs. Moreover, accurate numerical modeling can be utilized to substantially expand both preliminary and final design space for a composite structure.

Continuum damage mechanics (CDM) has been demonstrated to be extremely useful for PDA of materials and structures [5,6], including PMCs [7]. However, a composite structure contains numerous relevant length scales, and it is still debated at which scale the CDM models should be implemented. Both macroscale modeling (macromechanics) and microscale modeling (micromechanics) have advantages and disadvantages. The appropriate

Abbreviations: CDM, Continuum damage mechanics; CLT, Classical lamination theory; GMC, Generalized method of cells; ISV, Internal state variable; MAC/GMC, Micromechanics Analysis Code with Generalized Method of Cells; MMCDM, Multi-axial mixed-mode continuum damage model; PDA, Progressive damage analysis; PMC, Polymer matrix composite; RUC, Repeating unit cell; RVE, Representative volume element; ST, Schapery theory.

* Corresponding author.
E-mail address: evan.j.pineda@nasa.gov (E.J. Pineda).

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tool should be chosen based upon the desired objectives of the specific analysis.

Macroscale models are computationally efficient because multiple length scales are not traversed during an analysis. Additionally, the input parameters for these models can usually be characterized easily with coupon level experiments. However, the theory must include assumptions that must be made about the complex interaction of constituent failure modes. In addition, macromechanics cannot discern subscale phenomena such as variation in the fiber volume fraction, fiber packing, fiber misalignment, void/defect content, polymer processing, residual stresses, and statistical variability. Therefore, they require recalibration of such materials when any of these factors change.

Micromechanics differs from macromechanics in that the various phases of the composite (constituents) are modeled explicitly through the definition of a representative volume element (RVE) or repeating unit cell (RUC). Thus, the aforementioned subscale phenomena are incorporated into the model directly, at the appropriate scale. Simpler damage and failure models can typically be employed to represent constituent behavior, and the interaction between modes, observed at the macroscale, will arise naturally. A homogenization scheme can then be employed to determine the constitutive behavior of the composite. Micromechanics also allows designers to engineer (tailor) the actual material to meet performance requirements resulting in a fully optimized structure. Unfortunately, it is difficult to characterize the constituents of PMCs because of *in-situ* effects [8]. Often, the models must be calibrated using coupon data only, thereby making it difficult to separate error in the CDM or deformation models (used to represent the mechanical behavior of the constituent) from error in the micromechanics model (used to capture the constitutive response of the composite).

The focus of this paper is not to compete these two valid modeling approaches (macroscale and micro/multiscale), but rather to assess the predictive PDA capabilities of both techniques. Additionally, it is of interest to discern how impactful the theoretical form of the CDM models applied at different length scales are on PDA predictions. As such, two different types of CDM models are used at the two different scales: a thermodynamically-consistent, work potential model (at the macroscale), and a more phenomenological damage model (at the microscale) that incorporates concepts from fracture mechanics.

A promising lamina-level (transversely isotropic) theory for modeling matrix microdamage is the Schapery theory (ST) [9–11]. This thermodynamically-based, work potential model utilizes the first and second laws of thermodynamics, along with the stationarity of work potential to derive the evolution equations for damage. The main inputs for ST include a set of matrix microdamage functions, which relates degradation in the stiffness tensor of the composite to an internal state variable (ISV) that represents the damage state. ST, in conjunction with classical lamination theory (CLT), was successfully used to predict the behavior of numerous off-axis unidirectional, angle-ply and multi-angle AS4/3502 laminates [12].

The generalized method of cells (GMC) is a semi-analytical micromechanics theory capable of predicting the constitutive response of composites through homogenization of an RUC [13,14]. The Micromechanics Analysis Code with Generalized Method of Cells (MAC/GMC), developed by the NASA Glenn Research Center, uses a combination of GMC and CLT to model solid laminates containing unidirectional plies [15,16]. In this work, the multi-axial mixed-mode continuum damage model (MMCDM) was utilized to model the non-linear behavior of the matrix, due to the accumulation of microdamage within a PMC RUC [17]. The input parameters for the MMCDM, within the micromechanics theory, were calibrated to match the same experimental data [12] that was used previously to characterize the microdamage input functions for ST.

Results from the calibrated micromechanics model, using MMCDM, were compared to the macro ST results, and both models were validated against experimental results for additional off-axis, angle ply, and multi-angle laminates. Finally, the effect of fiber volume fraction on the damage evolution in the composite was studied using MAC/GMC-MMCDM.

2. Multiaxial mixed-mode continuum damage model for matrix constituents

The MMCDM, developed in Ref. [17], was implemented within MAC/GMC and used to model progressive damage in the matrix constituent subcells. Damage initiation in each subcell is determined using quadratic definitions of damage strain $\varepsilon_i^D, i = 1, 2, 3$ (a 3-D extension of the strain-based Hashin criterion [18]), where i indicates the material direction and $i = 1$ is aligned with the fiber direction in a lamina, or RUC. For example,

$$\varepsilon_1^D = \sqrt{\left(\frac{\varepsilon_{11}}{X_\varepsilon}\right)^2 + \left(\frac{\gamma_{12}}{S_\varepsilon}\right)^2 + \left(\frac{\gamma_{13}}{S_\varepsilon}\right)^2} \tag{1}$$

where ε_{11} is the normal strain components, γ_{12} and γ_{13} are the corresponding engineering shear strains. The other two damage strains (ε_2^D and ε_3^D) are defined similarly to Eq. (1). The normal and shear strain allowables (X_ε and S_ε) utilized in Eq. (1) (and similarly for ε_2^D and ε_3^D) assume the material behavior is isotropic. However, different normal strain allowables are used when the stress state is tensile or compressive. Damage initiates when any of the damage strains exceed one.

$$\varepsilon_i^D \geq 1; \quad i = 1, 2, 3 \tag{2}$$

It is assumed the damage takes the form of an array of microcracks aligned perpendicular to the direction of the normal component of strain contributing to the damage strain (e.g., see Eq. (1)) that has exceeded one. These microcracks grow perpendicular to x_i under mixed-mode (I, II, III) loading conditions.

As such, damage is introduced through scalar damage variables D_i, where $i = 1, 2, 3$ and are determined from the damage strain(s) ε_i^D that have exceeded one. It is assumed that the damage variables serve to degrade both normal and shear engineering material properties in such a manner so as to simulate mixed mode microcracking. To retain generality, the damage state can be different in tension and compression.

Evolution of the damage variables D_i is controlled by damage stress σ_i^D versus damage strain ε_i^D constitutive laws, as shown in Fig. 1. From this curve, the damage increment can be determined.

$$dD_i = (1 - D_i - k'_i)\frac{d\varepsilon_i^D}{\varepsilon_i^D} \tag{3}$$

where D_i is the damage state at the previous increment, $d\varepsilon_i^D$ is the damage strain increment, $k'_i = k_i/E_i^0$, and k_i is the instantaneous tangent stiffness of the damage stress-damage strain curve. In Eq. (3), k'_i is taken to be an exponential function of the damage strain and two constants, A and B, which may vary in tension or compression.

$$k'_i = Ae^{\frac{-\varepsilon_i^D}{B}} \tag{4}$$

In addition a set of weighting parameters b_{ij} are required, which are used to define the mode-mixity of the damage evolutions.