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Micromechanical modeling of composites with mechanical interface – Part II: Damage mechanics assessment

Nicola Bonora *, Andrew Ruggiero

DiMSAT – Department of Mechanics, Structures and Environment, University of Cassino, Via G. Di Biasio 43, I-03043 Cassino, Italy

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Abstract

Continuing the work initiated in the Part I [Bonora N, Ruggiero A. Micromechanical modeling of composites with mechanical interface – Part I: unit cell model development and manufacturing process effects. Compos Sci Technol 2003], in this paper the possibility to account for different damage mechanisms, in the unit cell model (UCM), explicitly developed for composites with mechanical interface, is discussed and results for Ti-15-3/SCS-6 composite laminates are presented. Starting from the analysis of the constituent behaviors a probabilistic model based on Weibull statistics is developed for fiber failure, while a ductile damage model which incorporates stress triaxiality effect has been used for predicting metal matrix progressive failure. Fiber–matrix debonding process has been naturally predicted incorporating the material manufacturing process in the stress/strain history. Numerical results performed with the UCM applied to 0° and 90° unidirectional laminates, loaded both in tension and compression, have been compared with experimental results at both macro- and microscopic scale.

Keywords: Ductile damage; CDM; MMC; FEM; Plasticity; Multiscale damage

1. Introduction

Composite materials find a new field of application almost every day, often as a lighter substitute material to more traditional steels and light alloys, due to their high specific resistance capabilities, low weight, and for the possibility to design components and parts assigning the desired material properties where needed most.

Metal matrix composites represent a different generation of materials explicitly designed for high temperature applications. Here, the idea of combining the strength of ceramic reinforcement with the ductility of metal matrix leaded to materials capable to offer high stiffness and strength, as well as fatigue resistance and reduced overall weight, at elevated temperature up to 700 °C, approximately. The major structural differences of these composites, with respect to polymeric matrix based composites, mainly are: the elastic–plastic behavior of the matrix, which can sustain large plastic deformation, and the nature of interface between the matrix and the reinforcement. Usually, in these composites the interface is mechanical, in the sense that no chemical bond exists between the fiber and the matrix. The joining of the matrix with fiber occurs as a result of the differential shrinkage, due to the mismatch in the α-thermal expansion coefficients, during the cooling down from the assembly temperature to room temperature.

A fundamental conceptual difference in the design with composite materials is that the material itself can be designed, at different dimensional scales (constituents, laminate stack sequence, and component) according to the most effectively required behaviors. To this purpose, reliable and practical design tools, capable to accurately

* Corresponding author.
E-mail address: nbonora@unicas.it (N. Bonora).

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predict overall material constitutive behavior at different dimensional scales, have been investigated in the last decades. In this framework, micromechanics approach has been widely used by a number of authors [1–3]. Typically, a unit cell model (UCM) is built on the assumption of material periodic microstructure. Finite element technology is used to calculate cell response incorporating complex features, such as constituents' non-linear behavior, contact, combined thermo-mechanical loading, etc.

This approach allows predicting the occurrence of failure conditions if the micro-mechanisms of failure, characteristic for the material, are identified and appropriate damage modeling is added in. In this way, damage evolution in the material microstructure can also be followed and the progressive degradation of the composite overall constitutive response accurately predicted.

In the part I [5], the authors analyzed the role of the manufacturing process performing an extensive finite element investigation on SCS-6/Ti-15-3 unidirectional laminates. They demonstrated that if the consolidating phase, that is commonly performed by hot isostatic press (HIP) technique, is simulated within the UCM, the composite macroscopic response can be accurately predicted without the need to develop artificial model for the interface strength.

In this paper, continuing the previous work, microstructural damage evolution in SCS-6/Ti-15-3 composite laminates has been investigated. The damage mechanisms, which may occur in the microstructure under both tension and compression loading, have been identified and specific damage model for each of them have been developed and implemented in the UCM. Damage evolution during loading has been compared with experimental in situ observations, given by Majumdar and Newaz [23], in order to verify the accuracy of the proposed approach in predicting how, where, and when damage develops. In Section 2, the UCM formulation proposed by the authors is briefly reviewed; in Section 3, the damage mechanisms and the modeling are presented; in Section 4 the description of the material used in the present investigation is given; in Section 5 the finite element results are discussed and compared with experimental data available in the literature.

2. Unit cell model and finite element modeling

A UCM can be developed according to the periodicity of the material structure and the dimensional scale of interest. For a composite laminate, the smallest RVE can be taken at single-fiber level if the thickness of the lamina is big enough with respect to the fiber diameter. For closed package fiber layers, the UCM should account for between-fiber distance in order to accurately model local stress concentration and constraint. In metal matrix composites, fibers are quite bigger in diameter with respect to more traditional carbon or glass fibers. For instance, in the case of SCS-6 fiber the average diameter is 140 μm approximately, in contrast to 7 μm diameter of standard T300 carbon fiber. In addition, foil-fibers-foil assembly technique, used for this material, assures a high degree of regularity in the fiber alignment and arrangement, resulting in real periodic microstructure.

Since, the fiber diameter is comparable with the distance between two adjacent fibers, both along the lamina in-plane direction and the laminate thickness direction, the choice of the UCM may be influenced by the presence of an horizontal shift in the stacked plies as sketched in Fig. 1, where different choices for the UCM are depicted.

Periodic boundary condition can be applied to the cell imposing either "plane-remains-plane" or "unified" periodic boundary conditions. Xia et al. [4] showed that the first is appropriate for in plane symmetric loading but can be over-constraining for shear loading while the latter performs better in all cases.

Using plane strain or generalized plane strain elements the same UCM can be used to investigate both 90° and 0° unidirectional laminate response. If expanded in 3D, the same UCM can be used to investigate both cross-ply and angle ply laminate [4].

As far as concern SCS-6/Ti-15-3 composite laminates investigated here, the author observed that, according to microstructural visual observations, the more appropriate UCM is the one given in Fig. 2, due to the presence of a systematic shift in the ply stacking sequence.

Under plane strain assumptions, imposing periodic "plane-remains-plane" boundary conditions, the average meso-strain and meso-stress are defined through the displacement and reaction forces at the cell boundaries as follows:

$$E_x = \ln\left(1+\frac{u}{L_x^0}\right),\quad E_z = \ln\left(1+\frac{w}{L_z^0}\right),\quad E_y = 0, \tag{1}$$

where u, w, L_x^0, L_z^0 are the displacement along x- and z-axes and the cell reference dimensions, respectively. The in-plane meso-stresses are defined as:

$$\Sigma_i = \frac{F_i}{L_j \cdot B} i, j = x, z, \tag{2}$$

where B is the cell thickness, v is Poisson ratio, and L_x and L_z the actual cell dimensions (i.e., $L_x = L_x^0 + u$). Under generalized plane strain assumption, also the meso-strain and meso-stress along the normal axis (here, y-axis) can be also given as:

$$E_y = \ln\left(1+\frac{v}{B}\right), \tag{3}$$

$$\Sigma_i = \frac{F_y}{L_x \cdot L_z}. \tag{4}$$