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A continuum damage model for composite laminates: Part II – Computational implementation and validation

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Abstract

This papers describes the computational implementation of a new damage model for laminated composites proposed in a previous paper. The objectivity of the numerical solution is assured by regularizing the energy dissipated at a material point by each failure mechanism. A viscous model is proposed to mitigate the convergence difficulties associated with strain softening constitutive models. To verify the accuracy of the approach, analyses of coupon specimens were performed, and the numerical predictions were compared with experimental data.

Keywords: Fracture mechanics; Continuum damage mechanics; Composite materials

1. Introduction

This paper describes the second part of a new methodology developed to predict the onset and propagation of intralaminar failure mechanisms (matrix cracks and fiber fractures) in laminated composites. A new constitutive model was described in detail in an accompanying paper (Maimí et al., submitted for publication). The model proposed predicts the onset of intralaminar failure mechanisms using a modification of LaRC failure criteria (Dávila et al., 2005; Pinho et al., 2004), and accounts for the effects of the ply thickness and configuration (unidirectional ply or constrained ply) on the onset of matrix cracking. Furthermore, the constitutive model represents the closure and opening of cracks under load reversal cycles by defining the damage variables as functions of the normal components of the stress tensor (Maimí et al., submitted for publication).

It is clear that the model proposed in the first part of this work can only be useful for the prediction of the inelastic response of composite structures, from the onset of intralaminar failure mechanisms up to final structural collapse, if it is implemented in a computational model. Therefore, the objective of this work is to develop a computational model with the implementation of the model proposed in Maimí et al. (submitted for publication).

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The computational implementation of softening constitutive equations poses difficulties because the boundary value problem becomes ill-posed (de Borst, 2001). As a consequence, the solution obtained from a finite element model may depend upon the mesh refinement. The solution proposed here to ensure an objective solution consists in applying Bažant's crack band model (Bažant and Oh, 1983) for each intralaminar failure mode considered in the model. The existence of a maximum size of the finite elements that ensures an admissible solution is demonstrated, and a strategy to enable the use of elements larger than the critical size is described. In addition, a modification of the constitutive model developed in part I, corresponding to the implementation of viscous effects, is proposed to alleviate convergence difficulties.

The accuracy of the model is assessed by comparing the predictions with experimental data for an open-hole carbon-fiber specimen loaded in tension.

2. Computational model

Two different inelastic responses have to be taken into account in the numerical simulation of damage using Continuum Damage Mechanics. While the stress–strain response of a material exhibits a positive-definite tangent stiffness tensor there is an initial stage of damage commonly referred to as diffuse damage, and the numerical solution is independent of the numerical discretization.

When the tangent stiffness tensor is not positive definite, damage localizes in a narrow band, and the numerical solution depends upon the numerical discretization: decreasing the element size in the localized zone decreases the computed energy dissipated. Therefore, the structural response is not objective because it does not converge to a unique solution with mesh refinement.

The damage model proposed in Maimí et al. (submitted for publication) uses a constitutive model that forces localization as soon as one of the damage activation functions (F_N) associated with the onset of transverse ($N = 2+$, $2-$) or longitudinal ($N = 1+$, $1-$) cracking is satisfied, i.e., when $F_N = \phi_N - r_N = 0$, where ϕ_N are the loading functions and r_N are the elastic domain thresholds previously defined by the authors (Maimí et al., submitted for publication).

In order to guarantee that the numerical solution is independent of the discretization a characteristic element length is used in the constitutive model using a procedure based on the crack band model proposed by Bažant and Oh (1983).

2.1. Damage laws in softening regime: crack band model

Bažant's crack band model (Bažant and Oh, 1983) ensures the objective response of the global finite element model by regularizing the computed dissipated energy using a characteristic dimension of the finite element and the fracture toughness

$$g_M = \frac{G_M}{l^*}, \quad M = 1+, 1-, 2+, 2-, 6 \tag{1}$$

where G_M is the fracture toughness, g_M is the energy dissipated per unit volume, and l^* is the characteristic length of the finite element. For square elements, with an aspect ratio approximately equal to one, the characteristic element length can be approximated by the following expression (Bažant and Oh, 1983):

$$l^* = \frac{\sqrt{A_{IP}}}{\cos(\gamma)} \tag{2}$$

where $|\gamma| \leqslant 45°$ is the angle of the mesh lines with the crack direction and A_{IP} is the area associated with each integration point. For an unknown direction of crack propagation, the average of this expression can be used, $\bar{l}^* = \frac{\pi}{4}\int_0^{\frac{\pi}{4}} l^*\,\mathrm{d}\gamma = 1.12\sqrt{A_{IP}}$.

When the crack propagation path can be estimated in advance, it is recommended to align the mesh with the direction of crack propagation because cracks tend to evolve along the mesh lines. If the crack propagation is aligned with the mesh lines, the characteristic length must be the square root of the area corresponding to an element integration point, i.e., $\gamma = 0$.

For triangular elements, the typical characteristic length is determined by the expression:

$$l^* = 2\sqrt{\frac{A_{IP}}{\sqrt{3}}} \tag{3}$$

A more accurate measure of the characteristic element length would be obtained using the element projections for both possible crack directions, transverse and longitudinal.

The crack band model assumes that the failure process zone can be represented by a damaged finite element zone that has the width of one element. This approximated method for achieving the objectivity of the global response is appropriate for the