Modeling of Damage Growth in Composite Laminates

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Abstract

A progressive damage growth model is developed for composite laminates under compression. The mechanics of damage initiation and growth in a single lamina is modeled in a 2D plane stress setting using a system of orthotropic nonlinear elastic relations and a set of internal state variables. Amongst these are the voumetric analog of cohesive fracture energy, which we have termed kinking toughness. The concept of a kinking toughness was introduced by us earlier and here it is extended and implemented into the FE formulation. The lamina are stacked up to make a laminate. A thermodynamically consistent set of equations is developed for the evolution of damage growth. The formulation is numerically implemented using the commercially available finite element package, ABAQUS. The present method is applied to analyze the problem of damage growth in a compressively loaded notched laminate. Predictions of the model are compared against available experimental results.

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1 Introduction

The development of computational methodologies for the prediction of progressive damage growth in continuous fiber composite laminates is presently an active area of research. Available predictive methods are based on defining strength based criteria at the lamina level. Based on critical values for tensile, compressive and shear 'strengths', these methods compute pre-defined damage indices that are expressed in functional form in terms of the current stress state. When any of these indices exceeds a predefined critical value, the material is said to have failed (Chang and Chang (1987)). Beyond initial failure, a consistent and rigorous methodology to account for progressive material deterioration has not been investigated thoroughly. An exception to this is the work by Schapery and co-workers, (Schapery and Sicking (1995)), who carried out lamina level tests, and validated the test results by developing a thermodynamically based progressive damage formation and growth model. In these studies, Schapery and co-workers assumed that the fiber direction response is essentially linear (slight elastic nonlinearity in the fiber direction was accounted for), but, damage (microcracking and transverse cracking) formation affects the response in the transverse direction. Consequently, internal state variables that are related to the damage mechanisms in the transverse direction were identified and evolution laws that specify the growth of damage and hence its influence on the transverse direction response were prescribed. In contrast to the transverse direction, in which damage accumulation results in progressively decreasing but smooth variations in instantaneous tangent moduli, damage accumulation in the fiber direction leads to non-smooth abrupt changes in the corresponding moduli due to the onset of a microstructural instability (kinking). These observations must be properly captured if progressive damage growth in composite laminates is to be modeled accurately. In the present paper, Schapery's theory (ST) is extended to account for fiber direction damage by incorporating the notion of a kink toughness. The new development is termed extended Schapery Theory (EST), see Basu et al. (2003), for details.

Coupon level tests in the fiber direction, transverse to the fiber direction and off axis tests are commonly used to obtain material behavior at the lamina level. These tests supply a complete response (stress-strain) curve (usually non-linear) with valuable information beyond the proportional limit. Lamina level coupon tests in tension have shown that fiber direction modulus, E_{11}, and poisson's ratio, ν_{12}, can be assumed to be independent of microdamage (matrix cracking and/or fiber fracture) that influences E_{22} and G_{12}. This situation is also true for compression until the onset of kinking (the axial compression load reaches a maximum limit load, under uniaxial compression, at the point in which a kink band starts to form, for example, as shown in Lee and Waas (1999). However, under more general conditions, stress multiaxiality does influence the in-situ compressive strength). During and after kink band formation and propagation, it is likely that the resulting damage does influence E_{11}, ν_{12}, E_{22} and G_{12}. In addition, it is known that compression strength is strongly influenced by stress multiaxiality. That is, compressive strength of a lamina under unidirectional loading may be quite different from the same under multiaxial stress states. These observations need to be properly incorporated into computational tools that are used to study progressive failure of multidirectional laminates. The present theory

(EST) for predicting progressive failure of compsoite laminates is based on input that uses only measured and available test data in conjunction with the laminate stacking sequence and geometry of the problem configuration.

References

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