A Mechanistic Model for Fatigue Life of Polymer Matrix Composites

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Current fatigue life and reliability analysis methods for polymer matrix composite laminates are almost exclusively based on empirical *rules* developed for particular material systems and applications. Although various levels of physical mechanical analysis are often used in the development of these methods, close inspection reveals that almost all of them amount to *curve fits* of experimental data. As a result, the fundamental material properties and damage mechanisms that are responsible for failure are not addressed. This amounts to a major limitation of the current fatigue life analysis tools because they must be calibrated to each specific set of material properties and loading conditions.

To enable the use of advanced polymer matrix composites in greater numbers of primary structure applications, questions regarding the reliability and lifetime performance of the materials must be answered. Several recent high-profile failures of composite structures have highlighted the unknowns associated with the use of composites. A prime example is the failure of the vertical stabilizer on Flight 587, an Airbus A-300 airliner that occurred in November 2001. Although the accident was a result of an over-load condition, questions pertaining to the reliability of composites structures and the wide variation of analysis methods used to design and evaluate them have highlighted the lack of fundamental understanding of composite damage and failure mechanisms.

The objective of this work is to further the fundamental understanding of damage growth and failure of polymer matrix composites under tensile fatigue loading conditions. Examples of current and past methods for describing tensile damage growth and failure for PMCs are presented. Close examination and comparison of the methods presented clearly show that some of the fundamental physical mechanisms responsible for fatigue of composite materials are inadequately understood. In particular, a mechanistic model for damage growth and failure of uniaxial laminates (or plies) is missing. This is a critical component of general composite fatigue theory because the failure of a general laminate is dependent on the failure of the uniaxial plies within it. This idea is known as *Critical Element Theory* and is described in detail.

Damage growth and failure of unidirectional composite laminates under axial tension-tension fatigue loading is studied. It is applicable to continuous fiber, polymer matrix laminates such as those used in high performance aircraft structures. Understanding and modeling of the fatigue behavior of unidirectional laminates is critical to understanding fatigue failure of more general composite

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laminates because the fatigue life of a uniaxial laminate is the limiting factor for the tension-tension fatigue life of a general, angle-plied laminate.

A mechanism-based model for the fatigue life of unidirectional polymer matrix composites is developed. This model is based on physical damage mechanisms at the fiber/matrix scale and its formulation does not include empirical S-N data. Instead basic material properties (such as stiffness) and quasi-static strength test data are used to predict damage growth and failure as a result of fatigue loading. The failure model is probabilistic and therefore differs from the deterministic S-N curve type of analyses that are commonly seen.

The theory developed in this work has roots in two major areas: fracture mechanics and non-deterministic methods. Fracture mechanics techniques are employed to model damage growth between the fibers and matrix, and non-deterministic analysis methods are used to characterize the initial damage state and the probability of failure as a result of fatigue loading. The two techniques complement each other for the case of composites, which consist of two distinct micro-structural phases. By applying non-deterministic methods, macroscopic fracture mechanics methods can be used to describe the mass behavior of many microscopic defects. In other words, the use of non-deterministic methods allows fracture mechanics techniques to be applied to the composite material as if it were a homogenous, single-phase material with *smeared* properties. This is analogous to the ideas used in classical mechanical analysis methods for composites.