Cracking and Fatigue in Fiber-Reinforced Metal and Ceramic Matrix Composites

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ABSTRACT The damage that occurs in unidirectional ceramic and metal matrix composites upon monotonic and cyclic loading involves coupled considerations of mechanics and stochastic processes. Some of the basic principles are described and models presented that both characterize damage evolution and govern mechanism changes. Comparisons are presented between predictions and experimental data for such phenomena as modulus degradation caused by matrix cracking, fatigue crack growth and tensile strength.

8.1 Introduction

The fracture and fatigue of fiber-reinforced metal, ceramic and intermetallic matrix composites involves coupled considerations of mechanics and weakest link statistics. Frank McClintock (1976) was among the first to address problems that required linkage between these two disciplines. These initial concepts and linkages have grown and become the foundation for understanding some of the mechanical properties of composite systems at the micromechanics level. To provide focus on these issues, a broad view of composite properties is not attempted in this chapter. Instead, emphasis is given to unidirectional materials, but with the appreciation that the associated mechanical responses provide a fundamental framework for addressing the properties of multi-directional laminated and woven systems.

The three fundamental constituents of fracture and fatigue models for unidirectional composites are schematically represented on Fig. 8.1. First, debonding occurs at fiber/matrix interfaces, requiring an understanding of interface fracture mechanics in mixed-mode (He and Hutchinson, 1989; Evans and Marshall, 1989). Second, fibers exert tractions on the crack surfaces, requiring a mechanics of large-scale bridging (Evans and Marshall, 1989; Aveston et al., 1971; Marshall et al., 1985; Zok and Hom, 1990; Bowling and Groves, 1979). Third, fiber fracture may occur, usually at locations away from the matrix crack plane, as a result of weakest link.
FIGURE 8.1. The various mechanisms that accompany mode I matrix crack propagation in unidirectional composites.

statistics (Thouless and Evans, 1980; Curtin, 1991a; Sutcu, 1989), resulting in pull-out. The dominant dissipation mechanism that allows fibers to enhance the fracture and fatigue resistance is caused by frictional sliding along previously debonded interfaces (Evans, 1990). Such dissipation occurs at both intact and failed fibers. However, the extent of the zone that provides dissipation is strongly influenced by the fiber failure site relative to the crack plane, which governs the pull-out length. This phenomenon arises from the stochastic nature of fiber failure. Large pull-out lengths relative to the crack opening also lead to large-scale bridging (LSB) (Zok et al., 1991), wherein the nominal crack growth resistance depends on crack size and specimen geometry. Consequently, there is an intimate connection between the probabilistic nature of fiber failure and the mechanics of crack growth.

A comprehensive understanding of crack growth and fatigue also recognizes that several crack growth mechanisms are possible, dependent upon the properties of the matrix, fiber and interfaces (Evans, (in press)) (Fig. 8.2); i) splitting can occur by either mixed-mode or mode II crack growth within the matrix and along the interfaces; ii) a single mode I crack may form, usually accompanied by fiber failure; iii) multiple mode I cracking may proceed with minimal fiber failure. The same range of behaviors occurs in the monotonic loading of brittle matrix composites and in the cyclic loading of metal matrix composites. This chapter deals with the two