BEM analysis of crack onset and propagation along fiber–matrix interface under transverse tension using a linear elastic–brittle interface model

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Abstract

The behavior of the fiber–matrix interface under transverse tension is studied by means of a new linear elastic–brittle interface model. Similar models, also called weak or imperfect interface models, are frequently applied to describe the behavior of adhesively bonded joints. The interface is modeled by a continuous distribution of linear-elastic springs which simulates the presence of a thin adhesive layer (interphase). In the present work a new linear elastic–brittle constitutive law for the continuous distribution of springs is introduced. In this law the normal and tangential stresses across the undamaged interface are, respectively, proportional to the relative normal and tangential displacements. This model not only allows for the study of crack growth but also for the study of crack onset. An important feature of this law is that it takes into account the variation of the fracture toughness with the fracture mode mixity of a crack growing along the interface between bonded solids, in agreement with previous experimental results. The present linear elastic–brittle interface model is implemented in a 2D boundary element method (BEM) code to carry out micromechanical analysis of the fiber–matrix interface failure in fiber-reinforced composite materials. It is considered that the behavior of the fiber–matrix interface can be modeled by the present model although, strictly speaking, there is usually no intermediate material between fiber and matrix. A linear-elastic isotropic behavior of both fiber and matrix is assumed, the fiber being stiffer than the matrix. The failure mechanism of an isolated fiber under transverse tension, i.e., the onset and growth of the fiber–matrix interface crack, is studied. The present model shows that failure along the interface initiates with an abrupt onset of a partial debonding between the fiber and the matrix, caused by presence of the maximum radial stress at the interface, and this debonding further develops as a crack growing along the interface.

Keywords: Crack BEM Imperfect interface Interphase Fiber–matrix interface Composites Energy release rate Fracture toughness Fracture energy Fracture mode mixity Britteness number

1. Introduction

Composite unidirectional laminates usually exhibit a failure mechanism called matrix failure or interfiber failure when they are subjected to loads transverse to the fibers. This failure mechanism is characterized by the debonding of some fibers when the tension loads are driving the failure process. The connection between the initial debonds and the final macrocrack has several steps: the onset and growth of the debonds (as fiber–matrix interface cracks), the kinking of some of these cracks into the matrix and the final coalescence of the cracks kinked from different fiber–matrix interfaces, see París et al. [1], Correa et al. [2,3], and Mantič et al. [4].

The problem of an elastic circular (in 2D) or cylindrical (in 3D) inclusion embedded in an elastic matrix with a partial debond at their interface (modeled as an interface crack) subjected to a remote uniaxial load at infinity has been intensively studied in the past. A theoretical basis for any analysis of this problem was established by the seminal work of Toya [5], where the perfect fiber–matrix interface model and the open model of interface cracks were assumed. Toya deduced analytical expressions for stresses, displacements, and the total energy release rate (ERR) as a function of the debond angle and applied the latter in a fracture criterion to assess the debond growth along the fiber–matrix interface.

Zhang et al. [6] presented experimental results for transverse single-fiber specimens, and Varna et al. [7] studied the debond growth along the fiber–matrix interface modifying Toya’s [5] ERR based fracture criterion in order to take into account an increasing participation of the shear fracture mode when the debond grows. París et al. [8] and Varna et al. [9] compared different aspects of Toya’s [5] solution and the elastic solution obtained by the collocational boundary element method (BEM) [10–14] using a contact algorithm [15]. Recently, Mantič [16] applied Toya’s...