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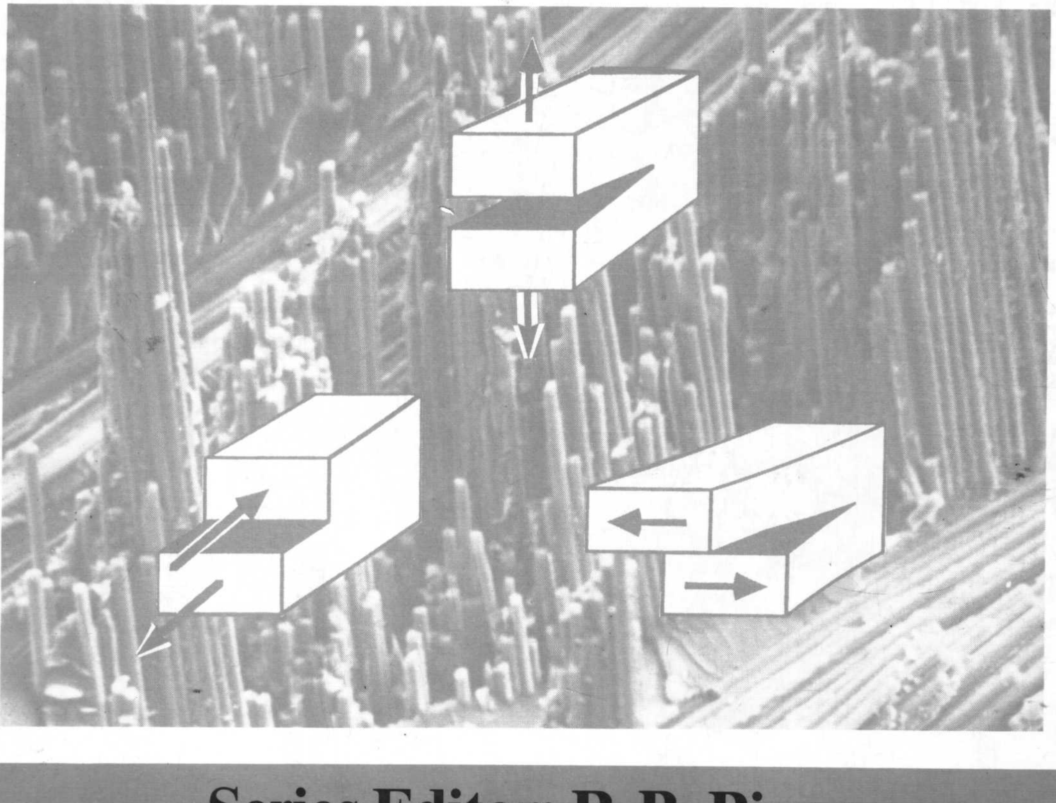
APPLICATION OF FRACTURE MECHANICS TO COMPOSITE MATERIALS

Editor: Klaus Friedrich



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APPLICATION OF FRACTURE MECHANICS TO COMPOSITE MATERIALS

edited by

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The editor dedicates this book to
Prof. E. Hornbogen
In honour of his 60th birthday, in February 1990

PREFACE

Synthetic composites distinguish themselves from conventional materials such as metals, ceramics or polymers by the fact that they consist of two, or more, physically distinct and mechanically separable materials. They can be made by mixing the separate materials in such a way that the dispersion of one material in the other can be done in a controlled way to achieve optimum properties. Their properties are superior, and possibly unique in some specific respects, to the properties of the individual components [1]. Because of their complex microstructure the individual events of failure development and final fracture can be complex too. Fracture of the individual phases in the composite, between them and between certain well-defined arrays can take place separately, sequentially or simultaneously, depending on the type of loading, the external testing conditions, the particular microstructure of the composite and other factors.

In recent years there has been a tremendous interest in the fracture behavior of polymer (see, e.g., refs. [2–4]) and composite materials (see, e.g., refs. [5–7]). One reason for this is the increasing use of polymers and composites in structural components of aircraft, automotive, sporting and other industries. In such circumstances it is essential to have as complete an understanding as possible of the fracture behavior of the materials. This book is designated to meet the requirements of those who need to be informed of the latest developments in the field of composite fracture. The main emphasis is upon the use of fracture mechanics methods in the study of composite materials fracture. Further prominence is given to the relationships between microstructure, fracture mechanical properties and the micromechanisms of damage development and fracture processes.

The book is divided into several parts: the first part deals with a general introduction to fracture mechanics of anisotropic materials (by J.G. Williams) and with statistical concepts in the study of fracture properties of fibers and composites (by H.D. Wagner). The second part is especially concerned with the fracture of polymer composite materials. It can be sub-divided into three major portions, the first of which is the great area of interlaminar fractures in continuous fiber/polymer composite laminates under mode-I (P. Davies, M.L. Benzeggagh) and mode-II conditions (L.A. Carlsson and J.W. Gillespie Jr), respectively. Relationships of polymer matrix toughness to interlaminar fracture toughness of corresponding fiber composites are discussed by W.L. Bradley. The second portion of part II deals with fracture problems of injection moldable short-fiber reinforced, thermoplastic matrix composites. In particular, microstructure/fracture mechanical relationships in this group of composites are outlined by J. Karger-Kocsis, and the concept of crack layer theory applied to polymers and short-fiber composites is introduced by A. Dolgopolsky and J. Botsis. Finally, the third portion of part II concentrates on complex fractures in polymer composite laminates. This includes the fracture mechanics of translaminar fractures in notched carbon/epoxy laminates (K. Kageyama), the effects of environment on the fracture mechanical performance of polymer composites (G. Marom), and the damage mechanisms, including edge effects, in carbon-fiber reinforced polymer composite laminates (K. Schulte and W.W. Stinchcomb). Part II is concluded by a chapter on the fractographic analysis of polymer composites, summarizing interlaminar fracture mechanisms in continuous fiber composites, translaminar fractures in woven fabric structures, and damage development and failure mechanisms in short-fiber composites (by K. Friedrich).

Besides the large group of synthetic polymer composites, there exist composites with metallic or ceramic matrices and the natural composites. The fracture mechanical properties of the latter are discussed in part III of this book. S. Ochiai reports about a fracture mechanical approach to metal-matrix composites, and R.W. Davidge describes how the mechanical properties and the fracture behavior of ceramics depend on additional reinforcement by continuous fibers. The fracture of whisker-reinforced ceramics is outlined in a chapter by R. Warren and V.K. Sarin. Finally, W. Bonfield and J.C. Behiri have concentrated their efforts on the characterization of fracture toughness of natural composites with special reference to cortical bone. In summary, F.X. de Charentenay gives, in the concluding part of this book, a critical outlook about the complexity of fracture in composites in general and the prerequisites and limits of applicability of fracture mechanics methods to composite materials in particular.

For whom should this volume be of special interest? Undoubtedly, it will be a useful help to those researchers who are active or intend to become active in the field of testing and evaluation of composite materials (mechanical engineers, structural designers, material scientists). But it should also prove invaluable for advanced students taking final year undergraduate or post-graduate courses in the science of composite materials.

Thanks are due to Professor R.B. Pipes, editor-in-chief of this Elsevier Composite Materials Series, for the invitation to organize this particular volume. In addition, many sincere thanks have to go to the contributors, who so kindly agreed to collaborate on this book, for their hard and efficient work.

January, 1989 K. Friedrich

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PART I

General Aspects

Application of Fracture Mechanics to Composite Materials
edited by K. Friedrich

Chapter 1

Fracture Mechanics of Anisotropic Materials

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Contents

Abstract

A review of the basic energy release rate, G, analysis for linear but anisotropic elastic materials is given including the definition in terms of contours. For many composites it is noted that crack growth is self-similar because of delamination and this leads to a rather simple general scheme of determining G via local moments and forces. In addition, it is possible to partition this G value into modes I and II in a simple but rigorous manner. Several solutions are given for test specimens which give various forms of mixed-mode loading, including constant and variable ratios. Some discussion of the rather complicated case of G for buckled laminates under compression is also given. For cracked plates it is necessary to resort to the stress intensity factor, K, solutions via complex-function analysis and this is developed in some detail to render it accessible to the general reader and the relationships between G and K for the anisotropic case are derived. The very important result that K is almost the same for anisotropic and isotropic materials is derived and demonstrated via numerical results. Some discussion of damage zone sizes is also given.

1. Introduction

Conventional fracture mechanics deals with homogeneous, isotropic materials and has been highly successful because so many practically useful materials are reasonable approximations to these assumptions. The same is true, of course, for stress analysis in general, and most elasticity texts contain only a passing reference to anisotropy. The notable exceptions to this have been work generated as a result of efforts to design load bearing structures in wood [1]. In particular early aircraft structures employed wood and there was much interest in calculating stress concentration factors around holes [2,3]. The use of fibre composites to make laminates and also the design of plywood has produced a considerable literature and in particular the text by Lekhnitskii [4,5] which employed a development of the well-known Muskhelishvili [6] complex-number form of stress function analysis to produce a wide range of solutions to problems of practical importance. In more recent times, many computer codes have been developed employing finite elements and boundary integrals which will give solutions for anisotropic materials.

Fracture mechanics has been investigated in some detail for wood [7–9] and found to be a very useful tool for design purposes. It is interesting to note that material variability is large for wood, even by composites standards, and yet the method proved useful. In spite of this, the use of fracture mechanic analysis for composites has been rather limited. This would appear to stem from a suspicion that conventional analysis could not cope with the anisotropy and inhomogeneity of composites and that some other scheme was necessary. Anisotropy can be included in the analysis by employing the appropriate methods and, although inhomogeneity is always a problem, it can be dealt with via size parameters. Fracture mechanics is a *macro* theory and defines parameters which characterize failure over regimes of known size. The particular problem of composites is that the sizes may be large and rather careful development of the methods is necessary. Thus what is required is the *development* of the basic methods and not their abandonment. This has been recognized in a growing interest and literature in recent years, and is reflected in this volume.

While much remains to be done in this development there is a large body of useful analysis available via anisotropic elasticity and fracture mechanics analysis. Many rather daunting problems lead to surprisingly simple solutions, and provide a wide base from which to tackle those especially difficult problems, such as inhomogeneity, inherent in composites. This chapter will give a review of these available results and methods. Most of the analysis will assume linear, elastic and homogeneous behaviour so that the results may be described as linear elastic fracture mechanics (LEFM) but for anisotropic materials. The fractures analyzed are thus brittle in character having small damage zones in comparison with other dimensions in accordance with LEFM. As in LEFM, some consideration will be given to crack tip zone sizes.

2. Basic considerations

We shall employ the scheme for developing fracture mechanics described in ref. [10] in which two assumptions are made:

(1) All bodies contain cracks or flaws, and fracture mechanics is concerned with analysing the growth of such cracks; and

(2) The crack growth may be characterized in terms of the energy per unit area necessary to create new surface area, the crack resistance R.

The first assumption precludes all discussion of creating flaws in otherwise perfect bodies which is not a serious restriction in composites and is arguably no restriction at all for real materials. The second assumption does not imply that R is a constant but may vary with any number of variables. For simplicity of presentation we shall consider a crack of length a in a sheet of uniform thickness B undergoing self-similar propagation so that the change of crack area is given by

$$\mathrm{d}A = B\,\mathrm{d}a.$$

The analysis is based upon the energy balance during a time interval $\mathrm{d}t$ for a crack moving at velocity $\dot{a}$ for which we can write

$$\dot{U}_\mathrm{e} = \dot{U}_\mathrm{d} + \dot{U}_\mathrm{s} + \dot{U}_\mathrm{k} + BR\dot{a}, \tag{1}$$

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where U_e is the external work performed, U_d the energy dissipation, U_s the stored elastic energy and U_k the kinetic energy. Such a relationship enables all situations to be analyzed including those involving visco-elastic dissipation (U_d) and high-rate processes (U_k). Here we shall adopt the usual static LEFM assumptions that all dissipation is embodied in R, and also ignore kinetic energy. We shall then define the parameter "energy release rate" G which is written as

$$G = \frac{1}{B}\left(\frac{\mathrm{d}U_\mathrm{e}}{\mathrm{d}a} - \frac{\mathrm{d}U_\mathrm{s}}{\mathrm{d}a}\right), \tag{2}$$

and may be regarded as the crack driving force since we may write, at fracture, from eq. (1)

$$BG\dot{a} = \dot{U}_\mathrm{e} - \dot{U}_\mathrm{s} = BR\dot{a}, \quad \text{i.e.,} \quad G = R.$$

It is usual to derive G separately and then define $G = R$ as fracture but then to note that if $G > R$ the system is unstable since U_k will increase. Energy balance is, of course, always maintained via eq. (1). G may be derived for a general body containing a crack of length a as shown in fig. 1 which has a load P applied giving