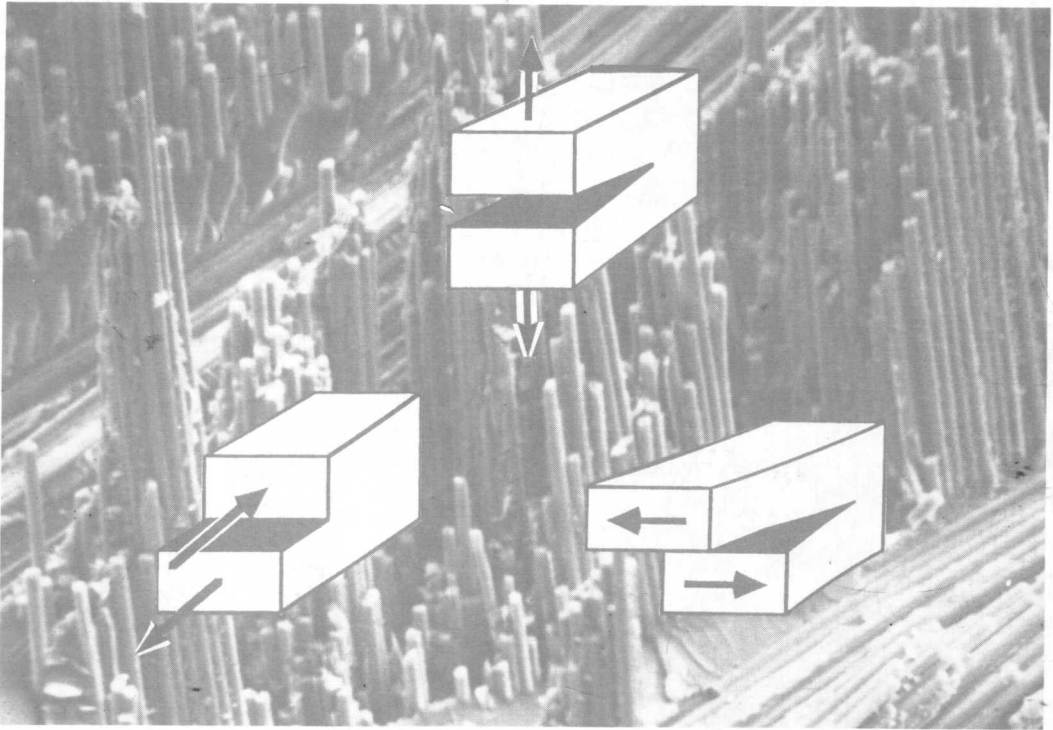


Volume 6

Composite Materials Series

**APPLICATION OF
FRACTURE MECHANICS
TO COMPOSITE MATERIALS**

Editor: Klaus Friedrich



Series Editor: R. B. Pipes

Elsevier

Composite Materials Series, 6

**APPLICATION OF
FRACTURE MECHANICS
TO COMPOSITE MATERIALS**

edited by

Klaus Friedrich

Technical University Hamburg-Harburg, Hamburg, F.R.G.



ELSEVIER

Amsterdam—Oxford—New York—Tokyo 1989

ELSEVIER SCIENCE PUBLISHERS B.V.
Sara Burgerhartstraat 25
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

Distributors for the United States and Canada:

ELSEVIER SCIENCE PUBLISHING COMPANY INC.
655 Avenue of the Americas
New York, NY 10010, USA

Library of Congress Cataloging-in-Publication Data

Application of fracture mechanics to composite materials/edited by
Klaus Friedrich.

p. cm. — (Composite materials series: 6)

Includes bibliographies and index.

ISBN 0-444-87286-8

1. Composite materials — Fracture. 2. Fracture mechanics.

I. Friedrich, Klaus, 1945— . II. Series.

TA418.9.C6A46 1989

620.1'186 — dc20

89-32866

CIP

ISBN 0-444-87286-8 (vol. 6)
ISBN 0-444-42525-X (Series)

© Elsevier Science Publishers B.V., 1989

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior written permission of the publisher, Elsevier Science Publishers B.V., Physical Sciences and Engineering Division, P.O. Box 103, 1000 AC Amsterdam, The Netherlands.

Special regulations for readers in the USA—This publication has been registered with the Copyright Clearance Center Inc. (CCC), Salem, Massachusetts. Information can be obtained from the CCC about conditions under which photocopies of parts of this publication may be made in the USA. All other copyright questions, including photocopying outside of the USA, should be referred to the publisher.

No responsibility is assumed by the publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein.

This book is printed on acid-free paper.

Printed in The Netherlands

*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 translamellar 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 interlamellar fracture mechanisms in continuous fiber composites, translamellar 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

References

- [1] D. Hull, *Introduction to Composite Materials* (Cambridge University Press, Cambridge, UK, 1981).
- [2] A.J. Kinloch and R.J. Young, *Fracture Behavior of Polymers* (Elsevier Applied Science Publishers, Barking, UK, 1983).
- [3] H.H. Kausch, *Polymer Fracture* (Springer, Berlin, 1978).
- [4] J.G. Williams, *Fracture Mechanics of Polymers*, Ellis Horwood Series (Ellis Horwood, Chichester, UK, 1984).
- [5] M.R. Piggott, *Load Bearing Fiber Composites* (Pergamon Press, Kronberg, FRG, 1980).
- [6] A.G. Atkins and Y.W. Mai, *Elastic and Plastic Fracture*, Ellis Horwood Series (Ellis Horwood, Chichester, UK, 1985).
- [7] A.C. Roulin-Moloney, *Fractography and Failure Mechanisms of Polymers and Composites* (Elsevier Applied Science Publishers, Barking, UK, 1989).

CONTENTS

Preface v

PART I. GENERAL ASPECTS

Chapter 1 (J.G. Williams)

Fracture mechanics of anisotropic materials 3

Abstract 3

1. Introduction 4
 2. Basic considerations 5
 3. G determinations 9
 4. Stability 22
 5. Cracks in anisotropic sheets 25
 6. Damage zones 35
 7. Conclusions 36
- List of symbols 37
References 38

Chapter 2 (H.D. Wagner)

Statistical concepts in the study of fracture properties of fibers and composites 39

Abstract 39

1. Introduction 40
 2. Brittle fracture as a statistical phenomenon 41
 3. Definition and significance of size effects 44
 4. Kinetic and probabilistic aspects of fracture 46
 5. Size effects in fibers: Comparison of LEFM and statistical approaches 50
 6. Conjectures about size effects in fibers 61
 7. Statistical fracture of model composites: Recent developments 67
 8. Recommended research 73
- List of symbols 74
References 75

PART II. FRACTURE OF POLYMER COMPOSITES**PART IIA. *Interlaminar fracture studies*****Chapter 3 (P. Davies and M.L. Benzeggagh)****Interlaminar mode-I fracture testing 81**

Abstract 82

1. Introduction 82
 2. Historical background 83
 3. Specimen preparation 83
 4. Data-reduction methods and models 85
 5. Test results 93
 6. The influence of test parameters 99
 7. Delamination mechanisms under mode-I loading 102
 8. Mode-I fatigue 107
 9. Standardization of a mode-I delamination test 107
- References 109

Chapter 4 (L.A. Carlsson and J.W. Gillespie Jr)**Mode-II interlaminar fracture of composites 113**

Abstract 114

1. Introduction 114
 2. Background 117
 3. Analytical approaches 119
 4. Numerical approaches 135
 5. Experimental approaches 144
 6. Conclusions 152
- References 154

Chapter 5 (W.L. Bradley)**Relationship of matrix toughness to interlaminar fracture toughness 159**

Abstract 159

1. Introduction 160
2. Micromechanisms of interlaminar fracture 161
3. Strain field mapping around crack tips during interlaminar fracture 170
4. Mode-I and mode-II critical energy release rates for various composite material systems 174
5. Models for predicting delamination fracture toughness 179

6. Summary	186
References	186

PART IIB. *Fracture of short-fiber reinforced thermoplastics*

Chapter 6 (J. Karger-Kocsis)

Microstructure and fracture mechanical performance of short-fiber reinforced thermoplastics 189

Abstract 189

1. Introduction	190
2. Microstructural details of SFRP	191
3. Toughness testing methods	202
4. Effects of microstructural parameters on the fracture toughness of selected SFRP systems	205
5. <i>J</i> -integral studies with SFRP	222
6. Concluding comparison of fracture mechanical data (K_{Ic} , G_c and J_c) of neat polymers and their short-fiber reinforced composites	224
7. Concluding remarks	225
Appendix	228
References for Appendix	242
List of symbols	244
References	245

Chapter 7 (A. Dolgopolsky and J. Botsis)

The crack layer approach to polymers and composites 249

Abstract 249

1. Introduction	250
2. The crack layer theory	253
3. Applications of the CL model	261
4. Closing remarks	266
5. Appendix	267
References	270

PART IIC. *Complex fracture in composite laminates*

Chapter 8 (K. Schulte and W.W. Stinchcomb)

Damage mechanisms – including edge effects – in carbon fiber-reinforced composite materials 273

Abstract 274

1. Introduction	274
-----------------	-----

- 2. Experimental 277
- 3. Mechanical properties of composite laminates 278
- 4. Damage mechanisms 296
- 5. Summary 322
- List of symbols 323
- References 323

Chapter 9 (K. Kageyama)

Fracture mechanics of notched carbon/epoxy laminates 327

Abstract 328

- 1. Introduction 328
- 2. Fundamental theory of fracture mechanics 329
- 3. Two-dimensional stress intensity factors 332
- 4. In-plane fracture toughness test 338
- 5. Radiographic observation 347
- 6. Three-dimensional analysis of notched composite laminates 352
- 7. Numerical simulation of crack extensions 370
- 8. Electrical potential drop technique 373
- 9. Acoustic emission wave analysis 378
- 10. Stress analysis by thermoelastic technique 384
- 11. Summary 394
- References 395

Chapter 10 (G. Marom)

Environmental effects on fracture mechanical properties of polymer composites 397

Abstract 397

- 1. Introduction 398
- 2. Environmental processes in composites 400
- 3. Effects of environmental conditions on delamination 403
- 4. Summary and conclusions 422
- References 423

Chapter 11 (K. Friedrich)

Fractographic analysis of polymer composites 425

Abstract 426

- 1. Introduction 426
- 2. Failure behavior of short-fiber reinforced thermoplastic matrix composites 428
- 3. Interlaminar fractures in continuous-fiber/polymer composite laminates 441

4. Microstructure, fracture toughness and fractography of polymer composite laminates 468
List of symbols 483
References 485

PART III. FRACTURE OF METALLIC, CERAMIC AND NATURAL COMPOSITES

Chapter 12 (S. Ochiai)

Fracture mechanical approach to metal-matrix composites 491

Abstract 492

1. Introduction 492
2. Blunting of the notch tip due to matrix yielding and splitting 494
3. Influence of damage zone at the notch tip on load-COD curve 498
4. Influence of splitting on fracture behavior 502
5. Work done at notch tip and work of fracture 504
6. Fracture criteria 508
7. The influence of structural and environmental factors on fracture behavior 535

List of symbols 540

References 542

Chapter 13 (R.W. Davidge)

The mechanical properties and fracture behavior of ceramic-matrix composites (CMC) reinforced with continuous fibers 547

Abstract 548

1. Introduction 548
2. Practical systems and fabrication considerations 549
3. Unidirectional composites - Basic behavior 552
4. Test methods 558
5. Experimental data 561
6. Conclusion 567

References 568

Chapter 14 (R. Warren and V.K. Sarin)

Fracture of whisker-reinforced ceramics 571

Abstract 572

1. Introduction 572

2. General description of whisker-reinforced ceramics	573
3. Micromechanics of fiber and whisker reinforcement	579
4. Brief qualitative preview of toughening mechanisms	587
5. Whisker toughening models	593
6. Effects of whiskers on strength variability (Weibull statistics)	601
7. Sub-critical crack growth - High-temperature and fatigue fracture	602
8. Experimental studies	605
9. Conclusions	610
List of symbols	611
References	612

Chapter 15 (W. Bonfield and J.C. Behiri)

Fracture toughness of natural composites with reference to cortical bone 615

Abstract 615

1. Structure of bone	616
2. Mechanical properties of cortical bone	618
3. Fracture mechanics of cortical bone	623
4. Conclusions	634
References	634

PART IV. CONCLUDING REMARKS

Chapter 16 (F.X. de Charentenay)

Concluding remarks on the application of fracture mechanics to composite materials 639

1. Introduction	639
2. Is fracture mechanics applicable?	639
3. The definition of fracture mechanics parameters	640
4. Anisotropy	641
5. Micromechanics and damages	641
6. Conclusions	642
References	644

Author Index 645

Subject Index 661

PART I

General Aspects

Chapter 1

Fracture Mechanics of Anisotropic Materials

J.G. WILLIAMS

Mechanical Engineering Department, Imperial College, London, UK

Contents

Abstract	3
1. Introduction	4
2. Basic considerations	5
3. G determinations	9
3.1. Method of analysis	10
3.2. Double cantilever beam (DCB) tests	12
3.3. A variable-ratio mixed-mode test	15
3.4. Large displacements in DCB tests	15
3.5. Transverse splitting from notches	18
3.6. Buckling under compression	20
4. Stability	22
5. Cracks in anisotropic sheets	25
5.1. Basic method	25
5.2. The crack problem	29
5.3. The calculation of G	32
5.4. The calculation of K	33
6. Damage zones	35
7. Conclusions	36
List of symbols	37
References	38

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

$$dA = B da.$$

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

$$\dot{U}_e = \dot{U}_d + \dot{U}_s + \dot{U}_k + BR\dot{a}, \quad (1)$$

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

$$G = \frac{1}{B} \left(\frac{dU_e}{da} - \frac{dU_s}{da} \right), \quad (2)$$

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

$$BG\dot{a} = \dot{U}_e - \dot{U}_s = BR\dot{a}, \quad \text{i.e.,} \quad G = R.$$

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