David Broek

ELEMENTARY ENGINEERING FRACTURE MECHANICS

Third revised edition

Martinus Nijhoff Publishers

Elementary engineering fracture mechanics

DAVID BROEK

1982
MARTINUS NIJHOFF PUBLISHERS
THE HAGUE/BOSTON/LONDON

Distributors:

for the United States and Canada

Kluwer Boston, Inc.
190 Old Derby Street
Hingham, MA 02043
USA

for all other countries

Kluwer Academic Publishers Group
Distribution Center
P.O. Box 322
3300 AH Dordrecht
The Netherlands

Library of Congress Catalog Card Number 82-45135

ISBN 90-247-2580-1 (hard back)

ISBN 90-247-2656-5 (paperback)

Copyright © 1982 by Martinus Nijhoff Publishers, The Hague.

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, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher,
Martinus Nijhoff Publishers, P.O. Box 566, 2501 CN The Hague, The Netherlands.

PRINTED IN THE NETHERLANDS

Elementary engineering fracture mechanics

Preface to the first edition

When asked to start teaching a course on engineering fracture mechanics, I realized that a concise textbook, giving a general oversight of the field, did not exist. The explanation is undoubtedly that the subject is still in a stage of early development, and that the methodologies have still a very limited applicability. It is not possible to give rules for general application of fracture mechanics concepts. Yet our comprehension of cracking and fracture behaviour of materials and structures is steadily increasing. Further developments may be expected in the not too distant future, enabling useful prediction of fracture safety and fracture characteristics on the basis of advanced fracture mechanics procedures. The user of such advanced procedures must have a general understanding of the elementary concepts, which are provided by this volume.

Emphasis was placed on the practical application of fracture mechanics, but it was aimed to treat the subject in a way that may interest both metallurgists and engineers. For the latter, some general knowledge of fracture mechanisms and fracture criteria is indispensable for an appreciation of the limitations of fracture mechanics. Therefore a general discussion is provided on fracture mechanisms, fracture criteria, and other metallurgical aspects, without going into much detail. Numerous references are provided to enable a more detailed study of these subjects which are still in a stage of speculative treatment. Metallurgists and mechanicists need to know the particular problems of industry in order to be able to respond to the demands of engineers. Therefore, some pertinent practical problems are discussed.

No attempt was made to present a detailed review of every aspect of

此为试读,需要完整PDF请访问: www.ertongbook.com

the principles and application of fracture mechanics. Such a treatment has already been given in the seven volumes "Fracture, An advanced treatise", edited by Liebowitz. Instead, as the title indicates, an attempt was made to deal with the elementaries and with those engineering applications that have found some acceptance. The text may serve as an introduction to the literature and as a basis for the understanding of forthcoming development. Although I have tried to arrive at a balanced presentation of the various subjects, the treatment of certain subjects may betray my personal interests.

In view of the stage of development of fracture mechanics, a certain degree of speculation could not be avoided. Where appropriate, speculative discussions are specified as such. Attention is focussed on subjects that are promising for quantitative use in design. Qualitative fracture analysis procedures and testing, such as the use of Charpy test data, Robertson tests and dynamic tear tests, are not considered, because these have been amply treated elsewhere.

The text is considered suitable for advanced undergraduate or first year graduate students. But it may also serve as a general introduction to this relatively new discipline for engineers and metallurgists who have not been confronted earlier with fracture mechanics.

I am indebted to my former colleagues at the National Aerospace Laboratory N.L.R., in whose enthusiastic fracture mechanics group I participated during twelve years. Without their encouragement I would not have developed to a stage where writing this text would have been possible. In particular, I want to thank Dr. R. J. H. Wanhill, who scrutinized the text and made many useful suggestions for improvement. I am grateful to Miss Lucy Loomans for her assistance in the preparation of the manuscript, to Mr. L. van de Eijkel for the art work, and to Ir. B. Pennekamp for his help in correcting the proofs. Finally, I want to apologize to all who have suffered from my limited interest in other matters during preparation of the manuscript.

Delft, January 1974 David Broek

Preface to the second edition

Since the publication of the first edition the prediction of fatigue crack propagation has become common practice in several areas of industry. Therefore it seemed appropriate to add an extra chapter 17 dealing with crack growth prediction. Apart from that this second edition is essentially the same as the first, although a few areas, such as dynamic fracture and mixed mode loading, were expanded.

I want to emphasize that the objective of this book is to deal in particular with those areas of fracture mechanics that have found practical application. The background, assumptions and limitations are presented and the problems of engineering application are pointed out. The text touches upon matters presently under development, but I do not believe that more extensive treatment is appropriate in a textbook on engineering fracture mechanics.

I am grateful for the many appreciative comments I received upon publication of the first edition.

Columbus, May 1978 David Broek

Preface to the third edition

During the last five years a considerable amount of research on elastic-plastic fracture mechanics has been conducted. Although elastic-plastic fracture concepts are still mostly in the stage of paper and laboratory studies, some technical applications begin to emerge. Therefore it seemed appropriate to expand this text to cover elastic-plastic fracture mechanics in more detail. To this end, the J integral has been given more coverage in chapter 5 as an energy concept and in chapter 9 as a stress field parameter and a fracture criterion, whereas chapter 15 has been extended with a discussion of the practical aspects of fracture predictions in structures of high toughness materials.

In the area of fatigue crack propagation, a more detailed discussion of similitude requirements was felt necessary. This resulted in an extension of chapter 10.

It is the aim of this book to show the use and application of fracture mechanics to practical problems. The numerous compromises that have to be made in practical applications have to be based on sound engineering judgement. For this reason shortcomings and limitations of the various fracture mechanics concepts are strongly emphasized, and on the other hand, approximative and simplified concepts are amply discussed because they are often more useful than the "formal" methods.

I am grateful that there is still sufficient interest in this text, so that the publisher would entertain a third edition.

Columbus, January 1981 David Broek

Contents

Preface to the first edition XI
Preface to the second edition XIII
Preface to the third edition XIV

Part I PRINCIPLES

Chapter 1

Summary of basic problems and concepts 3

1.1 Introduction 3
1.2 A crack in a structure 6
1.3 The stress at a crack tip 8
1.4 The Griffith criterion 15
1.5 The crack opening displacement criterion 17
1.6 Crack propagation 18
1.7 Closure 22

Chapter 2

Mechanisms of fracture and crack growth 24

2.1 Introduction 24
2.2 Cleavage fracture 31
2.3 Ductile fracture 38
2.4 Fatigue cracking 48
2.5 Environment assisted cracking 59
2.6 Service failure analysis 62

Chapter 3

The elastic crack-tip stress field 67

3.1 The Airy stress function 67
3.2 Complex stress functions 68
3.3 Solution to crack problems 69
3.4 The effect of finite size 73
3.5 Special cases 77
3.6 Elliptical cracks 80
3.7 Some useful expressions 86

Chapter 4

The crack tip plastic zone 91

4.1 The Irwin plastic zone correction 91
4.2 The Dugdale approach 94
4.3 The shape of the plastic zone 96
4.4 Plane stress *versus* plane strain 101
4.5 Plastic constraint factor 105
4.6 The thickness effect 107

Chapter 5

The energy principle 115

5.1 The energy release rate 115
5.2 The criterion for crack growth 119
5.3 The crack resistance (R curve) 122
5.4 Compliance 127
5.5 The J integral 131
5.6 Tearing modulus 136
5.7 Stability 137

Chapter 6

Dynamics and crack arrest 142

6.1 Crack speed and kinetic energy 142
6.2 The dynamic stress intensity and elastic energy release rate 147
6.3 Crack branching 150
6.4 The principles of crack arrest 155
6.5 Crack arrest in practice 162
6.6 Dynamic fracture toughness 165

Chapter 7

Plane strain fracture toughness 170

7.1 The standard test 170
7.2 Size requirements 174
7.3 Non-linearity 177
7.4 Applicability 181

Chapter 8

Plane stress and transitional behaviour 185

8.1 Introduction 185
8.2 An engineering concept of plane stress 185
8.3 The *R* curve concept 193
8.4 The thickness effect 199
8.5 Plane stress testing 208
8.6 Closure 216

此为试读,需要完整PDF请访问: www.ertongbook.com

Chapter 9

Elastic-plastic fracture 219

9.1 Fracture beyond general yield 219
9.2 The crack tip opening displacement 221
9.3 The possible use of the CTOD criterion 224
9.4 Experimental determination of CTOd 225
9.5 Parameters affecting the critical CTOD 228
9.6 Limitations, fracture at general yield 231
9.7 Use of the J integral 235
9.8 Limitations of the J integral 237
9.9 Measurement of J_{Ic} and J_R 240
9.10 Closure 245

Chapter 10

Fatigue crack propagation 250

10.1 Introduction 250
10.2 Crack growth and the stress intensity factor 250
10.3 Factors affecting crack propagation 256
10.4 Variable amplitude service loading 262
10.5 Retardation models 266
10.6 Similitude 271
10.7 Small cracks 278
10.8 Closure 282

Chapter 11

Fracture resistance of materials 288

11.1 Fracture criteria 295
11.2 Fatigue cracking criteria 295
11.3 The effect of alloying and second phase particles 297
11.4 Effect of processing, anisotropy 304
11.5 Effect of temperature 309
11.6 Closure 311

Part II APPLICATIONS

Chapter 12

Fail-safety and damage tolerance 317

12.1 Introduction 317
12.2 Means to provide fail-safety 318
12.3 Required information for fracture mechanics approach 323
12.4 Closure 326

Chapter 13

Determination of stress intensity factors 328

13.1 Introduction 328
13.2 Analytical and numerical methods 330
13.3 Finite element methods 330
13.4 Experimental methods 338

Chapter 14

Practical problems 347

14.1 Introduction 347
14.2 Through cracks emanating from holes 347
14.3 Corner cracks at holes 352
14.4 Cracks approaching holes 356
14.5 Combined loading 359
14.6 Fatigue crack growth under mixed mode loading 366
14.7 Biaxial loading 369
14.8 Fracture toughness of weldments 371
14.9 Service failure analysis 374

Chapter 15

Fracture of structures 377

15.1 Introduction 377
15.2 Pressure vessels and pipelines 378
15.3 "Leak-before-break" criterion 388
15.4 Material selection 392
15.5 The use of the J integral for structural analysis 396
15.6 Collapse analysis 399
15.7 Accuracy of fracture calculations 404

Chapter 16

Stiffened sheet structures 408

16.1 Introduction 408
16.2 Analysis 409
16.3 Fatigue crack propagation 413
16.4 Residual strength 415
16.5 The R curve and the residual strength of stiffened panels 422
16.6 Other analysis methods 425
16.7 Crack arrest 427
16.8 Closure 431

Chapter 17

Prediction of fatigue crack growth 434

17.1 Introduction 434
17.2 The load spectrum 435
17.3 Approximation of the stress spectrum 437
17.4 Generation of a stress history 439
17.5 Crack growth integration 441
17.6 Accuracy of predictions 447
17.7 Safety factors 452

Author index 455

Subject index 462

Part I

Principles

1 Summary of basic problems and concepts

1.1 Introduction

Through the ages the application of materials in engineering design has posed difficult problems to mankind. In the Stone Age the problems were mainly in the shaping of the material. In the early days of the Bronze Age and the Iron Age the difficulties were both in production and shaping. For many centuries metal-working was laborious and extremely costly. Estimates go that the equipment of a knight and horse in the thirteenth century was of the equivalent price of a Centurion tank in World War II.

With the improving skill of metal working, applications of metals in structures increased progressively. Then it was experienced that structures built of these materials did not always behave satisfactorily, and unexpected failures often occurred. Detailed descriptions of castings and forgings produced in the Middle Ages exist. When judged with present day knowledge, these production methods must have been liable to build important technical deficiences into the structure. This must have made gunners pray—when igniting the charge—that the projectile would be properly delivered and the barrel not blown up ...

The vastly increasing use of metals in the nineteenth century caused the number of accidents and casualties to reach unknown levels. The number of people killed in railway accidents in Great Britain was in the order of two hundred per year during the decade 1860–1870. Most of the accidents were a result of derailing caused by fractures of wheels, axles or rails. Anderson [1] has recently made an interesting compilation of accident reports from the last two hundred years. A few quotations follow:

此为试读,需要完整PDF请访问: www.ertongbook.com