ENGINEERING FRACTURE MECHANICS

S. A. MEGUID

ENGINEERING FRACTURE MECHANICS

S. A. MEGUID

Department of Mechanical Engineering,
University of Toronto,
Canada

ELSEVIER APPLIED SCIENCE
LONDON and NEW YORK

ELSEVIER SCIENCE PUBLISHERS LTD
Crown House, Linton Road, Barking, Essex IG11 8JU, England

Sole Distributor in the USA and Canada
ELSEVIER SCIENCE PUBLISHING CO., INC.
655 Avenue of the Americas, New York,
NY 10010, USA

WITH 16 TABLES AND 195 ILLUSTRATIONS

British Library Cataloguing in Publication Data

Meguid, S. A.
Engineering fracture mechanics.
1. Materials. Fracture. Mechanics
I. Title
620.1'126

Library of Congress Cataloging-in-Publication Data

Meguid, S. A.
Engineering fracture mechanics.

Includes bibliographies and index.
1. Fracture mechanics. I. Title
TA409.M443 1989 620.1'126 88-24440

ISBN 1-85166-282-0

Phototypesetting by Tech-Set, Gateshead, Tyne & Wear
Printed in Great Britain by Galliard (Printers) Ltd, Great Yarmouth

Preface

Fracture mechanics, in its broad aspects, represents the applied mechanics framework necessary for the description of the behaviour of cracked components under applied loads. In common with other branches of continuum mechanics, the growth of this subject proceeded from a synthesis of special ideas and techniques devised to solve specific problems. This resulted in a patchwork of theories treating isolated classes of problems. The embedding of such diverse theories in a unified structure and the construction of the analytical, numerical and experimental tools necessary for the determination of the stress and strain fields in a cracked body are amongst the dominant features of the present effort.

This book, which presents an up-to-date account of the behaviour of cracked bodies, has been primarily written for engineers, designers, inspectors, educationalists and researchers working in the field of fracture mechanics. The choice of the subject matter was determined largely by the needs of aeronautical, mechanical and civil engineers and naval architects, although it is believed that the subject matter will be found just as useful for metallurgists and material scientists working in this important field.

It is an integrated effort which contains a compilation of the work of many investigators and accounts for some of the author's most recent work on the subject. It is believed that the order of presentation and rigour of covered topics differ significantly from other available texts. The arrangement of the material is the result of the author's experience in research and in teaching graduate and undergraduate courses in structural integrity, fracture mechanics and design at the University of Toronto, Cranfield Institute of Technology, Oxford Engineering Science Department and the University of Manchester Institute of

Science and Technology (UMIST) during the past 20 years.

Throughout the text, the author has tried to give a clear indication of the frontiers of the developments and has constantly kept in mind those readers whose principal concern is with the practical application of the theory. To this end, Chapter 1 is devoted to establishing the fundamental equations and assumptions underlying the entire field of fracture mechanics. Both Airy's stress function and Muskhelishvili's complex potentials as well as the pertinent aspects governing the elastic and elasto-plastic behaviours of solids are given the right coverage to provide the reader with the background knowledge and confidence necessary to pursue the subject matter fully. In Chapter 2, a detailed description of the different modes of failure is provided. In view of its importance to the basic concepts adopted in unstable crack growth, the author has devoted Chapter 3 to examining the critical parameters influencing and promoting brittle fracture via the use of a relevant case history. The energy balance approach, for ideally brittle materials, due to Griffith and the modified postulate due to Irwin and Orowan, for typical engineering materials, have also been considered.

Chapter 4 provides the foundation for linear elastic fracture mechanics (LEFM), enforces the concept of the stress intensity factor K as a characterising fracture parameter and outlines the similitude principle. A detailed description of the analytical, numerical and experimental techniques adopted in the determination of the stress intensity factor and the mixed-mode problem have also been provided in the same chapter. In view of the large stresses present in the vicinity of a crack-tip, it is inevitable that some plasticity will develop. Chapter 5 deals with the description of the plastic zone size and shape for cases involving limited plasticity. It is in this chapter that we identify the design concepts relating to the fracture toughness of the material, K_{Ic}.

In Chapter 6, non-linear effects are encountered and the principles of elasto-plastic fracture mechanics (EPFM) are outlined. Both Rice's J-integral and Well's crack opening displacement (COD) concepts have been given the deserved coverage; the theoretical and experimental aspects of both techniques are considered.

The pertinent aspects of fatigue crack growth and the residual strength necessary for the prediction of service lives of engineering structures are provided in Chapter 7. Both long and short crack propagation, including the 'anomalous' behaviour of cracks, have been examined and the critical aspects of fatigue crack growth are investigated with reference to the Kitagawa–Takahashi diagram.

Special attention has been given to cracks emanating from high stress concentration features.

The subject matter is then supported by a number of pertinent case studies, relating to the aerospace industry, designed to highlight the application of the principles of fracture mechanics towards the improvement of the structural integrity of mechanical components. This is detailed in Chapter 8. Indeed, it is in this chapter that we provide the reader with the new fatigue design concepts which have recently been incorporated in standards and codes of practice.

Chapter 9 assembles most of the experimental techniques currently adopted in fracture mechanics. The material contained in this chapter is intended to provide knowledge of the principles, procedures, application and limitations of these techniques. Essentially, the material included in the book is self-contained and the readers are required to have an acquaintance with the basic fundamentals of the relevant courses.

Finally, I wish to acknowledge the support, patience and understanding of my wife Eli and daughter Jenna during the different stages of this project; their sacrifice was immense — my gratitude is profound.

S. A. MEGUID

Contents

Chapter 1

Fundamentals of Elastic and Plastic Behaviours of Solids

In this chapter we shall discuss briefly some of the essential topics of the theories of elasticity and plasticity which are pertinent to the subject of fracture mechanics. Every attempt has been made to provide the reader with the necessary background to enable him or her to pursue the subject matter more fully and effectively. Further details of the topics covered can be obtained from, for example, Refs [1.1]–[1.16].

1.1 THE SIGN CONVENTIONS

In this text the normal stresses are denoted σ_{xx}, σ_{yy} and σ_{zz} and the shear stresses are denoted τ_{xy}, τ_{yz} and τ_{zx}. Figure 1.1 shows a general three-dimensional element in a field of uniform stress. The stresses shown are all positive, and this figure establishes the sign conventions used throughout this text. The subscripts on the stresses define their location and orientation. For example, the shearing stress τ_{xy} denotes a stress acting on the face of the element which is perpendicular to the x-axis with the stress acting in the direction of the y-axis.

1.2 THE STATE OF STRESS AT A POINT

One cannot ask for the stresses at a given point in a body, since there is an infinite number of stresses in existence at any one point; one resultant stress corresponding to each distinctly inclined plane passing through the point. The request must be made for either the stresses at the point which act on a given plane passing through it, or, more generally, the stresses acting on all planes passing through that point. Both of

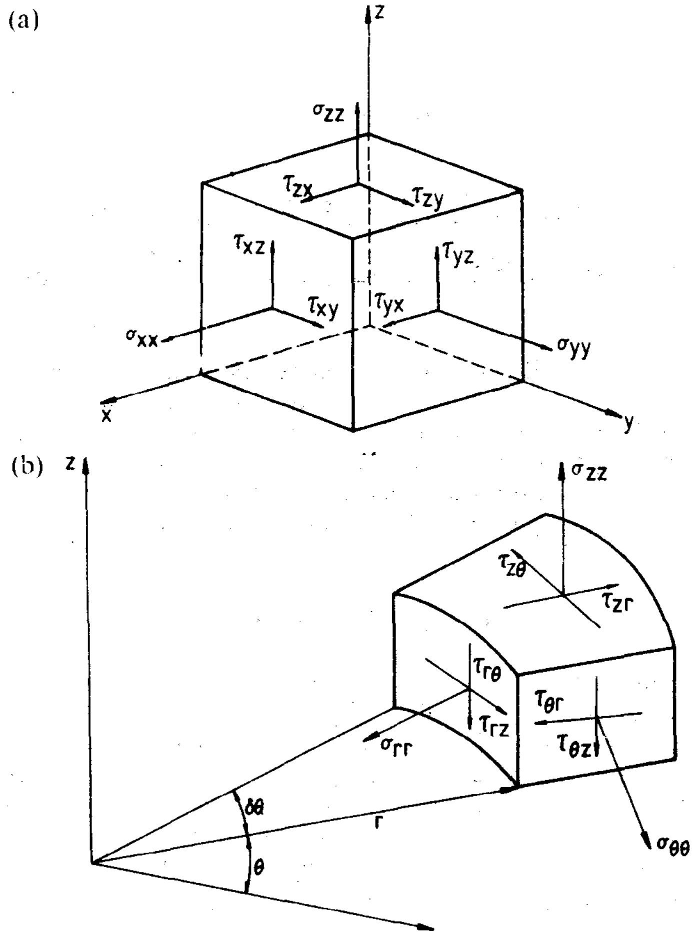


Fig. 1.1. Sign conventions: (a) stress components referred to cartesian co-ordinates; (b) stress components referred to cylindrical polar co-ordinates.

these requests can be answered very simply if the stresses at the point which act on planes, for example, parallel to the cartesian co-ordinates are known

Typically, as shown in Fig. 1.1, the state of stress at the point can be given by the cartesian stresses

$$\begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix} \tag{1.1}$$

or, equivalently, it may be given in terms of the cylindrical polar components

$$\begin{bmatrix} \sigma_{rr} & \tau_{r\theta} & \tau_{rz} \\ \tau_{\theta r} & \sigma_{\theta\theta} & \tau_{\theta z} \\ \tau_{zr} & \tau_{z\theta} & \sigma_{zz} \end{bmatrix} \tag{1.2}$$

or simply by the stress tensor σ_{ij}.

Actually, not all the nine components of the stress are independent, since rotational equilibrium enforces

$$\left.\begin{aligned} \tau_{ij} &= \tau_{ji} \\ \text{i.e.} \quad \tau_{xy} &= \tau_{yx},\ \tau_{yz} = \tau_{zy} \text{ and } \tau_{zx} = \tau_{xz} \end{aligned}\right\} \tag{1.3}$$

or equivalently

$$\tau_{r\theta} = \tau_{\theta r},\ \tau_{\theta z} = \tau_{z\theta} \text{ and } \tau_{zr} = \tau_{rz} \tag{1.4}$$

thus indicating that there are only three independent shear stresses. Consequently, the complete three-dimensional uniform stress field at a point can be determined by six stresses. Since these are tensor quantities, they must be measured in terms of a defined set of co-ordinate axes as indicated above by expressions (1.1) and (1.2).

1.3 STRESS BOUNDARY CONDITIONS

The prescribed force intensities acting on the surface of a solid tetrahedron, S, are denoted by the quantities S_{xx}, S_{yy} and S_{zz}. Force equilibrium at the boundary of the tetrahedron shown in Fig. 1.2 requires that

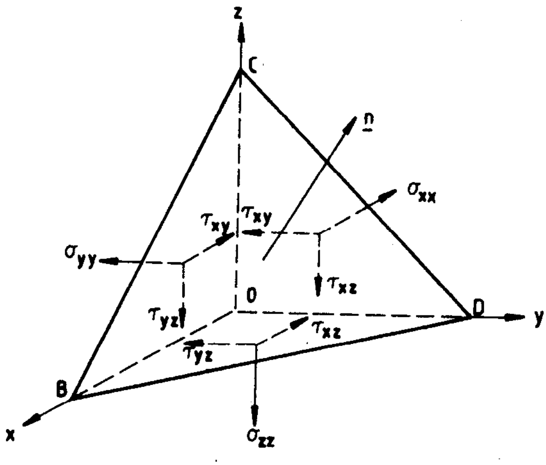
$$\begin{bmatrix} S_{xx} \\ S_{yy} \\ S_{zz} \end{bmatrix} = \begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix} \begin{bmatrix} l \\ m \\ n \end{bmatrix} \tag{1.5}$$

where l, m and n are the direction cosines of the normal $\boldsymbol{n}$ and are given by

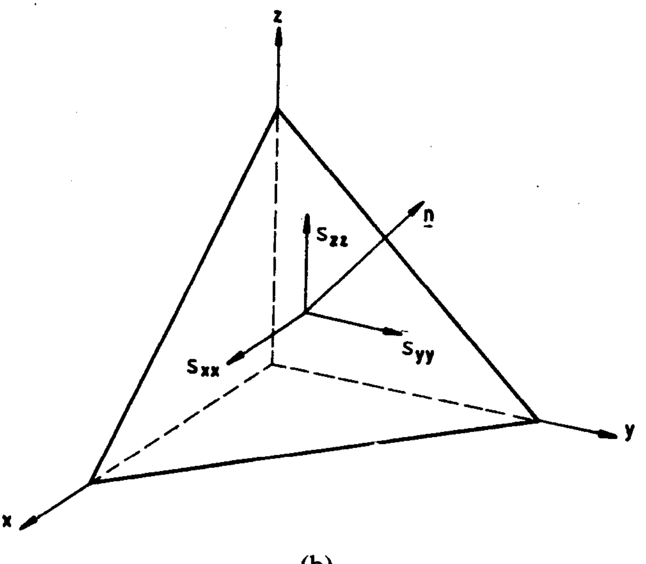
$$l = \cos(\boldsymbol{n}, x),\ m = \cos(\boldsymbol{n}, y), n = \cos(\boldsymbol{n}, z) \tag{1.6}$$

1.4 EIGENVALUES AND EIGENVECTORS OF STRESS TENSOR

The characteristic equation needed for determining the eigenvalues and eigenvector for the stress tensor, σ_{ij}, is given by



(a)



(b)

Fig. 1.2. Forces on an infinitesimal tetrahedron: (a) stress state at a point; (b) components of resultant stress vector.

$$[\sigma_{ij} - \sigma\delta_{ij}]\,[l_j] = 0 \tag{1.7}$$

with

$$[l_j]\,[l_j]^{\mathrm{T}} = 1 \tag{1.8}$$

or in the long form by

$$\begin{bmatrix} \sigma_{xx} - \sigma & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} - \sigma & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} - \sigma \end{bmatrix} \begin{bmatrix} l \\ m \\ n \end{bmatrix} = 0 \tag{1.9}$$

with

$$[l \;\; m \;\; n] \begin{bmatrix} l \\ m \\ n \end{bmatrix} = 1 \tag{1.10}$$

Equations (1.9) are homogeneous in the variables (l, m, n) and can admit a non-trivial solution if, and only if, the determinant

$$|\sigma_{ij} - \sigma\delta_{ij}| = 0 \tag{1.11}$$

i.e.

$$\begin{vmatrix} \sigma_{xx} - \sigma & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} - \sigma & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} - \sigma \end{vmatrix} = 0 \tag{1.12}$$

or

$$\sigma^3 - I_1\sigma^2 + I_2\sigma - I_3 = 0$$

where

$$I_1 = \sigma_{ii} = \sigma_{xx} + \sigma_{yy} + \sigma_{zz}$$
$$I_2 = \tfrac{1}{2}(\sigma_{ii}\sigma_{jj} - \sigma_{ij}\sigma_{ji})$$

i.e.

$$I_2 = \begin{vmatrix} \sigma_{xx} & \tau_{xy} \\ \tau_{yx} & \sigma_{yy} \end{vmatrix} + \begin{vmatrix} \sigma_{yy} & \tau_{yz} \\ \tau_{zy} & \sigma_{zz} \end{vmatrix} + \begin{vmatrix} \sigma_{xx} & \tau_{xz} \\ \tau_{zx} & \sigma_{zz} \end{vmatrix}$$

and

$$I_3 = \begin{vmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{vmatrix}$$

I_1, I_2 and I_3 are known as the stress invariants.