FRACTURE MECHANICS

SOLID MECHANICS AND ITS APPLICATIONS
Volume 123

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Aims and Scope of the Series

The fundamental questions arising in mechanics are: *Why?, How?,* and *How much?* The aim of this series is to provide lucid accounts written bij authoritative researchers giving vision and insight in answering these questions on the subject of mechanics as it relates to solids.

The scope of the series covers the entire spectrum of solid mechanics. Thus it includes the foundation of mechanics; variational formulations; computational mechanics; statics, kinematics and dynamics of rigid and elastic bodies: vibrations of solids and structures; dynamical systems and chaos; the theories of elasticity, plasticity and viscoelasticity; composite materials; rods, beams, shells and membranes; structural control and stability; soils, rocks and geomechanics; fracture; tribology; experimental mechanics; biomechanics and machine design.

The median level of presentation is the first year graduate student. Some texts are monographs defining the current state of the field; others are accessible to final year undergraduates; but essentially the emphasis is on readability and clarity.

For a list of related mechanics titles, see final pages.

Fracture Mechanics

An Introduction

Second Edition

by

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Springer

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Cover picture:
Image of an indent performed with a cube corner indenter loaded with a force of 2 mN in a low-k dielectric film on a silicon wafer. The film has a thickness of 600 nm. Cracks emanating from the corners of the indenter are shown. Courtesy of Hysitron Inc., Minneapolis, Minnesota, USA

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Contents

Conversion table

Length	
1 m = 39.37 in	1 in = 0.0254 m
1 ft = 0.3048 m	1 m = 3.28 ft
Force	
1 N = 0.102 Kgf	1 Kgf = 9.807 N
1 N = 0.2248 lb	1 lb = 4.448 N
1 dyne = 10^{-5} N	
1 kip = 4.448 kN	1 kN = 0.2248 kip
Stress	
1 Pa = 1 N/m^2	
1 lb/in^2 = 6.895 kPa	1 kPa = 0.145 lb/in^2
1 ksi = 6.895 MPa	1 MPa = 0.145 ksi
Stress intensity factor	
1 MPa$\sqrt{\text{m}}$ = 0.910 ksi$\sqrt{\text{in}}$	1 ksi$\sqrt{\text{in}}$ = 1.099 MPa$\sqrt{\text{m}}$

Preface to the Second Edition

Since the first edition of the book, new developments in the applications of fracture mechanics to engineering problems have taken place. Composite materials have been used extensively in engineering applications. Quasi-brittle materials including concrete, cement pastes, rock, soil, etc. are benefiting from fracture mechanics. Layered materials and especially thin film/substrate systems are becoming important in small volume systems used in micro- and nano-electromechanical systems (MEMS and NEMS). Nanostructured materials are being introduced into our everyday life. In all these problems fracture mechanics plays a major role for the prediction of failure and safe design of materials and structures. These new challenges motivated me to proceed with the Second Edition of the book.

The second edition contains four new chapters in addition to the ten chapters of the first edition. The fourteen chapters of the book cover the basic principles and traditional applications, as well as the latest developments of fracture mechanics as applied to problems of composite materials, thin films, nanoindentation and cementitious materials. Thus the book provides an introductory coverage of the traditional and contemporary applications of fracture mechanics in problems of the utmost technological importance.

Chapter 11 presents an analysis of the effects of cracks and delaminations on the strength of laminated fiber composites using the principles of fracture mechanics. The strength of composites with through-thickness cracks and the delamination of laminated composites under mode-I, mode-II, mode-III and mixed-mode I and II loading are studied. In Chapter 12 the principles of fracture mechanics are applied to layered materials and especially to thin film/substrate systems. The problems of interfacial fracture and test methods for measuring thin film adhesion are studied. In these applications the thickness of the film is measured in nanometers or micrometers, while the thickness of the substrate typically is in the order of millimeters or centimeters. In Chapter 13 we present the basic principles of nanoindentation for measuring the mechanical properties, fracture toughness of brittle materials and interface fracture toughness of thin films on substrates. Finally, Chapter 14 presents the basic principles of fracture mechanics of cementitious materials with emphasis on concrete. The importance of the fracture process zone ahead of the macrocrack where the material presents strain softening behavior is analyzed. Experimental methods for measuring the fracture toughness are presented and the importance of the size effect in concrete structures is analyzed.

With the addition of the four new chapters the book provides a comprehensive treatment of fracture mechanics. It includes the basic principles and traditional applications as well as the new frontiers of fracture mechanics during the last two decades in topics of contemporary importance such as composites, thin films, nanoindentation and cementitious materials.

Xanthi, Greece, 2004 EMMANUEL E. GDOUTOS

Preface

Traditional failure criteria cannot adequately explain many structural failures that occur at stress levels considerably lower than the ultimate strength of the material. Example problems include bridges, tanks, pipes, weapons, ships, railways and aerospace structures. On the other hand, experiments performed by Griffith in 1921 on glass fibers led to the conclusion that the strength of real materials is much smaller, typically by two orders of magnitude, than their theoretical strength. In an effort to explain these phenomena the discipline of fracture mechanics has been created. It is based on the realistic assumption that all materials contain crack-like defects which constitute the nuclei of failure initiation. A major objective of fracture mechanics is to study the load-carrying capacity of structures in the presence of initial defects, where a dominant crack is assumed to exist.

A new design philosophy is therefore introduced by fracture mechanics as opposed to the use of the traditional fracture criteria. Since structures that have no defects cannot be constructed on the grounds of practicality, the safe design of structures should proceed along two lines: either the safe operating load should be determined when a crack of a prescribed size is assumed to exist in the structure; or, given the operating load, the size of the crack that is created in the structure should be determined.

Design by fracture mechanics necessitates knowledge of a critical crack size and a parameter which characterizes the propensity of a crack to extend. Such a parameter should be able to relate laboratory test results to structural performance, so that the response of a structure with cracks can be predicted from laboratory test data. This is determined as a function of material behavior, crack size, structural geometry and loading conditions. On the other hand, the critical value of this parameter – known as fracture toughness, a property of the material – is determined from laboratory tests. Fracture toughness expresses the ability of the material to resist fracture in the presence of cracks. By equating this parameter to its critical value we obtain a relation between applied load, crack size and structure geometry which gives the necessary information for structural design. Fracture toughness is used to rank the ability of a material to resist fracture within the framework of fracture mechanics, in the same way that yield or ultimate strength is used to rank the resistance of the material to yield or fracture in the conventional design criteria. In selecting materials for structural applications we must choose between materials with a high yield strength, but comparatively low fracture toughness, or those with a lower yield strength, but higher fracture toughness.

This book has been prepared to meet the continuing demand for a text designed to present a clear, consistent, straightforward and unified interpretation of the basic concepts and underlying principles of the discipline of fracture mechanics. A general survey of the field would serve no purpose other than give a collection of references and outline equations and results. A realistic application of fracture mechanics could not be made without a sound understanding of the fundamentals. The book is self-contained; the presentations are concise and each topic can be understood by advanced undergraduates in material science and continuum mechanics. Each chapter contains illustrative example problems and homework problems. A total of about fifty example problems and more than two hundred unsolved problems are included in the book.

The book is divided into ten chapters. The first, introductory, chapter gives a brief account of some characteristic failures that could not be explained by the traditional failure criteria, and of Griffith's experiments which gave impetus to the development of a new philosophy in engineering design based on fracture mechanics. The next two chapters deal with the determination of the stress and deformation fields in cracked bodies, and provide the necessary prerequisite for the development of the criteria of fracture mechanics. More specifically, Chapter 2 covers the Westergaard method for determining the linear elastic stress field in cracked bodies, with particular emphasis on the local behavior around the crack tip, and Chapter 3 is devoted to the determination of the elastic-plastic stress and displacement distribution around cracks for time-independent plasticity. Addressed in the fourth chapter is the theory of crack growth based on the global energy balance of the entire system. The fifth chapter is devoted to the critical stress intensity factor fracture criterion. The sixth chapter deals with the theoretical foundation of the path-independent J-integral and its use as a fracture criterion. Furthermore, a brief presentation of the crack opening displacement fracture criterion is given. Chapter 7 studies the underlying principles of the strain energy density theory and demonstrates its usefulness and versatility in solving a host of two- and three-dimensional problems of mixed-mode crack growth in brittle and ductile fracture. Chapter 8 presents in a concise form the basic concepts and the salient points of dynamic fracture mechanics. Addressed in Chapter 9 is the phenomenon of fatigue and environment-assisted crack growth which takes place within the framework of the macroscopic scale level. Finally, Chapter 10 briefly outlines the basic mechanisms of fracture which take place in metals at the microscopic scale level and presents a concise description of the more widely used nondestructive testing methods for defect detection.

Most of the material of the theoretical presentation of the various chapters of the book is contained in the previous book by the author *Fracture Mechanics Criteria and Applications*, published By Kluwer Academic Publishers. That book contains a more detailed description of the various aspects of fracture mechanics than the present book and includes an extensive list of references for further study. The present book was especially written as a potential textbook for fracture mechanics courses at undergraduate and postgraduate level. The instructive character of the book is enhanced by many illustrative example problems and homework problems included in each chapter.

The author wishes to express his gratitude to Professor G.C. Sih for very stimulating discussions and his comments and suggestions during the writing of the book. Thanks are also extended to my secretary Mrs L. Adamidou for typing the manuscript and to my student Mr N. Prassos for the preparation of illustrations. Finally, I wish to express my profound gratitude to my wife, Maria, and my children, Eleftherios and Alexandra-Kalliope for their understanding and patience during the writing of the book.

Xanthi, Greece, 1993 EMMANUEL E. GDOUTOS