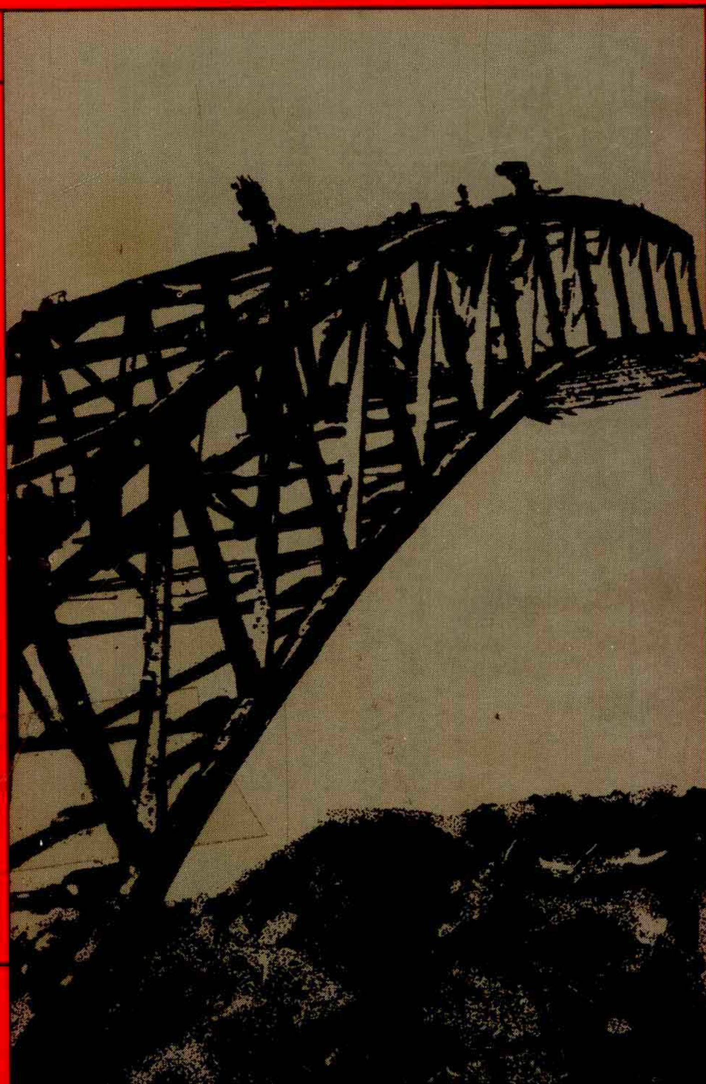
FRACTURE & FATIGUE CONTROL IN STRUCTURES

APPLICATIONS OF FRACTURE MECHANICS

SECOND EDITION



JOHN M. BARSOM
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Applications of Fracture Mechanics

SECOND EDITION

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To
Valentina and Phyllis

Foreword

In his well-known text on "Mathematical Theory of Elasticity," Love inserted brief discussions of several topics of engineering importance for which linear elastic treatment appeared inadequate. One of these topics was rupture. Love noted that various safety factors, ranging from 6 to 12 and based upon ultimate tensile strength, were in common use. He commented that "the conditions of rupture are but vaguely understood." The first edition of Love's treatise was published in 1892. Fifty years later, structural materials had been improved with a corresponding decrease in the size of safety factors. Although Love's comment was still applicable in terms of engineering practice in 1946, it is possible to see in retrospect that most of the ideas needed to formulate the mechanics of fracturing on a sound basis were available. The basic content of modern fracture mechanics was developed in the 1946 to 1966 period. Serious fracture problems supplied adequate motivation and the development effort was natural to that time of intensive technological progress.

Mainly what was needed was a simplifying viewpoint, progressive crack extension, along with recognition of the fact that real structures contain discontinuities. Some discontinuities are prior cracks and others develop into cracks with applications of stress. The general idea is as follows. Suppose a structural component breaks after some general plastic yielding. Clearly a failure of this kind could be traced to a design error which caused inadequate section strength or to the application of an overload. The fracture failures which were difficult to understand are those which occur in a rather brittle manner at stress levels no larger than were expected when the structure was designed. Fractures of this second kind, in a special way, are also due to overloads. If one considers the stress redistribution around a pre-existing crack subjected to tension, it is clear that the region adjacent to the perimeter of the crack is overloaded due to the severe stress concentration and that local plastic strains must occur. If the toughness is limited, the plastic strains at the crack border may be accompanied by crack extension. However, from similitude, the crack border overload increases with crack size. Thus progressive crack extension tends to be self stimulating. Given a prior crack, and a material of limited toughness, the possibility for development of rapid fracturing prior to general yielding is therefore evident.

Analytical fracture mechanics provides methods for characterizing the "overload" at the leading edge of a crack. Experimental fracture mechanics collects information of practical importance relative to fracture toughness, fatigue cracking, and corrosion cracking. By centering attention on the active region involved in progressive fracturing, the collected laboratory data are in a form which can be transferred to the leading edge of a crack in a structural component. Use of fracture mechanics analysis and data has explained many service fracture failures with a satisfactory degree of quantitative accuracy. By studying the possibilities for such fractures in advance, effective fracture control plans have been developed.

Currently the most important task is educational. It must be granted that all aspects of fracture control are not yet understood. However, the information now available is basic, widely applicable, and should be integrated into courses of instruction in strength of materials. The special value of this book is the emphasis on practical use of available information. The basic concepts of fracture mechanics are presented in a direct and simple manner. The descriptions of test methods are clear with regard to the essential experimental details and are accompanied by pertinent illustrative data. The discussions of fracture control are well-balanced. Readers will learn that fracture control with real structures is not a simple task. This should be expected and pertains to other aspects of real structures in equal degree. The book provides helpful fracture control suggestions and a sound viewpoint. Beyond this the engineer must deal with actual problems with such resources as are needed. The adage "experience is the best teacher" does not seem to be altered by the publication of books. However, the present book by two highly respected experts in applications of fracture mechanics provides the required background training. Clearly the book serves its intended purpose and will be of lasting value.

George R. Irwin

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Preface

The field of fracture mechanics has become the primary approach to controlling brittle fracture and fatigue failures in structures. This book introduces the field of fracture mechanics from an application viewpoint. Since the first publication of this book in 1977, the field of fracture mechanics has grown significantly. Almost all specifications for fracture and fatigue control now either use fracture mechanics directly or are based on concepts of fracture mechanics. In this book, we emphasize applications of fracture mechanics to the fields of fracture and fatigue control in structures. We believe that the book will serve as an introduction to the field of fracture mechanics for seniors or beginning graduate students, but more importantly, it introduces the practicing engineer to a field that has become increasingly important. In recent years, structural failures and the desire for increased safety and reliability of structures have led to the development of various fracture criteria for many types of structures, including bridges, airplanes, pipelines, and nuclear pressure vessels.

The development of fracture-control plans for new and unusual structures such as offshore drilling rigs, nuclear power plants, space shuttles, etc., has become more widespread. Each of the topics of fracture criteria and fracture control is developed from an engineering viewpoint, including economic and practical considerations. The textbook should assist engineers to become aware of the fundamentals of fracture mechanics, and, in particular, of their responsibility in controlling brittle fracture and fatigue failures in structures.

Chapter 1 serves as an overview of the problem of fracture and fatigue in structures as well as an introduction to the field of fracture mechanics. Chapter 2 provides the theoretical development of stress-intensity factors, K_I, and Chapter 3 describes the test methods for obtaining critical stress intensity factors, K_{Ic}, $K_{Ic}(t)$ for intermediate loading rates, or K_{Id} for impact loading rates. Chapter 4 describes the effect of temperature, loading rate, and plate thickness on the fracture toughness of a wide variety of structural materials, primarily structural steels. Because many structural materials have fracture toughness levels outside the range of linear-elastic fracture mechanics at service temperatures and loading rates, correlations with other more common notch toughness tests are widely used, and these are described in Chapter 5. Chapter 6 describes the relationship between stress, flaw size, and material toughness, with specific design examples. These first six chapters provide the fundamental basis of linear-elastic fracture mechanics and the principles for applications of fracture mechanics.

Chapters 7 through 13 deal with sub-critical crack initiation and growth by fatigue, stress corrosion, or corrosion fatigue. It is in these areas that linear-elastic fracture mechanics has perhaps had its greatest field of application. Chapter 7 introduces the field of fatigue; Chapter 8 describes a method of analyzing fatigue-crack initiation from a blunt-notch using fracture mechanics terminology. Chapter 9 describes one of the most widespread uses of fracture mechanics, namely fatigue-crack propagation under constant-amplitude load fluctuation. Chapter 10 describes fatigue-crack propagation under variable-amplitude load fluctuation and the use of the root-mean-square ΔK value, ΔK_{RMS}.

Chapters 11, 12, and 13 introduce the effects of environments on subcritical crack initiation and growth, namely stress corrosion cracking and corrosion fatigue initiation and propagation. Chapter 14 describes the fatigue behavior of weldments.

Chapter 15 introduces the various factors affecting fracture criteria and presents examples of existing fracture criteria currently in use. Chapter 16 develops the principles of fracture-control and explains existing fracture-control plans for nuclear pressure vessels and bridges.

Chapter 17 introduces the field of elastic-plastic fracture-mechanics as analyzed by crack-opening displacement (CTOD), *R*-curve, or *J*-integral.

Based on the student's background and course hours, an introductory course might consist of Chapters 1 through 7, with the more advanced topics covered in Chapters 8 through 17. After reading Chapters 1, 2, and 7, the practicing engineer who is generally familiar with behavior of structural materials could move to any chapter of particular interest.

The authors wish to express their appreciation to their respective organizations, U.S. Steel Corporation and The University of Kansas, for their support in preparing this revision. Most importantly, however, we wish to acknowledge the support of our many colleagues, both within and outside our organizations, who have contributed to the development of this book, as well as the continued encouragement and support of our families.

John Barsom
Stan Rolfe

Contents

chapter 4

Effect of Temperature, Loading Rate, and Plate Thickness on Fracture Toughness, *109*

chapter 5

Correlations Between Fracture Mechanics and Other Fracture-Toughness Test Results, *159*

chapter 8

Fatigue-Crack Initiation, *250*

chapter 9

Fatigue-Crack Propagation under Constant-Amplitude Load Fluctuation, *278*

chapter 10

Fatigue-Crack Propagation under Variable-Amplitude Load Fluctuation, *320*

chapter 11

Stress-Corrosion Cracking, *345*

chapter 12

Corrosion-Fatigue-Crack Initiation, *373*

chapter 13

Corrosion-Fatigue-Crack Propagation, *392*

chapter 14

Fatigue and Fracture Behavior of Welded Components, *425*