FRACTURE and FATIGUE CONTROL in STRUCTURES

Applications of Fracture Mechanics

THIRD EDITION

John M. Barsom
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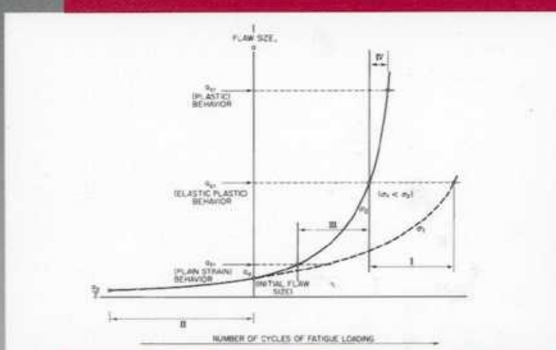

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PART IV: FRACTURE AND FATIGUE CONTROL

Foreword

(George Irwin wrote the following foreword for the first and second editions of this book in 1977 andd 1987. Dr. Irwin, the father of fracture mechanics, passed away in 1998.)

IN HIS WELL-KNOWN TEST 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 recogniition of the fact that real structures contain discontinuities. Some discontinuities are prior cracks and others develop into cracks with applications of stress. The general ideas is as follows. Suppose a structural component breaks after some general plastic yield. 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 fracture and fatigue failures in structures of all types. This book introduces the field of fracture mechanics from an applications viewpoint. Then it focuses on fitness for service, or life extension, of existing structures. Finally, it provides case studies to allow the practicing professional engineer or student to see the applications of fracture mechanics directly to various types of structures.

Since the first publication of this book in 1977, and the second edition in 1987, the field of fracture mechanics has grown significantly. Several 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 prevent fracture and fatigue failures in structures, rather than the theoretical aspects of fracture mechanics.

The concepts of *driving force* and *resistance force,* widely used in structural engineering, are used to help the reader differentiate between the mathematical side of fracture mechanics and the materials side of fracture mechanics. The driving force, K_I, is a calculated value dependent only upon the structure (or specimen) geometry, the applied load, and the size and shape of a flaw. Material properties are *not* needed to calculate values of K_I. It is analogous to the calculation of the applied stress, σ, in an unflawed structure. In fatigue, the driving force is $\Delta K = K_{I_{max}} - K_{I_{min}}$, analogous to $\Delta\sigma = \sigma_{max} - \sigma_{min}$.

In contrast, the resistance force, K_c(or K_{Ic}, or δ_c, or J_{Ic}, etc.), is a material property that can be obtained only by testing. Furthermore, this property can vary widely within a given ASTM composition, depending upon thermomechanical processing as well as a function of temperature, loading rate, and constraint, depending on the material. It is analogous to the measurement of yield strength.

By focusing on whether fracture mechanics is being used to *calculate* the driving force or to *measure* the resistance force, much of the mystery of fracture mechanics is eliminated. In the same manner that the driving stress, σ, is kept below the resistance stress, σ_{ys}, to prevent yielding, K_I should be kept below K_c to prevent fracture.

We believe the book will serve as an introduction to the field of fracture mechanics to practicing engineers, as well as seniors or beginning graduate students. This field has become increasingly important to the engineering community. In recent years, structural failures and the desire for increased safety and reliability of structures have led to the development of various fracture and fatigue criteria for many types of structures, including bridges, planes, pipelines, ships, buildings, pressure vessels, and nuclear pressure vessels.

In addition, the development of fracture-control plans for new and unusual types of structures has become more widespread. More importantly, the growing age of all types of structures, coupled with the economic fact that they may not be able to be replaced, necessitates a close look at the current safety and reliability of existing structures, i.e, a fitness for service or life extension consideration.

In this book, each of the topics of fracture criteria and fracture control is developed from an engineering viewpoint, including some economic and practical considerations. The book should assist engineers to become aware of the fundamentals of fracture mechanics and, in particular, of controlling fracture and fatigue failures in structures. Finally, the use of fracture mechanics in determining fitness for service or life extension of existing structures whose *design* life may have expired but whose *actual* life can be continued is covered.

In Parts I and II, the fundamentals of fracture mechanics theory are developed. In describing fracture behavior, the concepts of driving force (K_I), Part I, and the resistance force (K_c), Part II, are introduced. Examples of the calculations or the measurement of these two basic parts of fracture mechanics are presented for both linear-elastic and elastic-plastic conditions.

The effects of temperature, loading rate, and constraint on the measurement of various resistance forces (K_c, K_{Ic}, or δ_c, or J_{Ic}, etc.) are presented in Part II. Correlations between various types of fracture tests also are described.

In Part III, fatigue behavior (i.e., repeated loading) in structures is introduced by separating fatigue into initiation and propagation lives. The total fatigue life of a test specimen, member or structure, N_t, is composed of the initiation life, N_i, and the propagation life, N_p. Analysis of both of these components is presented as separate topics. In calculating the driving force, ΔK_I, the same K_I expressions developed in Part I for fracture are used in fatigue analyses of members with cracks subjected to repeated loading. Fatigue of weldments is also treated as a separate topic. Environmental effects (K_{Iscc}) complete the topics covered in Part III.

Parts I, II, and III focus on an introduction to the complex field of fracture mechanics as applied to fracture and fatigue in a straightforward, logical manner. The authors believe that Parts I, II, and III will serve the very vital function of introducing the topic to students and practicing engineers from an applied viewpoint.

Part IV focuses on applying the principles described in Parts I, II, and III to fracture and fatigue control as well as fitness for service of existing structures. Also called life extension, fitness for service is becoming widely used in many fields.

Many of today's existing bridges, ships, pressure vessels, pipelines, etc. have reached their original design life. If, from an economic viewpoint, it is desirable to continue to keep these structures in service, fracture mechanics concepts can be used to evaluate the structural integrity and reliability of existing structures. This important engineering field has been referred to as *fitness for service* or *life extension* and is described in Part IV.

Part V, Applications of Fracture Mechanics—Case Studies, should be invaluable to practicing engineers responsible for assessing the safety and reliability of existing structures, as well as showing students real world applications. The importance of the factors affecting fracture and fatigue failures is illustrated by case studies of actual failures. Case studies are described in terms of the importance of factors such as fracture toughness, fabrication, constraint, loading rate, etc. in the particular case study. Thus, for example, a case study describing the importance of constraint in a failure can easily be used in other types of structures where constraint is important.

Finally, the authors wish to acknowledge the support of our many colleagues, some of whom are former students who have contributed to the development of this book as well as to the continued encouragement and support of our families.

John Barsom
Stan Rolfe

ABOUT THE AUTHORS

DR. JOHN BARSOM is a consultant in the area of fracture mechanics, failure analysis, and accident reconstruction. He retired after 31 years with USX as Research Fellow and was chief of the Materials Behavior Division. Dr. Barsom has published more than 70 technical papers on fracture, fatigue, environmental effects, and steel properties.

Past chairman of ASTM Committee E08 on Fracture Testing, Dr. Barsom is a recipient of the ASTM Award of Merit and a fellow of the Society. He is also a fellow of the ASM International, a fellow of ASME, and, in 1983, was named Engineer of the Year by the ASME Pittsburgh Chapter. He is a member of the Project Oversite Committee of the SAC Steel Project on earthquake design and a member of the AISC (American Institute of Steel Construction) Committee on Specifications. He was chairman of the PVRC (Pressure Vessel Research Council) Committee on Failure Modes of Components, the AISI Committee on Transportation and Infrastructure, and the NSBA (National Steel Bridge Alliance) Committee on Technology and Education.

Dr. Barsom holds a Ph.D. in mechanical engineering, an M.S. in mathematics, and a B.S. in physics from the University of Pittsburgh.

DR. STANLEY ROLFE is the Albert P. Learned Professor of Engineering at the University of Kansas and has for the past 30 years taught and conducted research on the fracture and fatigue behavior of materials, experimental stress analysis, fracture mechanics, and behavior of structural materials as related to the design of structures. He has published more than 70 technical papers on fracture, fatigue, and behavior.

He received the Irvin E. Youngberg Research Award from the University of Kansas and the University of Illinois College of Engineering Alumni Honor Award for distinguished service in engineering.

Dr. Rolfe holds a Ph.D. in civil engineering from the University of Illinois. He is a registered professional engineer in Pennsylvania and Kansas and a member of the National Academy of Engineering.

> ***One of the biggest improvements over previous editions is that a new section on case studies of classic failures of steel structures is included. As one involved in reliability of steel structures for over 35 years, I find this book an indispensable addition to my actively utilized library.***
>
> ROBERT J. (JIM) GOODE, P.E., *Consulting Engineer*

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