FRACgURE AND FATIGUE CONTROL IN STRUCTURES
Applications of Fracture Mechanics
THIRD EDITION
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ASTM
Contents

Foreword xv
Preface xvii

PART I: INTRODUCTION TO FRACTURE MECHANICS

Chapter 1
Overview of the Problem of Fracture and Fatigue in Structures 3
   1.1 Historical Background 3
   1.2 Ductile vs. Brittle Behavior 9
   1.3 Notch Toughness 10
   1.4 Introduction to Fracture Mechanics 14
      1.4.1 Driving Force, $K_I$ 14
      1.4.2 Resistance Force, $K_c$ 15
   1.5 Fracture Mechanics Design 16
   1.6 Fatigue and Stress-Corrosion Crack Growth 19
   1.7 Fracture and Fatigue Control 23
   1.8 Fracture Criteria 24
   1.9 Fitness for Service 25
   1.10 Case Studies 26
   1.11 References 26

Chapter 2
Stress Analysis for Members with Cracks—$K_I$ 28
   2.1 Introduction 28
   2.2 Stress-Concentration Factor—$k_t$ 29
   2.3 Stress-Intensity Factor—$K_I$ 30
   2.4 Stress-Intensity-Factor Equations 35
      2.4.1 Through-Thickness Crack 35
      2.4.2 Single-Edge Notch 35
### CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4.3 Embedded Elliptical or Circular Crack in Infinite Plate</td>
<td>37</td>
</tr>
<tr>
<td>2.4.4 Surface Crack</td>
<td>39</td>
</tr>
<tr>
<td>2.4.5 Cracks Growing from Round Holes</td>
<td>40</td>
</tr>
<tr>
<td>2.4.6 Single Crack in Beam in Bending</td>
<td>40</td>
</tr>
<tr>
<td>2.4.7 Holes or Cracks Subjected to Point or Pressure Loading</td>
<td>41</td>
</tr>
<tr>
<td>2.4.8 Estimation of Other $K_I$ Factors</td>
<td>42</td>
</tr>
<tr>
<td>2.4.9 Superposition of Stress-Intensity Factors</td>
<td>47</td>
</tr>
<tr>
<td>2.5 Crack-Tip Deformation and Plastic Zone Size</td>
<td>49</td>
</tr>
<tr>
<td>2.6 Effective $K_I$ Factor for Large Plastic Zone Size</td>
<td>51</td>
</tr>
<tr>
<td>2.7 $J_I$ and $\delta_I$ Driving Forces</td>
<td>54</td>
</tr>
<tr>
<td>2.7.1 $J$ Integral</td>
<td>54</td>
</tr>
<tr>
<td>2.7.2 CTOD ($\delta_I$)</td>
<td>55</td>
</tr>
<tr>
<td>2.8 Summary</td>
<td>55</td>
</tr>
<tr>
<td>2.9 References</td>
<td>57</td>
</tr>
<tr>
<td>Appendix</td>
<td>58</td>
</tr>
<tr>
<td>2.10 Griffith, CTOD and $J$-Integral Theories</td>
<td>58</td>
</tr>
<tr>
<td>2.10.1 The Griffith Theory</td>
<td>58</td>
</tr>
<tr>
<td>2.10.2 Crack-Tip Opening Displacement (CTOD)</td>
<td>58</td>
</tr>
<tr>
<td>and the Dugdale Model</td>
<td>60</td>
</tr>
<tr>
<td>2.10.3 $J$-Integral</td>
<td>63</td>
</tr>
</tbody>
</table>

**PART II: FRACTURE BEHAVIOR**

**Chapter 3**

**Resistance Forces—$K_c$, $J_c$, $\delta_c$**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 General Overview</td>
<td>67</td>
</tr>
<tr>
<td>3.2 Service Conditions Affecting Fracture Toughness</td>
<td>69</td>
</tr>
<tr>
<td>3.2.1 Temperature</td>
<td>70</td>
</tr>
<tr>
<td>3.2.2 Loading Rate</td>
<td>70</td>
</tr>
<tr>
<td>3.2.3 Constraint</td>
<td>71</td>
</tr>
<tr>
<td>3.3 ASTM Standard Fracture Tests</td>
<td>76</td>
</tr>
<tr>
<td>3.4 Fracture Behavior Regions</td>
<td>79</td>
</tr>
<tr>
<td>3.5 General ASTM Fracture Test Method</td>
<td>80</td>
</tr>
<tr>
<td>3.5.1 Test Specimen Size</td>
<td>80</td>
</tr>
<tr>
<td>3.5.2 Test Specimen Notch</td>
<td>82</td>
</tr>
<tr>
<td>3.5.3 Test Fixtures and Instrumentation</td>
<td>82</td>
</tr>
<tr>
<td>3.5.4 Analysis of Results</td>
<td>85</td>
</tr>
<tr>
<td>3.6 Relations Between $K$-$J$-$\delta$</td>
<td>87</td>
</tr>
<tr>
<td>3.7 References</td>
<td>90</td>
</tr>
<tr>
<td>3.8 Appendix A: $K$, $J$, CTOD ($\delta$) Standard Test Method—E 1820</td>
<td>91</td>
</tr>
</tbody>
</table>
### Chapter 4
#### Effects of Temperature, Loading Rate, and Constraint

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Introduction</td>
<td>95</td>
</tr>
<tr>
<td>4.2 Effects of Temperature and Loading Rate on</td>
<td>96</td>
</tr>
<tr>
<td>$K_{ic}$, $K_{ic}(t)$, and $K_{ld}$</td>
<td></td>
</tr>
<tr>
<td>4.3 Effect of Loading Rate on Fracture Toughness</td>
<td>98</td>
</tr>
<tr>
<td>4.4 Effect of Constraint on Fracture Toughness</td>
<td>101</td>
</tr>
<tr>
<td>4.5 Loading-Rate Shift for Structural Steels</td>
<td>109</td>
</tr>
<tr>
<td>4.5.1 CVN Temperature Shift</td>
<td>109</td>
</tr>
<tr>
<td>4.5.2 $K_{ic}$-$K_{ld}$ Impact-Loading-Rate Shift</td>
<td>110</td>
</tr>
<tr>
<td>4.5.3 $K_{ic}(t)$ Intermediate-Loading Rate Shift</td>
<td>111</td>
</tr>
<tr>
<td>4.5.4 Predictive Relationship for Temperature Shift</td>
<td>112</td>
</tr>
<tr>
<td>4.5.5 Significance of Temperature Shift</td>
<td>112</td>
</tr>
<tr>
<td>4.6 References</td>
<td>116</td>
</tr>
</tbody>
</table>

### Chapter 5
#### CVN-$K_{ld}$-$K_c$ Correlations

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 General</td>
<td>118</td>
</tr>
<tr>
<td>5.2 Two-Stage CVN-$K_{ld}$-$K_c$ Correlation</td>
<td>119</td>
</tr>
<tr>
<td>5.3 $K_c$-CVN Upper-Shelf Correlation</td>
<td>120</td>
</tr>
<tr>
<td>5.4 $K_{ld}$ Value at NDT Temperature</td>
<td>123</td>
</tr>
<tr>
<td>5.5 Comparison of CVN-$K_{ld}$-$K_c$-$J$ and $\delta$ Relations</td>
<td>126</td>
</tr>
<tr>
<td>5.6 References</td>
<td>131</td>
</tr>
</tbody>
</table>

### Chapter 6
#### Fracture-Mechanics Design

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Introduction</td>
<td>133</td>
</tr>
<tr>
<td>6.2 General Fracture-Mechanics Design Procedure for</td>
<td>136</td>
</tr>
<tr>
<td>Terminal Failure</td>
<td></td>
</tr>
<tr>
<td>6.3 Design Selection of Materials</td>
<td>142</td>
</tr>
<tr>
<td>6.4 Design Analysis of Failure of a 260-In.-Diameter</td>
<td>146</td>
</tr>
<tr>
<td>Motor Case</td>
<td></td>
</tr>
<tr>
<td>6.5 Design Example—Selection of a High-Strength Steel for a Pressure</td>
<td>150</td>
</tr>
<tr>
<td>Vessel</td>
<td></td>
</tr>
<tr>
<td>6.5.1 Case I—Traditional Design Approach</td>
<td>150</td>
</tr>
<tr>
<td>6.5.2 Case II—Fracture-Mechanics Design</td>
<td>151</td>
</tr>
<tr>
<td>6.5.3 General Analysis of Cases I and II</td>
<td>157</td>
</tr>
<tr>
<td>6.6 References</td>
<td>159</td>
</tr>
</tbody>
</table>
PART III: FATIGUE AND ENVIRONMENTAL BEHAVIOR

Chapter 7
Introduction to Fatigue 163
7.1 Introduction 163
7.2 Factors Affecting Fatigue Performance 164
7.3 Fatigue Loading 164
  7.3.1 Constant-Amplitude Loading 165
  7.3.2 Variable-Amplitude Loading 166
7.4 Fatigue Testing 167
  7.4.1 Small Laboratory Tests 168
    7.4.1a Fatigue-Crack-Initiation Tests 168
    7.4.1b Fatigue-Crack-Propagation Tests 173
  7.4.2 Tests of Actual or Simulated Structural Components 174
7.5 Some Characteristics of Fatigue Cracks 174
7.6 References 181

Chapter 8
Fatigue-Crack Initiation 182
8.1 General Background 182
8.2 Effect of Stress Concentration on Fatigue-Crack Initiation 184
8.3 Generalized Equation for Predicting the Fatigue-Crack-Initiation Threshold for Steels 187
8.4 Methodology for Predicting Fatigue-Crack Initiation from Notches 189
8.5 References 192

Chapter 9
Fatigue-Crack Propagation under Constant and Variable-Amplitude Load Fluctuation 194
9.1 General Background 194
9.2 Fatigue-Crack-Propagation Threshold 196
9.3 Constant Amplitude Load Fluctuation 200
  9.3.1 Martensitic Steels 200
  9.3.2 Ferrite-Pearlite Steels 201
  9.3.3 Austenitic Stainless Steels 202
  9.3.4 Aluminum and Titanium Alloys 202
9.4 Effect of Mean Stress on Fatigue-Crack Propagation Behavior 204
9.5 Effects on Cyclic Frequency and Waveform 205
Chapter 10
Fatigue and Fracture Behavior of Welded Components

10.1 Introduction

10.2 Residual Stresses

10.3 Distortion

10.4 Stress Concentration

10.5 Weld Discontinuities and Their Effects

10.5.1 Fatigue Crack Initiation Sites

10.6 Fatigue Crack Behavior of Welded Components

10.6.1 Fatigue Behavior of Smooth Welded Components

10.6.1.1 Specimen Geometries and Test Methods

10.6.1.2 Effects of Surface Roughness

10.6.2 Fatigue Behavior of As-Welded Components

10.6.2.1 Effect of Geometry

10.6.2.2 Effect of Composition

10.6.2.3 Effect of Residual Stress

10.6.2.4 Effect of Postweld Heat Treatment

10.7 Methodologies of Various Codes and Standards

10.7.1 General

10.7.2 AASHTO Fatigue Design Curves for Welded Bridge Components

10.8 Variable Amplitude Cyclic Loads
Chapter 11

K_{scc} and Corrosion Fatigue Crack Initiation and Crack Propagation

11.1 Introduction 281
11.2 Stress-Corrosion Cracking 281
11.2.1 Fracture-Mechanics Approach 283
11.2.2 Experimental Procedures 284
11.2.3 K_{scc}—A Material Property 286
11.2.4 Test Duration 290
11.2.5 K_{scc} Data for Some Material-Environment Systems 291
11.2.6 Crack-Growth-Rate Tests 294
11.3 Corrosion-Fatigue Crack Initiation 296
11.3.1 Test Specimens and Experimental Procedures 296
11.3.2 Corrosion-Fatigue-Crack-Initiation Behavior of Steels 298
11.3.2.1 Fatigue-Crack-Initiation Behavior 299
11.3.2.2 Corrosion Fatigue Crack-Initiation Behavior 299
11.3.2.3 Effect of Cyclic-Load Frequency 302
11.3.2.4 Effect of Stress Ratio 302
11.3.2.5 Long-Life Behavior 303
11.3.2.6 Generalized Equation for Predicting the Corrosion-Fatigue Crack-Initiation Behavior for Steels 304
11.4 Corrosion-Fatigue-Crack Propagation 305
11.4.1 Corrosion-Fatigue Crack-Propagation Threshold 306
11.4.2 Corrosion-Fatigue-Crack-Propagation Behavior Below K_{scc} 311
11.4.3 Effect of Cyclic-Stress Waveform 318
11.4.4 Environmental Effects During Transient Loading 320
11.4.5 Generalized Corrosion-Fatigue Behavior 322
11.5 Prevention of Corrosion-Fatigue Failures 325
11.6 References 326
PART IV: FRACTURE AND FATIGUE CONTROL

Chapter 12
Fracture and Fatigue Control 333
12.1 Introduction 333
12.2 Historical Background 337
12.3 Fracture and Fatigue Control Plan 339
   12.3.1 Identification of the Factors 340
   12.3.2 Establishment of the Relative Contribution 342
   12.3.3 Determination of Relative Efficiency 346
   12.3.4 Recommendation of Specific Design Considerations 353
12.4 Fracture Control Plan for Steel Bridges 354
   12.4.1 General 354
   12.4.2 Design 354
   12.4.3 Fabrication 355
   12.4.4 Material 355
   12.4.5 AASHTO Charpy V-Notch Requirements 356
   12.4.6 Verification of the AASHTO Fracture Toughness Requirement 357
   12.4.7 High-Performance Steels 357
12.5 Comprehensive Fracture-Control Plans—George R. Irwin 357
12.6 References 363

Chapter 13
Fracture Criteria 364
13.1 Introduction 364
13.2 General Levels of Performance 366
13.3 Consequences of Failure 368
13.4 Original 15-ft-lb CVN Impact Criterion for Ship Steels 370
13.5 Transition-Temperature Criterion 373
13.6 Through-Thickness Yielding Criterion 374
13.7 Leak-Before-Break Criterion 378
13.8 Fracture Criterion for Steel Bridges 381
13.9 Summary 382
13.10 References 382

Chapter 14
Fitness for Service 384
14.1 Introduction 384
14.2 Use of Fracture Mechanics in Fitness-for-Service Analysis 385
  14.2.1 General 385
  14.2.2 Effect of Loading Rate 386
  14.2.3 Effect of Constraint 389
  14.2.4 Effect of Many Factors 394
14.3 Existing Fitness-for-Service Procedures 396
  14.3.1 General 396
  14.3.2 PD 6493 397
  14.3.3 ASME Section XI 401
  14.3.4 API 579 402
14.4 Benefits of a Proof or Hydro-Test to Establish Fitness for Continued Service 402
14.5 Difference Between Initiation and Arrest (Propagation) Fracture Toughness Behavior 404
14.6 References 408

PART V: APPLICATIONS OF FRACTURE MECHANICS—CASE STUDIES

Chapter 15
Importance of Fracture Toughness and Proper Fabrication Procedures—The Bryte Bend Bridge 413
15.1 Introduction 413
15.2 AASHTO Fracture Control Plan for Steel Bridges 414
15.3 Bryte Bend Bridge Brittle Fracture 414
15.4 Design Aspects of the Bryte Bend Bridge as Related to the AASHTO Fracture Control Plan (FCP) 420
15.5 Adequacy of the Current AASHTO Fracture Control Plan 423
  15.5.1 Implied vs. Guaranteed Notch Toughness 423
  15.5.2 Effect of Details on Fatigue Life 424
  15.5.3 Summary 426
15.6 References 427

Chapter 16
Importance of Constraint and Loading—The Ingram Barge 428
16.1 Introduction 428
16.2 Effect of Constraint on Structural Behavior 428
16.3 Constraint Experiences in the Ship Industry 431
16.4 Ingram Barge Failure 431
16.5 Summary 436
16.6 References 437
Chapter 17
Importance of Loading and Inspection—Trans Alaska Pipeline Service Oil Tankers

17.1 Introduction
17.2 Background
17.3 Fracture Mechanics Methodology
17.4 Application of Methodology to a Detail in an Oil Tanker
  17.4.1 Identification of Critical Details
  17.4.2 Fracture Toughness
  17.4.3 Stress Intensity Factors and Critical Crack Size for Critical Details
  17.4.4 Inspection Capability for Initial Crack Size, \( a_0 \)
  17.4.5 Determination of Histogram for Fatigue Loading
  17.4.6 Fatigue Crack Propagation in Bottom Shell Plates
17.5 Effect of Reduced Fatigue Loading
17.6 Summary
17.7 References

Chapter 18
Importance of Proper Analysis, Fracture Toughness, Fabrication, and Loading on Structural Behavior—Failure Analysis of a Lock-and-Dam Sheet Piling

18.1 Introduction
18.2 Description of the Failure
18.3 Steel Properties
18.4 Failure Analysis of Sheet 55
18.5 Summary
18.6 References

Chapter 19
Importance of Loading Rate on Structural Performance—Burst Tests of Steel Casings

19.1 Introduction
19.2 Material and Experimental Procedures
19.3 Experimental Procedure
19.4 Failure Analysis
19.5 Metallographic Analysis
19.6 Examination of API Specifications for J-55 and K-55 Casing
19.7 References
Chapter 20

Problems

Part I 491
Part II 494
Part III 499
Part IV 502

Index 507
(George Irwin wrote the following foreword for the first and second editions of this book in 1977 and 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 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 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, \( \sigma \), in an unflawed structure. In fatigue, the driving force is \( \Delta K = K_{I_{\text{max}}} - K_{I_{\text{min}}} \), analogous to \( \Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} \).

In contrast, the resistance force, \( K_c \) (or \( K_{IC} \) or \( \delta_c \) 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, \( \sigma \), is kept below the resistance stress, \( \sigma_{YS} \), 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 $\delta_{cr}$ 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, $\Delta K_I$, 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 ($K_{pecc}$) 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 Barson*

*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.

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