

The Practical Use of Fracture Mechanics

by

DAVID BROEK

FractuREsearch Inc., Galena, OH, USA



Kluwer Academic Publishers
Dordrecht / Boston / London

Contents

Preface	v
Notice	vii
Chapter 1. INTRODUCTION	1
1.1. Fracture control	1
1.2. The two objectives of damage tolerance analysis	3
1.3. Crack growth and fracture	8
1.4. Damage tolerance and fracture mechanics	15
1.5. The need for analysis: purpose of this book	17
1.6. Exercises	20
Chapter 2. EFFECTS OF CRACKS AND NOTCHES: COLLAPSE	22
2.1. Scope	22
2.2. An interrupted load path	22
2.3. Stress concentration factor	25
2.4. State of stress at a stress concentration	28
2.5. Yielding at a notch	31
2.6. Plastic collapse at a notch	35
2.7. Fracture at notches: brittle behavior	41
2.8. Measurement of collapse strength	44
2.9. Exercises	46
Chapter 3. LINEAR ELASTIC FRACTURE MECHANICS	48
3.1. Scope	48
3.2. Stress at a crack tip	48
3.3. General form of the stress intensity factor	52
3.4. Toughness	55
3.5. Plastic zone and stresses in plane stress and plane strain	57
3.6. Thickness dependence of toughness	61
3.7. Measurement of toughness	67
3.8. Competition with plastic collapse	70
3.9. The energy criterion	73
3.10. The energy release rate	75
3.11. The meaning of the energy criterion	79
3.12. The rise in fracture resistance: redefinition of toughness	79
3.13. Exercises	86

Chapter 4. ELASTIC-PLASTIC FRACTURE MECHANICS	88
4.1. Scope	88
4.2. The energy criterion for plastic fracture	88
4.3. The fracture criterion	90
4.4. The rising fracture energy	93
4.5. The residual strength diagram in EPFM: collapse	97
4.6. The measurement of the toughness in EPFM	98
4.7. The parameters of the stress-strain curve	102
4.8. The h -functions	106
4.9. Accuracy	109
4.10. Historical development of J	112
4.11. Limitations of EPFM	116
4.12. CTOD measurements	118
4.13. Exercises	121
Chapter 5. CRACK GROWTH ANALYSIS CONCEPTS	123
5.1. Scope	123
5.2. The concept underlying fatigue crack growth	123
5.3. Measurement of the rate function	126
5.4. Rate equations	130
5.5. Constant amplitude crack growth in a structure	133
5.6. Load interaction: Retardation	136
5.7. Retardation models	145
5.8. Crack growth analysis for variable amplitude loading	149
5.9. Parameters affecting fatigue crack growth rates	157
5.10. Stress corrosion cracking	163
5.11. Exercises	165
Chapter 6. LOAD SPECTRA AND STRESS HISTORIES	168
6.1. Scope	168
6.2. Types of stress histories	169
6.3. Obtaining load spectra	175
6.4. Exceedance diagram	176
6.5. Stress history generation	180
6.6. Clipping	192
6.7. Truncation	195
6.8. Manipulation of stress history	198
6.9. Environmental effects	204
6.10. Standard spectra	205
6.11. Exercises	205

Chapter 7. DATA INTERPRETATION AND USE	208
7.1. Scópe	208
7.2. Plane strain fracture toughness	209
7.3. Plane stress and transitional toughness, R-curve	212
7.4. Toughness in terms of J and J_R	214
7.5. Estimates of toughness	215
7.6. General remarks on fatigue rate data	218
7.7. Fitting the da/dN data	222
7.8. Dealing with scatter in rate data	232
7.9. Accounting for the environmental effect	236
7.10. Obtaining retardation parameters	238
7.11. Exercises	241
Chapter 8. GEOMETRY FACTORS	243
8.1. Scope	243
8.2. The reference stress	244
8.3. Compounding	247
8.4. Superposition	249
8.5. A simple method for asymmetric loading cases	255
8.6. Some easy guesses	258
8.7. Simple solutions for holes and stress concentrations	260
8.8. Simple solutions for irregular stress distributions	267
8.9. Finite element analysis	271
8.10. Simple solutions for crack arresters and multiple elements	274
8.11. Geometry factors for elastic-plastic fracture mechanics	278
8.12. Exercises	279
Chapter 9. SPECIAL SUBJECTS	282
9.1. Scope	282
9.2. Behavior of surface flaws and corner cracks	282
9.3. Break through: leak-before-break	290
9.4. Fracture arrest	293
9.5. Multiple elements, multiple cracks, changing geometry	300
9.6. Stop holes, cold worked holes and interference fasteners	311
9.7. Residual stresses in general	316
9.8. Other loading modes: mixed mode loading	319
9.9. Composites	327
9.10. Exercises	329
Chapter 10. ANALYSIS PROCEDURES	332
10.1. Scope	332
10.2. Ingredients and critical locations	332

10.3. Critical locations and flaw assumptions	334
10.4. LEFM versus EPFM	339
10.5. Residual strength analysis	345
10.6. Use of R-curve and J_R -curve	353
10.7. Crack growth analysis	355
10.8. Exercises	361
Chapter 11. FRACTURE CONTROL	362
11.1. Scope	362
11.2. Fracture control options	362
11.3. The probability of missing the crack	369
11.4. The physics and statistics of crack detection	373
11.5. Determining the inspection interval	377
11.6. Fracture control plans	379
11.7. Repairs	384
11.8. Statistical aspects	385
11.9. The cost of fracture and fracture control	387
11.10. Exercises	389
Chapter 12. DAMAGE TOLERANCE SUBSTANTIATION	391
12.1. Scope	391
12.2. Objectives	391
12.3. Analysis and damage tolerance substantiation	393
12.4. Options to improve damage tolerance	395
12.5. Aircraft damage tolerance requirements	397
12.6. Other requirements	404
12.7. Flaw assumptions	408
12.8. Sources of error and safety factors	410
12.9. Misconceptions	417
12.10. Outlook	420
12.11. Exercises	422
Chapter 13. AFTER THE FACT: FRACTURE MECHANICS AND FAILURE ANALYSIS	424
13.1. Scope	424
13.2. The cause of service fractures	425
13.3. Fractography	428
13.4. Features of use in fracture mechanics analysis	430
13.5. Use of fracture mechanics	436
13.6. Possible actions based on failure analysis	440
13.7. Exercises	440

Chapter 14. APPLICATIONS	443
14.1. Scope	443
14.2. Storage tank (fictitious example)	443
14.3. Fracture arrest in ships	447
14.4. Piping in chemical plant (fictitious example)	462
14.5. Fatigue cracks in railroad rails	465
14.6. Underwater pipeline	476
14.7. Closure	483
Chapter 15. SOLUTIONS TO EXERCISES	485
SUBJECT INDEX	515