

Contents

1	Designing Components and Structures According to Strength Criteria	1
1.1	Loads on Components and Structures	2
1.2	Stresses and Stress States in Components and Structures	5
1.2.1	Plane Stress State	6
1.2.2	Spatial Stress State	6
1.2.3	Principal Stresses	6
1.2.4	Plane Stress State or Plane Strain State	8
1.3	Proof of Static Strength	9
1.3.1	Equivalent Stress	9
1.3.2	Allowable Stress	10
1.3.3	Proof of Strength—Operational Sequence	11
1.3.4	Taking Account of the Notch Effect	12
1.3.5	Stress Concentration Factors	13
1.3.6	Material Parameters and Safety Factors	13
1.4	Proof of Fatigue Strength	18
1.4.1	Effective and Allowable Stresses	18
1.4.2	Material Parameters	19
1.4.3	Surface and Size Coefficients	21
1.4.4	Proof of Fatigue Strength with Notched Components	23
1.5	Proof of Structural Durability	23
1.6	Other Proofs	24
1.7	Limits of Classic Component Design	24
	References	25
2	Damages Caused by Crack Growth	27
2.1	Crack Initiation and Crack Growth	29
2.2	Stable and Unstable Crack Growth	31
2.3	Damage Analysis/Fracture Surface Analysis	32

2.4	Fatigue Crack Growth in an ICE Wheel Tire.	36
2.5	Crack Growth in a Press Frame.	37
2.6	Fatigue Crack Growth in the Fastener Body of an Internal High-Pressure Metal Forming Machine.	39
2.7	Fracture of the Drive Shaft of a Vintage Car.	39
2.8	Other Damage Events.	39
2.9	Basic Crack Paths and Crack Shapes in Components and Structures	41
2.9.1	Crack Paths of Basic Stress States	42
2.9.2	Crack Paths and Crack Shapes in Shafts.	43
2.9.3	Systematizing Crack Types in Components and Structures	45
2.10	Crack Detection Using Non-destructive Testing Methods	49
	References	51
3	Fundamentals of Fracture Mechanics	55
3.1	Cracks and Crack Modes	55
3.1.1	Mode I.	56
3.1.2	Mode II	57
3.1.3	Mode III.	57
3.1.4	Mixed Mode	57
3.2	Stress Distributions at Cracks	58
3.2.1	Solving Crack Problems with Elasticity Theory	58
3.2.2	Stress Distributions for Plane Crack Problems	59
3.2.3	Stress Distributions for Spatial Crack Problems	64
3.3	Displacement Fields Near the Crack.	66
3.4	Stress Intensity Factors.	67
3.4.1	Stress Intensity Factors for Crack Modes I, II and III.	67
3.4.2	Stress Intensity Factors for Basic Crack Problems	68
3.4.3	Superposition of Stress Intensity Factors, Equivalent Stress Intensity Factors.	77
3.5	Local Plasticity at the Crack Tip	84
3.5.1	Estimating the Plastic Zone.	84
3.5.2	Crack Length Correction.	87
3.5.3	Significance of the Plastic Zone in Fatigue Crack Propagation.	88
3.6	Energy Release Rate and the J -Integral.	88
3.6.1	Energy Release Rate	88
3.6.2	J -Integral	89

3.7	Determining the Stress Intensity Factors and Other Fracture-Mechanical Quantities	90
3.7.1	Determining the Stress Intensity Factors from the Stress Field in the Vicinity of the Crack	91
3.7.2	Determining the Stress Intensity Factors from the Displacement Field in the Vicinity of the Crack	92
3.7.3	Determining Fracture-Mechanical Quantities with the J -Integral	92
3.7.4	Determining Fracture-Mechanical Quantities with the Crack Closure Integral	93
3.8	Concepts for Predicting Unstable Crack Growth	95
3.8.1	K -Concept for Mode I	96
3.8.2	K -Concept for Mode II, Mode III and Mixed Mode Loadings.	96
3.8.3	Criterion of Energy Release Rate.	102
3.8.4	J -Criterion	102
3.9	Fracture Toughness	103
3.10	Assessing Components with Cracks Using Fracture-Mechanical Methods	103
3.10.1	Fracture-Mechanical Proof—Operational Sequence.	103
3.10.2	Applying the Fracture Criterion and the Fracture-Mechanical Analysis to Mode I Crack Problems	105
3.10.3	Applying the Fracture Criterion and the Fracture-Mechanical Analysis to Mode II, Mode III and Mixed Mode Problems	107
3.11	Combining Strength Calculation and Fracture Mechanics	108
	References	111
4	Fatigue Crack Growth Under Cyclic Loading with Constant Amplitude	113
4.1	Relation Between Component Loading and Cyclic Stress Intensity	114
4.1.1	Stress Fields with Time-Varying Mode I Loading	115
4.1.2	Cyclic Stress Intensity Factor for Mode I	115
4.1.3	R -ratio	116
4.1.4	Crack Propagation Process	117
4.1.5	Stress Field with Time-Varying Mode II, Mode III and Mixed-Mode Loading.	117
4.1.6	Cyclic Stress Intensity Factor for Mode II.	118
4.1.7	Cyclic Stress Intensity Factor for Mode III	119
4.1.8	Two-Dimensional Mixed-Mode Loading.	119
4.1.9	Three-Dimensional Mixed-Mode Loading	119

4.2	Relationship Between Crack Growth Rate and the Cyclic Stress Intensity Factor	120
4.2.1	Limits of Fatigue Crack Propagation for Mode I	122
4.2.2	Factors Influencing the Crack Growth Curve	122
4.2.3	Crack Closure Behavior During Fatigue Crack Growth	123
4.2.4	Threshold Value and Threshold Value Behavior	127
4.3	Crack Propagation Concepts for Mode I	132
4.3.1	Paris Law	133
4.3.2	Erdogan/Ratwani Law	133
4.3.3	Forman/Mettu Equation	134
4.3.4	Comparison of the Crack Propagation Equations	135
4.3.5	Determining Residual Lifetime	137
4.4	Crack Growth Under Mode II, Mode III and Mixed-Mode Loading	140
4.4.1	Crack Growth Under Mode II Loading on the Initial Crack	140
4.4.2	Crack Growth Under Mode III Loading on the Initial Crack	142
4.4.3	Crack Growth Under Two-Dimensional Mixed-Mode Loading	142
4.4.4	Crack Growth Under Three-Dimensional Mixed-Mode Loading	143
4.5	Procedure for Assessing Fatigue Crack Growth	144
4.5.1	Fracture-Mechanical Assessment of Fatigue Crack Growth	145
4.5.2	Determining the Crack Length at Which Fatigue Crack Growth Is Possible	146
4.5.3	Safety Against the Occurrence of Fatigue Crack Growth	147
4.5.4	Area of Fatigue Crack Growth	147
4.5.5	Defining Inspection Intervals	148
4.6	Combination of Fatigue Strength Calculation and Fracture Mechanics	149
	References	150
5	Experimental Determination of Fracture-Mechanical Material Parameters	153
5.1	Critical Stress Intensity Factor and Fracture Toughness	153
5.1.1	Determining Fracture Toughness According to ASTM E 399	154
5.1.2	Testing Methods for Determining the Fracture Toughness	158
5.1.3	K_{IC} or K_Q ?—Assessment of the Tests	158

5.2	Threshold Values and Crack Growth Curves	161
5.2.1	Determining Threshold Values and Crack Growth Curves Acc. to ASTM E 647	161
5.2.2	Methods of Determining the Threshold Value	165
5.2.3	Methods of Measuring Crack Length	168
5.2.4	Determining the Fatigue Crack Growth Rate	172
5.2.5	Evaluating the Threshold Value and Crack Growth Curve Tests.	173
5.3	Material Parameters for Mode I Crack Growth	175
5.3.1	Fracture Toughnesses	175
5.3.2	Threshold Values of Fatigue Crack Growth.	177
5.3.3	Fatigue Crack Growth Curves	177
5.4	Material Parameters for Mode II and Mixed-Mode Loading	179
5.4.1	Mode II Loading	181
5.4.2	Two-Dimensional Mixed-Mode Loading.	182
5.4.3	Three-Dimensional Mixed-Mode Loading	183
	References	185
6	Fatigue Crack Growth Under Service Loads.	187
6.1	Load Spectra and Cumulative Frequency Distribution.	187
6.1.1	Determining Service Loads	188
6.1.2	Counting Methods	188
6.1.3	Standard Load Spectra	189
6.2	Interaction Effects	191
6.2.1	Overloads	191
6.2.2	Underloads	196
6.2.3	Combinations of Underloads and Overloads	196
6.2.4	Overload Sequences.	196
6.2.5	Block Loading.	198
6.2.6	Service Loads	200
6.3	Crack Propagation Concepts for Variable Amplitude Loading	204
6.3.1	Global Analyses	204
6.3.2	Linear Damage Accumulation	205
6.3.3	Yield Zone Models	206
6.3.4	Crack Closure Models	213
6.3.5	Strip Yield Models.	214
6.4	Mixed-Mode Loading.	216
6.4.1	Crack Growth After a Change in the Loading Direction or in the Local Load at the Crack	217
6.4.2	Effect of Mixed-Mode Overloads on Fatigue Crack Growth.	218
	References	219

7	Simulations of Fatigue Crack Growth.	223
7.1	Analytical Crack Growth Simulations.	223
7.1.1	NASGRO and ESACRACK	224
7.1.2	AFGROW	225
7.2	Numerical Crack Growth Simulations.	226
7.2.1	Basic Procedure with Finite Elements.	226
7.2.2	Program System FRANC/FAM for Two-Dimensional Crack Propagation Simulations	229
7.2.3	Program System ADAPCRACK3D for Three-Dimensional Crack Propagation Simulations.	230
7.3	Determining the Effect of Load Changes with Finite Element Analyses.	232
	References	235
8	Crack Initiation Under Cyclic Loading.	239
8.1	Models for Describing Crack Initiation.	240
8.1.1	Threshold Value Curve Concept	241
8.1.2	Theories of Critical Distances	243
8.1.3	Fatigue Crack Resistance Curve Concept	244
8.1.4	$\sqrt{a_{rea}}$ Concept.	246
8.2	Short Crack Growth.	248
	References	249
9	Practical Examples	251
9.1	Leak in a Pipeline	251
9.1.1	Stresses in the Pipe	251
9.1.2	Stress Intensity Factors for the Crack	253
9.1.3	Safety Against Unstable Crack Propagation.	253
9.1.4	Crack Length at Which Unstable Crack Propagation Initiates	254
9.2	Investigating Fatigue Crack Growth in ICE Tires.	254
9.2.1	Structure and Load of Rubber-Sprung Wheels.	254
9.2.2	Numerical Stress Analysis.	256
9.2.3	Damage Analysis of the Wheel Tire Fracture	257
9.2.4	Fracture-Mechanical Characterization of the Tire Material	258
9.2.5	Numerical Simulation of Fatigue Crack Growth.	258
9.2.6	Experimental Simulation of Crack Growth	260
9.3	Simulation of Fatigue Crack Growth in a Press Frame	262
9.4	Preventing Crack Growth in a Piston	265
9.5	Investigating Crack Growth in an Aircraft Structure.	267

9.6	Parameter Study of a Surface Crack in a Shaft Under Rotating Bending Load	270
9.6.1	Influence of the Cumulative Frequency Distribution	271
9.6.2	Influence of the Notch Effect and Press-Fit Stresses	273
9.6.3	Influence of the Initial Crack Depth and Geometry on Residual Life Simulation	274
9.7	Restoration of a Press.	275
9.7.1	Modeling the Crack Geometry in the Sealing Cap	276
9.7.2	Stress Analysis for the Cap	276
9.7.3	Results of the FE Analyses for the Cracked Sealing Cap	277
9.7.4	Fracture-Mechanical Assessment of the FE Results	277
9.7.5	Consequences for Continued Machine Operation	278
9.8	Measures for Extending the Residual Life of Machines and Equipment	278
9.8.1	Continued Operation of a Machine or System After Crack Detection.	279
9.8.2	Optimization Measures for a New Design	281
	References	282
	Index	285

Fatigue Crack Growth

Detect - Assess - Avoid

Richard, H.A.; Sander, M.

2016, XIX, 292 p. 226 illus., Hardcover

ISBN: 978-3-319-32532-3