

Mechanical Behavior of Materials

Engineering Methods for Deformation,
Fracture, and Fatigue

Third Edition

Norman E. Dowling

*Engineering Science and Mechanics Department, and
Materials Science and Engineering Department
Virginia Polytechnic Institute and State University
Blacksburg, Virginia*



Upper Saddle River, New Jersey 07458

Contents

PREFACE	xi
ACKNOWLEDGMENTS	xvii
1 Introduction	1
1.1 Introduction	1
1.2 Types of Material Failure	2
1.3 Design and Materials Selection	10
1.4 Technological Challenge	16
1.5 Economic Importance of Fracture	18
1.6 Summary	19
References	20
Problems and Questions	20
2 Structure and Deformation in Materials	23
2.1 Introduction	23
2.2 Bonding in Solids	25
2.3 Structure in Crystalline Materials	29
2.4 Elastic Deformation and Theoretical Strength	33
2.5 Inelastic Deformation	38
2.6 Summary	44
References	45
Problems and Questions	46
3 A Survey of Engineering Materials	48
3.1 Introduction	48
3.2 Alloying and Processing of Metals	49
3.3 Irons and Steels	55
3.4 Nonferrous Metals	63

3.5	Polymers	67	
3.6	Ceramics and Glasses	77	
3.7	Composite Materials	83	
3.8	Materials Selection for Engineering Components	88	
3.9	Summary	94	
	References	96	
	Problems and Questions	97	
4	Mechanical Testing: Tension Test and Other Basic Tests		101
4.1	Introduction	101	
4.2	Introduction to Tension Test	106	
4.3	Engineering Stress–Strain Properties	111	
4.4	Trends in Tensile Behavior	120	
4.5	True Stress–Strain Interpretation of Tension Test	126	
4.6	Compression Test	135	
4.7	Hardness Tests	140	
4.8	Notch-Impact Tests	147	
4.9	Bending and Torsion Tests	152	
4.10	Summary	158	
	References	159	
	Problems and Questions	160	
5	Stress–Strain Relationships and Behavior		171
5.1	Introduction	171	
5.2	Models for Deformation Behavior	172	
5.3	Elastic Deformation	182	
5.4	Anisotropic Materials	195	
5.5	Summary	204	
	References	206	
	Problems and Questions	206	
6	Review of Complex and Principal States of Stress and Strain		214
6.1	Introduction	214	
6.2	Plane Stress	215	
6.3	Principal Stresses and the Maximum Shear Stress	225	
6.4	Three-Dimensional States of Stress	233	
6.5	Stresses on the Octahedral Planes	240	
6.6	Complex States of Strain	242	

6.7	Summary	247	
	References	249	
	Problems and Questions	249	
7	Yielding and Fracture under Combined Stresses		254
7.1	Introduction	254	
7.2	General Form of Failure Criteria	256	
7.3	Maximum Normal Stress Fracture Criterion	258	
7.4	Maximum Shear Stress Yield Criterion	261	
7.5	Octahedral Shear Stress Yield Criterion	267	
7.6	Discussion of the Basic Failure Criteria	274	
7.7	Coulomb–Mohr Fracture Criterion	280	
7.8	Modified Mohr Fracture Criterion	290	
7.9	Additional Comments on Failure Criteria	297	
7.10	Summary	300	
	References	301	
	Problems and Questions	302	
8	Fracture of Cracked Members		312
8.1	Introduction	312	
8.2	Preliminary Discussion	315	
8.3	Mathematical Concepts	322	
8.4	Application of K to Design and Analysis	326	
8.5	Additional Topics on Application of K	337	
8.6	Fracture Toughness Values and Trends	349	
8.7	Plastic Zone Size, and Plasticity Limitations on LEFM	359	
8.8	Discussion of Fracture Toughness Testing	368	
8.9	Extensions of Fracture Mechanics Beyond Linear Elasticity	369	
8.10	Summary	376	
	References	379	
	Problems and Questions	380	
9	Fatigue of Materials: Introduction and Stress-Based Approach		391
9.1	Introduction	391	
9.2	Definitions and Concepts	393	
9.3	Sources of Cyclic Loading	404	
9.4	Fatigue Testing	405	
9.5	The Physical Nature of Fatigue Damage	410	
9.6	Trends in S - N Curves	413	
9.7	Mean Stresses	426	
9.8	Multiaxial Stresses	438	

9.9	Variable Amplitude Loading	443	
9.10	Summary	453	
	References	454	
	Problems and Questions	456	
10	Stress-Based Approach to Fatigue: Notched Members		466
10.1	Introduction	466	
10.2	Notch Effects	468	
10.3	Notch Sensitivity and Empirical Estimates of k_f	472	
10.4	Estimating Long-Life Fatigue Strengths (Fatigue Limits)	476	
10.5	Notch Effects at Intermediate and Short Lives	481	
10.6	Combined Effects of Notches and Mean Stress	484	
10.7	Estimating S - N Curves	494	
10.8	Use of Component S - N Data	502	
10.9	Designing to Avoid Fatigue Failure	510	
10.10	Discussion	516	
10.11	Summary	517	
	References	519	
	Problems and Questions	520	
11	Fatigue Crack Growth		535
11.1	Introduction	535	
11.2	Preliminary Discussion	536	
11.3	Fatigue Crack Growth Rate Testing	544	
11.4	Effects of $R = S_{\min}/S_{\max}$ on Fatigue Crack Growth	549	
11.5	Trends in Fatigue Crack Growth Behavior	559	
11.6	Life Estimates for Constant Amplitude Loading	565	
11.7	Life Estimates for Variable Amplitude Loading	576	
11.8	Design Considerations	582	
11.9	Plasticity Aspects and Limitations of LEFM for Fatigue Crack Growth	584	
11.10	Environmental Crack Growth	591	
11.11	Summary	596	
	References	598	
	Problems and Questions	599	
12	Plastic Deformation Behavior and Models for Materials		612
12.1	Introduction	612	
12.2	Stress–Strain Curves	615	
12.3	Three-Dimensional Stress–Strain Relationships	623	
12.4	Unloading and Cyclic Loading Behavior from Rheological Models	631	
12.5	Cyclic Stress–Strain Behavior of Real Materials	639	

- 12.6 Summary 652
- References 654
- Problems and Questions 655

13 Stress–Strain Analysis of Plastically Deforming Members 664

- 13.1 Introduction 664
- 13.2 Plasticity in Bending 665
- 13.3 Residual Stresses and Strains for Bending 674
- 13.4 Plasticity of Circular Shafts in Torsion 678
- 13.5 Notched Members 681
- 13.6 Cyclic Loading 693
- 13.7 Summary 704
- References 705
- Problems and Questions 706

14 Strain-Based Approach to Fatigue 715

- 14.1 Introduction 715
- 14.2 Strain Versus Life Curves 718
- 14.3 Mean Stress Effects 728
- 14.4 Multiaxial Stress Effects 736
- 14.5 Life Estimates for Structural Components 740
- 14.6 Discussion 750
- 14.7 Summary 758
- References 759
- Problems and Questions 760

15 Time-Dependent Behavior: Creep and Damping 772

- 15.1 Introduction 772
- 15.2 Creep Testing 774
- 15.3 Physical Mechanisms of Creep 779
- 15.4 Time–Temperature Parameters and Life Estimates 790
- 15.5 Creep Failure under Varying Stress 802
- 15.6 Stress–Strain–Time Relationships 804
- 15.7 Creep Deformation under Varying Stress 810
- 15.8 Creep under Multiaxial Stress 817
- 15.9 Component Stress–Strain Analysis 820
- 15.10 Energy Dissipation (Damping) in Materials 825
- 15.11 Summary 834
- References 836
- Problems and Questions 837

Appendix A	Review of Selected Topics from Mechanics of Materials	849
A.1	Introduction	849
A.2	Basic Formulas for Stresses and Deflections	849
A.3	Properties of Areas	851
A.4	Shears, Moments, and Deflections in Beams	853
A.5	Stresses in Pressure Vessels, Tubes, and Discs	853
A.6	Elastic Stress Concentration Factors for Notches	858
A.7	Fully Plastic Yielding Loads	859
	References	868
Appendix B	Statistical Variation in Materials Properties	869
B.1	Introduction	869
B.2	Mean and Standard Deviation	869
B.3	Normal or Gaussian Distribution	871
B.4	Typical Variation in Materials Properties	874
B.5	One-Sided Tolerance Limits	874
B.6	Discussion	876
	References	877
BIBLIOGRAPHY		878
INDEX		891