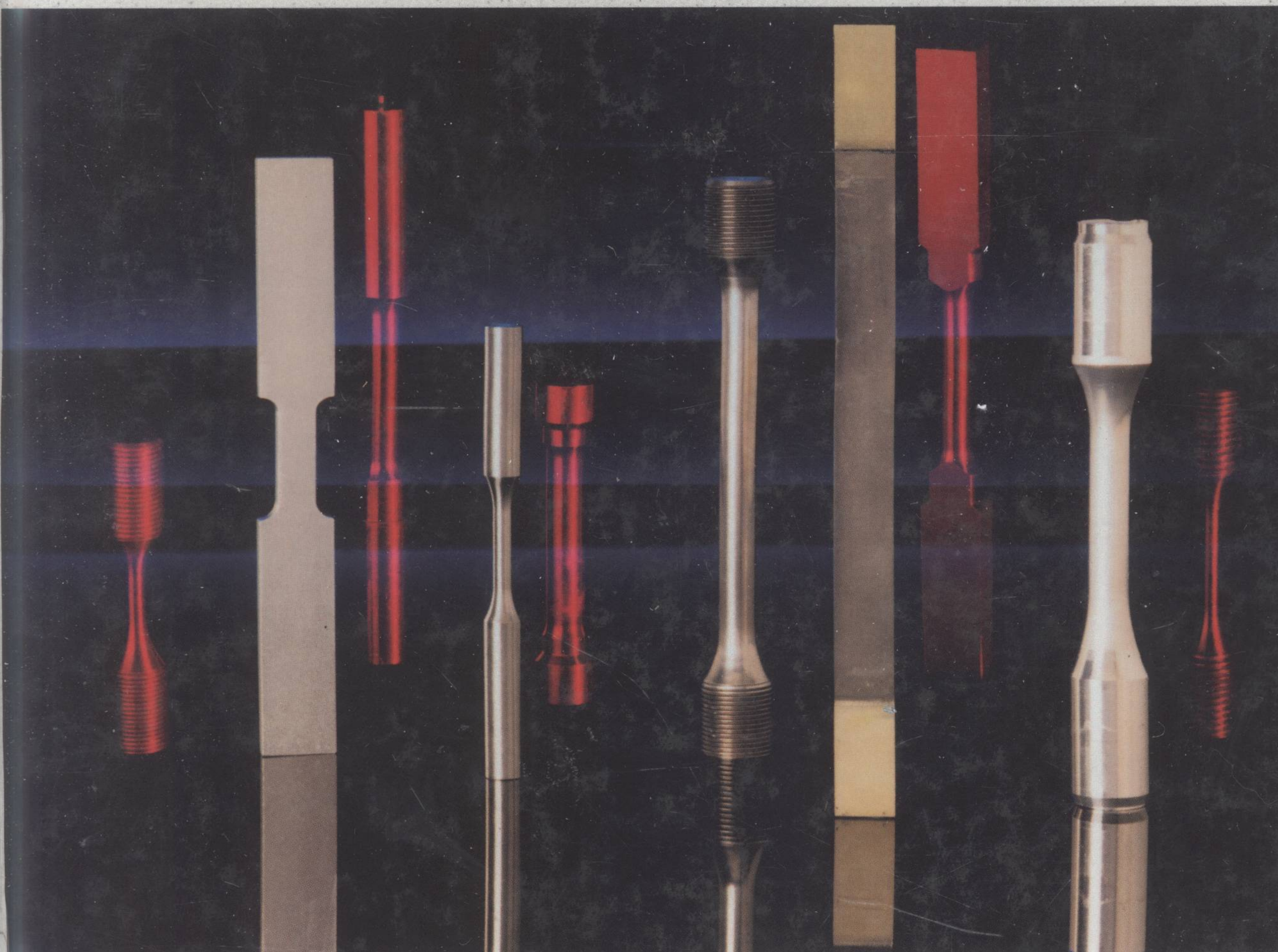
MECHANICAL BEHAVIOR OF MATERIALS

Engineering Methods for Deformation, Fracture, and Fatigue

Second Edition



NORMAN E. DOWLING

MECHANICAL BEHAVIOR OF MATERIALS

Engineering Methods for Deformation, Fracture, and Fatigue

Second Edition

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MATERIALS PROPERTIES LOCATOR

Table No.	Page	Material Type	Data Listed
2.2	38	Whiskers, fibers, wires	E, σ_u
3.1	50	Metals, alloys	T_m, ρ, E
3.9	72	Polymers	T_g, T_m
3.10	79	Ceramics, glasses	T_m, ρ, E, σ_u, σ_{uc}
3.13	90	Representative	E, σ_o or σ_u, ρ, cost
4.2	120	Metals	E, σ_o, σ_u, $100\varepsilon_f$, $\%RA$
4.3	121	Polymers	E, σ_o, σ_f, $100\varepsilon_f$, Izod energy, T_d
4.4	122	SiC in Al composite	E, σ_o, σ_u, $100\varepsilon_f$
4.7	133	Metals	$\tilde{\sigma}_{fB}$, $\tilde{\varepsilon}_f$, H, n, HB
4.8	144	Ceramics, glasses	E, σ_{fb}, HV
5.2	178	Metals, polymers, ceramics, glasses	E, ν
5.3	192	Fibers, epoxy, composites	E, G, ν, ρ
8.1	291	Metals	K_{Ic}; also σ_o, σ_u, $100\varepsilon_f$, $\%RA$
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9.1	365	Metals	σ_a-N_f constants; also, σ_o, σ_u, $\tilde{\sigma}_{fB}$
11.1	495	Steels by class	da/dN-ΔK constants
11.2	506	Steels, aluminums	da/dN-ΔK constants (Walker); also K_{Ic}, σ_o
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14.1	655	Metals	ε_a-N_f constants; E, H', n'; also σ_o, σ_u, $\tilde{\sigma}_{fB}$, $\%RA$
15.2	727	Metals	S-D and L-M parameter constants
15.3	741	Metals	σ-ε-t nonlinear creep constants
B.5	804	Metals, rock, concrete	K_{Ic} and statistics; also σ_o or σ_{uc}

Explanation of Symbols for Materials Properties

E	Elastic modulus	$100\varepsilon_f$	Percent elongation
G	Shear modulus	$\tilde{\varepsilon}_f$	True fracture strain
H, n	Monotonic σ-ε constants (Ramberg-Osgood)	ν	Poisson's ratio
H', n'	Cyclic σ-ε constants (Ramberg-Osgood)	ρ	Density
HB	Brinell hardness	σ_f	Engineering fracture strength
HV	Vickers hardness	$\tilde{\sigma}_{fB}$	True fracture strength
K_{Ic}	Plane strain fracture toughness	σ_{fb}	Bend strength
$\%RA$	Percent reduction in area	σ_o	Yield strength
T_d	Heat deflection temperature	σ_u	Ultimate tensile strength
T_g	Glass transition temperature	σ_{uc}	Ultimate compressive strength
T_m	Melting temperature		

UNITS AND CONVERSION FACTORS

Quantity	SI Unit	U.S. Unit	SI Equivalent to U.S. Unit
Length	meter (m)	inch (in)	0.0254 m
	millimeter (mm)	inch (in)	25.4 mm
Force	newton (N)	pound (lb)	4.448 N
	kilonewton (kN)	kilopound (kip)	4.448 kN
Moment or Torque	N·m	lb·in	0.1130 N·m
Energy	joule (J) = N·m	in·lb	0.1130 J
		ft·lb	1.356 J
		calorie (cal)	4.19 J
Energy per Unit Volume	J/m^3	$in \cdot lb/in^3$	6895 J/m^3
Stress or Pressure	pascal (Pa) = N/m^2	psi = lb/in^2	6895 Pa
	MPa = MN/m^2 = N/mm^2	ksi = kip/in^2	6.895 MPa
Stress Intensity K of Fracture Mechanics	$MPa\sqrt{m}$	$ksi\sqrt{in}$	1.099 $MPa\sqrt{m}$

Notes:

(1) Under standard gravity on earth, a 1 kilogram (kg) mass has a weight force of 9.807 N or 2.205 lb. Also, for stress, $(\sigma,\ kg/mm^2) \times 9.807 = (\sigma,\ MPa)$.

(2) Time is given in units of seconds (s), minutes (min), or hours (h).

(3) Temperature is given in degrees Celsius (°C), or on the absolute scale of kelvins (K), or in degrees Fahrenheit (°F). Conversions are

$$T(K) = T(°C) + 273.15, \qquad T(°C) = \frac{T(°F) - 32}{1.8}$$

(4) Prefixes indicating changes in the order of magnitude of the basic units, such as 10^3 N = kN, are as follows:

Prefix	giga	mega	kilo	centi	milli	micro	nano
Symbol	G	M	k	c	m	μ	n
Factor	10^9	10^6	10^3	10^{-2}	10^{-3}	10^{-6}	10^{-9}

FREQUENTLY USED SYMBOLS

Roman Letters

a	Crack length
A	Cross-sectional area; creep coefficients; stress-life coefficient
b	Maximum possible crack length; stress-life exponent; thickness where t is time
B	Bulk modulus; Bridgman correction factor; stress-life exponent
B_f	Number of repetitions to failure
c	Half-depth of beam; radius of shaft; plastic strain versus life exponent; dashpot constant
C	Fatigue crack growth coefficient
d	Diameter; damping exponent
e	Base of natural logarithms ($e = 2.718\ldots$)
E	Modulus of elasticity
F	Finite width factor of fracture mechanics
G	Shear modulus; strain energy release rate
h	Height; half-height of cracked bodies
H	Strength coefficient for stress-strain curves
I	Area moment of inertia about an in-plane axis
J	Polar moment of inertia; J-integral; damping coefficient
k	Stress concentration factor; spring constant
K	Stress intensity factor of fracture mechanics
L	Length
m	Fatigue limit reduction factor; fatigue crack growth exponent; creep exponent
M	Bending moment
n	Strain hardening exponent
N	Number of cycles
p	Pressure
P	Force (load)
q	Notch sensitivity
Q	Activation energy
Q^{-1}	Loss coefficient in damping
r	Radius
R	Stress ratio for cyclic loading (minimum $\div$ maximum); universal gas constant
S	Nominal (average) stress
t	Time; thickness
T	Temperature; torque
u	Energy per unit volume
U	Energy
v	Displacement
V	Volume
w	Width
x, y, z	Spatial coordinates
X	Safety factor

Greek Letters

α	Coefficient of thermal expansion; angle; relative crack length ($\alpha = a/b$); Peterson constant
β	Neuber constant
γ	Shear strain; Walker exponent
δ	Slope reduction factor; crack-tip opening displacement; phase angle
ε	Normal strain
η	Tensile viscosity
θ	Angle
λ	Stress biaxiality ratio σ_2/σ_1
ν	Poisson's ratio
ρ	Notch-tip radius
σ	Normal stress at a point, or in a uniformly stressed member
τ	Shear stress
ω	Angular velocity

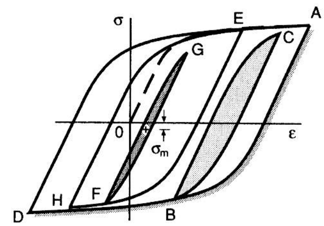
Subscripts: Meaning (Example)

a	Amplitude (σ_a)	max	Maximum (σ_{max})
ar	Completely reversed amplitude (σ_{ar})	min	Minimum (σ_{min})
c	Creep (ε_c); critical (K_c); value at $y = c$ location (σ_c)	*n*	Net section (S_n); at notch (ε_n)
		o	Yield (σ_o); fully-plastic value (M_o)
e	Elastic (ε_e); fatigue limit (σ_e)	*p*	Plastic (ε_p); proportional limit (σ_p); periodic inspection interval (N_p)
f	Final (A_f); failure (N_f)		
g	Gross section (S_g)	*r*	Residual (σ_r); rupture (t_r)
h	Value for octahedral planes (τ_h)	*sc*	Steady-state creep (ε_{sc})
i	Initial (A_i); initial yield value (M_i); summation index	*tc*	Transient creep (ε_{tc})
		u	Ultimate (σ_u)
j	Summation index where *i* means *initial*	*x, y, z*	Direction (σ_x); axis (I_z)
		xy, yz, zx	Plane (τ_{xy})
m	Mean (σ_m)	1, 2, 3	Principal direction (σ_1)

Modifiers: Meaning (Example)

Δ	Range in cyclic loading ($\Delta\sigma$)	*hat*	Actual service value ($\hat{S}$)
tilde	True ($\tilde{\sigma}$)	*dot*	Time rate ($\dot{\varepsilon}$)
bar	Effective ($\bar{\sigma}$); equivalent	*prime*	Value for cyclic loading (n'); other special values

Preface



Designing machines, vehicles, and structures that are safe, reliable, and economical requires both efficient use of materials and assurance that structural failure will not occur. It is therefore appropriate for undergraduate engineering majors to study the mechanical behavior of materials, specifically such topics as deformation, fracture, and fatigue.

This book may be used as a text for courses on mechanical behavior of materials at the junior or senior undergraduate level, and it may also be employed at the first-year graduate level by emphasizing the later chapters. The coverage includes traditional topics in the area, such as materials testing, yielding and plasticity, stress-based fatigue analysis, and creep. The relatively new methods of fracture mechanics and strain-based fatigue analysis are also considered and are in fact treated in some detail. For a practicing engineer with a bachelor's degree, this book provides an understandable reference source on the topics covered.

Emphasis is placed on analytical and predictive methods that are useful to the engineering designer in avoiding structural failure. These methods are developed from an engineering mechanics viewpoint, and the resistance of materials to failure is quantified by properties such as yield strength, fracture toughness, and stress-life curves for fatigue or creep. The intelligent use of materials property data requires some understanding of how the data are obtained so that their limitations and significance are clear. Thus, the materials tests used in various areas are generally discussed prior to considering the analytical and predictive methods.

In many of the areas covered, the existing technology is more highly developed for metals than for nonmetals. Nevertheless, data and examples for nonmetals, such as polymers and ceramics, are included where appropriate. Highly anisotropic materials, such as continuous fiber composites, are also considered, but only to a limited extent. Detailed treatment of these complex materials is not attempted here.

Relative to the first edition, this second edition features improvements and updates throughout. Some of the areas that received particular attention in the revisions are fracture mechanics, stress-based fatigue, and creep, and also reorganization of the chapter on stress-strain relationships. Two appendices have been added, one that reviews useful topics from elementary mechanics of materials, and another that considers statistical variation in materials properties. More than one-third of the student exercises are new or are substantially revised, and there are additional worked examples.

The remainder of this preface provides some comments on use of this book by anyone, whether student, instructor, or practicing engineer.

PREREQUISITES

Elementary mechanics of materials, also called strength of materials or mechanics of deformable bodies, provides an introduction to the subject of analyzing stresses and strains in engineering components, such as beams and shafts, for linear-elastic behavior. Completion of a standard (typically sophomore) course of this type is an essential prerequisite to the treatment provided here. Some useful review and reference material in this area is given in Appendix A, along with a treatment of fully plastic yielding analysis.

Many engineering curricula include an introductory (again, typically sophomore) course in materials science, including such subjects as crystalline and noncrystalline structure, dislocations and other imperfections, deformation mechanisms, processing of materials, and naming systems for materials. Prior exposure to this area of study is also recommended. However, as such a prerequisite may be missing, limited introductory coverage is given in Chapters 2 and 3. These two chapters can be used as a brief review, or they can be skipped entirely when a course in materials science has been taken by the students.

Mathematics through elementary calculus is also needed. A number of the worked examples and student problems involve basic numerical analysis, such as least-squares curve fitting, iterative solution of equations, and numerical integration. Hence, some background in these areas is useful, but not essential, as is an ability to perform plotting and numerical analysis on a personal computer. The numerical analysis needed is described in most introductory textbooks on the subject, such as Chapra (1998), which is listed at the end of this Preface.

REFERENCES AND BIBLIOGRAPHY

Each chapter contains a list of *References* near the end that identifies sources of additional reading and information. These lists are in some cases divided into categories such as general references, sources of material properties, and useful handbooks. Where a reference is mentioned in the text, the first author's name and the year of publication are given, allowing the reference to be quickly found in the list at the end of that chapter.

Where specific data or illustrations from other publications are used, these sources are identified by information in brackets, such as [Richards 61] or [ASM 88], where the two-digit numbers indicate the year of publication. All such *Bibliography* items are listed in a single section near the end of the book.

PRESENTATION OF MATERIALS PROPERTIES

Experimental data for specific materials are presented throughout the book in numerous illustrations, tables, examples, and problems. These are always real laboratory data. However, the intent is only to present typical data, not to give comprehensive information on materials properties. For actual engineering work, additional sources of materials properties, such as those listed at the ends of various chapters, should be consulted as needed. Also, materials property values are subject to statistical variation, as discussed in Appendix B, so that typical values from this book, or from any other source, need to be used with appropriate caution.

Where materials data are presented, any external source is identified as a Bibliography item. If no source is given, then such data are either from the author's research or from test results obtained in laboratory courses at Virginia Tech.

UNITS

The International System of Units (SI) is emphasized, but U.S. Customary Units are also included in most tables of data. On graphs, the scales are either SI or dual, except for a few cases of other units where illustrations from another publication are used in their original form. Only SI units are given in most exercises and where values are given in the text, as the use of dual units in these situations invites confusion.

The SI unit of force is the newton (N), and the U.S. unit is the pound (lb). It is often convenient to employ thousands of newtons (kilonewtons, kN) or thousands of pounds (kilopounds, kip). Stresses and pressures in SI units are thus given in newtons per square meter, N/m^2, which in the SI system is given the special name of pascal (Pa). Millions of pascals (megapascals, MPa) are generally appropriate for our use.

$$1\ \text{MPa} = 1\ \frac{\text{MN}}{\text{m}^2} = 1\ \frac{\text{N}}{\text{mm}^2}$$

where the latter equivalent form using millimeters (mm) is sometimes convenient. In U.S. units, stresses are generally given in kilopounds per square inch (ksi).

These units and others frequently used are listed, along with conversion factors, inside the front cover. As an illustrative use of this listing, let us convert a stress of 20 ksi to MPa. Since 1 ksi is equivalent to 6.895 MPa, we have

$$20\ \text{ksi} = 20\ \text{ksi}\left(6.895\ \frac{\text{MPa}}{\text{ksi}}\right) = 137.9\ \text{MPa}$$

Conversion in the opposite direction involves dividing by the equivalence value.

$$137.9\ \text{MPa} = \frac{137.9\ \text{MPa}}{\left(6.895\ \frac{\text{MPa}}{\text{ksi}}\right)} = 20\ \text{ksi}$$

It is also useful to note that strains are dimensionless quantities, so that no units are necessary. Strains are most commonly given as straightforward ratios of length change to length, but percentages are sometimes used, $\varepsilon_{\%} = 100\varepsilon$.

MATHEMATICAL CONVENTIONS

Standard practice is followed in most cases. The function *log* is understood to indicate logarithms to the base ten, and the function *ln* to indicate logarithms to the base $e = 2.718\ldots$, that is, natural logarithms. To indicate selection of the largest of several values, the function MAX( ) is employed.

NOMENCLATURE

In journal articles and in other books, and in various test standards and design codes, a wide variety of different symbols are used for certain variables that are needed. This situation is handled by using a consistent set of symbols throughout, while following the most common conventions wherever possible. However, a few exceptions or modifications to common practice are necessary to avoid confusion.

For example, K is used for the stress intensity of fracture mechanics, but not for stress concentration factor, which is designated k. Also, H is used instead of K or k for the strength coefficient describing certain stress-strain curves. The symbol S is used for nominal or average stress, whereas σ is the stress at a point, and also the stress at any point in a uniformly stressed member. Dual use of symbols is avoided except where the different usages occur in separate portions of the book. A list of the more commonly used symbols is given inside the back cover. More detailed lists are given near the end of each chapter in a section on *New Terms and Symbols*.

USE AS A TEXT

The various chapters are constituted so that considerable latitude is possible in choosing topics for study. A semester-length course could include at least portions of all chapters through 11, and also portions of Chapter 15. This covers the introductory and review topics in Chapters 1 to 6, and yield and fracture criteria for uncracked material in Chapter 7. Fracture mechanics is applied to static fracture in Chapter 8, and to fatigue crack growth in Chapter 11. Also, Chapters 9 and 10 cover the stress-based approach to fatigue, and Chapter 15 covers creep. If time permits, some topics on plastic deformation could be added from Chapters 12 and 13, and also from Chapter 14 on the strain-based approach to fatigue.

If the students' background in materials science is such that Chapters 2 and 3 are not needed, the new Section 3.8 on materials selection may still be useful. Note that the order of Chapters 4 and 5 has been reversed compared to the previous edition, as many teaching from the book covered the material in this order. However, Chapters 4, 5, and 6 are nearly independent of one another, so that they may be taught in any sequence that seems appropriate to the instructor.

Particular portions of certain chapters are not strongly required as preparation for the remainder of that chapter, nor are they crucial for later chapters. Thus, although the topics involved are generally important in their own right, they may be omitted or delayed if desired without serious loss of continuity. These include the sections listed in Table I.

After completion of Chapter 8 on fracture mechanics, one option is to proceed directly to Chapter 11, which extends the topic to fatigue crack growth. This can be done by passing over all of Chapters 9 and 10 except Sections 9.1 to 9.3.

Various options exist for limited but still coherent coverage of the relatively advanced topics in Chapters 12 through 15. For example, it might be useful to include some material from Chapter 14 on strain-based fatigue, but not all details. Section 14.4 on multiaxial stresses could then be omitted, as could all of Section 14.5 except 14.5.1, which limits the coverage to constant amplitude loading. If this is done, then Section 12.3 on multiaxial stresses is not needed beforehand, and the only text from Chapter 13 that is essential is the introductory Section 13.1 and Section 13.5 on notched members. In Chapter 15, Sections 15.1 to 15.4 provide a reasonable introduction to the topic of creep that does not depend heavily on any other material beyond Chapter 4. Section 15.5 and those following are relatively independent of one another, but some of these do depend on particular portions of Chapters 12 and 13.

TABLE I SECTIONS NOT SERIOUSLY AFFECTING CONTINUITY

Section	Topic
4.5	True stress-strain for tension test
4.6 to 4.9	Compression, hardness, impact, and bending tests
5.4	Anisotropic elasticity
7.7 and 7.8	Failure criteria for brittle materials
8.6 to 8.8	Plastic zones, toughness testing, and nonlinear fracture mechanics
10.7	Estimating *S-N* Curves
11.7	Crack growth for variable amplitude loading
11.9	Plasticity and limitations of LEFM for crack growth
13.3	Residual stresses and strain for bending

A *Solutions Manual* is available to individuals who are instructors in courses that employ the main text. Also, a laboratory manual is planned.

REFERENCES

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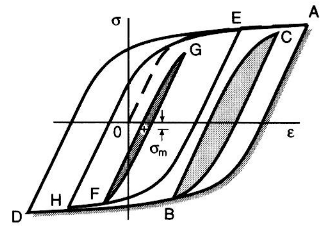

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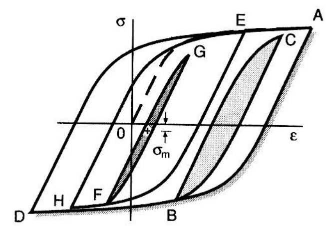

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