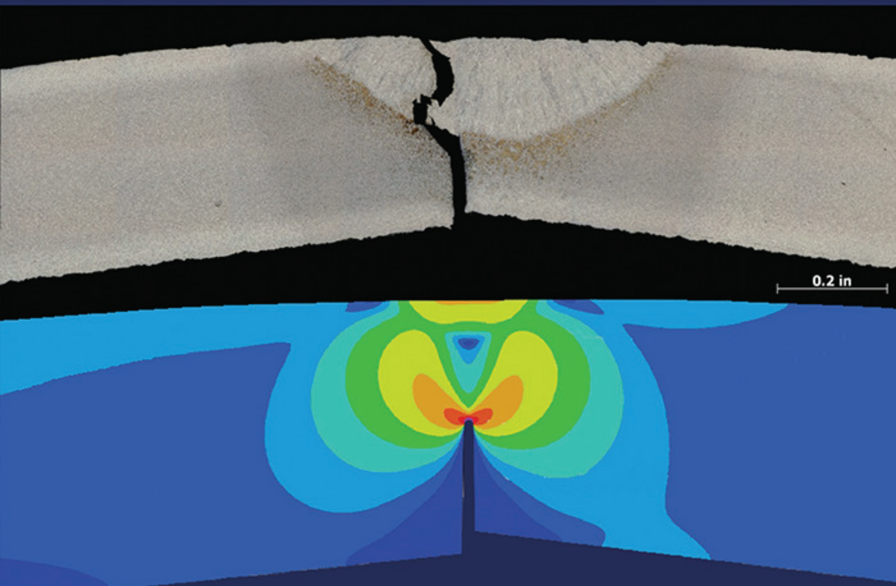
GLOBAL EDITION

Mechanical Behavior of Materials

Engineering Methods for Deformation, Fracture, and Fatigue



FIFTH EDITION

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MATERIALS PROPERTIES LOCATOR

Table No.	Page	Material Type	Data Listed
2.2	57	Whiskers, fibers, wires	E, σ_u
3.2	90	Metals	E, σ_o, σ_u, $100\varepsilon_f$, $\%RA$
3.3	91	Polymers	E, σ_o, σ_f, $100\varepsilon_f$, Izod energy, T_d
3.4	92	Ceramics, glasses, stone	T_m, ρ, E, σ_u, σ_{uc}
3.5	93	SiC in Al composite	E, σ_o, σ_u, $100\varepsilon_f$
3.7	107	Metals	$\tilde{\sigma}_{fB}$, $\tilde{\varepsilon}_f$, H, n, HB
3.8	108	Representative	E, σ_o or σ_u, ρ, cost
4.1	134	Ceramics, glasses	E, σ_{fb}, HV
5.2	166	Metals, polymers, ceramics	E, ν
5.3	181	Fibers, epoxy, composites	E, G, ν, ρ
7.1	266	Stone, concrete, gray iron	σ_u, σ_{uc}, C-M fitting constants
8.1	300	Metals	K_{Ic}; also σ_o, σ_u, $100\varepsilon_f$,$\%RA$
8.2	301	Polymers, ceramics	K_{Ic}
9.1	383	Metals	σ_a-N_f constants; also σ_o, σ_u, $\tilde{\sigma}_{fB}$
10.1	464	Metals	Fatigue limit estimates
10.2	480	Metals	S-N curve estimates at 10^3 cycles
11.1	524	Steels by class	da/dN-ΔK constants
11.2	535	Steels, aluminums	da/dN-ΔK constants (Walker); also K_{Ic}, σ_o
11.3	538	Metals	da/dN-ΔK constants (Forman); also K_{Ic}, σ_o
12.1	594	Metal alloys	K_{IEAC}, $\dot{a}$, K_{Ic}
12.5	605	Solvents, polymers	δ_e, δ_p
13.1	641	Steels, aluminums	E, H', n'; also σ_o, σ_u
15.1	727	Metals	ε_a-N_f constants; E, H', n'; σ_o, σ_u, $\tilde{\sigma}_{fB}$, $\%RA$
16.3	802	Metals	L-M parameter constants
16.4	816	Metals	σ-ε-t nonlinear creep constants
B.5	881	Metals, stone, concrete	K_{Ic} and statistics; also σ_o or σ_{uc}
C.1	886	Metals, alloys	T_m, ρ, E
C.9	907	Polymers	T_g, T_m

Explanation of Symbols for Materials Properties

$\dot{a}$	Crack velocity	T_m	Melting temperature
E	Elastic modulus	δ_e, δ_p	Solubility parameters
G	Shear modulus	$100\varepsilon_f$	Percent elongation
H, n	Monotonic σ-ε constants	$\tilde{\varepsilon}_f$	True fracture strain
H', n'	Cyclic σ-ε constants	ν	Poisson's ratio
HB	Brinell hardness	ρ	Density
HV	Vickers hardness	σ_f	Engineering fracture strength
K_{Ic}	Plane strain fracture toughness	$\tilde{\sigma}_{fB}$	True fracture strength
K_{IEAC}	Environmental cracking threshold	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

(b) Consider a uniaxial tension test, and on this basis define a convenient effective stress.

(c) In three-dimensional principal normal stress space, describe the failure surface corresponding to the equation given. Also describe the failure locus for the special case of plane stress.

(d) Describe a critical experiment, consisting of one or a few mechanical tests, and a minimum of experimentation, that provides a definitive choice among the aforementioned three criteria. Some mechanical tests that are feasible are uniaxial tension and compression, torsion of tubes and rods, internal and external pressure of closed-end tubes, biaxial tension in pressurized diaphragms, and hydrostatic compression.

Section 7.7

7.42 The results of two tests on sand–cement mortar are given in Table P7.42: (A) a uniaxial compression test, and (B) a confined compression test with lateral pressure $\sigma_1 = \sigma_2$.

(a) Assume that the Coulomb–Mohr fracture criterion applies, and use the results of these tests to determine the slope and intercept constants μ and τ_i for Eq. 7.42.

(b) Accurately plot the resulting $|\tau|$ versus σ failure envelope line. Also accurately plot the corresponding σ_1 versus σ_2 (biaxial stress) failure locus similar to Fig. 7.17.

Table P7.42

Test	σ_3, MPa	$\sigma_1 = \sigma_2$, MPa
A	−31.8	0
B	−154.1	−41.4

Source: Data in [Campbell 62].
Note: Three results are averaged for Test A, and two for Test B.

7.43 Test data are given in Table P7.43 for limestone under simple tension, simple compression, and compression with lateral pressure. The values of σ_3 correspond to fracture, except at the highest lateral pressure, where a maximum load was reached without complete fracture. Proceed as in Ex. 7.7 for these data.

Table P7.43

σ_3 MPa	$\sigma_1 = \sigma_2$ MPa
4	0
−83	0
−519	−100
−820	−200

Source: Data in [Jaeger 69] pp. 75 and 156.

7.44 Test data are given in Table P7.44 for diabase rock from Virginia under simple tension, simple compression, and compression with lateral pressure. The values of σ_3 correspond to fracture. Proceed as in Ex. 7.7 for these data.

Table P7.44

σ_3 MPa	$\sigma_1 = \sigma_2$ MPa
17.60	0
−226	0
−426	−10.34
−475	−19.31
−548	−30.3

Source: Data in [Karfakis 03].

7.45 Test data are given in Table P7.45 for Portland cement concrete, made with Thames Valley flint gravel as the aggregate, under simple tension, simple compression, and compression with lateral pressure. The values of σ_3 correspond to failure, which occurred as distinct fractures for lateral pressures of zero and 2.5 MPa. For the higher lateral pressures, the peak compressive stress occurred after considerable nonlinear deformation, with an array of internal splitting cracks being observed. The tests were done after 56 days of aging, and any water appearing in compression was allowed to drain from the ends of the specimen. Proceed as in Ex. 7.7 for these data.

Table P7.45

σ_3 MPa	$\sigma_1 = \sigma_2$ MPa
1.70	0
−45.3	0
−58.8	−2.5
−72.0	−5.0
−96.2	−10.0
−117.6	−15.0
−137.5	−20.0
−155.2	−25.0

Source: Data in [Hobbs 71].

7.46 Consider the test data of Table P7.45, but ignore the simple tension test on the first line.

(a) Fit these data to the alternative form of the C-M criterion of Eq. 7.59, where h and $|\sigma'_{uc}|$ are the fitting constants.

(b) Also fit these data to Eq. 7.60, where k and a are the fitting constants, and $|\sigma_{uc}|$ is the value from the simple compression test.

(c) Comment on the relative success of the two equations in representing the data.

Section 7.8

7.47 For the situation of Ex. 7.8, accurately plot the σ_1 versus σ_2 failure locus for plane stress, as in Fig. 7.20(a). Then use this plot to graphically verify the two safety factors.

7.48 A brittle material has an ultimate tensile strength of 300 MPa, and for compression-dominated behavior, it has a Coulomb–Mohr failure envelope line given by $\tau_i = 387$ MPa and $\mu = 0.259$.

(a) Accurately plot the modified Mohr failure envelope on σ versus $|\tau|$ coordinates.

(b) Calculate σ'_{uc} and σ_i, and then accurately plot the biaxial failure locus on σ_1 versus σ_2 coordinates.

(c) Graphically determine the safety factor for the following cases of biaxial principal stresses:

(1) $\sigma_1 = 200$, $\sigma_2 = -100$ MPa

(2) $\sigma_1 = 100$, $\sigma_2 = -600$ MPa

(3) $\sigma_1 = -300$, $\sigma_2 = -600$ MPa

(d) Confirm the values from (c) by applying Eq. 7.65.

7.49 In a compression test, a cylinder of unreinforced concrete has an ultimate strength of 40 MPa, and the fracture is observed to occur on a plane inclined to the direction of loading by an angle of approximately $\theta_c = 26°$. If this same concrete is subjected to lateral (compressive) stresses of $\sigma_1 = \sigma_2 = -18$ MPa, estimate the stress σ_3 necessary to cause failure in compression. (Suggestion: If the tensile strength is needed, this may be estimated as 10% of the compressive strength.)

7.50 A cylinder of the mortar of Table 7.1 is subjected to an axial compressive stress σ_z of 50 MPa, along with equal lateral compressive stresses, $\sigma_x = \sigma_y$.

(a) What is the safety factor against fracture if the lateral compressive stresses are 12 MPa?

(b) Let σ_z remain unchanged. But let the lateral compression be reduced, that is, $|\sigma_x| = |\sigma_y| < 12$ MPa. Can $\sigma_x = \sigma_y$ approach zero without fracture occurring? At what value of $\sigma_x = \sigma_y$ is fracture expected to occur?

7.51 A building column 400 mm in diameter is made of the sandstone of Table 7.1.

(a) What is the safety factor against fracture if the column is subjected to a compressive force of 1250 kN?

(b) What is the safety factor against fracture if the column is subjected to a torque of 20 kN·m?

(c) What is the safety factor against fracture if the column is subjected at the same time to both the 1250 kN compressive force and the 20 kN·m torque?

(*Problem continues*)

(d) Compare the safety factors calculated in (a), (b), and (c), and explain the trends in their values.

7.52 A block of the concrete of Table 7.1 is loaded with a pressure p applied to all sides, and also with a shear stress, $\tau_{xy} = 30$ MPa, as shown in Fig. P7.29.

(a) Will the block fracture if $p = 40$ MPa?

(b) What smallest value of p such that the block will not fracture?

7.53 A block of the mortar of Table 7.1 is loaded with a shear stress $\tau_{xy} = 1.0$ MPa, and also with a normal stress σ_z, as shown in Fig. P7.30.

(a) What is the safety factor against fracture if $\sigma_z = 0$?

(b) What is the safety factor against fracture if σ_z is 15 MPa compression?

(c) For the safety factor to be not less than 2.5, what is the most severe compressive σ_z that can be applied?

7.54 Consider a 50 mm diameter shaft of the gray cast iron of Table 7.1. If a safety factor of 3.0 against fracture is required, what is the largest torque that can be applied along with a compressive axial force of 250 kN?

7.55 A building column 300 mm in diameter is made of the sandstone of Table 7.1. It resists a compressive force P and a torque $T = 15{,}000$ N·m, and a safety factor of 4.0 against fracture is required.

(a) What is the largest compressive force P that can be permitted?

(b) If only the torsion is applied, that is $P = 0$, is the safety factor requirement met? If not, what minimum value of compressive force P must be applied to satisfy the safety factor?

7.56 A thick-walled tube has inner and outer radii of 30 and 50 mm, respectively, and it is made of the gray cast iron of Table 7.1.

(a) What is the safety factor against fracture for an internal pressure of 20 MPa?

(b) What is the safety factor against fracture if a compressive axial force of 700 kN is applied, in addition to the internal pressure in part (a)?

8

Fracture of Cracked Members

OBJECTIVES

- Understand the effects of cracks on materials and why the *fracture toughness*, K_{Ic}, is a measure of a material's ability to resist failure due to a crack. Explore trends in K_{Ic} with material and with variables such as temperature, loading rate, and processing.
- Evaluate the effects of cracks in engineering components, using linear-elastic fracture mechanics. Apply the *stress intensity factor*, K, to combine stress, geometry, and crack size to characterize the severity of a crack situation.
- Analyze the effects of plasticity in cracked members, including plastic zone sizes, constraint effects due to thickness, and fully plastic limit loads; briefly introduce advanced fracture mechanics methods.

8.1 INTRODUCTION

The presence of a crack in a component of a machine, vehicle, or structure may weaken it so that it fails by fracturing into two or more pieces. This can occur at stresses below the material's yield strength, where failure would not normally be expected. Where cracks are difficult to avoid, a special methodology called *fracture mechanics* can be used to aid in selecting materials and designing components to minimize the possibility of fracture.

In addition to cracks themselves, other types of flaws that are cracklike in form may easily develop into cracks, and these need to be treated as if they were cracks. Examples include deep surface scratches or gouges, voids in welds, inclusions of foreign substances in cast and forged materials, and delaminations in layered materials. For example, Fig. 8.1 describes a natural gas pipeline fracture, which occurred as a result of faulty welds that created cracklike flaws. The fracture resulted in an explosion and large fire in a residential neighborhood, where there were eight deaths, numerous injuries, 38 homes destroyed, and 70 others damaged. As a further example, a photograph of a crack starting from a large inclusion in the wall of a forged steel artillery tube is shown in Fig. 8.2.

The study and use of fracture mechanics is of major engineering importance simply because cracks or cracklike flaws occur more frequently than we might at first think. For example, the periodic inspections of large commercial aircraft frequently reveal cracks, sometimes numerous cracks, that must be repaired. Cracks or cracklike flaws also commonly occur in ship structures, bridge structures, pressure vessels and piping, heavy machinery, and ground vehicles. They are also a source of concern for various parts of nuclear reactors.

Prior to the development of fracture mechanics in the 1950s and 1960s, specific analysis of cracks in engineering components was not possible. Engineering design was based primarily on tension, compression, and bending tests, along with failure criteria for nominally uncracked material—that is, the methods discussed in Chapter 7. Such methods automatically include the effects of the microscopic flaws that are inherently present in any sample of material. But they provide no means of accounting for larger cracks, so their use involves the implicit assumption that no unusual cracks are present. Notch-impact tests, as described in Section 4.4, do represent an attempt to deal with cracks. These tests provide a rough guide for choosing materials to resist failure due to cracks, and they aid in identifying temperatures where particular materials are brittle. But there is no direct means of relating the fracture energies measured in notch-impact tests to the behavior of an engineering component.

In contrast, fracture mechanics provides materials properties that can be related to component behavior, allowing specific analysis of strength and life as limited by various sizes and shapes of cracks. Hence, it provides a basis for choosing materials and design details so as to minimize the possibility of failure due to cracks.

Effective use of fracture mechanics requires inspection of components, so that there is some knowledge of what sizes and geometries of cracks are present or might be present. For example, periodic inspections are commonly performed on large aircraft and bridges so that a crack cannot grow to a dangerous size before it is found and repaired. Inspection for cracks and other flaws is called *nondestructive testing* (NDT), or *nondestructive evaluation* (NDE).

An obvious method of detecting cracks is simple *visual examination*, which may be aided by magnification and/or digital image enhancement. More sophisticated methods include *X-ray imaging*, which is capable of detecting internal flaws. The *ultrasonic method* consists of propagating high-frequency sound waves into a component, with the return reflections providing evidence of flaws that might be present. In the *eddy-current method*, a wire coil with an alternating current is employed to induce electrical currents in the test material, and the response is examined for abnormalities that indicate a flaw. The *dye-penetrant method* uses a low-surface-tension fluid, which is drawn into cracks by capillary action, and then subsequently detected. And there are numerous other methods. If a crack is found, repairs may be necessary, such as replacing a part, or modifying it, as by machining away a small crack to leave a smooth surface, or by reinforcing the cracked region in some manner.

In this chapter, we will introduce fracture mechanics and study its application to failure under static loading. Later, in Chapters 11 and 12, we will consider growth of cracks due to cyclic loading and due to hostile chemical environments.