SUMMARY

Introduction

- The three usual causes of failure are
  - Improper materials selection and processing
  - Inadequate component design
  - Component misuse

Fundamentals of Fracture

- Fracture in response to tensile loading and at relatively low temperatures may occur by ductile and brittle modes.
- Ductile fracture is normally preferred because
  - Preventive measures may be taken inasmuch as evidence of plastic deformation indicates that fracture is imminent.
  - More energy is required to induce ductile fracture than for brittle fracture.
- Cracks in ductile materials are said to be *stable* (i.e., resist extension without an increase in applied stress).
- For brittle materials, cracks are *unstable*—that is, crack propagation, once started, continues spontaneously without an increase in stress level.

Ductile Fracture

- For ductile metals, two tensile fracture profiles are possible:
  - Necking down to a point fracture when ductility is high (Figure 8.1*a*)
  - Only moderate necking with a cup-and-cone fracture profile (Figure 8.1*b*) when the material is less ductile

Brittle Fracture

- For *brittle fracture*, the fracture surface is relatively flat and perpendicular to the direction of the applied tensile load (Figure 8.1*c*).
- *Transgranular* (through-grain) and *intergranular* (between-grain) crack propagation paths are possible for polycrystalline brittle materials.

Principles of Fracture Mechanics

- The significant discrepancy between actual and theoretical fracture strengths of brittle materials is explained by the existence of small flaws that are capable of amplifying an applied tensile stress in their vicinity, leading ultimately to crack formation. Fracture ensues when the theoretical cohesive strength is exceeded at the tip of one of these flaws.
- The maximum stress that may exist at the tip of a crack (oriented as in Figure 8.8*a*) is dependent on crack length and tip radius, as well as on the applied tensile stress according to Equation 8.1.
- Sharp corners may also act as points of stress concentration and should be avoided when designing structures that are subjected to stresses.
- There are three crack displacement modes (Figure 8.10): opening (tensile), sliding, and tearing.
- A condition of plane strain is found when specimen thickness is much greater than crack length—that is, there is no strain component perpendicular to the specimen faces.
- The fracture toughness of a material is indicative of its resistance to brittle fracture when a crack is present. For the plane strain situation (and mode I loading), it is dependent on applied stress, crack length, and the dimensionless scale parameter Y as represented in Equation 8.5.
- K_{Ic} is the parameter normally cited for design purposes; its value is relatively large for ductile materials (and small for brittle ones) and is a function of microstructure, strain rate, and temperature.
- With regard to designing against the possibility of fracture, consideration must be given to material (its fracture toughness), the stress level, and the flaw size detection limit.

Fracture Toughness Testing

- Three factors that may cause a metal to experience a ductile-to-brittle transition are exposure to stresses at relatively low temperatures, high strain rates, and the presence of a sharp notch.
- Qualitatively, the fracture behavior of materials may be determined using the Charpy and the Izod impact testing techniques (Figure 8.12).
- On the basis of the temperature dependence of measured impact energy (or the appearance of the fracture surface), it is possible to ascertain whether a material experiences a ductile-to-brittle transition and, if it does, the temperature range over which such a transition occurs.
- Low-strength steel alloys typify this ductile-to-brittle behavior and, for structural applications, should be used at temperatures in excess of the transition range. Furthermore, low-strength FCC metals, most HCP metals, and high-strength materials do not experience this ductile-to-brittle transition.
- For low-strength steel alloys, the ductile-to-brittle transition temperature may be lowered by decreasing grain size and lowering the carbon content.

Fatigue

- Fatigue is a common type of catastrophic failure in which the applied stress level fluctuates with time; it occurs when the maximum stress level may be considerably lower than the static tensile or yield strength.

Cyclic Stresses

- Fluctuating stresses are categorized into three general stress-versus-time cycle modes: reversed, repeated, and random (Figure 8.17). Reversed and repeated modes are characterized in terms of mean stress, range of stress, and stress amplitude.

The *S–N* Curve

- Test data are plotted as stress (normally, stress amplitude) versus the logarithm of the number of cycles to failure.
- For many metals and alloys, stress decreases continuously with increasing number of cycles at failure; fatigue strength and fatigue life are parameters used to characterize the fatigue behavior of these materials (Figure 8.19*b*).

- For other metals (e.g., ferrous and titanium alloys), at some point, stress ceases to decrease with, and becomes independent of, the number of cycles; the fatigue behavior of these materials is expressed in terms of fatigue limit (Figure 8.19*a*).

Crack Initiation and Propagation

- Fatigue cracks normally nucleate on the surface of a component at some point of stress concentration.
- Two characteristic fatigue surface features are beachmarks and striations.
  - *Beachmarks* form on components that experience applied stress interruptions; they normally may be observed with the naked eye.
  - Fatigue *striations* are of microscopic dimensions, and each is thought to represent the crack tip advance distance over a single load cycle.

Factors That Affect Fatigue Life

- Measures that may be taken to extend fatigue life include the following:
  - Reducing the mean stress level
  - Eliminating sharp surface discontinuities
  - Improving the surface finish by polishing
  - Imposing surface residual compressive stresses by shot peening
  - Case hardening by using a carburizing or nitriding process

Environmental Effects

- Thermal stresses may be induced in components that are exposed to elevated temperature fluctuations and when thermal expansion and/or contraction is restrained; fatigue for these conditions is termed *thermal fatigue*.
- The presence of a chemically active environment may lead to a reduction in fatigue life for corrosion fatigue. Measures that may be taken to prevent this type of fatigue include the following:
  - Application of a surface coating
  - Use of a more corrosion-resistant material
  - Reducing the corrosiveness of the environment
  - Reducing the applied tensile stress level
  - Imposing residual compressive stresses on the surface of the specimen

Generalized Creep Behavior

- The time-dependent plastic deformation of metals subjected to a constant load (or stress) and at temperatures greater than about $0.4T_m$ is termed *creep*.
- A typical creep curve (strain versus time) normally exhibits three distinct regions (Figure 8.29): transient (or primary), steady-state (or secondary), and tertiary.
- Important design parameters available from such a plot include the steady-state creep rate (slope of the linear region) and rupture lifetime (Figure 8.29).

Stress and Temperature Effects

- Both temperature and applied stress level influence creep behavior. Increasing either of these parameters produces the following effects:
  - An increase in the instantaneous initial deformation
  - An increase in the steady-state creep rate
  - A decrease in the rupture lifetime
- An analytical expression was presented that relates $\dot{\epsilon}_s$ to both temperature and stress—see Equation 8.25.

Data Extrapolation Methods

- Extrapolation of creep test data to lower-temperature/longer-time regimes is possible using a plot of logarithm of stress versus the Larson–Miller parameter for the particular alloy (Figure 8.33).

Alloys for High-Temperature Use

- Metal alloys that are especially resistant to creep have high elastic moduli and melting temperatures; these include the superalloys, the stainless steels, and the refractory metals. Various processing techniques are employed to improve the creep properties of these materials.

Equation Summary

Equation Number	*Equation*	*Solving For*	*Page Number*
8.1	$\sigma_m = 2\sigma_0 \left(\dfrac{a}{\rho_t}\right)^{1/2}$	Maximum stress at tip of elliptically shaped crack	258
8.4	$K_c = Y\sigma_c\sqrt{\pi a}$	Fracture toughness	260
8.5	$K_{Ic} = Y\sigma\sqrt{\pi a}$	Plane-strain fracture toughness	261
8.6	$\sigma_c = \dfrac{K_{Ic}}{Y\sqrt{\pi a}}$	Design (or critical) stress	262
8.7	$a_c = \dfrac{1}{\pi}\left(\dfrac{K_{Ic}}{\sigma Y}\right)^2$	Maximum allowable flaw size	263
8.14	$\sigma_m = \dfrac{\sigma_{max} + \sigma_{min}}{2}$	Mean stress (fatigue tests)	270
8.15	$\sigma_r = \sigma_{max} - \sigma_{min}$	Range of stress (fatigue tests)	270
8.16	$\sigma_a = \dfrac{\sigma_{max} - \sigma_{min}}{2}$	Stress amplitude (fatigue tests)	270
8.17	$R = \dfrac{\sigma_{min}}{\sigma_{max}}$	Stress ratio (fatigue tests)	270
8.23	$\sigma = \alpha_l E \Delta T$	Thermal stress	281
8.24	$\dot{\epsilon}_s = K_1\sigma^n$	Steady-state creep rate (constant temperature)	283
8.25	$\dot{\epsilon}_s = K_2\sigma^n \exp\left(-\dfrac{Q_c}{RT}\right)$	Steady-state creep rate	284
8.27	$m = T(C + \log t_r)$	Larson–Miller parameter	285

List of Symbols

Symbol	*Meaning*
a	Length of a surface crack
C	Creep constant; normally has a value of about 20 (for T in K and t_r in h)
E	Modulus of elasticity
K_1, K_2, n	Creep constants that are independent of stress and temperature
Q_c	Activation energy for creep
R	Gas constant (8.31 J/mol·K)
T	Absolute temperature
ΔT	Temperature difference or change
t_r	Rupture lifetime
Y	Dimensionless parameter or function
α_l	Linear coefficient of thermal expansion
ρ_t	Crack tip radius
σ	Applied stress

(*continued*)

Symbol	*Meaning*
σ_0	Applied tensile stress
σ_{max}	Maximum stress (cyclic)
σ_{min}	Minimum stress (cyclic)

Important Terms and Concepts

brittle fracture
case hardening
Charpy test
corrosion fatigue
creep
ductile fracture
ductile-to-brittle transition
fatigue
fatigue life
fatigue limit
fatigue strength
fracture mechanics
fracture toughness
impact energy
intergranular fracture
Izod test
plane strain
plane strain fracture toughness
stress raiser
thermal fatigue
transgranular fracture