Chapter 8: Mechanical Failure

ISSUES TO ADDRESS...

• How do cracks that lead to failure form?
• How is fracture resistance quantified? How do the fracture resistances of the different material classes compare?
• How do we estimate the stress to fracture?
• How do loading rate, loading history, and temperature affect the failure behavior of materials?

Ship-cyclic loading from waves.
Adapted from chapter-opening photograph, Chapter 8, Callister & Rethwisch 8e. (by Neil Boenzi, The New York Times.)

Computer chip-cyclic thermal loading.
Adapted from Fig. 22.30(b), Callister 7e.
(Fig. 22.30(b) is courtesy of National Semiconductor Corporation.)

Hip implant-cyclic loading from walking.
Adapted from Fig. 22.26(b), Callister 7e.
Tour info

Mon July 2  Perkins Engines / Peterborough Cathedral
leave 7:00  Return 18:00

Wed July 4  4th of July Party at Jay's house

Thur July 5  Rolls - Royce
leave 7:30  Return 17:00

Tues July 10  Univ. of Birmingham, Interdisciplinary Research Center
leave 7:30  return 18:00

Wed July 11  Warick
leave 8:15  return 17:00

Thur July 12  Bath
leave 8  return 17:00
Fracture mechanisms

• Ductile fracture
  – Accompanied by significant plastic deformation

• Brittle fracture
  – Little or no plastic deformation
  – Catastrophic
Ductile vs Brittle Failure

• Classification:
  Fracture behavior:
  Very Ductile
  Moderately Ductile
  Brittle

%AR or %EL
  Large
  Moderate
  Small

• Ductile fracture is usually more desirable than brittle fracture!
  Ductile: Warning before fracture
  Brittle: No warning

Adapted from Fig. 8.1, *Callister & Rethwisch 8e.*
Example: Pipe Failures

- **Ductile failure:**
  -- one piece
  -- large deformation

- **Brittle failure:**
  -- many pieces
  -- small deformations

Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66. John Wiley and Sons, Inc., 1987. Used with permission.
Moderately Ductile Failure

- Failure Stages:
  - necking
  - void nucleation
  - void growth and coalescence
  - shearing at surface
  - fracture

- Resulting fracture surfaces (steel) particles serve as void nucleation sites.


Fracture surface of tire cord wire loaded in tension. Courtesy of F. Roehrig, CC Technologies, Dublin, OH. Used with permission.
Moderately Ductile vs. Brittle Failure

cup-and-cone fracture  brittle fracture

Adapted from Fig. 8.3, *Callister & Rethwisch 8e.*
Brittle Failure

Arrows indicate point at which failure originated

Adapted from Fig. 8.5(a), Callister & Rethwisch 8e.
Brittle Fracture Surfaces

- **Intergranular** (between grains)
  - **304 S. Steel** (metal)

- **Transgranular** (through grains)
  - **316 S. Steel** (metal)
    - Reprinted with permission from "Metals Handbook", 9th ed, Fig. 650, p. 357. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by D.R. Diercks, Argonne National Lab.)

  - **Polypropylene** (polymer)

  - **Al Oxide** (ceramic)
    - Reprinted with permission from "Failure Analysis of Brittle Materials", p. 78. Copyright 1990, The American Ceramic Society, Westerville, OH. (Micrograph by R.M. Gruver and H. Kirchner.)
Ideal vs Real Materials

• Stress-strain behavior (Room $T$):

$\sigma$ vs $\varepsilon$:
- $E/10$: perfect mat’l-no flaws
- $E/100$: typical mat’ls
- $0.1$: typical ceramics
- Typical polymer

• DaVinci (500 yrs ago!) observed...
  -- the longer the wire, the smaller the load for failure.

• Reasons:
  -- flaws cause premature failure.
  -- larger samples contain longer flaws!

Flaws are Stress Concentrators!

- Griffith Crack

\[ \sigma_m = 2\sigma_o \left( \frac{a}{\rho_t} \right)^{1/2} = K_t \sigma_o \]

where

\( \rho_t = \) radius of curvature

\( \sigma_o = \) applied stress

\( \sigma_m = \) stress at crack tip

Adapted from Fig. 8.8(a), *Callister & Rethwisch 8e.*
Concentration of Stress at Crack Tip

Adapted from Fig. 8.8(b), Callister & Rethwisch 8e.
Engineering Fracture Design

- Avoid sharp corners!

\[
K_t = \frac{\sigma_{\text{max}}}{\sigma_0}
\]

Adapted from Fig. 8.2W(c), Callister 6e.
(Fig. 8.2W(c) is from G.H. Neugebauer, Prod. Eng. (NY), Vol. 14, pp. 82-87 1943.)
Crack Propagation

Cracks having sharp tips propagate easier than cracks having blunt tips

- A plastic material deforms at a crack tip, which “blunts” the crack.

Energy balance on the crack

- Elastic strain energy-
  - energy stored in material as it is elastically deformed
  - this energy is released when the crack propagates
  - creation of new surfaces requires energy
Criterion for Crack Propagation

Crack propagates if crack-tip stress \( (\sigma_m) \) exceeds a critical stress \( (\sigma_c) \)

\[
\text{i.e., } \sigma_m > \sigma_c
\]

\[
\sigma_c = \left( \frac{2E\gamma_s}{\pi a} \right)^{1/2}
\]

where

- \( E \) = modulus of elasticity
- \( \gamma_s \) = specific surface energy
- \( a \) = one half length of internal crack

For ductile materials => replace \( \gamma_s \) with \( \gamma_s + \gamma_p \)

where \( \gamma_p \) is plastic deformation energy
Fracture Toughness Ranges

Based on data in Table B.5, *Callister & Rethwisch 8e*.

Composite reinforcement geometry is: f = fibers; sf = short fibers; w = whiskers; p = particles. Addition data as noted (vol. fraction of reinforcement):

2. (55 vol%) Courtesy J. Cornie, MMC, Inc., Waltham, MA.
4. Courtesy CoorsTek, Golden, CO.
Design Against Crack Growth

- Crack growth condition:
  \[ K \geq K_c = Y \sigma \sqrt{\pi a} \]

- Largest, most highly stressed cracks grow first!

  --Scenario 1: Max. flaw size dictates design stress.
  \[ \sigma_{\text{design}} < \frac{K_c}{Y \sqrt{\pi a_{\text{max}}}} \]

  --Scenario 2: Design stress dictates max. flaw size.
  \[ a_{\text{max}} < \frac{1}{\pi} \left( \frac{K_c}{Y \sigma_{\text{design}}} \right) \]
$K_{IC}$

Mode II

In plane shear

Mode I

opening

Mode III

Out of plane shear

Fig. 8.10
$K_I \rightarrow \text{loading parameter}$

$K_{IC} \rightarrow \text{material property}$

$\sigma, a, \gamma$

$K_I$ is to applied stress ($\sigma$)
as $K_{IC}$ is to $\sigma_y$
8.9) Calculate the max. crack length for 7075 Al loaded to a stress one half its yield strength. \( Y = 1.35 \)

\[ \sigma_y = 495 \text{ MPa} \quad K_{IC} = 24 \text{ MPa} \]

Eq. 8.7

\[ a_c = \frac{1}{\pi} \left( \frac{K_{IC}}{\sigma_y} \right)^2 = \frac{1}{\pi} \left[ \frac{24 \text{ MPa} \sqrt{\text{m}}}{(1.35)(495/2)} \right]^2 \]

\[ r = \frac{\sigma_y}{2} \]

\[ = 0.0016 \text{ m} = 1.6 \text{ mm} \]
Design Example: Aircraft Wing

- Material has $K_{lc} = 26$ MPa-m$^{0.5}$
- Two designs to consider...

  **Design A**
  - largest flaw is 9 mm
  - failure stress = 112 MPa

  **Design B**
  - use same material
  - largest flaw is 4 mm
  - failure stress = ?

- Use...
  \[ \sigma_c = \frac{K_{lc}}{Y \sqrt{\pi a_{max}}} \]

- Key point: $Y$ and $K_{lc}$ are the same for both designs.
  \[ \frac{K_{lc}}{Y \sqrt{\pi}} = \sigma a = \text{constant} \]

- Result:
  \[ \left( \sigma_c \sqrt{a_{max}} \right)_A = \left( \sigma_c \sqrt{a_{max}} \right)_B \]

Answer: $(\sigma_c)_B = 168$ MPa
Impact Testing

- Impact loading:
  -- severe testing case
  -- makes material more brittle
  -- decreases toughness

Adapted from Fig. 8.12(b), Callister & Rethwisch 8e. (Fig. 8.12(b) is adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, The Structure and Properties of Materials, Vol. III, Mechanical Behavior, John Wiley and Sons, Inc. (1965) p. 13.)
Influence of Temperature on Impact Energy

- **Ductile-to-Brittle Transition Temperature (DBTT)**...

![Diagram showing the relationship between temperature, impact energy, and ductility of different materials.](image)

- **FCC metals (e.g., Cu, Ni)**

- **BCC metals (e.g., iron at \( T < 914^\circ C \))**

- **Polymers**

- **High strength materials (\( \sigma_y > E/150 \))**

Adapted from Fig. 8.15, *Callister & Rethwisch 8e.*
Design Strategy: Stay Above The DBTT!

• Pre-WWII: The Titanic

![Image of the Titanic](image1.png)

• WWII: Liberty ships

![Image of Liberty ships](image2.png)

• Problem: Steels were used having DBTT’s just below room temperature.


Fatigue

- **Fatigue** = failure under applied cyclic stress.

- Stress varies with time.
  - key parameters are $S$, $\sigma_m$, and cycling frequency

- Key points: Fatigue...
  - can cause part failure, even though $\sigma_{max} < \sigma_y$.
  - responsible for ~ 90% of mechanical engineering failures.

Adapted from Fig. 8.18, *Callister & Rethwisch 8e.*
(Fig. 8.18 is from *Materials Science in Engineering, 4/E* by Carl. A. Keyser, Pearson Education, Inc., Upper Saddle River, NJ.)
Types of Fatigue Behavior

• Fatigue limit, $S_{fat}$:
  --no fatigue if $S < S_{fat}$

• For some materials, there is no fatigue limit!
Rate of Fatigue Crack Growth

- Crack grows \textit{incrementally}

\[
\frac{da}{dN} = (\Delta K)^m \sim (\Delta \sigma)\sqrt{a}
\]

typ. 1 to 6

- Failed rotating shaft
  - crack grew even though
    \[ K_{max} < K_c \]
  - crack grows faster as
    \begin{itemize}
    \item $\Delta \sigma$ increases
    \item crack gets longer
    \item loading freq. increases
    \end{itemize}

Adapted from Fig. 8.21, \textit{Callister & Rethwisch 8e}. (Fig. 8.21 is from D.J. Wulpi, \textit{Understanding How Components Fail}, American Society for Metals, Materials Park, OH, 1985.)
Improving Fatigue Life

1. Impose compressive surface stresses (to suppress surface cracks from growing)

   --Method 1: shot peening

   --Method 2: carburizing

2. Remove stress concentrators.

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N = Cycles to failure

$S = \text{stress amplitude}$

$\sigma_m = \text{stress amplitude near zero or compressive}$

$\sigma_m = \text{moderate tensile}$

$\sigma_m = \text{Larger tensile}$

Adapted from Fig. 8.24, Callister & Rethwisch 8e.

Adapted from Fig. 8.25, Callister & Rethwisch 8e.
Creep

Sample deformation at a constant stress ($\sigma$) vs. time

Primary Creep: slope (creep rate) decreases with time.

Secondary Creep: steady-state i.e., constant slope ($\Delta \varepsilon / \Delta t$).

Tertiary Creep: slope (creep rate) increases with time, i.e. acceleration of rate.

Adapted from Fig. 8.28, Callister & Rethwisch 8e.
Creep: Temperature Dependence

- Occurs at elevated temperature, $T > 0.4 \ T_m$ (in K)

Adapted from Fig. 8.29, *Callister & Rethwisch 8e.*
Secondary Creep

- Strain rate is constant at a given $T$, $\sigma$
  -- strain hardening is balanced by recovery

- Strain rate increases with increasing $T$, $\sigma$

\[
\dot{\varepsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)
\]

Adapted from Fig. 8.31, Callister 7e.
(Fig. 8.31 is from Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials, and Special Purpose Metals, Vol. 3, 9th ed., D. Benjamin (Senior Ed.), American Society for Metals, 1980, p. 131.)
Creep Failure

• Failure: along grain boundaries.

From V.J. Colangelo and F.A. Heiser, Analysis of Metallurgical Failures (2nd ed.), Fig. 4.32, p. 87, John Wiley and Sons, Inc., 1987. (Orig. source: Pergamon Press, Inc.)
Prediction of Creep Rupture Lifetime

- Estimate rupture time

S-590 Iron, $T = 800^\circ$C, $\sigma = 20,000$ psi

$$L_t = \frac{1}{(K-h)(10^3 \text{ psi})}$$

Data for S-590 Iron

Adapted from Fig. 8.32, Callister & Rethwisch 8e. (Fig. 8.32 is from F.R. Larson and J. Miller, Trans. ASME, 74, 765 (1952).)

Time to rupture, $t_r$

$$T(20 + \log t_r) = L$$

Temperature function of applied stress
time to failure (rupture)

$(1073 \text{ K})(20 + \log t_r) = 24 \times 10^3$

Ans: $t_r = 233$ hr
Estimate the rupture time for S-590 Iron, $T = 750^\circ$C, $\sigma = 20,000$ psi

- **Solution:**

\[ T(20 + \log t_r) = L \]

\[ (1023 \text{ K})(20 + \log t_r) = 24 \times 10^3 \]

**Ans:** $t_r = 2890$ hr

Adapted from Fig. 8.32, Callister & Rethwisch 8e. (Fig. 8.32 is from F.R. Larson and J. Miller, Trans. ASME, 74, 765 (1952).)
SUMMARY

• Engineering materials not as strong as predicted by theory
• Flaws act as stress concentrators that cause failure at stresses lower than theoretical values.
• Sharp corners produce large stress concentrations and premature failure.

• Failure type depends on $T$ and $\sigma$:
  - For simple fracture (noncyclic $\sigma$ and $T < 0.4T_m$), failure stress decreases with:
    - increased maximum flaw size,
    - decreased $T$,
    - increased rate of loading.
  - For fatigue (cyclic $\sigma$):
    - cycles to fail decreases as $\Delta \sigma$ increases.
  - For creep ($T > 0.4T_m$):
    - time to rupture decreases as $\sigma$ or $T$ increases.
For Tomorrow

Prob. 8.15
8.34

Read Chapt. 9 (Phase diagrams)