CHAPTER 8: Mechanical failure

ISSUES TO ADDRESS...

- How do flaws in a material initiate failure?
- How is fracture resistance quantified; how do different material classes compare?
- How do we estimate the stress to fracture?
- How do loading rate, loading history, and temperature affect the failure stress?

Ship-cyclic loading from waves.
Adapted from Fig. 8.0, Callister 6e. (Fig. 8.0 is by Neil Boenzi, The New York Times.)

Computer chip-cyclic thermal loading.
Adapted from Fig. 18.11W(b), Callister 6e. (Fig. 18.11W(b) is courtesy of National Semiconductor Corporation.)

Hip implant-cyclic loading from walking.
Adapted from Fig. 17.19(b), Callister 6e.
Ductile vs brittle failure

• Classification:

<table>
<thead>
<tr>
<th>Fracture behavior:</th>
<th>Very Ductile</th>
<th>Moderately Ductile</th>
<th>Brittle</th>
</tr>
</thead>
<tbody>
<tr>
<td>%AR or %EL:</td>
<td>Large</td>
<td>Moderate</td>
<td>Small</td>
</tr>
<tr>
<td>Ductile fracture is desirable!</td>
<td>Ductile: warning before fracture</td>
<td>Brittle: No warning</td>
<td></td>
</tr>
</tbody>
</table>

Adapted from Fig. 8.1, Callister 6e.
Ex: Failure of a pipe

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

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

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

• Evolution to failure:
  - necking
  - void nucleation
  - void growth and linkage
  - shearing at surface
  - fracture

  \[ \sigma \]

• Resulting fracture surfaces (steel)

  50 \( \mu \)m

  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.
Brittle fracture surfaces

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

- **Intragranular** (within grains)
  - 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.)

• Stress-strain behavior (Room T):

- **σ**
- **ε**

- **E/10:** perfect mat’l-no flaws
- **E/100:** carefully produced glass fiber
- **Typical ceramic**
- **Typical strengthened metal**
- **Typical polymer**

• DaVinci (500 yrs ago!) observed...
  -- the longer the wire, the smaller the load to fail it.

• Reasons:
  -- flaws cause premature failure.
  -- Larger samples are more flawed!

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Flaws are stress concentrators!

- Elliptical hole in a plate:

\[ \sigma_0 \]

\[ \sigma \]

\[ 2a \]

- Stress concentration factor:

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

- Stress distribution in front of a hole:

\[ \sigma_{\text{max}} \approx \sigma_0 \left( 2\sqrt{\frac{a}{\rho_t}} + 1 \right) \]

- Large \( K_t \) promotes failure:

\( K_t = 3 \)  
\( K_t >> 3 \)
Engineering fracture design

• Avoid sharp corners!

\[ t = \frac{\sigma_{\text{max}}}{\sigma_o} \]

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.)
When does a crack propagate?

- $\rho_t$ at a crack tip is very small!

- Result: crack tip stress is very large.

  - Crack propagates when: the tip stress is large enough to make crack unstable (?):
When does a crack propagate?

Strain energy \[ U_s = U_0 + V_0 \left( \frac{\sigma^2}{2E} \right) - \frac{\pi a^2 t}{2} \left( \frac{\sigma^2}{2E} \right) \]

Energy of a crack \[ U_{\text{crack}} = 2\gamma at \]

Total energy = Strain energy + Energy of the crack

Crack will propagate if energy decreases, i.e. crack length is greater than \( a_{\text{crit}} \)

\[ \sigma \sqrt{2\pi a_{\text{crit}}} > \sqrt{2\gamma E} \]

\[ \sigma \sqrt{2\pi a} > K_{\text{IC}} \]
Geometry, load, & material

• Condition for crack propagation:

\[ K \geq K_c \]

Stress Intensity Factor:
--Depends on load & geometry.

Fracture Toughness:
--Depends on the material, temperature, environment, & rate of loading.

• Values of \( K \) for some standard loads & geometries:

\[ K = \sigma \sqrt{\pi a} \]

units of \( K \):
MPa\(\sqrt{m}\)
or ksi\(\sqrt{in}\)

Adapted from Fig. 8.8, Callister 6e.
Fracture toughness

Based on data in Table B5, Callister 6e.

Composite reinforcement geometry is: \( f = \) fibers; \( sf = \) short fibers; \( w = \) whiskers; \( p = \) particles. Additional 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 stressed cracks grow first!

--Result 1: Max flaw size dictates design stress.

\[ \sigma_{\text{design}} < \frac{K_c}{Y\sqrt{\pi a_{\text{max}}}} \]

--Result 2: Design stress dictates max. flaw size.

\[ a_{\text{max}} < \frac{1}{\pi} \left( \frac{K_c}{Y\sigma_{\text{design}}} \right)^2 \]
Design example: Aircraft wing

- Material has $K_C = 26 \text{ MPa-m}^{0.5}$
- Two designs to consider...
  
  **Design A**
  --largest flaw is 9 mm
  --failure stress = 112 MPa

- Use...
  $$\sigma_c = \frac{K_C}{Y\sqrt{\pi a_{\text{max}}}}$$

- Key point: $Y$ and $K_C$ are the same in both designs.
  --Result:
  \[ (\sigma_c \sqrt{a_{\text{max}}})_A = (\sigma_c \sqrt{a_{\text{max}}})_B \]

- Reducing flaw size pays off!

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

Answer: $(\sigma_c)_B = 168 \text{ MPa}$
Loading rate

- Increased loading rate...
  --increases $\sigma_y$ and TS
  --decreases %EL
- Why? An increased rate gives less time for disl. to move past obstacles.

- Impact loading:
  --severe testing case
  --more brittle
  --smaller toughness

Adapted from Fig. 8.11(a) and (b), *Callister 6e*. (Fig. 8.11(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.)
Temperature

- Increasing temperature... --increases %EL and $K_C$
- **Ductile-to-brittle transition temperature (DBTT)**...

Design strategy: stay above the DBTT!

- Pre-WWII: The Titanic
- WWII: Liberty ships

- Problem: Used a type of steel with a DBTT ~ Room temp.
Fatigue

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

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

- Key points: Fatigue...
  - can cause part failure, even though $\sigma_{\text{max}} < \sigma_c$.
  - causes $\sim 90\%$ of mechanical engineering failures.

Adapted from Fig. 8.16, *Callister 6e*. (Fig. 8.16 is from *Materials Science in Engineering, 4/E* by Carl A. Keyser, Pearson Education, Inc., Upper Saddle River, NJ.)
Fatigue design parameters

S-N curve

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

  (Endurance limit)

• Sometimes, the fatigue limit is zero!

![S-N curve for steel (typ.)](Adapted from Fig. 8.17(a), Callister 6e.)

![S-N curve for Al (typ.)](Adapted from Fig. 8.17(b), Callister 6e.)

Fatigue strength

Fatigue life

Chapter 8- 18
Fatigue mechanism

• Crack grows *incrementally*

\[
\frac{da}{dN} = (\Delta K)^m \sim (\Delta\sigma)^{1/2}a
\]

typ. 1 to 6

increase in crack length per loading cycle

• Failed rotating shaft
  --crack grew even though
    \(K_{\text{max}} < K_c\)
  --crack grows faster if
    • \(\Delta\sigma\) increases
    • crack gets longer
    • loading freq. increases.

Adapted from Fig. 8.19, *Callister 6e.*
(Fig. 8.19 is from D.J. Wulpi, *Understanding How Components Fail,* American Society for Metals, Materials Park, OH, 1985.)
Fatigue striations in Al
Improving fatigue life

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

---Method 1: shot peening

2. Remove stress concentrators.

Adapted from Fig. 8.22, Callister 6e.

\[ S = \text{stress amplitude} \]
\[ N = \text{Cycles to failure} \]

Adapted from Fig. 8.23, Callister 6e.
Creep

- Occurs at elevated temperature, $T > 0.4 T_{\text{melt}}$
- Deformation changes with time.

Adapted from Figs. 8.26 and 8.27, Callister 6e.
**Secondary creep**

- Most of component life spent here.
- Strain rate is constant at a given $T$, $\sigma$
  --strain hardening is balanced by recovery

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

- Strain rate increases for larger $T$, $\sigma$

Adapted from Fig. 8.29, *Callister 6e*. (Fig. 8.29 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.)
Summary

• Engineering materials don't reach theoretical strength.

• Flaws produce stress concentrations that cause premature failure.

• Sharp corners produce large stress concentrations and premature failure.

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