Chapter 8: Mechanical Failure

Topics...

• How do loading rate, loading history, and temperature affect the failure stress?

Ship-cyclic loading from waves.
Failure

• Classification:
  Fracture behavior:
  - Very Ductile
  - Moderately Ductile
  - Brittle

• Ductile fracture is usually desirable!
  %AR or %EL
  - Large
  - Moderate
  - Small

Adapted from Fig. 8.1, Callister 7e.

Ductile: warning before fracture
Brittle: No warning

Chapter 8 - 2
Fatigue

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

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

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

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

- Sometimes, the fatigue limit is zero!

Adapted from Fig. 8.19(a), *Callister 7e.*

Adapted from Fig. 8.19(b), *Callister 7e.*
Fatigue Mechanism

• Crack grows *incrementally*

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

Typ. 1 to 6

Increase in crack length per loading cycle

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

Adapted from Fig. 8.21, *Callister 7e.*
(Fig. 8.21 is from D.J. Wulpi, *Understanding How Components Fail*, American Society for Metals, Materials Park, OH, 1985.)
Improving Fatigue Life

1. Impose a compressive surface stress (to suppress surface cracks from growing)
   - Method 1: shot peening
     - Put surface into compression
   - Method 2: carburizing
     - C-rich gas

2. Remove stress concentrators.
   - Adapted from Fig. 8.24, Callister 7e.
   - Adapted from Fig. 8.25, Callister 7e.

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

- Increasing \( \sigma_m \)
- Near zero or compressive \( \sigma_m \)
- Moderate tensile \( \sigma_m \)
- Larger tensile \( \sigma_m \)
Factors that affect fatigue life

- Mean stress
- Surface effects
  - Design factors
  - Surface treatments
  - Case hardening
Environmental effects

- Thermal fatigue: induced at elevated temperatures by fluctuating thermal stresses.

\[ \sigma = \alpha_i E\Delta T \]

- Corrosion fatigue: failure occurs by the simultaneous action of a cyclic stress and chemical attack
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.

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

Adapted from Fig. 8.28, Callister 7e.
Creep

- Occurs at elevated temperature, $T > 0.4 \ T_m$

Adapted from Figs. 8.29, Callister 7e.
Secondary Creep

• 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
- material const.
- applied stress
- stress exponent (material parameter)
- activation energy for creep (material parameter)

• Strain rate increases for higher $T, \sigma$

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.

- **Time to rupture,** \( t_r \)
  
  \[
  T(20 + \log t_r) = L
  \]

- **Estimate rupture time**
  
  S-590 Iron, \( T = 800^\circ C, \sigma = 20 \text{ ksi} \)

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

  \[24 \times 10^3 \text{ K-log hr} \]

  \[1073 \text{ K} \]

  **Ans:** \( t_r = 233 \text{ hr} \)

  Adapted from Fig. 8.32, *Callister 7e*. (Fig. 8.32 is from F.R. Larson and J. Miller, *Trans. ASME, 74*, 765 (1952).)

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.)
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.