Canopy fracture – related to corrosion of the Al alloy used as a skin material.

**FIGURE 9.3–2**
Boeing 737 Aloha Airlines incident: (a) schematic drawing of plane in flight; (b) Photograph of fuselage after landing. The canopy of the aircraft fractured in midflight over Hawaii. Subsequent investigation revealed that the canopy was weakened as a result of extensive corrosion and fatigue. (Source: (b) © Robert Nichols, Black Star.)
8.2 Fundamentals of Fracture

- Fracture is the separation of a body into two or more pieces in response to an applied stress.
- The fracture process
  1. Crack formation
  2. Crack propagation
8.3 & 8.4 Ductile & Brittle Fracture

Extremely soft materials like gold & lead

Figure 8.1 (a) Highly ductile fracture in which the specimen necks down to a point. (b) Moderately ductile fracture after some necking. (c) Brittle fracture without any plastic deformation.
• How might Ductile and Brittle failures differ:
  – Speed of crack growth
  – Stability of crack
  – Amount of plasticity effects
Moderately Ductile Fracture
- Cup-and-cone fracture

**Figure 8.2** Stages in the cup-and-cone fracture. (a) Initial necking. (b) Small cavity formation. (c) Coalescence of cavities to form a crack. (d) Crack propagation. (e) Final shear fracture at a 45° angle relative to the tensile direction. (From K. M. Ralls, T. H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*, p. 468. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

This angle is approximately 45 degrees, why?
Ductile Vs. Brittle fracture

Irregular and fibrous appearance indicative of plastic deformation

Figure 8.3  (a) Cup-and-cone fracture in aluminum. (b) Brittle fracture in a mild steel.
8.5 Principles of Fracture Mechanics

- Material properties
- Stress level
- Crack-producing flaws
- Crack propagation mechanisms
The presence of a crack amplifies local stress in the vicinity of the flaw

- Consider two glass rods of equal dimensions, one of which has been scratched with a file. Which one is easier to break?
  - the applied stress is amplified by the crack
Stress Concentration

• Measured failure strengths << theoretical predictions
  – Caused by flaws or cracks at the surface or within the material
  – The applied stress is amplified at the crack
  – These flaws are called stress raisers
Figure 8.7  (a) The geometry of surface and internal cracks. (b) Schematic stress profile along the line $X-X'$ in (a), demonstrating stress amplification at crack tip positions.
Consider a crack similar to an elliptical hole through a plate and oriented perpendicular to the applied stress.

Maximum stress at the crack tip:

\[ \sigma_m = 2\sigma_0 \left( \frac{a}{\rho_t} \right)^{1/2} \]

where \( \sigma_0 \) is the applied tensile stress, \( \rho_t \) is the radius of curvature of the crack tip, and \( a \) is the length of a surface crack or half the length of an internal crack.
Stress concentration factor

Stress concentration factor:

\[ K_t = \frac{\sigma_m}{\sigma_0} = 2 \left( \frac{a}{\rho_t} \right)^{1/2} \]

- A measure of the degree to which the applied stress is amplified at the crack tip
- A long & relatively thin crack has a high stress concentration factor
Critical fracture stress

The critical stress required for crack propagation in a brittle material

Critical stress:

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

where \( E \) is the elastic modulus and \( \gamma_s \) is the specific surface energy.

Which is more likely to propagate, long or short cracks?
Stress concentration in ductile materials

- Plastic deformation leads to a more uniform distribution of stress in the vicinity of the stress raiser

Stress concentration in brittle materials

- Effect of stress raiser is more significant
Example 8.1

• A relatively large plate of a glass is subjected to a tensile stress of 40 MPa. If the specific surface energy and modulus of elasticity for this glass are 0.3 J/m² and 69 GPa, respectively, determine the maximum length of a surface flaw that is possible without fracture.
Example 8.1

Given:
- surface flaw
- plate of glass
\( \sigma_0 = 40 \, MPa \)
\( \gamma_s = 0.3 \, J / m^2 \)
\( E = 69 \, GPa \)
\( a = ? \)

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

Limiting case:
\[
\sigma_c = \sigma_0
\]
\( \Rightarrow a = 8.2 \times 10^{-6} \, m \)
An oil tanker that fractured in a brittle manner by crack propagation around its girth.

(Photography by Neal Boenzi. Reprinted with permission from The New York Times.)
Sequence of events leading to brittle fracture

1. A small flaw forms either during fabrication (welding, riveting, etc.) or during operation (fatigue, corrosion, etc.).
2. The flaw then propagates…initial growth rate is slow.
3. Fracture occurs when the crack reaches a critical size for the load…final fracture proceeds rapidly.
Fracture Toughness

• Measure of a material’s resistance to brittle fracture when a crack is present.

Fracture toughness:

\[ K_c = Y\sigma_c \sqrt{\pi a} \]

where \( Y \) is a dimensionless parameter that depends on the crack size, specimen size, geometries and type of load application.
Figure 8.8 Schematic representations of (a) an interior crack in a plate of infinite width, and (b) an edge crack in a plate of semi-infinite width.
The three modes of crack surface displacement.

**Figure 8.9** The three modes of crack surface displacement. (a) Mode I, opening or tensile mode; (b) mode II, sliding mode; and (c) mode III, tearing mode.
Plane strain fracture toughness

• When specimen thickness is much greater than the crack dimensions, $K_c$ becomes independent of the thickness

$$K_{lc} = Y\sigma\sqrt{\pi a}$$

where $K_{lc}$ is for mode I crack displacement.

What is plane strain?
• How would you expect $K_{IC}$ to vary with
  – Potential for rapid fracture growth (catastrophic)
  – Ductility, why?
  – Temperature, why?
  – Strain rate, why?

The ability for plastic deformation to occur in front of an advancing crack is the influential factor on $K_{IC}$
### Table 8.1 Room-Temperature Yield Strength and Plane Strain Fracture Toughness Data for Selected Engineering Materials

<table>
<thead>
<tr>
<th></th>
<th>Yield Strength</th>
<th>K&lt;sub&gt;Ic&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
<td>ksi</td>
</tr>
<tr>
<td><strong>Metals</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Alloy&lt;sup&gt;a&lt;/sup&gt; (7075-T651)</td>
<td>495</td>
<td>72</td>
</tr>
<tr>
<td>Aluminum Alloy&lt;sup&gt;a&lt;/sup&gt; (2024-T3)</td>
<td>345</td>
<td>50</td>
</tr>
<tr>
<td>Titanium Alloy&lt;sup&gt;a&lt;/sup&gt; (Ti-6Al-4V)</td>
<td>910</td>
<td>132</td>
</tr>
<tr>
<td>Alloy Steel&lt;sup&gt;a&lt;/sup&gt; (4340 tempered @ 260°C)</td>
<td>1640</td>
<td>238</td>
</tr>
<tr>
<td>Alloy Steel&lt;sup&gt;a&lt;/sup&gt; (4340 tempered @ 425°C)</td>
<td>1420</td>
<td>206</td>
</tr>
<tr>
<td><strong>Ceramics</strong></td>
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</tr>
<tr>
<td>Concrete</td>
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<td>—</td>
</tr>
<tr>
<td>Soda-Lime Glass</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Aluminum Oxide</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>Polymers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Polymethyl Methacrylate (PMMA)</td>
<td>53.8–73.1</td>
<td>7.8–10.6</td>
</tr>
<tr>
<td>Polycarbonate (PC)</td>
<td>62.1</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Ductile materials
Brittle materials
8.6 Impact Fracture Testing
- Impact testing techniques

• The Charpy V-notch (CVN) technique is most commonly used in the United States.
  – Measure impact energy (notch-toughness)
  – Determine whether material experiences ductile-brittle transition with decreasing temperature
Ductile-to-Brittle Transition

- Materials undergo ductile-to-brittle transition
  - With decreasing temperature
**Figure 8.12**

Temperature dependence of the Charpy V-notch impact energy (curve A) and percent shear fracture (curve B) for an A283 steel. (Reprinted from *Welding Journal*. Used by permission of the American Welding Society.)
Ductile-to-brittle transition behavior

- Materials that exhibit this behavior should be used only at temperatures above the transition temperature.
- BCC & HCP metals exhibit DTBT
FCC metals remain ductile at even extremely low temperatures.
Influence of alloy composition on DTBT

**Figure 8.14** Influence of carbon content on the Charpy V-notch energy-versus-temperature behavior for steel. (Reprinted with permission from ASM International, Metals Park, OH 44073-9989, USA; J. A. Reinbolt and W. J. Harris, Jr., “Effect of Alloying Elements on Notch Toughness of Pearlitic Steels,” *Transactions of ASM*, Vol. 43, 1951.)
Hull fracture – related to the welding methods used to construct the ships.

An example of failure

• During WWII a number of welded transport ships, (away from combat) suddenly split in half.
  – Steel alloy which was ductile at room-temperature but brittle at 40 F.
  – Cracks originated at points of stress concentration and propagated around the entire girth of the ship.
Fatigue

- Failure that occurs after a long period of repeated stress or strain cycling.
- Largest cause of failure in metals \(\sim 90\%\)
- Occurs very suddenly and without warning
- Brittle like in nature even in normally ductile materials
8.7 Cyclic Stresses

Reversed stress cycle

Repeated stress cycle

Random stress cycle

Figure 8.15 Variation of stress with time that accounts for fatigue failures. (a) Reversed stress cycle, in which the stress alternates from a maximum tensile stress (+) to a maximum compressive stress (−) of equal magnitude. (b) Repeated stress cycle, in which maximum and minimum stresses are asymmetrical relative to the zero-stress level; mean stress $\sigma_m$, range of stress $\sigma_r$, and stress amplitude $\sigma_a$ are indicated. (c) Random stress cycle.
Mean stress:

\[ \sigma_m = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} \]

Range of stress:

\[ \sigma_r = \sigma_{\text{max}} - \sigma_{\text{min}} \]

Stress amplitude:

\[ \sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{2} \]

Stress ratio:

\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \]

**Figure 8.15** Variation of stress with time that accounts for fatigue failures. (a) Reversed stress cycle, in which the stress alternates from a maximum tensile stress (+) to a maximum compressive stress (−) of equal magnitude. (b) Repeated stress cycle, in which maximum and minimum stresses are asymmetrical relative to the zero-stress level; mean stress \( \sigma_m \), range of stress \( \sigma_r \), and stress amplitude \( \sigma_a \) are indicated. (c) Random stress cycle.
8.8 The S-N Curve
- ferrous and titanium alloys

Fatigue limit or Endurance limit

Fatigue failure will not occur
The S-N Curve
- non ferrous alloys

Stress level at which failure will occur for $N$ cycles

Fatigue strength at $N_1$ cycles

Stress amplitude, $S$

Fatigue life at stress $S_1$

Cycles to failure, $N$
(logarithmic scale)
• Fatigue strength – stress level at which failure will occur for N cycles.
• Fatigue life ($N_f$) - the number of cycles to cause failure at a specified stress level.
Macroscopic & microscopic views of a fatigue fracture of an alloy steel crankshaft from a truck diesel engine.
8.11 Factors that affect fatigue life
- Surface effects

• For many common loading situations, the maximum stress within a component or structure occurs at its surface.
Design Factors

- Stress raisers
  - Notches, grooves, holes, keyways, etc.
  - Sharp changes in contour

**Figure 8.23** Demonstration of how design can reduce stress amplification. *(a)* Poor design: sharp corner. *(b)* Good design: fatigue lifetime improved by incorporating rounded fillet into a rotating shaft at the point where there is a change in diameter.
Surface Treatments

• Polishing
  – Removes scratches, etc.

• Shot peening
  – small particles of hard metal are shot at a high velocity onto the surface.
  – Strain hardening

• Case hardening
  – Carburizing or nitriding of steels
Creep

- Deformation due to applied stresses at elevated temperatures.
- Time-dependent
- Important for metals at temperatures $> 0.4 \ T_m$
8.14 Generalized Creep Behavior
Creep curve of strain vs. time at a constant stress and constant temperature

- **primary creep**
  - creep rate decreases with time

- **secondary creep**
  - lasts longest

\[ \varepsilon = \varepsilon_0 + \beta t \]

\[ \beta - \text{min creep rate} \]

(material constant)

\[ \varepsilon = At^{1/3} \]

A - material constant

\[ t - \text{time} \]

\[ \varepsilon_0 - \text{instantaneous elastic strain} \]
Creep curve of strain vs. time at a constant stress and constant temperature

- final creep
  - gross defects begin to appear rapidly
- fracture

\[ \varepsilon = B + C \exp(\gamma t) \]
\[ \gamma, B, C - \text{material constants} \]
Which of these stages is most important to engineers?