Outline

- Failure - Introduction
- Safety factor
- Types of failure
  - Ductile fracture
  - Brittle fracture
- Fractography
- Principles of fracture mechanics
- Stress concentration and,
- Griffith theory

Failure and Fracture

- Failure of engineering materials is an undesirable occurrence!!
  - can lead to loss of human life
  - economic losses
- prevention is through good design and materials selection

Failure and Fracture

- Alaska MD-80 crash (1999)
  - Death 88 people
  - Excessive wear on stabilizer jackscrew

Failure and Fracture

- Challenger (1986)
  - failure of an O-ring seal (polymer)

Design Strength and Safety Factors

- Uncertainties occur in magnitudes of design loads due to inaccuracies in load calculations and mechanical properties
- Design allowances are made to avoid potential failure using a design stress $\sigma_d$
  - For static loading and ductile materials, the calculated stress level $\sigma_c$ and design factor, $N'$ are used
    $$\sigma_d = N' \sigma_c$$
    where $\sigma_y \geq \sigma_d$ and $N' > 1$
- A safe working stress may be assigned $\sigma_w$ based on the yield stress:
  $$\sigma_w = \frac{\sigma_y}{N}$$
  where $N$ is the ...............
**Types of Failure**

- Most fundamental types of failure are *ductile* and *brittle*
- Also have impact, fatigue and creep rupture
- Fracture involves crack initiation and propagation under an applied stress
- Cracks may exist but they are ............ and do not propagate under the particular loading conditions

- **Ductile**: warning before fracture
- **Brittle**: no warning
- **Ductile** fracture is ....................

**Fracture Modes**

- **Cup & cone**
- **Brittle**

**Example: Failure of a Pipe**

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

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

- Ductile failure: as a crack propagates, substantial plastic deformation occurs with *absorption of energy* (*energy of fracture*)
- Highly ductile materials deform plastically under load to the fracture point:
  - **metals**: gold and lead at room temperature
  - **polymers** and **glasses** at high temperature

**Moderately Ductile Failure**

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

Resulting fracture surfaces *(steel)*

Particulates serve as void nucleation sites.
Ductile “Cup and Cone” Fracture

*Cup and cone* ductile fracture is common and includes:
- ........ due to local plastic instability
- microvoid formation (fracture initiation)
- microvoid coalescence
- final shear failure forming shear lips

- Formation of classical *dimples* on fracture surface:
  - equiaxed dimples
  - elongated in shear region

Brittle Fracture

- No ........ deformation prior to crack initiation
- Crack initiates at a *defect or flaw*
- Fracture propagates *perpendicular* to load application
- Fracture surface has characteristic pattern
  - steel plates contain *chevrons* which point back to fracture origin
  - alternatively, have radial (fan-like) ridges emanating from fracture origin
  - or very smooth surface as in glasses or ceramics

Brittle fracture mode is by breaking of atomic bonds along particular crystallographic planes
- *cleavage* and *transgranular* as it passes through the grains of the material (........ grains)
- *intergranular* or along grain boundaries due to weakening or embrittlement of grain boundaries (........ grains)

Fractography

- SEM Fractograph of ductile cast iron shows a *transgranular* fracture surface.
- SEM Fractograph of an *intergranular* fracture surface.
**Principles of Fracture Mechanics**

- **Quantitative** study of failure is called *fracture mechanics*
- Fracture mechanics is the relationship between materials properties, stress, crack-producing flaws and mechanisms of crack propagation
- The aim is: “design to prevent structural failure”
- Quantify relationships between:
  - material properties
  - stress level
  - presence of cracks/defects in material
  - types of crack-propagating mechanisms

Intention is to allow better design, only works well if we understand fracture and the above inter-relationships and material’s limitations.

**Stress Concentrations**

- Fracture strength is a function of cohesive forces holding atoms together.
- Theoretical cohesive strength of a brittle, elastic material is ~E/10
  - .......... E/100 to E/10,000
- Griffith (*in 1920s*) proposed that this difference is due to microscopic flaws amplifying the local stress and producing a stress concentration

Local increment in stress is a stress raiser (.................)

**Elliptical hole in a plate: Stress distrib. in front of a hole:**

- Stress conc. factor: \( K_t = \frac{\sigma_{\text{max}}}{\sigma_o} \)
- Large \( K_t \) promotes failure:
  - \( K_t = 3 \) \( \Rightarrow \) NOT SO BAD
  - \( K_t > 3 \) \( \Rightarrow \) BAD!

\( \sigma_{\text{max}} \approx \sigma_o \left( 2 \left( \frac{a}{\rho t} + 1 \right) \right) \)

**Assume an elliptical crack of length, 2a, the local stress is:**

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

where \( \sigma_o \) is the nominal applied stress and \( \rho_t \) is the radius of curvature of the crack tip

- If \( (a/\rho_t) \) is very large – the crack is long and thin, therefore:
  \[ \sigma_m \approx 2 \sigma_o \left( \frac{a}{\rho_t} \right)^{1/2} \]

- **stress concentration factor** is \( K_t = \sigma_m/\sigma_o \):\[ K_t = 2 \left( \frac{a}{\rho_t} \right)^{1/2} \]
Engineering Fracture Design

Avoid sharp corners!

![Graph showing Stress Concentration Factor, K = σ_max/σ_o vs. r/h]

Theoretical Stress Concentrations

Stress concentrations can also apply to corners and holes as well as defects.

![Graph showing Stress Concentration Factor, K vs. r/h]

Stress concentrations have much more significance in materials as no plastic deformation can occur.

Griffith Theory of Brittle Fracture

Griffith proposed that there is a population of defects in all brittle materials of various sizes, shapes and orientations. When an applied stress creates a concentrated stress at one of these defects which is higher than the cohesive strength then the defect or crack propagates and fracture occurs.

- During crack propagation elastic strain energy is released.
- Fracture creates new surfaces which raise the surface energy.
- Griffith performed balance between two energies and derived a critical stress σ_c for propagation of an elliptical crack.

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

(Griffith Equation)

where,

- E = elastic modulus
- \(\gamma_s\) = specific surface energy (energy to break bonds/unit area)
- a = one half of the length of an elliptical internal crack (2a)
Ductile behaviour

• In ………… materials, energy of fracture involves both generation of new surfaces (\(\gamma_s\)) and plastic deformation (\(\gamma_p\)) particularly at the crack tip

• Therefore Griffith’s equation becomes:

\[
\sigma_c = \left( \frac{2E(\gamma_s + \gamma_p)}{\pi a} \right)^{1/2}
\]  
(Irwin, 1940s):

• For ……… ductile materials where \(\gamma_p >> \gamma_s\):

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

• Critical strain energy release rate:

\[
G_c = 2(\gamma_s + \gamma_p)
\]

\[
\Rightarrow G_c = \frac{\pi\sigma^2a}{E}
\]

Crack extension occurs when \(\pi\sigma^2a/E > G_c\)

A plastic zone develops at the tip. As the load increases, the plastic zone increases in size until the crack grows and the elastically strained material behind the crack tip unloads. This loading and unloading cycle leads to the dissipation of energy as heat.

Next Time

Continue Fracture Mechanics