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*

Alaska MD-80 crash (1999)

Death 88 people

Excessive wear on stabilizer jackscrew

Challenger (1986)

failure of an O-ring seal (polymer)

Failure and Fracture

So, Failure sometimes takes place!!!.

Why does it occur?

What actually happens during fracture?

How can we prevent it?

Engineer should anticipate & plan for possible failure, and if failure does occur find out why and prevent re-occurrence.

Design Strength and Safety Factors

➢ Uncertainties occur in magnitudes of design loads due to inaccuracies in load calculations and …………………… in mechanical properties

➢ **Design allowances** are made to avoid potential failure using a *design stress* σ_d

➢ For static loading and ductile materials, the calculated stress level σ_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 σ_w based on the yield stress:

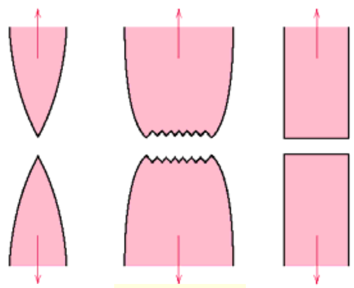
$$\sigma_w = \frac{\sigma_y}{N}$$

where N is the ……………

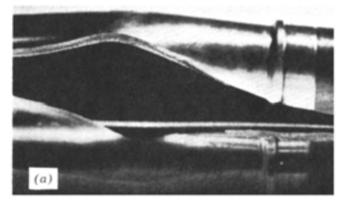
Types of Failure

- 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 ……………..!



Example: *Failure of a Pipe*

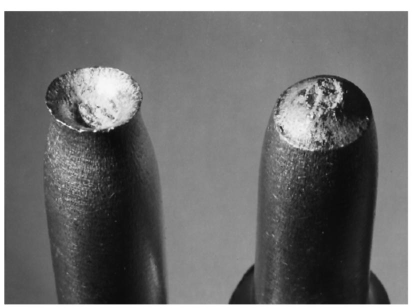


- **Ductile** failure:
  - one piece
  - large deformation
  - …….
- Brittle failure:
  - many pieces
  - small deformation
  - ……..

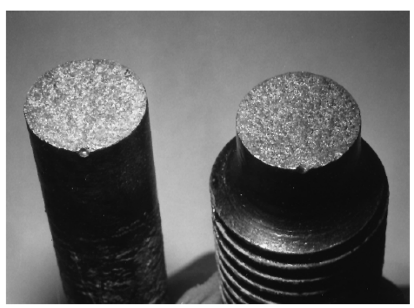
- Ductile failure: as a crack propagates, substantial plastic deformation occurs with absorption of energy (*energy of fracture*)
- Highly ductile materials deform plastically under load to the fracture *point*:
  - metals: gold and lead at room temperature
  - polymers and glasses at high temperature

Fracture Modes

Cup & cone

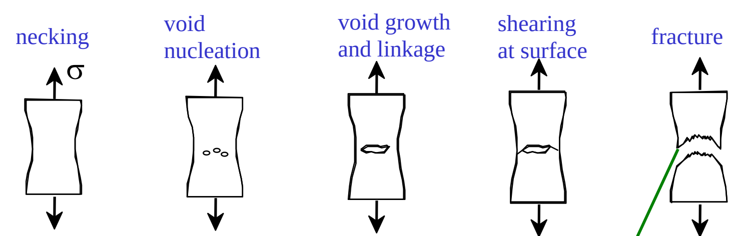


Brittle

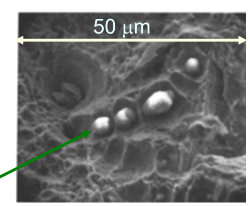


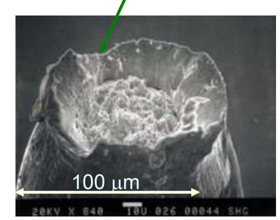
Moderately Ductile Failure

- Evolution to failure:



Resulting fracture surfaces (steel)

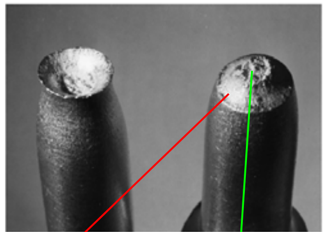


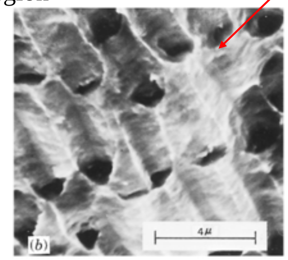


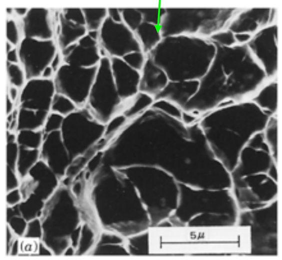
Particles serve as void nucleation sites.

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



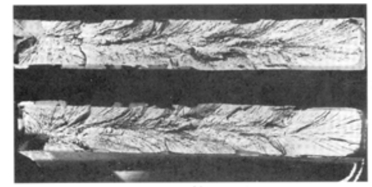




(a) Equiaxed dimples
(b) Elongated due to shear

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



Origin of the crack

Approx. 2X

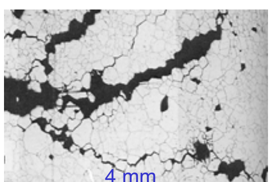
FIGURE 8.5 (a) Photograph showing V-shaped "chevron" markings

Brittle Fracture

Brittle fracture mode is by breaking of atomic bonds along particular crystallographic planes

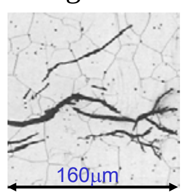
- *cleavage and transgranular* as it passes through the grains of the material (……….. grains)
- *intergranular* or along grain boundaries due to weakening or *embrittlement of grain boundaries* (……….. grains)

Intergranular

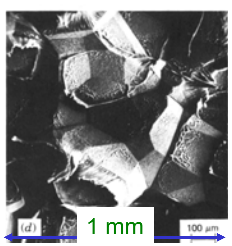


304 S. Steel (metal)

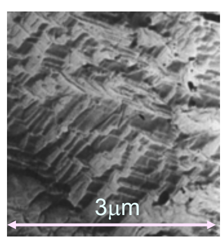
Transgranular



316 S. Steel (metal)

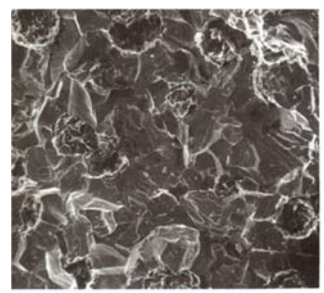


Polypropylene (polymer)



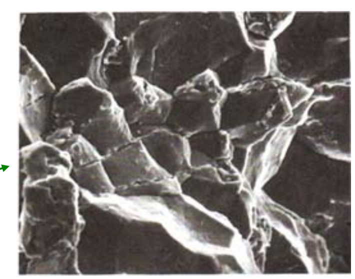
Al_2O_3 (ceramic)

Fractugraphy



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*"

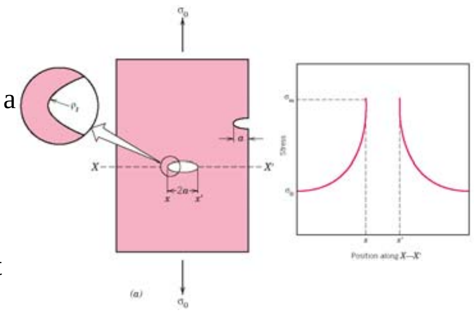
Quantify relationships between:

- ✓ 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 …………… 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* (……………………)

Stress Concentrations

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

Maximum stress occurs at the tip

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

where σ_o is the nominal applied stress and ρ_t is the radius of curvature of the crack tip

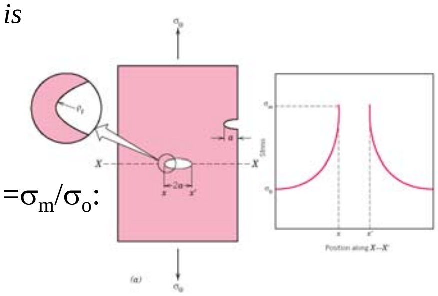
Where ρ_t is the radius of the crack tip and a is the length of a **surface** crack or half the length of an **internal** crack.

✓ If (a/ρ_t) is very large – *the crack is long and thin, therefore*:

$$\sigma_m \approx 2\sigma_o\left(\frac{a}{\rho_t}\right)^{1/2}$$

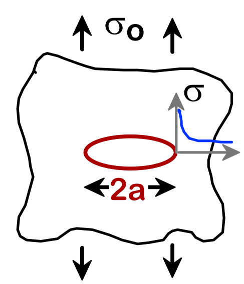
✓ *stress concentration factor* is $K_t = \sigma_m/\sigma_o$:

$$K_t = 2\left(\frac{a}{\rho_t}\right)^{1/2}$$

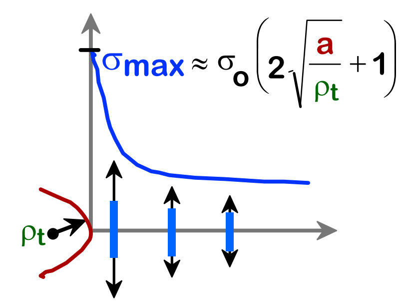


Flaws are Stress Concentrators!

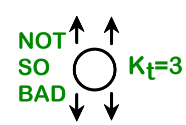
Elliptical hole in a plate:

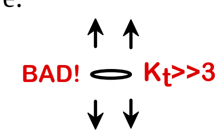


Stress distrib. in front of a hole:



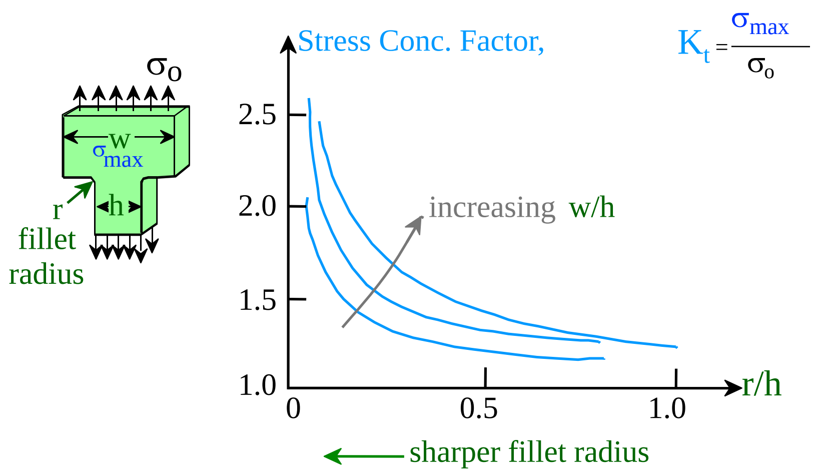
- Stress conc. factor: $K_t = \sigma_{max}/\sigma_o$
- Large K_t promotes failure:





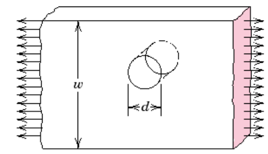
Engineering Fracture Design

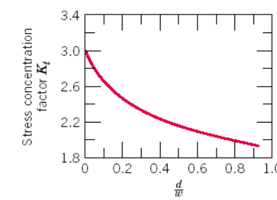
Avoid sharp corners!



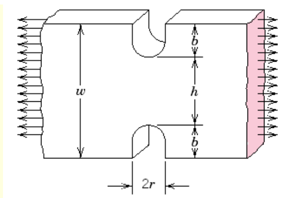
Theoretical Stress Concentrations

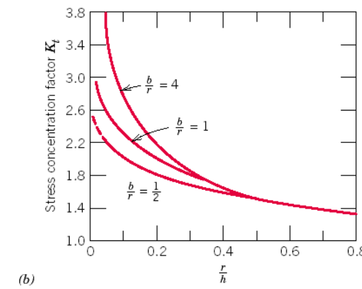
Stress concentrations can also apply to corners and holes as well as ………….. defects.





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.

Griffith Theory of Brittle Fracture

*If the change in elastic strain energy due to crack extension is higher than the energy required to create new crack surfaces, **crack propagation** will occur*

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2} \quad \text{(Griffith Equation)}$$

where,

E = elastic modulus
γ_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* (γ_s) and *plastic deformation* (γ_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 $\gamma_p >> \gamma_s$:

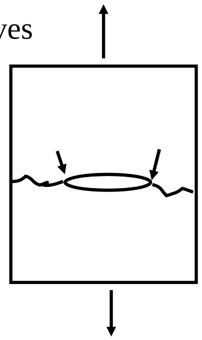
$$\sigma_c \approx \left(\frac{2E\gamma_p}{\pi a} \right)^{1/2}$$

- *Critical strain energy release rate*:

$$G_c = 2(\gamma_s + \gamma_p)$$

$$\Rightarrow \quad G_C = \frac{\pi \sigma^2 a}{E}$$

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



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