# Fracture and Toughening of Materials

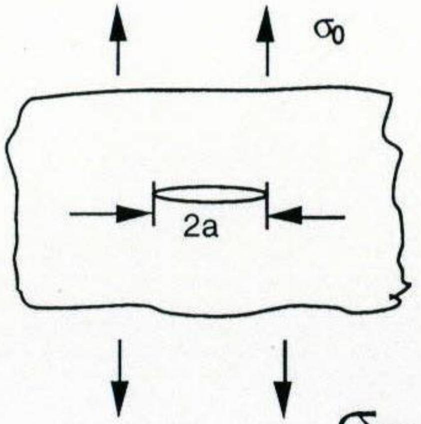
Wole Soboyejo and Jing Du
AUST-Abuja
And
Princeton University

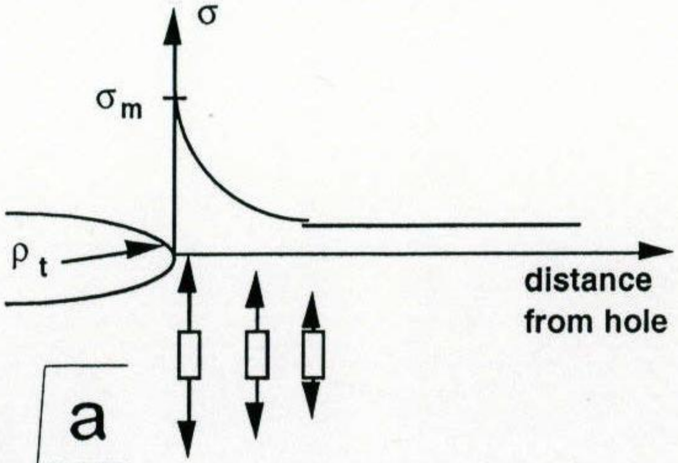
# Fracture and Toughening of Materials

- All materials can fracture at sufficiently high stresses
- Fundamentals of fracture are presented for failure under monotonic loading
- We will consider the stress concentration associated with notches and cracks
- The fundamentals of fracture mechanics will then be presented
- Ways of improving the fracture resistance of solids will then be examined-toughening mechanisms
- Examples of toughened biomaterials will then be presented

# Flaws and Stress Concentration

- **Elliptical hole in a plate:**



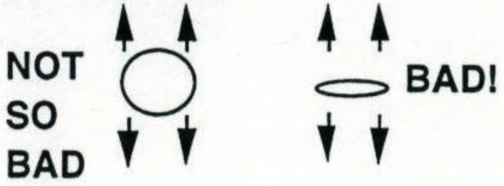


$$\sigma_m \approx 2\sigma_0\sqrt{\frac{a}{\rho_t}}$$

- **Stress concentration factor:**

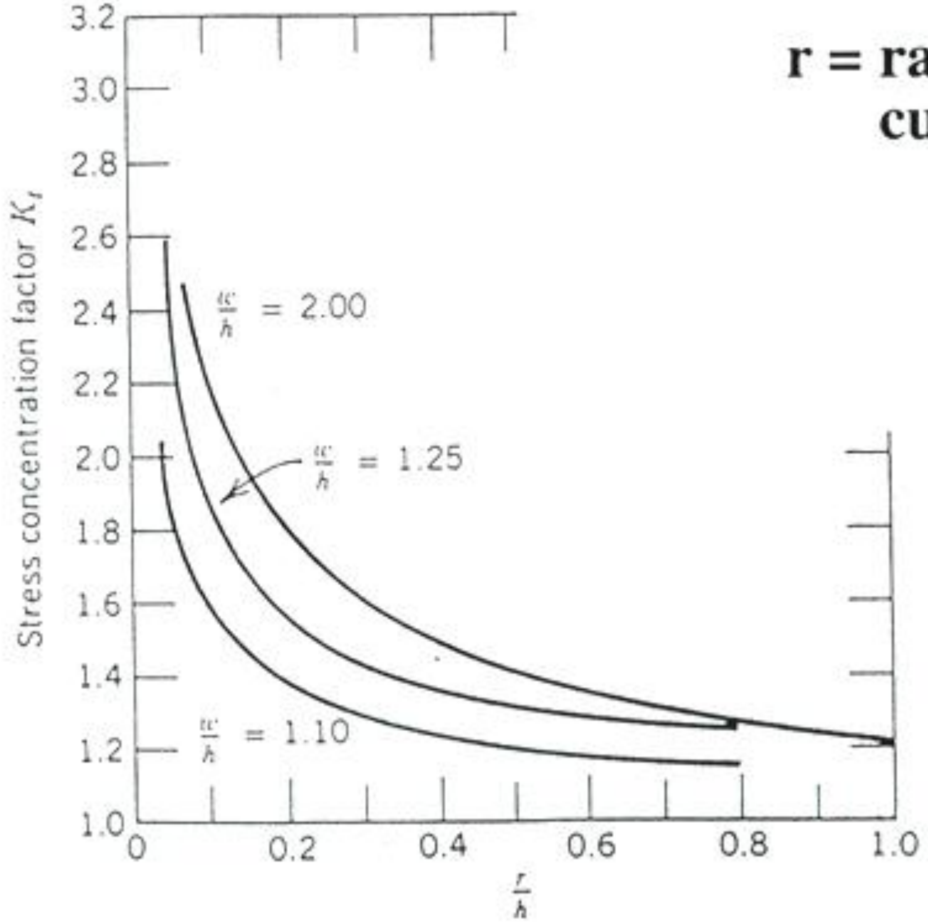
$$K_t = \frac{\sigma_m}{\sigma_0} = \frac{\text{internal stress}}{\text{applied stress}}$$

- **Large Kt promotes failure**
  **-- Bad: large, sharp, cracks**



# Engineering Design

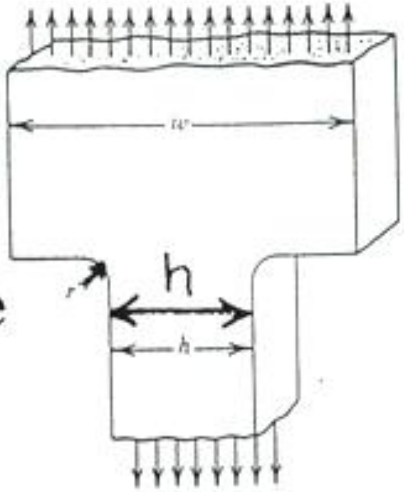
- **Avoid sharp corners!**



**SHARP CORNER**

**GRADUAL CORNER**

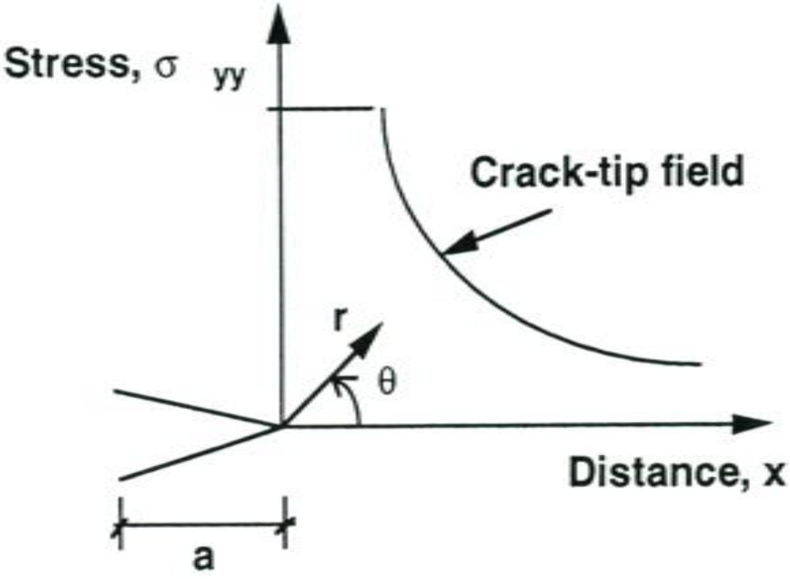
**r = radius of curvature**



# Driving Force For Crack Growth

- **Irwin proposed the stress intensity factor K as the crack driving force**

- **K is the amplitude of the crack-tip stress fields**

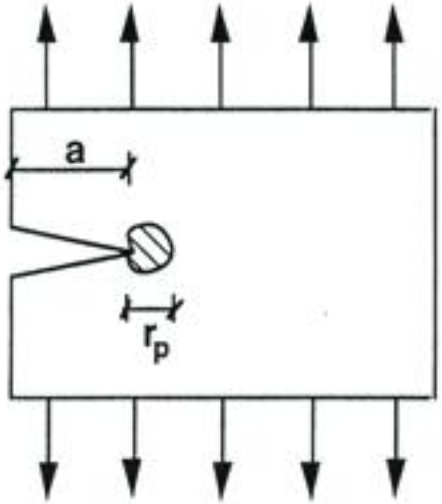


$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f(r,\theta)$$

# Introduction to Linear Elastic Fracture Mechanics

- Assumes that all structures contain cracks
- Assumes that crack size much bigger than plastic zone size

$$\frac{r_p}{a} \leqslant \frac{1}{50}$$



K= Stress Intensity Factor

K= Driving Force For Crack Growth

$$K_Q = Y\,\sigma\sqrt{\pi\, a}$$

Where: Y = f(geometry)

a = Crack length

$\sigma$ = stress

- Concept of similitude (lab versus real structures)
- Can use to determine critical conditions

# The Stress Intensity Factor - Applications and Basic Definitions

- The stress intensity factor, K, is generally given by

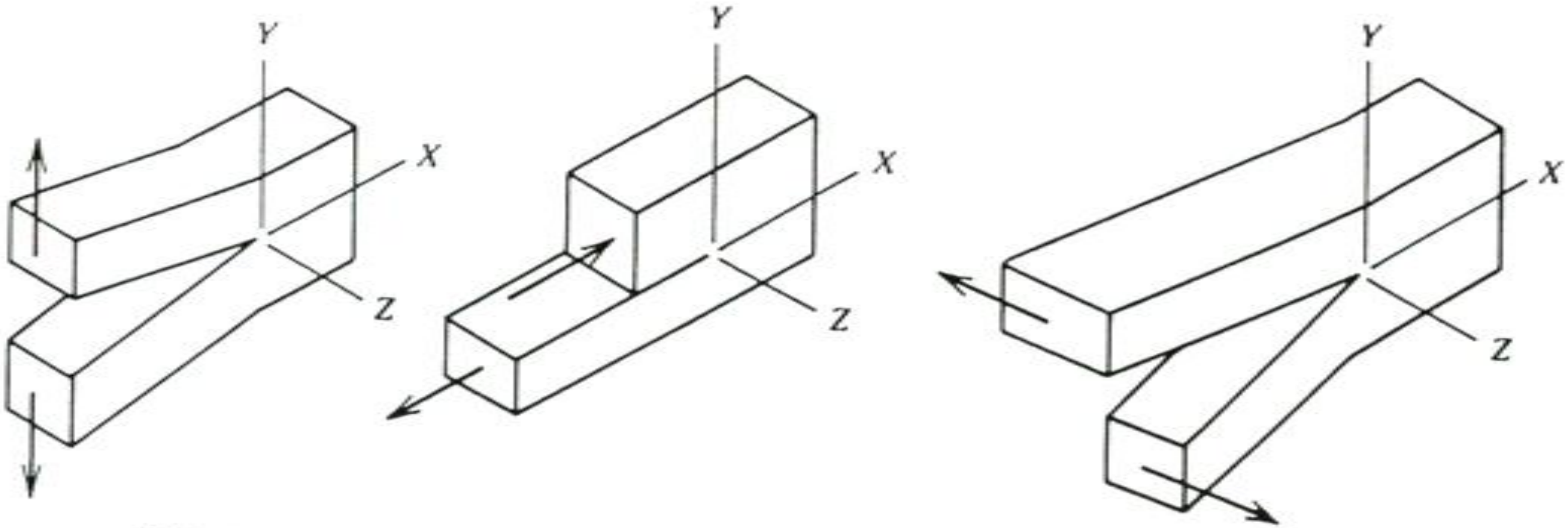
$$K = F\left(\frac{a}{w}\right)\sigma\sqrt{\pi a}$$

where - $F\left(\frac{a}{w}\right)$ is a function of geometry

- $\sigma$ is the applied stress
- a is the crack length

- Concept of similitude makes it possible to apply K to a wide range of specimen geometries - from lab specimens to real structures
- K represents the driving force for crack growth

# Possible Modes of Loading



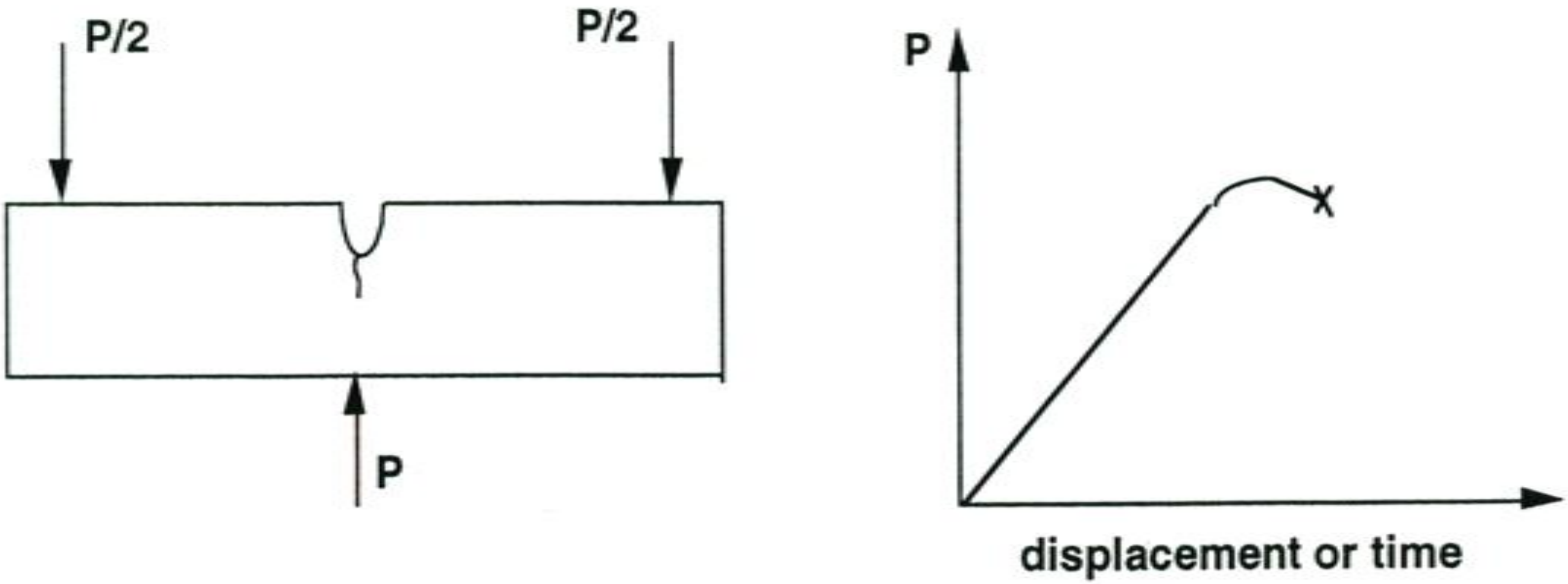
Mode I

Mode II

Mode III

# Fracture Toughness Testing

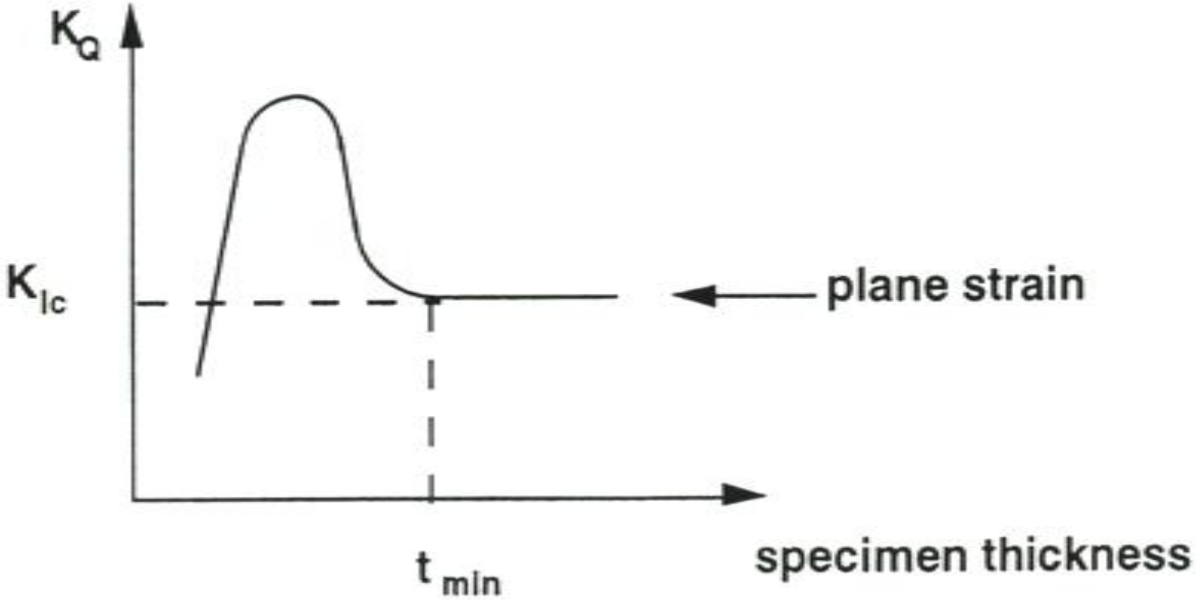
- **Often use ASTM E399 testing code**



$K_Q = Y\sigma\sqrt{\pi a}$ **= Fracture Toughness**

**$K_Q = K_{Ic}$ if we satisfy code requirements**

# Effects of Specimen Thickness on Fracture Toughness



$K_{Ic}$ is a thickness independent material property

# Fracture Design

- Crack Growth Condition:

$$K = K_{Ic}$$

- Max. flaw size dictates design stress

$$\sigma_c \le \frac{K_{Ic}}{Y\sqrt{\pi a}} \qquad Y = \begin{cases} 1.0 \\ 1.1 \end{cases}$$

- Design stress dictates max. flaw size

$$a_c \le \frac{1}{\pi}\left(\frac{K_{Ic}}{\sigma Y}\right)^2$$

# Design Example

Aircraft wing

-material has $K_{Ic} = 26\text{MPa}\sqrt{m}$

For design A

-largest flaw is 9mm

-failure stress is 112MPa

For design B

-largest flaw is 4mm

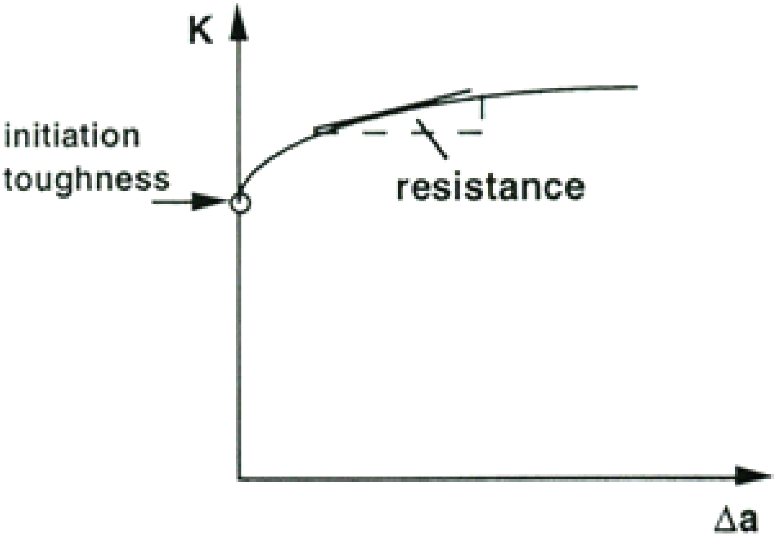
- What is the new failure stress?
- Use $\sigma_c = \dfrac{K_{Ic}}{Y\sqrt{\pi a}}$ $\quad \sigma_c^B = \sigma_c^A \sqrt{a^A / a^B}$

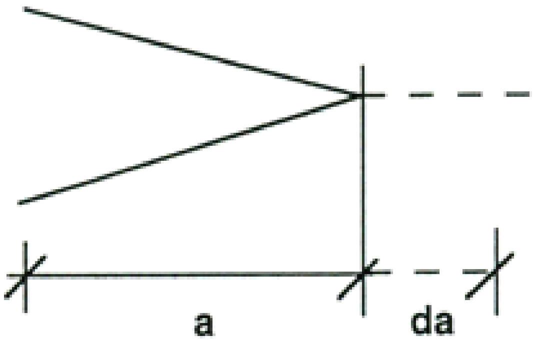
$$\sigma_c \sqrt{a} = \text{const.}$$

$$= 168\text{MPa}$$

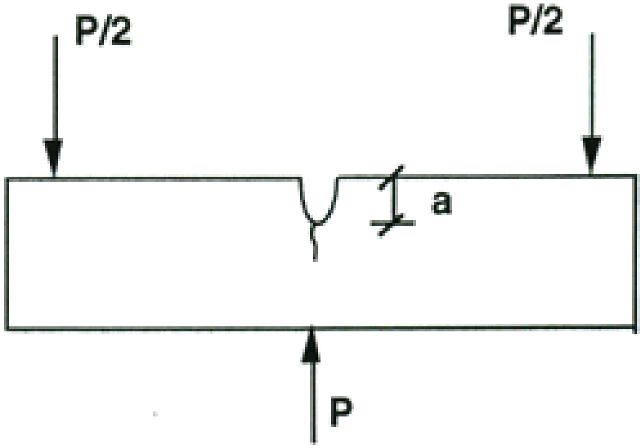
# Fracture Toughness (Another material Property)

- A measure of the resistance to crack initiation or crack growth





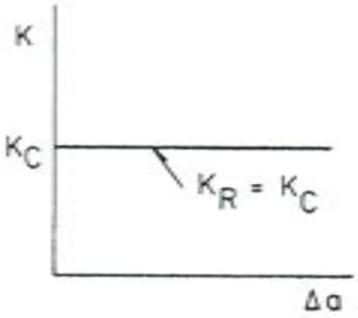
- Measured with standard cracked fracture mechanics specimen



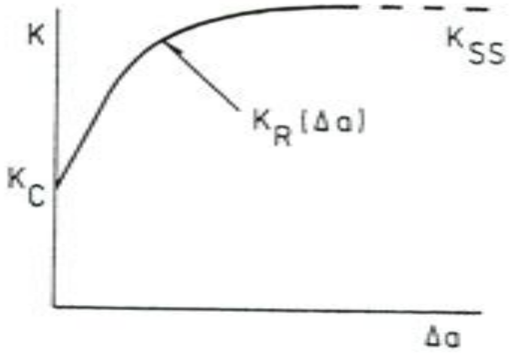
# Resistance-Curve Behavior in Materials

- Perfectly brittle materials exhibit no resistance to crack growth
- Most materials exhibit some kind of resistance-curve behavior
- Resistance-curve behavior is due largely to crack-tip shielding mechanisms
- Observed in biomaterials such as bone, dental ceramics, titanium alloys, etc.

No Resistance to Crack Growth



Resistance-Curve Behavior



# Toughening Due to Crack-Tip Shielding

- The basic idea behind the toughening of all materials is really quite simple
- The idea is to reduce the crack-tip stress by controlling the structure of the underlying material
- Processes that reduce the crack-tip stress are known as crack-tip shielding processes
- The effective stress, $K_{eff}$ intensity factor is now given by

$$K_{eff} = K_{app} - K_s$$

- Fracture or stable crack growth occur when $K_{eff}$ reaches critical values

# Schematic of Possible Toughening Mechanisms

- Taken from a review article by R.O. Ritchie

- CRACK DEFLECTION
- MICROCRACK TOUGHENING:

  $\Delta(K) \sim E' f_v \varepsilon_s^m \sqrt{h}$

- TRANSFORMATION TOUGHENING:

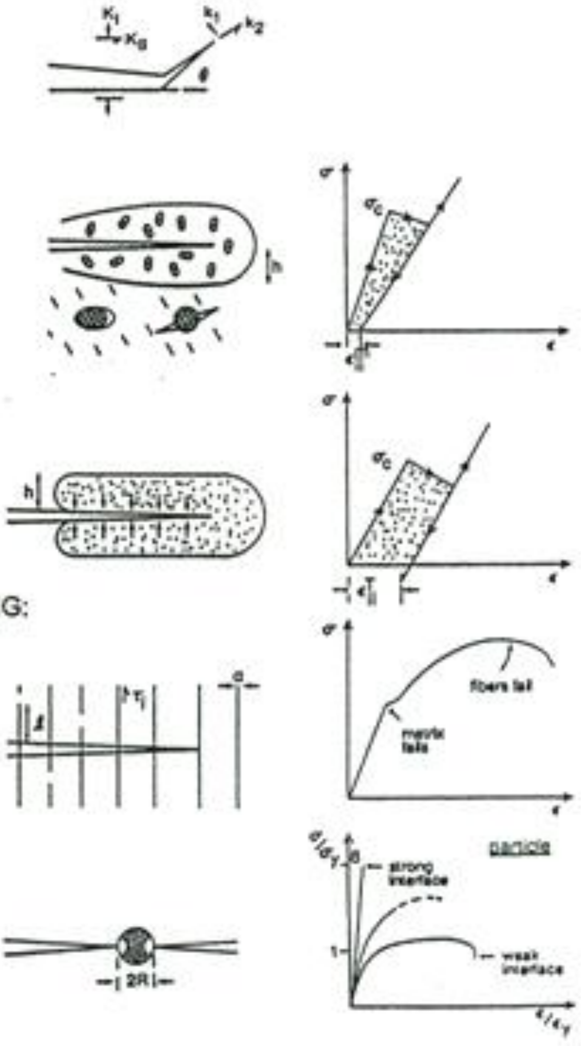
  $\Delta(K) \sim E' f_v \varepsilon_s^T \sqrt{h}$

- BRITTLE FIBER/WHISKER TOUGHENING:
  (crack bridging)

  $\Delta(K) \sim (2 f_v E' \tau_i \ell^2 / \alpha)^{1/2}$

- DUCTILE PARTICLE TOUGHENING:

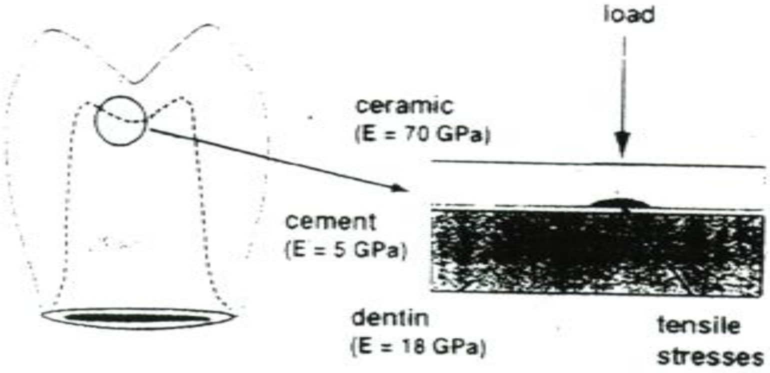
  $\Delta(K) \sim (C E' \sigma_y R f_v)^{1/2}$



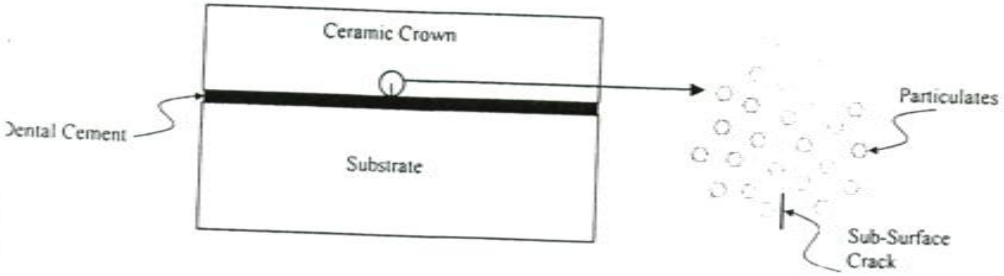
# Toughening of Dental Ceramics - A Case Study in the Design of Biomaterials

- The design of ceramics for crown applications requires considerations of two major properties
  - aesthetics
  - fracture toughness
- Major competition between the requirements for these two properties
- Often the materials that are tough are not aesthetic and vice-versa

Schematic of Crown on Dentin



Schematic of Composite on Dentin



# Toughening of Dental Ceramic Composites for Crown Applications

- Glass matrices are often selected - aesthetics (color) controlled by the use of pigments

- However, glass matrices have limited fracture resistance

- Hence, extrinsic toughening is used to improve fracture resistance

- Typical glass ceramic composites include

  - glass matrix + leucite particles
  - glass matrix + alumina ($Al_2O_3$) particles
  - glass matrix + mica particles
  - glass matrix + partially stabilized zirconia particles

# The Fracture Toughness of Dental Ceramic Composites

- The glass matrices (close to soda lime glass) have fracture toughness levels of ~ 0.6 MPa$\sqrt{m}$
- Alumina and mica-reinforced composites have fracture toughness levels of ~ 0.7-1.2 MPa$\sqrt{m}$
- Zirconia-reinforced composites have fracture toughness levels between 2 and 6 MPa$\sqrt{m}$
- So why don't we use zirconia toughened ceramics as the materials of choice in most crowns
- The reason is poor aesthetics - greenish looking teeth is simply not appealing!

# Summary and Concluding Remarks

- An introduction to fracture and toughening of materials was presented
- Fracture occurs by the separation of bonds - with or without prior plasticity (microscopically brittle or ductile processes are possible)
- Crack nucleation sites often associated with local stress concentrations especially around notches - avoid stress concentrations in design
- The stress intensity factor, K, represents the driving force for crack growth
- Fracture toughness values, $K_{Ic}$, are material properties that characterize the resistance to crack "initiation" while crack growth resistance is best characterized on resistance-curves
- Improved biomaterials can be designed using crack-tip shielding concepts - however, other factors such as aesthetics may be just as important as fracture toughness