Fracture

Objectives:

- *identify* design parameters limiting fracture and fatigue
- *distinguish* between catastrophic failure vs slow (!) fracture - *leak before break*
- *predict* life of structures based on fatigue and creep phenomena
- *identify* failure mechanisms and parameters controlling them

Ductile vs Brittle ⇔ Fig.8.1 - 8.3

Fracture involves (i) crack initiation and (ii) crack propagation

\(stable\ vs\ \ unstable\)

(brittle)
Ductile vs Brittle

Ductile
- extensive plastic deformation
- high $e_t$ or RA
- dull fracture surface
- stable crack propagation
  (no further crack propagation when $\sigma \rightarrow 0$)
- cup-and-cone type fracture

Brittle
- little or no plastic deformation
- very low $e_t$ or RA
- bright/shiny
- unstable
  (once cracks start propagating, they continue till fracture)
- leads to catastrophic crack propagation & failure
- grainy-faceted fracture surfaces

brittle fracture: crack motion is nearly $\perp r$ to the tensile stress axis
- yields a relatively flat fracture surface
Fracture Mechanics

Stress Concentration at crack tips (Fig. 8.7)

\[ \sigma_{\text{crack-tip max}} = 2 \sigma_o \sqrt{\frac{a}{\rho_t}} \]

\( \sigma_o \) is net section stress (nominal applied stress)

\[ \kappa = \frac{\sigma_{\text{max}}}{\sigma_o} = 2 \sqrt{\frac{a}{\rho_t}} \quad \text{(Eq. 8.2)} \]

Griffith theory of brittle fracture:

- fracture occurs when the tensile stress at some crack tip exceeds theoretical cohesive strength of the material

(implies that when there are no cracks at all (!), fracture strength would be equal to the theoretical cohesive strength)

With cracks (real situation) \( \Rightarrow \) elastic strain energy released during crack propagation equals the surface energy increase due to the creation of 2 new surfaces \( \Rightarrow \)

Eq. 8.3 : \( \sigma_c = \sqrt{\frac{2E\gamma_s}{\pi a}} \) defines the critical stress needed for crack propagation

If there is some plastic deformation (true in majority of cases), add plastic strain energy in Eq. 8.3 (Eq. 8.4) : \( \sigma_c = \sqrt{\frac{2E(\gamma_s + \gamma_p)}{\pi a}} \)
Fracture Toughness:

Modes I, II and III

Stress fields around cracks and stress intensity factor (K): Eqs. 8.5 \( \sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta) \)

\( r \) is distance from the crack tip & \( i,j = x, y \); \( K \) specifies stress distribution at crack tip
Just like when \( \sigma_c \) is approached, crack propagation can occur;

define a critical fracture toughness \( K_c = Y \sigma \sqrt{\pi a} \) (Eq. 8.6), \( Y \approx 1 \)

\( K_c \) depends on the specimen geometry (specifically thickness) and decreases as size increases (Fig. 8.12) and it reaches a minimum value for thick specimens known as plane strain fracture toughness \( K_{lc} \)

which is a material parameter \{f(T, \dot{\varepsilon}, microstructure); \( K_{lc} \) \( \uparrow \) as grain-size \( \uparrow \}\}

\[
\begin{align*}
\{\text{condition for plane strain : } B & \geq 2.5 \left( \frac{K_{lc}}{\sigma_y} \right)^2 \} \\
\text{i.e. when the applied fracture toughness, } K_I & = Y \sigma \sqrt{\pi a} \text{ reaches } K_{lc}, \\
\text{fracture occurs or crack propagates}[\text{analogous to applied stress vs yield strength}] \\
\text{(units of } K_I) & \leftrightarrow \text{ large for ductile and low for brittle}
\end{align*}
\]

Design using Fracture Mechanics

\[
K_{lc} \text{ (material parameter)}
\]

Eqs. 8.9 & 8.10 \( \Rightarrow \) 3 variables:

\[
\begin{align*}
K_{lc} & \text{ (material parameter)} \\
\{\text{applied or imposed stress (}\sigma\text{)} \\
\text{flaw size (a)}
\end{align*}
\]

\begin{align*}
\text{case (i): if } K_{lc} \text{ and } a & \text{ are specified } \Rightarrow \text{design stress } \sigma_c \leq \frac{K_{lc}}{Y \sqrt{\pi a}} \\
\text{case (ii): if } K_{lc} \text{ and } \sigma & \text{ are specified } \Rightarrow \text{maximum allowable flaw size } a_c = \frac{1}{\pi} \left( \frac{K_{lc}}{\sigma Y} \right)^2
\end{align*}

“a” is measured using various NDT methods (UT, optical, radiography, etc.)

Fracture Testing: CV etc.