Chapter 14 – Fracture Mechanics

Stress Concentrations

- discontinuities typically exist in structures (holes, cross-section changes, keyways, etc.)
- discontinuities $\Rightarrow$ locally increase stress (stress raisers)
- K_t , theoretical stress concentration factor, used to quantify stress magnification in critical location:

$$K_t = \sigma_m / \sigma_0$$

σ_m - maximum stress
σ_0 - nominal stress

- note K_t is dimensionless
- designers use K_t data extensively for structural design
- shortcomings ?? based on elastic behavior; doesn't account for cracks; more significant for brittle materials

Fracture Mechanics vs. Fracture Mechanisms

Fracture Mechanics:

- a specific mechanics approach to quantify failure
- assumes materials contain flaws and uses engineering mechanics methods to characterize crack growth behavior and crack instability

Fracture Mechanisms:

- defines failure processes in materials (microscopic and macroscopic)
- physical methods of failures (ex: intergranular separation, crazing, cleavage, etc.)

Theoretical Cohesive Strength

Theoretical Predictions of Strength:

Separation of atomic planes in tension:

$$\sigma_c = [\, E\,\gamma / a_o \,]^{1/2}$$

where:

- σ_c is critical tensile stress for separation
- E is Young's Modulus
- γ is surface energy of newly formed crack surface
- a_o is equilibrium atomic spacing

and using simplifying assumptions:

$$\sigma_c \sim E / \pi$$

Shear of adjacent atomic planes:

$$\tau_c = G b / 2 \pi a$$

where:

- τ_c is critical shear stress to cause slip
- G is shear modulus
- B is the slip distance
- a is interplanar atomic spacing

and using simplifying assumptions:

$$\tau_c \sim G / 2 \pi$$

Substituting values of E and G into above equations and comparing to experimentally measured strengths, it is found these models predict theoretical strengths >>>> than observed strengths.

Why???? $\Rightarrow$ $\Rightarrow$ $\Rightarrow$ $\Rightarrow$ defects in materials:

- flaws
- dislocations

* Existence of dislocations postulated ~ 1930's

* Concept of preexisting flaws: Griffith (1920)

Griffith Approach

* Concept of preexisting flaws

* A crack propagates when the amount of elastic strain energy released exceeds the surface energy of the newly formed crack.

Thus for the following geometry stressed in tension:

infinitely wide, thin sheet

center crack of length 2a, oriented normal to the stress direction

crack is elliptical, through-the-thickness

$$\sigma_c = [\, 2 \gamma E / \pi a \,]^{1/2}$$

where:

- σ_c is critical tensile stress for crack instability
- γ is surface energy of newly formed crack surface
- E is Young's Modulus
- a is half crack length

* His early experimental results on glass verified this theory, but they were fortuitous

* Initially proposed in 1920, but no significant acceptance until the late 1940's after Irwin and Orowan modifications

Irwin Modification

In 1948 Orowan and Irwin showed the importance of local plastic deformation at the crack tip

Dissipative processes involved in fracture >>>>> γ term envisioned by Griffith

Resulted in modified Griffith equation:

$$\sigma_c = [\, G_c E / \pi a \,]^{1/2}$$

where:

- σ_c is critical tensile stress for crack instability
- G_c is critical strain energy release rate (which equals γ + P, with P being a "plastic" dissipation of energy)
- E is Young's Modulus
- a is half crack length

Irwin showed equivalence to his newly developed stress intensity approach, which was the founding of Linear Elastic Fracture Mechanics (LEFM)

Stress Intensity Approach

$$G = K^2 / E$$

where:

- G is strain energy release rate
- K is stress intensity factor
- E is Young's Modulus

thus for an infinitely wide, thin sheet containing a center, through-the-thickness crack of length 2a under a tensile stress σ:

$$K = \sigma [\pi a]^{1/2}$$

in general, for any cracked body:

$$K = Y \sigma [\pi a]^{1/2}$$

where Y is a geometric factor

at crack instability:

$$K_{Ic} = Y \sigma_c [\pi a_c]^{1/2}$$

where:

- "c" represents the critical condition
- K_{Ic} is the critical stress intensity (for Mode I loading) and is called "plane strain fracture toughness", assuming certain validity aspects are maintained

Nomenclature

Types of Failure

- brittle vs. ductile
- brittle: little overall plastic deformation occurring before or during fracture
- ductile: appreciable plastic deformation occurring before or during fracture

"Toughness" or Toughness Measures

- area under stress – strain curve
- notched impact (e.g., Charpy)
- fracture toughness (K_{Ic}, G_{Ic})
- plasticity extent at stress concentration (r_y)

- notched-to-smooth tensile strength ratio
- others……….

Macroscopic Failure Modes

Surface Flatness

flat fracture	slant fracture	mixed slant/ flat fracture
⇓	⇓	⇓
lower toughness	higher toughness	intermediate toughness
⇓	⇓	⇓
plane strain	plane stress	mixed plane strain/plane stress

Surface Markings

- fatigue beachmarks
- chevron markings
- stress corrosion areas
- fast fracture areas
- etc.

Microscopic Failure Modes

Surface Markings

metals – transgranular, intergranular, microvoid coalescence (dimpled rupture), cleavage, quasi-cleavage, ……

polymers – crazes, fibrils, hackles, mirror, ……

ceramics – mirror, mist, hackle, ……

Plane Stress vs. Plane Strain

loads applied in plane of body

plane stress (thin sections):

$$\sigma_z = 0 \qquad \varepsilon_z \neq 0$$

plane strain (thick sections):

$$\sigma_z \neq 0 \qquad \varepsilon_z = 0$$

Fracture Mechanics Terminology

Crack surface displacement modes:

Mode I - opening mode

Mode II - edge-sliding mode

Mode III - tearing mode

where: I, II, III are subscripted on G, K fracture mechanics terms, as applicable

Common fracture mechanics terms:

K - stress intensity factor

K_I - mode I stress intensity factor

K_{II} - mode II stress intensity factor

K_{III} - mode III stress intensity factor

K_{Ic} - mode I critical stress intensity factor; plane strain fracture toughness; fracture toughness

K_c - often used to designate mode I plane stress fracture toughness (not universally accepted)

ΔK - range in stress intensity factor in fatigue loading cycle

G - strain energy release rate or crack extension force

G_{Ic} - mode I critical strain energy release rate or crack extension force; fracture toughness

Application Areas of Fracture Mechanics

Critical Crack Instability

- quasi-static fracture toughness: K_{Ic}
- dynamic fracture toughness: K_{Id}

Subcritical Crack Growth

- fatigue crack propagation: da/dN vs. ΔK

- environmentally assisted crack growth:

  K_I vs. da/dt K_{Iscc} K_{IEAC} t_f

Typical Fracture Mechanics Applications

- fracture instability
- fatigue crack propagation/retardation effects
- stress corrosion
- stress corrosion/fatigue
- hydrogen embrittlement
- proof testing of pressure vessel
- failure analysis

Areas of Fracture Mechanics Utilization

- aircraft components
- turbines
- rockets and missiles
- oil industry
- nuclear industry
- rock mechanics
- rail transportation
- marine applications

Historical Development

1958 Department of Defense, ASTM initiate study of fracture problems in rocket propellant tanks

1959 ASTM Committee E24 on Fracture Toughness Testing of Metallic Materials formed

1964 First symposium devoted solely to sharp crack fracture mechanics

Paris (Lehigh Univ.) proposes use of stress intensity for correlating fatigue crack propagation

1965 Brown (NRL) first to employ precracked fracture mechanics specimens to stress corrosion studies

NASA pressure vessel failures – requirement for fracture mechanics qualification of pressure vessel materials and proof test fluids

1969 Critical defect in F-111 steel wing pivot fitting

1972 ASTM adopts standard fracture toughness testing procedures (E399)

U. S. Air Force develops Aircraft Structural Integrity Program (MIL-STD-1530)

1974 U. S. Air Force develops Airplane Damage Tolerant Design Requirements (MIL-A-83444)

1979 British develop methods for Crack-Tip-Opening-Displacement (CTOD) Testing (BS5762)

1981 ASTM adopts standard practice for R-Curve determination (E561)

1985 ASTM adopts standard for J_{Ic} testing (E813)

- Many subsequent additions/modifications to many applications
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