Lecturer:  Prof. R. O. Ritchie, Rm. 324 HMMB (or 62-239, MSD, LBNL)

TA:  Amy Wat:  email: amy.wat@berkeley.edu

BRIEF COURSE DESCRIPTION:
A presentation is given of deformation and fracture in engineering materials, including elastic and plastic deformation from simple continuum mechanics and microscopic viewpoints, dislocation theory, alloy hardening and creep deformation, fracture mechanisms, linear elastic and nonlinear elastic fracture mechanics, toughening of metals, ceramics and composites, environmentally-assisted cracking, fatigue failure, subcritical crack growth, stress/life and damage-tolerant design approaches.

GRADING:

Homeworks:  15%
Mid-Term I:  20%
Mid-Term II:  20%
Final:  45%
MSE 113
Required and Reference Texts


Mechanical Behavior of Materials:
F.A. McClintock, A.S. Argon: Mechanical Behavior of Materials (Addison-Wesley, 1966)*

Fracture Mechanics:
H. L. Ewalds, R. J. Wanhll: Fracture Mechanics (Arnold, 1984)*

Fatigue:
S. Suresh: Fatigue of Materials (Cambridge Univ. Press, 1998, 2nd ed.)*

Environmentally-Influenced Failure:

Mechanical Testing:

Failure Analysis/Fractography:

Continuum Mechanics/Elasticity:
Why Mechanical Properties are Important

• Why does stuff fail?

• How does it fail?

• What type of stuff fails?
  • ships, bridges and planes
  • micromachines
  • medical devices
  • you! (bones, teeth)

• Can we prevent it?
Length Scales in Material Behavior

Atomic structure
sub-nanometer
(\(<10^{-10} \text{ m}\))

Jet engine

Macro Structures
cm to m
\((10^{-2} \text{ to } 1 \text{ m})\)

Microstructures
micrometers
\((\sim 10^{-3} \text{ m})\)

Crack in a human tooth
1 \(\mu\text{m}\)

Fatigue crack in Ni alloy blade
10 \(\mu\text{m}\)

Ceramic crystal
0.1 \(\text{nm}\)

Prosthetic device
10 mm

Silicon Nitride (\(\text{Si}_3\text{N}_4\))

Enamel

Dentin

DEJ

Micromachines
10 \(\mu\text{m}\)

MEMS/NEMS – Micro/ Nano-electromechanical systems
How do things break?

- by plastic deformation - yielding
  - e.g., by bending a paper clip
- by (instantaneous) fracture
  - e.g., by breaking a pencil or a tooth or by impact fracture
- by fatigue (delayed fracture)
  - e.g., by bending that paper clip back and forth several times
- by environmentally-assisted cracking (delayed fracture)
  - e.g., by bending that paper clip back and forth under (salt) water
- by corrosion and/or wear (surface damage)
  - e.g., by corroding away or simply wearing something out
Failure by Plastic Deformation

- plastic (permanent) deformation of a bridge
- deformation led to eventual collapse
- Tacoma Narrows suspension bridge, near Puget Sound, failed on at 11 am Nov. 7, 1940, after only having been open for traffic a few months
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• 500 T2 tankers and 2700 Liberty ships were built during WWII
• prefabricated all-welded construction, with brittle steel
• one vessel was built in 5 days!

Brittle fracture of SS Schenectady, Jan. 1943

• initially, some 30% of Liberty ships suffered catastrophic failure
• cracks started at stress concentrations (e.g., hatchways) and propagated rapidly through the steel hull as the metal became too brittle at low temperatures

SS John P. Gaines split in two in 1943
• Air France charter flight from Paris to New York - July 25, 2000
• the Concorde crashed into a hotel shortly after take-off, 5 miles from airport, with 109 fatalities
• attributed to a piece of metal on the runway causing the bursting of a tire
• the impact of the tire debris on the fuel tank punctured it, leading to loss of engine power, and the subsequent crack
• an example of foreign-object damage (FOD)
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Fatigue & Delayed Fracture

- De Havilland Comet, first commercial jet aircraft, had five major crashes in 1952 - 54 period
  - caused by fatigue cracks initiated at square windows, driven by cabin pressurization and depressurization

- Aloha Airlines Boeing 737, in route from Hilo to Honolulu (April 1998) undergoes explosive decompression – 1 fatality
  - caused by a weakening of the fuselage due to corrosion and small cracks – led to Aging Aircraft Initiative
McDonnell Douglas DC-10 Crashes

July 19, 1989, Souix City, Iowa

- McDonnell–Douglas DC-10 is a three-engine medium-range wide-body aircraft
- The aircraft suffered many notable crashes
  - March 3, 1974 (Paris) - Turkish Airlines flight 981, rear cargo door blew out – all 333 passengers & 12 crew lost
  - May 25, 1979 (Chicago) - American Airlines 191 lost left engine on take-off – all 258 passengers & 13 crew lost
  - July 19, 1989 (Souix City) – United Airlines 232 crashed killing 110 of 258 passengers

A fatigue crack in the fan disk in the tailed-mounted engine fractured the disk; the resulting debris severed all three hydraulic control systems. The only way to steer the plane was by adjusting the thrust of the two remaining wing-mounted engines. However, on landing the tip of the right wing contacted and the aircraft skidded, somersaulted and caught fire.
United 232 Souix City Iowa Crash

- Ti alloy (Ti-6Al-4V) fan disk fractured due to 0.6-inch fatigue crack, that initiated from a 0.015-0.055 inch $\alpha$-inclusion in the cast metal

- The crack from the bore grew for many years and was missed by some 6 inspections

- Debris from failure severed all hydraulic control lines

- Parts of the fractured fan disks were not found for several months

July 19, 1989, Souix City, Iowa
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Failure due to Wear

• A major wear problem is with railroad tracks, where surface wear from metal-to-metal rolling contact can damage the rails leading to derailment.

Rail collapse leads to derailment of a locomotive in UK, in 1981

Derailment of 100 ton tank wagon and the rest of the train in Lincolnshire, UK in 1982

(from http://danger-ahead.railf.net)

surface wear (delamination) can lead to catastrophic fatigue fracture of the rail

crack initiation
Fractography

Ductile fracture

Brittle fracture

Creep fracture

Fatigue fracture
Ductile Fracture

- **ductile fracture** is the “desirable” form of fracture as it requires high energy
- it results from the coalescence of small voids formed around particles, e.g., inclusions, precipitates, in the metal

Brittle Fractures

- most materials are polycrystalline consisting of many crystals (grains)
- brittle fracture is generally transgranular (cleavage) with the crack propagating through the grains
- when the grain boundaries are “embrittled”, fracture can be intergranular

- segregation of impurity element atoms, e.g., S, P, O, H, to grain boundaries can cause such embrittlement
Many materials, like steels (and rubber), show a ductile-to-brittle transition (glass transition)

- Rubber shows a glass transition temperature, below which it is brittle, like glass, and above which it behaves like rubber.
- Similarly, many metals like steel display a ductile-to-brittle transition temperature. Above this temperature, they are ductile, whereas below they are brittle with typically an order of magnitude lower toughness (energy required for fracture).
Sinking of the RMS Titanic

• On April 14, 1912, RMS Titanic hit an iceberg in the north Atlantic and sank in just over 2 hrs
• 1500 of Titanic’s 2223 passengers lost

Why did the ship sink so fast?

1. **poor steel**: steel was very brittle with high O & S content

2. **poor rivets**: hull held together by 3 million very brittle wrought iron rivets containing excessive slag

Fatigue Fractures

- more than 80% of all failures are caused by fatigue, i.e., prolonged failure under cyclic (alternating) loads
- to the naked eye, fatigue fractures are characterized by smooth, “half-moon”, regions with radiating bands
- microscopically, smaller bands, called striations, can often be seen – these are the location of the crack each cycle

Fatigue vs. Instantaneous Failure

Failure of an axial shaft (e.g., a car’s steering column or axle)

- Fatigue (rotary) failure
  - medium carbon steel (AISI 1050) automobile axle

- Bending (overload) fracture
  - A fatigue failure would imply a process that has occurred over some period of time, and would have likely caused the accident
  - An overload fracture would be an instantaneous event likely caused by the accident

What about small structures?

• The dimensions of current micro-machines (MEMS) are on the order of micrometers (microns – μm), i.e., millionths of a meter
• next generation machines (NEMS) may be on the order of tens to hundreds of nanometers (nm), i.e., nearly a trillionth of a meter!

• a silicon MEMS micromotor next to a strand of human hair
• the diameter of the hair is about 50 μm (50,000 nm!)
What are Micromachines?

- Micromachines are known as MEMS
  - micro-electro-mechanical-systems
  - many applications are used today
    - inertial sensors (e.g., in air bags)
    - medical devices
    - memory and mass storage
    - micro-mirrors for digital projection
  - not to mention future applications
    - “pocket turbines” (to power the soldier of the future!)

- Next generation of machines may even be smaller - NEMS
  - nano-electro-mechanical-systems
Micromachines or MEMS

Schmidt et al., MIT

Microturbine

R. Conant, 1999

Micron-scale moveable mirrors

Gears

50 μm

Microhinge

MCNC/Cronos
Applications: cogs and gears

- Micron-scale cogs and gears are used extensively in mechanical micromachines

10 \mu m
Mechanical Testing at the Microscale

- 2 μm thick n-type polysilicon thin films fail at >10⁹ cycles at half their strength
- bulk silicon is not susceptible to fatigue
- fatigue due to moisture-induced nanoscale cracks in SiO₂ oxide layer

Brown, Van Arsdell, Muhlstein et al. testing to >10¹¹ cycles

Muhlstein, Stach, Ritchie, Acta Mater., 2002
Alloptropic Forms of Carbon

**diamond**
- all strong (covalent) bonds

a = 0.534 nm

**graphite**
- strong bonds in layers
- weak (Van der Waals) bonds between layers

**graphene**
- strong bonds in sheets

**carbon C\(_{60}\)**
- all strong (covalent) bonds

**carbon C\(_{70}\)**

**carbon nanotubes**
- strong bonds in tubes
- weak bonds between tubes

single wall
multi wall
Mechanical Testing of Carbon Nanotubes

- Carbon nanotubes, few nm in diameter, claimed to be the world’s strongest material!

- Strength of the nanotube was measured as 150 GPa, i.e., roughly 5 times stronger than Kevlar or carbon fibers and more than 50 times stronger than hardened steel.

in situ mechanical test in TEM to measure the strength of a 12-nm thick carbon nanotube
• by reversing the electrical current along a CNT, metal can be transported along the tube.
• by putting the metal globs between two nanotubes, we can move them apart and do work (linear nano-motor).

thermally-activated electrically-directed In surface diffusion

motor force \( \sim 1 \text{ nN} \)

power densities \( \sim 20 \text{ MW/m}^3 - 8 \text{ GW/m}^3 \)


• most materials only deform reversibly (i.e., elastically) when deformed a small amount (e.g., when stretched for less than 1% change in length)
• after that the deformation is permanent (plastic deformation)
• however, a very few metals, so-called shape-memory/superelastic metals, e.g., Nitinol, are much more flexible

Nitinol is a 50:50 nickel-titanium alloy

Nitinol is used for eyeglass frames, dental drills and endovascular stents
Stenting of Arteries

- Stents manufactured with:
  - stainless steel
  - cobalt-chromium alloy
  - Nitinol (Ni-Ti alloy)

uninflated NiTi stent

made by NDC, a J&J Company, Fremont, CA
Stress-Life Predictions for Stents

radial pulsatile loading

worst-case fatigue location

FEA Generated Data
Modified Goodman Equation
Numerical Integration Point Closest to Goodman Curve

Predicted Stress Amplitude, $\Delta \sigma$ /2 {MPa}

Predicted Mean Stress, $\sigma_m$ {MPa}

Co-Cr alloy

Cordis cardiovascular stent

Internal pressures representing systolic & diastolic loads

small cracks formed during ultrasonic cleaning

failure envelope

stent in artery

Ramesh, Bergermeister, Grishaber, Ritchie, Biomaterials 2006
Failure of Vena Cava Filters

Bard vena cava filter

Hooks on legs prematurely fail due fatigue cracks initiated in the grinding marks; this causes the filter to migrate & promotes perforations & further fractures.

Filters made with 6 arms (shorter wires to arrest blood clots) & 6 legs (longer wires with anchor hooks), made from super-elastic Nitinol.

Fatigue cracks, often initiated in bending from surface markings, prematurely fracture the arms.
• **building blocks**: collagen & nano-crystalline hydroxyapatite mineral
• **at nano-scale**: mineralized collagen fibrils
• **at micron scale**: lamellar structure of collagen fibers
• **at micron scale**: in dentin - tubules
• **at hundreds of microns**: in bone - osteons/ Haversian canals
• **at macro scale**: size and type of the tooth or bone

**Bone**

- **Collagen molecule**: 2.86 nm
- **Collagen fibers**: 64 nm
- **Haversian canal**: 1 μm

**Dentin**

Dentin is:
- 45 vol% apatite
- 30 vol% collagen
- 25 vol% fluid

**Structure of Teeth & Bone**
Seven Hierarchies of Structure of Bone

Weiner & Wagner, Rev. Mat. Sci., 1998

Origins of Toughening in Bone
Extrinsic Toughening Mechanisms

2-D *in situ* SEM imaging

- monitoring *in situ* of how cracks interact with the microstructure, while simultaneously taking quantitative R-curve toughness measurements

3-D computed X-ray tomography

- 3-D imaging of crack paths and resulting toughening mechanisms

Crack Arrest in the DEJ Region in Teeth

- cracks in harder enamel do not necessarily break the tooth as they arrest “at” the dentin-enamel junction (DEJ)
- cracks arrest when they form elastic bridges in the (mantle) dentin due to the formation of uncracked ligaments in the crack wake

Alcohol Toughens Teeth – for a while!

86-proof Black & White scotch whiskey

- compared to water, alcohol increases the toughness of dentin
- but you do need to keep the alcohol in your mouth, as the effect is reversible!
- effect associated with direct collagen-collagen H-bonding in polar solvants