Chapter 16: Composite Materials

ISSUES TO ADDRESS...

• What are the classes and types of composites?

• Why are composites used instead of metals, ceramics, or polymers?

• How do we estimate composite stiffness & strength?

• What are some typical applications?
Composites

• Combine materials with the objective of getting a more desirable combination of properties
  – Ex: get flexibility & weight of a polymer plus the strength of a ceramic

• structure materials for aircraft engine:
  low densities, strong, stiff, abrasion and impact resistant and corrosion resistant.

GE engine:
http://www.geae.com/education/theatre/genx/
http://www.geae.com/education/theatre/ge90/

• Principle of combined action
  – Mixture gives “averaged” properties
    better property combinations are fashioned by the combination of 2 or more distinct materials.
Composite is considered to be any multiphase materials that exhibits a significant proportion of the properties of both constituent phases such that a better combination of properties is realized.

Schematic representations of the various geometrical and spatial characteristics of particles of the dispersed phase that may influence the properties of composites: (1) concentration, (b) size, © shape, (d) distribution, and (e) orientation.
**Terminology/Classification**

- **Composites:**
  - Multiphase material with significant proportions of each phase.

- **Matrix:**
  - The continuous phase
  - Purpose is to:
    - Transfer stress to other phases
    - Protect phases from environment
  - Classification: MMC, CMC, PMC

- **Dispersed phase:**
  - Purpose: Enhance matrix properties.
    - **MMC:** Increase $\sigma_y$, $TS$, creep resist.
    - **CMC:** Increase $Kc$
    - **PMC:** Increase $E$, $\sigma_y$, $TS$, creep resist.
  - Classification: Particle, fiber, structural

Reprinted with permission from D. Hull and T.W. Clyne, *An Introduction to Composite Materials*, 2nd ed., Cambridge University Press, New York, 1996, Fig. 3.6, p. 47.
Composite Survey

Composites
- Particle-reinforced
  - Large-particle
  - Dispersion-strengthened
  - Continuous (aligned)
  - Discontinuous (short)
- Fiber-reinforced
- Structural
  - Laminates
  - Sandwich panels

10-100nm

Adapted from Fig. 16.2, Callister 7e.
Composite Survey: Particle-I

Particle-reinforced

- Spheroidite steel
  - matrix: ferrite ($\alpha$) (ductile)
  - particles: cementite ($\text{Fe}_3\text{C}$) (brittle)

- WC/Co cemented carbide
  - matrix: cobalt (ductile)
  - $V_m$: 10-15 vol%!
  - particles: WC (brittle, hard)

- Automobile tires
  - matrix: rubber (compliant)
  - particles: C (stiffer)

Fiber-reinforced

- Structural
  - Adapted from Fig. 10.19, Callister 7e.
    (Fig. 10.19 is copyright United States Steel Corporation, 1971.)
  - Adapted from Fig. 16.4, Callister 7e.
    (Fig. 16.4 is courtesy Carboloy Systems, Department, General Electric Company.)
  - Adapted from Fig. 16.5, Callister 7e.
    (Fig. 16.5 is courtesy Goodyear Tire and Rubber Company.)
Composite Survey: Particle-II

**Concrete** – gravel + sand + cement
  - Why sand *and* gravel?  Sand packs into gravel voids

**Reinforced concrete** - Reinforce with steel rerod or remesh
  - increases strength - even if cement matrix is cracked

**Prestressed concrete** - remesh under tension during setting of concrete. Tension release puts concrete under compressive force
  - Concrete much stronger under compression.
  - Applied tension must exceed compressive force

**Post tensioning** – tighten nuts to put under tension

http://www.metacafe.com/watch/338535/concrete_forming_system_showing_reinforced_concrete_housing/
Fractured reinforced concrete
How prestressed concrete is made?

High strength steel

A tarp is placed over and heat is applied

The prestressing strand is stretched across the casting bed, 30000 pounds of tension will be applied.

The prestressing strands are cut and removed from the casting bed.

Cement, sand, stone, and water make up concrete.

Chapter 16 - 10
Post-tensioning

- Post-tensioning is the method of achieving pre-stressing after the concrete has hardened and takes advantage of concrete's inherent compressive strength.
- Concrete is exceptionally strong in compression, but generally weak when subjected to tension forces or forces that pull it apart. These tension forces can be created by concrete shrinkage caused during curing or by flexural bending when the foundation is subjected to design loads (dead and live loads from the structure and/or expansive soil induced loads). This tension can result in cracking which can lead to large deflections that can cause distress in the building's structure.
- The application of an external force into the concrete, recompressing it before it is subjected to the design loads, makes the foundation less likely to crack.

http://www.youtube.com/watch?v=d51lcZrWF0
Elastic modulus, $E_C$, of composites:
-- two approaches.

**Particle-reinforced**

![Graph showing the relationship between elastic modulus ($E_C$) and vol% tungsten.](chart)

- **Upper limit**: "rule of mixtures"
  $$E_C = V_mE_m + V_pE_p$$

- **Lower limit**
  $$\frac{1}{E_C} = \frac{V_m}{E_m} + \frac{V_p}{E_p}$$

Data:
- Cu matrix
- w/tungsten particles

**Application to other properties**:
-- Electrical conductivity, $\sigma_e$: Replace $E$ in equations with $\sigma_e$.
-- Thermal conductivity, $k$: Replace $E$ in equations with $k$.

Adapted from Fig. 16.3, *Callister 7e*. (Fig. 16.3 is from R.H. Krock, ASTM Proc, Vol. 63, 1963.)
Composite Survey: Fiber-I

- **Fibers very strong**
  - Provide significant strength improvement to material
  - Ex: fiber-glass
    - Continuous glass filaments in a polymer matrix
    - Strength due to fibers
    - Polymer simply holds them in place

Influence of fiber materials, orientation, concentration, length, etc
Composite Survey: Fiber-II

Fiber-reinforced

Particle-reinforced

Structural

• Fiber Materials
  – Whiskers - Thin single crystals - large length to diameter ratio
    • graphite, SiN, SiC
    • high crystal perfection – extremely strong, strongest known
    • very expensive
  – Fibers
    • polycrystalline or amorphous
    • generally polymers or ceramics
    • Ex: Al₂O₃, Aramid, E-glass, Boron, UHMWPE
  – Wires
    • Metal – steel, Mo, W
Fiber Alignment

Aligned continuous

Aligned discontinuous

Random
Composite Survey: Fiber-III

- **Aligned Continuous fibers**
- **Examples:**
  - **Metal:** $\gamma'(\text{Ni}_3\text{Al})-\alpha(\text{Mo})$ by eutectic solidification.
  - **Matrix:** $\alpha(\text{Mo})$ (ductile)

- **Fiber-reinforced**
  - **Ceramic:** Glass w/SiC fibers formed by glass slurry
    
    $E_{\text{glass}} = 76$ GPa; $E_{\text{SiC}} = 400$ GPa.


From F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. (a) Fig. 4.22, p. 145 (photo by J. Davies); (b) Fig. 11.20, p. 349 (micrograph by H.S. Kim, P.S. Rodgers, and R.D. Rawlings). Used with permission of CRC Press, Boca Raton, FL.
Composite Survey: Fiber-IV

- **Discontinuous, random 2D fibers**
  - Example: Carbon-Carbon
    - Process: fiber/pitch, then burn out at up to 2500°C.
    - Uses: disk brakes, gas turbine exhaust flaps, nose cones.

- Other variations:
  - Discontinuous, random 3D
  - Discontinuous, 1D

(a) Fig. 4.24(a), p. 151; (b) Fig. 4.24(b) p. 151.
(Courtesy I.J. Davies) Reproduced with permission of CRC Press, Boca Raton, FL.

Carbon fiber-reinforced polymer composites
Composite Survey: Fiber-V

Particle-reinforced  |  Fiber-reinforced  |  Structural

• **Critical** fiber length for effective stiffening & strengthening:
  - Fiber strength in tension
  - Fiber diameter
  - Shear strength of fiber-matrix interface
  
  \[ \text{fiber length} > 15 \frac{\sigma_f d}{\tau_c} \]

• Ex: For fiberglass, fiber length > 15 mm needed
• Why? Longer fibers carry stress more efficiently!

  Shorter, thicker fiber:
  \[ \text{fiber length} < 15 \frac{\sigma_f d}{\tau_c} \]
  Poorer fiber efficiency

  Longer, thinner fiber:
  \[ \text{fiber length} > 15 \frac{\sigma_f d}{\tau_c} \]
  Better fiber efficiency

Adapted from Fig. 16.7, *Callister 7e.*

Load transmittance: the magnitude of the interfacial bond between the fiber and matrix phase
Composite Strength: Longitudinal Loading

Continuous fibers - Estimate fiber-reinforced composite strength for long continuous fibers in a matrix

- Longitudinal deformation

\[ \sigma_c = \sigma_m V_m + \sigma_f V_f \]

but

\[ \varepsilon_c = \varepsilon_m = \varepsilon_f \]

Modulus of elasticity

\[ E_{ce} = E_m V_m + E_f V_f \]

longitudinal (extensional) modulus

\[ \frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m} \]

where:

- \( f \) = fiber
- \( m \) = matrix
Composite Strength: Transverse Loading

- In transverse loading the fibers carry less of the load - isostress

\[ \sigma_c = \sigma_m = \sigma_f = \sigma \]
\[ \varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f \]

\[ \frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f} \]

\[ \text{transverse modulus} \]
Composite Strength

Particle-reinforced  Fiber-reinforced  Structural

- Estimate of $E_c$ and $TS$ for discontinuous fibers:
  - valid when fiber length $> 15 \frac{\sigma_f d}{\tau_c}$
  - Elastic modulus in fiber direction:
    \[
    E_c = E_m V_m + KE_f V_f
    \]
    **efficiency factor:**
    - aligned 1D: $K = 1$ (aligned $||$)
    - aligned 1D: $K = 0$ (aligned $\perp$)
    - random 2D: $K = 3/8$ (2D isotropy)
    - random 3D: $K = 1/5$ (3D isotropy)

- $TS$ in fiber direction:
  \[
  (TS)_c = (TS)_m V_m + (TS)_f V_f
  \]  (aligned 1D)

Values from Table 16.3, *Callister 7e.*
(Source for Table 16.3 is H. Krenchel, *Fibre Reinforcement*, Copenhagen: Akademisk Forlag, 1964.)
Composite Production Methods-I

- **Pultrusion**
  - Continuous fibers pulled through resin tank, then performing die & oven to cure

Adapted from Fig. 16.13, *Callister 7e*. 
Composite Production Methods-II

- Filament Winding
  - Ex: pressure tanks
  - Continuous filaments wound onto mandrel

Adapted from Fig. 16.15, *Callister 7e*. [Fig. 16.15 is from N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials*, The Macmillan Company, New York, 1981.]
Composite Survey: Structural

Particle-reinforced  
Fiber-reinforced  
Structural

A structural composite is normally composed of both homogeneous and composite materials.

- Stacked and bonded fiber-reinforced sheets
  - stacking sequence: e.g., $0^\circ/90^\circ$
  - benefit: balanced, in-plane stiffness

- Sandwich panels
  - low density, honeycomb core
  - benefit: small weight, large bending stiffness

Adapted from Fig. 16.16, *Callister 7e*.

Composite Benefits

- **CMCs:** Increased toughness

  ![Graph showing force vs. bend displacement with different reinforcement types (fiber-reinf, particle-reinf, un-reinf)]

- **PMCs:** Increased $E/\rho$

  ![Graph showing $E$ (GPa) vs. Density, $\rho$ [mg/m³] with different material categories (polymers, ceramics, metal/metal alloys)]


- **MMC:** Increased creep resistance

  ![Graph showing $\dot{\varepsilon}_{ss}$ (s⁻¹) vs. $\sigma$ (MPa) for 6061 Al and 6061 Al w/SiC whiskers]

Chapter 16 - 25
Summary

- Composites are classified according to:
  -- the matrix material (CMC, MMC, PMC)
  -- the reinforcement geometry (particles, fibers, layers).
- Composites enhance matrix properties:
  -- MMC: enhance $\sigma_y$, $TS$, creep performance
  -- CMC: enhance $K_c$
  -- PMC: enhance $E$, $\sigma_y$, $TS$, creep performance
- Particulate-reinforced:
  -- Elastic modulus can be estimated.
  -- Properties are isotropic.
- Fiber-reinforced:
  -- Elastic modulus and $TS$ can be estimated along fiber dir.
  -- Properties can be isotropic or anisotropic.
- Structural:
  -- Based on build-up of sandwiches in layered form.