16.982 Bio-Inspired Structures
Spring 2009

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?

TERMINOLOGY/CLASSIFICATION

- **Composites**:
  --Multiphase material w/significant proportions of ea. phase.
- **Matrix**:
  --The continuous phase
  --Purpose is to:
  transfer stress to other phases
  protect phases from environment
  --Classification: MMC, CMC, PMC
  (M = metal, C = ceramic, P = polymer)
- **Dispersed phase**:
  --Purpose: enhance matrix properties.
  MMC: increase σ_y, TS, creep resist.
  CMC: increase Kc
  PMC: increase E, σ_y, TS, creep resist.
  --Classification: Particle, fiber, structural

COMPOSITE SURVEY: Particle-I

Particle-reinforced | Fiber-reinforced | Structural

- Examples:

-Spheroidite steel

matrix: ferrite (α) (ductile)

Image removed due to copyright restrictions.

particles: cementite (Fe_3C) (brittle)

60μm

Adapted from Fig. 10.10, *Callister 6e*. (Fig. 10.10 is copyright United States Steel Corporation, 1971.)

-WC/Co cemented carbide

matrix: cobalt (ductile) V_m: 10-15vol%!

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particles: WC (brittle, hard)

600μm

Adapted from Fig. 16.4, *Callister 6e*. (Fig. 16.4 is courtesy Carboloy Systems, Department, General Electric Company.)

-Automobile tires

matrix: rubber (compliant)

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particles: C (stiffer)

0.75μm

Adapted from Fig. 16.5, *Callister 6e*. (Fig. 16.5 is courtesy Goodyear Tire and Rubber Company.)

COMPOSITE SURVEY: Particle-II

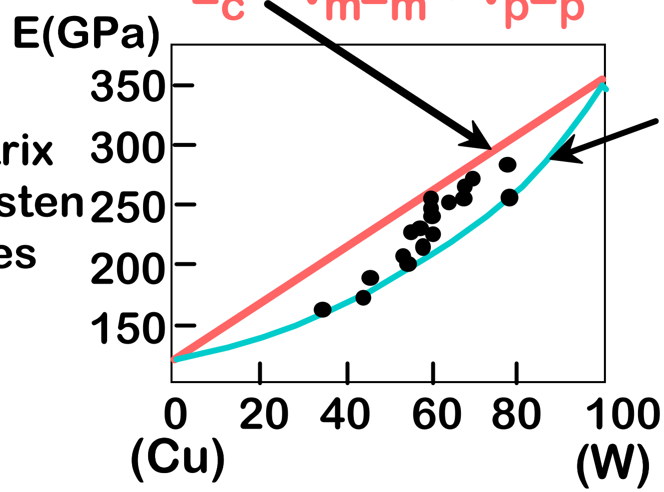
Particle-reinforced | Fiber-reinforced | Structural

- Elastic modulus, E_c, of composites:
  -- two approaches.

upper limit: “rule of mixtures”

$$E_c = V_m E_m + V_p E_p$$

Data:
Cu matrix
w/tungsten
particles



lower limit:

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_p}{E_p}$$

Adapted from Fig. 16.3, *Callister 6e*. (Fig. 16.3 is from R.H. Krock, *ASTM Proc*, Vol. 63, 1963.)

- Application to other properties:
  -- Electrical conductivity, σ_e: Replace E by σ_e.
  -- Thermal conductivity, k: Replace E by k.

COMPOSITE SURVEY: Fiber-I

Particle-reinforced | **Fiber-reinforced** | Structural

- **Aligned Continuous** fibers
- **Examples:**

--Metal: γ'(Ni_3Al)-α(Mo) by eutectic solidification.

matrix: α (Mo) (ductile)

Image removed due to copyright restrictions.

2μm

fibers: γ' (Ni_3Al) (brittle)

From W. Funk and E. Blank, "Creep deformation of Ni3Al-Mo in-situ composites", *Metall. Trans. A* Vol. 19(4), pp. 987-998, 1988. Used with permission.

--Glass w/SiC fibers formed by glass slurry

E_{glass} = 76GPa; E_{SiC} = 400GPa.

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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-II

Particle-reinforced | **Fiber-reinforced** | Structural

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

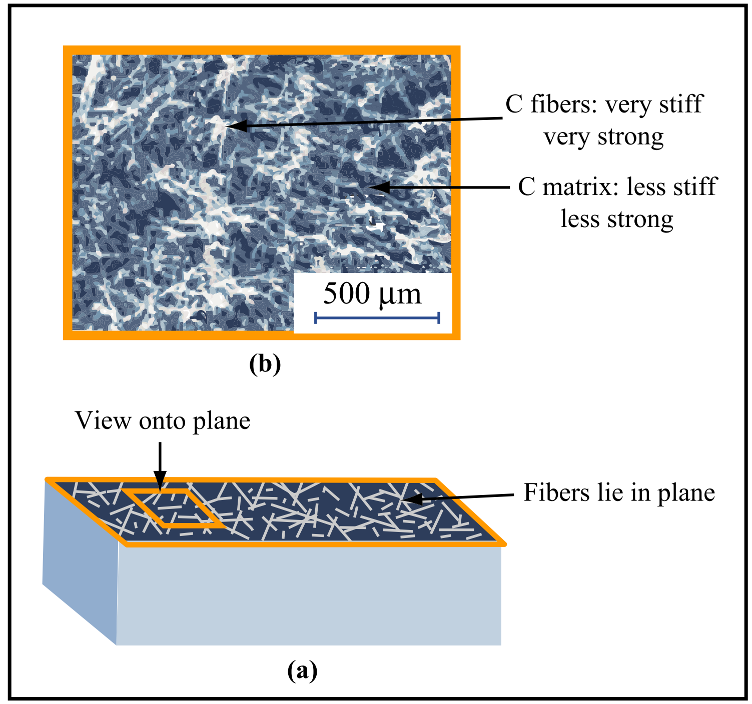


Figure by MIT OpenCourseWare.

Adapted from F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. (a) Fig. 4.24(a), p. 151; (b) Fig. 4.24(b) p. 151.

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

COMPOSITE SURVEY: Fiber-III

Particle-reinforced | **Fiber-reinforced** | Structural

- **Critical fiber length for effective stiffening & strengthening:**

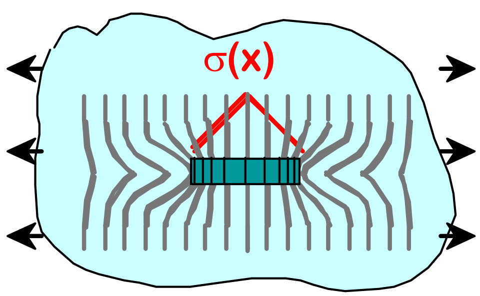
$$\text{fiber length} > 15\frac{\sigma_f d}{\tau_c}$$

- σ_f: fiber strength in tension
- d: fiber diameter
- τ_c: shear strength of fiber-matrix interface

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

Shorter, thicker fiber:

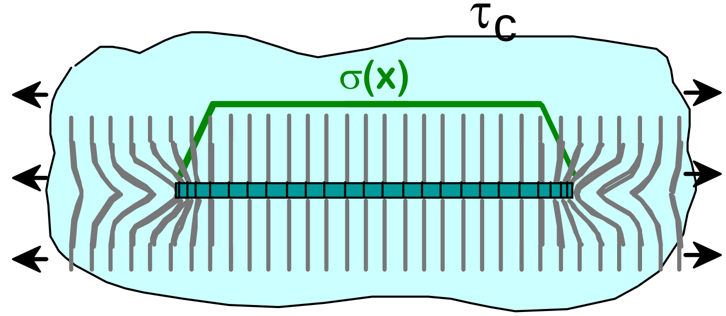
$$\text{fiber length} < 15\frac{\sigma_f d}{\tau_c}$$



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 6e.*

COMPOSITE SURVEY: Fiber-IV

Particle-reinforced | **Fiber-reinforced** | Structural

- **Estimate of E_c and TS:**

  --valid when fiber length $> 15 \frac{\sigma_f d}{\tau_c}$

  -- Elastic modulus in fiber direction:

$$E_c = E_m V_m + K E_f V_f$$

efficiency factor:

--aligned 1D: K = 1 (anisotropic)
--random 2D: K = 3/8 (2D isotropy)
--random 3D: K = 1/5 (3D isotropy)

Values from Table 16.3, *Callister 6e*. (Source for Table 16.3 is H. Krenchel, *Fibre Reinforcement*, Copenhagen: Akademisk Forlag, 1964.)

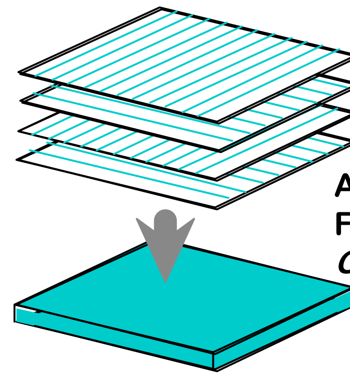
--TS in fiber direction:

$$(TS)_c = (TS)_m V_m + (TS)_f V_f$$ **(aligned 1D)**

COMPOSITE SURVEY: Structural

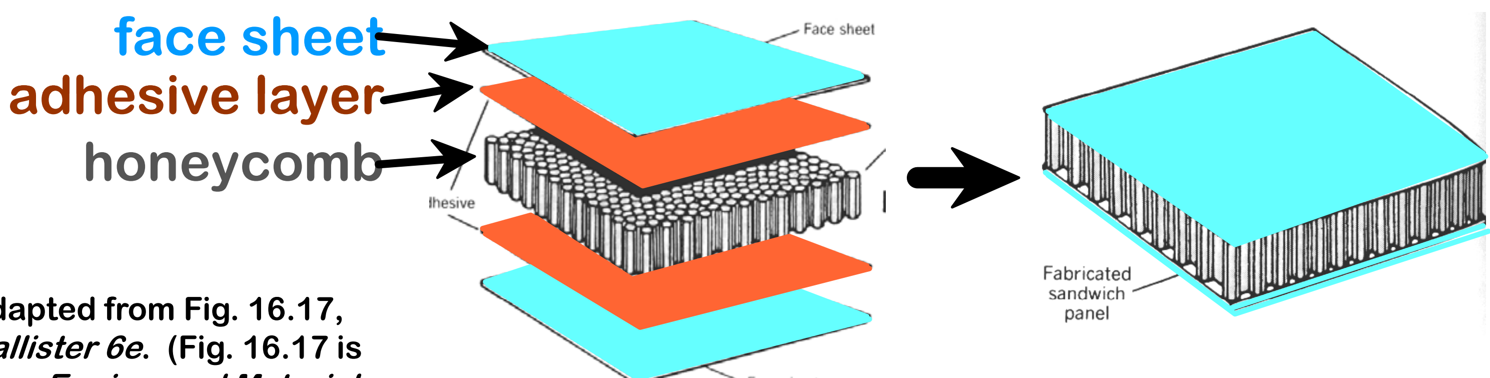
Particle-reinforced | Fiber-reinforced | **Structural**

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



Adapted from Fig. 16.16, *Callister 6e*.

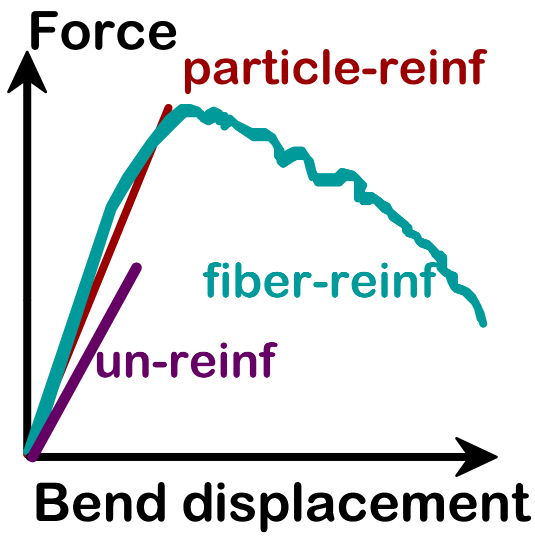
- **Sandwich panels**
  - -- low density, honeycomb core
  - -- benefit: small weight, large bending stiffness



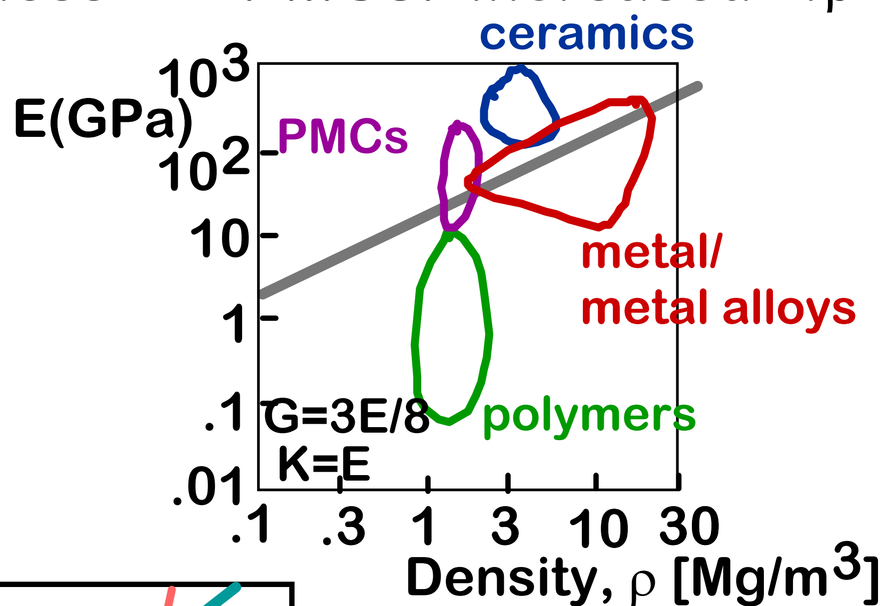
Adapted from Fig. 16.17, *Callister 6e*. (Fig. 16.17 is from *Engineered Materials Handbook*, Vol. 1, *Composites*, ASM International, Materials Park, OH, 1987.

COMPOSITE BENEFITS

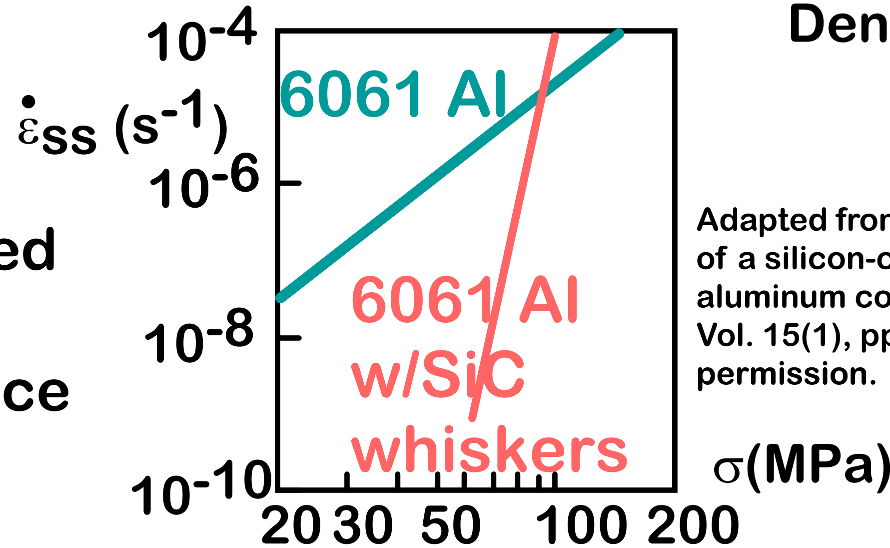
- **CMCs: Increased toughness**



- **PMCs: Increased E/ρ**



- **MMCs: Increased creep resistance**



Adapted from T.G. Nieh, "Creep rupture of a silicon-carbide reinforced aluminum composite", *Metall. Trans. A* Vol. 15(1), pp. 139-146, 1984. Used with permission.

SUMMARY

- Composites are classified according to:
  -- the matrix material (CMC, MMC, PMC)
  -- the reinforcement geometry (particles, fibers, layers).
- Composites enhance matrix properties:
  -- MMC: enhance σ_y, TS, creep performance
  -- CMC: enhance K_c
  -- PMC: enhance E, σ_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.