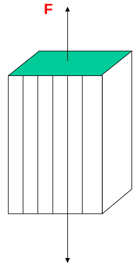
Class 2: Mechanical Properties of Fiber Reinforced Composites



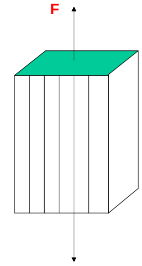
PRIME Modules
Project-based Resources for Introduction to Materials Engineering

Composites are classified by the shape and arrangement of the dispersed phase

The dispersed phase is defined by the shape
- particle
- structural
- fiber

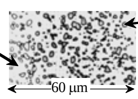
The mechanical properties of each composite are influenced by the amount and arrangement of the dispersed phase

Fiber reinforced polymer for civil infrastructures use continuous fibers in a polymer matrix. We are going to be focusing on this type of composite



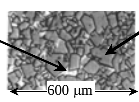
Cement and tires are examples of particle reinforced composites

-Spheroidite steel — matrix: ferrite (α) (ductile); particles: cementite (Fe_3C) (brittle)



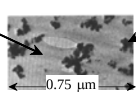
Adapted from Fig. 10.10, *Callister 6e.* (Fig. 10.10 is copyright United States Steel Corporation, 1971.)

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



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

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



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

Overhead adapted from Callister

The Young's modulus in particle reinforced composites is determined by the rule of mixing

The rule of mixing states the actual Young's modulus in a particle reinforced composite is between and upper and lower bound.

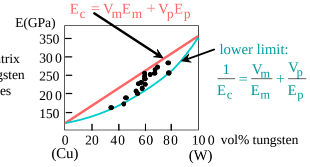
upper limit: "rule of mixtures"

$$E_c = V_m E_m + V_p E_p$$

lower limit:

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

Data: Cu matrix w/tungsten particles

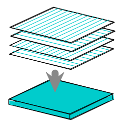


Adapted from Fig. 16.3, *Callister 6e.* (Fig. 16.3 is from R.H. Krock, *ASTM Proc*, Vol. 63, 1963.)

Overhead adapted from Callister

Structural composites are made up of layers or panels

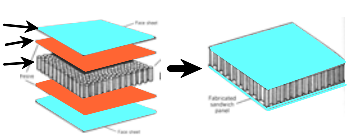
Ex: Stacked and bonded fiber-reinforced sheets
- -- stacking sequence: e.g., 0/90
- -- benefit: balanced, in-plane stiffness



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

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

face sheet
adhesive layer
honeycomb



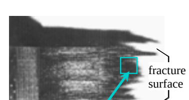
Adapted from Fig. 16.17, *Callister 6e.* (Fig. 16.17 is from *Engineered Materials Handbook*, Vol. 1, *Composites*, ASM International, Materials Park, OH, 1987.

Overhead adapted from Callister

Fiber reinforced composites can be continuous or discontinuous

Aligned Continuous fibers
Ex: Glass w/SiC fibers
E_{glass} = 76GPa; E_{SiC} = 400GPa.

(a)

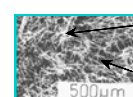


(b)

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.

Discontinuous, random 2D fibers
Ex: C fibers in a C matrix

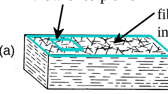
(b)



view onto plane

C fibers: very stiff very strong
C matrix: less stiff less strong
fibers lie in plane

(a)



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. (Courtesy I.J. Davies) Reproduced with permission of CRC Press, Boca Raton, FL.

Overhead adapted from Callister

In continuous fibers strain is constant for the fiber and matrix and stress is the sum

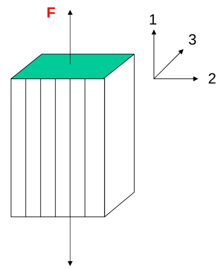
In aligned continuous fibers, the strain of the overall composite, the fiber, and the matrix are all equal.

$\varepsilon_C = \varepsilon_F = \varepsilon_M$

The stress supported by the composite is the sum of the stress supported by the fiber and matrix

$F_C = F_F + F_M$

$\sigma_C = \sigma_F + \sigma_M$



In longitudinal loading, the modulus of elasticity of the composite is the weighted sum of the fiber and matrix.

In aligned, continuous fibers, when the force is applied in the direction of the fiber (1, longitudinal loading)

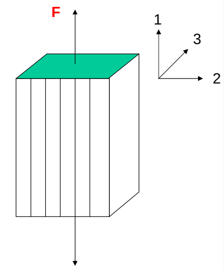
Volume fraction

$$\sigma_C = \sigma_M V_M + \sigma_F V_F$$

$$\frac{\sigma_C}{\varepsilon_C} = \frac{\sigma_M}{\varepsilon_M} V_M + \frac{\sigma_F}{\varepsilon_F} V_F$$

$$E_{C,L} = E_{C,1} = E_M V_M + E_F V_F = E_{max}$$

This only applies in the range when both components are behaving elastically



In transverse loading, the modulus of elasticity of the composite is limited by the lower of the components.

In aligned, continuous fibers, when the force is applied perpendicular to the fiber (2, transverse loading)

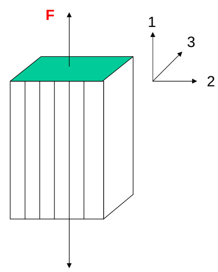
$$\sigma_C = \sigma_M = \sigma_F$$

$$\varepsilon_C = \varepsilon_M V_M + \varepsilon_F V_F$$

$$\frac{\sigma}{E_{C,T}} = \frac{\sigma}{E_M} V_M + \frac{\sigma}{E_F} V_F$$

$$E_{C,T} = E_{C,2} = \frac{E_M E_M}{V_M E_F + V_F E_M}$$

This only applies in the range when both components are behaving elastically

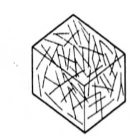


When the fibers are not aligned, the modulus is a fraction of the aligned value

Random-in-the-plane

$$E_{C,1} = E_{C,2} \approx \frac{3}{8} E_{max}$$

Aligned, longitudinal value

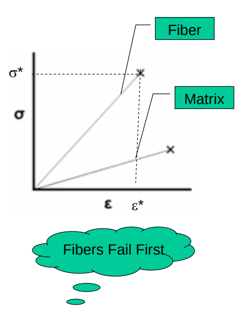


Random in 3 dimensions

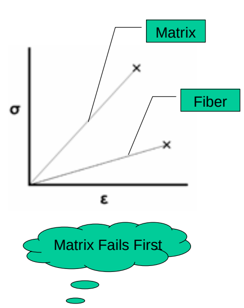
$$E_{C,1} = E_{C,2} = E_{C,3} \approx \frac{1}{5} E_{max}$$

In longitudinal loading, the overall strain is limited by the component with the least strain at failure

Case 1:



Case 2:



In case 1, the composite fails when the fiber fails if there is a significant amount of fiber

Case 1:

At low V_F:

$$\sigma_1^* = V_M \sigma_M^*$$

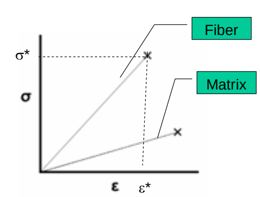
Matrix carries the load beyond fiber failure

At high VF:

$$\sigma_1^* = V_F \sigma_F^* + V_M \sigma_M^{'}$$

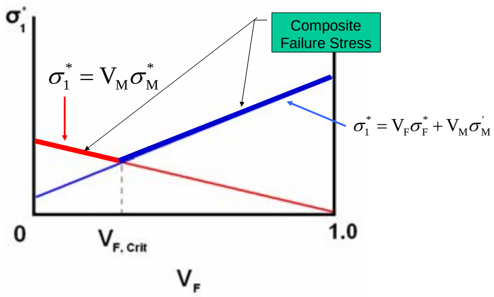
Stress in matrix when fibers fail

Composite failure when fiber fails



The critical volume of fiber for reinforcement depends on comparing the 2 σ_1* values

Case 1



$V_{F,crit}$ = Minimum V_F for reinforcement

In case 2, the composite fails when the matrix fails unless there is a significant amount of fiber

Case 2:

At low V_F:

Stress in fiber when matrix fails

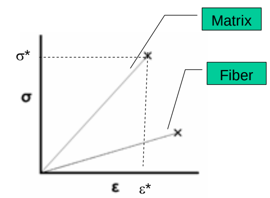
$\sigma_1^* = V_F \sigma_F^{'} + V_M \sigma_M^*$

Composite fails when matrix fails

At high VF:

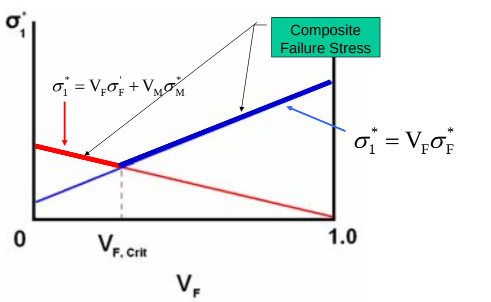
$\sigma_1^* = V_F \sigma_F^*$

Fiber carries the load beyond matrix failure



The critical volume of fiber for reinforcement depends on comparing the 2 σ_1* values

Case 2



$V_{F,crit}$ = Minimum V_F for reinforcement

In summary, the mechanical properties of the composite depend on the type and arrangement of the reinforcement

In particle reinforced composites, the modulus of elasticity has upper and lower bounds determined by the rule of mixing

In fiber reinforced composites, the modulus of elasticity, tensile strength, and strain at fracture depend on whether the fibers are continuous and how the aligned relative to the applied force