Objectives

- Definitions in composite materials
  - dispersed phase, matrix
- Structure of composites
  - particle-reinforced
  - fiber reinforced
  - structural composites

Introduction

- Engineering applications often require unusual combinations of properties
  - esp. aerospace, underwater, and transportation
  - can’t be achieved with a single material
  - e.g. - aerospace requires strong, stiff, light, and abrasion resistant material
    - most strong, stiff materials are dense and heavy
    - most light materials are not abrasion resistant
- Solution is in composite materials

Definition of Composite Materials

- Multiphase material
  - usually exhibits properties of both phases
  - usually improves performance over either individual phase
- Composites have already been discussed
  - multiphase metal alloys, or ceramics or polymers
  - example, pearlitic steels, alt. layers α + Fe_3C
- There are also composites spanning materials classes (e.g. ceramic and metals)

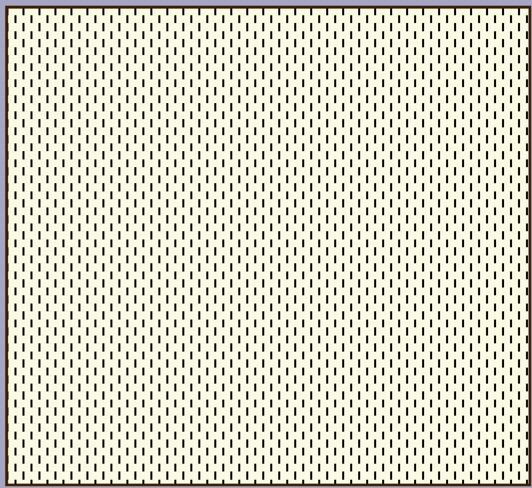
Examples of Composites

- Natural
  - Wood
    - flexible cellulose fibers held together with stiff lignin
  - Bone
    - strong protein collagen and hard, brittle apatite
- Artificial (man-made)
  - constituent phases are chemically distinct

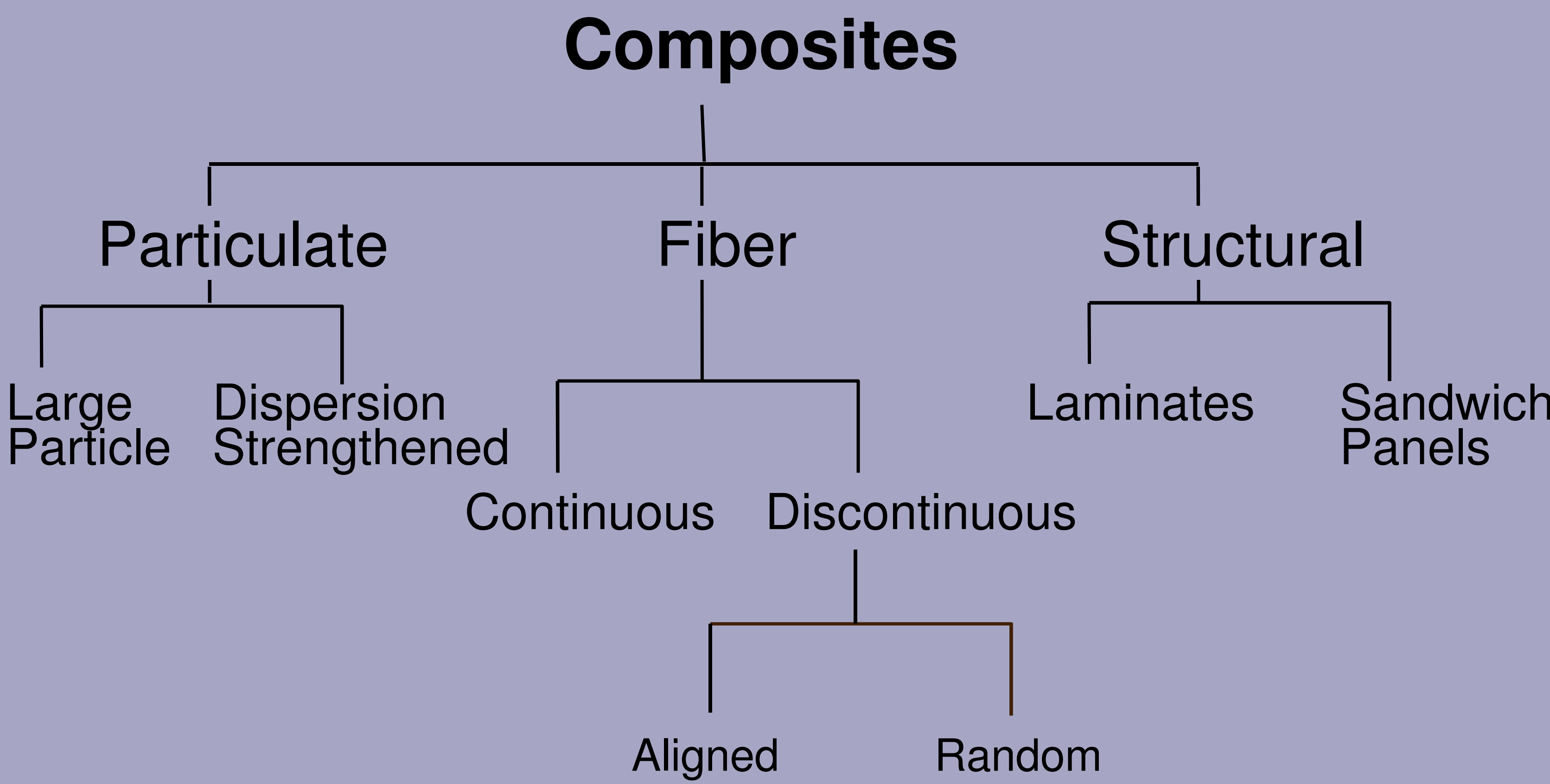
Definitions

- Composites often have only two phases
- <u>Matrix phase</u>
  - continuous - surrounds other phase
- <u>Dispersed phase</u>
  - discontinuous phase

Matrix (light)
Dispersed phase (dark)



Classification of Artificial Composites



Properties of Composites

Dependent on:

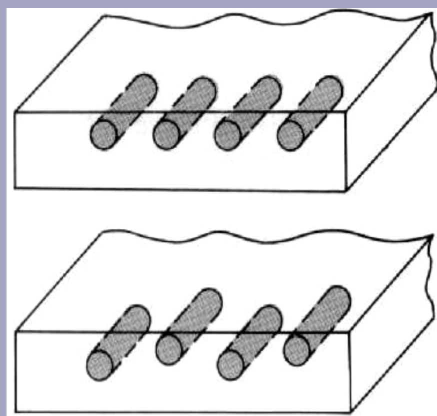
- constituent phases
- relative amounts
- geometry of dispersed phase
  - shape of particles
  - particle size
  - particle distribution
  - particle orientation

Composite Parameters

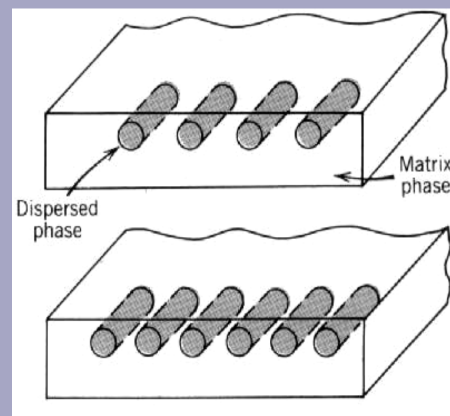
For a given matrix/dispersed phase system:

- Concentration
- Size
- Shape
- Distribution
- Orientation

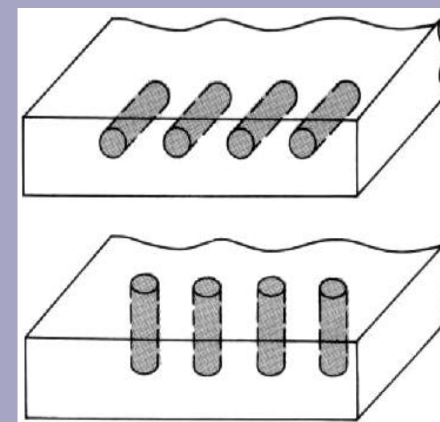
Parameters



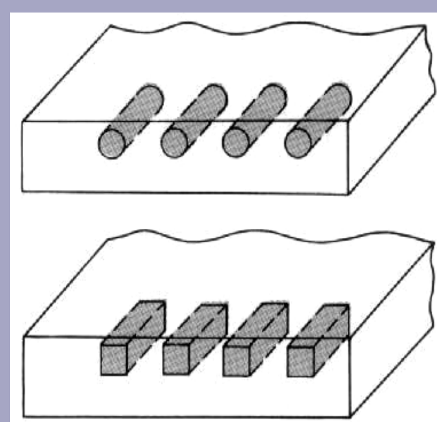
Distribution



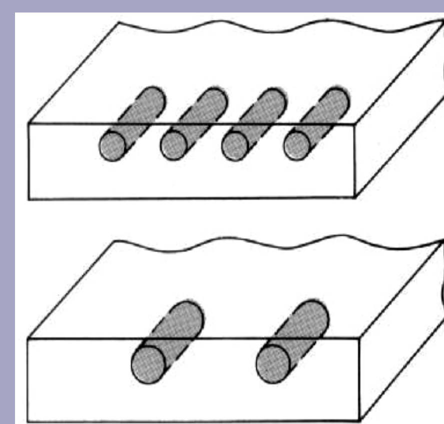
Concentration



Orientation

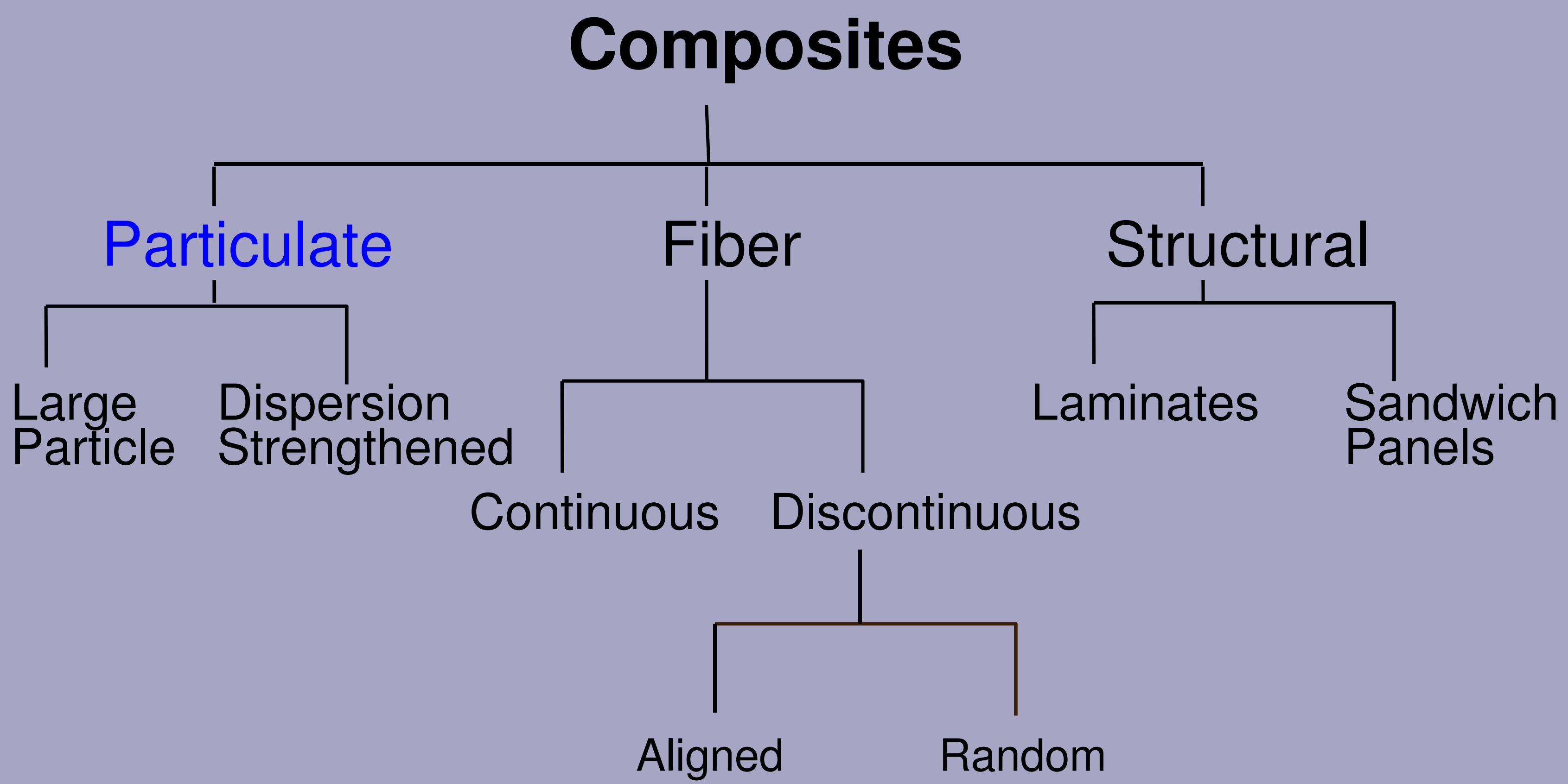


Shape



Size

Classification of Artificial Composites



Particle-Reinforced Composites

- Divided into two classes
  - (based on strengthening mechanism)
- Large particle
  - interaction between particles and matrix are not on the atomic or molecular level
  - particle/matrix interface strength is critical
- Dispersion strengthened
  - 0.01-0.1 μm particles
  - inhibit dislocation motion

Large Particle Composites

Examples:

- Some polymers with added fillers are really large particle composites
- Concrete (cement with sand or gravel)
  - cement is matrix, sand is particulate

Large Particle Composites

Desired Characteristics

- Particles should be approximately equiaxed
- Particles should be small and evenly distributed
- Volume fraction dependent on desired properties

Volume Fraction in Large Particle Composites

- Elastic modulus is dependent on the volume fraction
- "Rule of mixtures" equation
  - E- elastic modulus, V- volume fraction, m- matrix, p- particulate
  - upper bound

$$E_c = E_m V_m + E_p V_p$$

  - lower bound

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

Rule of Mixtures

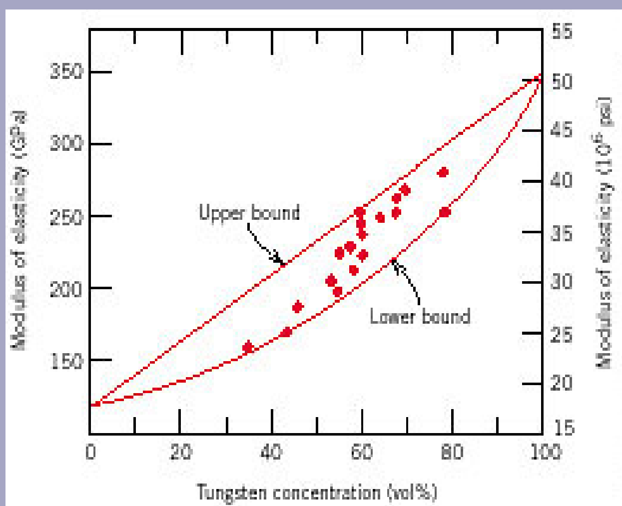
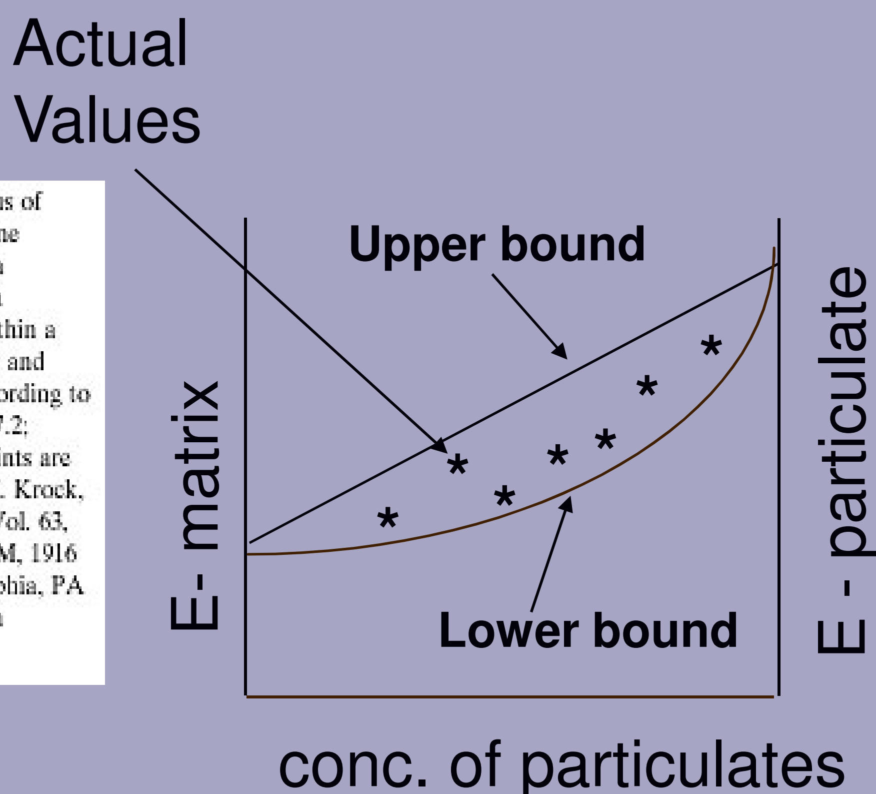


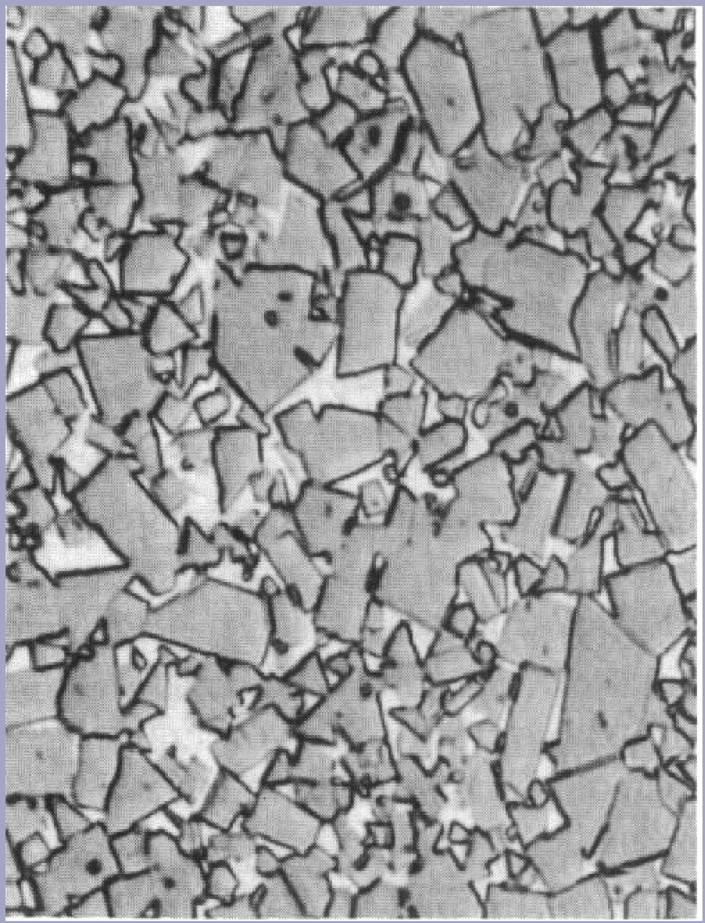
FIGURE 17.3 Modulus of elasticity versus volume percent tungsten for a composite of tungsten particles dispersed within a copper matrix. Upper and lower bounds are according to Equations 17.1 and 17.2; experimental data points are included. (From R. H. Krock, *ASTM Proceedings*, Vol. 63, 1963. Copyright ASTM, 1916 Race Street, Philadelphia, PA 19103. Reprinted with permission.)



Large-Particle Composite Materials

- All three material types
  - metals, ceramics, and polymers
- CERMET (ceramic-metal composite)
  - cemented carbide (WC, TiC embedded in Cu or Ni)
  - cutting tools (ceramic hard particles to cut, but a ductile metal matrix to withstand stresses)
  - large volume fractions are used (up to 90%!)

CERMET Cutting Tool



Light phase - Matrix (Cobalt)

Dark phase- Particulate (WC)

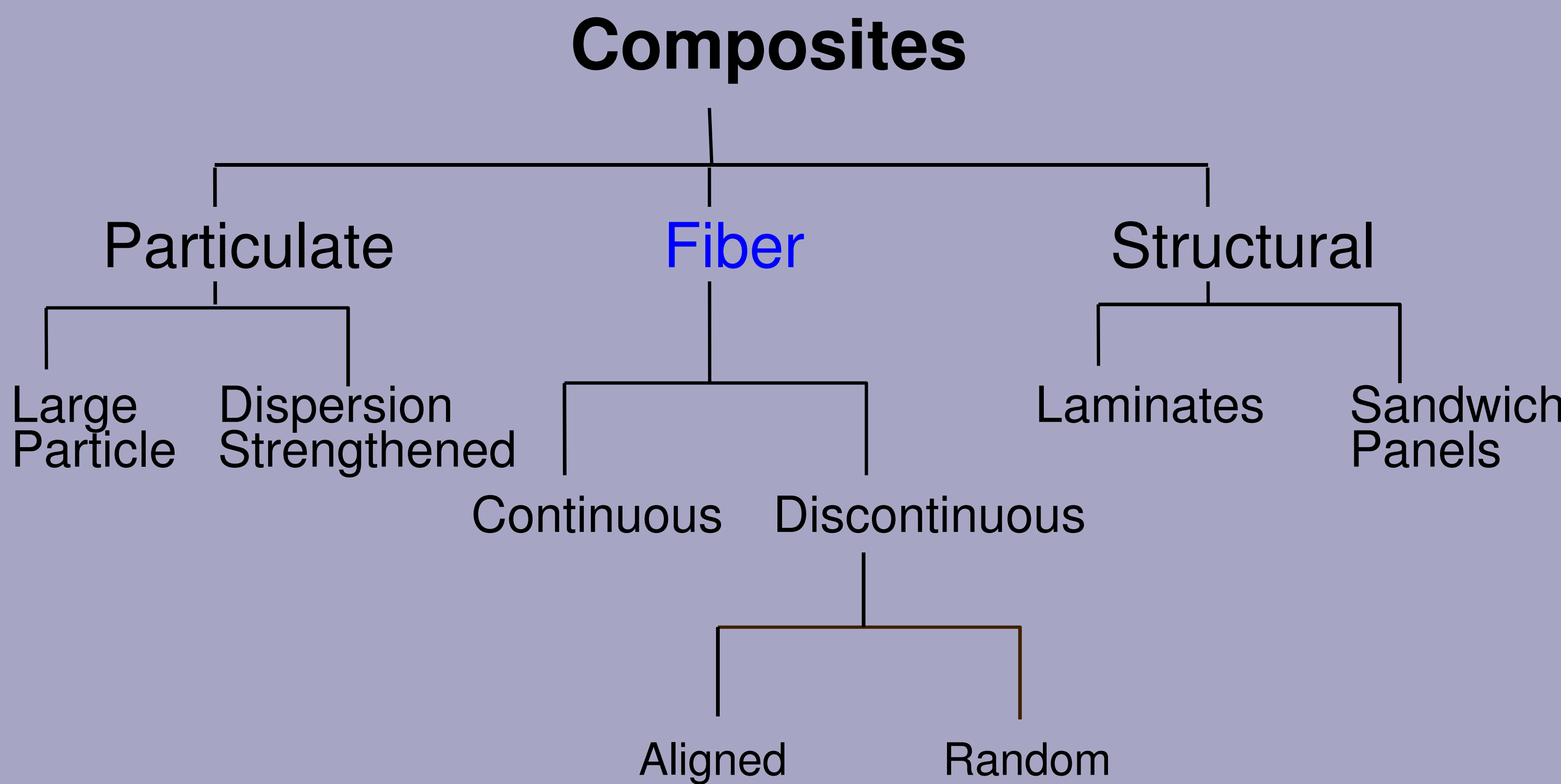
Large Particle Composites Concrete

- Concrete is **<u>not</u>** cement)
  - Concrete is the composite of cement and an aggregate (fine sand or coarse gravel)
- Reinforced concrete
  - a composite (large particle composite) - with a matrix which is a composite
  - steel rods, wires, bars (rebar, sometimes stretched elastically while concrete dries to put system in compression)

Dispersion Strengthened Composites

- Metals and metal alloys
  - hardened by uniform dispersion of fine particles of a very hard material (usually ceramic)
- Strengthening occurs through the interactions of dislocations and the particulates
- Examples
  - Thoria in Ni
  - Al/Al_2O_3 sintered aluminum powder SAP
  - GP zones in Al

Classification of Artificial Composites



Fiber-Reinforced Composites

- Technologically, the most important type of composite
- Characterized in terms of specific strength or specific modulus = strength (or E) per weight
  - usually want to maximize specific strength and modulus
- Subclasses:
  - Short fiber and continuous fiber lengths

Fiber Phase

Requirements for the fiber

- The small diameter fiber must be much stronger than the bulk material
- High tensile strength

Different classifications

- whiskers (single crystal - large aspect ratio)
- fibers (polycrystalline or amorphous)
- wires (large diameters - usually metal)

Matrix Phase

Function

- Binds fibers together
- Acts as a medium through which externally applied stress is transmitted and distributed to the fibers
- Protects fiber from surface damage
- Separates fibers and prevents a crack from one fiber from propagating through another

Matrix Phase

Requirements

- Ductile
- Lower E than for fiber
- Bonding forces between fiber and matrix must be high
  - otherwise fiber will just “pull-out” of matrix
- Generally, only polymers and metals are used as matrix material (they are ductile)

Influence of Fiber Length

- Mechanical properties depend on:
  - mechanical properties of the fiber
  - how much load the matrix can transmit to the fiber
    - depends on the interfacial bond between the fiber and the matrix

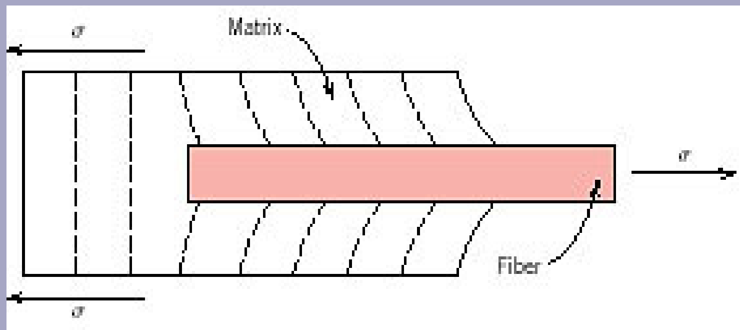


FIGURE 17.6 The deformation pattern in the matrix surrounding a fiber that is subjected to an applied tensile load.

- Critical fiber length - depends on
  - fiber diameter, fiber tensile strength
  - fiber/matrix bond strength

Influence of Fiber Length

- Critical fiber length - l_c
  - "Continuous" fibers $l >> 15\ l_c$
  - "Short" fibers are anything shorter $15\ l_c$

$$l_c = \sigma_f d / 2\tau_c$$

where

d = fiber diameter
τ_c = fiber-matrix bond strength
σ_f = fiber yield strength

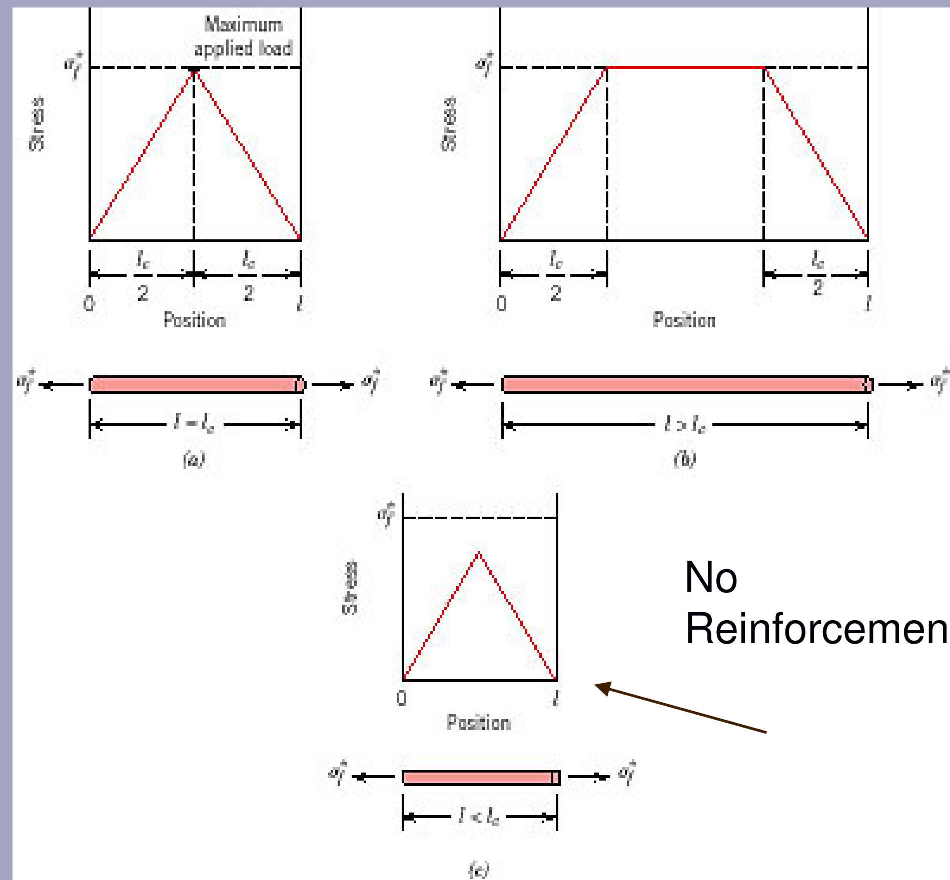


FIGURE 17.7 Stress–position profiles when fiber length l (a) is equal to the critical length l_c, (b) is greater than the critical length, and (c) is less than the critical length for a fiber-reinforced composite that is subjected to a tensile stress equal to the fiber tensile strength σ_f^*.

Influence of Fiber Orientation

- Fiber parameters
  - arrangement with respect to each other
  - distribution
  - concentration
- Fiber orientation
  - parallel to each other
  - totally random
  - some combination

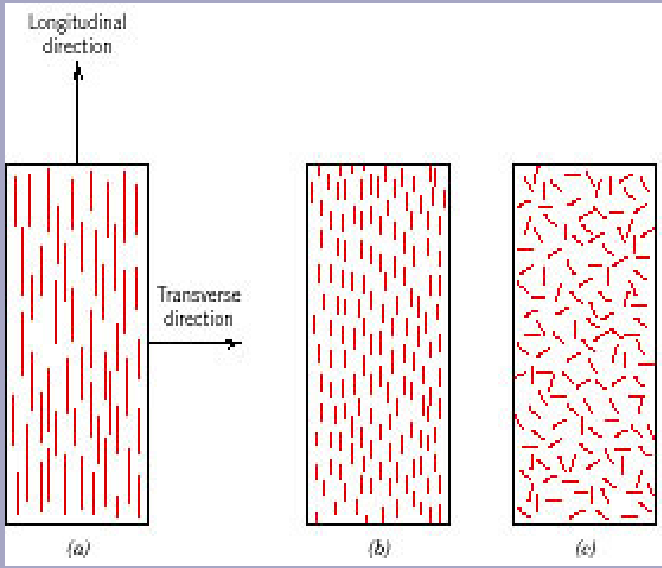
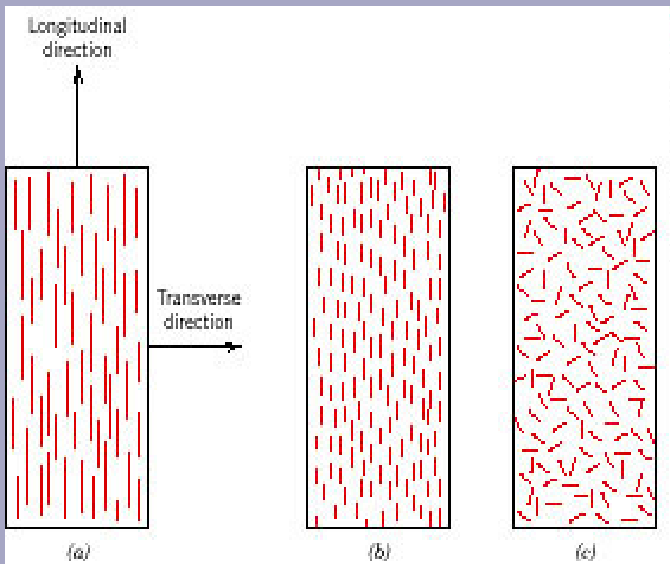


FIGURE 17.8 Schematic representations of (*a*) continuous and aligned, (*b*) discontinuous and aligned, and (*c*) discontinuous and randomly oriented fiber-reinforced composites.

Influence of Fiber Orientation



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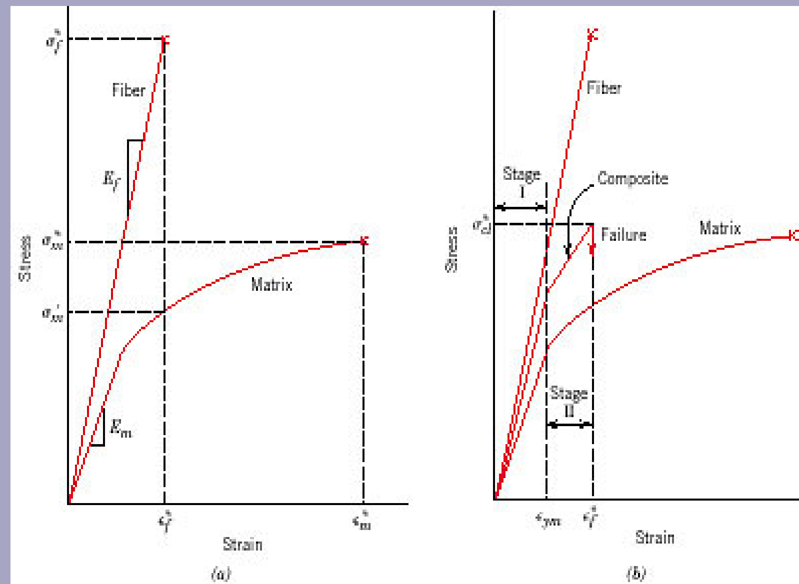


FIGURE 17.9 (*a*) Schematic stress–strain curves for brittle fiber and ductile matrix materials. Fracture stresses and strains for both materials are noted. (*b*) Schematic stress–strain curve for an aligned fiber-reinforced composite that is exposed to a uniaxial stress applied in the direction of alignment; curves for the fiber and matrix materials shown in part (*a*) are also superimposed.

- Stage I - elastic deformation with intermediate
- Stage II - matrix yields
- Failure - Non-catastrophic. When fibers fracture, you now have new fiber length and matrix is still present

Aligned Fibers

- **When fibers are aligned**
  - properties of material are highly anisotropic
  - modulus in direction of alignment is a function of the volume fraction of the E of the fiber and matrix
  - modulus perpendicular to direction of alignment is considerably less (the fibers do not contribute)

Randomly Oriented Fibers

- Properties are isotropic
  - not dependent on direction
- Ultimate tensile strength is less than for aligned fibers
- May be desirable to sacrifice strength for the isotropic nature of the composite

Fiberglass Reinforced Composites

Glass is a common reinforcement

- it is easily drawn into fibers
- it is cheap and readily available
- it is easy to process into composites
- it can produce very strong, very light composites (high specific strength)
- it is usually chemically inert (does not degrade in harsh environments)

Elastic Behavior Derivation
(Longitudinal Loading)

Consider longitudinal loading of continuous fibers, with good fiber/matrix bonding. under these conditions matrix strain = fiber strain (isostrain condition).

$$\varepsilon_m = \varepsilon_f = \varepsilon_c$$

The total load on the composite, F_c, is then equal to loads carried by the matrix and the fibers

$$F_c = F_m + F_f$$

Substituting for the stresses

$$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f$$

Rearranging

$$\sigma_c = \sigma_m A_m/A_c + \sigma_f A_f/A_c$$

were A_m/A_c and A_f/A_c are the area fractions of matrix and fibers, respectively. If the fiber length are all equal than then these terms are equivalent to the volume fractions

$$V_f = A_f/A_c \quad \& \quad V_m = A_m/A_c$$

$$\sigma_c = \sigma_m V_m + \sigma_f V$$

Using the isostrain constraint and Hookes Law, $\sigma = \varepsilon E$

$$E_c = E_m V_m + E_f V_f$$

Can also show ratio of load carried by fiber and matrix:
$F_f/F_m = E_f V_f / E_m V_m$
$F_c = F_f + F_m$

Elastic Behavior Derivation

(Transverse Loading)

Consider transverse loading of continuous fibers, with good fiber/matrix bonding. under these conditions matrix strain = fiber strain (isostress condition).

$$\sigma_m = \sigma_f = \sigma_c = \sigma$$

The total strain of the composite is given by

$$\varepsilon_c = \varepsilon_m V_m = \varepsilon_f V_f$$

Using Hookes Law $\varepsilon = \sigma/E$ and the isostress constraint

$$\sigma/E_c = (\sigma/E_m) V_m + (\sigma/E_f) V_f$$

Dividing by σ, Algebraically this becomes

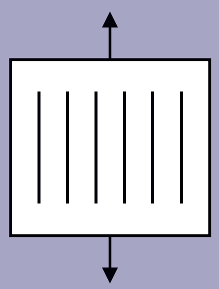
$$E_c = \frac{E_m E_f}{E_f V_m + E_m V_f}$$

Volume Fraction in Fiber Composites

- Elastic modulus is dependent on the volume fraction of fibers
- "Rule of mixtures" equation (again)
  - E - elastic modulus, V- volume fraction, m- matrix, f- fiber
  - upper bound

(iso-strain)

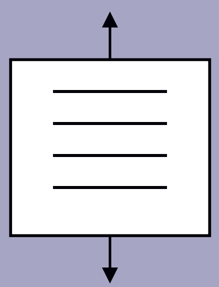
$$E_c = E_m V_m + E_f V_f$$



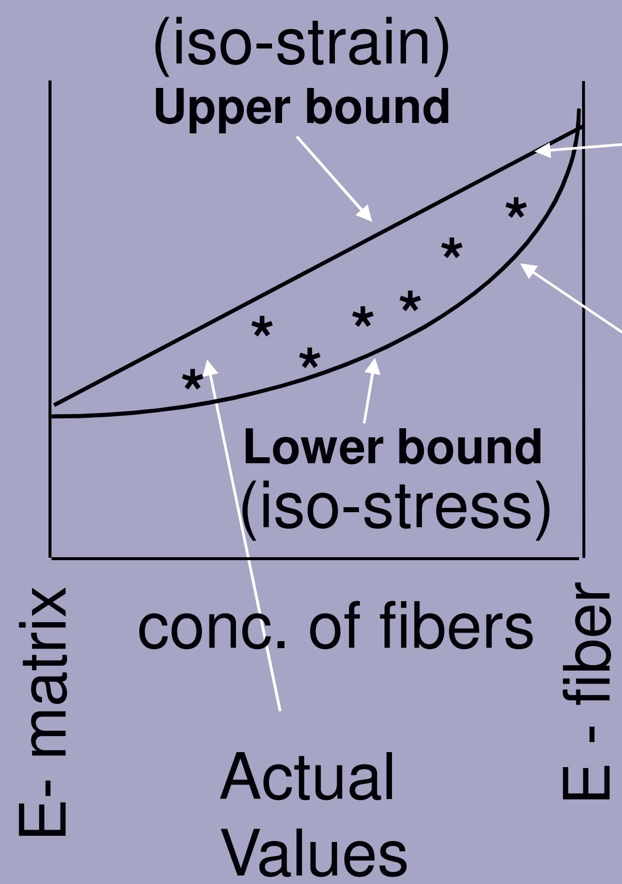
  - lower bound

(iso-stress)

$$E_c = \frac{E_m E_f}{E_f V_m + E_m V_f}$$



Rule of Mixtures



$$E_c = E_m V_m + E_f V_f$$

$$E_c = \frac{E_m E_f}{E_f V_m + E_m V_f}$$

Example

- Calculate the composite modulus for polyester reinforced with 60 vol% E-glass under iso-strain conditions.
  - $E_{polyester} = 6.9 \times 10^3$ MPa
  - $E_{E\text{-}glass} = 72.4 \times 10^3$ MPa

$$E_c = (0.4)(6.9\times10^3 \text{ MPa}) + (0.6)(72.4\times10^3 \text{ MPa})$$
$$= 46.2 \times 10^3 \text{ MPa}$$

In Class Example

A continuous and aligned glass reinforced composite consists of 40 vol% glass fiber having E = 69 GPa and a polyester resin matrix, that when hardened, has E = 3.4 GPa.

a) Compute modulus of elasticity under longitudinal and transverse loading.

b) If the cross-sectional area is 250 mm^2 and a stress of 50 MPa is applied longitudinally, compute magnitude of load carried by each the fiber and matrix phases.

c) Determine strain on each phase in c

Other Composite Properties

- In general, the rule of mixtures (for upper and lower bounds) can be used for any property X_c - thermal conductivity, density, electrical conductivity…etc.

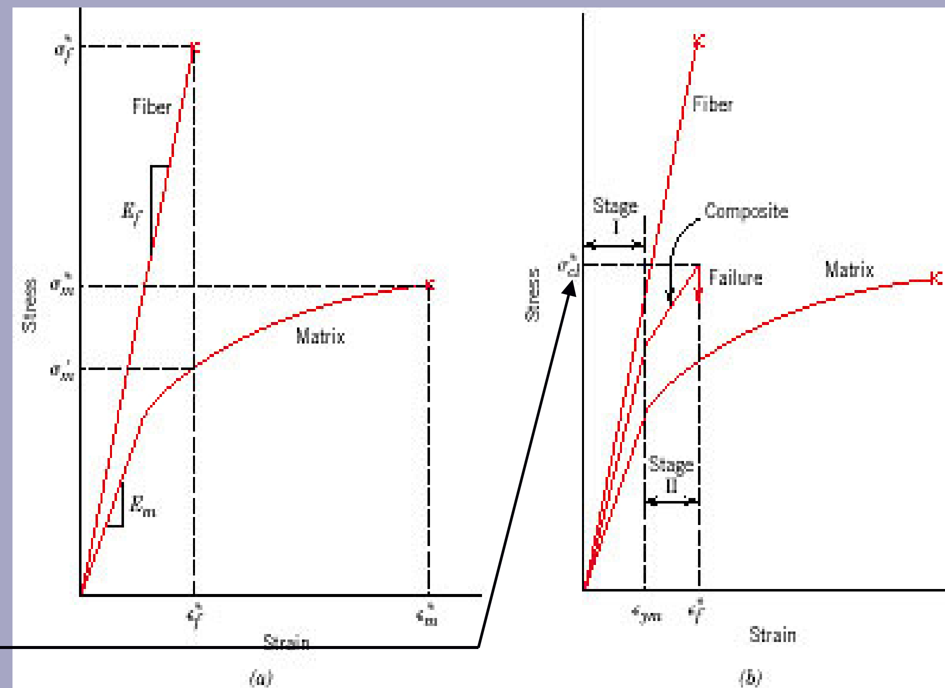
$$X_c = X_m V_m + X_f V_f$$

$$X_c = X_m X_f / (V_m X_f + V_f V_m)$$

Tensile Strength

- In longitudinal direction, the tensile strength is given by the equation below if we assume the fibers will fail before the matrix:

$$\sigma^*_c = \sigma'_m V_m + \sigma'_f V_f$$



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Discontinuous Fibers

- Aligned

$$\sigma^*_c = \sigma^*_f V_f (1 - l_c/2l) + \sigma'_m V_m \qquad \text{for} \quad l > l_c$$

$$\sigma^*_c = (l\tau_c/d) V_f + \sigma'_m V_m \qquad \text{for} \quad l < l_c$$

- Random

$$E_c = K E_f V_f + E_m V_m \qquad \text{where } K \sim 0.1 \text{ to } 0.6$$

Table 17.3 Reinforcement Efficiency of Fiber-Reinforced Composites for Several Fiber Orientations and at Various Directions of Stress Application

Fiber Orientation	*Stress Direction*	*Reinforcement Efficiency*
All fibers parallel	Parallel to fibers	1
	Perpendicular to fibers	0
Fibers randomly and uniformly distributed within a specific plane	Any direction in the plane of the fibers	$\frac{3}{8}$ 3/8
Fibers randomly and uniformly distributed within three dimensions in space	Any direction	$\frac{1}{5}$ 1/5

Source: H. Krenchel, *Fibre Reinforcement,* Copenhagen: Akademisk Forlag, 1964 [33].

Fiber and Matrix Phases

- Fibers
  - whiskers: flawless, large l/d ratio, very strong
  - fiber
  - wires
- Matrix
  - polymer or metal-matrix: used for their ductility
    - bind fibers, transmits load to fibers
    - matrix should be more ductile, fiber should have higher E
    - matrix protects fibers from surface damage (cracks)
    - matrix prevents cracks propagating from one fiber to the next which could cause catastrophic failure.
  - ceramics-matrix: used to increase fracture toughness of ceramic
- Essential that Fiber-Matrix bond be strong

Fiber and Matrix Phases

Table 17.4 Characteristics of Several Fiber-Reinforcement Materials

Material	*Specific Gravity*	*Tensile Strength [GPa (10^6 psi)]*	*Specific Strength (GPa)*	*Modulus of Elasticity [GPa (10^6 psi)]*	*Specific Modulus (GPa)*
		Whiskers			
Graphite	2.2	20 (3)	9.1	700 (100)	318
Silicon nitride	3.2	5–7 (0.75–1.0)	1.56–2.2	350–380 (50–55)	109–118
Aluminum oxide	4.0	10–20 (1–3)	2.5–5.0	700–1500 (100–220)	175–375
Silicon carbide	3.2	20 (3)	6.25	480 (70)	150
		Fibers			
Aluminum oxide	3.95	1.38 (0.2)	0.35	379 (55)	96
Aramid (Kevlar 49)	1.44	3.6–4.1 (0.525–0.600)	2.5–2.85	131 (19)	91
Carbon[a]	1.78–2.15	1.5–4.8 (0.22–0.70)	0.70–2.70	228–724 (32–100)	106–407
E-Glass	2.58	3.45 (0.5)	1.34	72.5 (10.5)	28.1
Boron	2.57	3.6 (0.52)	1.40	400 (60)	156
Silicon carbide	3.0	3.9 (0.57)	1.30	400 (60)	133
UHMWPE (Spectra 900)	0.97	2.6 (0.38)	2.68	117 (17)	121
		Metallic Wires			
High-strength steel	7.9	2.39 (0.35)	0.30	210 (30)	26.6
Molybdenum	10.2	2.2 (0.32)	0.22	324 (47)	31.8
Tungsten	19.3	2.89 (0.42)	0.15	407 (59)	21.1

[a] The term "carbon" instead of "graphite" is used to denote these fibers, since they are composed of crystalline graphite regions, and also of noncrystalline material and areas of crystal misalignment.

Polymer-Matrix Composites

- Fibers
  - Glass Fiber - fiberglass
  - Carbon fiber - graphitic and amorphous C
  - Aramid fiber - Kevlar, highly linear polymer chain
- Matrix
  - polyester and vinyl esters - fiberglass
  - epoxies - aerospace applications, stronger, resistant to moisture
  - polyimides - high temperature
  - high temperature thermoplastics - PEEK, PPS, PEI, aerospace

Metal Ceramic-Matrix Composites

Metal-Matrix Composites

Table 17.6 Properties of Several Metal-Matrix Composites Reinforced with Continuous and Aligned Fibers

Fiber	*Matrix*	*Fiber Content (vol%)*	*Density (g/cm^3)*	*Longitudinal Tensile Modulus (GPa)*	*Longitudinal Tensile Strength (MPa)*
Carbon	6061 Al	41	2.44	320	620
Boron	6061 Al	48	—	207	1515
SiC	6061 Al	50	2.93	230	1480
Alumina	380.0 Al	24	—	120	340
Carbon	AZ31 Mg	38	1.83	300	510
Borsic	Ti	45	3.68	220	1270

Source: Adapted from J. W. Weeton, D. M. Peters, and K. L. Thomas, *Engineers' Guide to Composite Materials*, ASM International, Materials Park, OH, 1987.

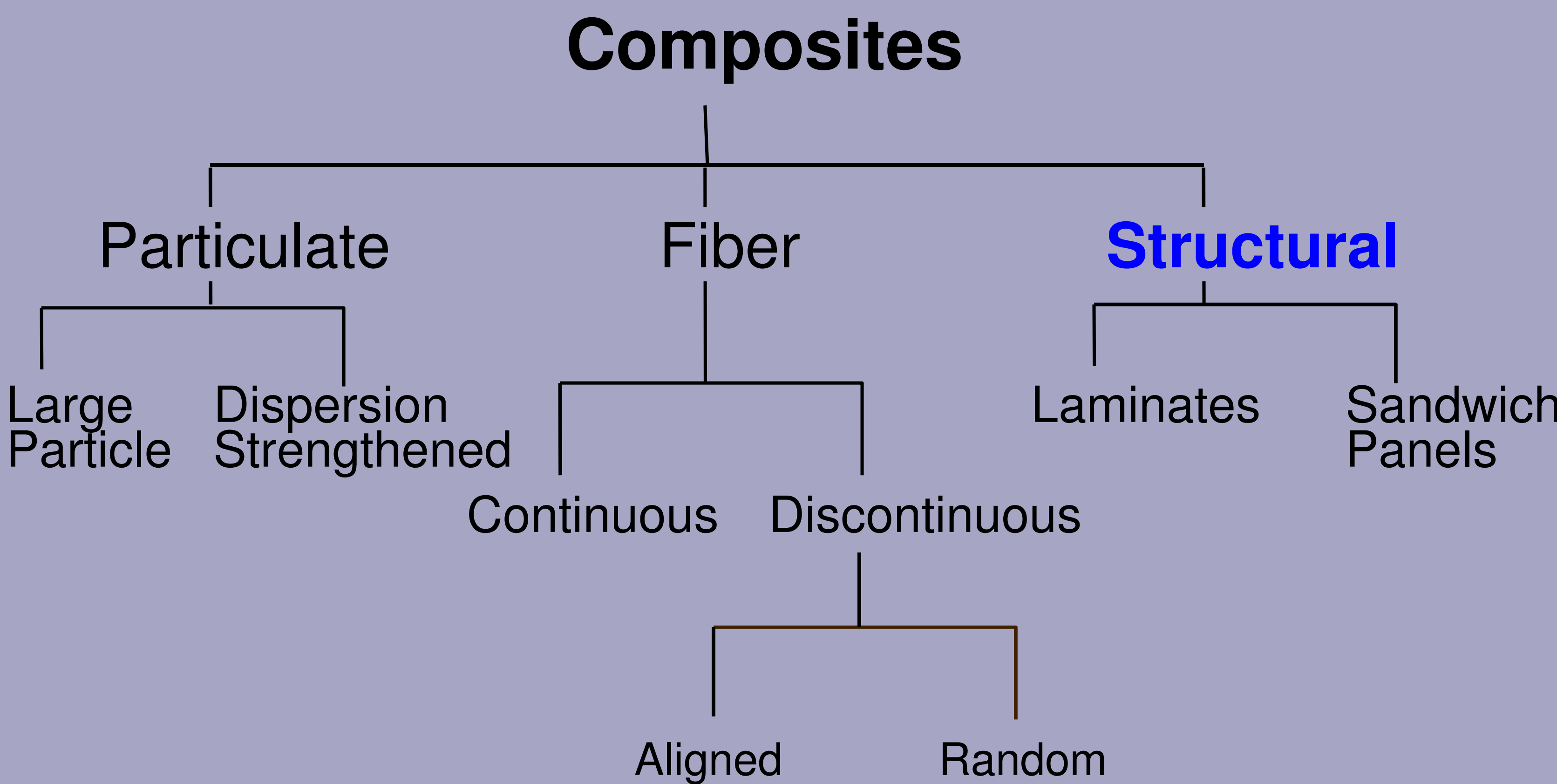
Ceramic-Matrix Composites

Employed to increase the fracture toughness of the ceramic
Example: Transformation toughened zirconia

Other Composites

- Carbon-Carbon Composites
  - carbon fiber in pyrolyzed carbon matrix
  - high tensile strength and modulus at high temperature (2000ºC)
  - low coefficient of thermal expansion
  - high thermal conductivities
  - low thermal shock potential
  - Applications include; rocket motors, friction materials in aircraft, advanced turbine engine components, ablative shields for reentry vehicles
- Hybrid composites
  - two or more different kinds of fibers.

Classification of Artificial Composites



Structural Composites

- Definition
  - composed of both homogeneous and composite materials
  - properties depend on constituent materials and on geometrical design of the elements
- Types
  - laminar composites
  - sandwich panels

Laminar Composites

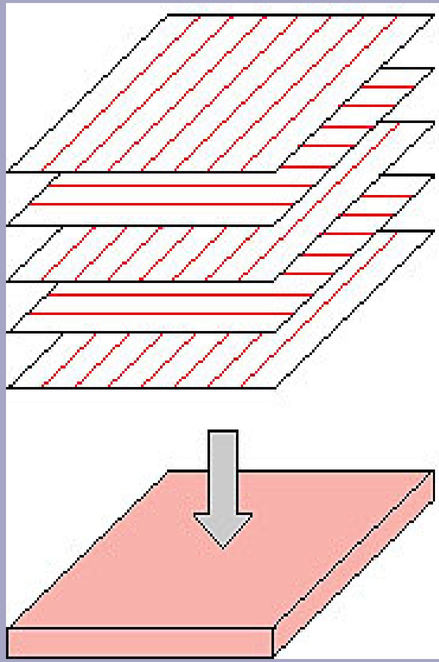


Figure 17.16 The stacking of successive oriented, fiber-reinforced layers for a laminar composite.

- Two dimensional sheets or panels with a preferred high-strength direction
  - Q. What is a natural example of this?
  - A. Wood
  - Q. What is a man made example
  - A. Plywood - Layers are stacked and subsequently bonded together so that the high strength direction varies

Plywood

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

QuickTime™ and a
Graphics decompressor
are needed to see this picture.

Sandwich Panels

- Two strong outer sheets (called faces) separated by a layer of less dense material or core (which has lower E and lower strength)
- Core
  - separates faces
  - resists deformation perpendicular to the faces
  - often honeycomb structures
- Used in roofs, walls, wings

Sandwich Panel