Composites

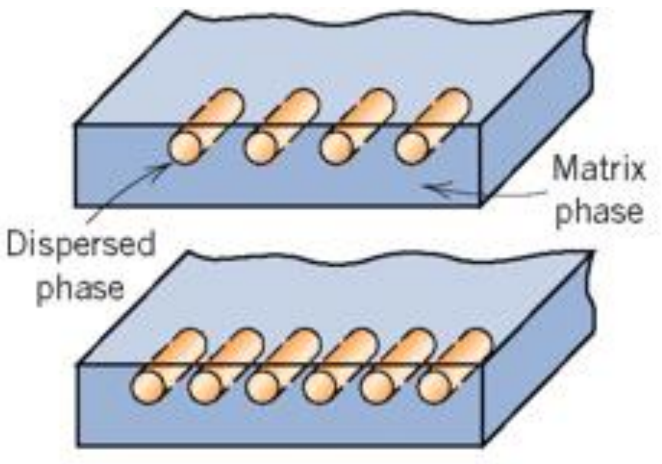
- Combine materials with the objective of getting a more desirable combination of properties
  - Ex: get flexibility & weight of a polymer plus the strength of a ceramic

- Principle of combined action
  - Mixture gives "averaged" properties

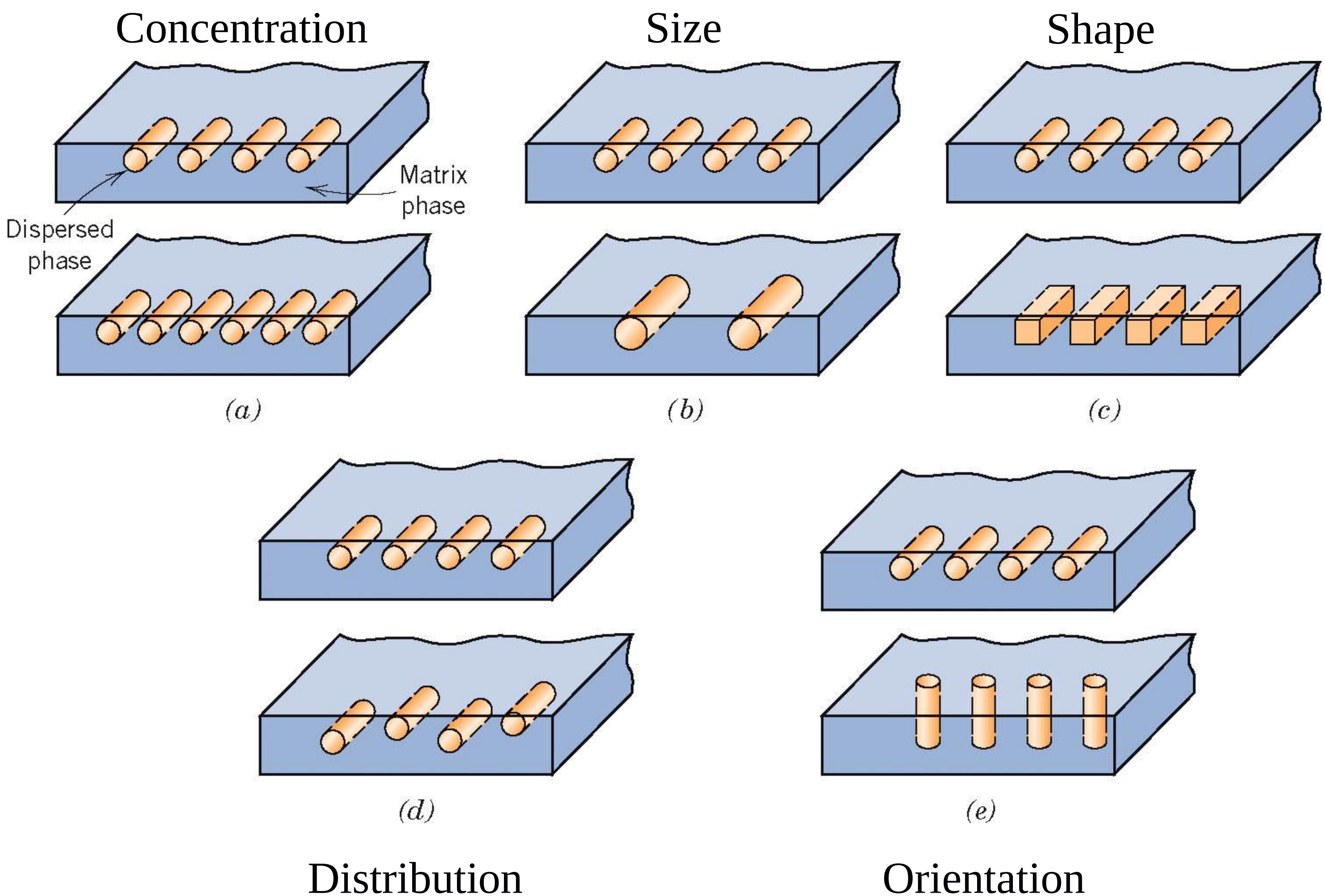
Terminology/Classification

- 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

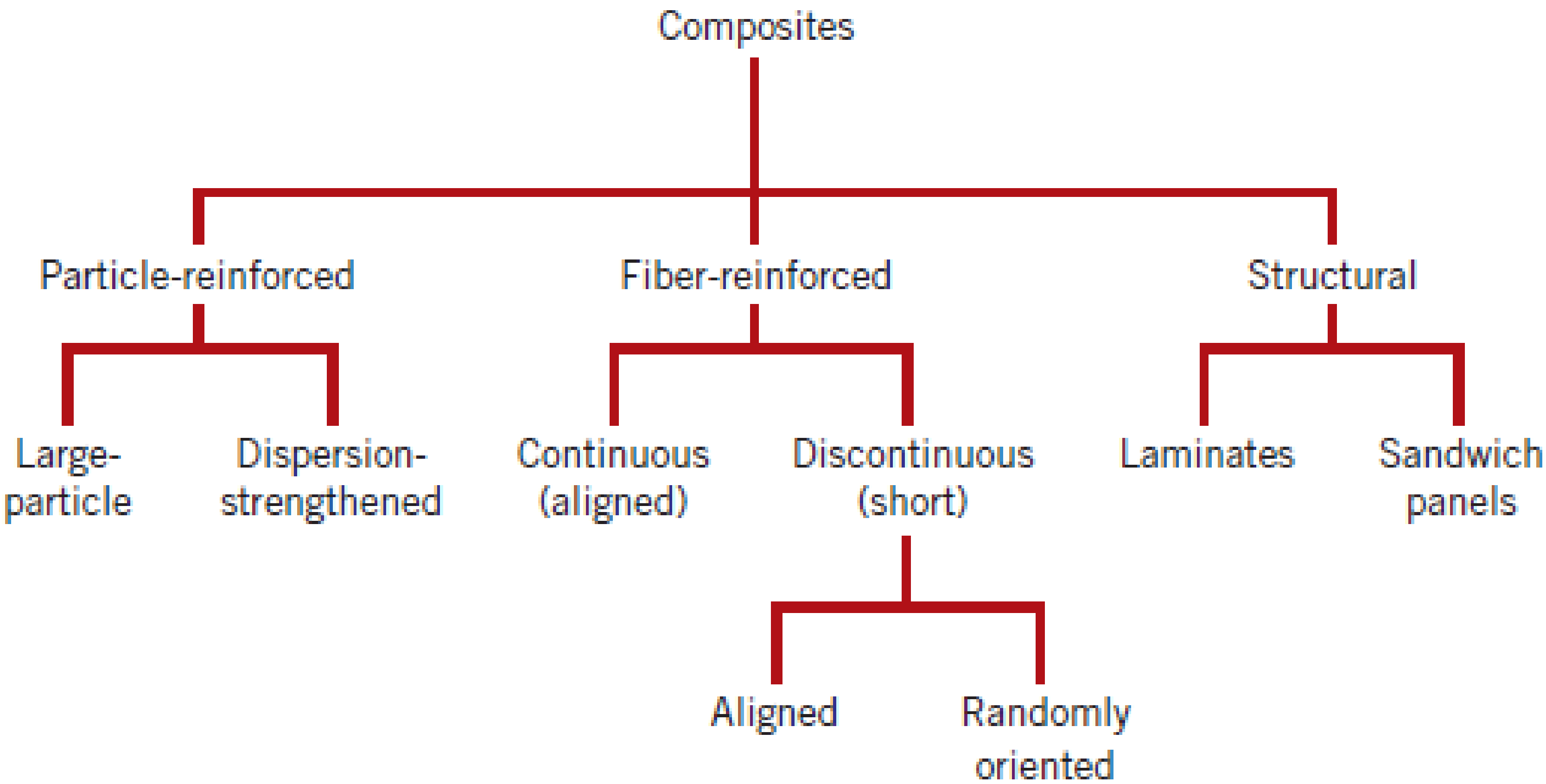
  metal ceramic polymer
- Dispersed phase:
  -- Purpose: enhance matrix properties.
  MMC: increase σ_y, *TS*, creep resist.
  CMC: increase *Kc*
  PMC: increase *E*, σ_y, *TS*, creep resist.
  -- Classification: Particle, fiber, structural



Matrix and Disperse phase of composites



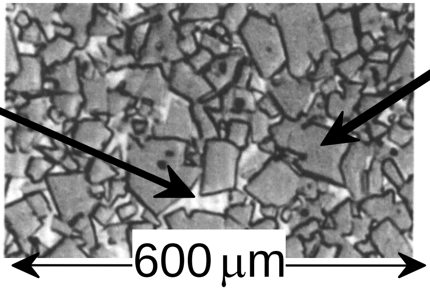
Composite Classification



Particle-reinforced Composites

- WC/Co cemented carbide

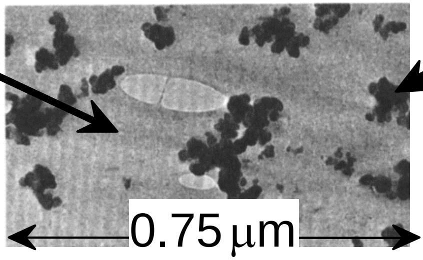
matrix: cobalt (ductile)
V_m: 10-15 vol%!



particles: WC (brittle, hard)

- Automobile tires

matrix: rubber (compliant)



particles: C (stiffer)

Particle-reinforced Composites

Concrete – gravel + sand + cement

- Why sand *and* gravel? Sand packs into gravel voids

  Good Compression strength but less tensile strength

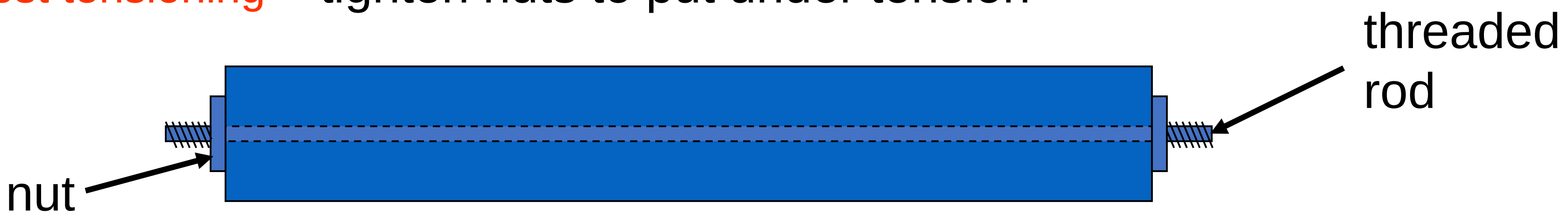
Reinforced concrete - Reinforce with steel rerod or remesh

- 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

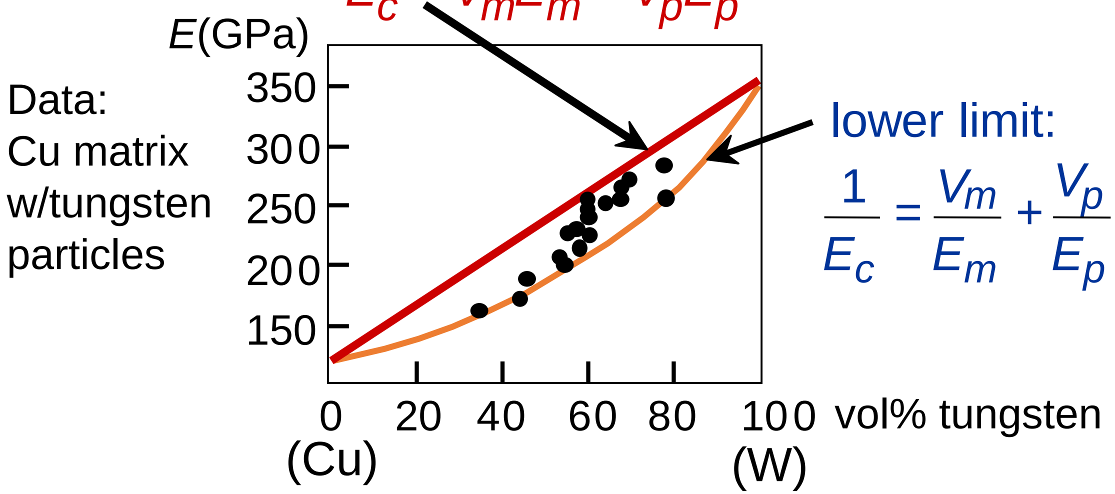


Particle-reinforced Composites

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

upper limit: "rule of mixtures"

$$E_c = V_m E_m + V_p E_p$$



lower limit:

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

- Application to other properties:
  -- Electrical conductivity, σ_e: Replace E in equations with σ_e.
  -- Thermal conductivity, k: Replace E in equations with k.

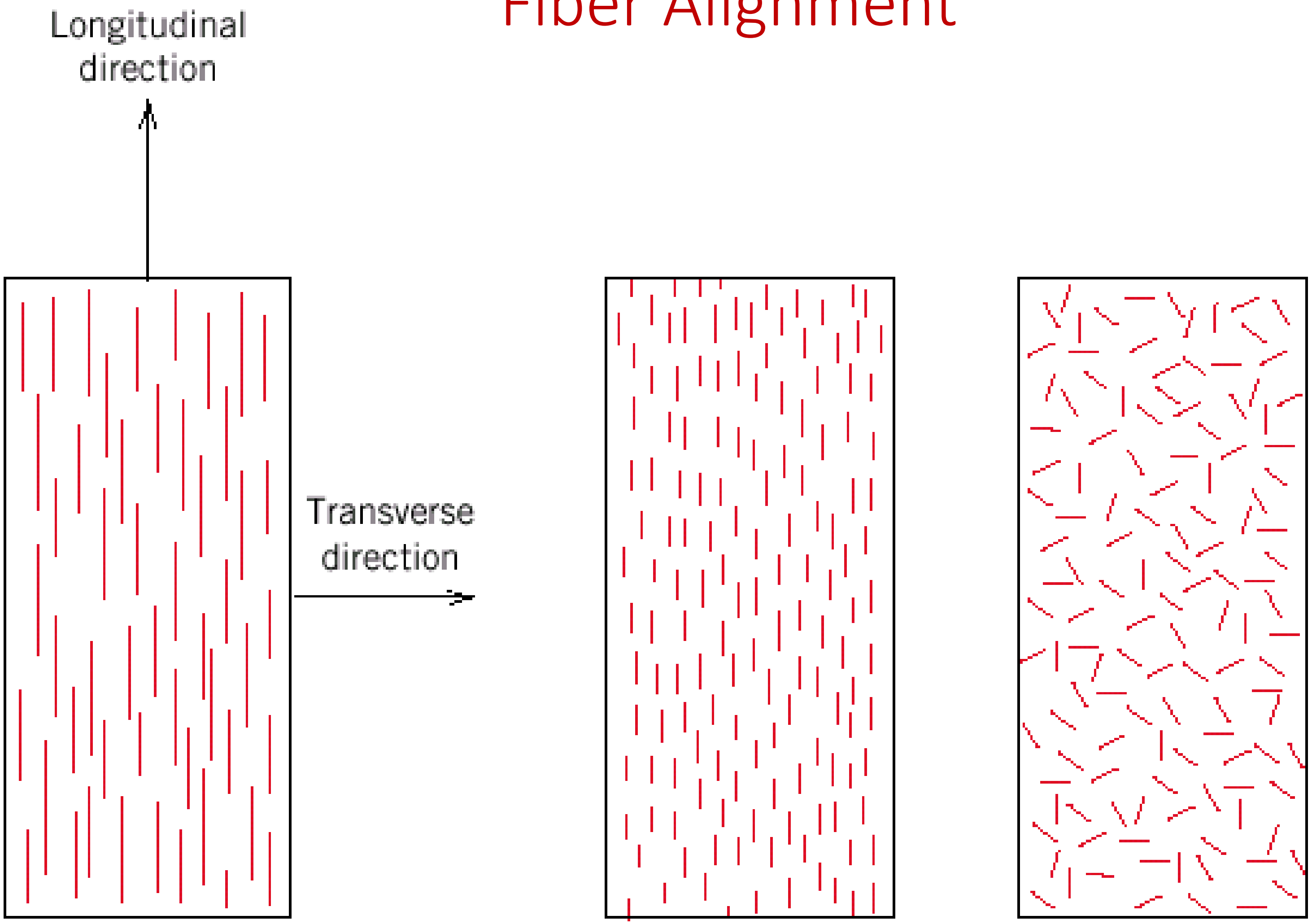
Fiber-reinforced Composites

- 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

Fiber-reinforced Composites

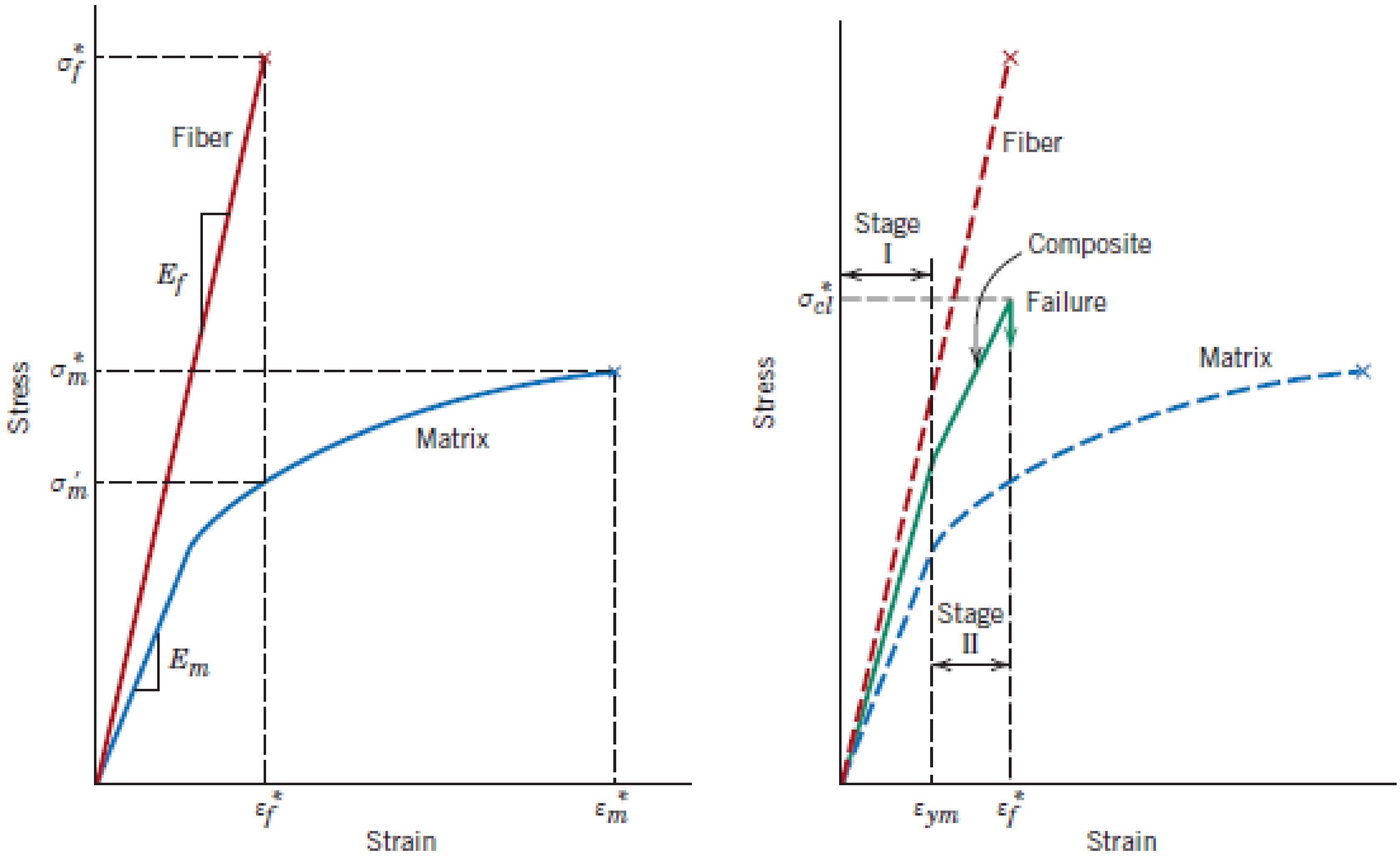
- Fiber Materials
  - Whiskers - Thin single crystals - large length to diameter ratio
    - graphite, SiN, SiC
    - high crystal perfection – extremely strong, strongest known
    - very expensive
  - Fibers
    - polycrystalline or amorphous
    - generally polymers or ceramics
    - Ex: Al_2O_3 , Aramid, E-glass, Boron, UHMWPE
  - Wires
    - Metal – steel, Mo, W

Fiber Alignment



aligned continuous

aligned random
discontinuous



σ_f^*
Fiber
E_f
Stress
σ_m^*
σ_m'
Matrix
E_m
ε_f^*
ε_m^*
Strain
Fiber
Stage
I
Composite
σ_{cl}^*
Failure
Stress
Matrix
Stage
II
ε_{ym}
ε_f^*
Strain

Critical Fiber Length

- Critical fiber length for effective stiffening & strengthening:

fiber strength in tension

fiber diameter

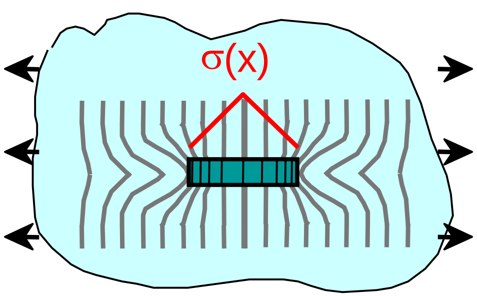
$$\text{fiber length} > 15\,\frac{\sigma_f d}{\tau_c}$$

shear strength of fiber-matrix interface

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

Shorter, thicker fiber:

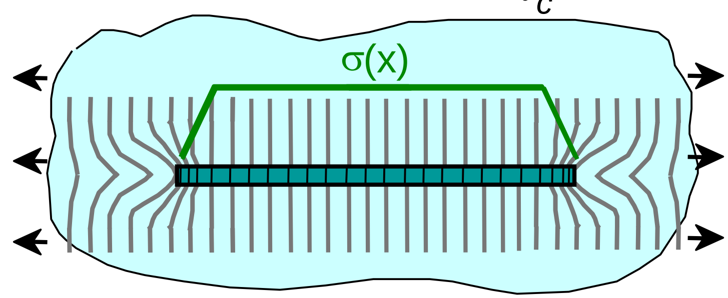
$$\text{fiber length} < 15\,\frac{\sigma_f d}{\tau_c}$$



Poorer fiber efficiency

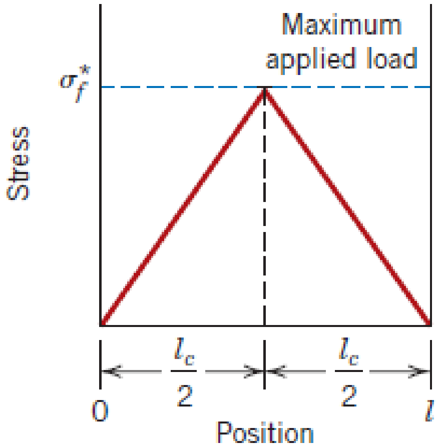
Longer, thinner fiber:

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

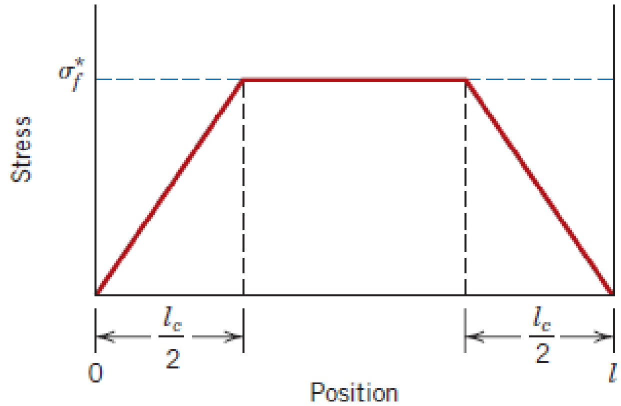


Better fiber efficiency

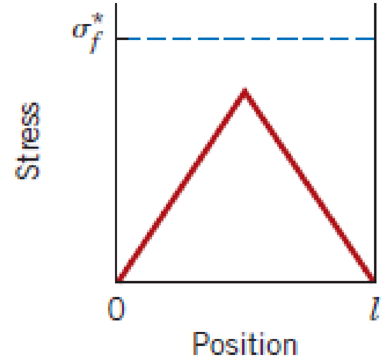
Stress transfer to fiber from matrix



Stress distribution along a fibre of length $l = l_c$.



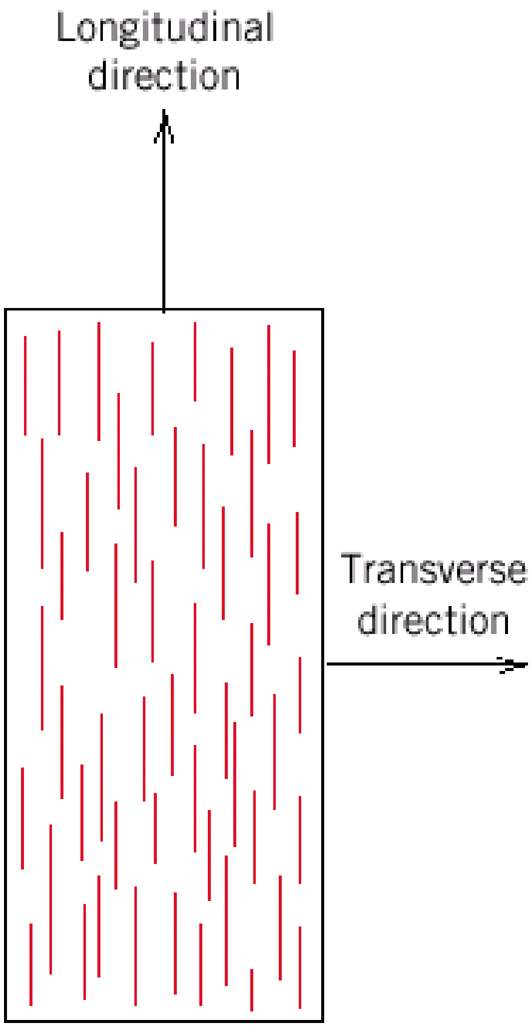
Stress distribution along a fibre of length $l > l_c$.



Stress distribution along a fibre of length $l < l_c$.

Fibres of length $l > 15l_c$ are called continuous. Discontinuous and short fibres are the ones whose lengths are shorter than this.

Assumption of an iso-strain state means that εc = εm = εf



$$F_c = F_m + F_f$$

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

$$\sigma_c = \sigma_m \frac{A_m}{A_c} + \sigma_f \frac{A_f}{A_c}$$

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

$$E_{cl} = E_m V_m + E_f V_f$$

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m}$$

Composite Strength: Longitudinal Loading

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

f = fiber
m = matrix

- Longitudinal deformation

$$F_c = F_m + F_f$$

$$\sigma_c = \sigma_m V_m + \sigma_f V_f \qquad \text{but} \qquad \varepsilon_c = \varepsilon_m = \varepsilon_f$$

volume fraction

isostrain

$$\therefore \quad \boxed{E_{ce} = E_m V_m + E_f V_f}$$

longitudinal (extensional) modulus

For longitudinal loading, that the ratio of the load car

the fibers to that carried by the matrix is

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m}$$

Composite Strength: Transverse Loading

- In transverse loading the fibers carry less of isostress

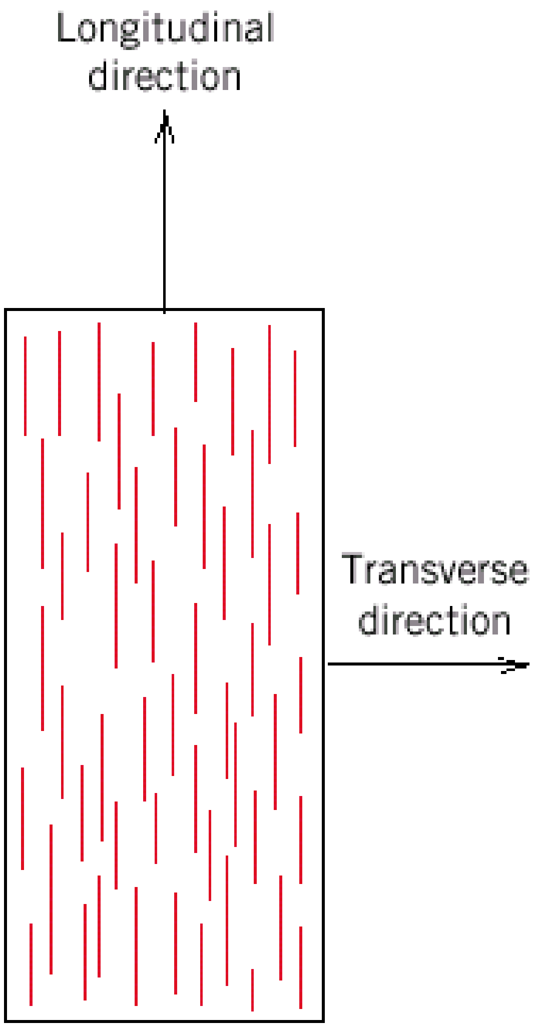
$\sigma_c = \sigma_m = \sigma_f = \sigma$

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

$$\therefore \quad \boxed{\frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f}}$$

transverse modulus

$$E_{ct} = \frac{E_m E_f}{V_m E_f + V_f E_m} = \frac{E_m E_f}{(1 - V_f) E_f + V_f E_m}$$



Property Determinations for a Glass Fiber–Reinforced Composite—Longitudinal Direction

A continuous and aligned glass fiber–reinforced composite consists of 40 vol% glass fibers having a modulus of elasticity of 69 GPa (10×10^6 psi) and 60 vol% polyester resin that, when hardened, displays a modulus of 3.4 GPa (0.5×10^6 psi).

(a) Compute the modulus of elasticity of this composite in the longitudinal direction.

(b) If the cross-sectional area is 250 mm^2 (0.4 $in.^2$) and a stress of 50 MPa (7250 psi) is applied in this longitudinal direction, compute the magnitude of the load carried by each of the fiber and matrix phases.

(c) Determine the strain that is sustained by each phase when the stress in part (b) is applied.

(a) The modulus of elasticity of the composite is calculated using Equation 16.10a:

$$\begin{aligned} E_{cl} &= (3.4 \text{ GPa})(0.6) + (69 \text{ GPa})(0.4) \\ &= 30 \text{ GPa } (4.3 \times 10^6 \text{ psi}) \end{aligned}$$

(b) To solve this portion of the problem, first find the ratio of fiber load to matrix load, using Equation 16.11; thus,

$$\frac{F_f}{F_m} = \frac{(69 \text{ GPa})(0.4)}{(3.4 \text{ GPa})(0.6)} = 13.5$$

or $F_f = 13.5\, F_m$.

In addition, the total force sustained by the composite F_c may be computed from the applied stress σ and total composite cross-sectional area A_c according to

$$F_c = A_c\sigma = (250 \text{ mm}^2)(50 \text{ MPa}) = 12{,}500 \text{ N } (2900 \text{ lb}_f)$$

whereas

$$F_f = F_c - F_m = 12{,}500 \text{ N} - 860 \text{ N} = 11{,}640 \text{ N } (2700 \text{ lb}_f)$$

Thus, the fiber phase supports the vast majority of the applied load.

$$A_m = V_m A_c = (0.6)(250 \text{ mm}^2) = 150 \text{ mm}^2 \ (0.24 \text{ in.}^2)$$

$$A_f = V_f A_c = (0.4)(250 \text{ mm}^2) = 100 \text{ mm}^2 \ (0.16 \text{ in.}^2)$$

$$\sigma_m = \frac{F_m}{A_m} = \frac{860 \text{ N}}{150 \text{ mm}^2} = 5.73 \text{ MPa (833 psi)}$$

$$\sigma_f = \frac{F_f}{A_f} = \frac{11{,}640 \text{ N}}{100 \text{ mm}^2} = 116.4 \text{ MPa (16,875 psi)}$$

, strains are computed as

$$\varepsilon_m = \frac{\sigma_m}{E_m} = \frac{5.73 \text{ MPa}}{3.4 \times 10^3 \text{ MPa}} = 1.69 \times 10^{-3}$$

$$\varepsilon_f = \frac{\sigma_f}{E_f} = \frac{116.4 \text{ MPa}}{69 \times 10^3 \text{ MPa}} = 1.69 \times 10^{-3}$$

erefore, strains for both matrix and fiber phases are identical, which the
ng to Equation 16.8 in the previous development.

Elastic Modulus Determination for a Glass Fiber–Reinforced
Composite—Transverse Direction

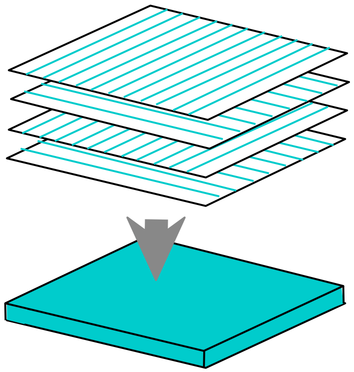
Compute the elastic modulus of the composite material described in previous Problem, but assume that the stress is applied perpendicular to the direction of fiber alignment.

$$E_{ct} = \frac{(3.4 \text{ GPa})(69 \text{ GPa})}{(0.6)(69 \text{ GPa}) + (0.4)(3.4 \text{ GPa})}$$

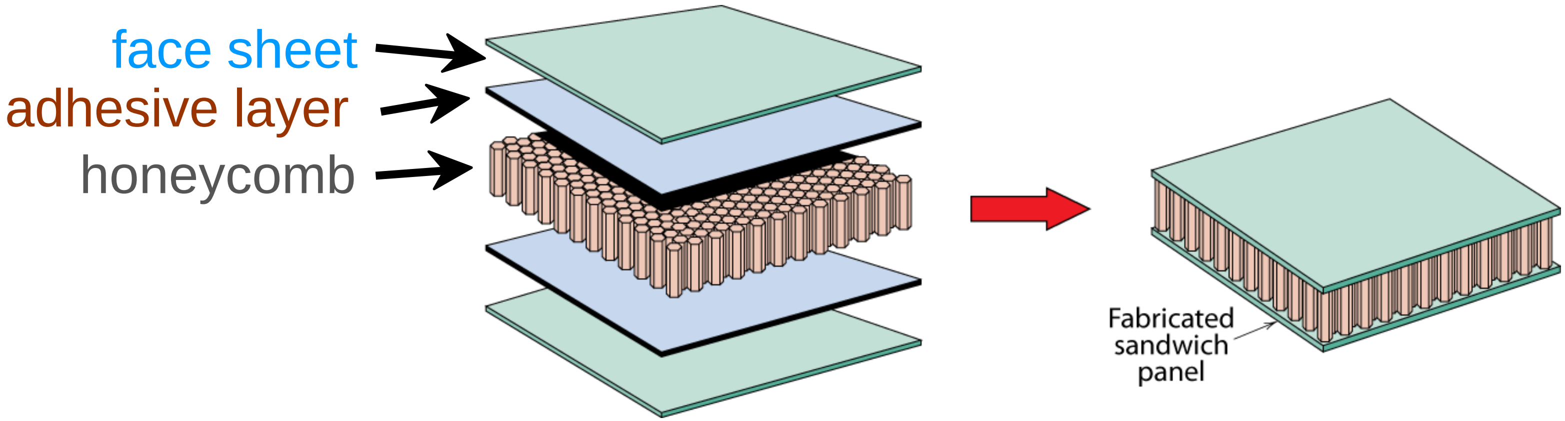
$$= 5.5 \text{ GPa } (0.81 \times 10^{6} \text{ psi})$$

Structural Composites

- Laminate fiber-reinforced sheets
  - -- stacking sequence: e.g., 0º/90º
  - -- benefit: balanced, in-plane stiffness

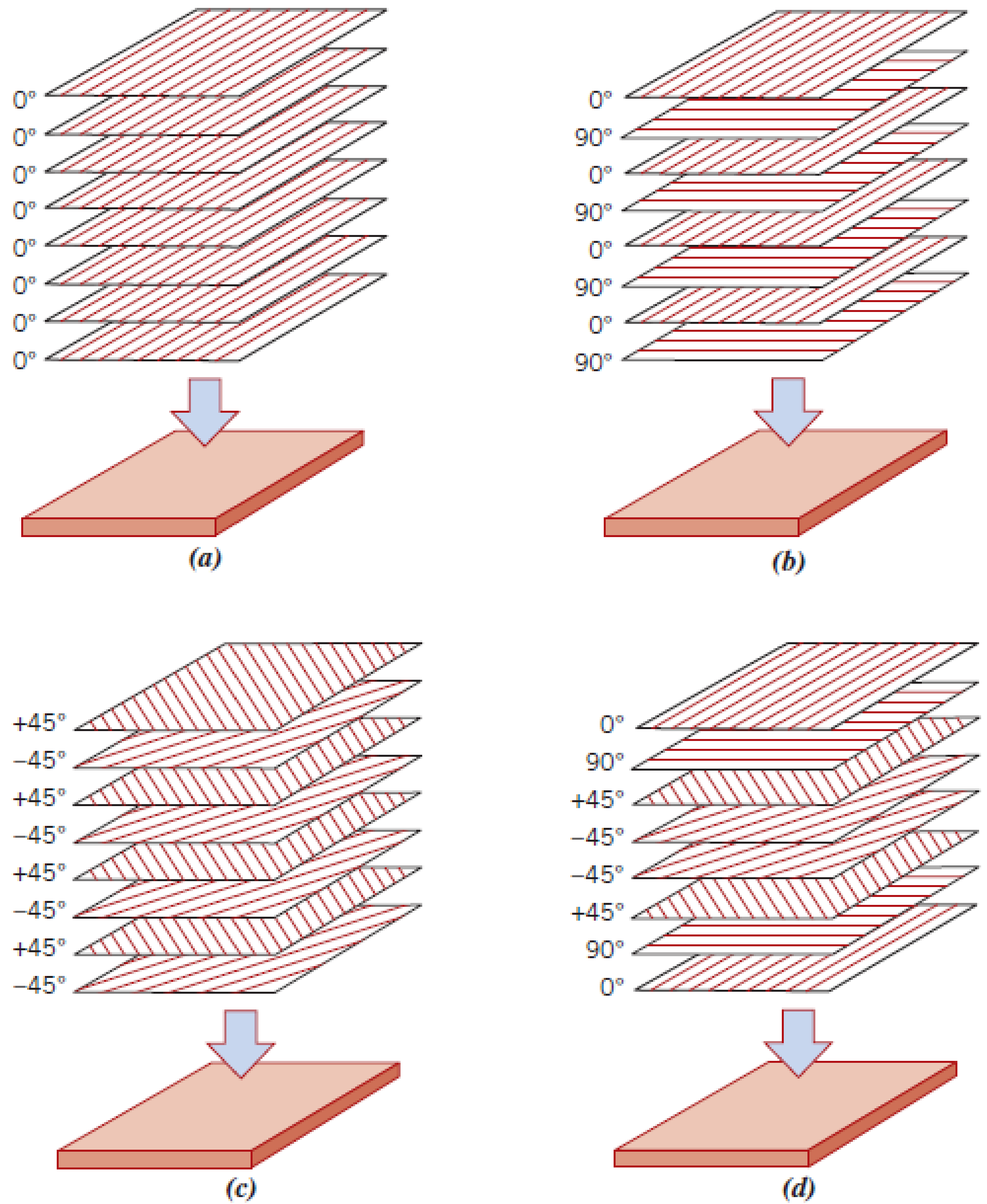


- Sandwich panels
  - -- low density, honeycomb core
  - -- benefit: small weight, large bending stiffness



Types of Laminate Lay ups

(*a*) Unidirectional;
(*b*) Cross-ply;
(*c*) Angle-ply;
(*d*) Multidirectional.



Polymer matrix composites

A PMC consisting of a *polymer matrix* imbedded with high-strength fibers

Fibers:

mainly - glass (GFRPs), carbon (CFRPs), aramid,

others - B, SiC, Al_2O_3

Polymer matrix materials:

Usually a thermosetting (TS) plastic such as unsaturated polyester or epoxy

Can also be thermoplastic (TP), such as nylons (polyamides), polycarbonate, polystyrene, and polyvinylchloride

Fiber reinforcement is widely used in rubber products such as tires and conveyor belts

- Glass Fiber Reinforced Composites (GFRP)
  – storage containers, plastic pipes, automotive & marine
- Carbon Fiber Reinforced Composites (CFRP)
  – golf clubs, fishing rods, pressure vessels
- Aramid Fiber Reinforced Composites
  – poly (paraphenylene terephthalamide)
  - Kevlar and Nomex (Trade Name)
    - Bullet proof vests and armor, sporting goods, tires, ropes.

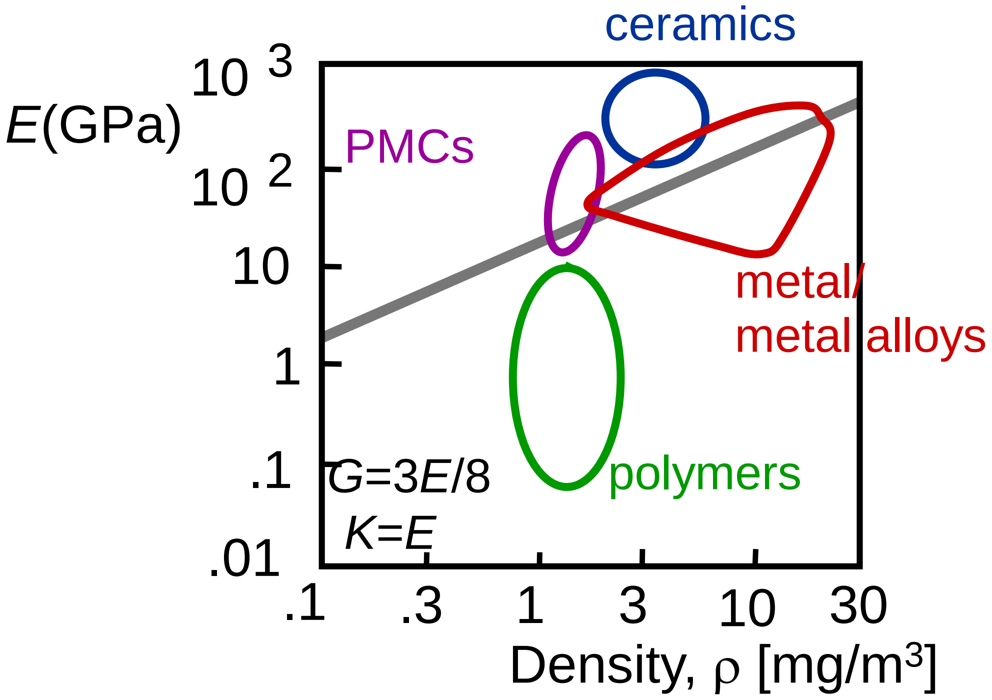
Property	***Glass (E-Glass)***	***Carbon (Standard Modulus)***	***Aramid (Kevlar 49)***
Specific gravity	2.1	1.6	1.4
Tensile modulus			
Longitudinal [GPa (10^6 psi)]	45 (6.5)	145 (21)	76 (11)
Transverse [GPa (10^6 psi)]	12 (1.8)	10 (1.5)	5.5 (0.8)
Tensile strength			
Longitudinal [MPa (ksi)]	1020 (150)	1520 (220)	1240 (180)
Transverse [MPa (ksi)]	40 (5.8)	41 (6)	30 (4.3)
Ultimate tensile strain			
Longitudinal	2.3	0.9	1.8
Transverse	0.4	0.4	0.5

[a] In all cases, the fiber volume fraction is 0.60.

Polymer Matric Composites:

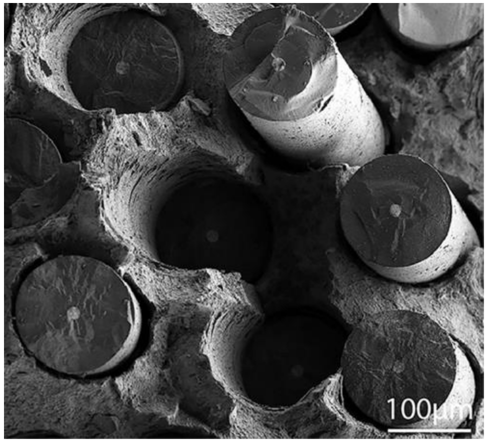
increase E, σ_y, TS, creep resist.

- PMCs: Increased E/ρ



Metal – Matrix Composites

- Dispersed phase usually ceramic and rarely metals
- Expensive than PMC
- Suitable for high temperature applications



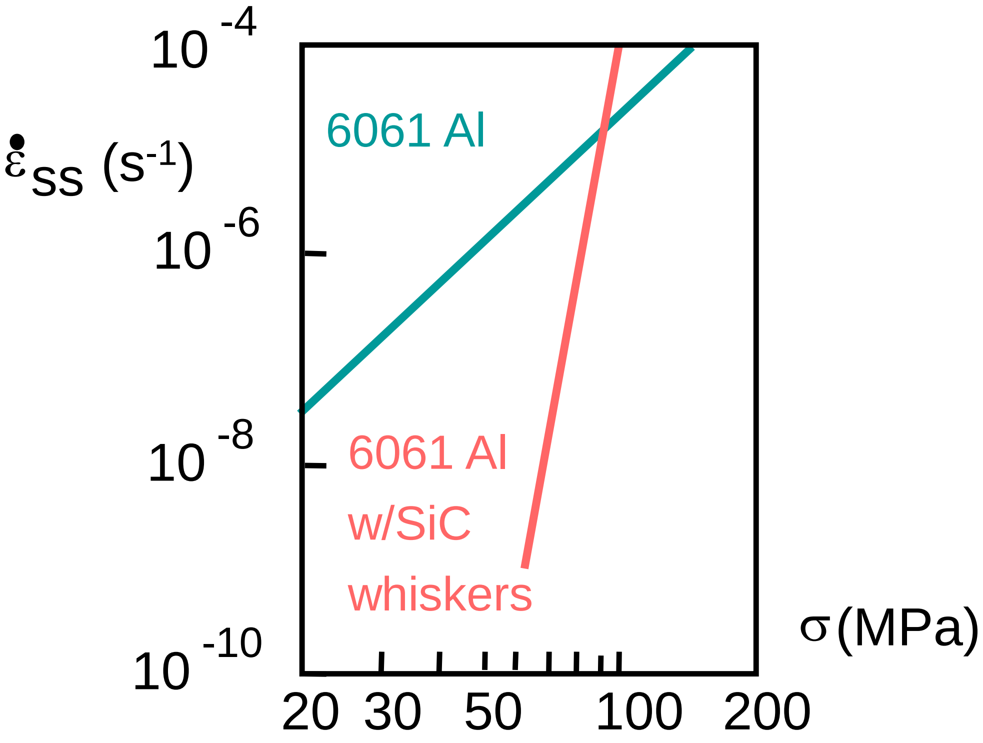
SiC particles in Ti

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

Metal Matrix Composites

increase σ_y, TS, creep resist.

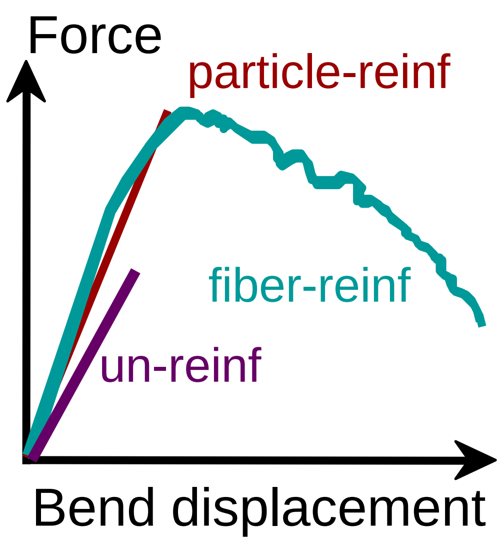
Increased creep resistance



Ceramic Matrix Composites

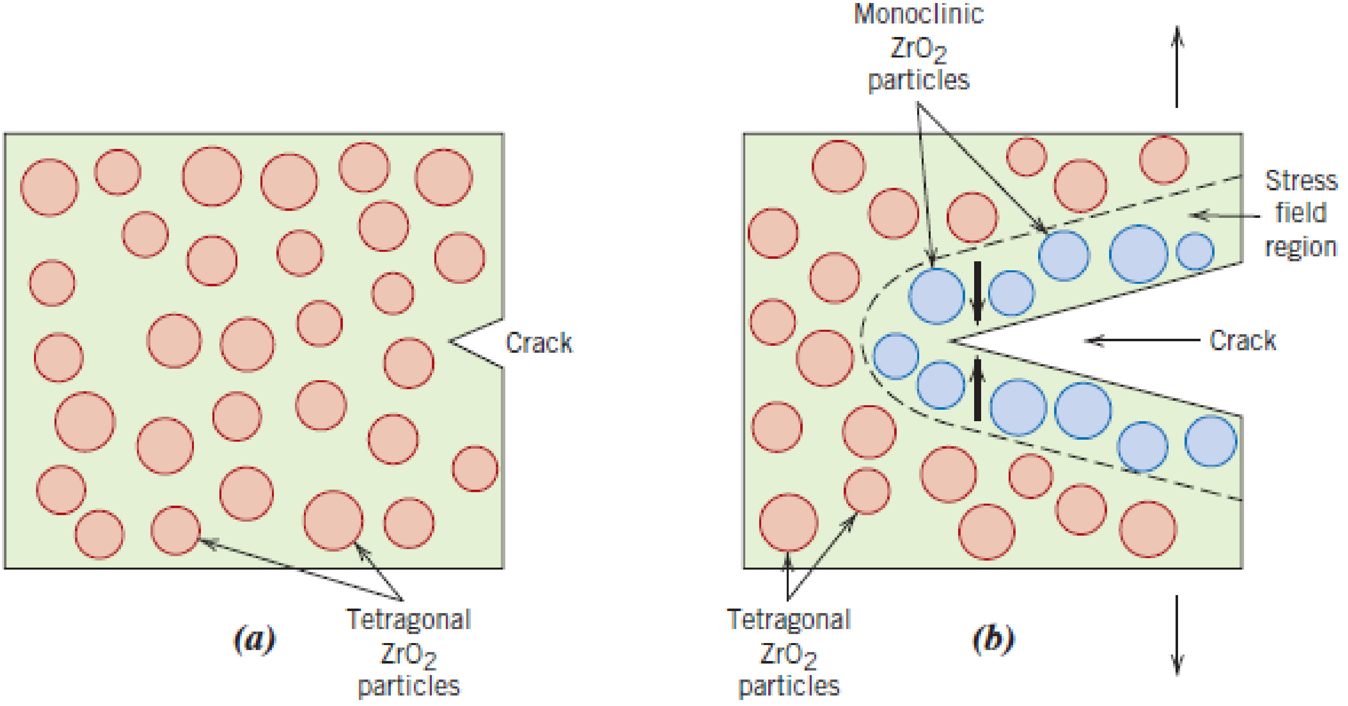
- ✓ They consist of ceramic fibers embedded in a ceramic matrix.
- ✓ CMCs: Increased toughness

Whisker Content (vol%)	*Fracture Strength (MPa)*	*Fracture Toughness ($MPa\sqrt{m}$)*
0	—	4.5
10	455 ± 55	7.1
20	655 ± 135	7.5–9.0
40	850 ± 130	6.0



Transformation toughening in CMC

Small particles of partially stabilized zirconia are dispersed within the matrix material, often Al_2O_3 or ZrO_2 itself.

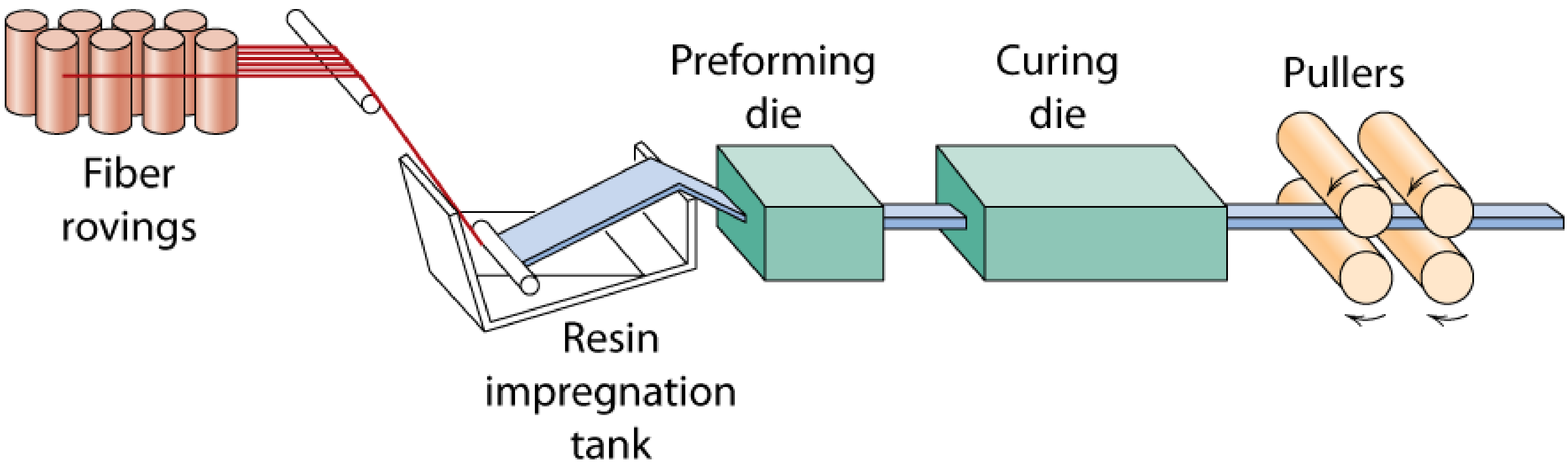


This transformation due to stress increases particle volume slightly, net result is that compressive stresses to pinch the crack shut, thereby arresting its growth.

Composite Production Methods-I

Pultrusion

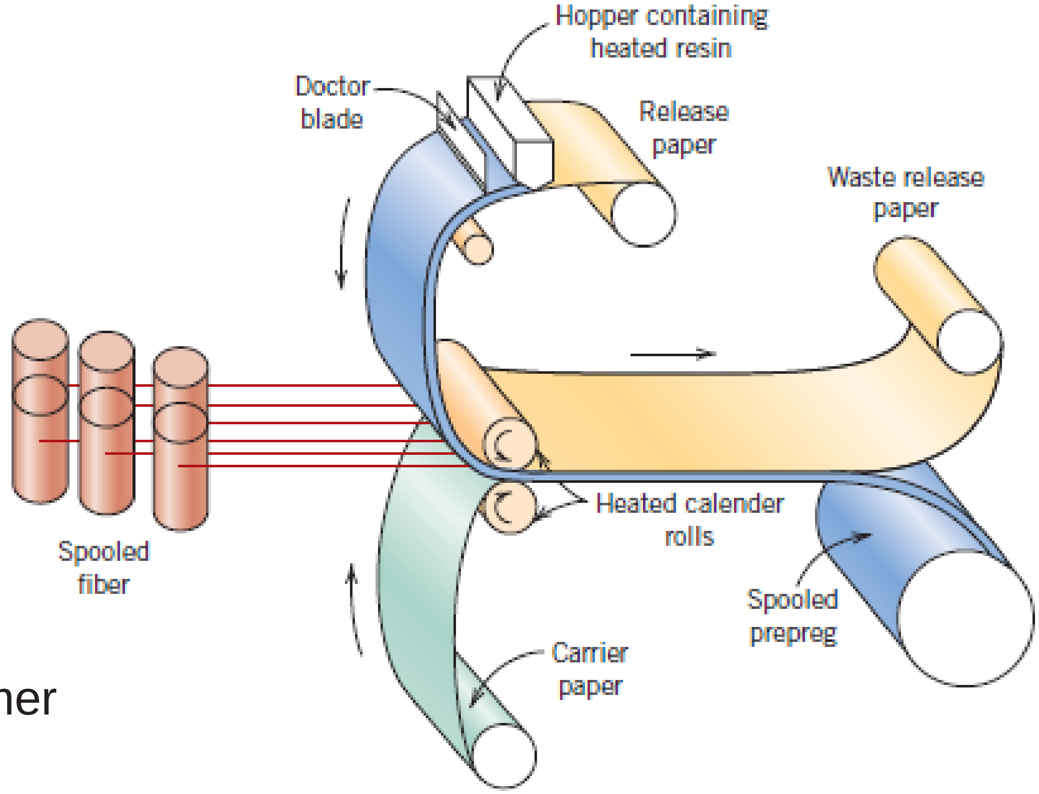
- Continuous fibers pulled through resin tank, then preforming die & oven to cure



Composite Production Methods-II

Prepreg Production Processes

Prepreg is the composite industry's term for continuous-fiber reinforcement preimpregnated with a polymer resin that is only partially cured. This material is delivered in tape form to the manufacturer, which then directly molds and fully cures the product without having to add any resin

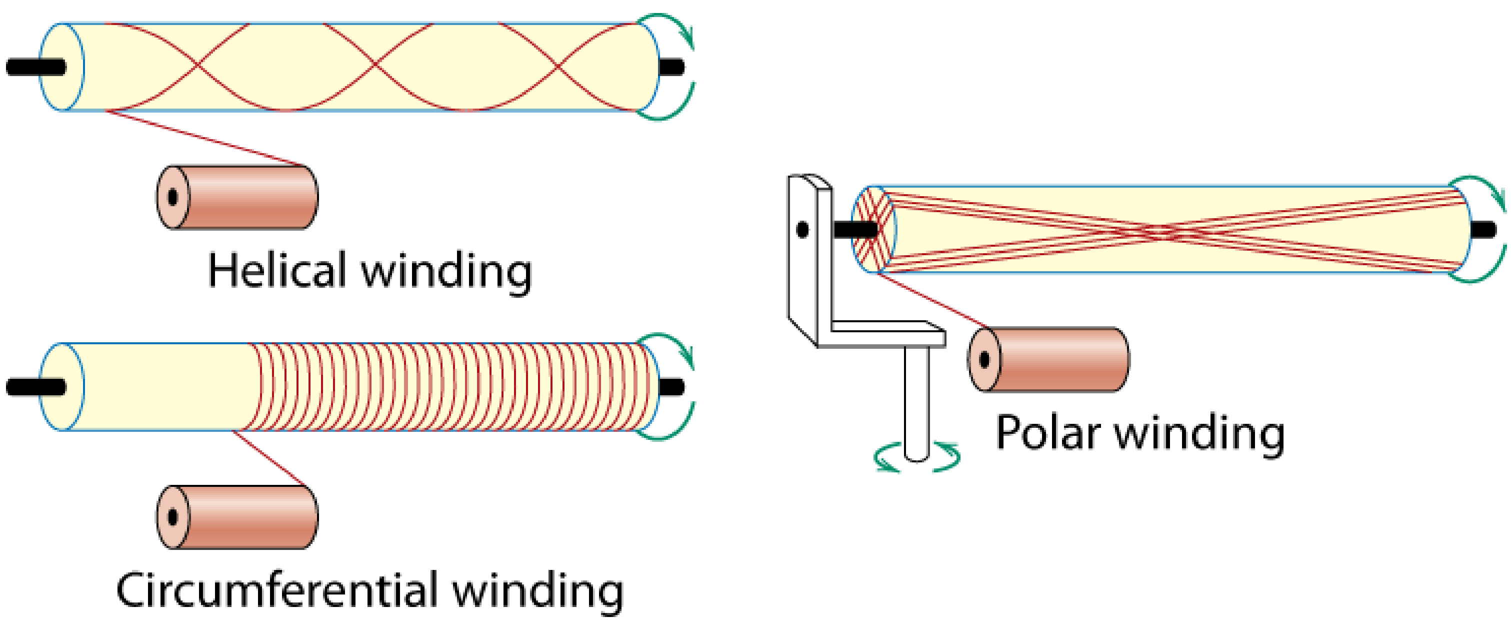


illustrating the production of prepreg tape using a thermoset polymer

Composite Production Methods-III

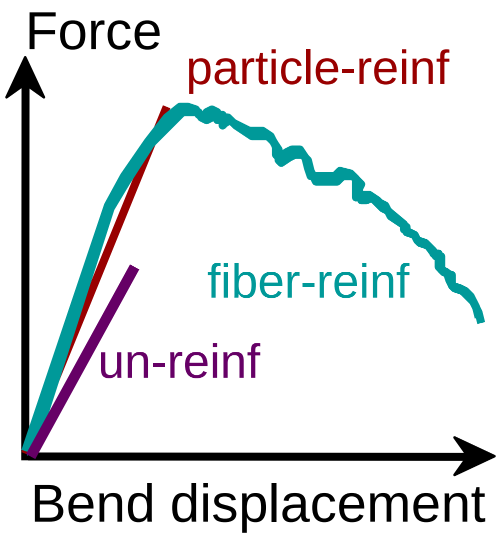
Filament Winding

- Ex: pressure tanks
- Continuous filaments wound onto mandrel

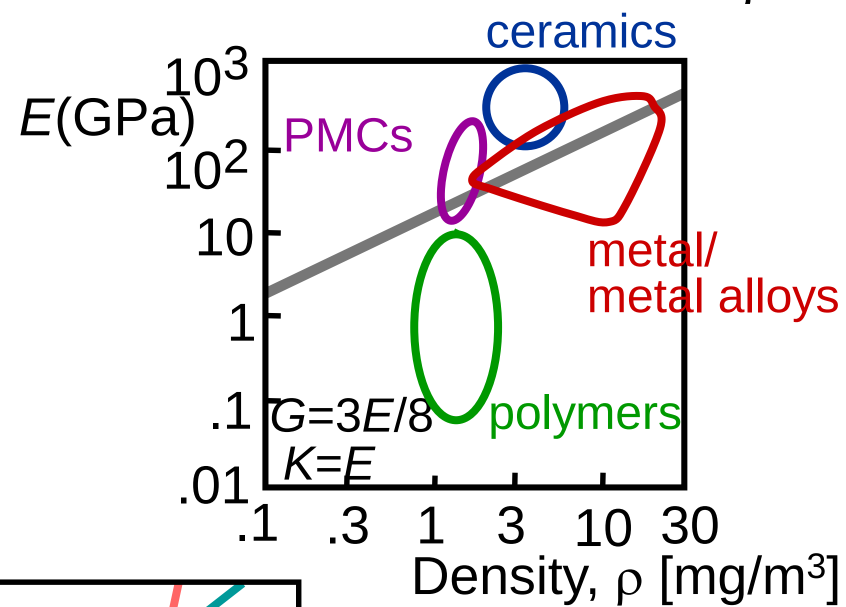


Composite Benefits

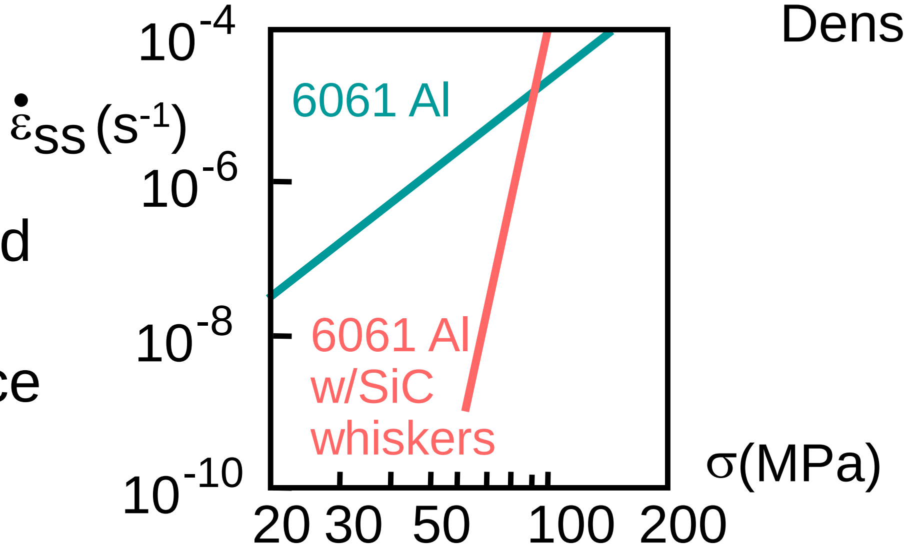
- CMCs: Increased toughness



- PMCs: Increased E/ρ



- MMCs:
  Increased creep resistance



Case Study: Composites in the Boeing 787 Dreamliner

Boeing 787 Dreamliner —a long-range, mid-size (210 to 290 *passenger capacity), twin-engine jet airliner—is the first to use composite materials for the majority of its construction.*

It is lighter in weight than its predecessors, which leads to

- ✓ 20% more fuel efficiency,
- ✓ fewer emissions, and
- ✓ longer flying ranges.

This composite construction makes flying more comfortable experience—

- ✓ cabin pressure and humidity levels are higher than for its ancestors and
- ✓ noise levels have been reduced.
- ✓ Overhead bins are roomier and windows are larger.

Continuous carbon fiber–epoxy laminates, the majority of which are used in the fuselage

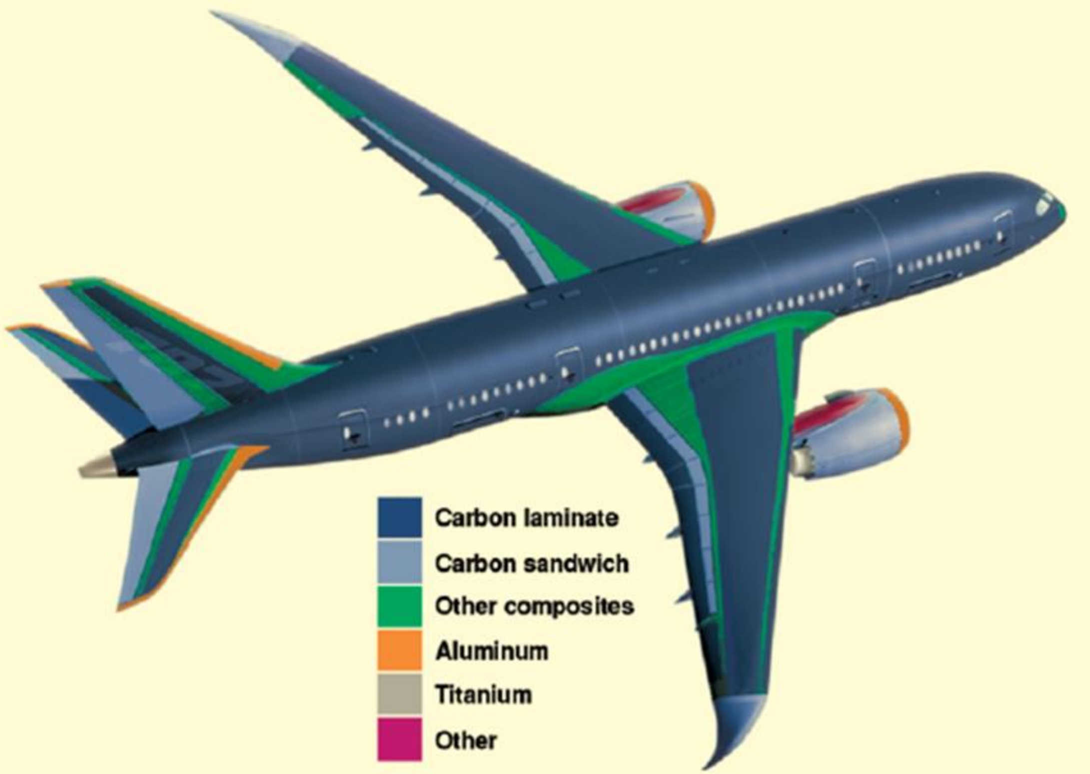
Reductions in assembly costs—approximately 1500 aluminum sheets that are fastened together with approximately 50,000 rivets are eliminated.

The fuselage of the Dreamliner was the first attempt to mass produce extremely large composite structures composed of carbon fibers embedded in a thermosetting polymer (i.e., an epoxy).

Thus, it became necessary for Boeing (and its subcontractors) to develop and implement new and innovative composite manufacturing

Material Types and Contents for Boeing 787 and 777 Aircraft

Aircraft	*Material Content (Weight Percent)*				
	Composites	*Al Alloys*	*Ti Alloys*	*Steel*	*Other*
787	50	20	15	10	5
777	11	70	7	11	1



Nanocomposites.

Nanocomposites are composed of nanosized particles (or *nanoparticles*) that are embedded in a matrix material. The largest particle dimension must on the order of at most 100 nm.

- ✓ They can be designed to have mechanical, electrical, magnetic, optical, thermal, biological, and transport properties that are superior to conventional filler materials;
- ✓ For these reasons, nanocomposites are becoming infused in a number of modern technologies.

An interesting and novel phenomenon accompanies the decrease in size of a nanoparticle—its physical and chemical properties experience dramatic changes;

- For example, the permanent magnetic behavior of some materials [e.g., iron, cobalt, and iron oxide (Fe3O4)] disappears for particles having diameters smaller than about 50 nm.

- ✓ As the size of a particle decreases, the relative ratio of surface atoms to bulk atoms increases; this means that surface phenomena begin to dominate.

- ✓ For extremely small particles, quantum effects begin to appear.

Dental restorations—Some newly developed dental restoration (i.e., filling) materials
are polymer nanocomposites.

Nano-filler ceramic materials

Silica nanoparticles (approximately 20 nm in diameter), and
Nanoclusters composed silica and zirconia.

Most polymer matrix materials

Belong to the dimethacrylate family.

These nanocomposite restoration materials have high fracture toughnesses, are wear
resistant, have short curing times and curing shrinkages, and can be made to have
the color and appearance of natural teeth.

Energy storage—Graphene nanocomposites are used in anodes for lithium-ion rechargeable batteries

Mechanical strength enhancements—High-strength and lightweight polymer
nanocomposites are produced by the addition of multi-walled carbon nanotubes
into epoxy resins;

nanotube contents that range between 20 and 30 wt% are normally required. These nanocomposites are used in wind turbine blades as well as some sports equipment (viz. tennis rackets, baseball bats, golf clubs, skis, bicycle frames, and boat hulls and masts).