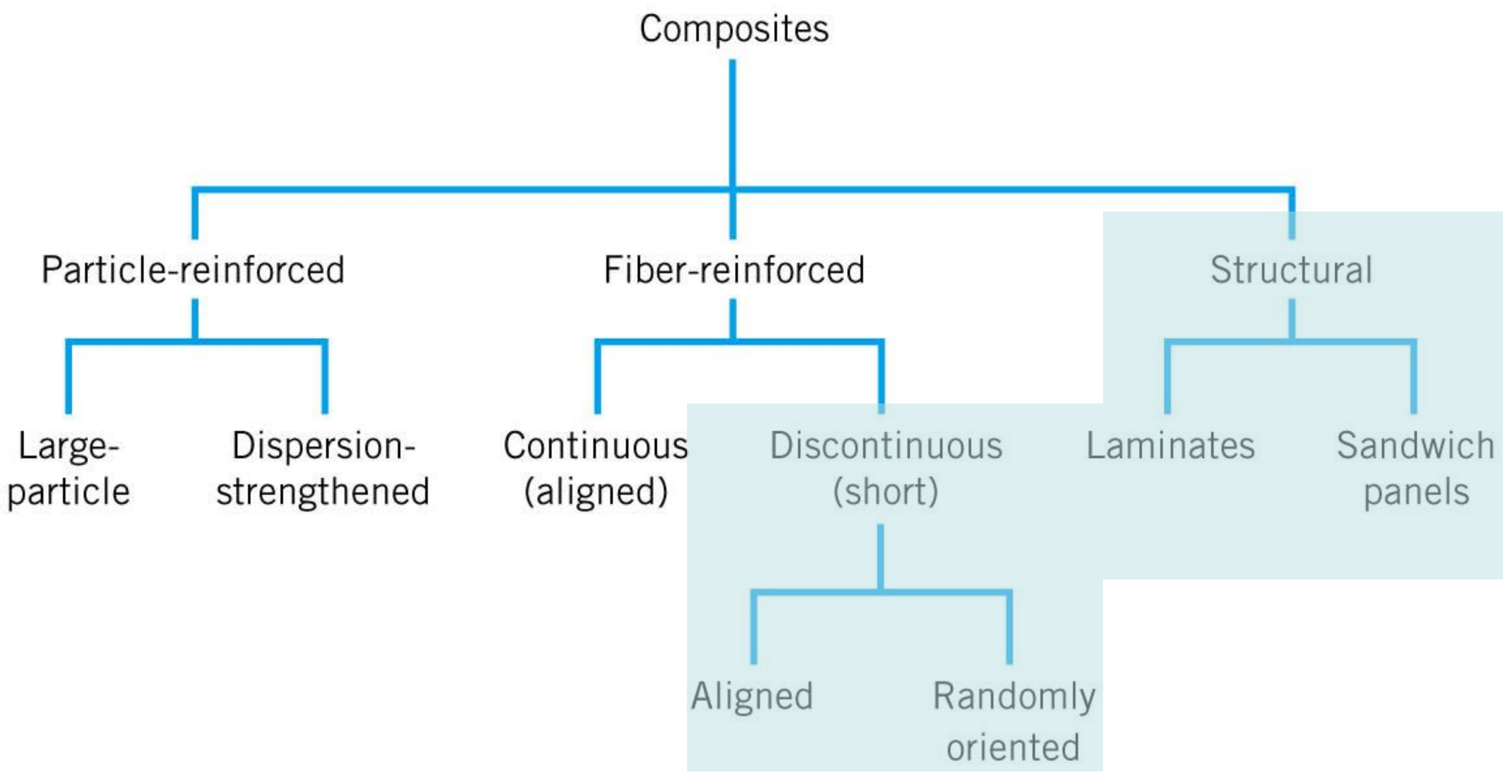
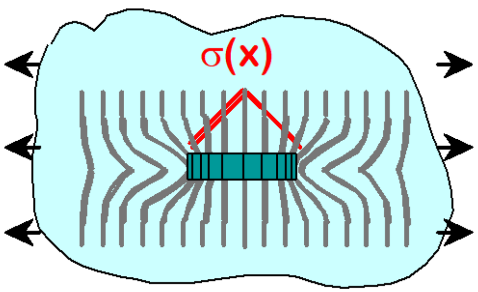
Today’s objectives-Composite Applications and Discontinuous (short) fibers

- Be able to calculate the longitudinal strength for long, short, and very short fiber composites.
- Be able to calculate the Young’s modulus for discontinuous fibers oriented in 3 dimensions, 2 dimensions, or 1 dimension.
- Know about GFRP, CFRP, and AFRP PMC’s—increased modulus/weight ratio.
- Know the strengthening mechanisms for fibers in a composite.
- Recall transformation toughened ceramics (Yttria stabilized zirconia).
- Be familiar with carbon-carbon, hybrid, and structural composites.
- Understand fiber composite fabrication: protrusion, prepreg, and winding.

Types of composites

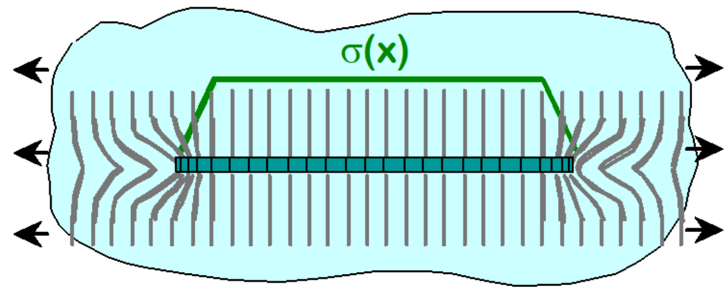


Optimal fiber length



Poorer fiber efficiency

$$L_c = \frac{\sigma_f^{\,*} d}{2\tau_c}$$



Better fiber efficiency

fiber strength in tension

fiber diameter

$$L_{optimal} \approx 30 L_c = 30\frac{\sigma_f d}{2\tau_c}$$

shear strength of fiber-matrix interface or the matrix itself (whichever is smaller)

- Long fibers are for $L > 30L_c$
- Short (discontinuous) fibers are for $L_c < L < 30{*}L_c$
- Very short (also discontinuous) fibers are for $L < L_c$.

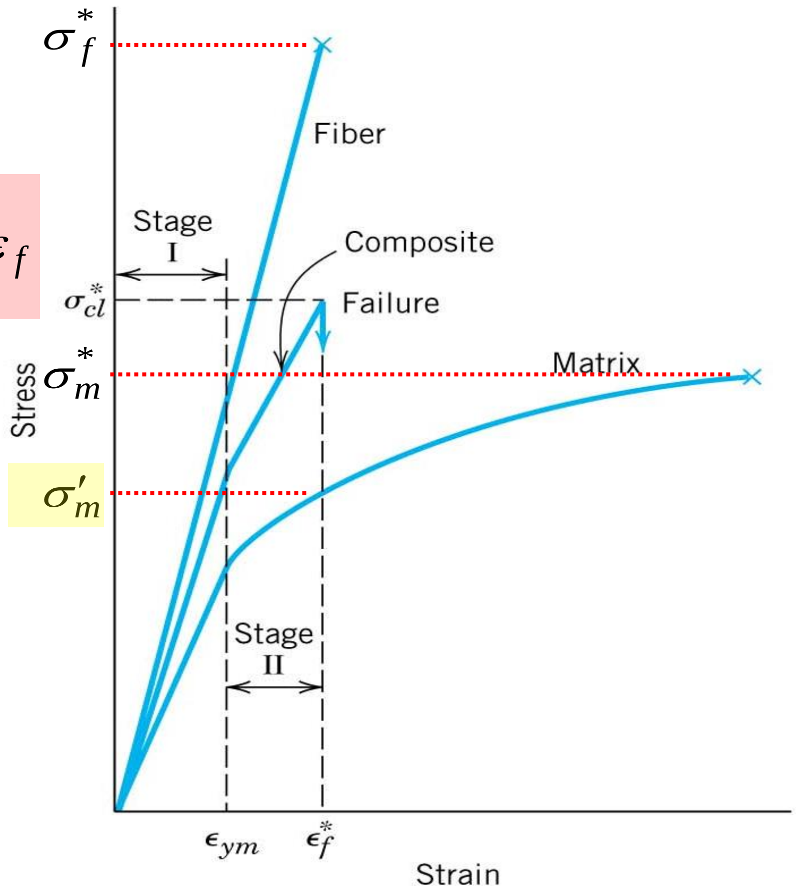
Review for Long Fibers ($L>L_c$):

- Longitudinal
  - Slope changes once the matrix begins to yield.
  - When the fibers are stressed sufficiently, the worst one fails.
  - Longitudinal tensile strength can be calculated.
  - The load transfers to the matrix with each fiber failure.
  - Overall part doesn't fail until all fibers and the matrix fail.

$$\sigma^*_{c,longitudinal} = \sigma'_m \frac{(1-V_f)}{V_c} + \sigma^*_f \frac{V_f}{V_c}$$

$$\sigma_{c^*,transverse} = E_c \frac{V_m}{V_c}\varepsilon_m + E_c \frac{V_f}{V_c}\varepsilon_f$$

- Transverse
  - The transverse tensile strength is usually at least one order of magnitude less than the longitudinal strength.
  - The matrix properties will dominate, along with the fiber/matrix bond strength.



Problem 16.16

- In an aligned and continuous glass-fiber-reinforced nylon6,6 matrix composite, the fibers are to carry 94% of a load applied in the longitudinal direction.
  - a) determine the volume fraction of fibers necessary.
  - b) What will be the tensile strength of the composite. Assume matrix stress at fiber failure is 30 MPa.

	E (GPa)	σ* (MPa)
Glass fiber	72.5	3400
Nylon 6,6	3	76

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m} = \frac{E_f V_f}{E_m (1 - V_f)}$$

$$\frac{F_f}{F_m} = \frac{0.94}{0.06} = 15.67$$

$$\frac{F_f}{F_m} = 15.67 = \frac{(72.5\ \text{GPa}) V_f}{(3.0\ \text{GPa})(1 - V_f)}$$

And, solving for Vf yields, Vf = 0.418

$$\sigma_{cl}^{*} = \sigma_m{}' \frac{(1 - V_f)}{V_c} + \sigma_f^{*} \frac{V_f}{V_c}$$

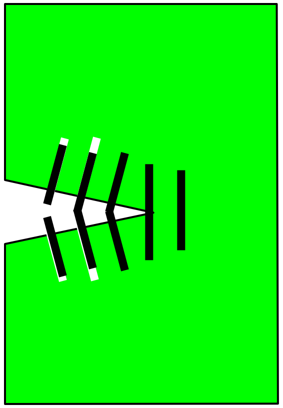
= 1440 MPa

And, to calculate the transverse strength:

$$\sigma_{c^*,transverse} = E_c \frac{V_m}{V_c} \varepsilon_m + E_c \frac{V_f}{V_c} \varepsilon_f$$

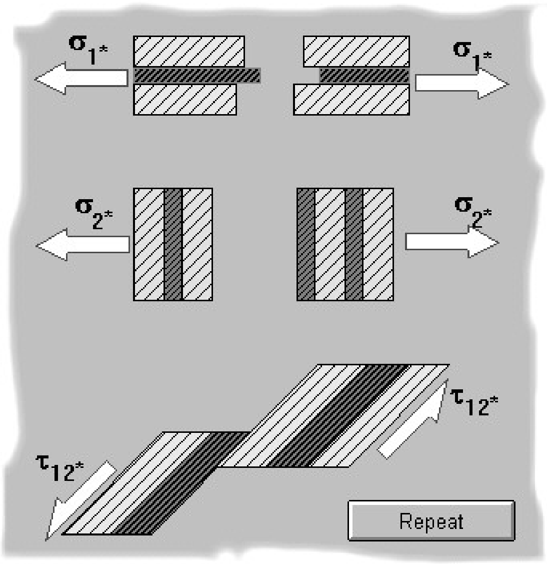
Fiber composite strengthening mechanisms

- Improvements are similar to those for particle dispersions (hindering crack propagation).
  - Redistributing stress near a crack tip and/or deflect cracks.
  - Form bridges across crack faces.
  - Absorb energy as whiskers are pulled out of the matrix by an advancing crack.
  - Absorb energy upon fracture of whiskers.



Fiber composite failure as a f(load orientation)

1. Fibers and matrix may fracture
2. Interface may fracture
3. Interface may shear



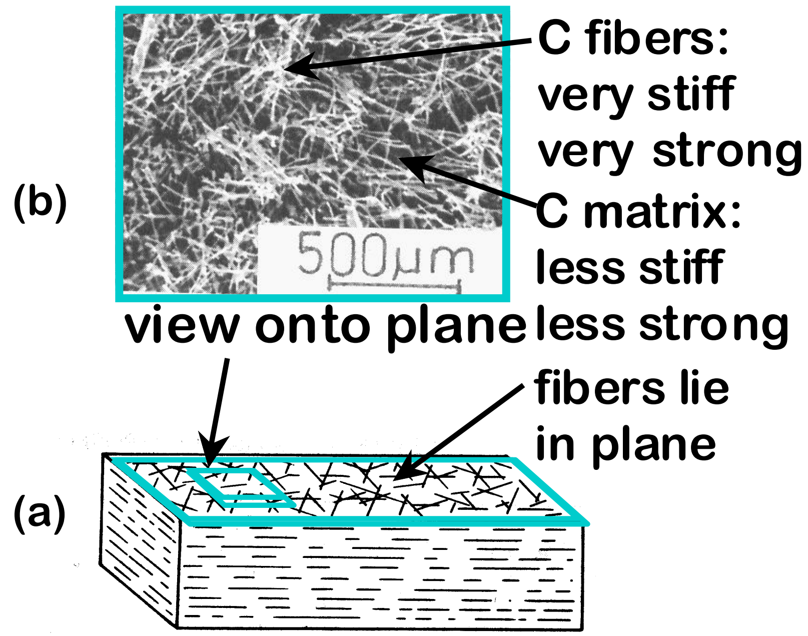
http://www.matter.org.uk/matscicdrom/manual/co.html#_Toc360435310

What if fibers are short (<$30L_c$="discontinuous")?

- They can still be partially oriented (in plane)
- It is even cheaper if they are totally randomly oriented

Discontinuous, random 2D fibers

- Examples: disk brakes, gas turbine exhaust flaps, nose cones.



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.

Strength for aligned fibers of various lengths

- Aligned shorter fibers can still be beneficial (and much cheaper).
  - Chopped glass, carbon, and aramid fibers are employed in tennis rackets, automobile parts, etc.
  - Fracture strength (σ_c*) up to ½ that of continuous fiber composites.
- The longitudinal strength for short, aligned fibers with $L_c<L<30L_c$:

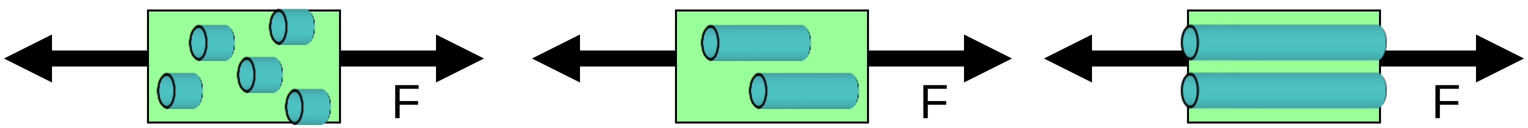
$$\sigma^*_{c,longitudinal,discontinuous,short} = \sigma'_m \frac{(1-V_f)}{V_c} + \sigma^*_f \frac{V_f}{V_c}\left(1-\frac{L_c}{2L}\right)$$

- The longitudinal strength for very short, aligned fibers with $L<L_c$:

$$\sigma^*_{c,longitudinal,discontinuous,very\ \ short} = \sigma'_m \frac{(1-V_f)}{V_c} + \frac{V_f}{V_c}\left(\frac{L\tau_c}{d}\right)$$

- Compare with the longitudinal strength for optimally long aligned fibers with $L>30L_c$ from earlier:

$$\sigma^*_{c,longitudinal} = \sigma'_m \frac{(1-V_f)}{V_c} + \sigma^*_f \frac{V_f}{V_c}$$

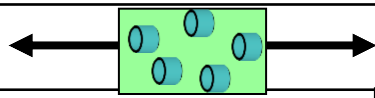
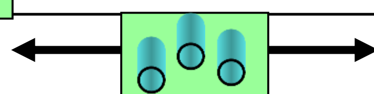
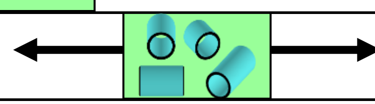


E for Discontinuous and random fibers

- For very short fibers ($L<L_c$) the elastic modulus follows a rule of mixtures (as if the fibers were simply particles).

$$E_{c,discontinuous,random} = KE_f \frac{V_f}{V_c} + E_m \frac{V_m}{V_c}$$

- The fibers may be oriented or random, dictating the composite properties (and the manufacturing cost).

Fiber Orientation	Stress Direction	K
Parallel 	Parallel to fibers	1
Parallel 	Perpendicular	0
Random, uniform, in plane 	Any in-plane direction	$^3/_8$
Random, uniform, in all directions	Any direction	$^1/_5$

- So, for uniaxial loads, aligned fibers are optimal. For isotropic loads, fibers should be uniformly randomly oriented either in plane or in all directions.

Summary of fiber orientation effects

- For uniform properties, the fiber distribution should be uniform.
- Continuous fibers should be aligned to take advantage of them.
- Discontinuous fibers benefit from parallel or random alignment depending on the application (uniaxial, biaxial, or arbitrary loading).
- For enhanced properties in many orientations: random orientations may be used, or multiple orthogonal layers can be stacked (structural composite).

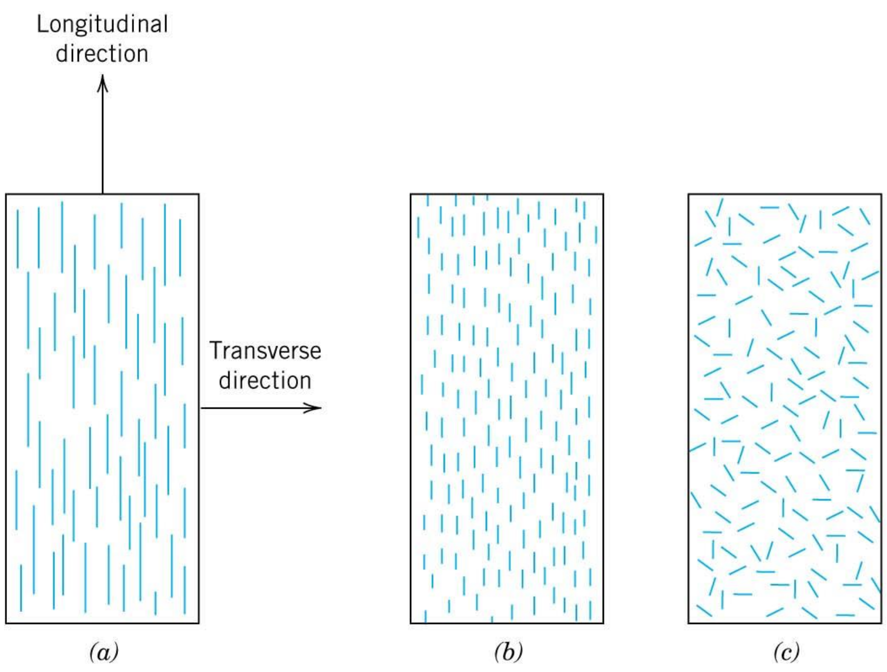


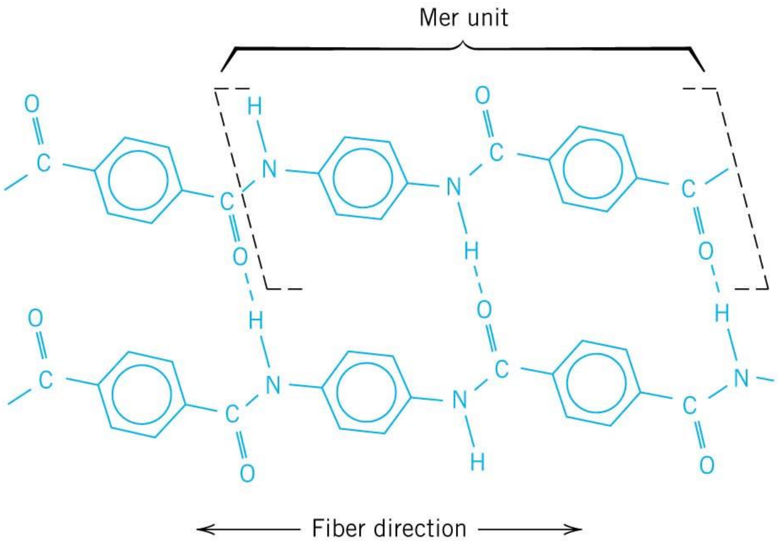
FIGURE 16.8 Schematic representations of (*a*) continuous and aligned, (*b*) discontinuous and aligned, and (*c*) discontinuous and randomly oriented fiber-reinforced composites.

Polymer matrix composites

- Primary composite type
- Glass Fiber Reinforced Polymer (GFRP, used in car bodies, boat hulls, pipes, containers, and flooring)
  - Fiberglass with fibers of 3-20 um diameter are typically used.
    - High strength to weight ratio (specific strength).
    - Relatively chemically inert if the surface is protected from environment.
    - Easily drawn into high strength fibers (flawless surfaces).
    - Processing is straightforward.
  - Some disadvantages of gfrp's too:
    - Polymer matrix begins to soften or deteriorate around 200C.
    - not rigid enough (E is small).
- Carbon Fiber Reinforced Polymer (CFRP, used in sporting goods, aero/astro)
  - Advantages of carbon fibers over glass:
    - Higher E and strength of all reinforcing materials.
    - Better high temperature response, except to oxidation.
    - Less sensitive to environment, fluids, etc.
    - Fiber properties can be tailored over a wide range of properties.
    - Reasonable manufacturing options

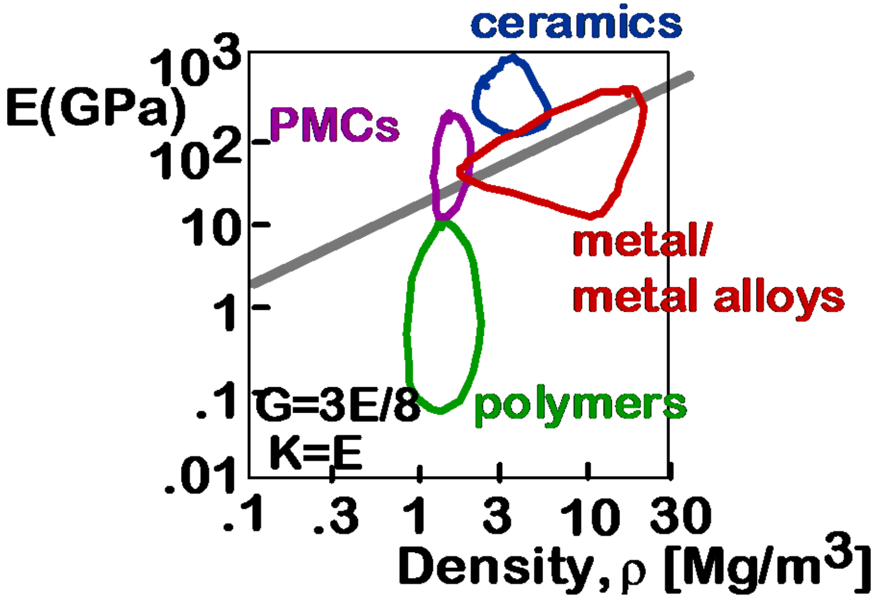
More polymer matrices

- Aramid fiber reinforced polymer composites (AFRP, used for bulletproofing, asbestos replacement, sporting goods)
  - Kevlar, Spectra
    - Excellent strength to weight ratio
    - Great longitudinal tensile strength
    - Excellent roughness, impact resistance
    - Great resistance to creep and fatigue failure
    - Resistant to combustion
    - Stable from -200 to 200C.
    - Inert unless strong acids or bases.
  - But:
    - Poor in compression
    - Poor transverse tensile strength
    - Expensive



Carbon-Carbon composites

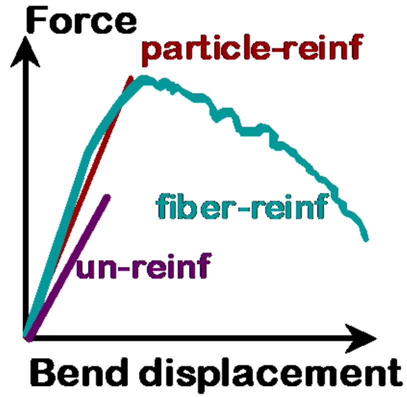
- Advantages
  - High tensile modulus and strength up to 2000C
  - Resistant to creep
  - Large fracture toughness
  - Low coefficient of thermal expansion
  - High thermal conductivity
    - Thus, thermal shock is relatively unimportant
- Disadvantages
  - High temperature oxidation
  - Very expensive
  - Complex and low volume processing/manufacturing



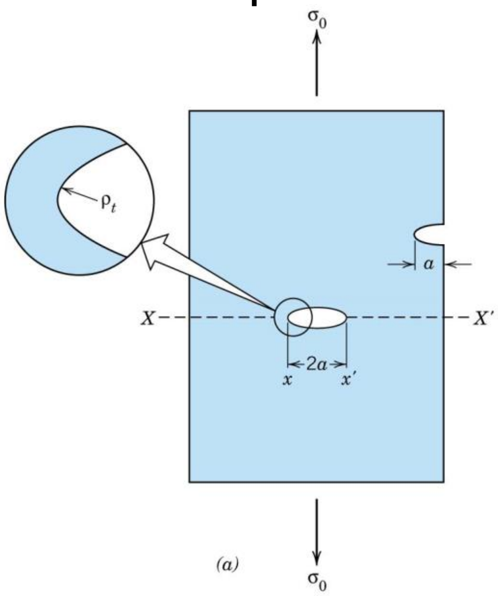
- Others fiber types include SiC, B, Al_2O_3

Ceramic Matrix Composites

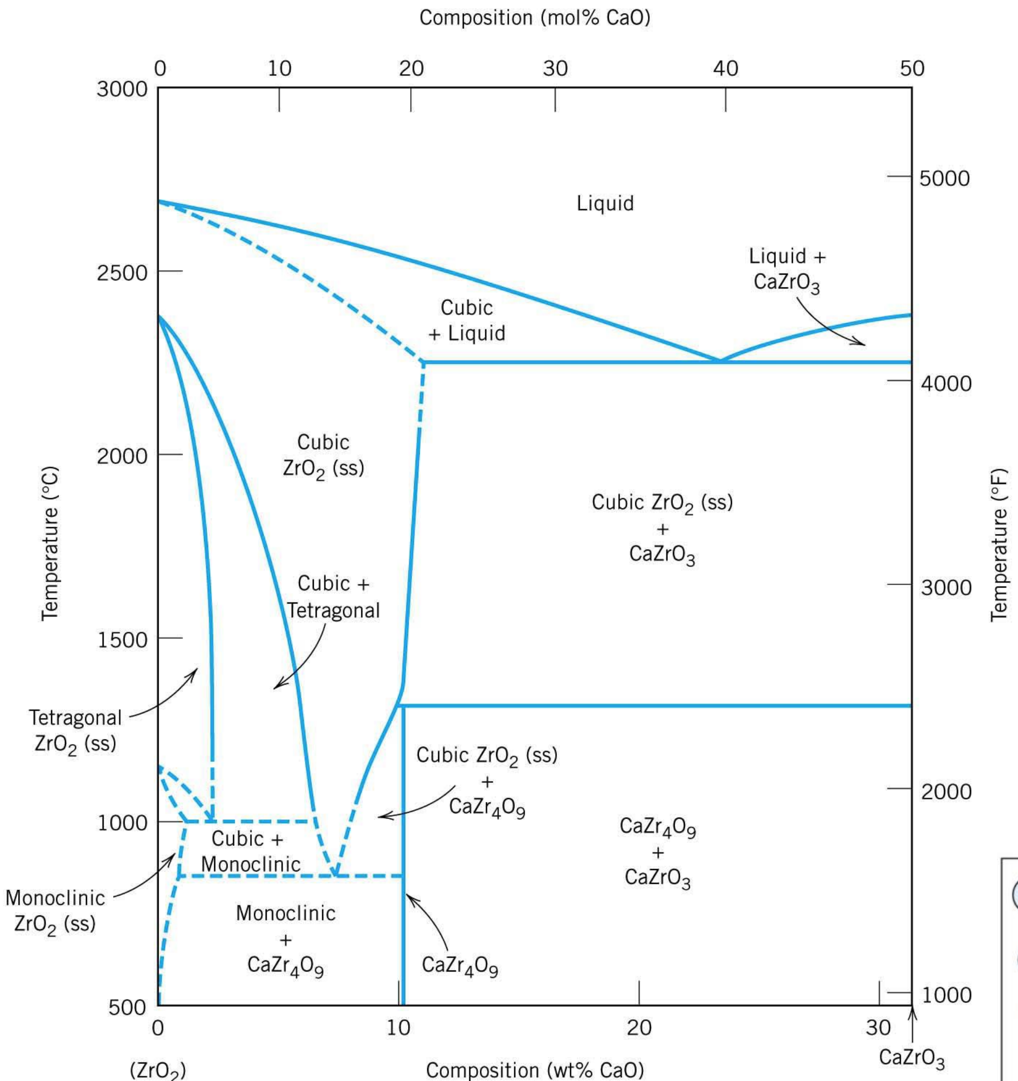
- Fracture toughness is the important parameter for CMC's.
  - K_{Ic} ranges from 1-5 for most ceramics, 15-150 for most metals, and 5-10 for ceramic matrix composites containing ceramic dispersants (particles, fibers, or whiskers).



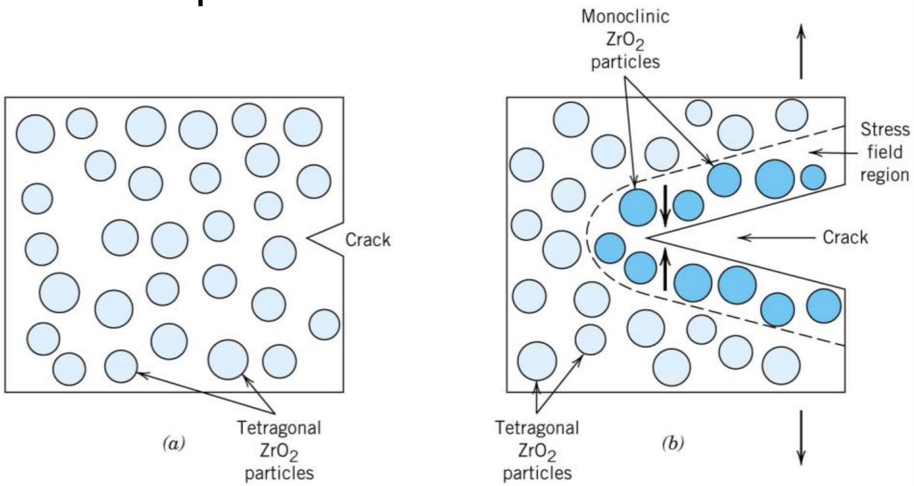
$$K_{Ic} = \left(\frac{Y\,2\sigma_o}{\rho_t} \right) \sqrt{\pi a^3}$$



Transformation Toughening

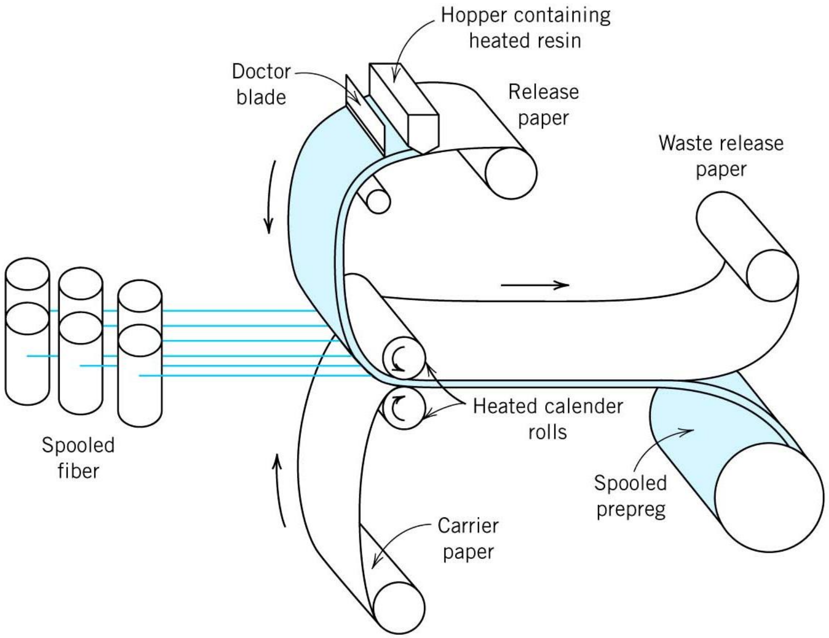


- Stress promotes transformation from one phase to another with a higher volume, causing a compressive stress.
  - Partially stabilized zirconia particles (tetragonal phase made to be stable at ambient conditions instead of the expected and higher volume monoclinic phase).
  - An approaching crack can be pinched shut.



(Mostly) uniaxial fiber composite fabrication

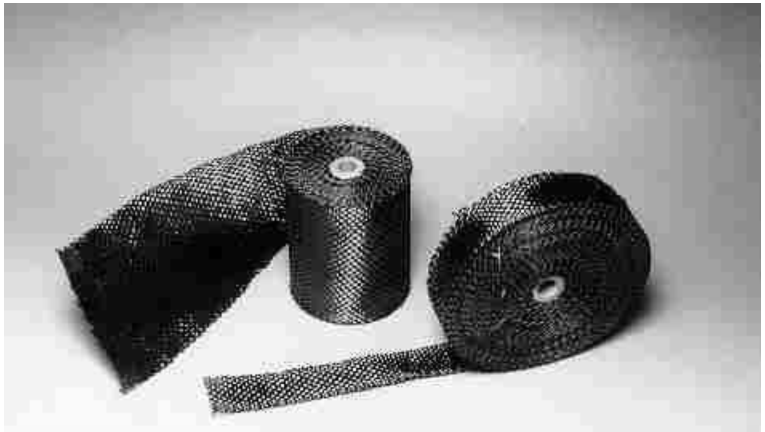
- **<u>Prepreg</u>** (preimpregnated with resin)
  - Resin added to fibers, then rolled (pressed) and heated into sheets, rolled and sold.
  - Cures at or just above room temperature, so generally must be stored at 0C.



- Designed for record solo non-stop round-world flight.
- Composite prepreg materials: carbon fibre and epoxy.
  - stiff carbon fibres in long wings
  - sandwich of carbon and epoxy with aramid honeycomb for skin.
- Same materials as SpaceShipOne, X Prize winner for "tourist" space flight.

http://www.netcomposites.com/news.asp?2714

Start to finish

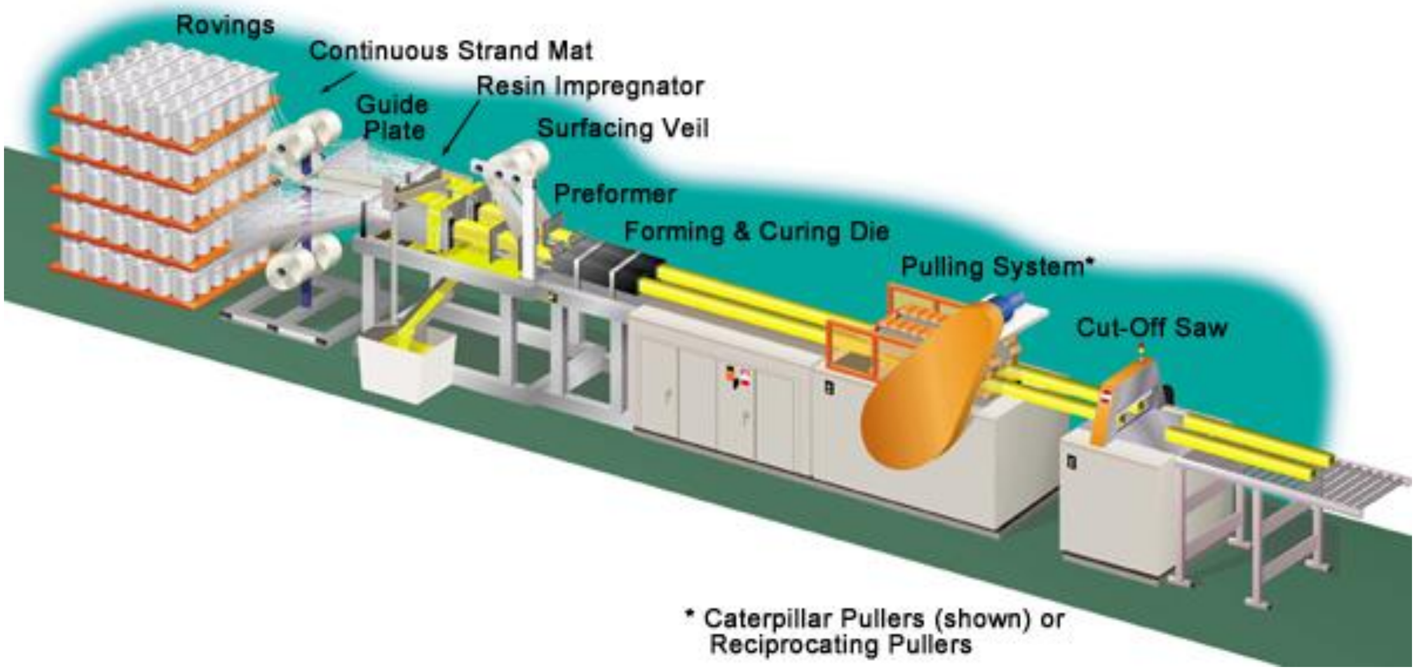


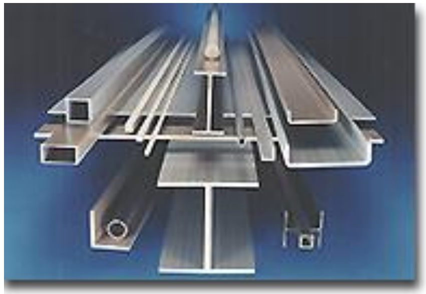
http://www.acp-composites.com/ACP-CAT.HTM

http://www.owenscorning.com/

More (mostly) uniaxial fiber composite fabrication

- **Pultrusion**
  - For continuous shape structures (rods, beams, pipes)
  - Start with fibers, impregnate with polymer resin, pass through a die of near final shape, pass through a die of final shape with simultaneous heating to cure (fix) the part, roll to finish, cut and sell.
  - Structures are high strength to weight, corrosion resistant, non conductive, electromagnetically transparent, have better thermal expansion than steel and aluminum, and work from -70 to 80 F.

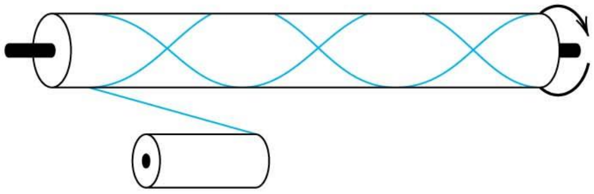


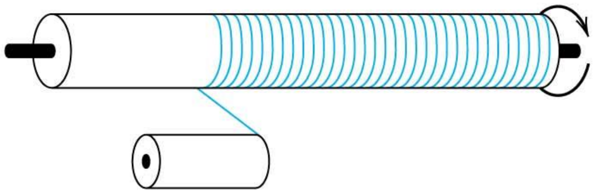


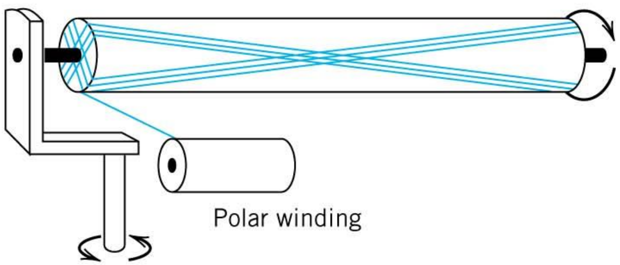
http://www.acmanet.org/pic/products/description.htm

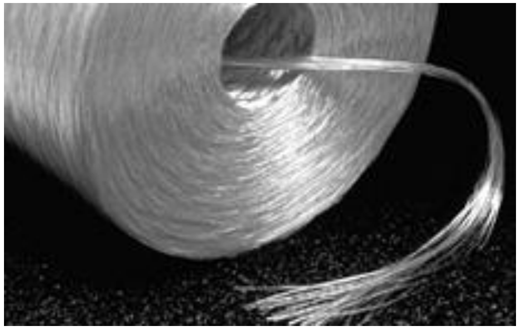
Fiber composite fabrication, not uniaxial

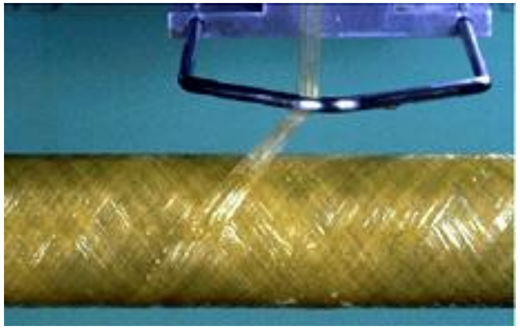
- Filament **<u>Winding</u>**
  - Wind either fibers or narrow prepreg structures around a mandrel using various patterns.
  - High strength to weight.
  - “Most economically attractive.”


Helical winding


Circumferential winding


Polar winding

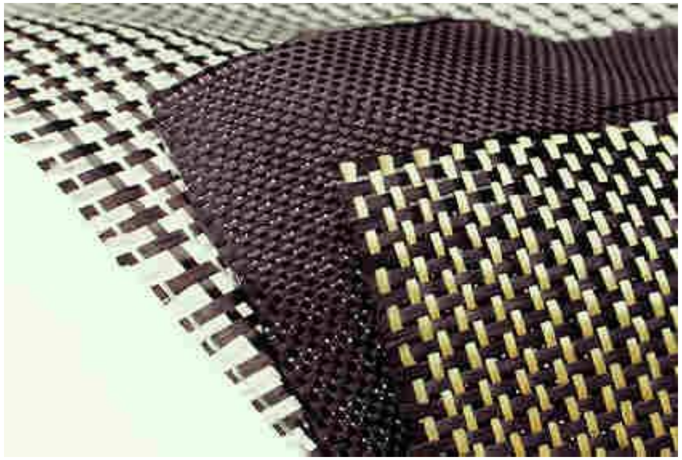




http://www.owenscorning.com/

Hybrids

- If we want to improve properties of a given part, we can make a composite.
- If we want to improve the composite, we can tweak the particle or fiber size (length), distribution, material, interface, or orientation.
- If we want to improve it still further, we might combine benefits from multiple composite types
  - Glass and carbon fibers



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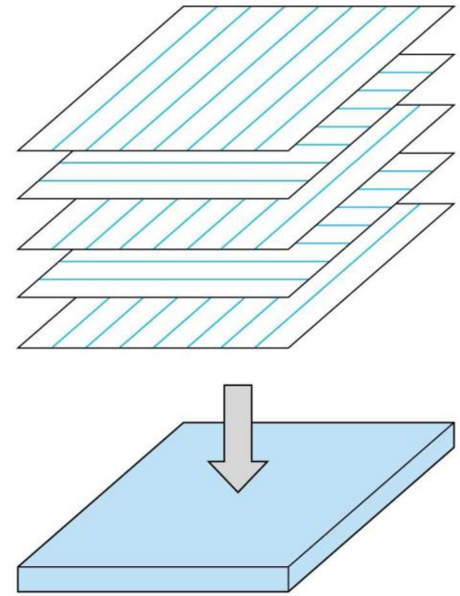
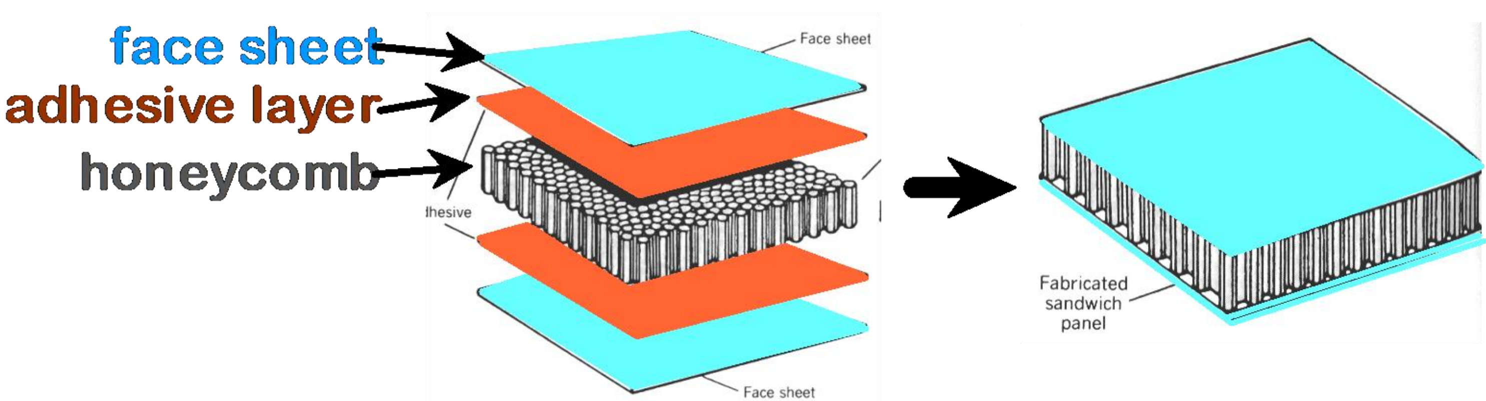
Structural Composites



- Laminar composites
  - 2-d sheets or panels
  - Stacked and bound with orientation in altering directions
  - Improved strength in 2 or more directions in 2d, but not 3d.

- Sandwich Panels
  - Face sheets with uniform strength are separated by a core or honeycomb.



SUMMARY

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