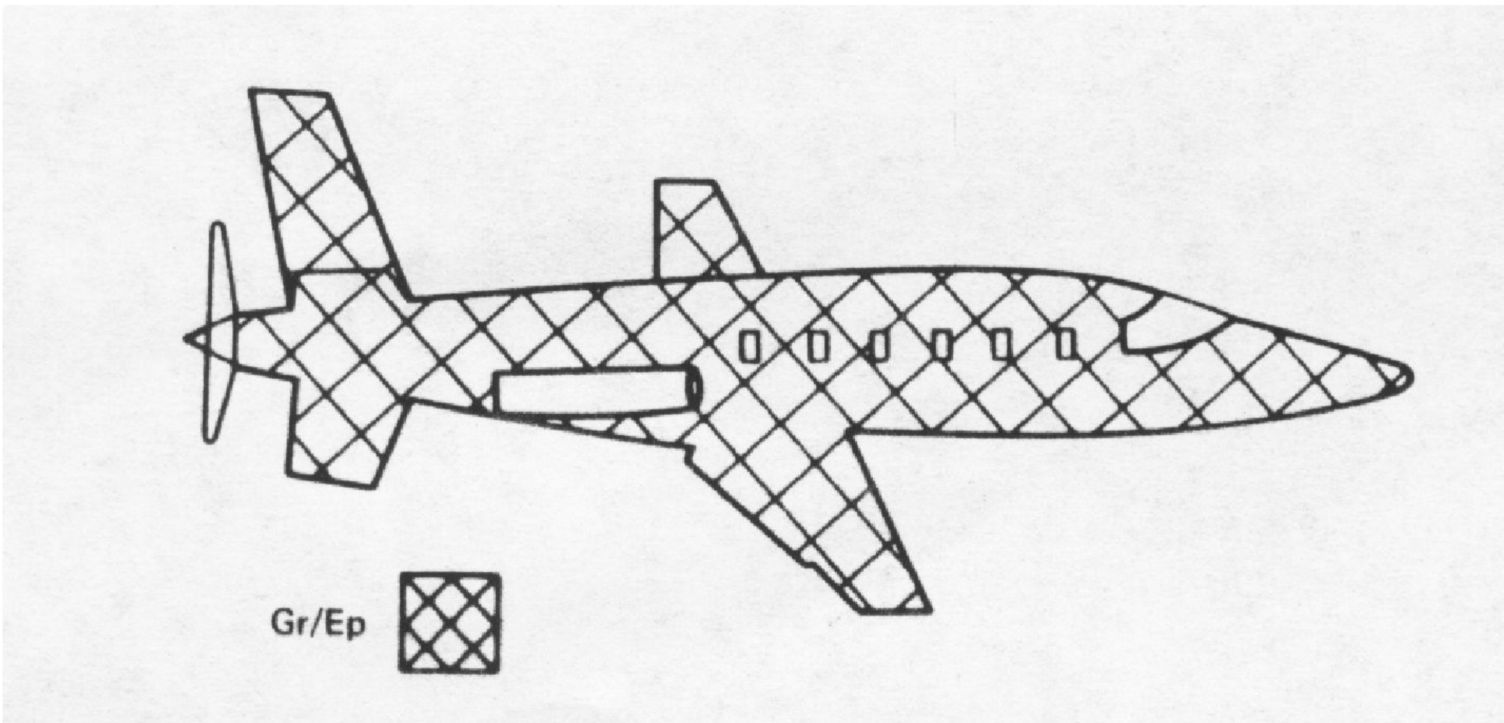
Composite Materials

Introduction

- A Composite material is a material system composed of two or more **macro constituents** that differ in shape and chemical composition and which are insoluble in each other. The history of composite materials dates back to early 20th century. In 1940, fiber glass was first used to reinforce epoxy.
- Applications:
  - Aerospace industry
  - Sporting Goods Industry
  - Automotive Industry
  - Home Appliance Industry

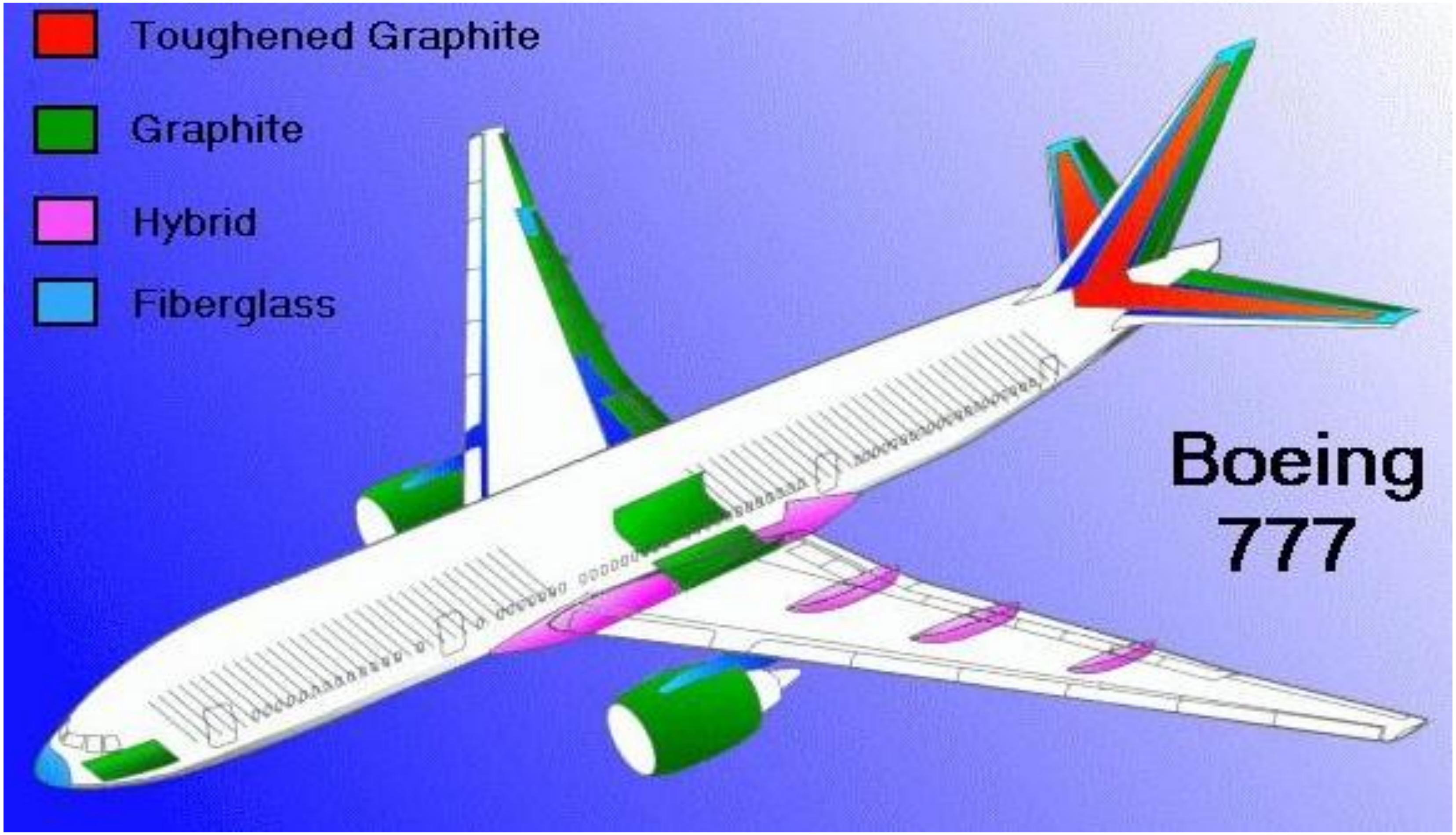
Advanced Aerospace Application:

Lear Fan 2100 "all-composite" aircraft



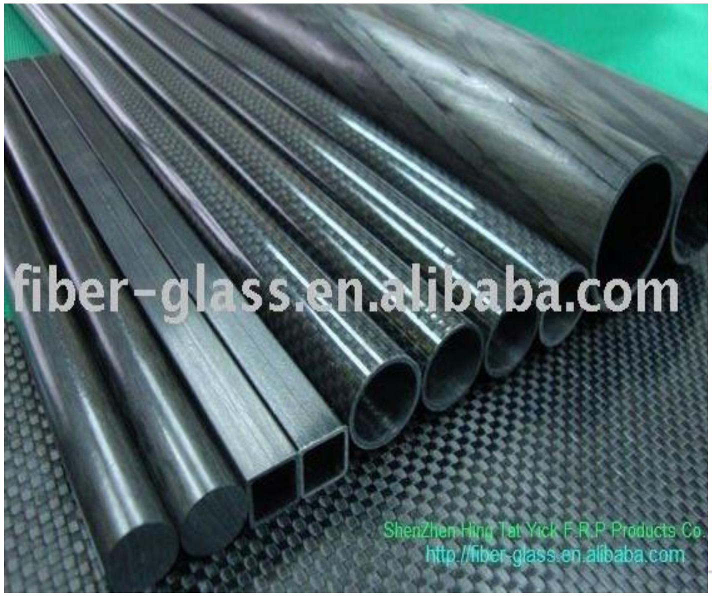
Advanced Aerospace Application:

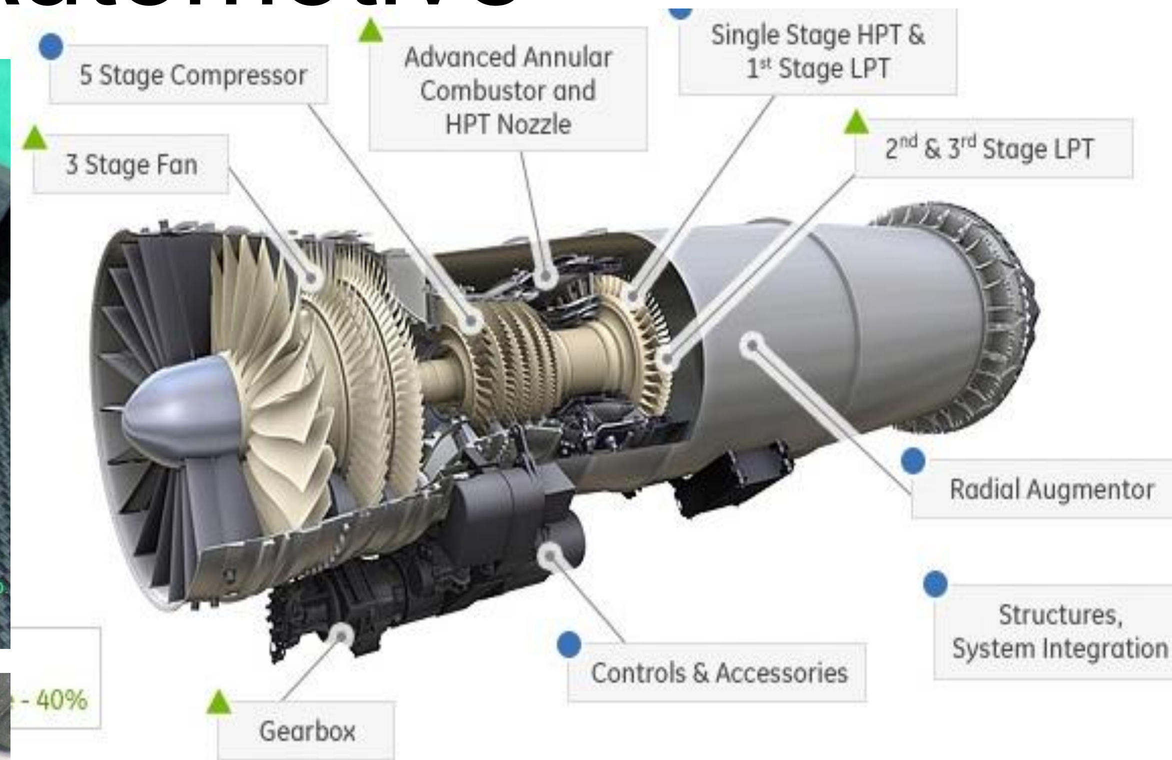
Boeing 767 ,777, 787 airplanes w/ the latest, full wing box is composite):



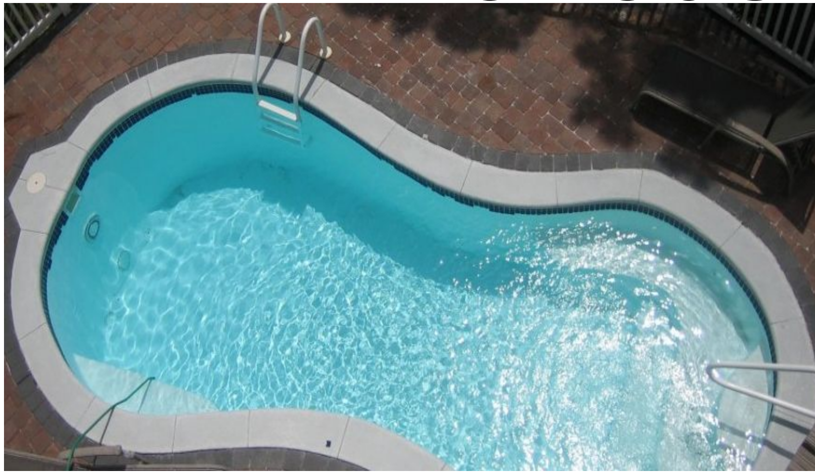
Sporting Goods

Automotive


fiber-glass.en.alibaba.com
ShenZhen Hing Tat Yick F.R.P Products Co.
http://fiber-glass.en.alibaba.com


5 Stage Compressor
Advanced Annular Combustor and HPT Nozzle
Single Stage HPT & 1st Stage LPT
3 Stage Fan
2nd & 3rd Stage LPT
Radial Augmentor
Structures, System Integration
Controls & Accessories
Gearbox
- 40%

Various applications



Terminology/Classification

- Composites:
  -- Multiphase material w/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

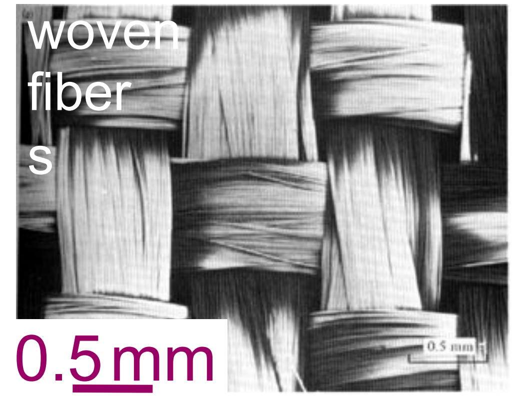
  metal → MMC, ceramic → CMC, polymer → PMC
- Dispersed phase:
  -- Purpose: enhance matrix properties.

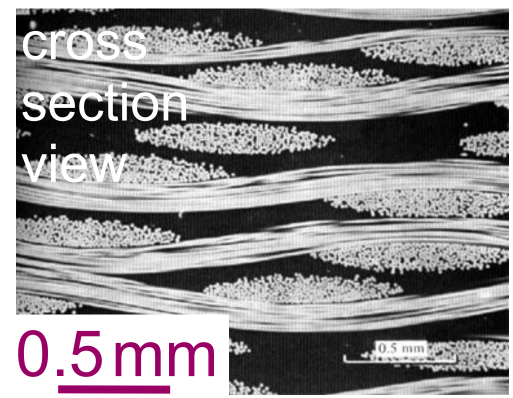
  MMC: increase σ_y, *TS*, creep resist.

  CMC: increase K_c

  PMC: increase *E*, σ_y, *TS*, creep resist.

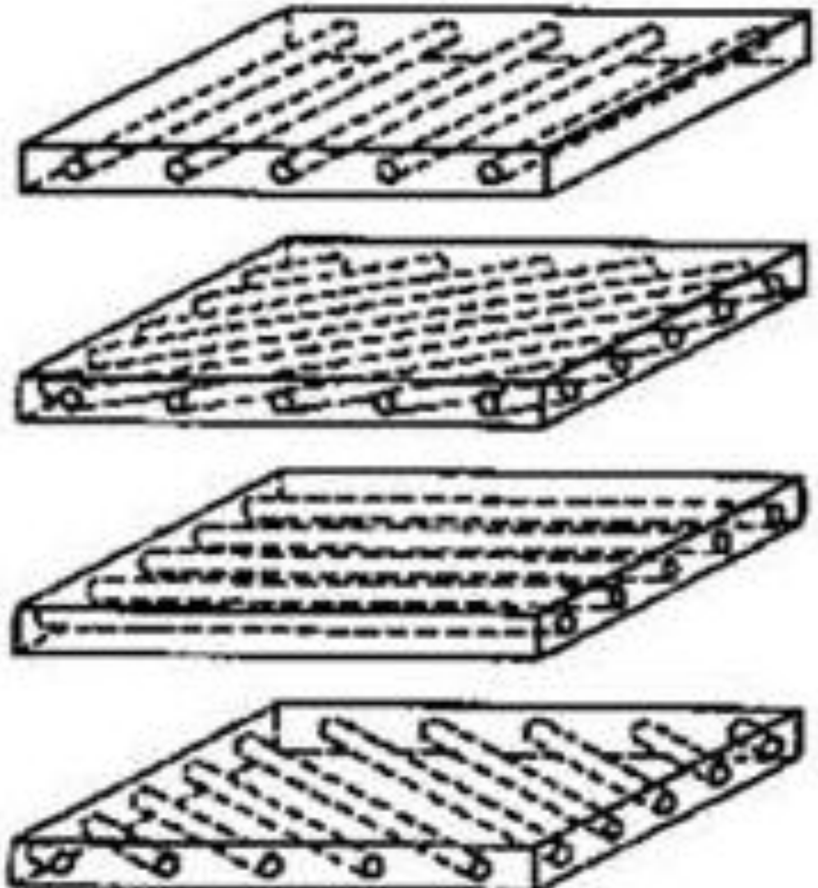
  -- Classification: Particle, fiber, structural



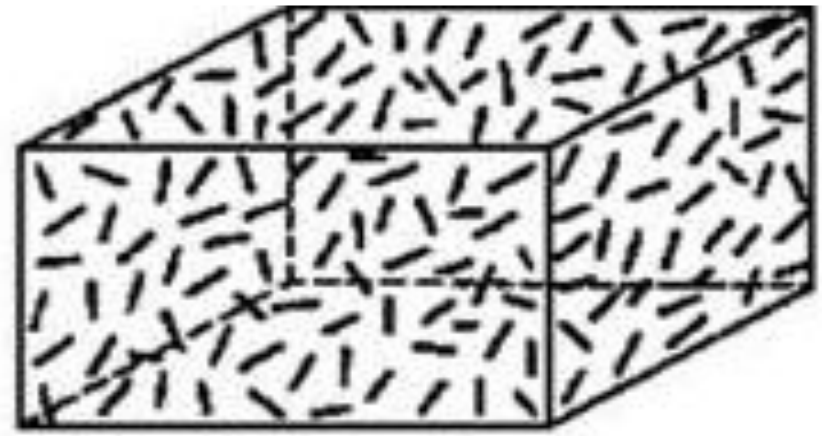


Elyaf dokuma

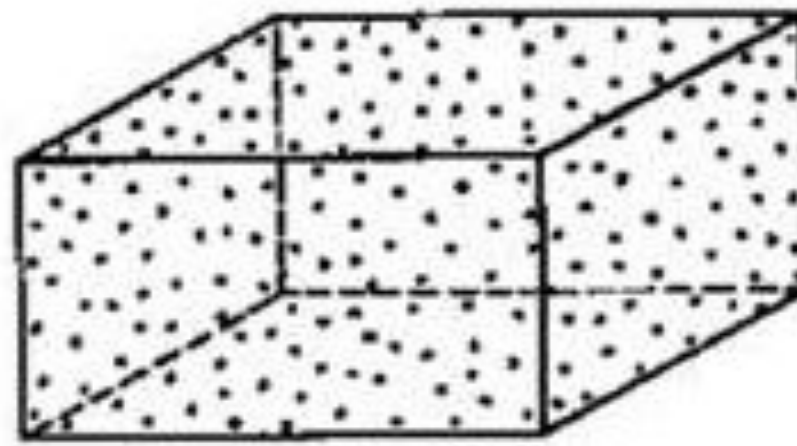
Composite Structural Organization: the design variations



Continuous Fibers



Short Fibers



Particles

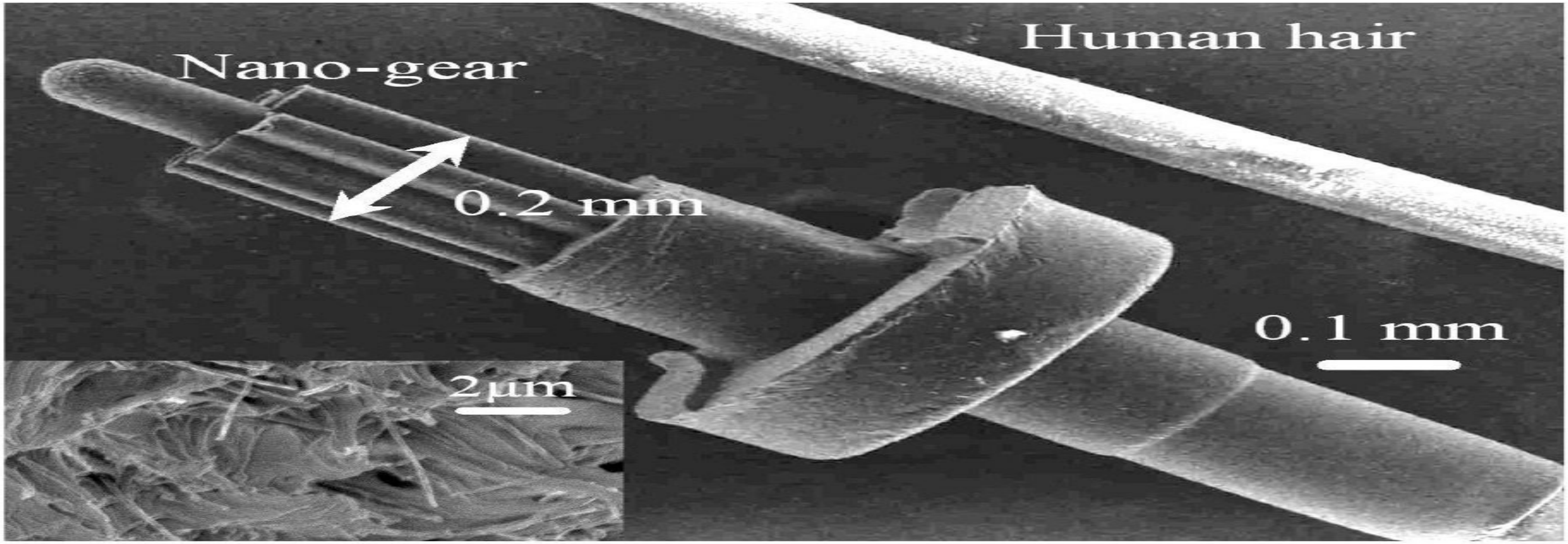


Fig. 1 SEM image of the smallest working gear (carbon nanotube/nylon composite); inset exhibits the fractured surface.

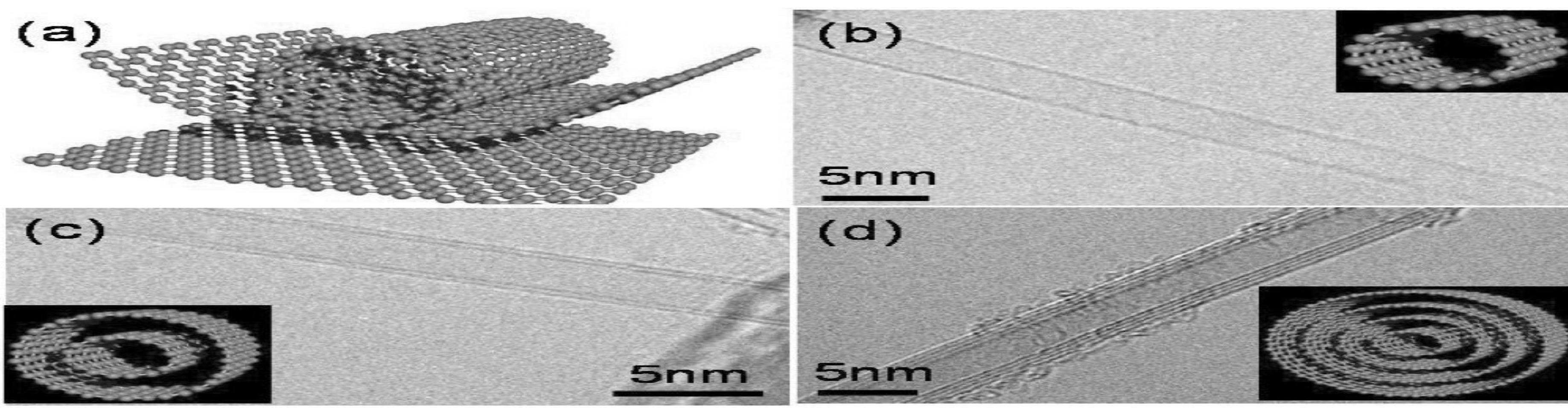
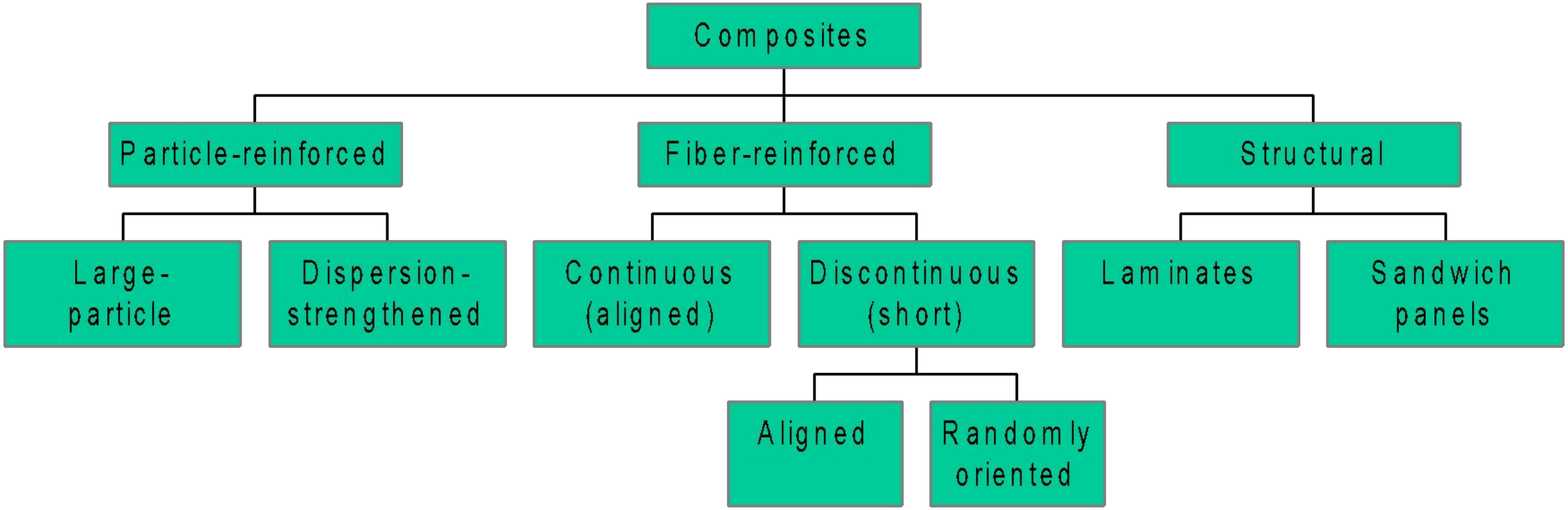


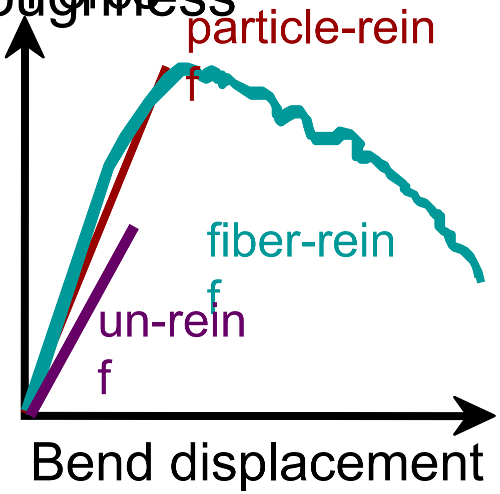
Fig. 2 (a) Schematic diagram of an individual layer of honeycomb-like carbon called graphene and how this could be rolled in order to form a carbon nanotube; (b)–(d) HR-TEM images of single, double- and multi-walled carbon nanotubes (insets are their corresponding images).

Composite Survey

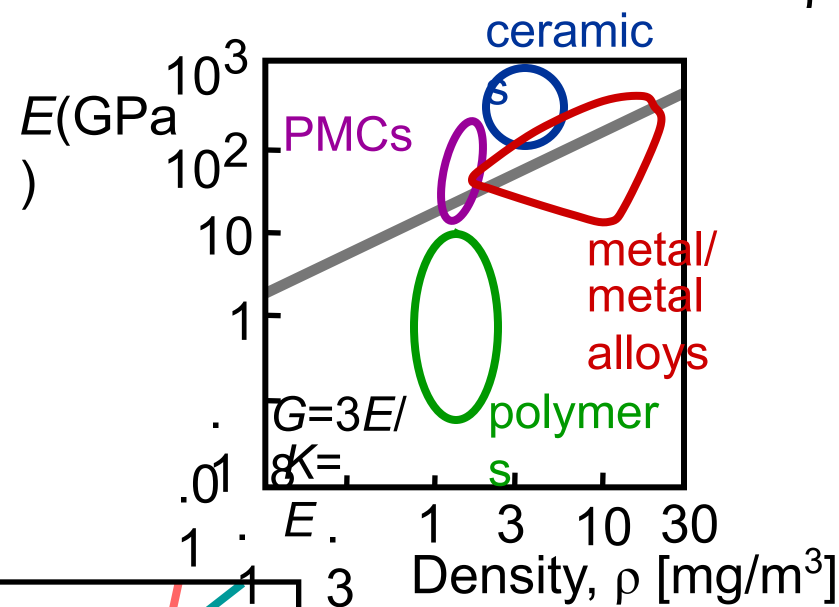


Composite Benefits

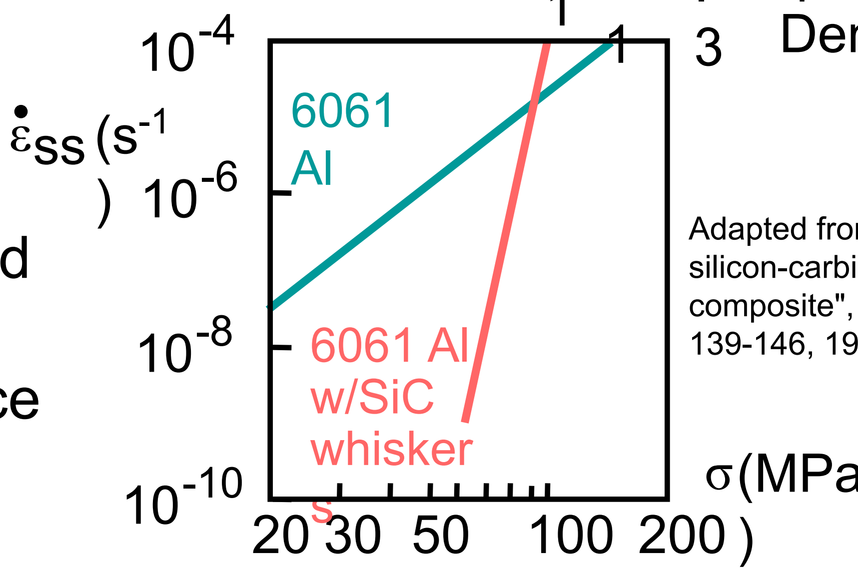
- CMCs: Increased toughness



- PMCs: Increased E/ρ



- MMCs: Increased creep resistance



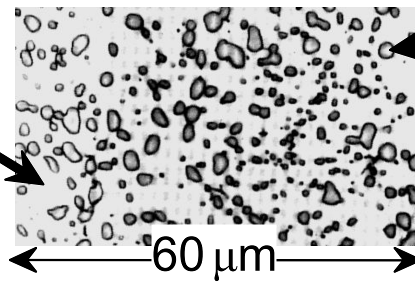
Adapted from T.G. Nieh, "Creep rupture of a silicon-carbide reinforced aluminum composite", *Metall. Trans. A* Vol. 15(1), pp. 139-146, 1984. Used with permission.

Composite Survey: Particle-I

Particle-reinforced | Fiber-reinforce d | Structura l

- Examples:
  - Spheroidite steel

    matrix: ferrite (α) (ductile)

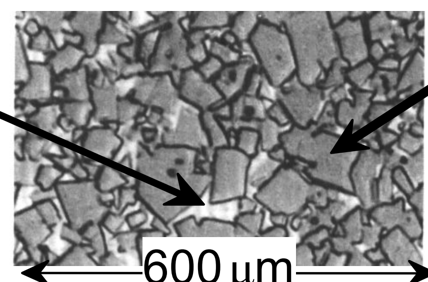
    

    particles: cementit e (Fe_3C) (brittle)

  - WC/Co cemented carbide

    matrix: cobalt (ductile)

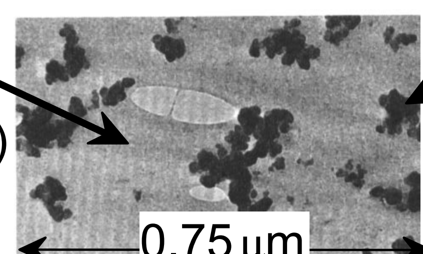
    V_m: 5-12 vol%!

    particles: WC (brittle, hard)

  - Automobile tires

    matrix: rubber (soft, ductile)

    particles: C (stiffer)

Composite Survey: Particle-II

Particle-reinforced | Fiber-reinforced | Structural

Concrete – gravel + sand + cement

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

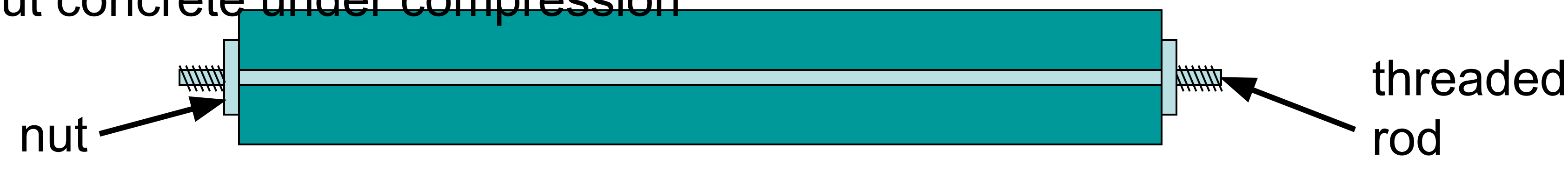
Reinforced concrete - Reinforce with steel rebar or remesh

- 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 rod under tension but concrete under compression



Composite Survey: Particle-III

Particle-reinforced | Fiber-reinforced | Structural

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

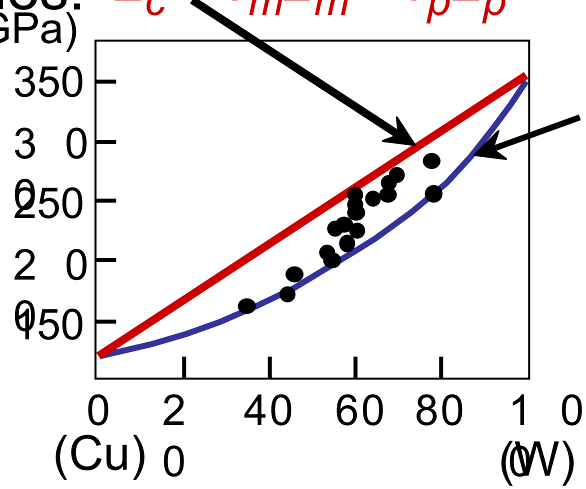
upper limit: "rule of mixtures"

$$E_c = V_m E_m + V_p E_p$$

lower limit:

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

Data:
Cu matrix
w/tungsten
particles



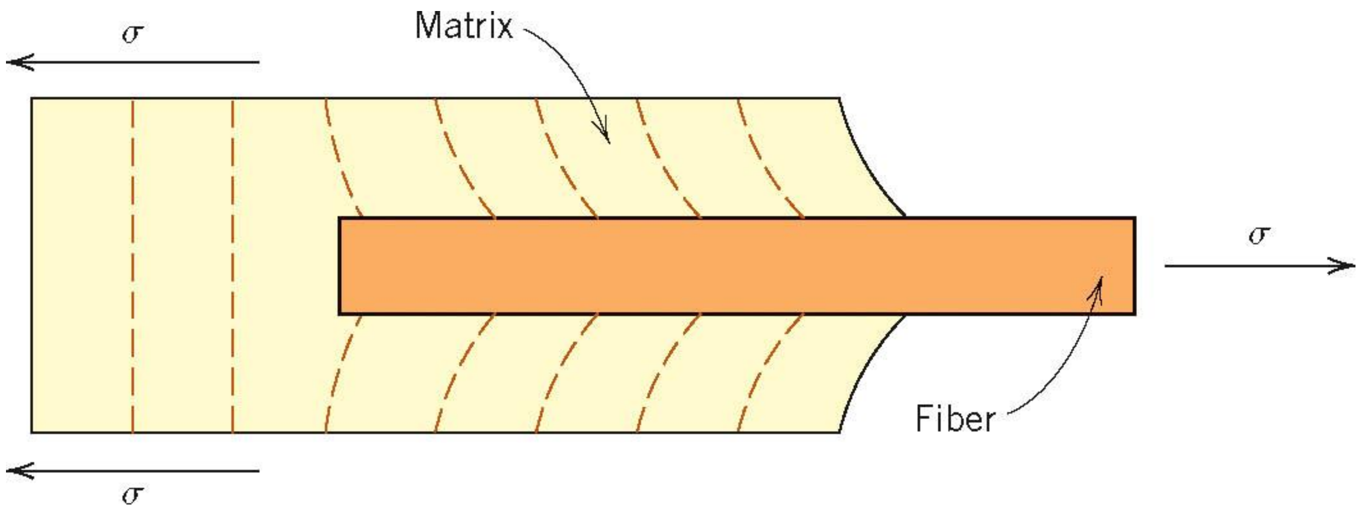
- Application to other properties:
  - -- Electrical conductivity, σ_e: Replace E in the above equations with σ_e.
  - -- Thermal conductivity, k: Replace E in above equations with k.

Composite Survey: Fiber

Particle-reinforced | Fiber-reinforced | Structural

- Fibers themselves are 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 and environmentally protects them**

Fiber Loading Effect under Stress:



Composite Survey: Fiber

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

- Critical fiber length (l_C) for effective stiffening & strengthening:

fiber strength in tension → σ_f; fiber diameter → d; shear strength of **fiber-matrix** interface → τ_c

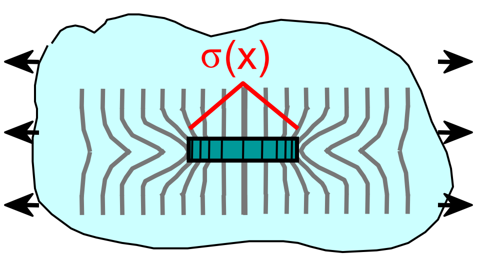
$$\text{fiber length} > 15\frac{\sigma_f d}{\tau_c}$$

- Ex: For fiberglass, a fiber length > 15 mm is needed since this length provides a "Continuous fiber" based on usual glass fiber properties

- Why? Longer fibers carry stress more efficiently!

Shorter, thicker fiber:

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

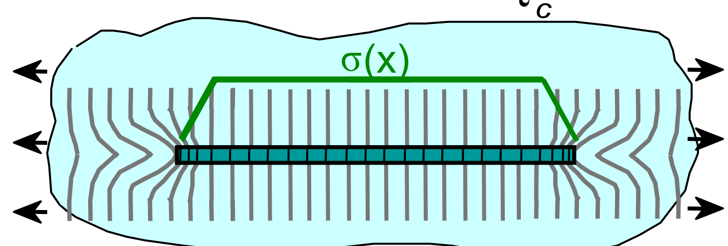


Poorer fiber efficiency

Adapted from Fig. 16.7, *Callister 7e*.

Longer, thinner fiber:

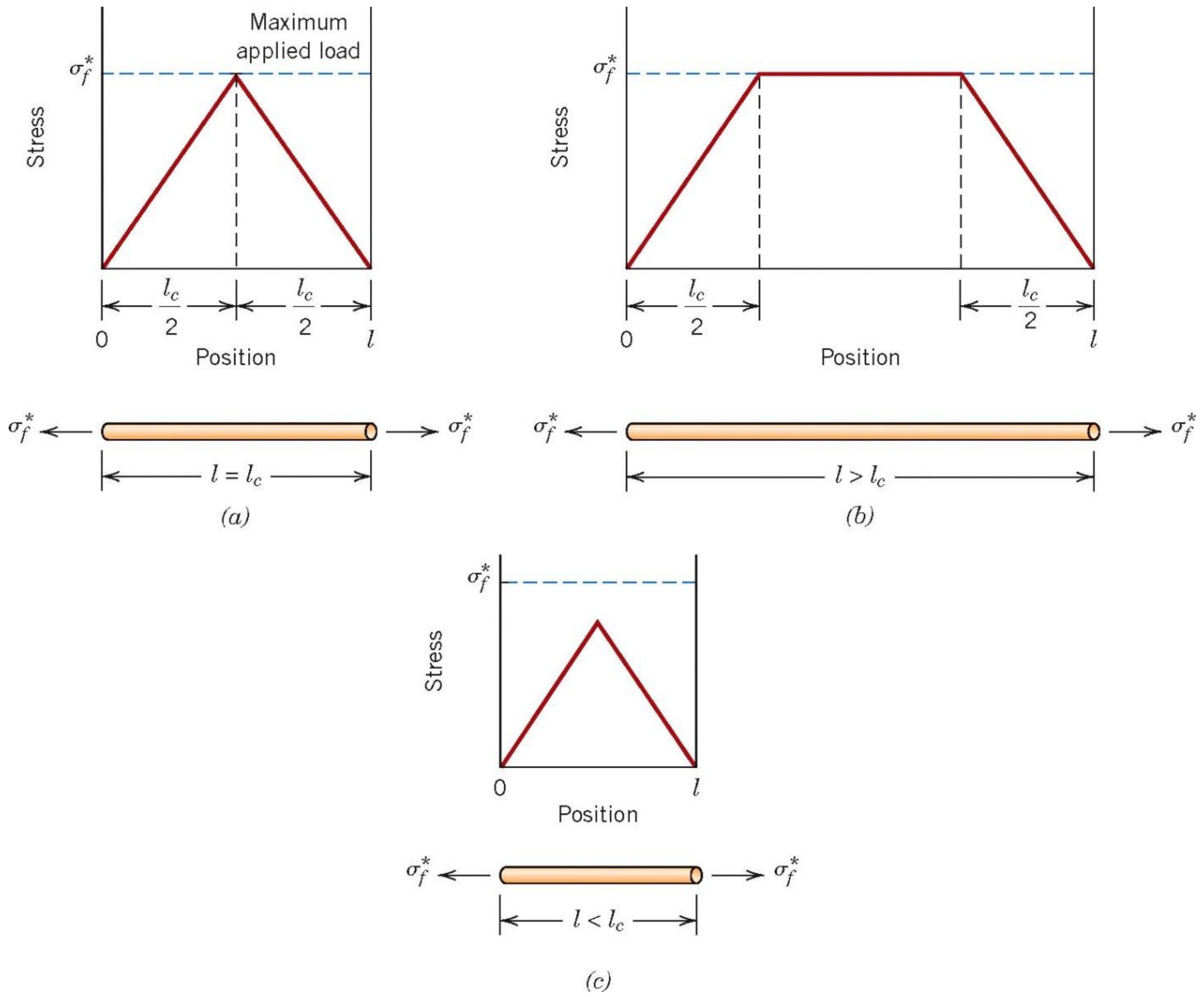
$$\text{fiber length} > 15\frac{\sigma_f d}{\tau_c}$$



Better fiber efficiency

Fiber Load Behavior under Stress:

$$l_c = \frac{\sigma^*{}_f d}{2\tau_c}$$

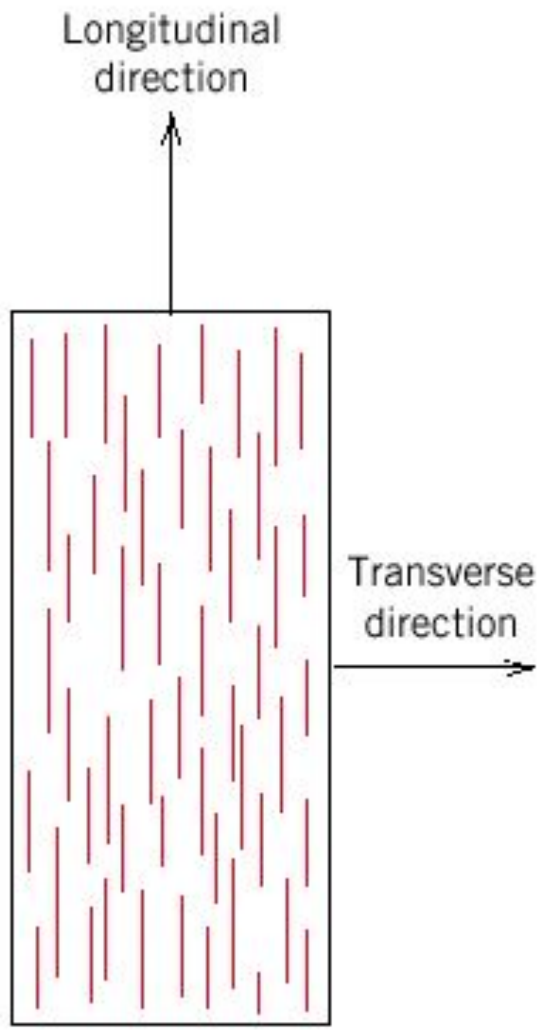


Composite Survey: Fiber

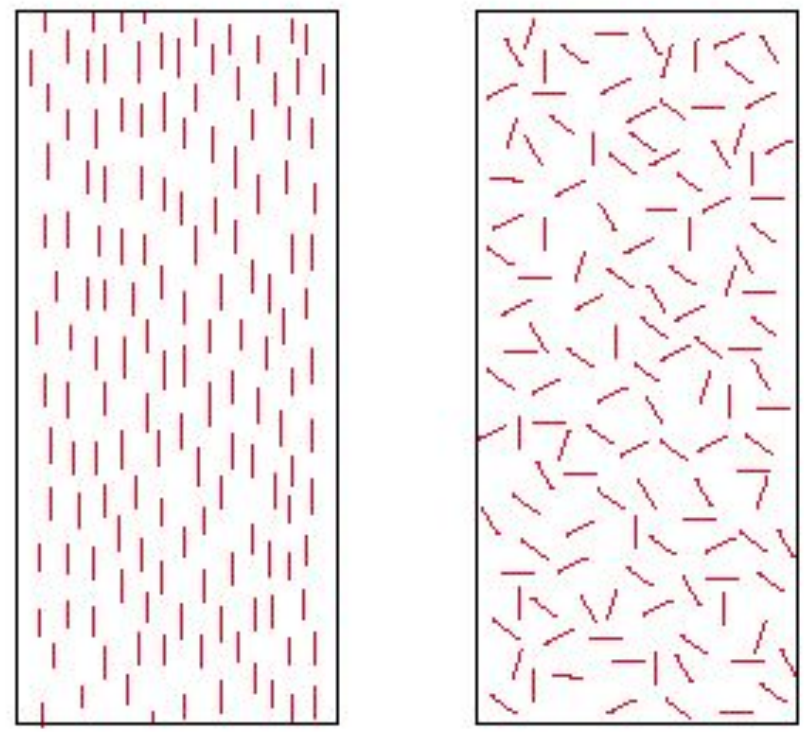
Particle-reinforced | Fiber-reinforced | Structural

- 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



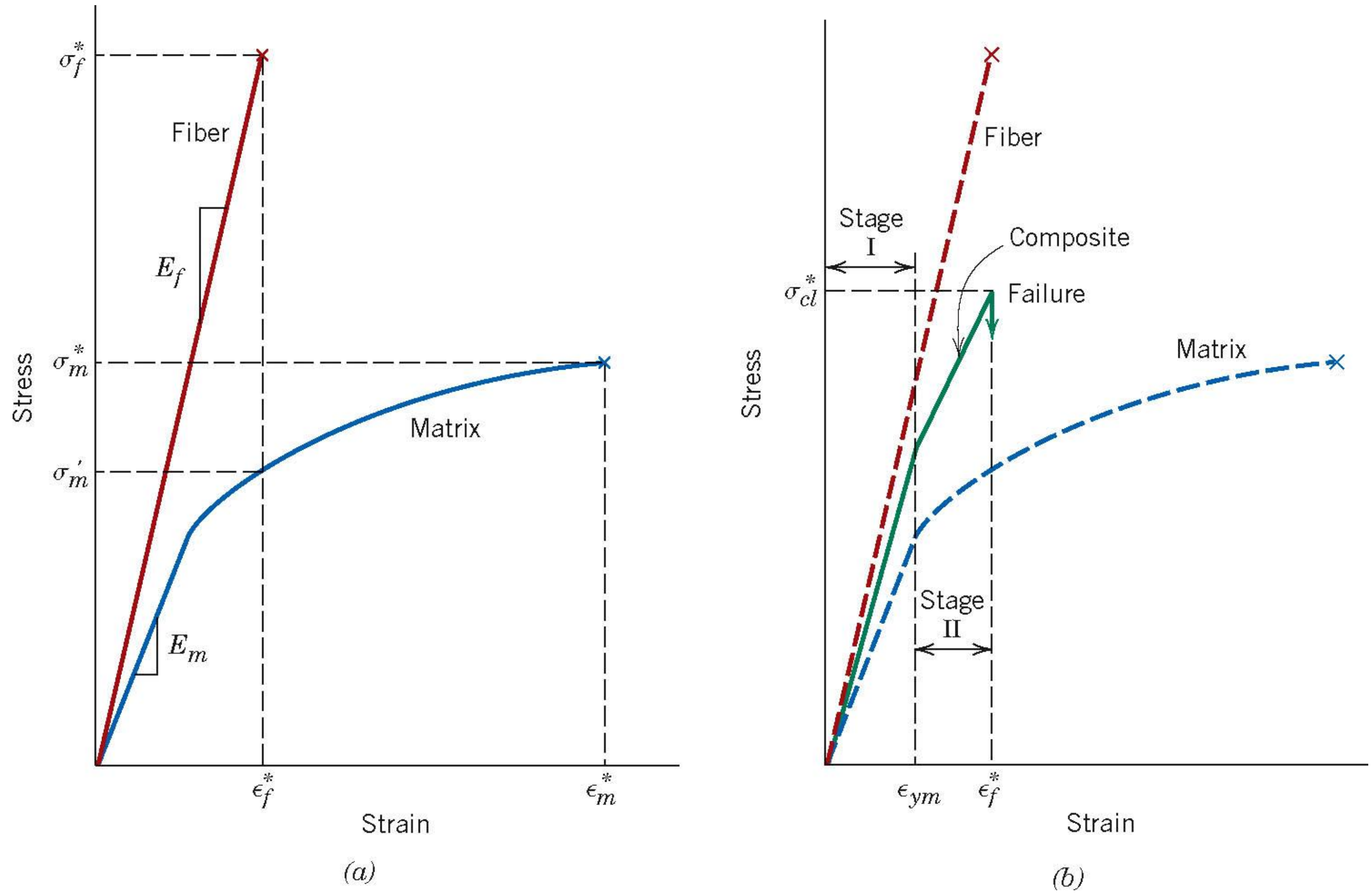
Adapted from Fig. 16.8, *Callister 7e*.



aligned continuous

aligned random
discontinuous

Behavior under load for Fibers & Matrix



Composite Strength: Longitudinal Loading

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

- Longitudinal deformation

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

volume fraction — isostrain

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

longitudinal (extensional) modulus

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

f = fiber
m = matrix

Remembering: E = σ/ε and note, this model corresponds to the "upper bound" for particulate composites

Composite Strength: Transverse Loading

- In transverse loading the fibers carry less of the load and are in a state of 'isostress'

$$\sigma_c = \sigma_m = \sigma_f = \sigma \qquad \varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f$$

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

transverse modulus

Remembering: E = σ/ε and note, this model corresponds to the "lower bound" for particulate composites

An Example:

Example: Given an epoxy/carbon unidirectional continuous fiber composite with $V_f = .60$ and the following fiber and matrix properties:

	Ultimate Strength σ_u psi	Modulus E_L psi
Epoxy	$\sigma_{um} = 8400$	$E_m = 550{,}000$
Carbon Fibers	$\sigma_{uf} = 305{,}000$	$E_f = 58{,}000{,}000$

UTS, SI	Modulus, SI
57.9 MPa	3.8 GPa
2.4 GPa	399.9 GPa

a) Calculate the longitudinal stiffness (moduli) of the composite (E_{cL}):

$$E_{cL} = E_f V_f + E_m V_m = 58{,}000{,}000(.60) + 550{,}000(.40) = 35{,}020{,}000 \text{ psi}$$

(241.5 GPa)

b) Calculate the transverse stiffness (moduli) of the composite (E_{cT}):

$$E_{cT} = \frac{E_f E_m}{V_f(E_m - E_f) + E_f} = \frac{58{,}000{,}000 \cdot 550{,}000}{.60(550{,}000 - 58{,}000{,}000) + 58{,}000{,}000} = 1{,}355{,}716 \text{ psi}$$

(9.34 GPa)

The transverse moduli ($E_{cT} = 1{,}355{,}716$ psi) is only 3.9% of the longitudinal moduli ($E_{cL} = 35{,}020{,}000$ psi).

Note: (for ease of conversion)

6870 N/m^2 per psi!

Composite Strength

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

- Estimate of E_c and TS for discontinuous fibers:

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

-- Elastic modulus in fiber direction:

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

efficiency factor:

-- aligned 1D: $K = 1$ (aligned $||$)
-- aligned 1D: $K = 0$ (aligned $\perp$)
-- random 2D: $K = 3/8$ (2D isotropy)
-- random 3D: $K = 1/5$ (3D isotropy)

Values from Table 16.3, *Callister 7e*. (Source for Table 16.3 is H. Krenchel, *Fibre Reinforcement*, Copenhagen: Akademisk Forlag, 1964.)

-- TS in fiber direction:

$$(TS)_c = (TS)_m V_m + (TS)_f V_f \qquad \text{(aligned 1D)}$$

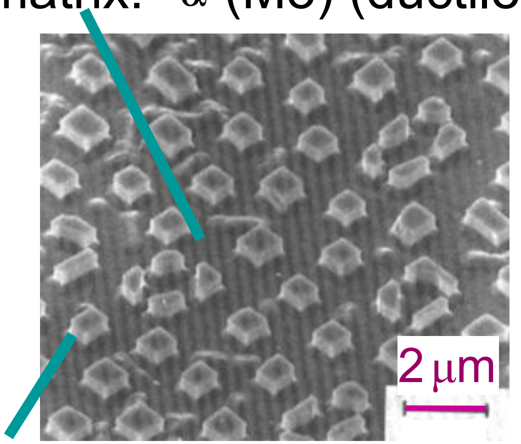
Composite Survey: Fiber

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

- Aligned Continuous fibers
- Examples:

-- Metal: $\gamma'(Ni_3Al)$-α(Mo) by eutectic solidification.

matrix: α (Mo) (ductile)

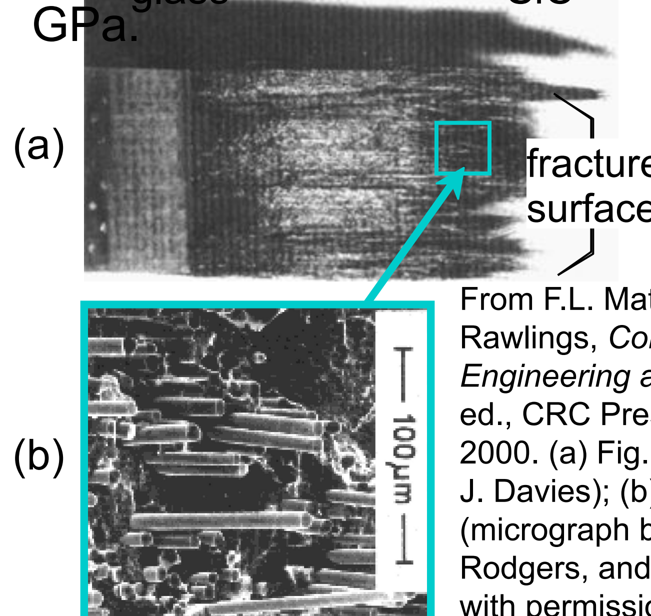


fibers: γ' (Ni_3Al) (brittle)

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.

-- Ceramic: Glass w/SiC fibers formed by glass slurry

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



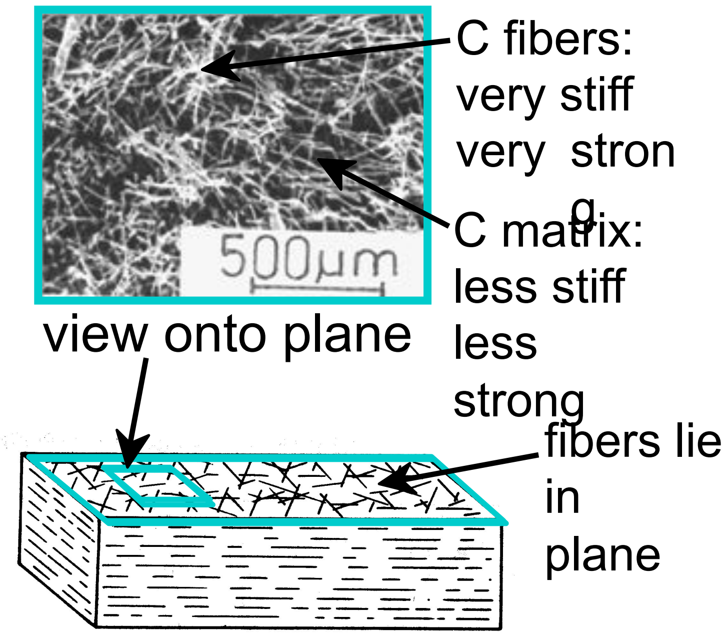
From F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. (a) Fig. 4.22, p. 145 (photo by J. Davies); (b) Fig. 11.20, p. 349 (micrograph by H.S. Kim, P.S. Rodgers, and R.D. Rawlings). Used with permission of CRC Press, Boca Raton, FL.

Composite Survey: Fiber

Particle-reinforced | Fiber-reinforce d | Structura l

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

(b)



(a)

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

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

efficiency factor:

-- random 2D: K = 3/8 (2D isotropy)

-- random 3D: K = 1/5 (3D isotropy)

Looking at strength:

$$l > l_C$$

$$\sigma_{cd}^{*} = \sigma_{f}^{*} V_f \left(1 - \frac{l_C}{2l}\right) + \sigma_{m}^{'} \left(1 - V_f\right)$$

where σ_f^* is fiber fracture strength

& $\sigma_m^{'}$ is matrix stress when composite fails

$$l < l_C$$

$$\sigma_{cd'}^{*} = \frac{l\tau_C}{d} V_f + \sigma_{m}^{'} \left(1 - V_f\right)$$

where: d is fiber diameter &

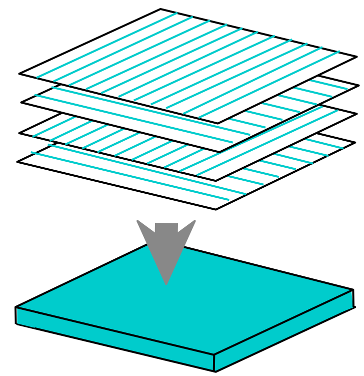
τ_C is smaller of Matrix Fiber shear strength

or matrix shear yield strength

Composite Survey: Structural

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

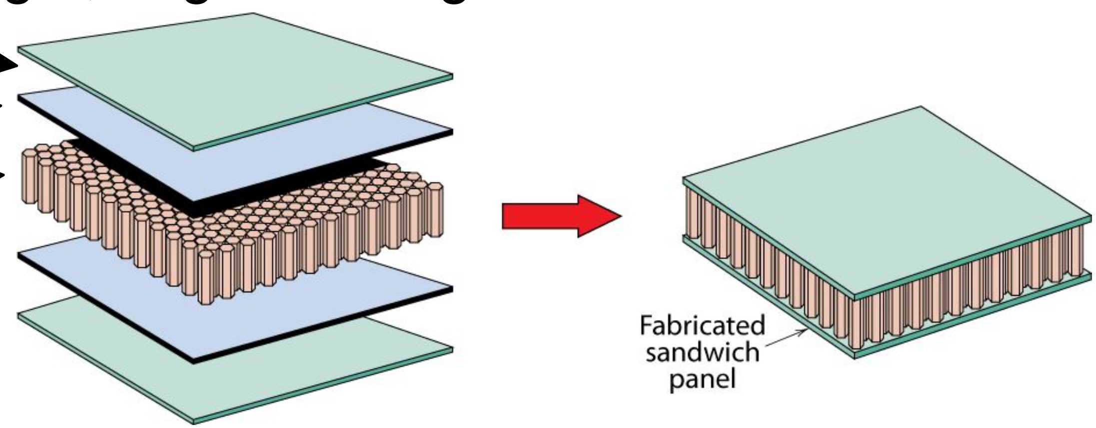
- Stacked and bonded fiber-reinforced sheets
  - -- stacking sequence: e.g., 0º/90º or 0°/45°/90º
  - -- benefit: balanced, in-plane stiffness



Adapted from Fig. 16.16, *Callister 7e*.

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

face sheet
adhesive layer
honeycomb



Adapted from Fig. 16.18, *Callister 7e*. (Fig. 16.18 is from *Engineered Materials Handbook*, Vol. 1, *Composites*, ASM International, Materials Park, OH, 1987.)

Composite Manufacturing Processes

- Particulate Methods: Sintering
- Fiber reinforced: Several
- Structural: Usually Hand lay-up and atmospheric curing or vacuum curing

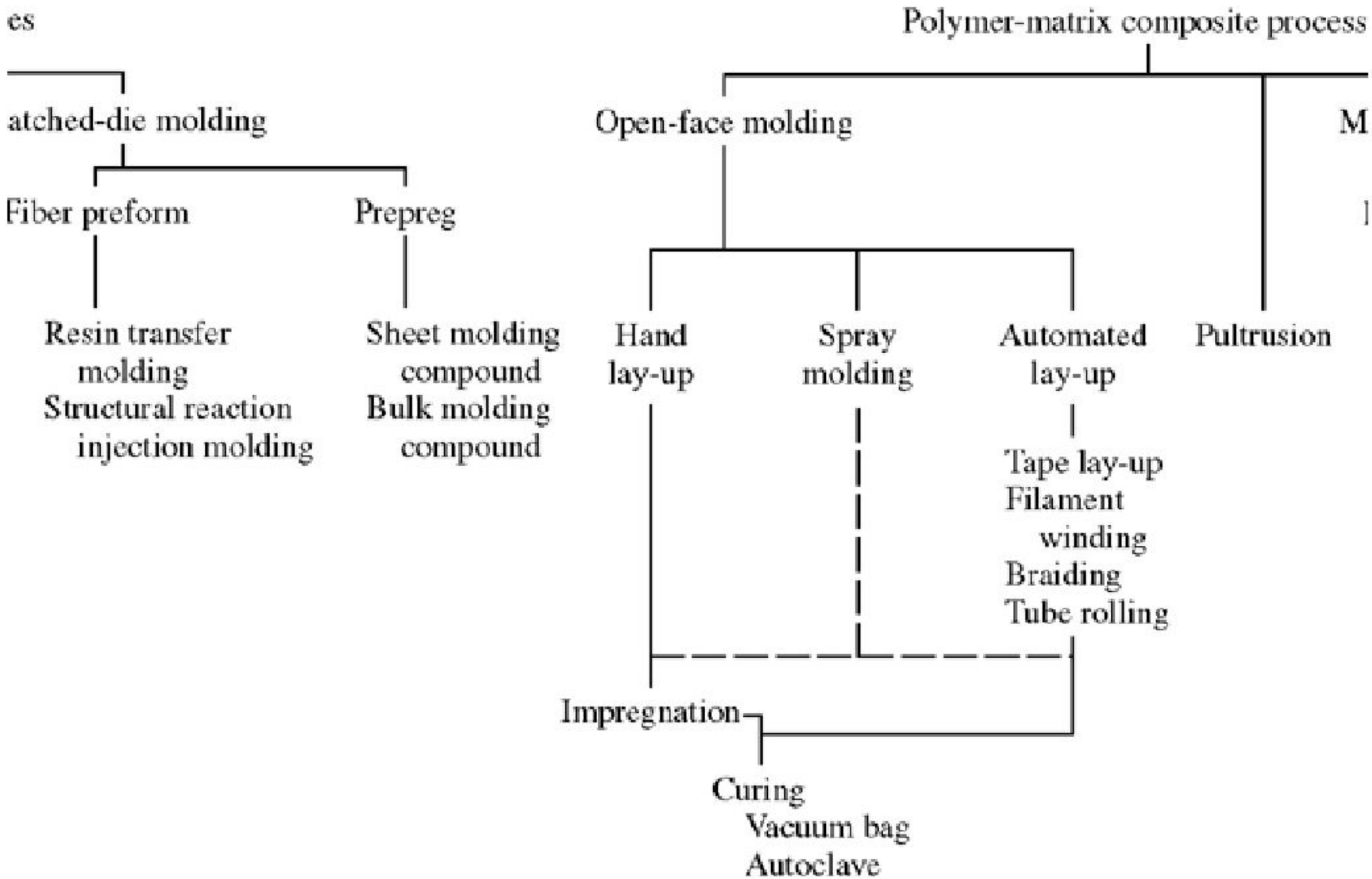

es
Polymer-matrix composite process
atched-die molding
Open-face molding
M
Fiber preform
Prepreg
Resin transfer molding
Structural reaction injection molding
Sheet molding compound
Bulk molding compound
Hand lay-up
Spray molding
Automated lay-up
Pultrusion
Tape lay-up
Filament winding
Braiding
Tube rolling
Impregnation
Curing
Vacuum bag
Autoclave

figure 15.4

Open Mold Processes

Only one mold (male or female) is needed and may be made of any material such as wood, reinforced plastic or , for longer runs, sheet metal or electroformed nickel. The final part is usually very smooth.

<u>Shaping</u>. Steps that may be taken for high quality

1. Mold release agent (silicone, polyvinyl alcohol, fluorocarbon, or sometimes, plastic film) is first applied.

2. Unreinforced surface layer (gel coat) may be deposited for best surface quality.

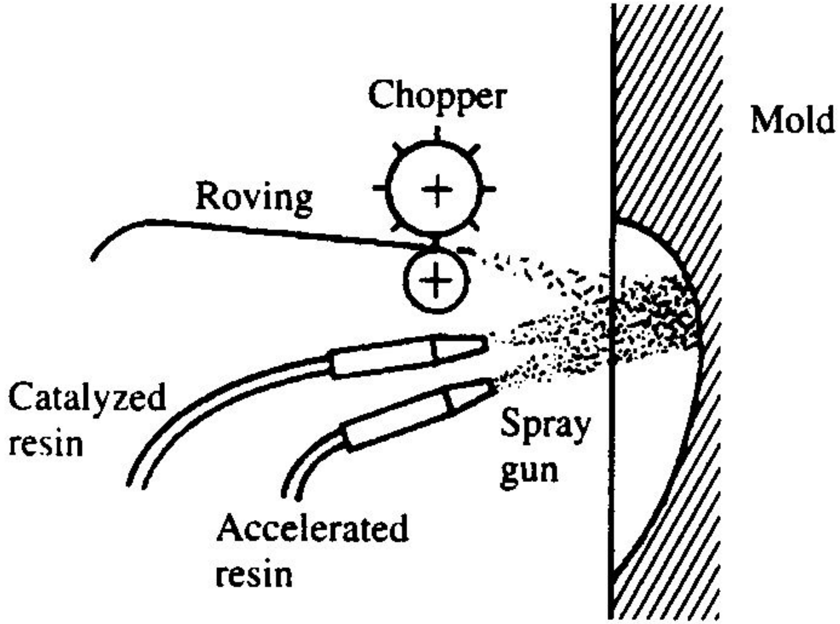
Hand Lay-Up: The resin and fiber (or pieces cut from prepreg) are placed manually, air is expelled with squeegees and if necessary, multiple layers are built up.

- Hardening is at room temperature but may be improved by heating.
- Void volume is typically 1%.
- Foam cores may be incorporated (and left in the part) for greater shape complexity. Thus essentially all shapes can be produced.
- Process is slow (deposition rate around 1 kg/h) and labor-intensive
- Quality is highly dependent on operator skill.
- Extensively used for products such as airframe components, boats, truck bodies, tanks, swimming pools, and ducts.

SPRAY-UP MOLDING

A spray gun supplying resin in two converging streams into which roving is chopped

- Automation with robots results in highly reproducible production
- Labor costs are lower

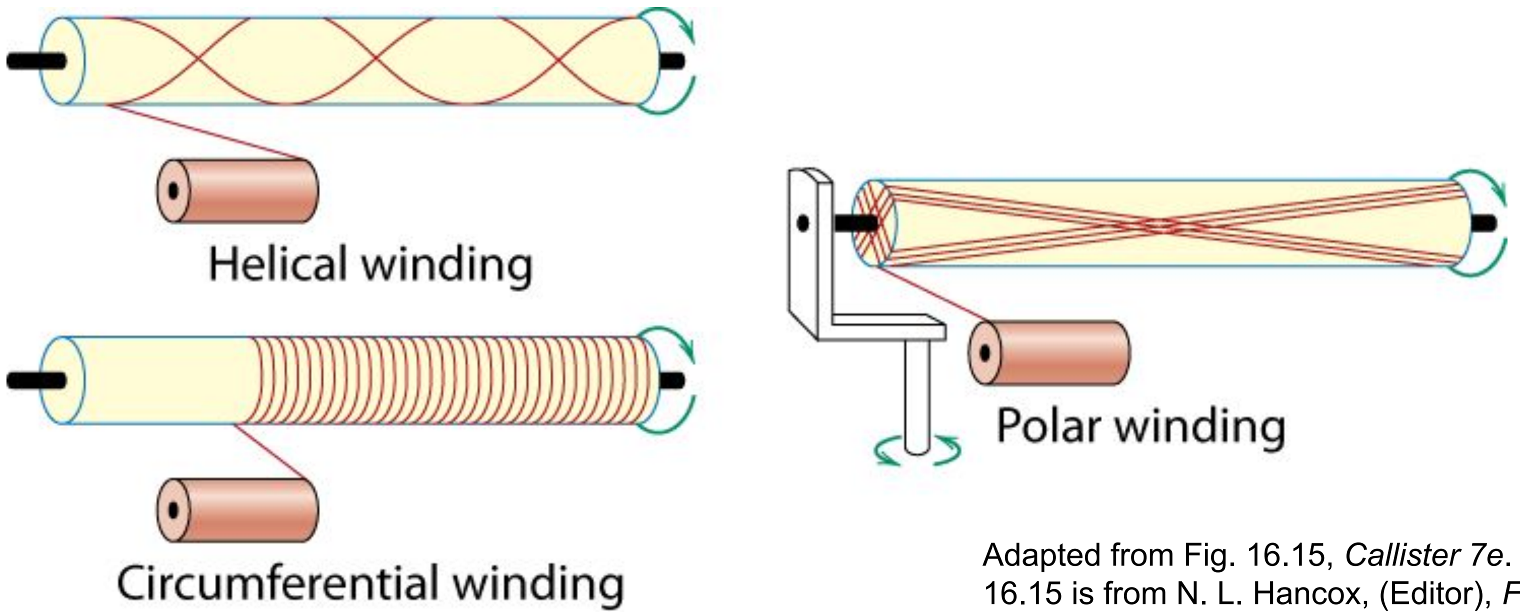


Tape-Laying Machines (Automated Lay-Up)

Cut and lay the ply or prepreg under computer control and without tension; may allow reentrant shapes to be made.

- Cost is about half of hand lay-up
- Extensively used for products such as airframe components, boats, truck bodies, tanks, swimming pools, and ducts.

- Filament Winding
  - Ex: pressure tanks
  - Continuous filaments wound onto mandrel



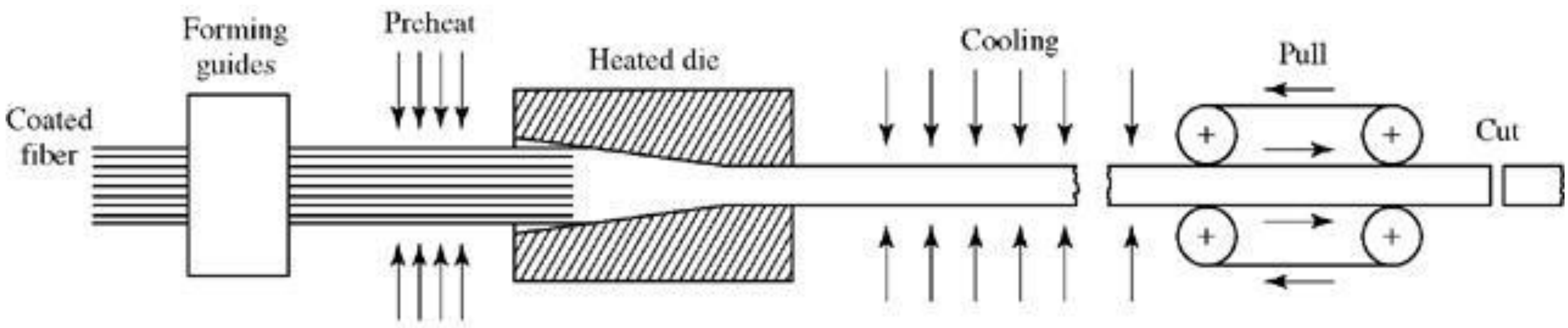
Adapted from Fig. 16.15, *Callister 7e*. [Fig. 16.15 is from N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials,* The Macmillan Company, New York, 1981.]

Filament Winding Characteristics

- Because of the tension, reentrant shapes cannot be produced.
- CNC winding machines with several degrees of freedom (sometimes 7) are frequently employed.
- The filament (or tape, tow, or band) is either precoated with the polymer or is drawn through a polymer bath so that it picks up polymer on its way to the winder.
- Void volume can be higher (3%)
- The cost is about half that of tape laying
- Productivity is high (50 kg/h).
- Applications include: fabrication of composite pipes, tanks, and pressure vessels. Carbon fiber reinforced rocket motor cases used for Space Shuttle and other rockets are made this way.

Pultrusion

- Fibers are impregnate with a prepolymer, exactly positioned with guides, preheated, and pulled through a heated, tapering die where curing takes place.

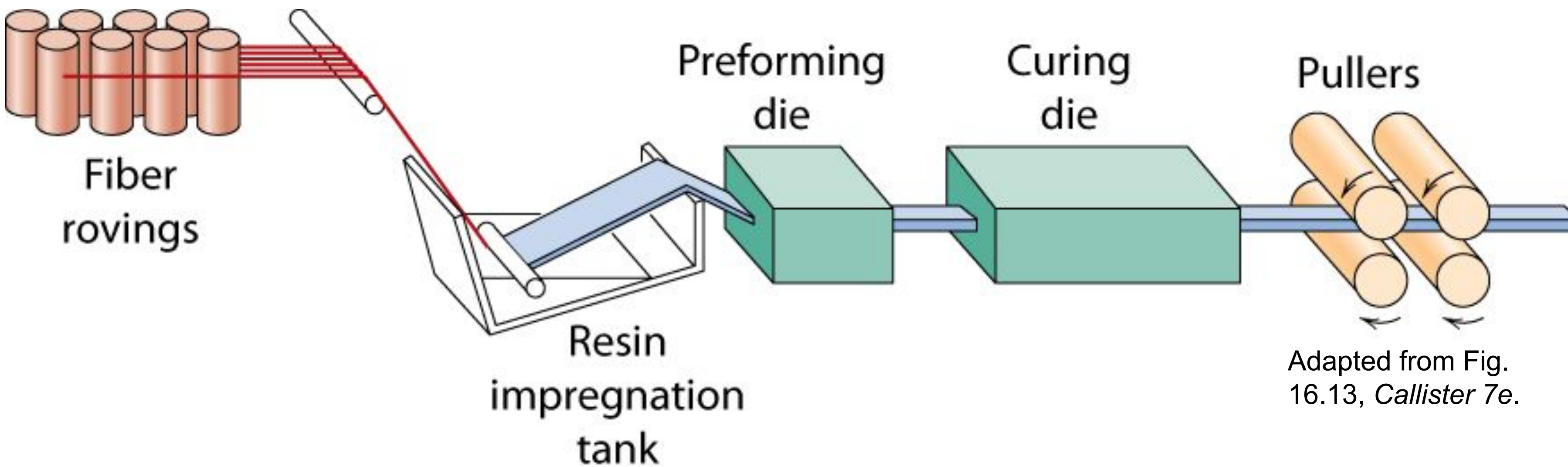


- Emerging product is cooled and pulled by oscillating clamps
- Small diameter products are wound up
- Two dimensional shapes including solid rods, profiles, or hollow tubes, similar to those produced by extrusion, are made, hence its name ‘pultrusion’

Composite Production Methods

Pultrusion

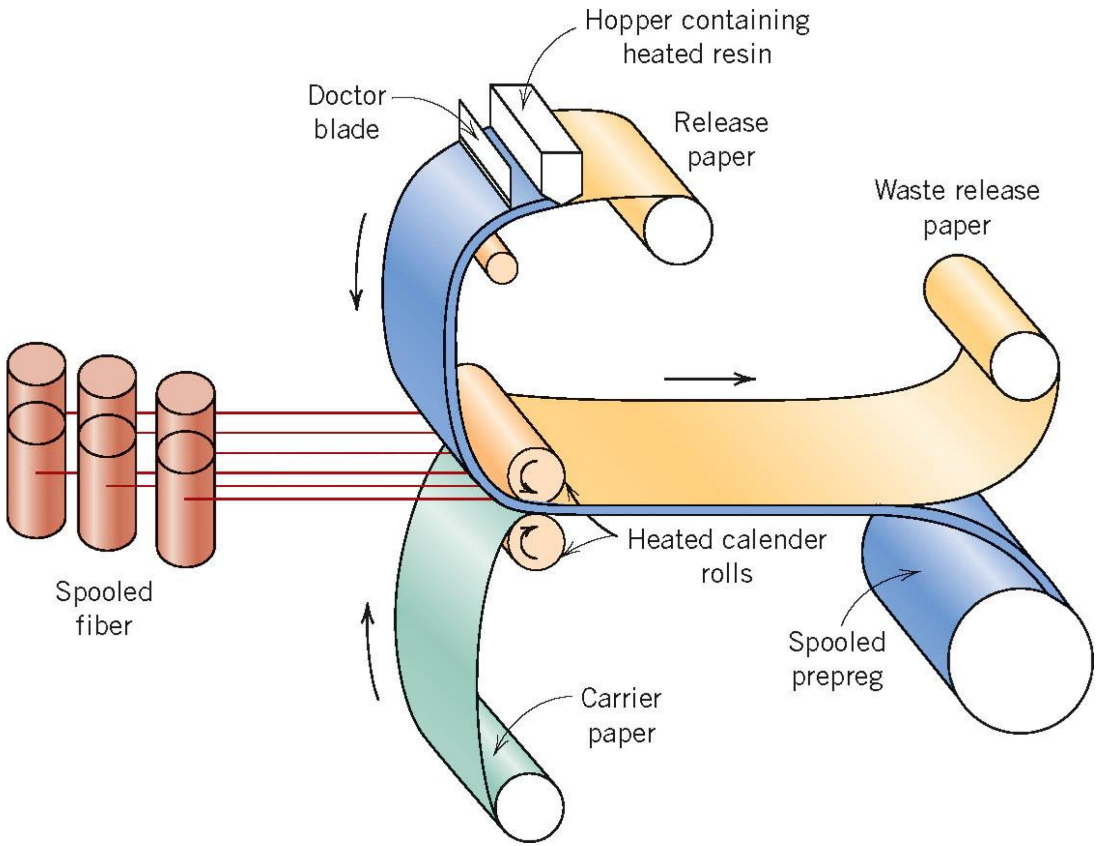
- Continuous fibers pulled through resin tank, then preforming die & oven to cure



Adapted from Fig. 16.13, *Callister 7e*.

- Production rates around 1 m/min.

- Applications are to sporting goods (golf club shafts), vehicle drive shafts (because of the high damping capacity), nonconductive ladder rails for electrical service, and structural members for vehicle and aerospace



PREPREG PRODUCTION PROCESSES

- Prepreg is the composite industry's term for continuous fiber reinforcement pre-impregnated with a polymer resin that is only partially cured.
- Prepreg is delivered in tape form to the manufacturer who then molds and fully cures the product without having to add any resin.
- This is the composite form most widely used for structural applications

PrePreg Process

- Manufacturing begins by collimating a series of spool-wound continuous fiber tows.
- Tows are then sandwiched and pressed between sheets of release and carrier paper using heated rollers (calendering).
- The release paper sheet has been coated with a thin film of heated resin solution to provide for its thorough impregnation of the fibers.

PrePreg Process

- The final prepreg product is a thin tape consisting of continuous and aligned fibers embedded in a partially cured resin
- Prepared for packaging by winding onto a cardboard core.
- Typical tape thicknesses range between 0.08 and 0.25 mm
- Tape widths range between 25 and 1525 mm.
- Resin content lies between about 35 and 45 vol%

PrePreg Process

- The prepreg is stored at 0°C (32 °F) or lower because thermoset matrix undergoes curing reactions at room temperature. Also the time in use at room temperature must be minimized. Life time is about 6 months if properly handled.
- Both thermoplastic and thermosetting resins are utilized: carbon, glass, and aramid fibers are the common reinforcements.
- Actual fabrication begins with the lay-up. Normally a number of plies are laid up to provide the desired thickness.
- The lay-up can be by hand or automated.

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.