Composite Materials

ISSUES TO ADDRESS...

- What are the classes and types of composites?
- Why are composites used instead of metals, ceramics, or polymers?
- How do we estimate composite stiffness & strength?

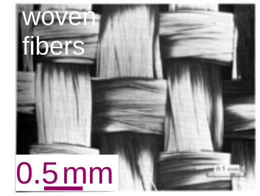
Composites Classification

- Composites: Multiphase material with significant proportions of each phase.

Matrix:

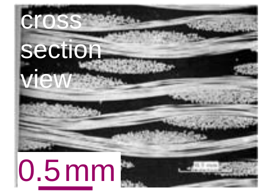
- The continuous phase
- Purpose is to:
  - *transfer stress to other phases*
  - *protect phases from environment*
- Classification: MMC, CMC, PMC

…….. ……… ……..



Dispersed phase:

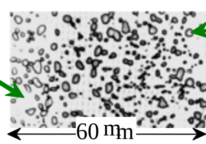
- Purpose: enhance matrix properties.
  - MMC: *increase σ_y, TS, creep resist.*
  - CMC: *increase Kc*
  - PMC: *increase E, σ_y, TS, creep resist.*
- Classification: Particle, fiber, structural



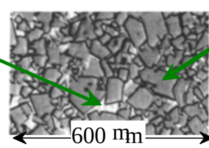
Particulates Composites

Particle-reinforced | Fiber-reinforced | Structural

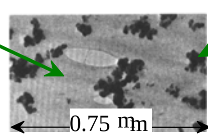
- Examples:
  - ✓ Spheroidite steel — matrix: Ferrite (α) ductile; particles: cementite (Fe_3C) brittle



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

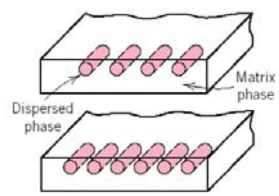


  - ✓ Automobile tires — matrix: rubber compliant; particles: C stiffer

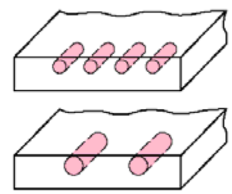


Particulates Composites

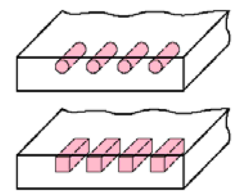
Properties of particulates composites depend on:



concentration



size



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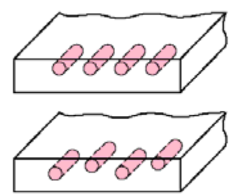
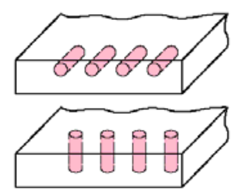


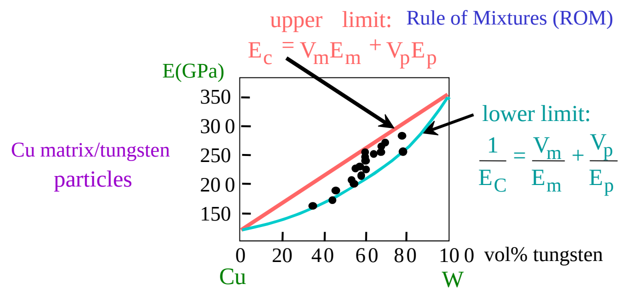
distribution



………..

Particulates Composites

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



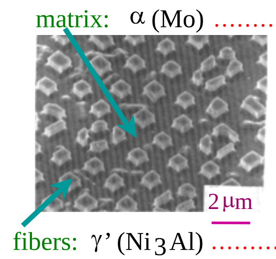
- Application to other properties:
  - Electrical conductivity, σ_e: Replace E by σ_e.
  - Thermal conductivity, k: Replace E by k.

Fiber Composites

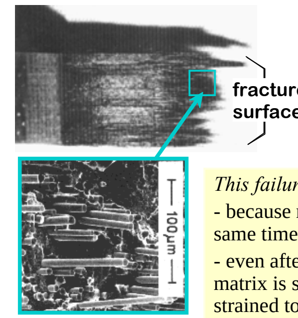
Particle-reinforced | fiber-reinforced | Structural

(1) Aligned Continuous fibers

- Examples:
  - ✓ Metal: $\gamma'(Ni_3Al)$-$\alpha(Mo)$



  - ✓ Glass reinforced with SiC fibers formed by glass slurry
    E_{glass} = 76GPa; E_{SiC} = 400GPa.

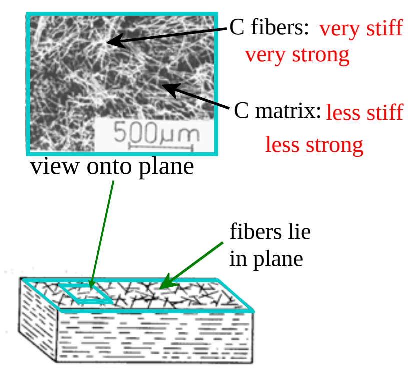


This failure is not catastrophic
- because not all fibers fail at the same time, and
- even after fibers failure the matrix is still intact until it is strained to its fracture point.

Fiber Composites

(2) Discontinuous, random 2D fibers

- Example: Carbon-Carbon
  - uses: disk brakes, gas turbine exhaust flaps, nose cones.



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

Fiber Composites

- Critical fiber length for effective stiffening & strengthening:

$$l_c = \frac{\sigma_f d}{2\tau_c}$$

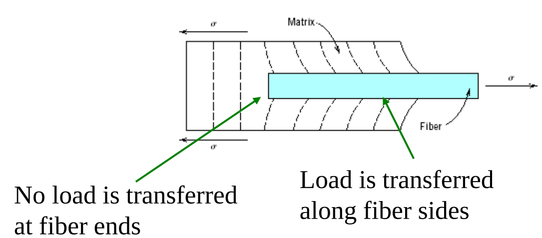
Fiber strength in tension (σ_f); Fiber diameter (d); shear strength of fiber-matrix interface (τ_c)

For glass and carbon composites, l_c is often around 1mm (20 - 150 x d_f)

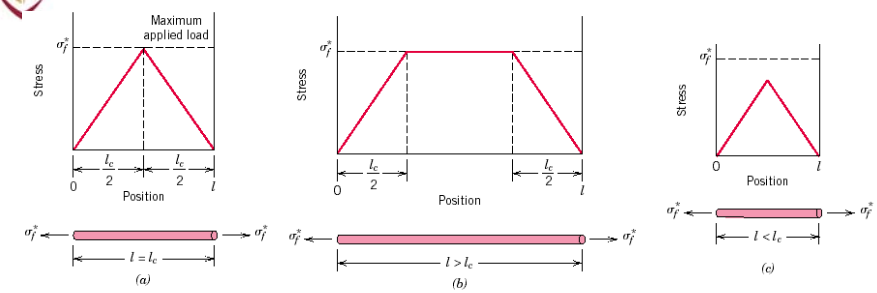
Fibers need to be long enough **to carry load**.

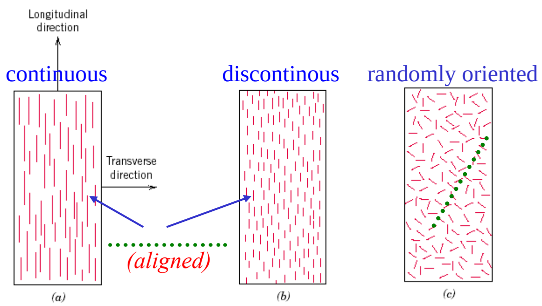
How does fiber strengthening work?

Transfer load from matrix to strong/stiff fiber. Requires a good ....



Fiber Composites





When:

$l >$ 15 l_c **"continuous"** fibers

$l \sim$ 10 l_c **"discontinuous"** fibers

$l < l_c$ **not acting as** fibers ***(particles)***.

Rule of Mixtures (RoM)

Volume of composite = Vol. of fibers + Vol. of matrix

Volume fraction of fibers: V_f = vol. of fibers/vol. of composite

Volume fraction of matrix: V_m = vol. of matrix/vol. of composite

$$V_f + V_m = 1 \qquad V_m = (1-V_f)$$

Thus density of composite can be written as:

$$\rho_c = V_f\,\rho_f + V_m\,\rho_m \quad \text{or} \quad \rho_c = V_f\,\rho_f + (1-V_f)\rho_m$$

Elastic Properties: Longitudinal loading

load carried by composite = loads carried by two phases:

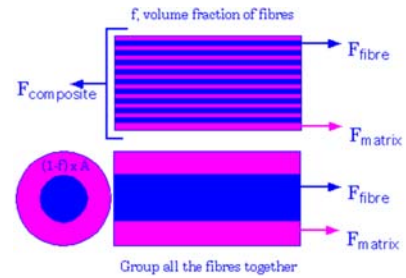
$F_c = F_m + F_f$ *since* $F = \sigma A$

$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f$ *Divide by* A_c

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

Area fraction = vol. fraction (if all fibers have the same length)

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



Isostrain case $\varepsilon_1 = \varepsilon_f = \varepsilon_m$

Elastic Properties: *Longitudinal loading*

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

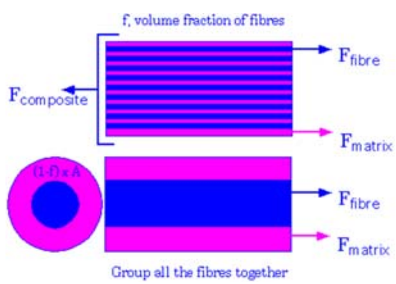
All stretch by same amount

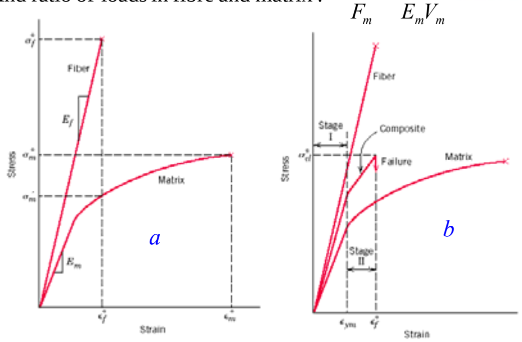
$$\sigma_c = \sigma_m V_m + \sigma_f V_f$$

$$\frac{\sigma_c}{\varepsilon_c} = \frac{\sigma_m}{\varepsilon_m} V_m + \frac{\sigma_f}{\varepsilon_f} V_f$$

$$E_c = E_m V_m + E_f V_f \quad \text{or} \quad E_c = E_m(1-V_f) + E_f V_f$$

And ratio of loads in fibre and matrix : $\dfrac{F_f}{F_m} = \dfrac{E_f V_f}{E_m V_m}$



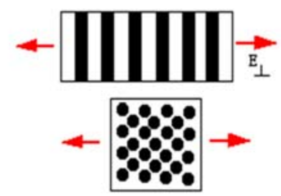


(a) *brittle fiber and ductile matrix.*

(b) *stress–strain curve for an aligned fiber-reinforced composite that is exposed to a uniaxial stress applied in the direction of alignment.*

Elastic Properties: *Transverse loading*

Isostress case $\sigma_c = \sigma_f = \sigma_m$



$\varepsilon_c A_c = \varepsilon_m A_m + \varepsilon_f A_f$ *From RoM*

but $\varepsilon = \sigma/E$

$$\Rightarrow \frac{\sigma}{E_{ct}} = \frac{\sigma_m}{E_m} V_m + \frac{\sigma_f}{E_f} V_f$$

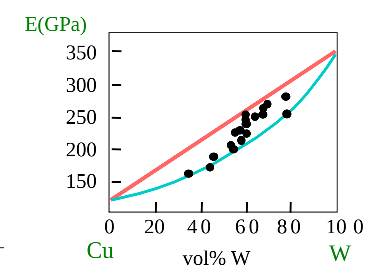
where E_{ct} is the transverse modulus.

(recall $\sigma_c = \sigma_f = \sigma_m$)

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

which can be rearranged to:

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



Strength of Aligned Cont. Fiber Composites

Matrix }
Fiber } ***Same strain***

Composite will fail at lower fracture strain

So, either
- **Matrix fails first**
  - ***Brittle matrices***
  - ***eg. epoxies***
- **Or, fiber fails first**
  - ***Ductile matrix***
  - ***eg. thermoplastic polymer***

If we assume that strain-to-failure of fiber is less than strain-to-failure of matrix as is most common: i.e. $\varepsilon_f^* < \varepsilon_m^*$

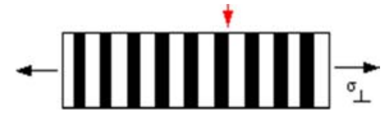
Then we can estimate the longitudinal strength of the composite as:

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

Where σ'_m is the stress in the matrix when the fibers fail.

Transverse Strength

Fiber-Matrix interface



- The transverse strength of unidirectional composites is usually very low.
- Fibers can actually act as ……….. rather than as reinforcements.
- Transverse strength can be approximated as …….. the *matrix strength* in many cases.

Material	*Longitudinal Tensile Strength (MPa)*	*Transverse Tensile Strength (MPa)*
Glass–Polyester	700	20
Carbon (High Modulus)–Epoxy	1000	35
Kevlar–Epoxy	1200	20

Typical Longitudinal and Transverse Tensile Strengths for three Unidirectional Fiber-Reinforced Composites.

The Fiber Content for Each is Approximately 50 Vol%

Discontinuous & Aligned Fiber Composites

Reinforcement efficiency is lower than that for continuous fibers but the composites are common for …………………….

- **Modulus of elasticity** can be up to …….. of continuous fiber composite
- **Tensile strength** can be up to …….. of continuous fiber composite

when $\ell > \ell_c$, the longitudinal strength, σ_{cd}^* is given by :

$$\sigma_{cd}^* = \sigma_f^* V_f \left(1 - \frac{\ell_c}{2\ell}\right) + \sigma_m^{'}(1 - V_f)$$

where σ_f^* and $\sigma_m^{'}$ represent the fiber fracture strength and the matrix stress at fiber failure respectively.

If the fiber length is less than the critical length, $\ell < \ell_c$, then :

$$\sigma_{cd'}^* = \frac{\ell \tau_c}{d} V_f + \sigma_m^{'}(1 - V_f)$$

where,
d = fiber diameter
*τ_c = the ……… of either **fiber – matrix** bond strength or **matrix** shear strength*

Discontinuous & Randomly Oriented Fiber Composites

When fiber orientation is random and the fibers are short, a "RoM" expression is used for the elastic modulus using an …………. factor, K (*which is less than unity- usually between 0.1 - 0.6)*).

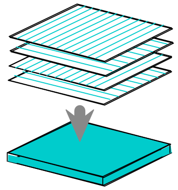
$$E_{cd} = K\, E_f V_f + E_m V_m$$

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	$\frac{3}{8}$
Fibers randomly and uniformly distributed within three dimensions in space	Any direction	$\frac{1}{5}$

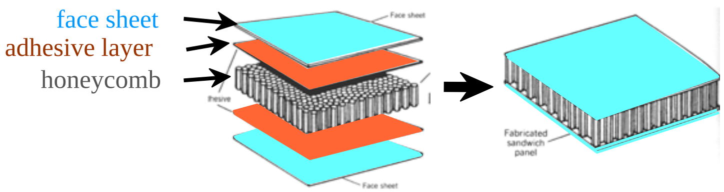
Structural Composites

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

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



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



Example

A continuous and aligned carbon fiber-epoxy composite consists of 60 vol% fibers. The moduli of elasticity are 700GPa and 3GPa for the fiber and the matrix respectively. Calculate the longitudinal and transverse composite modulus of elasticity? Compare the result with that of steel (E = 207 Gpa)? Calculate the density of the composite if the density of carbon fiber is 1.8 g/cm^3 and of the epoxy is 1.2 g/cm^3?

Next time:

Fracture Mechanics