Composite Materials - I

(Introduction)

Smart Materials Structures and Systems
Laboratory
IIT Kanpur

Contents

- ✓ Composite definition and history
- ✓ Composite Classification

What is Composite?

- Natural or artificial mixtures of two or more distinct phase/constituents.
- Mixtures may consist of metals, polymers or ceramics.
- Primary engineering goal is to achieve a better balance of properties from the combination of materials.

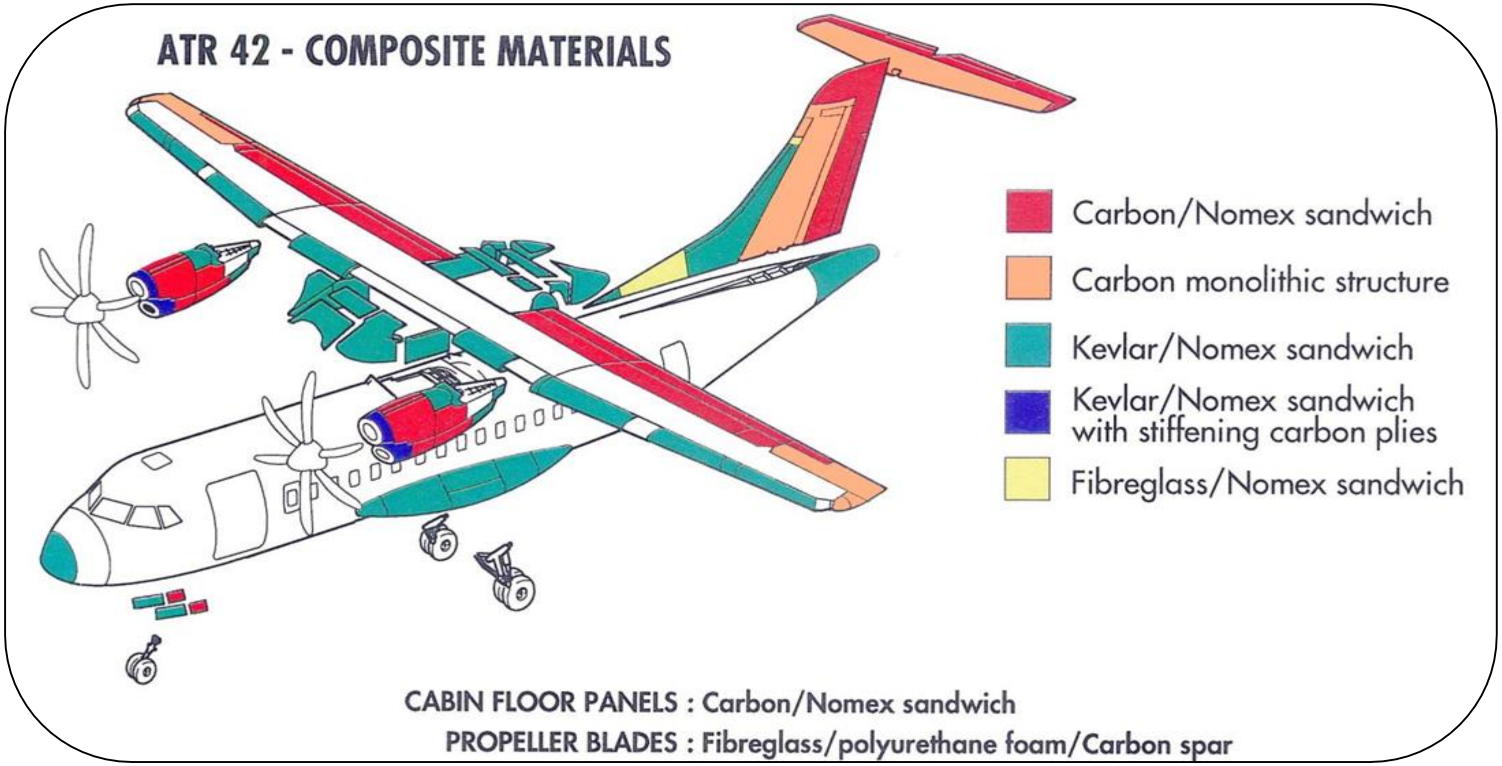
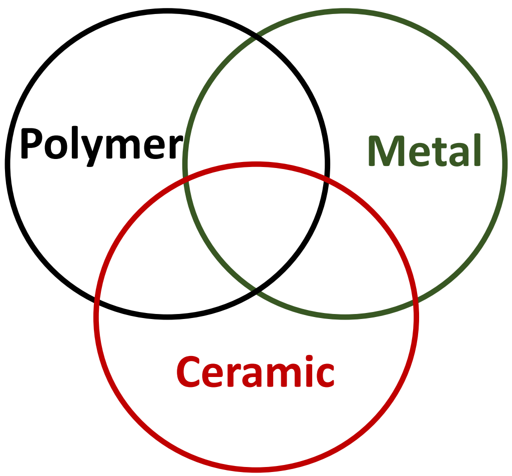
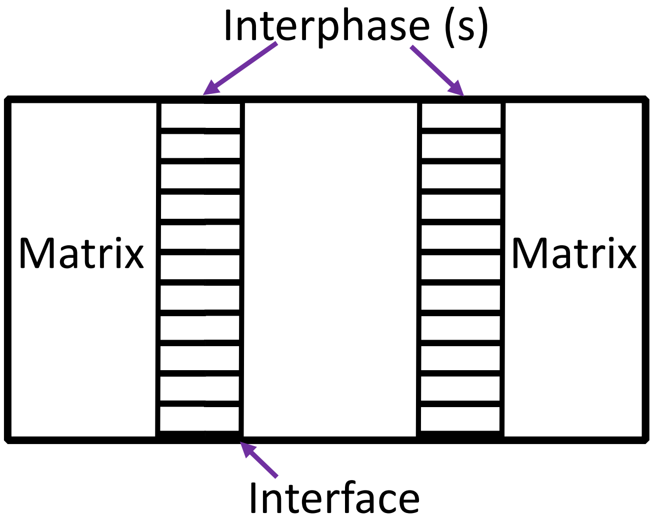


Image courtesy: http://www.compositesworld.com/

Domain of Composites





History of Composites

- Indus Civilization (~ 3000 B.C.) - Straw reinforced bricks.
- Hittites and the Samurai (~ 100 B.C.) - Steel composites (formed by the repeated folding of a steel bar back on itself).
- Industrial revolution (~ 1800 A.D.) - concrete and cast iron.
- Modern composites (~1950-present) - fiber-reinforced composites.

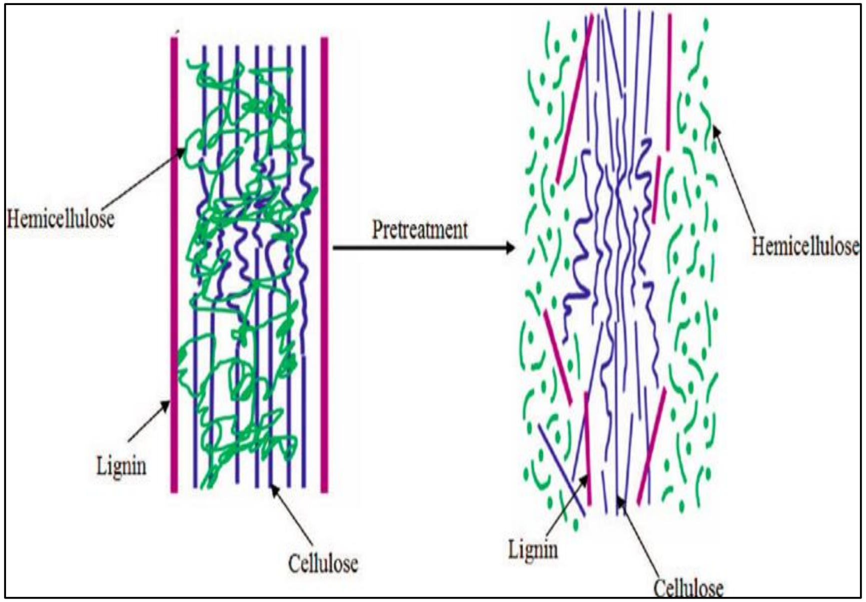
Straw + Mud brick

Samurai Sword

Concrete

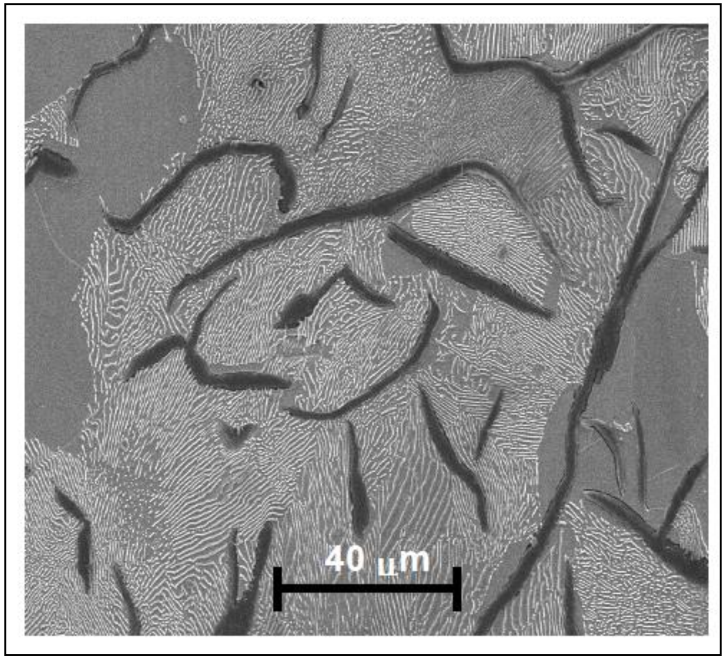
Natural Composites

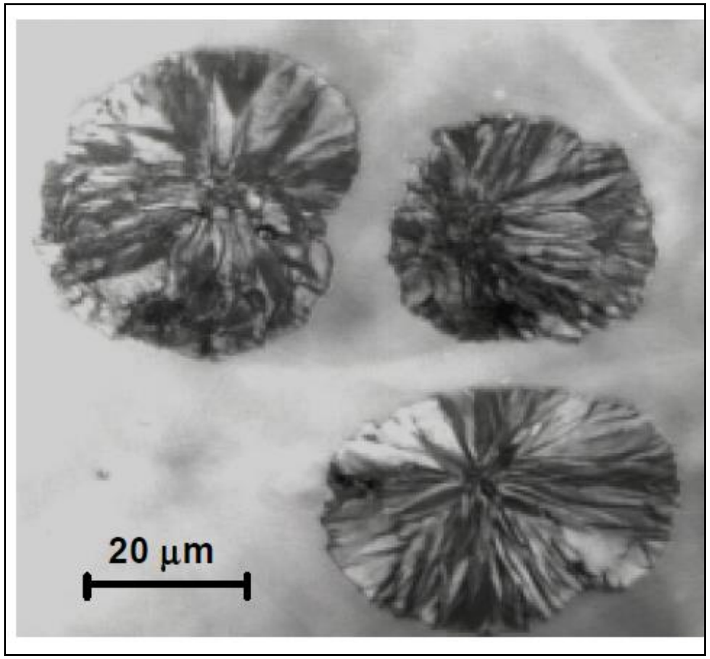
- Exist throughout nature - almost all natural materials
- Some examples:
- **wood** = lignin matrix + hemi-cellulose wound in a spiral form
- **bone** = organic fibers + inorganic crystals, water and fats
- 35% of bone consists of organic collagen protein fibers with small rod-like hydroxyapatite crystals



Reference: http://genomicsgtl.energy.gov/biofuels/

Cast Iron as Composite
Graphite Flakes and Graphite Nodules

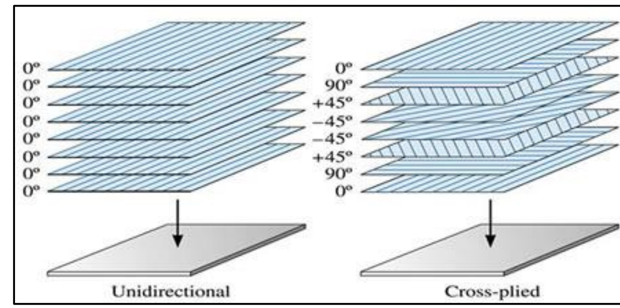




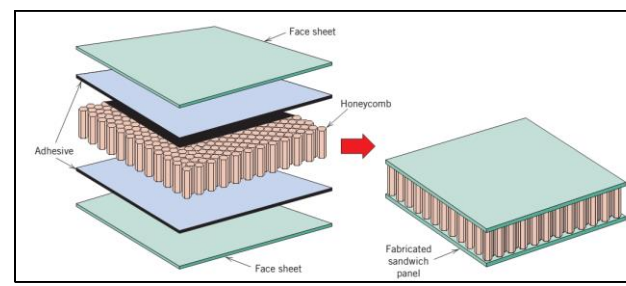
Reference: W.D Callister, 7 Ed.

Composites

- Particle-reinforced
  - Large-particle
  - Dispersion-strengthened
- Fiber-reinforced
- Structural



Laminates



Sandwich panel

Reference: W.D Callister, 7 Ed.

http://www.quartus.com/resources/white-papers/composites-101/

Particle –Reinforced Composites

Particle-reinforced

- Large-particle
- Dispersion-strengthened

LARGE–PARTICLE COMPOSITES

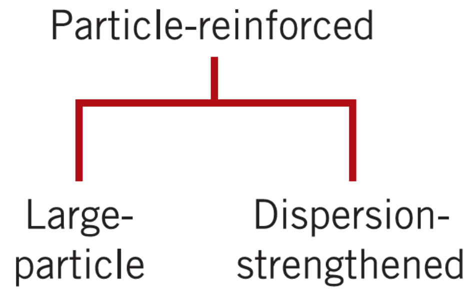
Example: **Concrete**, which is composed of cement (the matrix), and sand & gravel (the particulates)

- The **particulate phase** is **harder** and **stiffer** than the matrix.
- Reinforcing **particles** tend to **restrain movement** of the **matrix phase** in the vicinity of each particle.
- Matrix transfers fraction of applied load to particles.
- Improvement of mechanical behavior depends on strong bonding at the matrix–particle interface.

Cement

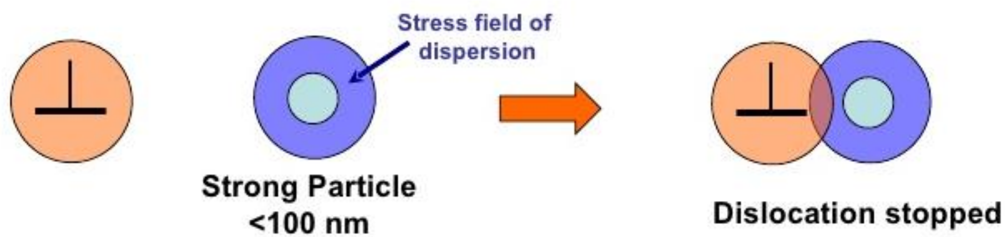
+ Sand, stones & water =

Concrete



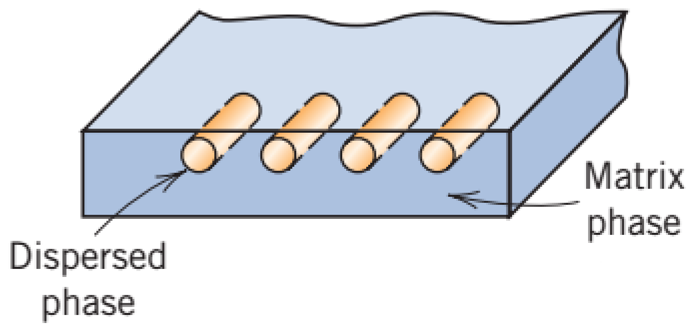
DISPERSION-STRENGTHENED COMPOSITES

- **Particles** are normally **much smaller**, with diameters between 10 – 100 nm.
- **Strengthening** occur on the **atomic or molecular level**.
- **Matrix** bears the **major** portion of an applied **load**, while the **small** dispersed **particles hinder** the motion of **dislocations**.
- Thus, **plastic deformation** is **restricted** such that yield and tensile strengths, as well as hardness **improves**.



Example: Sintered aluminum powder - flakes of Al coated with Al_2O_3, which are dispersed within an aluminum metal matrix.

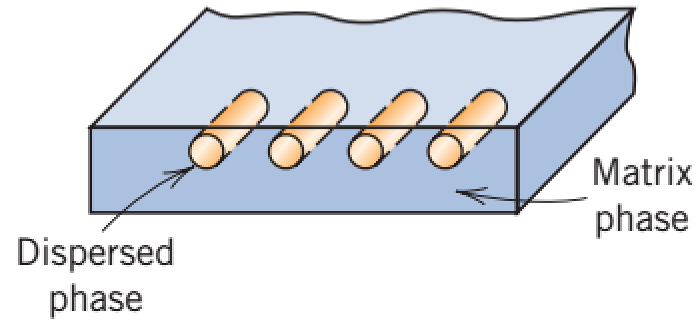
Fiber – Reinforced Composites



The Fiber Phase

Role of fibers in composites includes:

- To enhance stiffness
- To enhance strength
- To provide crack-bridging
- To enhance thermal resistance



On the basis of diameter and character, fiber phase can be grouped into

- **Whiskers** : They are very thin **single crystals** that have extremely large l/d ratio but has the form of fiber.
  - ✓ Flaw free and thus extremely high strength – but expensive.
  - ✓ Include graphite, silicon carbide, silicon nitride, and aluminum oxide, etc.
- **Fibers** : A material that has at least l/d ratio equal to 10 : 1
  - ✓ Either polycrystalline or amorphous.
  - ✓ Generally polymer and ceramics
- **Wires** : Relatively large diameters
  - ✓ Typical materials include steel, molybdenum, and tungsten

Reference: W.D Callister, 7 Ed.

The Matrix Phase

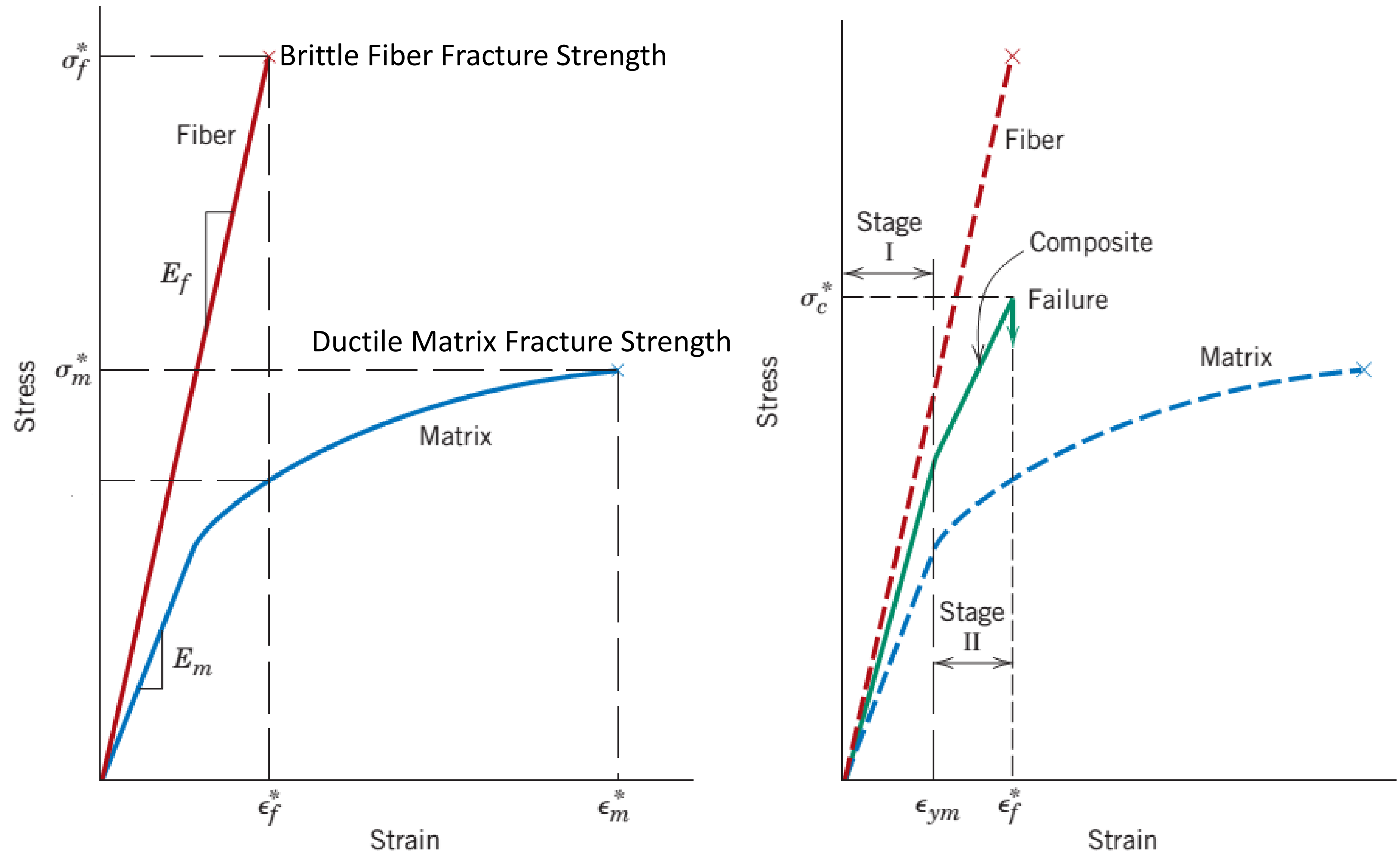
Role of matrix in composites includes

- Binding fibers together
- Protect the individual fibers from damage by external environment.
- Act as a medium to transmit and distribute externally applied stress to fibers.
- Serves as a barrier to crack propagation.

It should be noted that :

- ✓ The **matrix** material should be **ductile**.
- ✓ **Elastic modulus** of the **fiber** should be **much higher** than that of the **matrix.**
- ✓ There should be adequate bonding between matrix and fibers.

Stress-Strain Curves



Reference: W.D Callister, 7 Ed.

Volume Fractions

If V_f, V_m, V_v *and* Vc *are the volumes of fiber, matrix, void and composite, then*

$$\vartheta_f = \frac{V_f}{V_c} = fiber\ volume\ fraction$$

$$\vartheta_m = \frac{V_m}{V_c} = matrix\ volume\ fraction$$

$$\vartheta_v = \frac{V_v}{V_c} = void\ volume\ fraction$$

Where,

$$\vartheta_f + \vartheta_m + \vartheta_v = 1$$

$$V_c = V_f + V_m + V_v = Composite\ Volume$$

Weight Fractions

$$w_f = \frac{W_f}{W_c} = fiber\ weight\ fraction$$

$$w_m = \frac{W_m}{W_c} = matrix\ weight\ fraction$$

Where,

$$w_f + w_m = 1$$

$W_c = W_f + W_m = Composite$ Weight

Note: Weight of voids neglected

Densities

$$Density, \rho = \frac{W}{V}$$

Composite weight, $W_c = W_f + W_m$

Therefore, $\rho_c V_c = \rho_f V_f + \rho_m V_m$

Hence, Composite density, $\boldsymbol{\rho_c = \rho_f \vartheta_f + \rho_m \vartheta_m}$

"**Rule of Mixtures**" for density

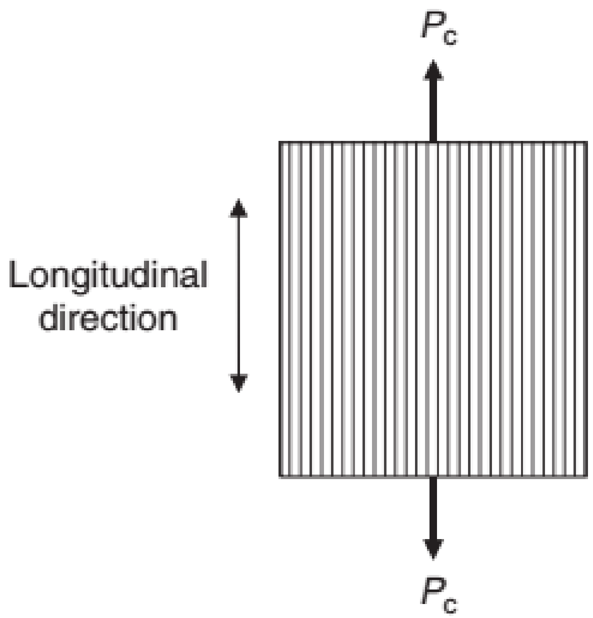
Longitudinal Modulus

The tensile load is acting along fiber direction.

Assuming perfect bonding between fibers and matrix,

$$\in_f = \in_m = \in_c \qquad (1)$$

where $\in_f$, $\in_m$, $\in_c$ are the longitudinal strains in fibers, matrix and composite respectively.



Since both fibres and matrix are elastic, the longitudinal stresses are

$$\sigma_f = E_f \in_f = E_f \in_c \qquad (2)$$

$$\sigma_m = E_m \in_m = E_m \in_c \qquad (3)$$

$Since\ E_f > E_m\ Hence\ \sigma_f > \sigma_m.$

The tensile load P_C applied on the composite lamina is shared by fiber and matrix. So,

$$P_C = P_f + P_m$$

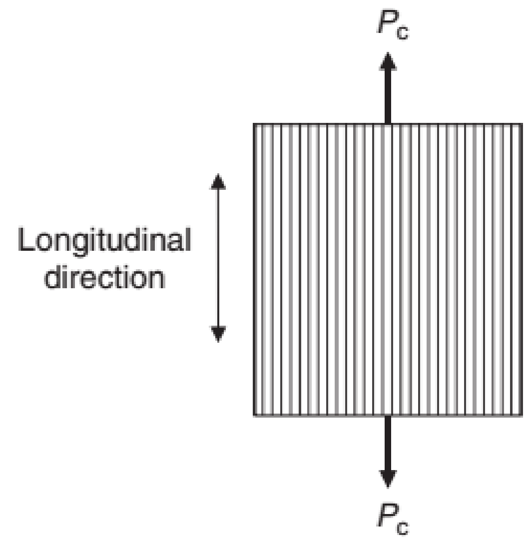
Since load = stress x area

Therefore, $\sigma_C A_C = \sigma_f A_f + \sigma_m A_m$

Now, $\sigma_C A_C = \sigma_f A_f + \sigma_m A_m$ (4)

Or

$$\sigma_C = \sigma_f \frac{A_f}{A_c} + \sigma_m \frac{A_m}{A_c} \quad (5)$$



where
σ_C = average tensile stress in the composite
A_f = net cross-sectional area for the fibres
A_m = net cross-sectional area for the matrix

$$A_c = A_f + A_m$$

Since, $\vartheta_f = \frac{A_f}{A_c}$ and $\vartheta_m = \frac{A_m}{A_c}$

Thus, $\sigma_C = \sigma_f \vartheta_f + \sigma_m \vartheta_m$

Dividing both sides by $\in_c$, and using (2), (3) we get

$(E_C)_{\text{longitudinal}} = E_f \vartheta_f + E_m \vartheta_m$, " Rule of Mixtures"

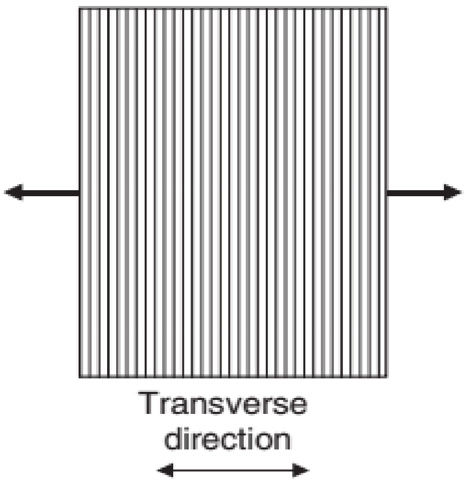
Transverse Modulus

- The tensile load is acting normal to the fibre direction.
- The total deformation (strain) in the transverse direction is the sum total fibre and matrix deformation.

$$\delta_C = \delta_f + \delta_m \qquad (1)$$

- Tensile stress in fibre, matrix and composite are equal.

$$\sigma_f = \sigma_m = \sigma_C \qquad (2)$$



From definition of normal strain

$$\delta_f = \in_f L_f$$

$$\delta_m = \in_m L_m$$

$$\delta_C = \in_c L_C$$

Substituting in Equation (1) and dividing by L_C both sides, we get

$$\epsilon_C = \epsilon_f \frac{L_f}{L_c} + \epsilon_m \frac{L_m}{L_c} \qquad (3)$$

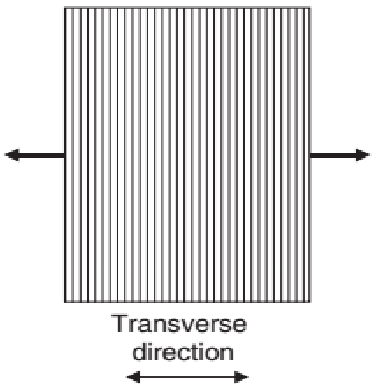
Since $\vartheta_f = {}^{L_f}/_{L_C}$ and $\vartheta_m = {}^{L_m}/_{L_c}$

Hence equation (3) becomes,

$\in_c = \in_f \vartheta_f + \in_m \vartheta_m$

This can be re-written using Hooke's law as

$$\frac{\sigma_C}{E_C} = \frac{\sigma_f}{E_f}\vartheta_f + \frac{\sigma_m}{E_m}\vartheta_m \qquad (4)$$



Since $\sigma_f = \sigma_m = \sigma_C$, equation (4) becomes

$$\frac{1}{E_C} = \frac{\vartheta_f}{E_f} + \frac{\vartheta_m}{E_m}$$

Or

$$(\boldsymbol{E_C})_{\boldsymbol{Transverse}} = \frac{\boldsymbol{E_f E_m}}{\boldsymbol{E_f \vartheta_m + E_m \vartheta_f}}$$

In the **next lecture**, we will learn about

- ✓ Applications of fibre reinforced composites
- ✓ Polymer matrix composites
- ✓ Metal-matrix composites
- ✓ Ceramic-matrix composites

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