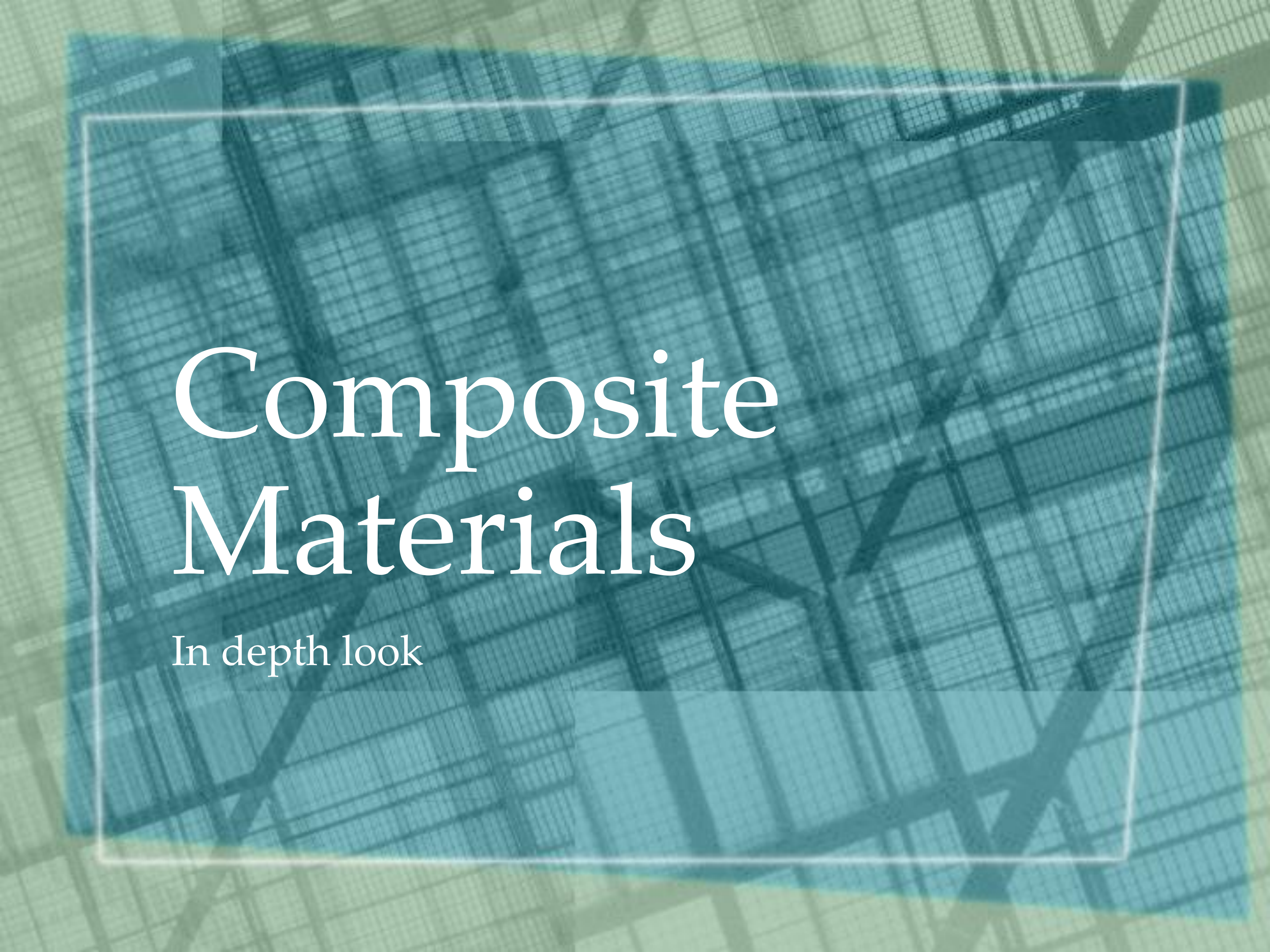
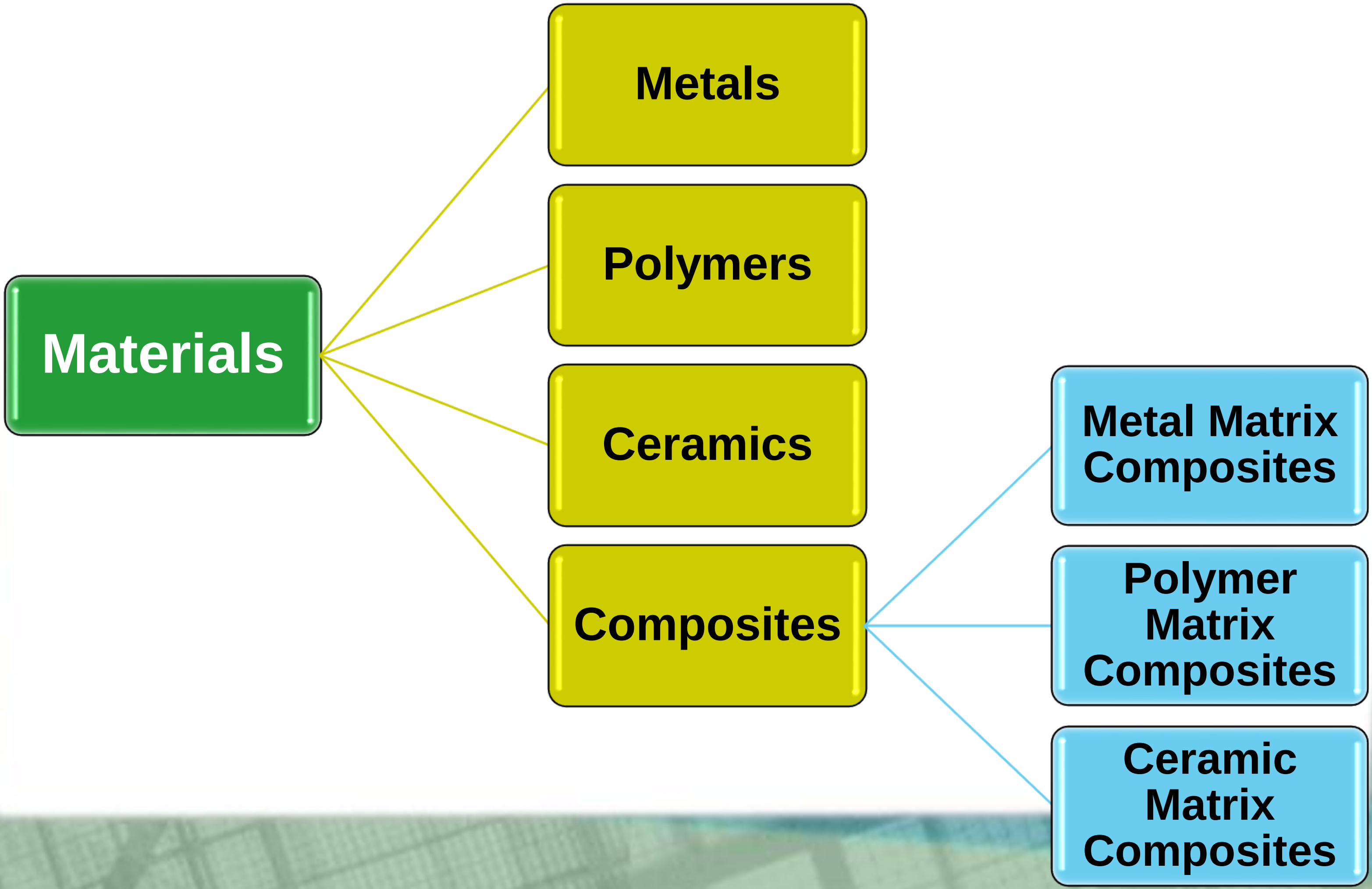


Composite Materials

In depth look

Classification of Composites



Materials

Metals

Polymers

Ceramics

Composites

Metal Matrix Composites

Polymer Matrix Composites

Ceramic Matrix Composites

Classification of Composites

Two broad classes of composites:

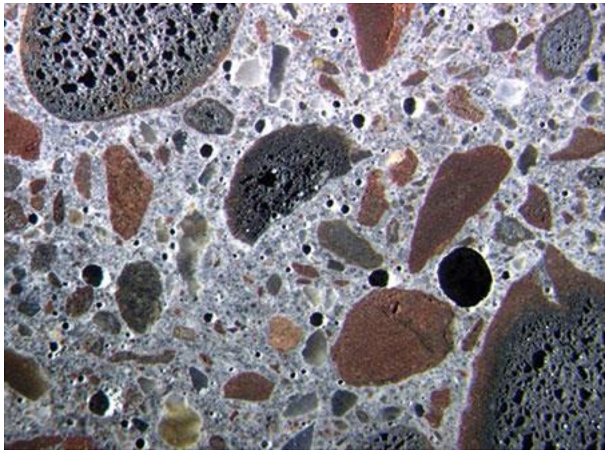
1. *Traditional composites*
   - *composite materials that occur in nature or have been produced by civilizations for ages*

   Examples: wood, concrete, asphalt

2. *Engineering composites*
   - *Synthetic material systems that are normally associated with the manufacturing industries*
   - *The components are first produced separately and then combined in a controlled way to achieve the desired structure, properties, and part geometry*

The most common traditional composite: Concrete

Traditionally cement or volcanic ash are strengthened by adding particulates. The use of different size (stone and sand) allows better packing factor than when using particles of similar size.



Concrete is improved by making the pores smaller (using finer powder, adding polymeric lubricants, and applying pressure during hardening.

Reinforced concrete: an engineering composite

Traditional concrete is made even stronger under tensile and flexural shear stresses by adding steel rods, wires, meshes.

Steel has the advantage of a similar thermal expansion coefficient, so there is reduced danger of cracking due to thermal stresses.

Pre-stressed concrete is obtained by applying tensile stress to the steel rods while the cement is setting and hardening. When the tensile stress is removed, the concrete is left under compressive stress, enabling it to sustain tensile loads without fracturing. A common use is in railroad or highway bridges.

Typical engineering composites

Primary Phase, Matrix

Secondary Phase, Reinforcement

	Metal	Ceramic	Polymer
Metal	**Powder metallurgy parts – combining immiscible metals**	**Cermets (ceramic-metal composite)**	**Brake pads**
Ceramic	**Cermets, TiC, TiCN** **Cemented carbides – used in tools** **Fiber-reinforced metals**	**SiC reinforced Al_2O_3** **Tool materials**	**Fiberglass in polyester** **Rubber with carbon (tires)** **Boron reinforced plastics**
Polymer	**Fiber reinforced metals** **Auto parts** **Aerospace**	**PLA reinforced Calcium Phosphate Cements**	**Kevlar fibers in an epoxy matrix**

Typical reinforcements

Function depends on matrix

- *Metal matrix: to increase the hardness and creep resistance at high temperature*
- *Polymer matrix: to improve stiffness, and strength*
- *Ceramic matrix: to improve toughness*

Typical reinforcements

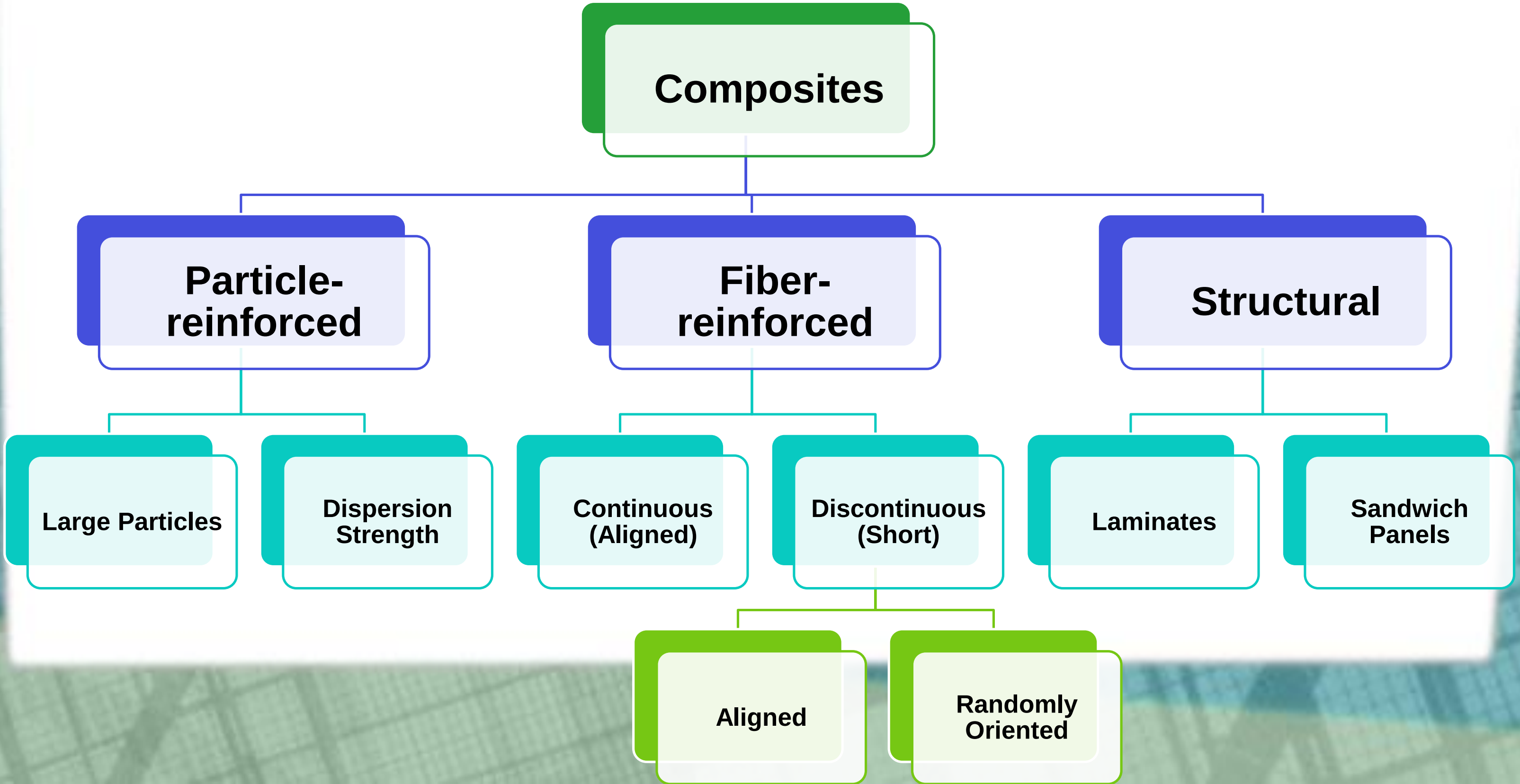
One reinforcement is common to all matrices: Air

Voids are created in materials to improve many properties like

- *Insulation (1/thermal conductivity)*
- *Density*
- *Shock absorption*
- *Biocompatibility*
- *Surface area*

Classification of the reinforcing phase

Composites can be engineered in terms of the amount, shape, size and distribution of the reinforcing phase, as well as the interface between the matrix and reinforcing phases



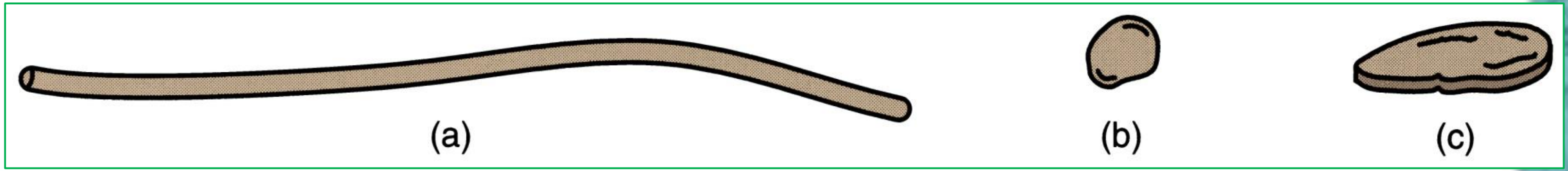
Composite types according to the reinforcing phase shape

If the reinforcement is similar in all dimensions, it is a particulate reinforced composite

If its shape is needle-shaped single crystals, it is whisker-reinforced composite

If the reinforcement is cut continuous filament, it is chopped fiber-reinforced composite

If the fiber is continuous, it is fiber composite.



Possible physical shapes of imbedded phases in composite materials:
(a) fiber, (b) particle, and (c) flake

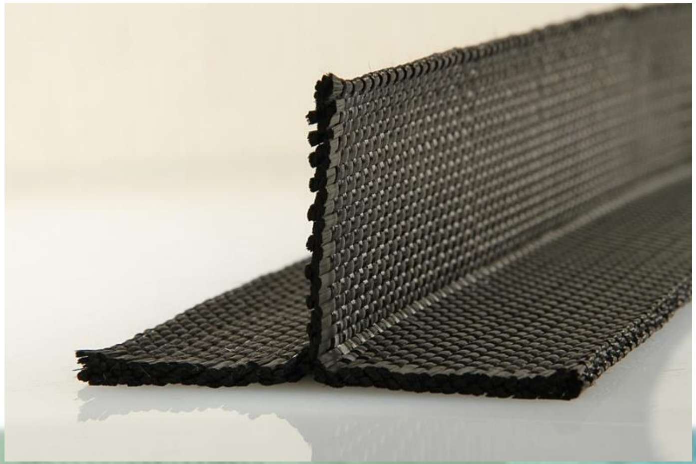
Composite types according to the reinforcing phase shape

For fiber composites, configuration gives a further category.

It is a uniaxial fiber composite if fibers are aligned in one direction

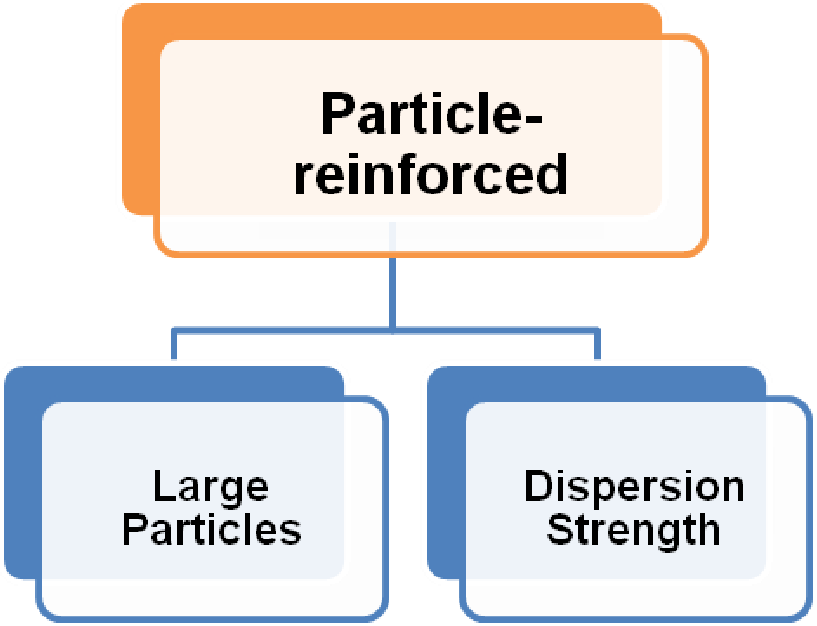
It is a laminar composite if fibers are arranged in layers

It is a 3D woven composite if fibers are arranged in a three-dimensional arrangement



Particle reinforced composites

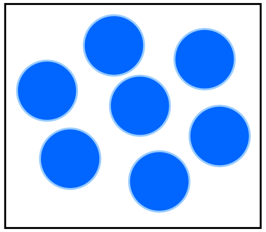
Very hard, small particles are dispersed generally to strengthen metals and metal alloys. The effect is like precipitation hardening but not so strong. Particles like oxides do not react so the strengthening action is retained at high temperatures.



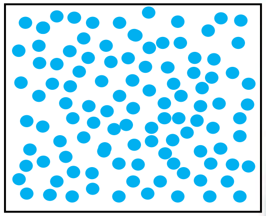
Particle-reinforced

Large Particles

Dispersion Strength

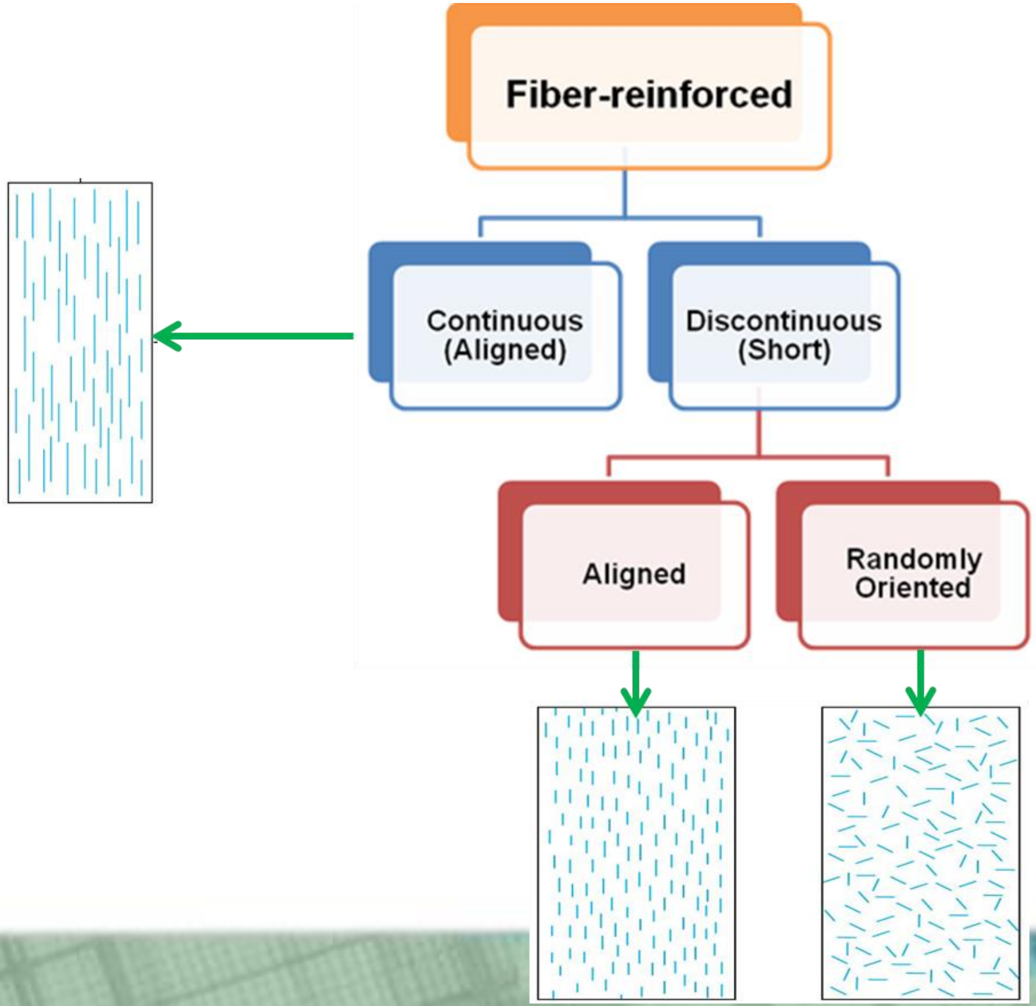


$D_{particle} > 100$ nm



$d_{particle} < 100$ nm

Fiber reinforced composites



Fiber-reinforced

Continuous (Aligned)

Discontinuous (Short)

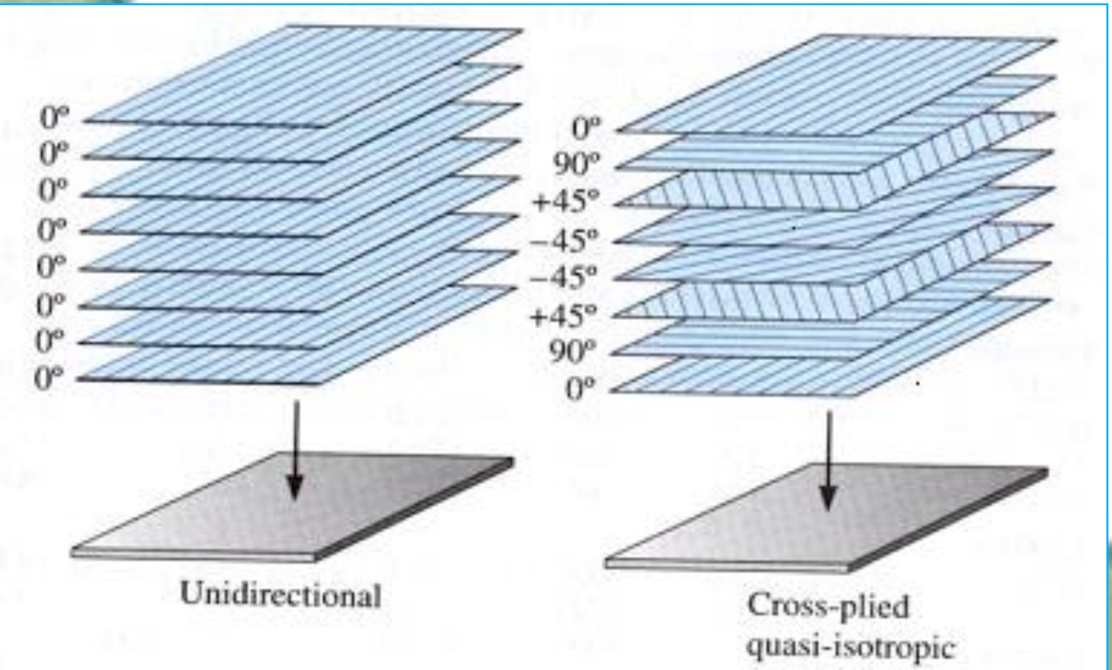
Aligned

Randomly Oriented

Structural composites

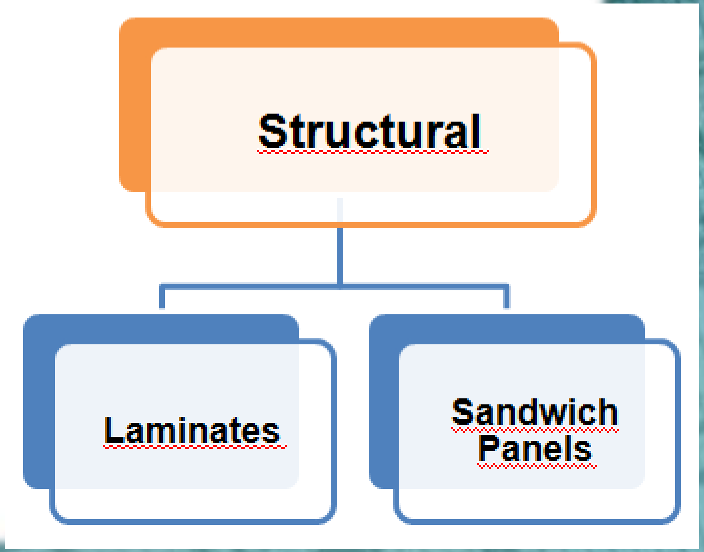
Laminates are thin 3-dimensional composite plates with imbedded multidirectional or unidirectional fibers

They can be thought of as sheets of continuous fiber composites laminated such that each layer has the fiber oriented in a given direction



Unidirectional

Cross-plied quasi-isotropic



Structural

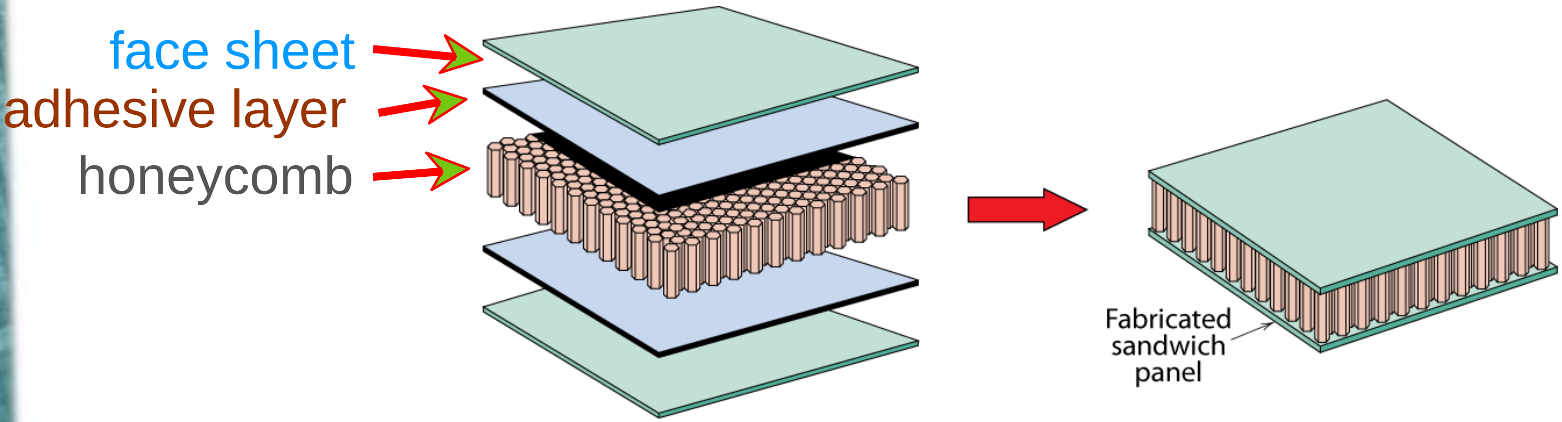
Laminates

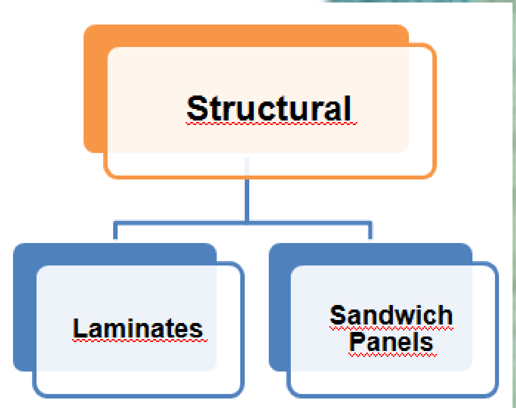
Sandwich Panels

Structural composites

Sandwich panels are low density plates with honeycomb core

-- benefit: light weight, large bending stiffness

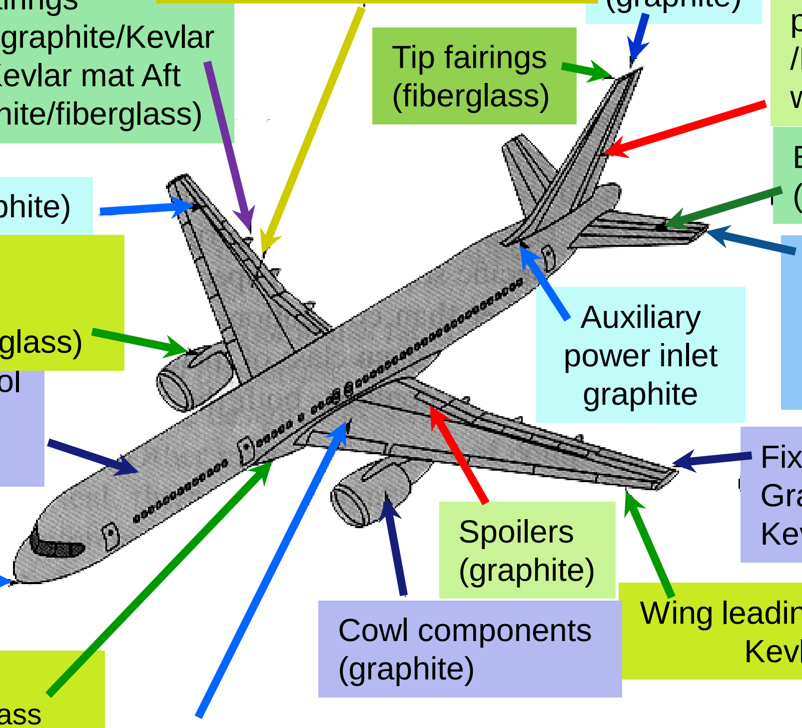



Structural

Laminates

Sandwich Panels

Reinforcements used in aerospace industry



Aft flaps
Outboard (graphite)
Inboard (graphite/fiberglass)

Rudder (graphite)

Flap support fairings Fwd segment (graphite/Kevlar + non-woven Kevlar mat Aft segment (graphite/fiberglass)

Tip fairings (fiberglass)

Fixed trailing edge panels graphite /Kevlar + non-woven Kevlar mat)

Elevators (graphite)

Ailerons (graphite)

Engine strut fairings (Kevlar/fiberglass)

Fixed trailing edge panels upper (graphite /fiberglass), lower (graphite /Kevlar + non-woven Kevlar mat)

Auxiliary power inlet graphite

Environmental control system ducts (Kevlar)

Fixed trailing edge panels Graphite/Kevlar + non-woven Kevlar mat

Nose landing gear doors (graphite)

Spoilers (graphite)

Wing leading edge lower panel Kevlar/fiberglass

Cowl components (graphite)

Wing to body fairings (graphite/Kevlar/Fiberglass and Graphite/Kevlar + non-woven Kevlar mat

Body main landing gear doors (graphite)
Trunnion fairings and wing landing gear doors (graphite/Kevlar)
Brakes(structural carbon)

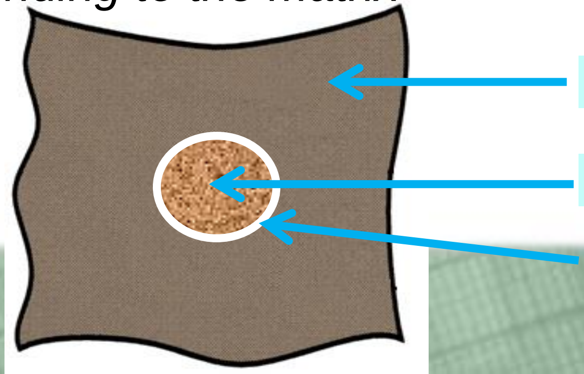
Composite microstructure

There is always an interface between constituent phases in a composite material.

Most of the time the phases must bond where they join at the interface for the composite to operate effectively

Interface: Zone across which matrix and reinforcing phases chemically, physically, mechanically interact

Function: to transfer the stress from matrix to reinforcement
Sometimes surface treatment is carried out to achieve the required bonding to the matrix



Primary (matrix) phase

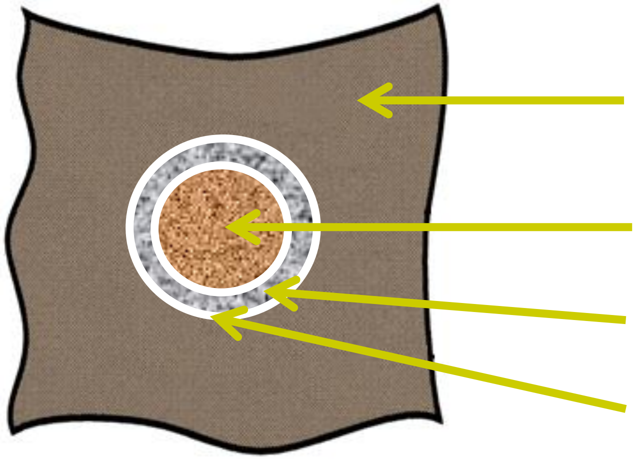
Secondary (reinforcing) phase, fiber

Interface

Composite microstructure

In some cases, a third ingredient must be added to achieve bonding of primary and secondary phases

Called an interphase, this third ingredient can be thought of as an adhesive.



Primary (matrix) phase

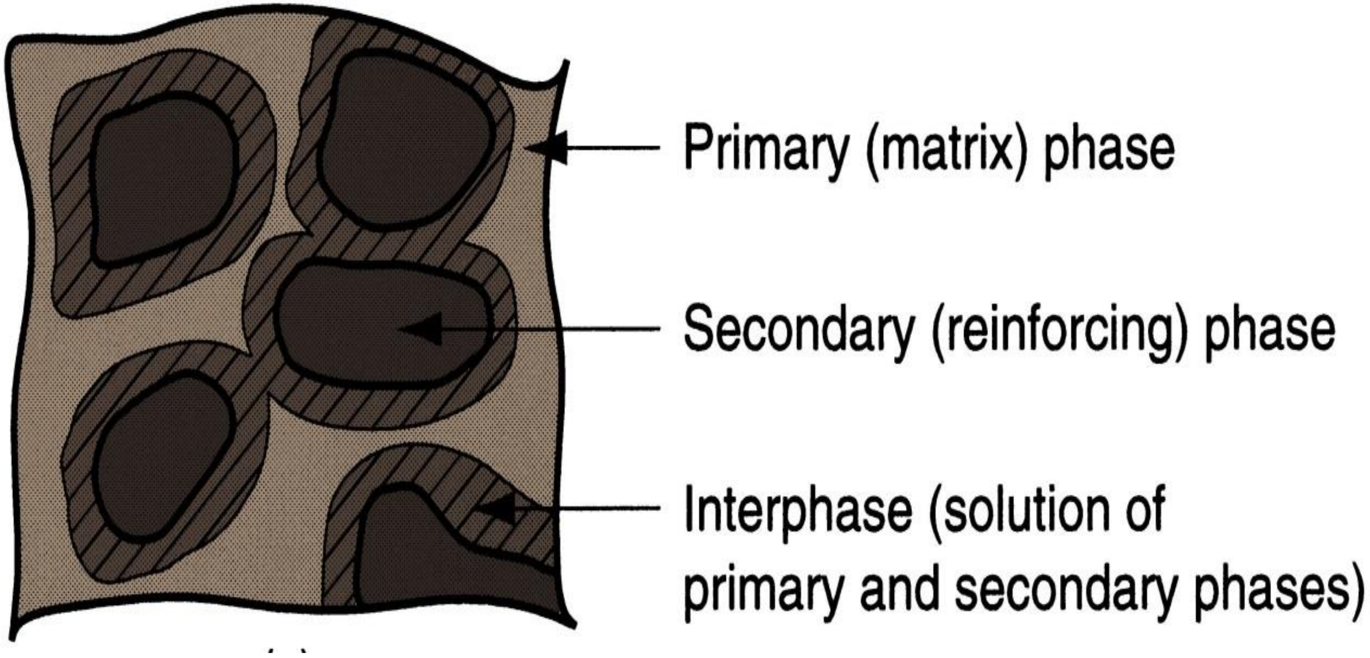
Secondary (reinforcing) phase, fiber

Interphase (third ingredient)

Interface

Composite microstructure

Interphase may be composed of a solution of the primary and secondary phases at their boundary by diffusion



Composite properties depend on the microstructure

- *properties of the matrix material,*
- *properties of reinforcement material,*
- *ratio of matrix to reinforcement,*
- *matrix-reinforcement bonding/adhesion,*
- *mode of fabrication*

determine the overall properties of the composite

Relations between the mechanical properties and structure

The tensile strength σ, the elastic modulus in the direction of the load E, and the longitudinal strain ϵ_L of a single phase material are obtained from the stress-strain response

$$\sigma = E\epsilon_L$$

The Poisson's ratio is obtained by measuring the contraction strain ϵ_T across the sample

$$\upsilon = -\frac{\epsilon_T}{\epsilon_L}$$

Since the sample contracts, ϵ_T is negative and υ has a positive value less than 1.0

The shear modulus, G is related to E and υ by

$$G = \frac{E}{2 * (1 + \upsilon)}$$

The shear stress τ and shear strain γ are related by G:

$$\tau = G * \gamma$$

Relations between the mechanical properties and structure

In metal systems the material is generally assumed to be linear, isotropic, and elastic such that only a few tests are required to obtain basic tensile stiffness properties

Only two values, the tensile modulus E, and the Poisson's ratio v are required because of the small degree of anisotropy or symmetry of the metal microstructure

Metals have an infinite number of symmetry planes
In contrast a material with no symmetry planes requires 21 material properties and extensive testing in order to design a structure

Most composites are developed in two dimensional form and have one plane of symmetry

Relations between the mechanical properties and structure

For example a laminate plate is a unidirectional material and is transversely isotropic

The stress-strain law governing this material is complicated as there are 5 material properties (σ,τ,ε,γ,E)

Stress-strain law for metals: $\sigma = E * \epsilon$

For laminate composite:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} E_{11} & E_{12} & E_{12} & 0 & 0 & 0 \\ & E_{22} & E_{23} & 0 & 0 & 0 \\ & & E_{22} & 0 & 0 & 0 \\ & & & 2(E_{22}-E_{23}) & 0 & 0 \\ Sym. & & & & E_{66} & 0 \\ & & & & & E_{66} \end{bmatrix} * \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{bmatrix}$$

Where $E_{22} = E_{33}$, $E_{12} = E_{13} = -E_{11}/\upsilon_{12} = -E_{22}/\upsilon_{21},\ E_{22} = -E_{22}/\upsilon_{23},\ \frac{1}{E_{55}} = \frac{1}{E_{66}} + \frac{1}{G_{12}}$

Relations between the mechanical properties and structure

E_{11} is determined from a tensile test conducted in the direction of the fiber orientation
The value of Poisson's ratio, v_{12} is obtained by measuring the lateral contraction strain

E_{22} is determined by cutting a laminate to pull it in tension transverse to the fiber direction
The value of Poisson's ratio, v_{21} is obtained by measuring the lateral contraction strain but
its value will be much less than v_{12} due to fiber constraint

Measuring v_{23} is hard. It is small and usually ignored because most composites are two dimensional (It is the ratio of the strain across the fibers relative to the thickness strain)

The value of G_{12}, the shear modulus is measured using simple circular tubes of the material. The tubes are twisted and the resultant shear stress and strain are determined

Relations between the mechanical properties and structure

The values of longitudinal modulus E_{11}, principle Poisson's ratio v_{11}, and principle thermal expansion coefficient α_{11} can be expressed in terms of the matrix/fiber properties and the volume fraction of the respective ingredients according to the rule of mixtures:

$$E_{11} = V_f * E_f + V_m * E_m$$
$$\nu_{11} = V_f * \nu_f + V_m * \nu_m$$
$$\alpha_{11} = V_f * \alpha_f + V_m * \alpha_m$$

Certain assumptions are made to relate the microstructure of the ingredients to these properties:

- *The composite ply is macroscopically homogeneous and linearly elastic*
- *The fibers are linearly elastic and homogeneous*
- *The matrix is linearly elastic and homogeneous*
- *Both the fiber and the matrix are free of voids*
- *The interface is completely bonded and there is no interphase between the matrix and reinforcement*
- *The mechanical properties of the individual constituents are the same whether they are made before or during the composite manufacturing process*

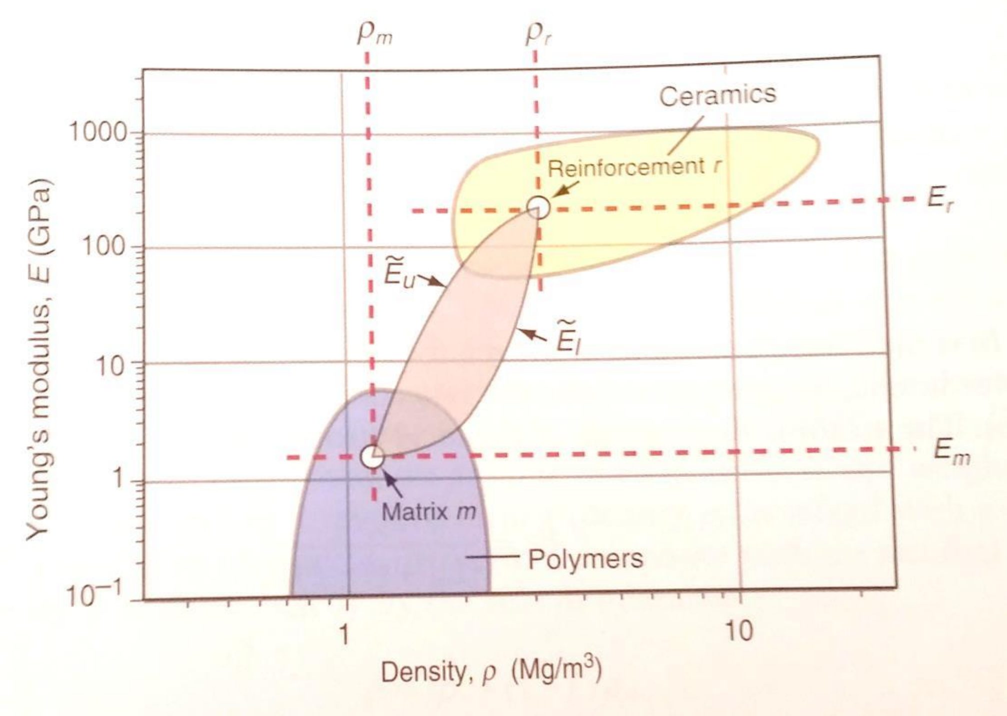
Relations between the mechanical properties and structure

The upper bound is found by assuming that the two components strain by the same amount, like springs in parallel

$$E_{11} = V_f * E_f + V_m * E_m$$

The lower bound is found by assuming that the two components carry the same stress, like springs in series

$$E_{11} = \frac{E_f * E_m}{V_f * E_f + V_m * E_m}$$

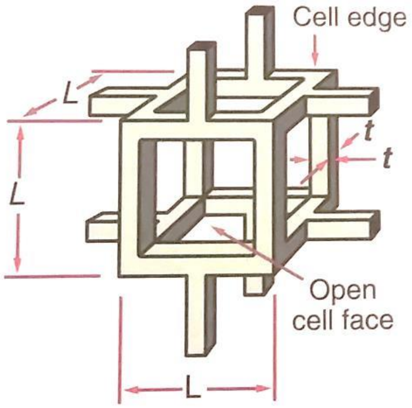


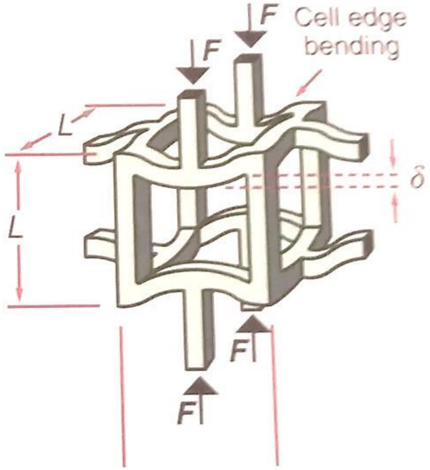
Relations between the mechanical properties and structure

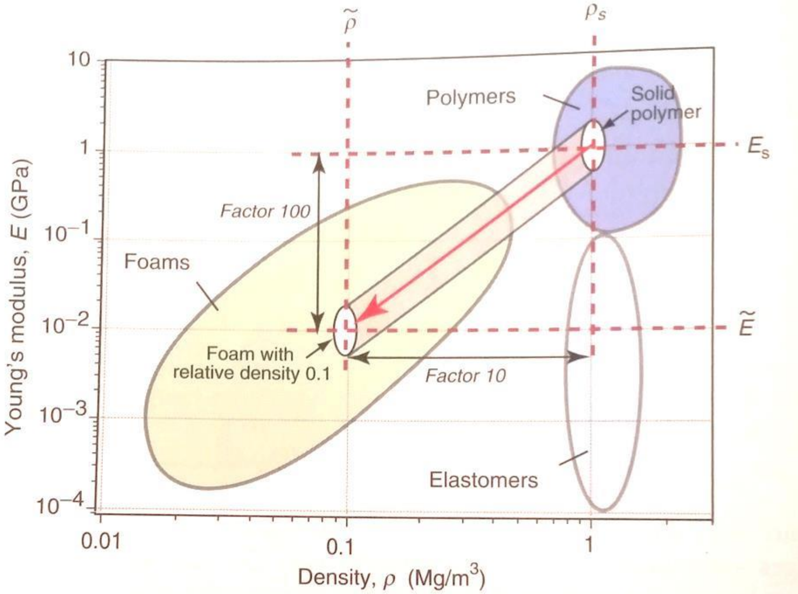
Cellular solids are characterized by their relative density, the fraction of the foam occupied by the solid

$$\frac{\rho_{foam}}{\rho_s} = \left(\frac{t}{L}\right)^2$$

$$\frac{E_{foam}}{E_s} = \left(\frac{\rho_{foam}}{\rho_s}\right)^2$$







Relations between the mechanical properties and structure

- In a composite material with a metal matrix and ceramic fibers, the bulk of the mechanical energy would be transferred through the matrix.
- In a composite consisting of a polymer matrix containing metallic fibers, the energy would be transferred through the fibers.
- For example, in a metal fiber-polymer matrix composite, coefficient of thermal expansion would be low and would depend on the length of the fibers, the volume fraction of fibers and how often the fibers touch one another.

- *Example – You have a unidirectional, graphite/epoxy composite with the following constituent properties and 65% volume loading of fiber:*

$E_f = 43$ GPa, $E_m = 0.5$ GPa

$v_f = 0.2$, $v_m = 0.4$

$\alpha_f = 1.5*10^{-6}/K$, $\alpha_f = 40*10^{-6}/K$

Calculate the E_{11}, v_{11}, *and* α_{11} *using the rule of mixtures*