Lecture 13: Composites

Prof. Nathan Szymanski
nszymanski@seas.ucla.edu
Department of Materials Science & Engineering

Recap: We have covered a variety of materials



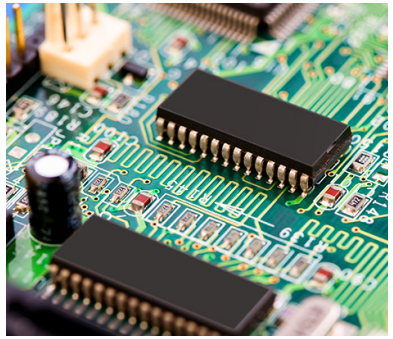
Metals

- Dense structure
- Moderate T_m
- Conductive
- Strong/ductile



Ceramics

- Less dense structure
- Very high T_m
- Insulating
- Hard but fragile



Semiconductors

- In between metals and ceramics
- Moderate strength, conductivity, *etc.*



Polymers

- Very low density (lightweight)
- Usually low T_m
- Insulating
- Often soft, ductile, and “stretchable”
- Cheap!

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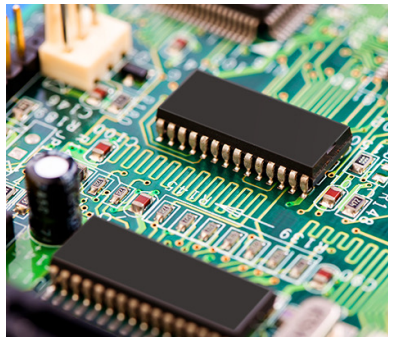

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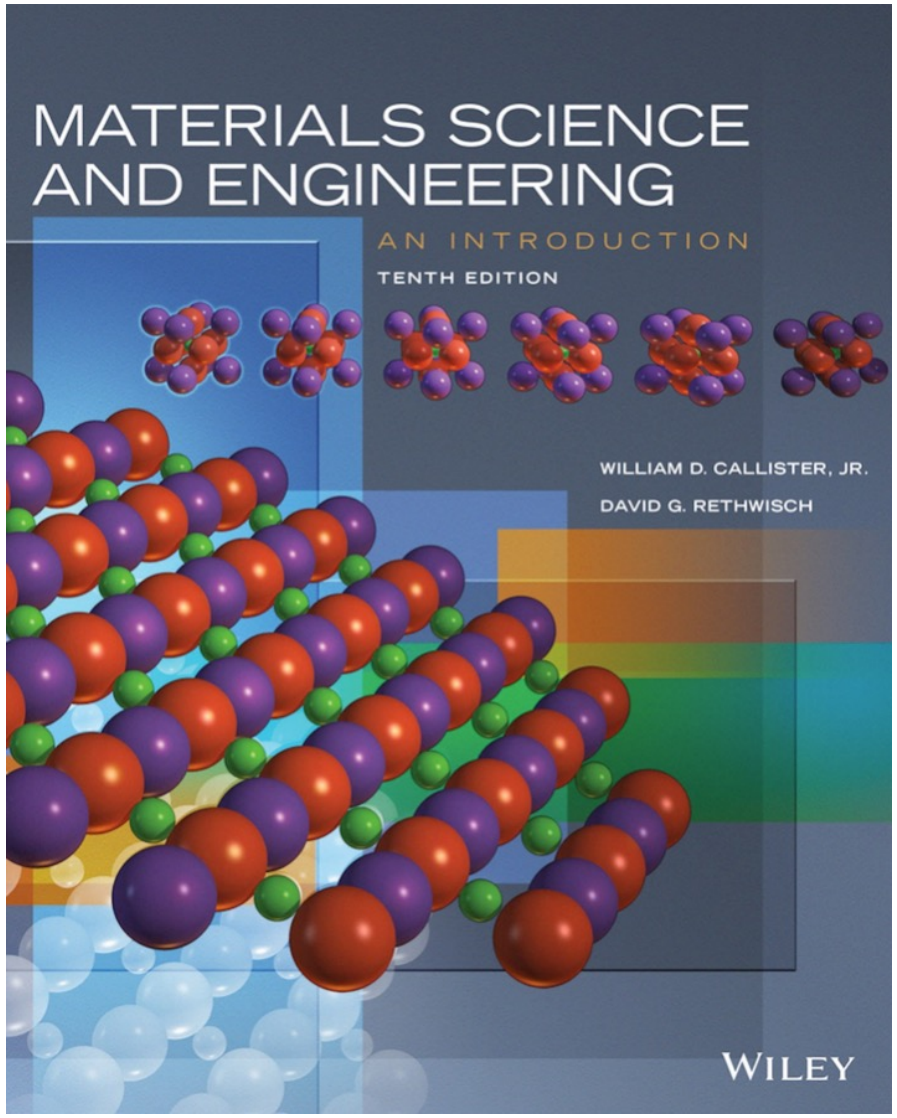
What if want a *combination* of these properties?

→ **Composites!**

Reading for this subject



Chapter 16 Composites

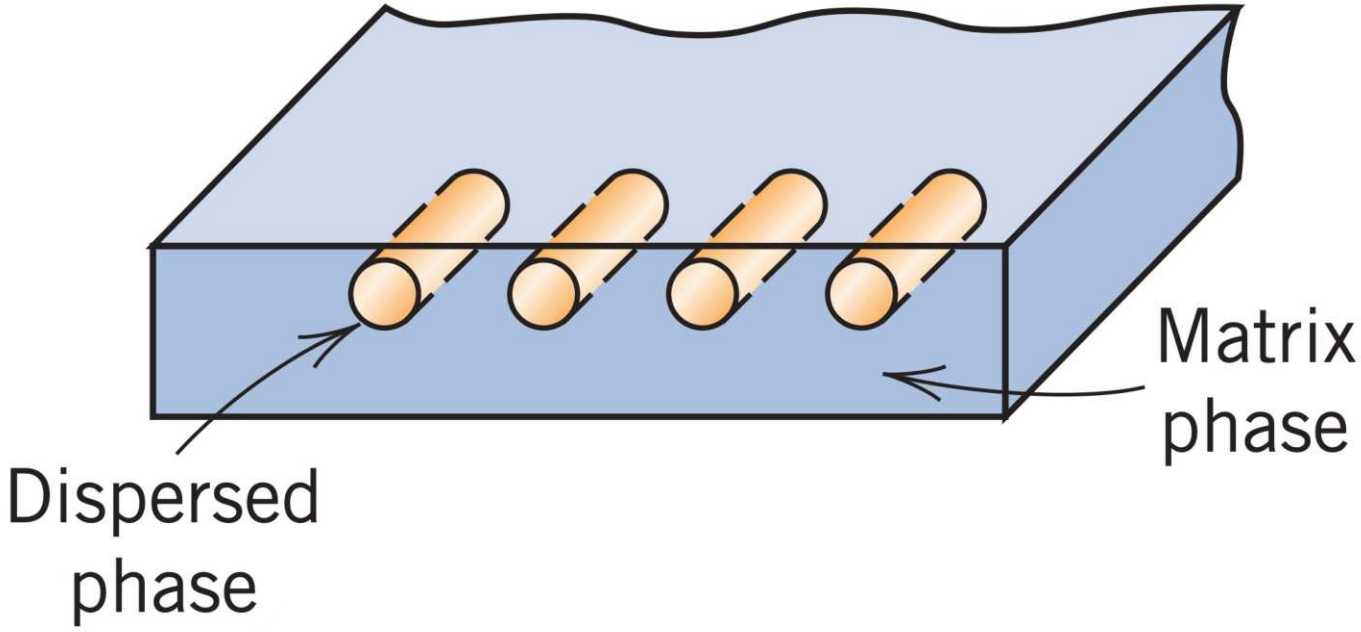
This discussion will closely follow **Chapter 16** of Callister, **pages 565-602** of the 10th edition.

Some terminology

A composite is a *deliberately engineered* material consisting of **two or more distinct phases that remain separate** and retain their individual properties, combined to achieve enhanced properties

Two-phase composites are most common.

The **matrix** is continuous and surrounds the other **(dispersed)** phase.



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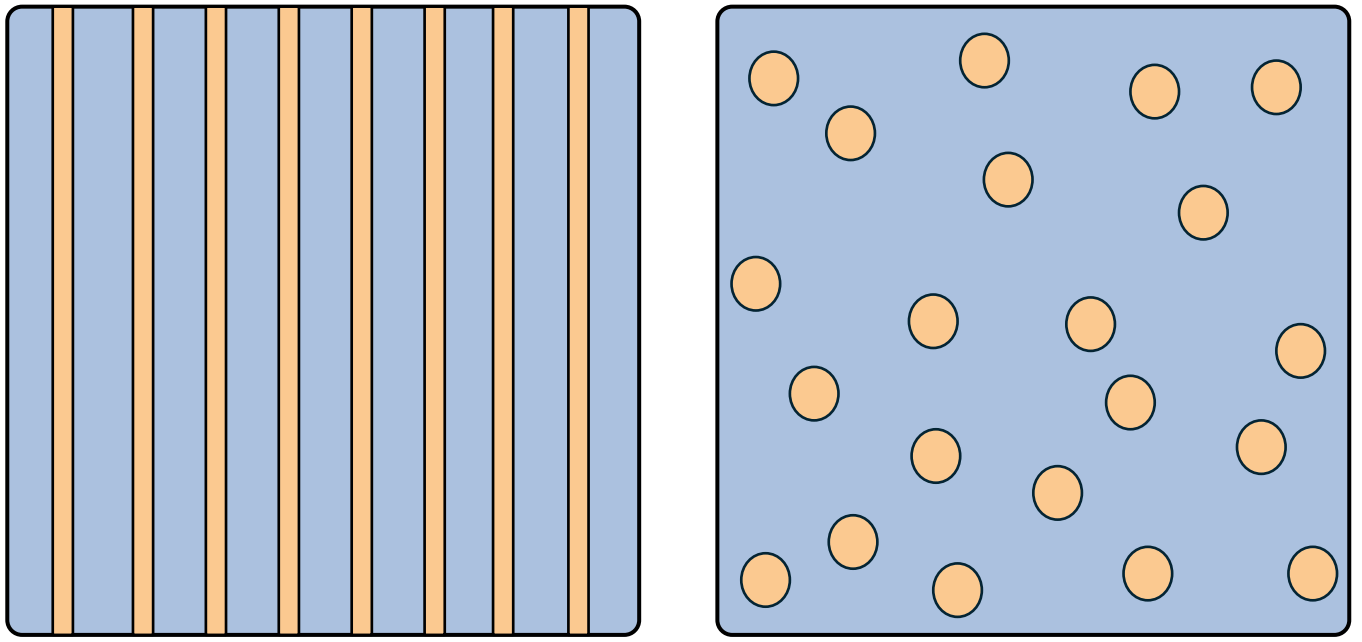
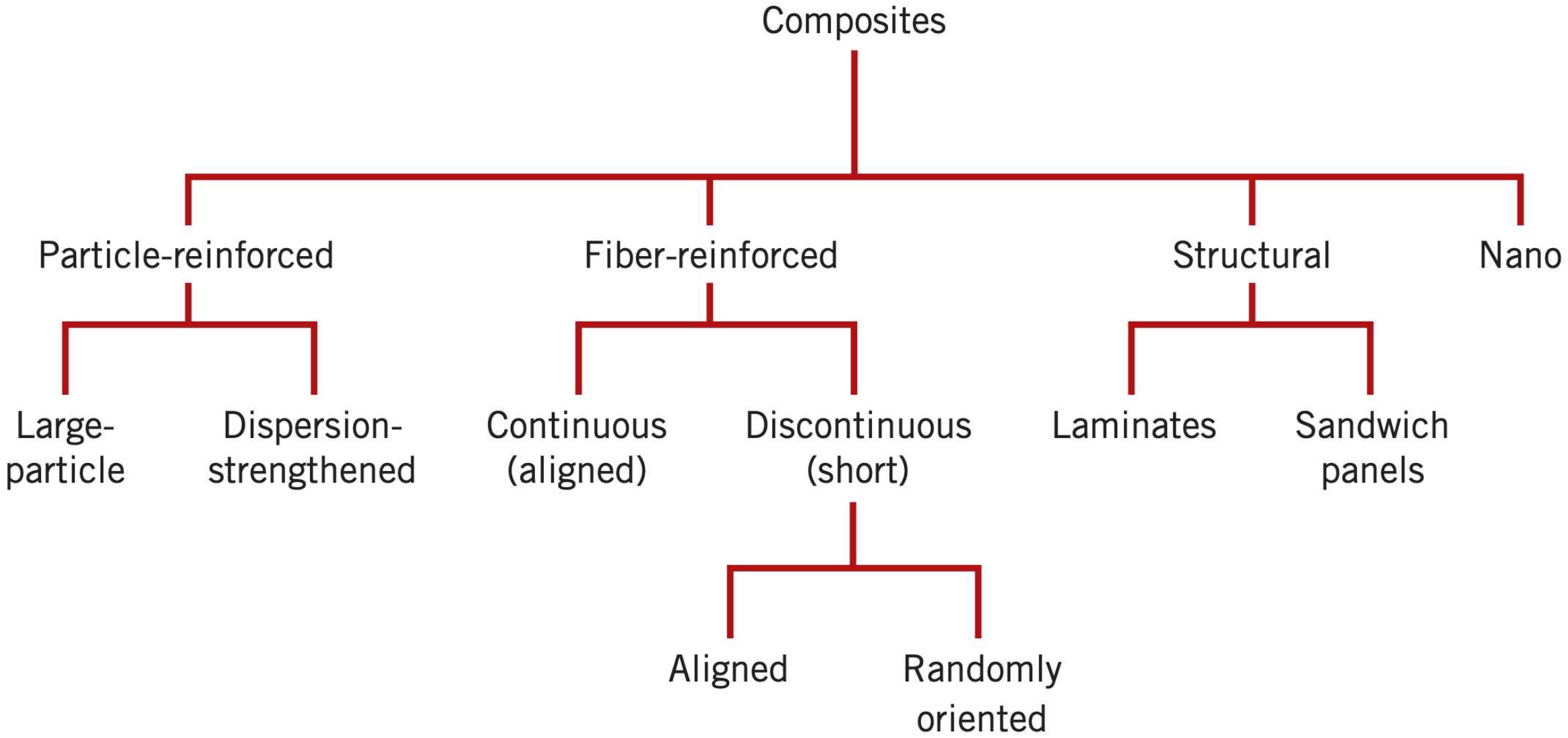
Layers, fibers, particles, …

Layers, fibers, particles, *etc.*

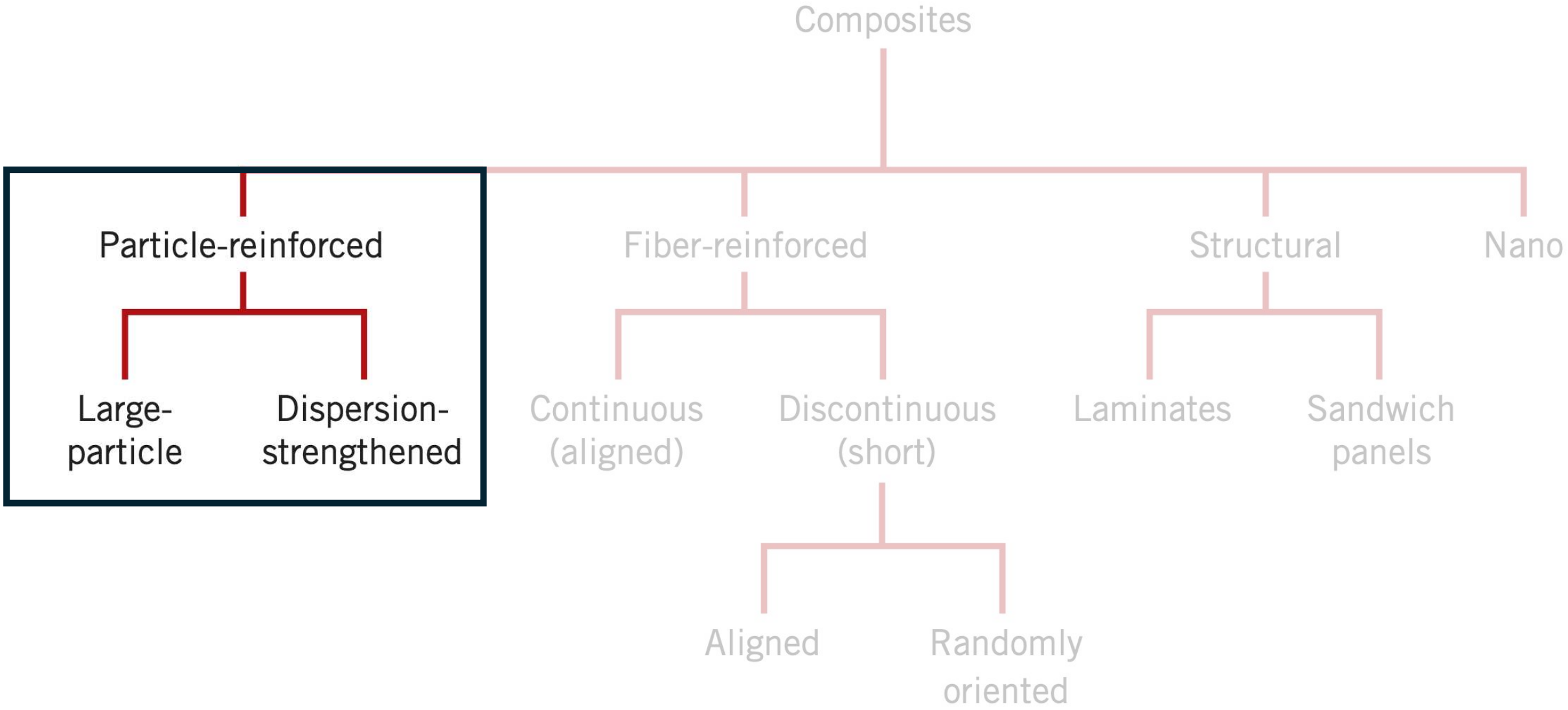


The dispersed phase can take on a **variety of shapes, sizes, and concentrations.**

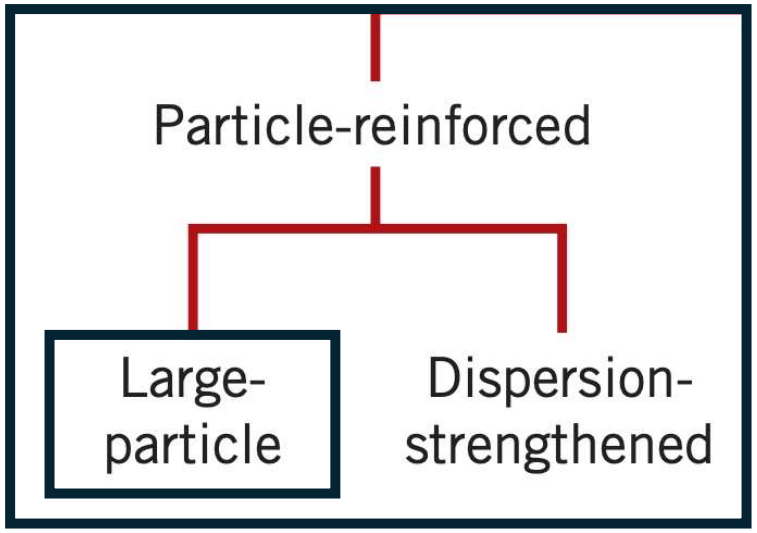
Different types of composites

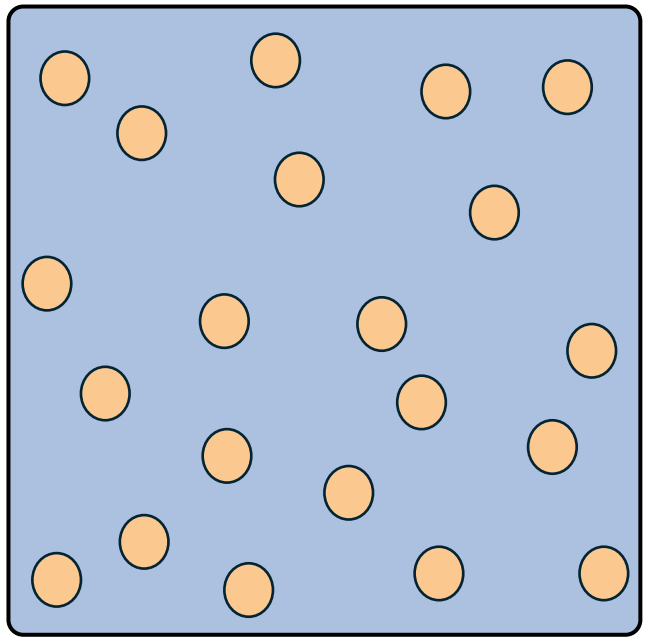


Different types of composites



Particle-reinforced composites





In this case, the dispersed phase is *equiaxed* → its particles are (very roughly) spherical

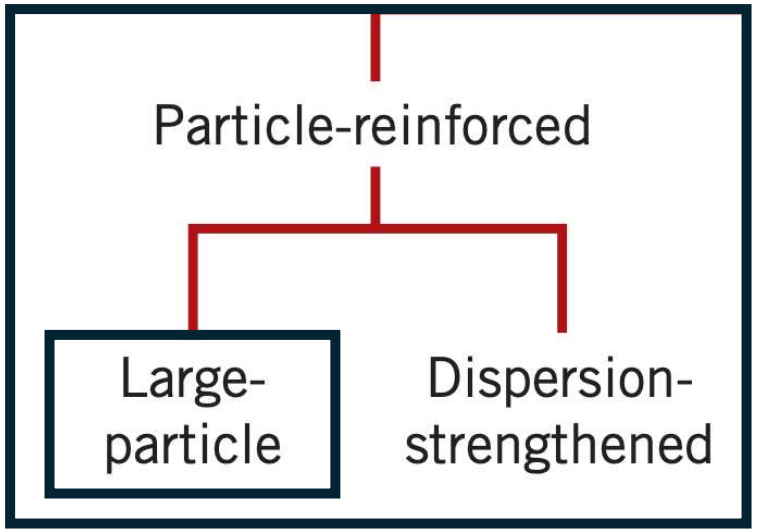
For **large particle**-reinforced composites, the dispersed phase is large enough ($\geq \mu m$) that we can **neglect atomic-scale interactions** and instead use continuum mechanics

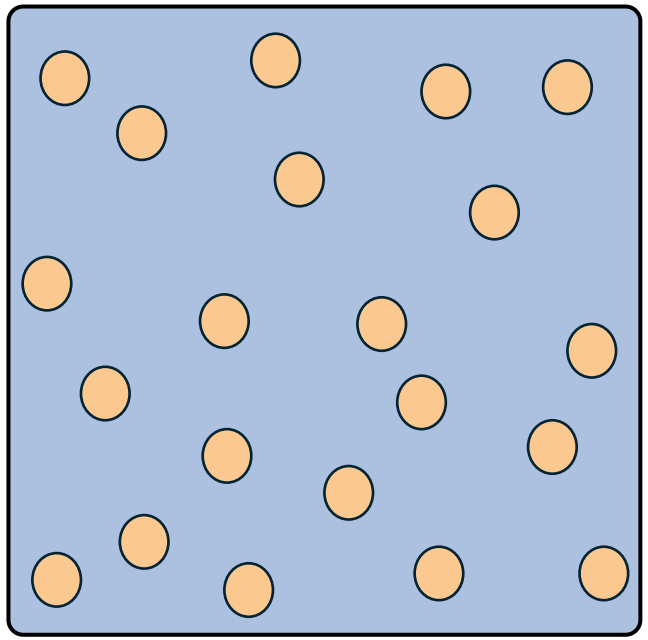
Properties roughly follow the **rule of mixtures:**

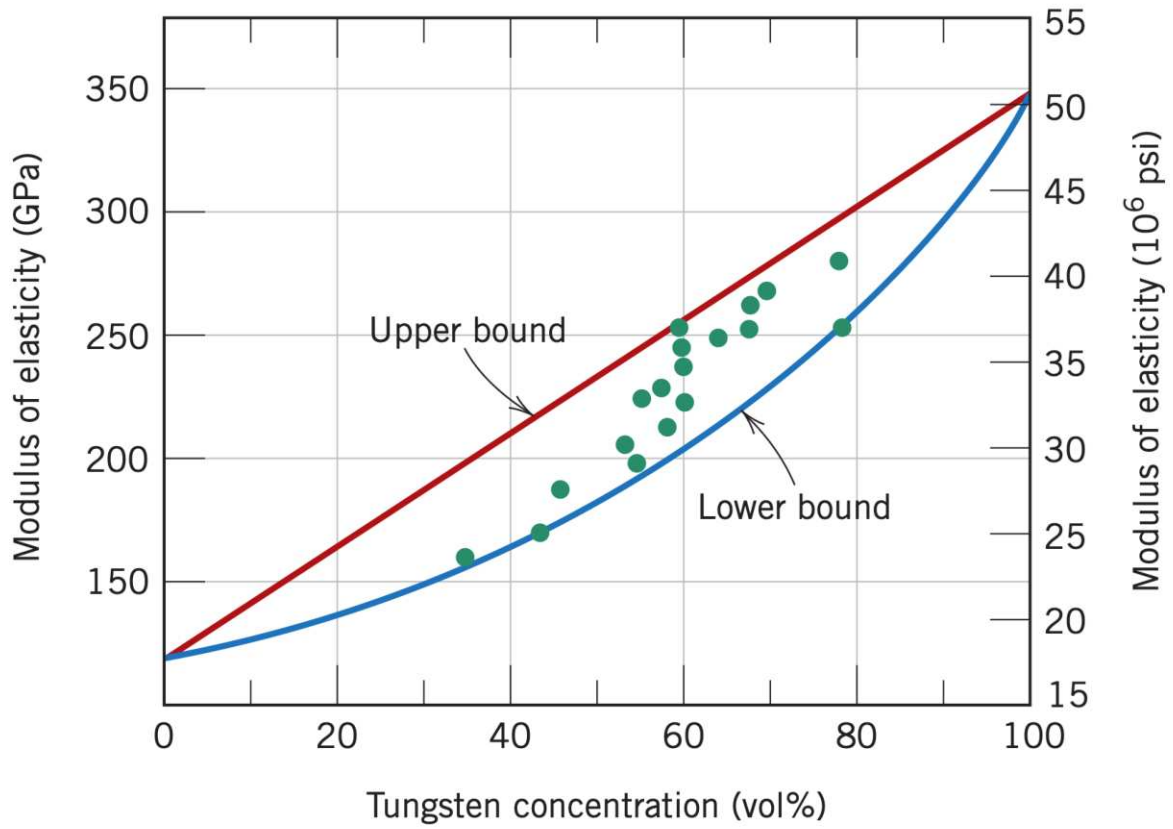
Upper limit $$E_c(u) = E_m V_m + E_p V_p$$

Lower limit $$E_c(l) = \frac{E_m E_p}{V_m E_p + V_p E_m}$$

E_i is the elastic modulus, V_i is the volume fraction







Note: this rule applies to properties other than E

Upper limit

$$E_c(u) = E_m V_m + E_p V_p$$

Lower limit

$$E_c(l) = \frac{E_m E_p}{V_m E_p + V_p E_m}$$

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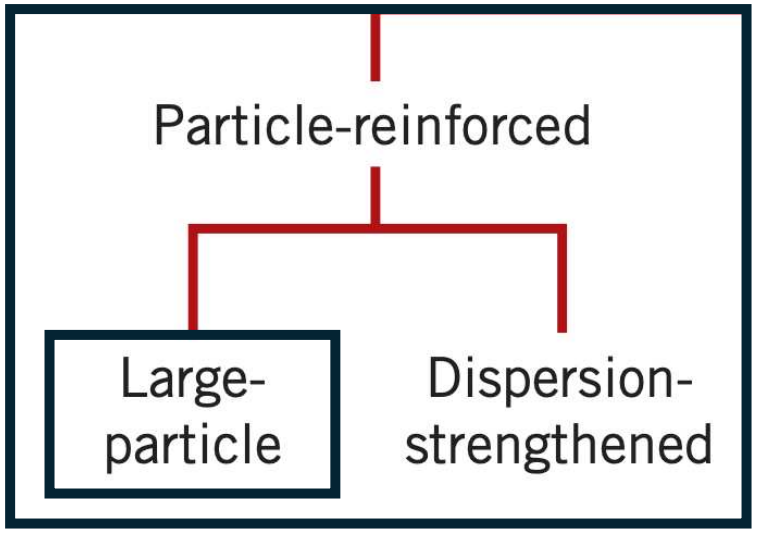
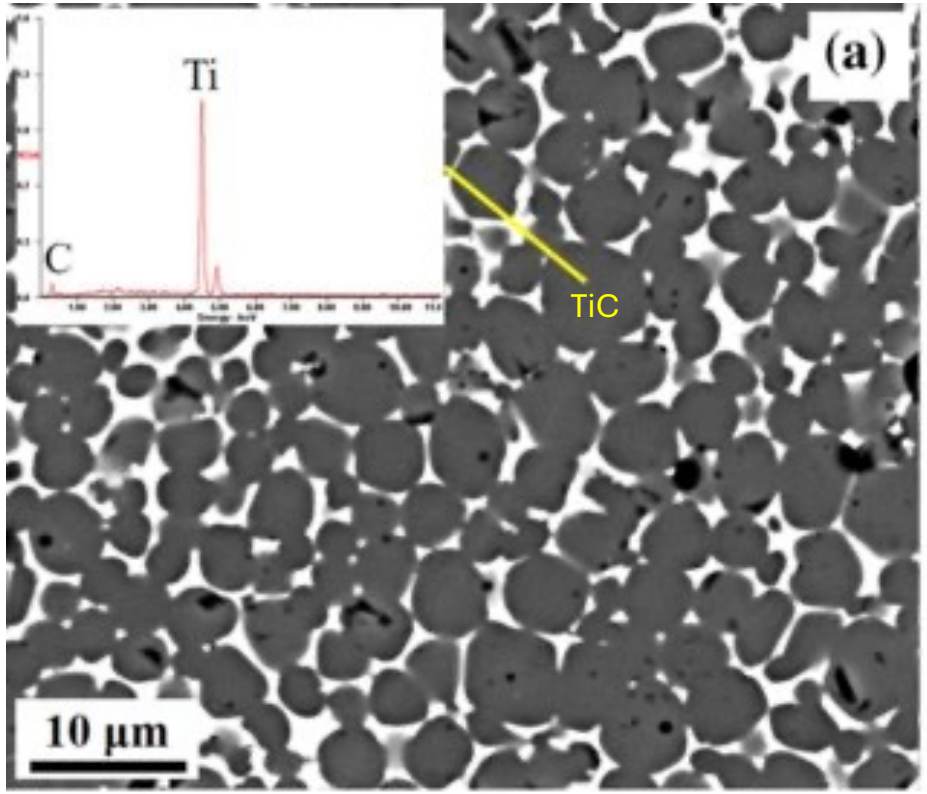
Examples of large particle-reinforced composites



The **cermets** have extremely hard ceramic particles (like WC or TiC) embedded in a softer, more ductile metal (like Co or Ni) matrix

Often used in **drilling/cutting** applications. The ceramic provides the hardness while the metal prevents brittle fracture.

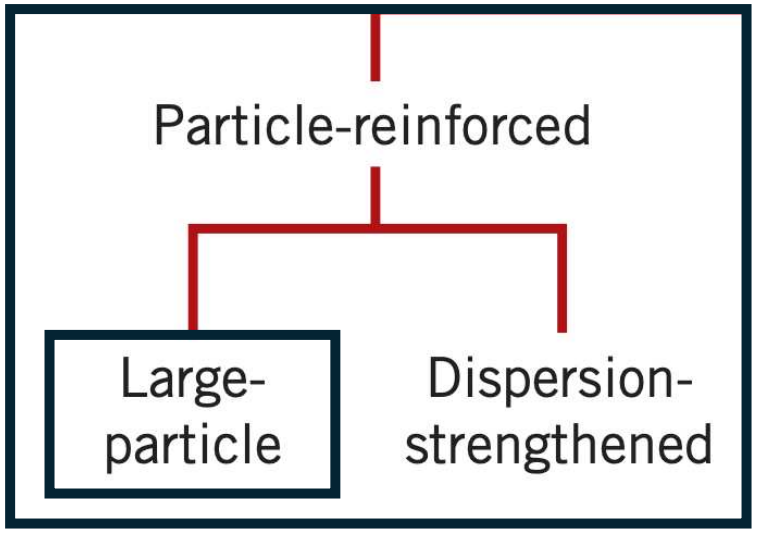




Ni matrix

Chen *et al.*, J. Mater. Sci. (2020).

Examples of large particle-reinforced composites



Modern rubbers are polymeric but rarely used on their own – rather, we disperse particulate materials such as carbon black to greatly improve their strength and abrasion resistance



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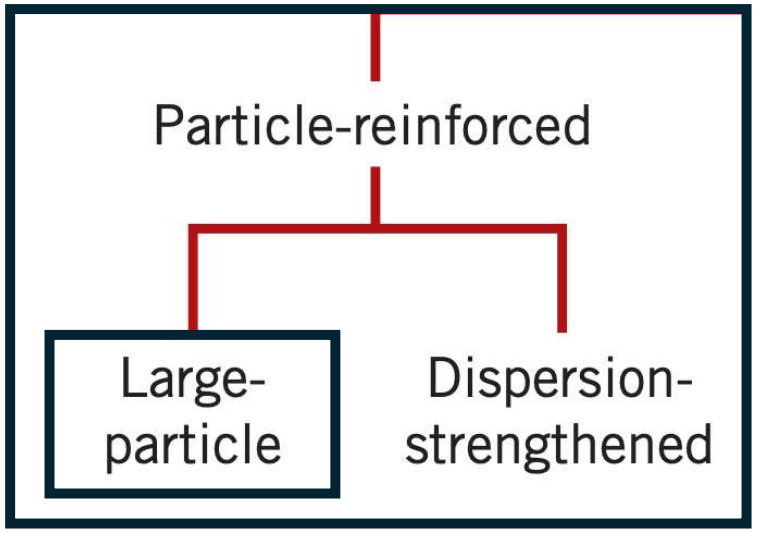
White tires in early 1900s

Modern tires generally contain 15-30% carbon by volume. Without this addition, tires wear much more quickly.

Examples of large particle-reinforced composites



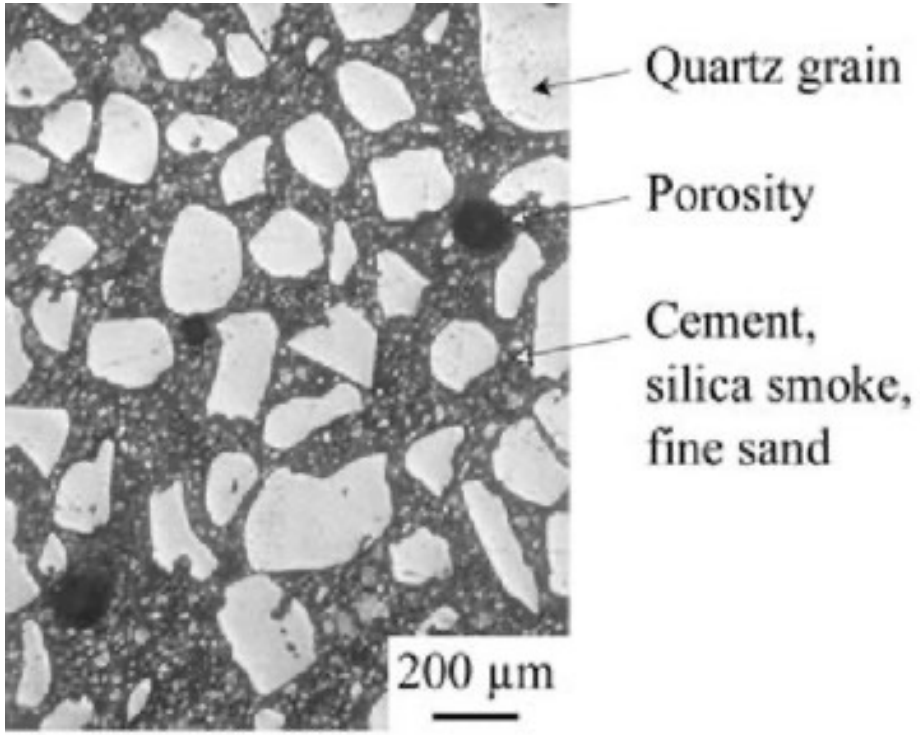
Concrete is another widely used composite, consisting of multiple ceramic materials.

Typical ingredients: large sand/gravel particles embedded in a binder (cement) – which activates upon adding water

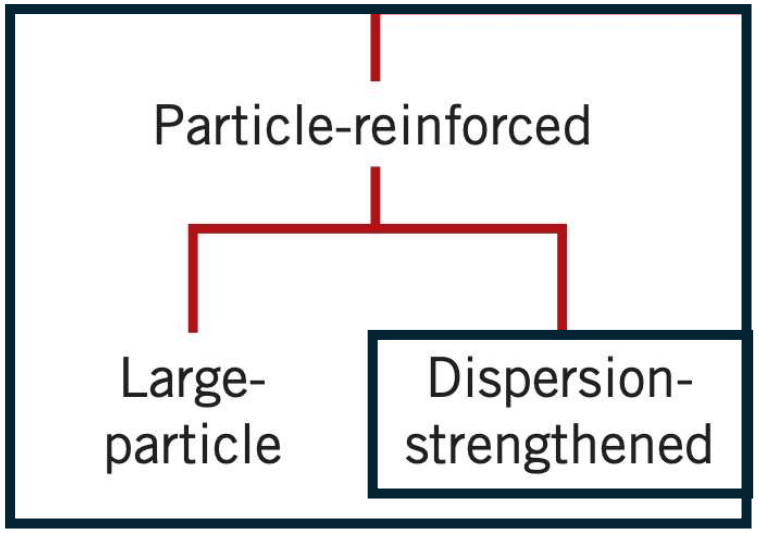
Adding sand/gravel to the cement matrix:

1) **Reduces cost**, as cement is more expensive
2) **Provides improved structural integrity**



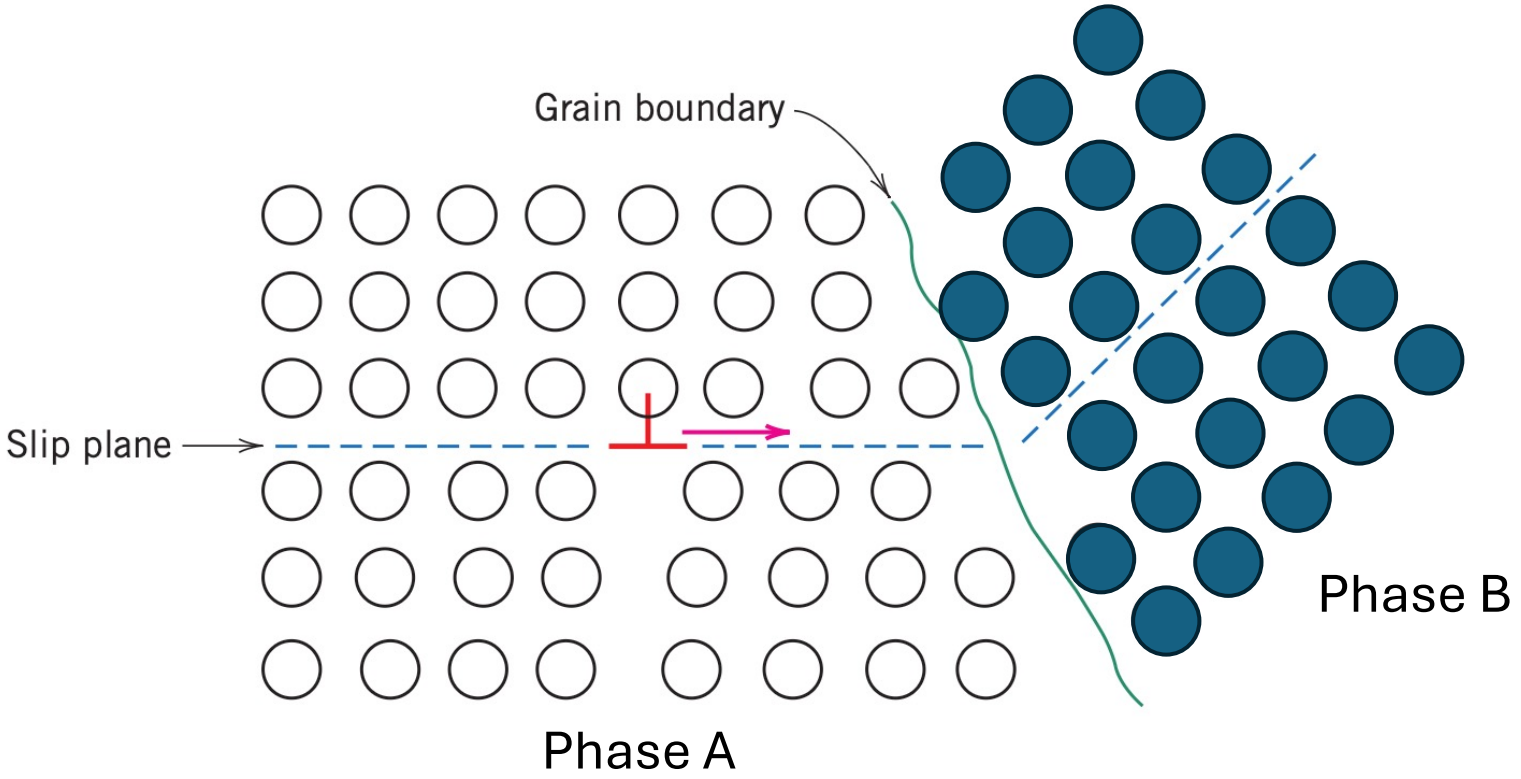


Dispersion strengthened particle composites



For **dispersion-strengthened** composites, the dispersed phase is very small ($< \mu m$) and dictates mechanical properties through **dislocation-particle interactions**

Example:
Ni alloys are often strengthened by adding 3% volume ThO_2



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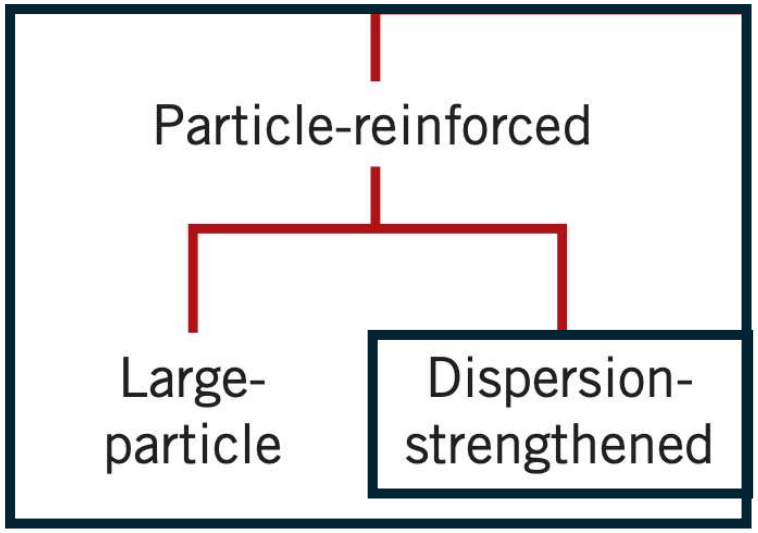
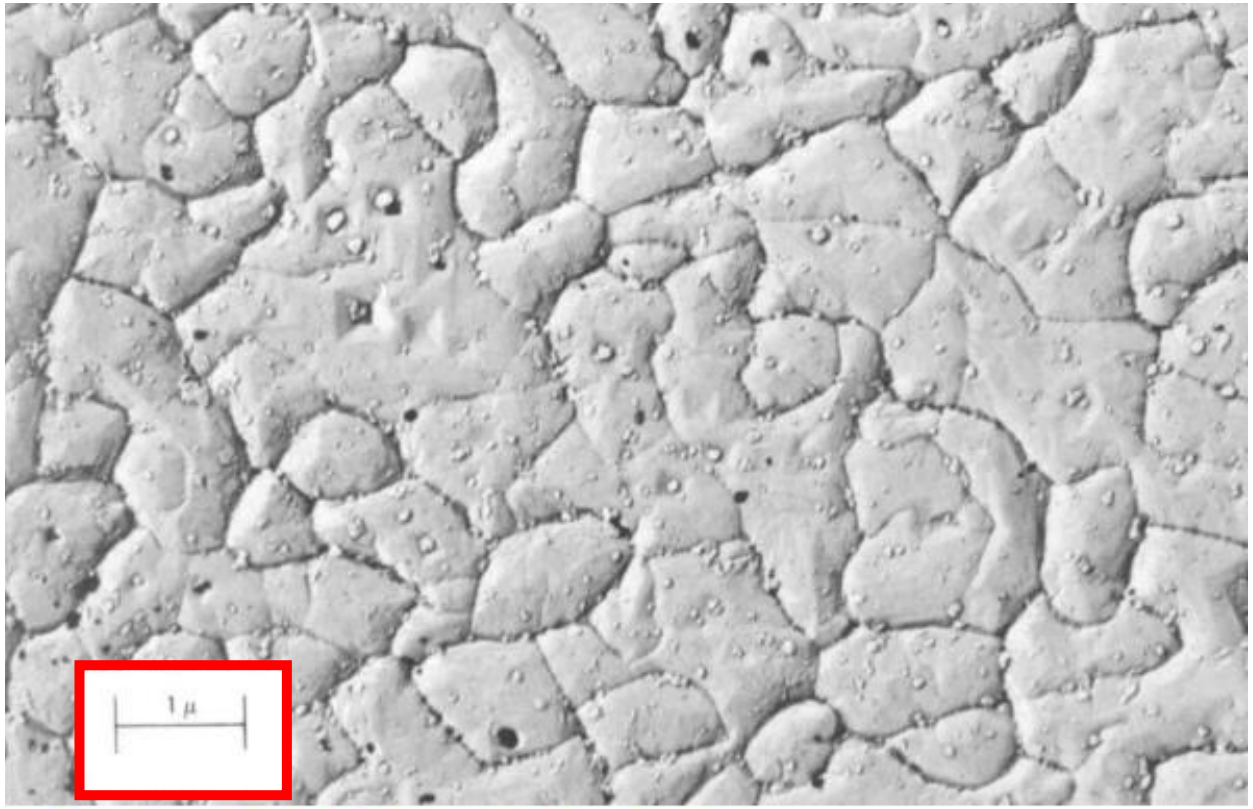




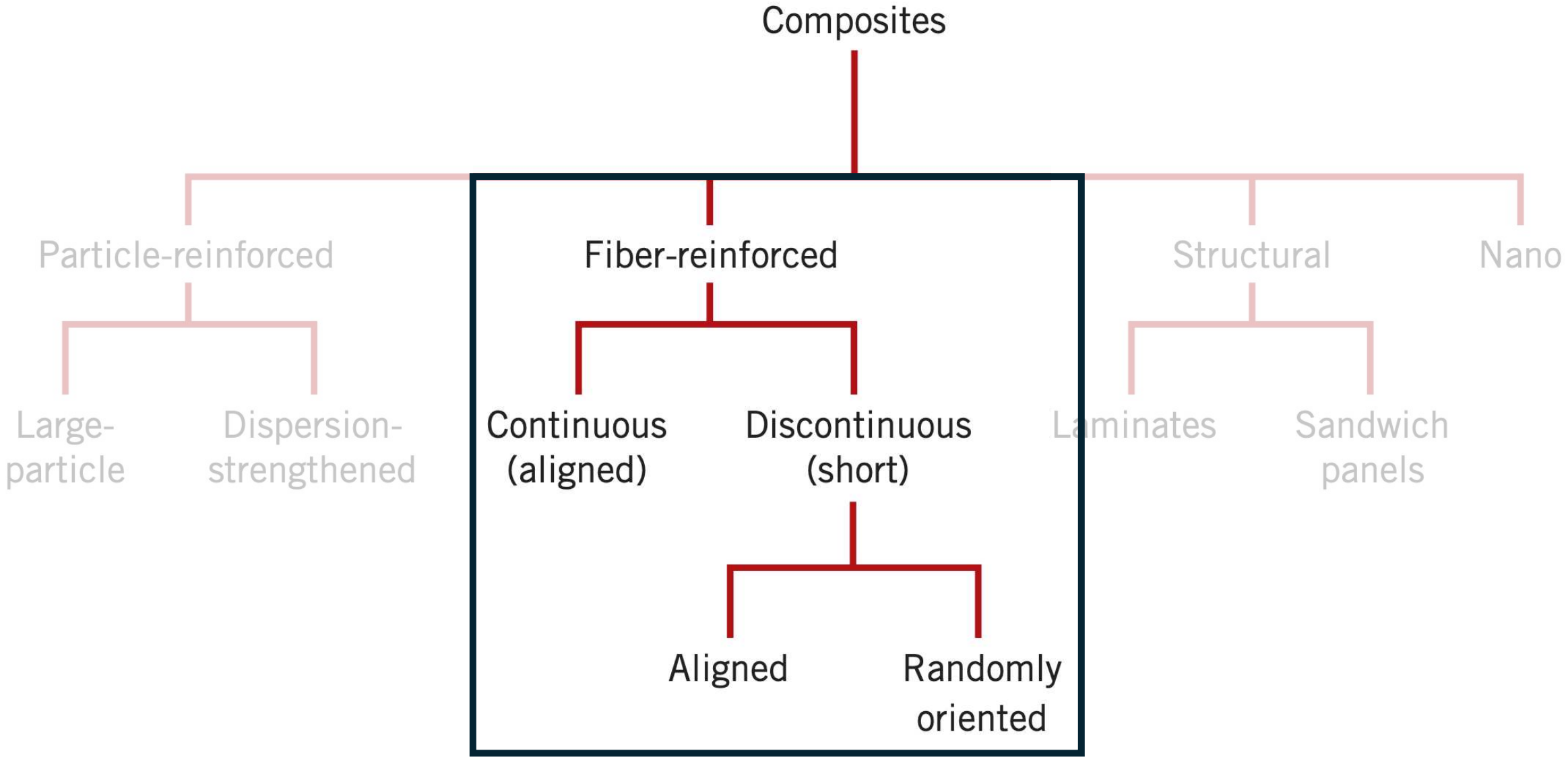
Very small dispersed particles!

Example:
Ni alloys are often strengthened by adding 3% volume ThO_2



These are good at resisting dislocation motion. They are commonly used for high-*T* applications (turbines).

Fiber-reinforced composites



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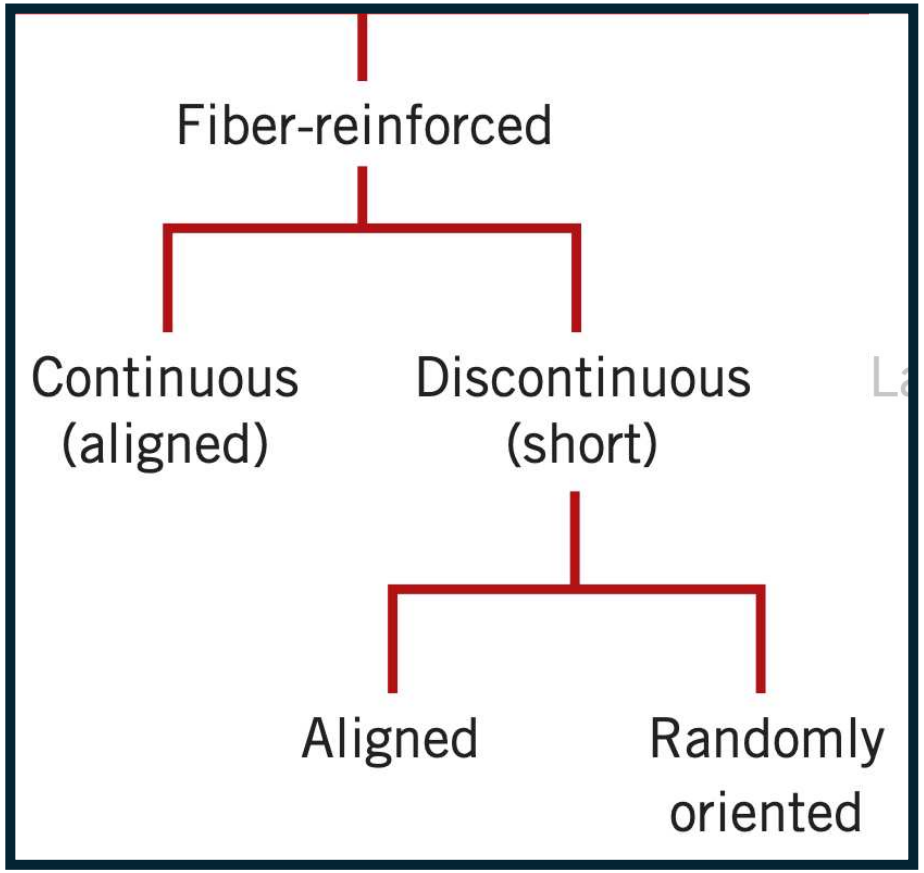
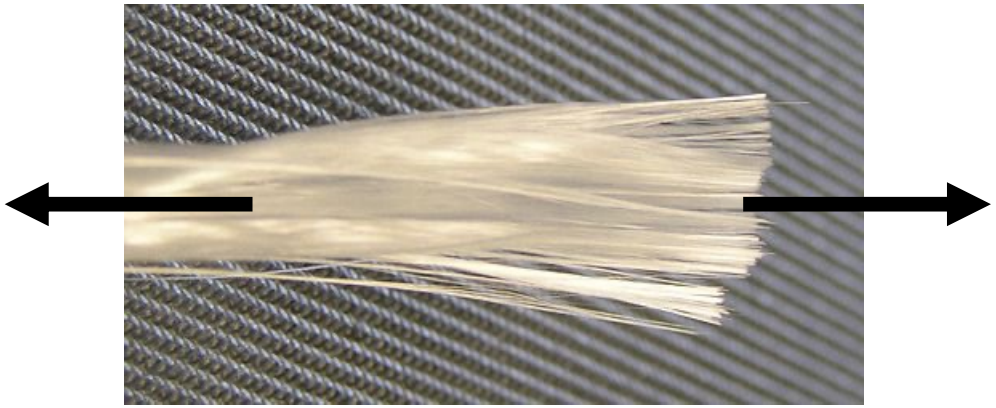


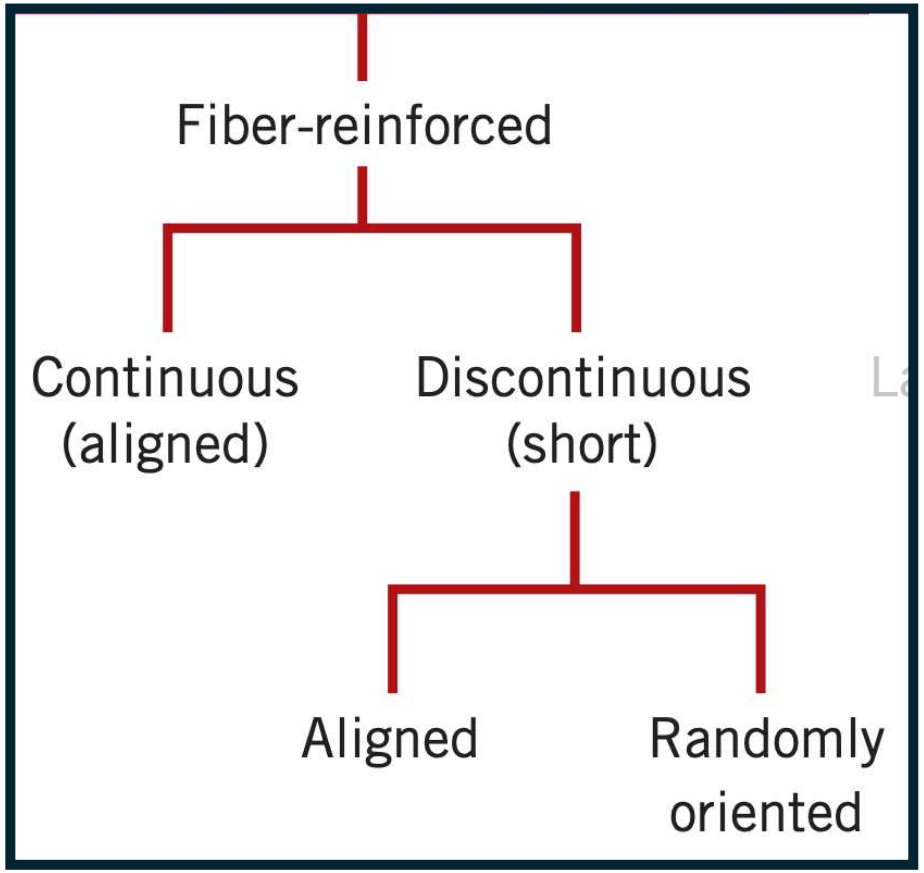
These are probably the most technologically important types of composites. Fibers have uniquely **high tensile strengths** while requiring little mass and volume.



These glass fibers are very strong is we try to pull them apart, but provide little to no structural integrity in the other directions

Solution:
Embed them in some bulk matrix

Fiber-reinforced composites



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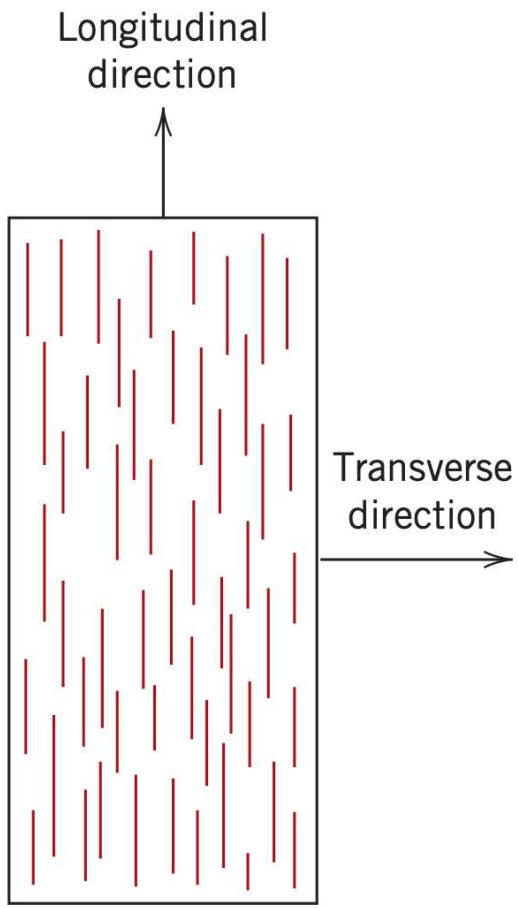
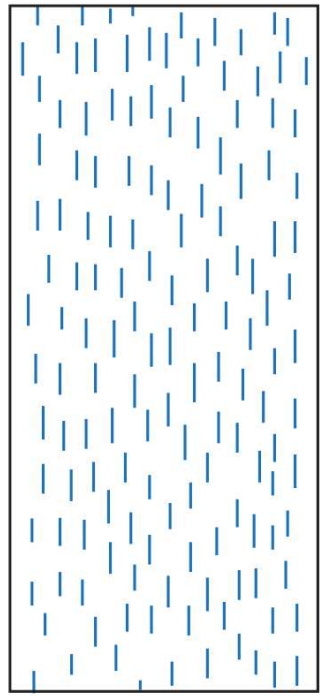
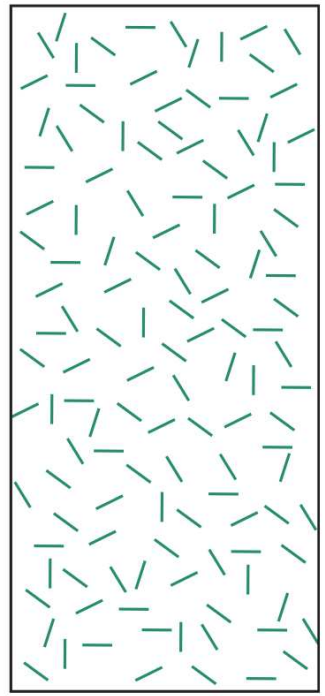






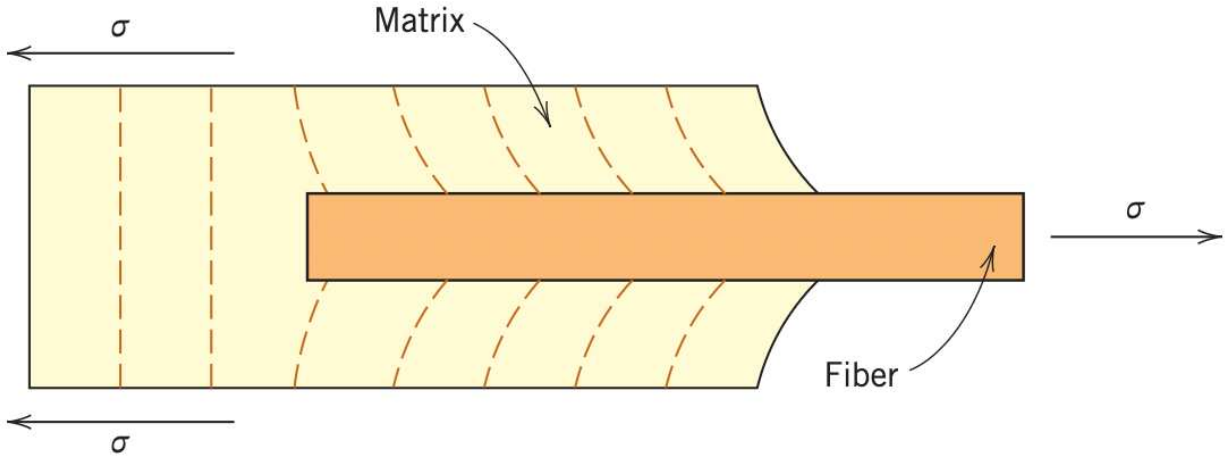
Continuous (aligned) **?** Discont (aligned)

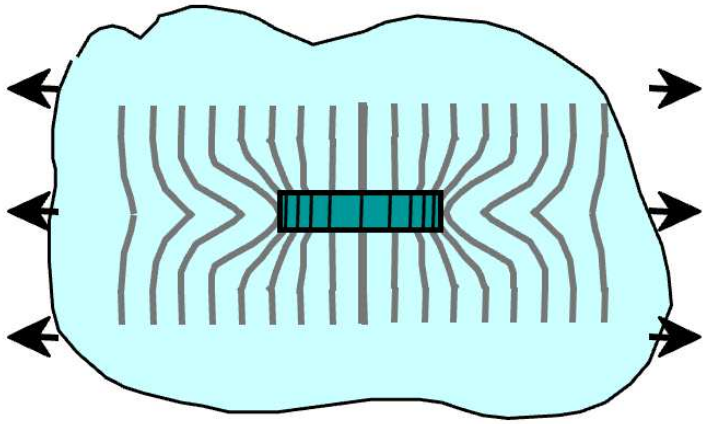
Distcont (random)

Fiber-reinforced composites

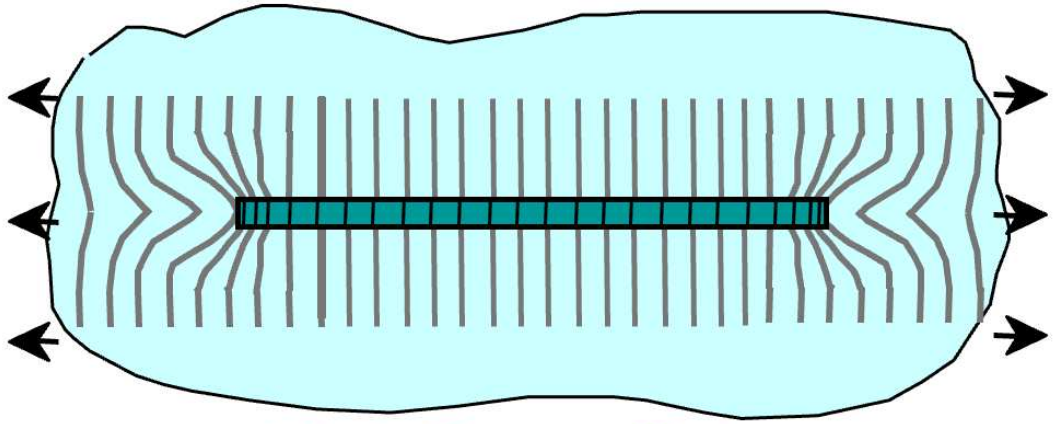
Fiber length dictates **how much load is transferred** from the matrix to the fiber

Longer fibers tend to be more effective in handling stresses





Low fiber efficiency



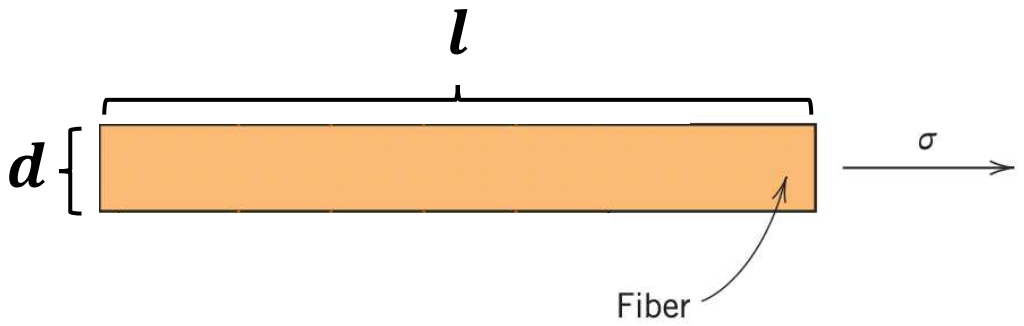
High fiber efficiency

Fiber-reinforced composites

Fiber length dictates **how much load is transferred** from the matrix to the fiber

The **critical length** necessary for effective strengthening:

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

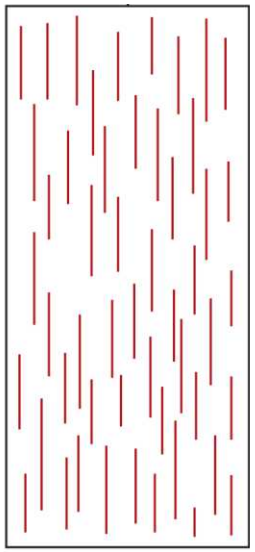


σ_f^* is the fiber tensile strength

d is the fiber diameter

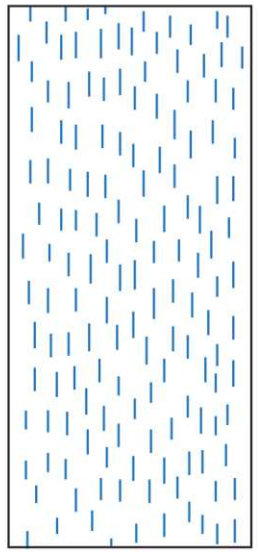
τ_c is the fiber-matrix bond strength

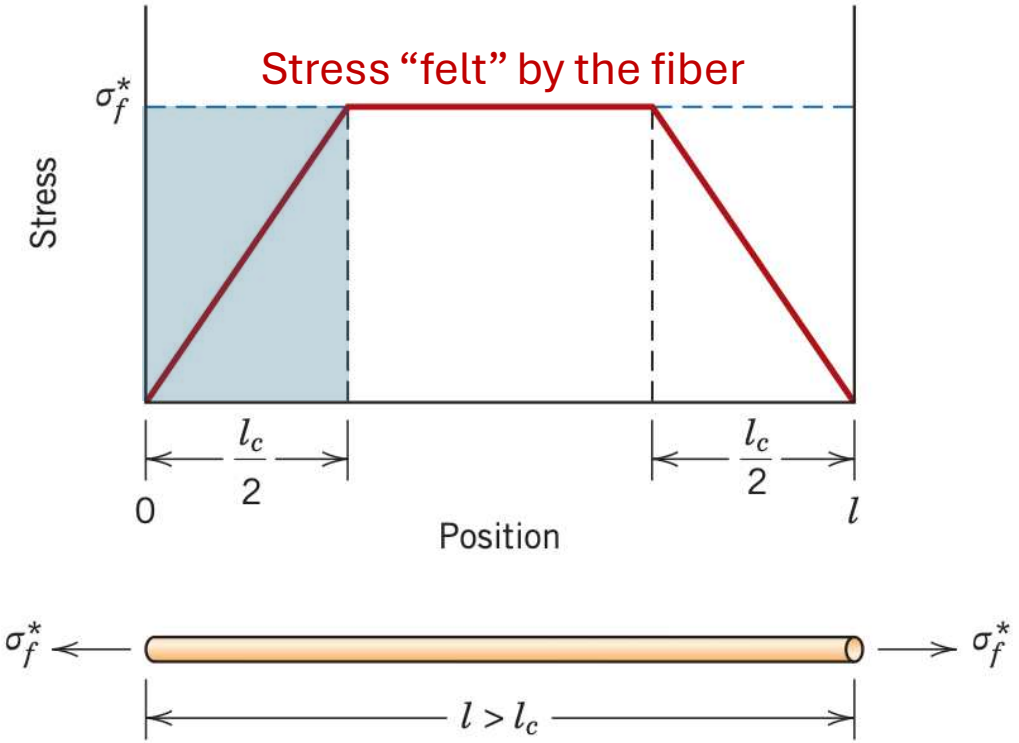
l_c is often on the order of mm

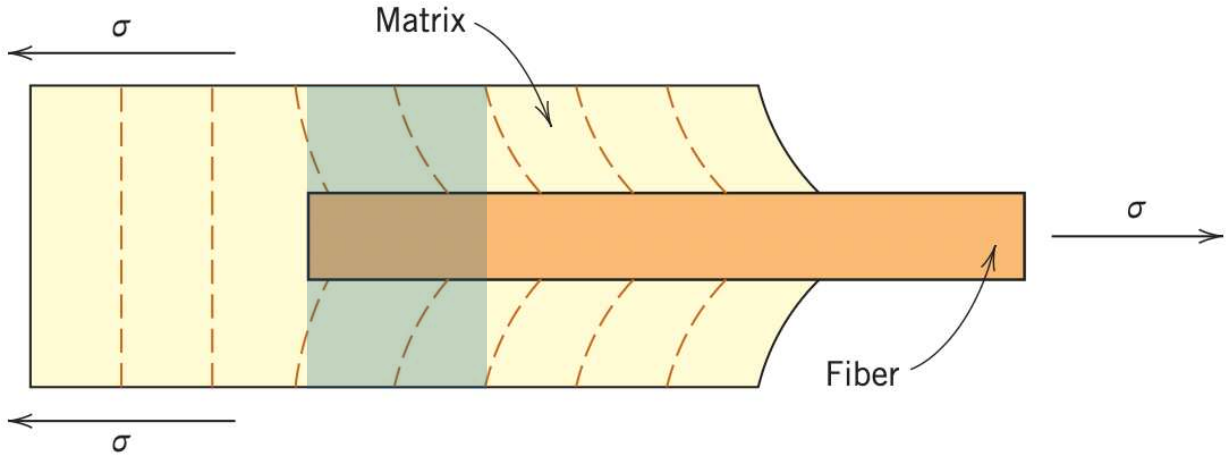


Continuous fibers usually means $l \gg l_c$ (e.g., $> 15\ l_c$)

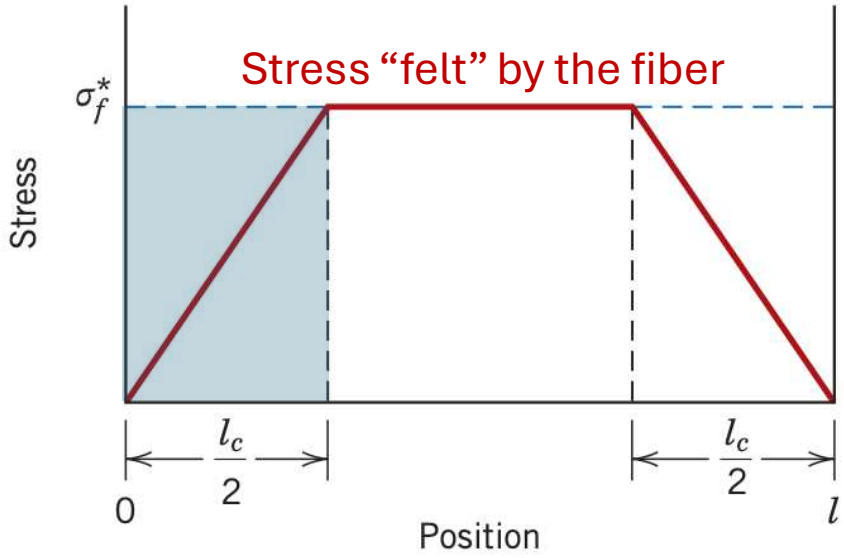
Discont fibers have $l \sim l_c$

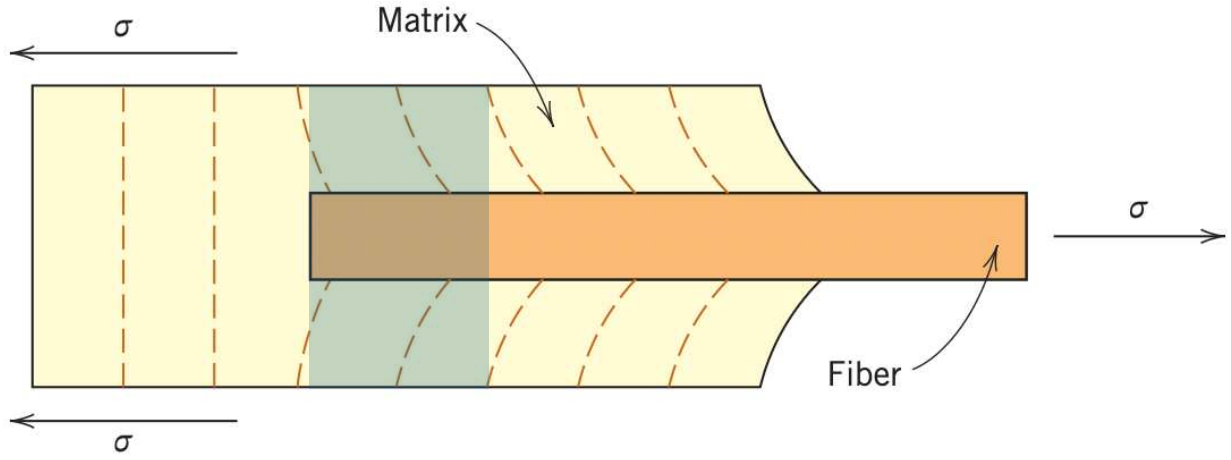


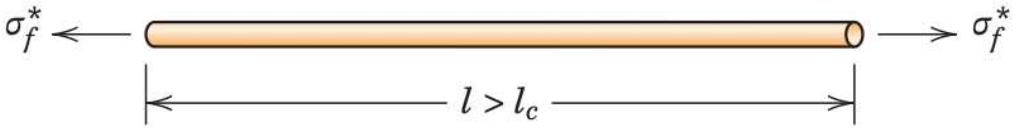


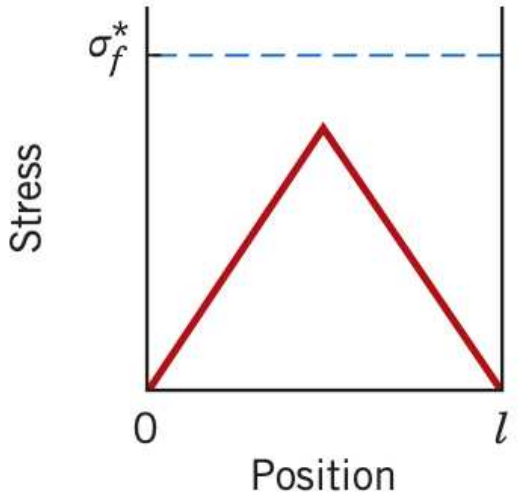


When $l > l_c$ there are parts of the fiber (near the ends) that do not fully contribute to the load resistance



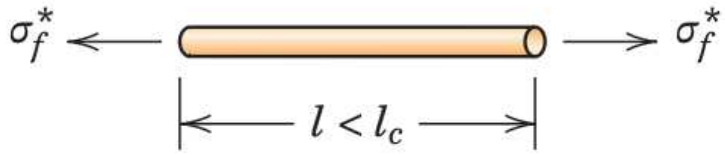






The fiber is not taking much of the load

When $l < l_c$ then **none** of the fiber contributes fully to the load resistance. In this case, the composite acts more like a particle-reinforced matrix.

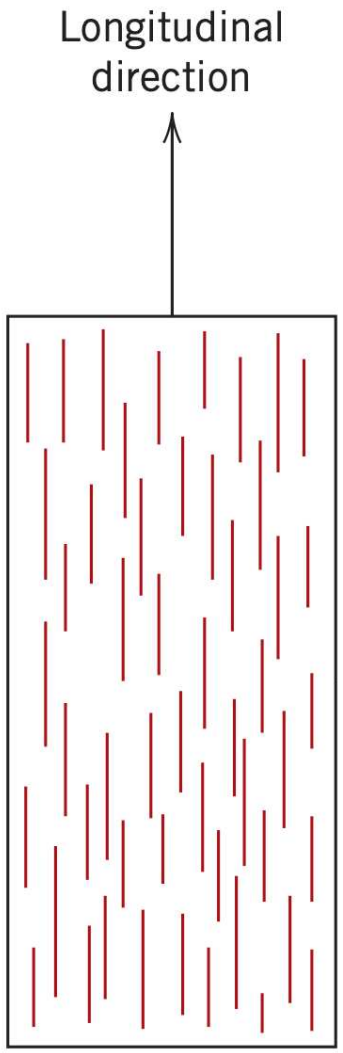


Questions of the effects of fiber length?

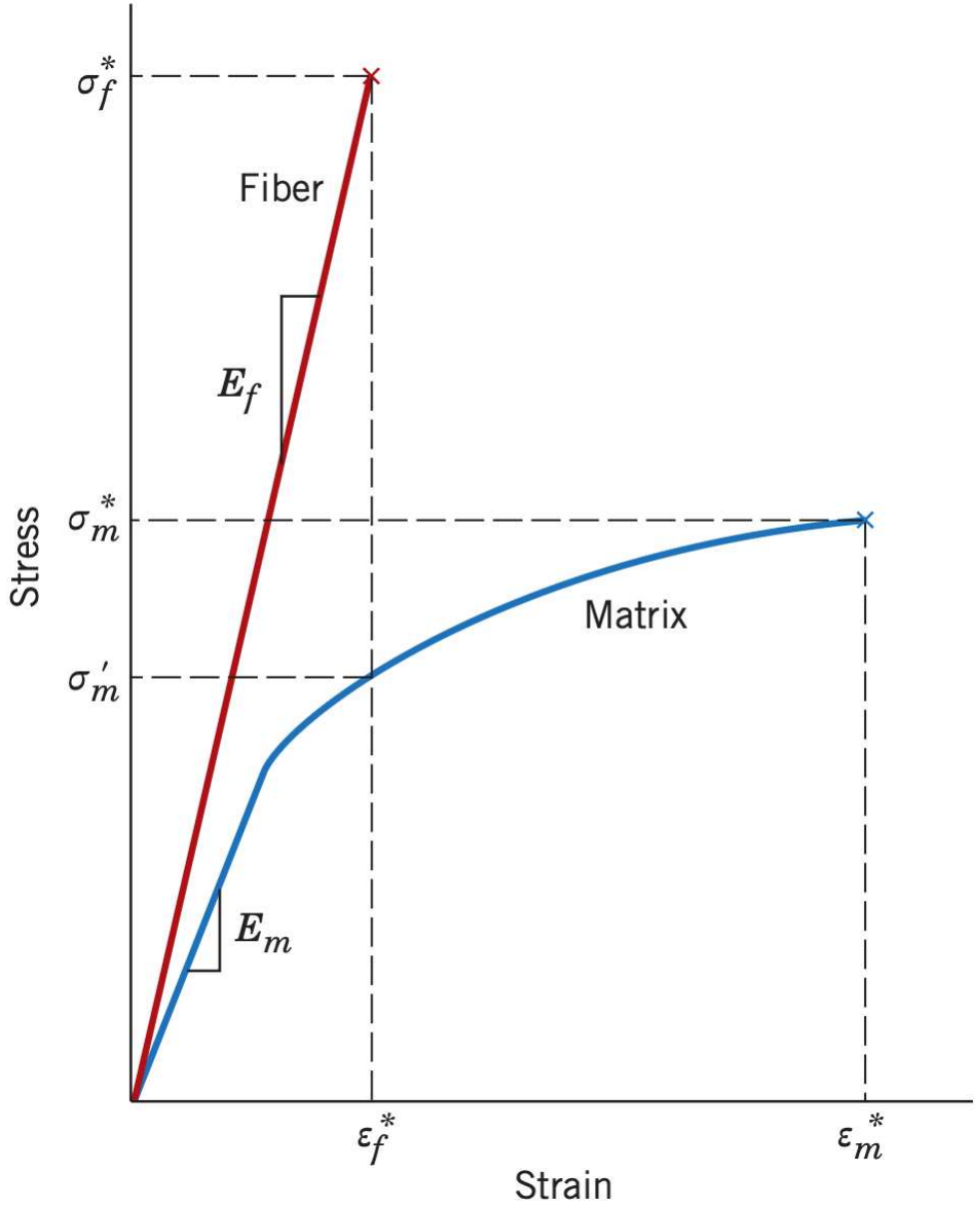
In general: longer fibers = better support

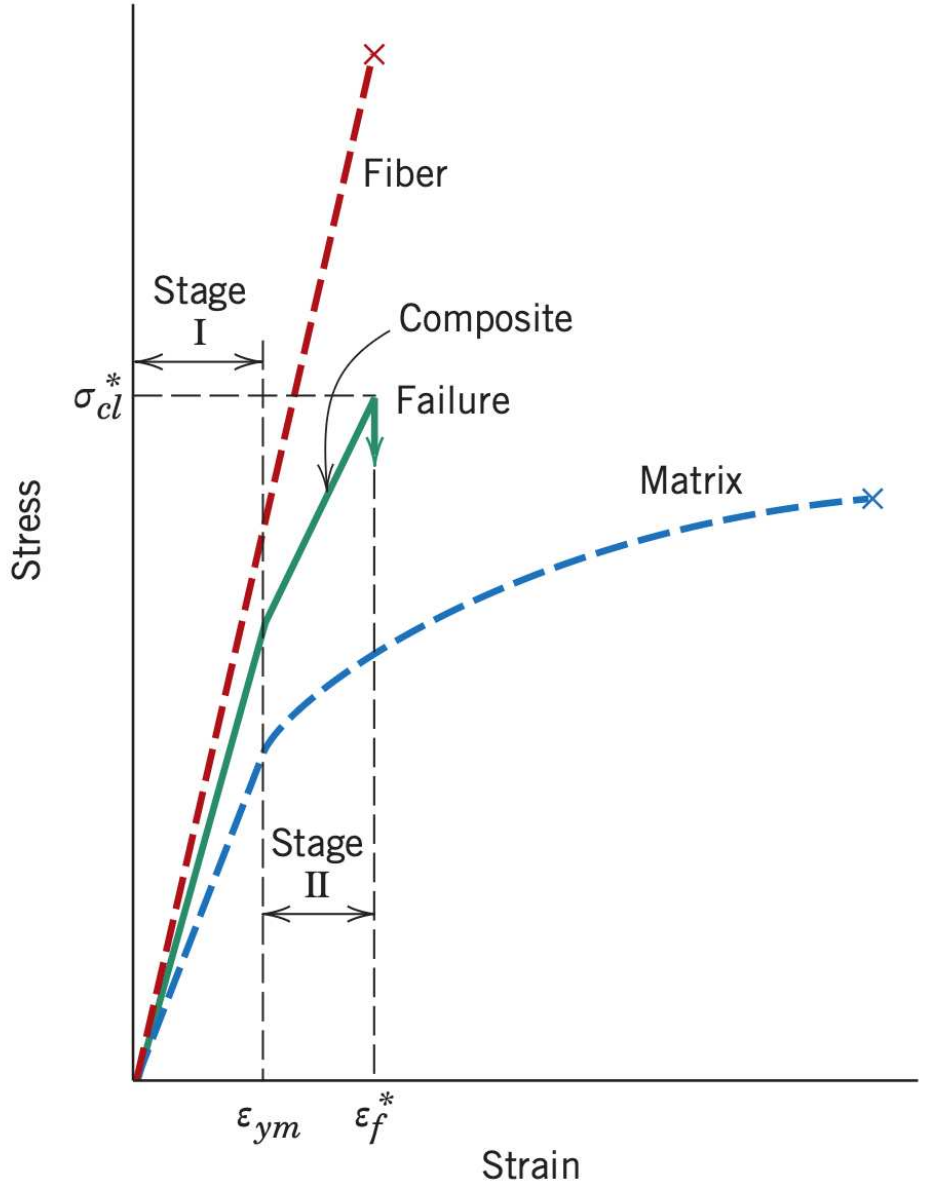
How about alignment?

Stress-strain of *aligned* fiber-reinforced composites

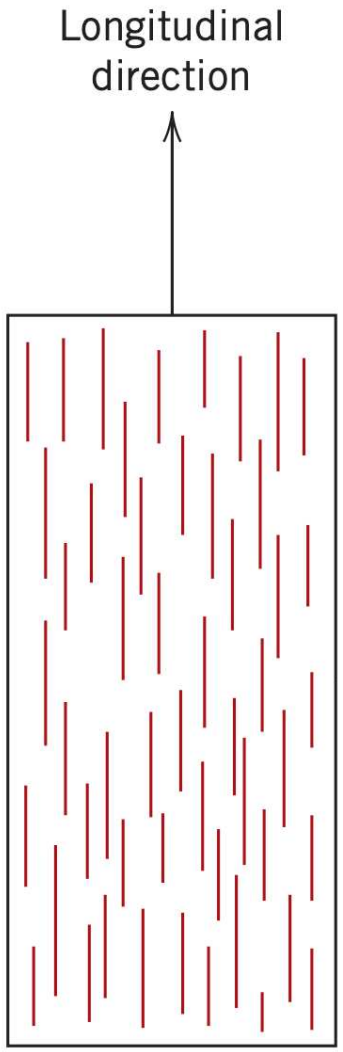


Continuous

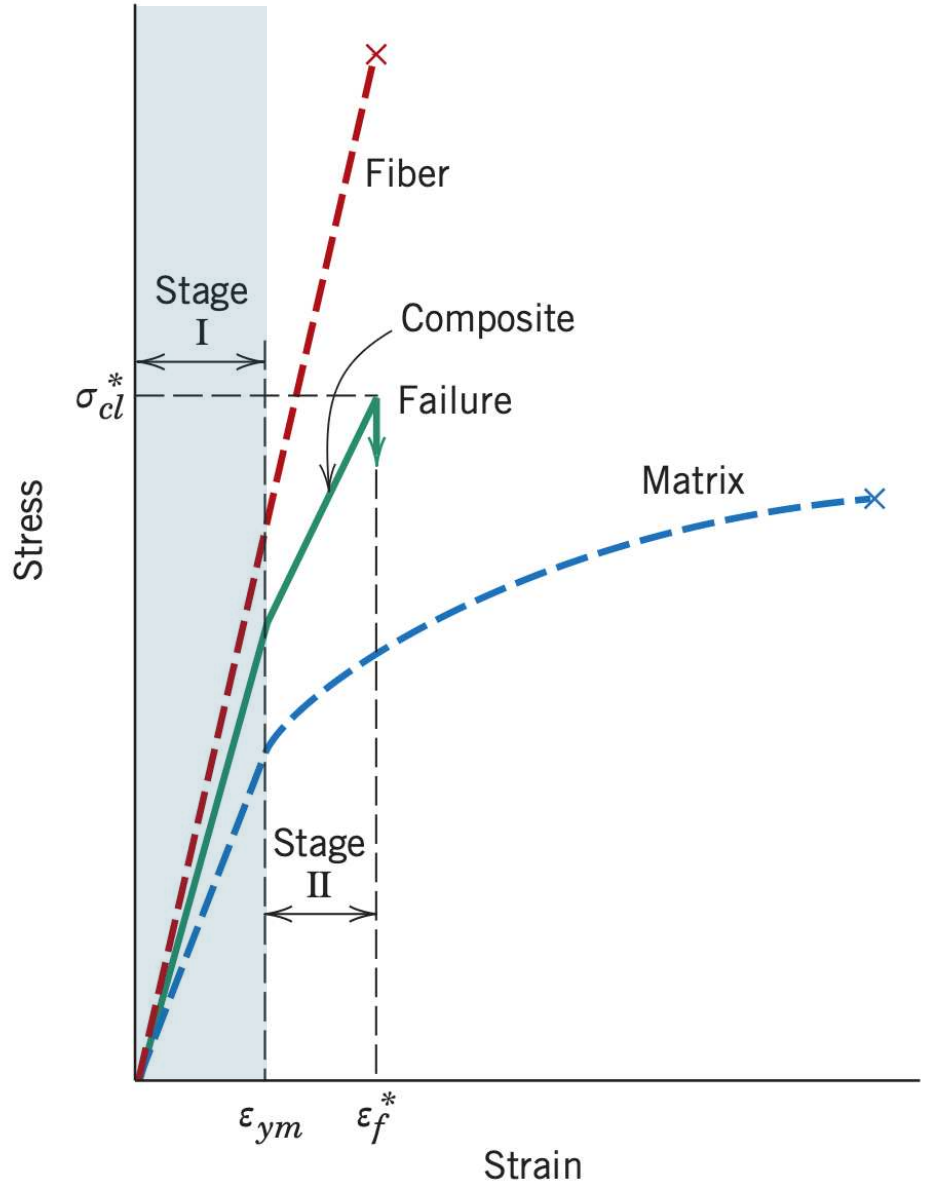




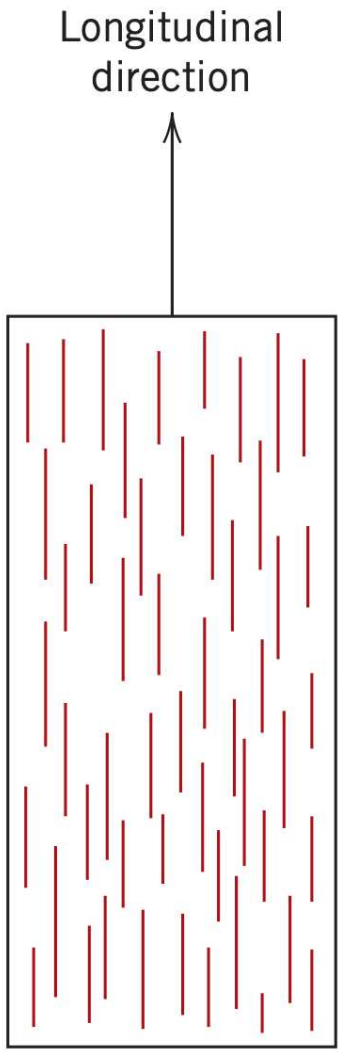
Stress-strain of *aligned* fiber-reinforced composites



Stage 1: both fibers and matrix deform elastically

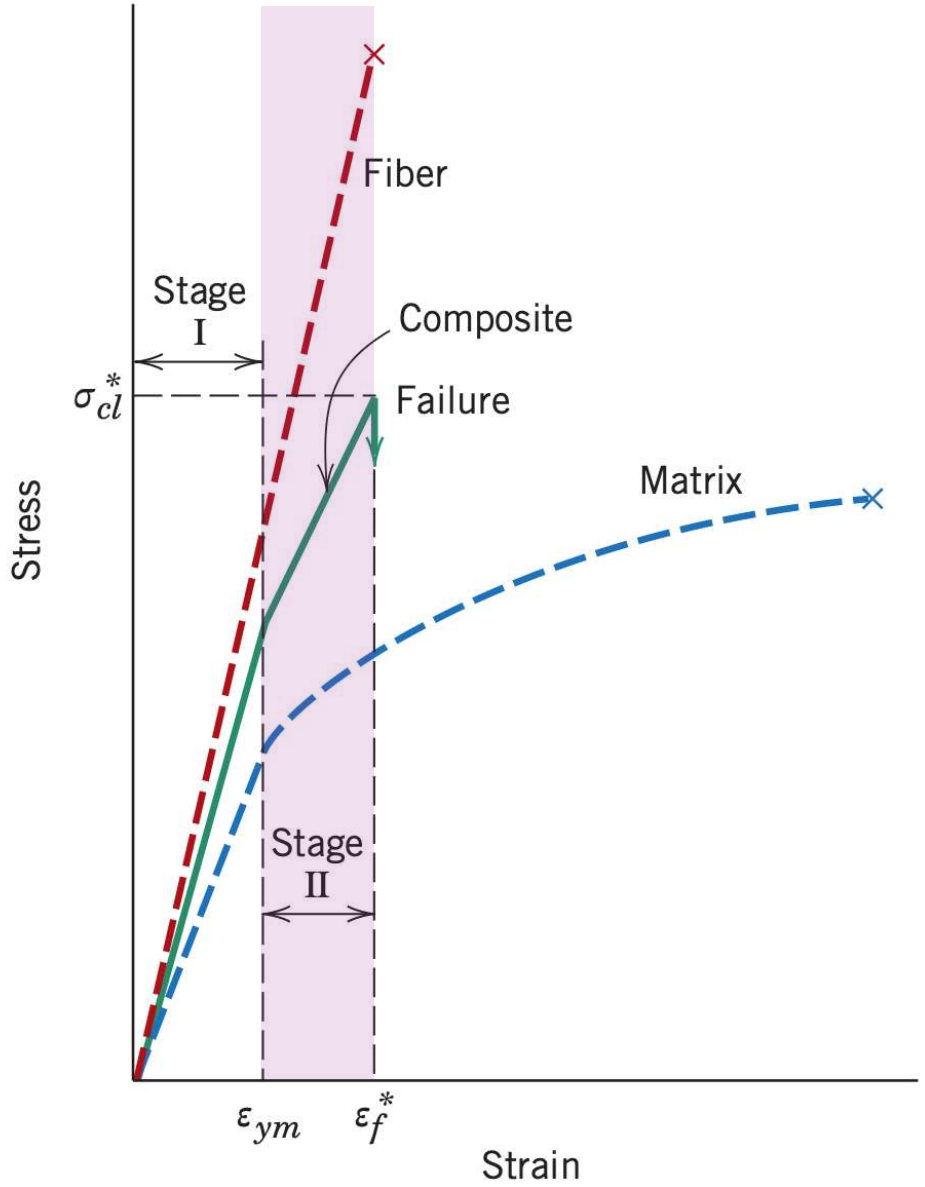


Stress-strain of *aligned* fiber-reinforced composites

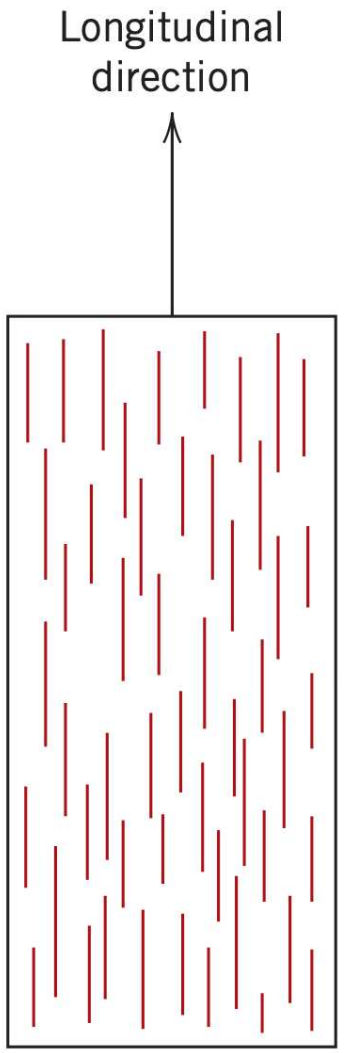


Stage 1: both fibers and matrix deform elastically

Stage 2: matrix deforms plastically while fibers continue to stretch elastically



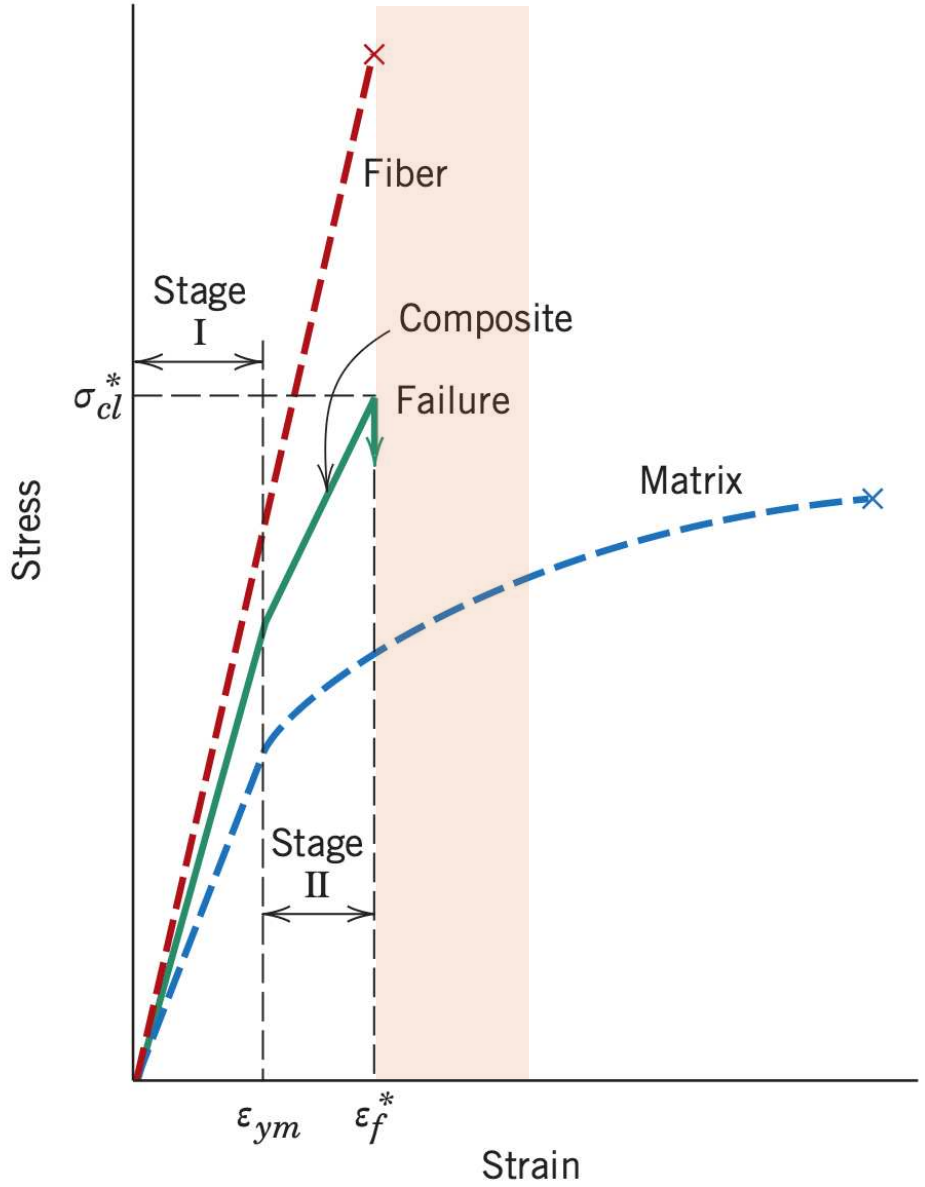
Stress-strain of *aligned* fiber-reinforced composites



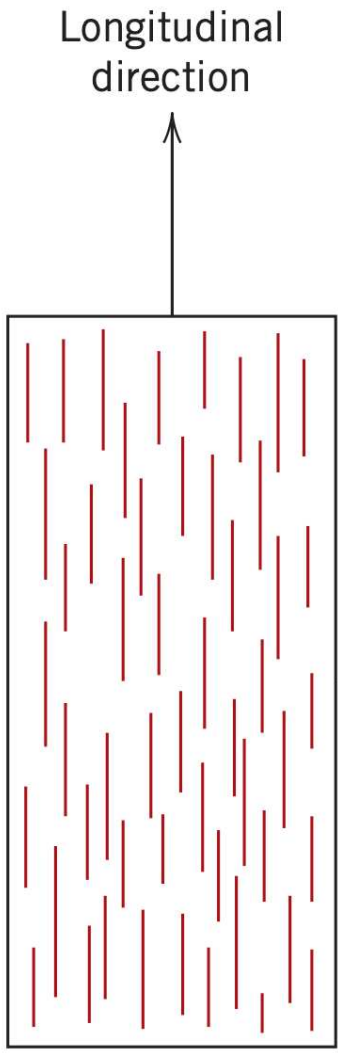
Stage 1: both fibers and matrix deform elastically

Stage 2: matrix deforms plastically while fibers continue to stretch elastically

Stage 3: fibers begin to break, transferring load to the matrix (whose fracture strength we already exceed → failure)

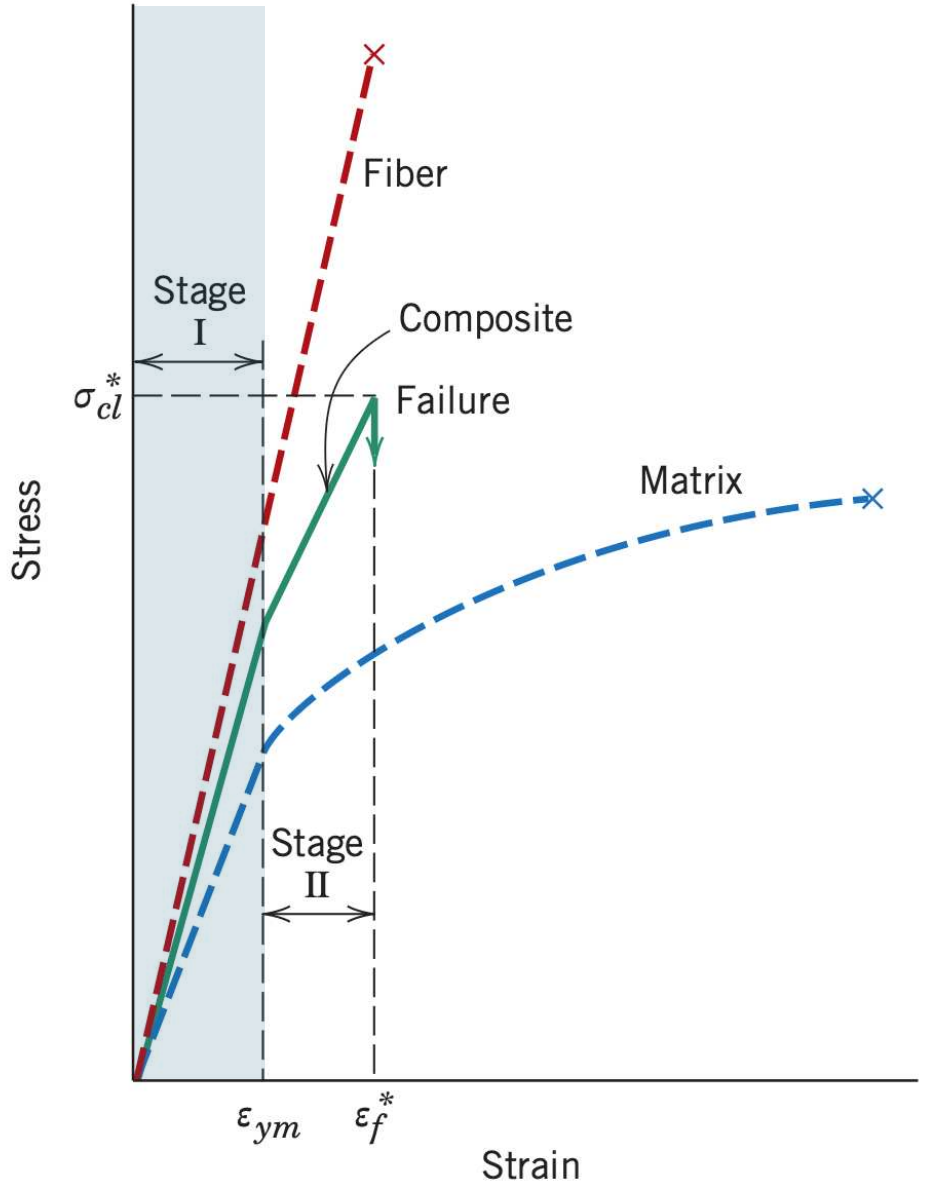


Stress-strain of *aligned* fiber-reinforced composites



Stage 1: both fibers and matrix deform elastically

Can we predict the slope of this line? What is the **elastic modulus** of the composite when loading is longitudinal?



Stress-strain of *aligned* fiber-reinforced composites

If the fibers are continuous ($l \gg l_c$) then:

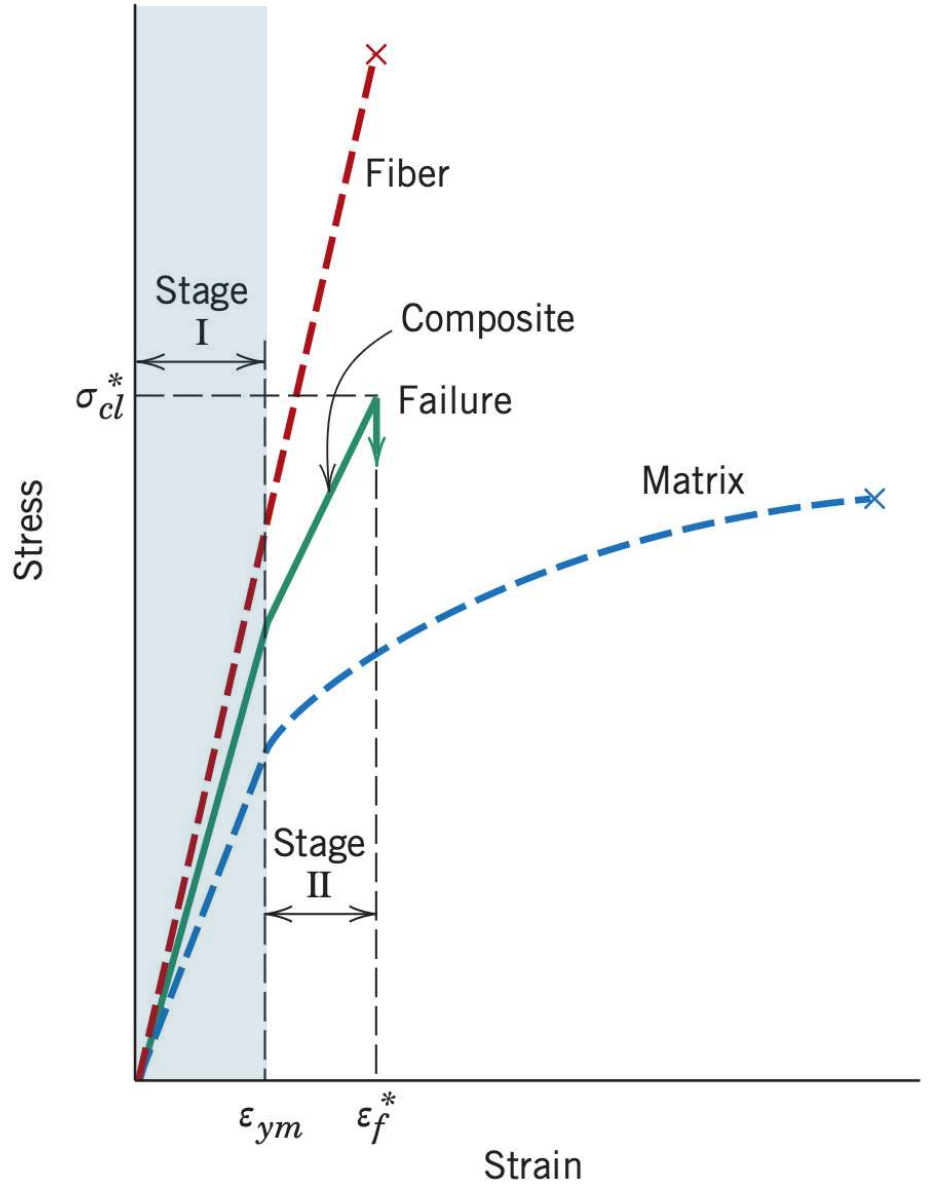
$$E_{\text{composite}} = E_m V_m + E_f V_f$$

Net elastic modulus (longitud)

Matrix elastic modulus and volume fraction

Fiber elastic modulus and volume fraction

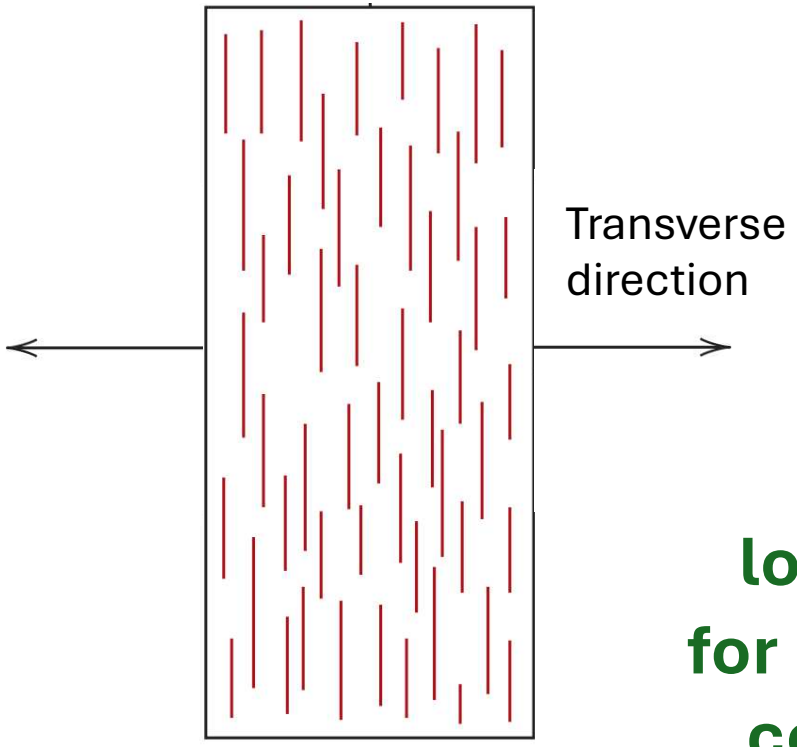
So, the composite has an elastic modulus that is equal to a volume-fraction weighted average of its components



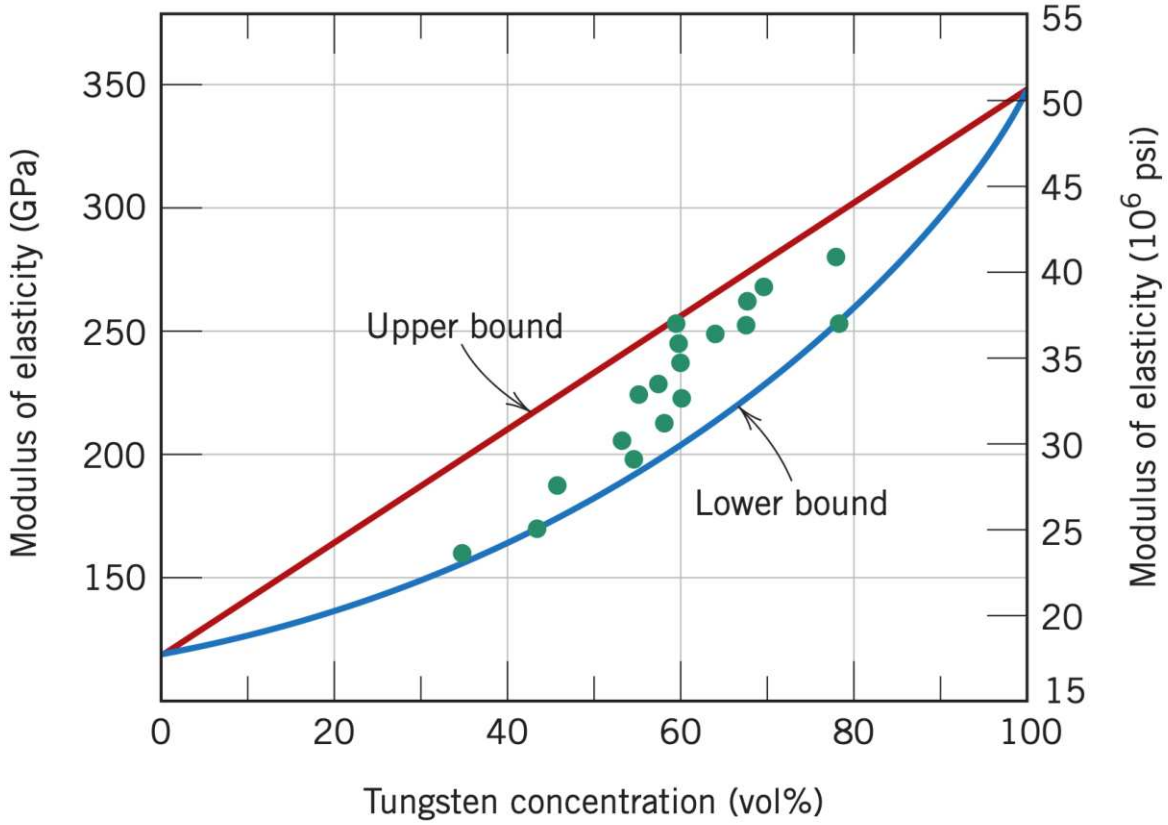
Stress-strain of *aligned* fiber-reinforced composites

What if we instead load in the **transverse direction**? Perpendicular to the fibers?

$$E_{\text{composite}} = \frac{E_m E_f}{V_m E_f + V_f E_m}$$



This is the lower-bound for particulate composites!



Example: fiberglass





Consider a **fiberglass** material consisting of a polyester resin matrix with **40% volume glass fibers** (these are continuous and aligned).

What is the **elastic modulus of the composite**, when loaded in the longitudinal direction?

$$E_{\text{polyester}} = 3.4 \text{ GPa}$$

$$E_{\text{glass}} = 69 \text{ GPa}$$

$$E_{\text{composite}} = E_m V_m + E_f V_f$$

$$E_{\text{composite}} = 0.6(3.4 \text{ GPa}) + 0.4(69 \text{ GPa})$$

$$E_{\text{composite}} = 30 \text{ GPa}$$

Example: fiberglass





Consider a **fiberglass** material consisting of a polyester resin matrix with **40% volume glass fibers** (these are continuous and aligned).

What if we now loaded in the **transverse** direction?

$$E_{\text{composite}} = \frac{E_m E_f}{V_m E_f + V_f E_m}$$

$$E_{\text{composite}} = \frac{(3.4\ \text{GPa})(69\ \text{GPa})}{0.6(69\ \text{GPa}) + 0.4(3.4\ \text{GPa})}$$

$$E_{\text{composite}} = 5.5\ \text{GPa}$$

Example: fiberglass

Consider a **fiberglass** material consisting of a polyester resin matrix with **40% volume glass fibers** (these are continuous and aligned).

What if we now loaded in the **transverse** direction?

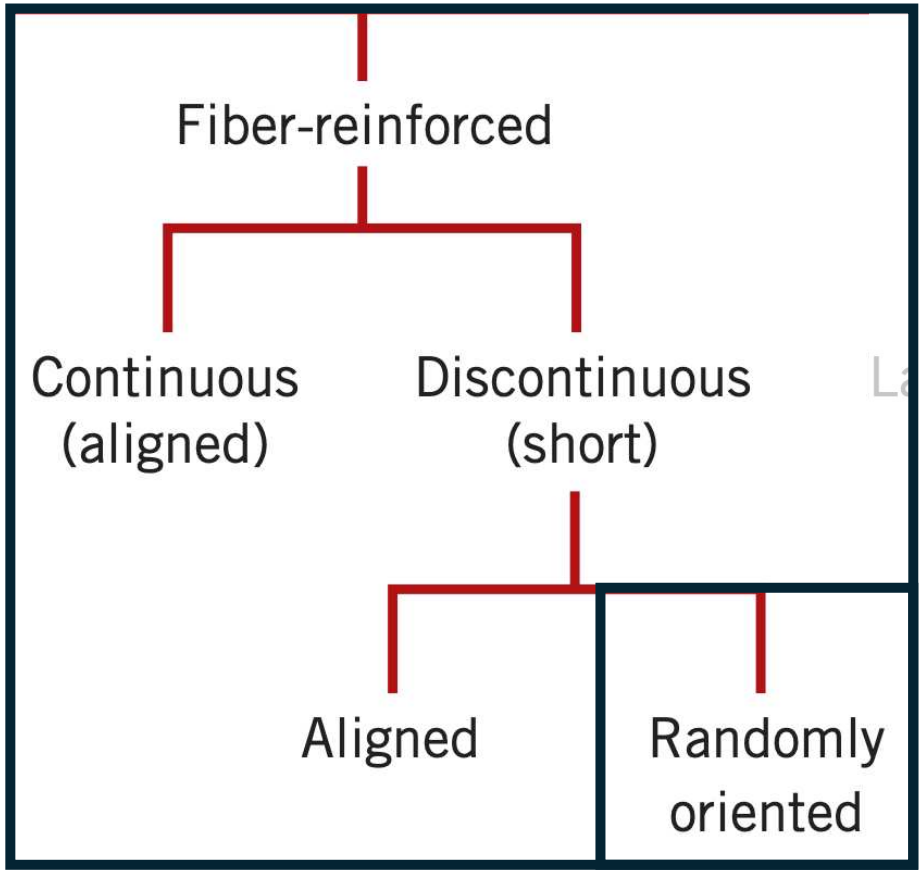
This high level of anisotropy is okay if we only plan to load in one direction…But if not, we may need some alternative solution.

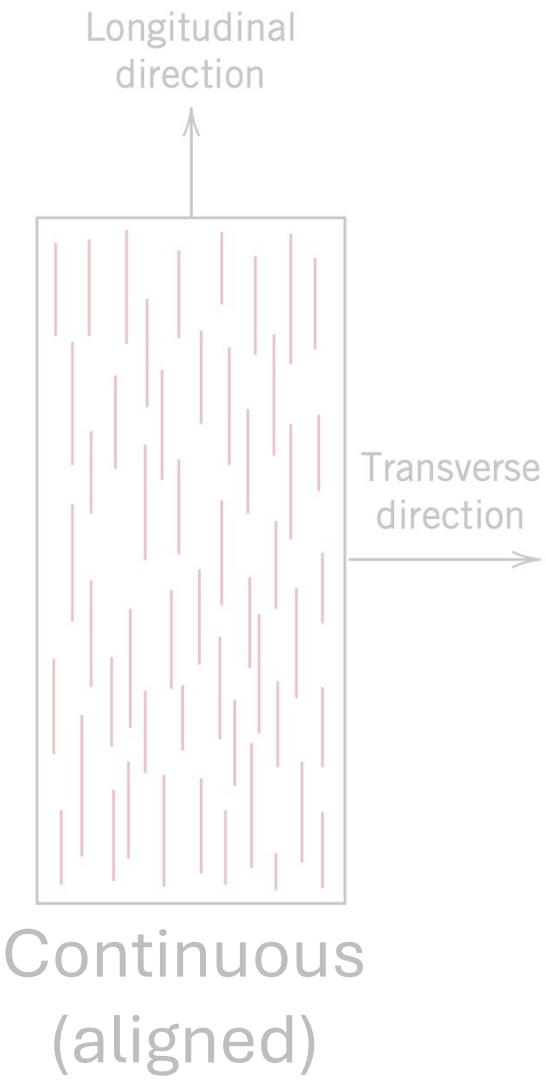
$$E_{\text{composite}} = \frac{E_m E_f}{V_m E_f + V_f E_m}$$

$$E_{\text{composite}} = \frac{(3.4\ \text{GPa})(69\ \text{GPa})}{0.6(69\ \text{GPa}) + 0.4(3.4\ \text{GPa})}$$

$$E_{\text{composite}} = 5.5\ \text{GPa}$$

Discontinuous fibers in random orientation

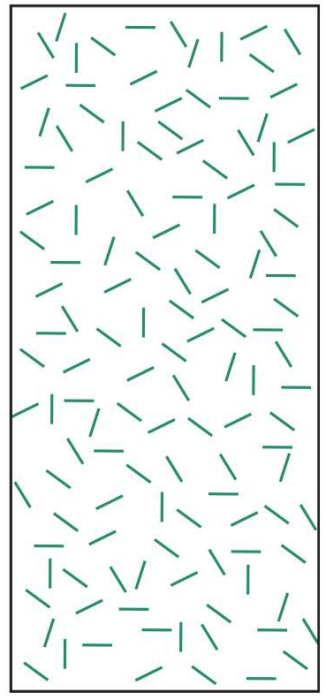




Continuous (aligned)



Discont (aligned)



Distcont (random)

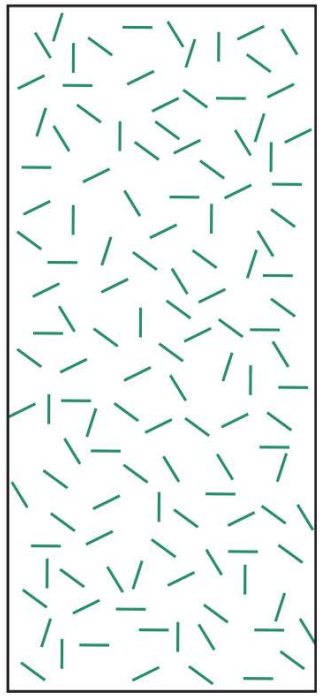
Discontinuous fibers in random orientation

In this case, we modify our rule of mixtures to estimate the elastic modulus of the composite:

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

K: An *efficiency factor* that depends on fiber orientation

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	$\frac{1}{5}$



Distcont (random)

Back to our example: fiberglass



Consider a **fiberglass** material consisting of a polyester resin matrix with **40% volume glass fibers.**

What is the elastic modulus if these fibers are now discontinuous and randomly oriented ?

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

$$K = 0.2 \text{ (random)}$$



$$E_{\text{composite}} = 0.6(3.4\ \text{GPa}) + 0.2(0.4)(69\ \text{GPa})$$

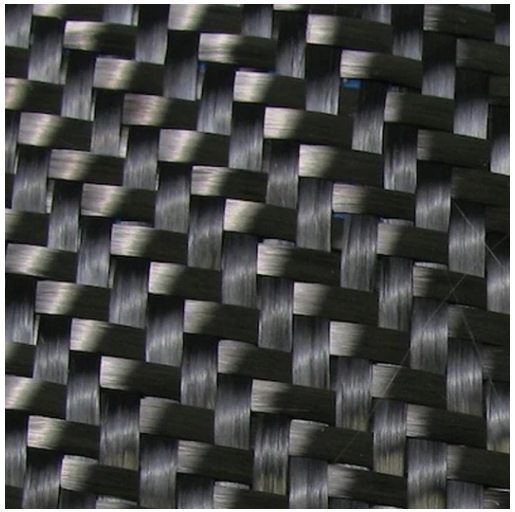
$$E_{\text{composite}} = 7.56\ \text{GPa}$$

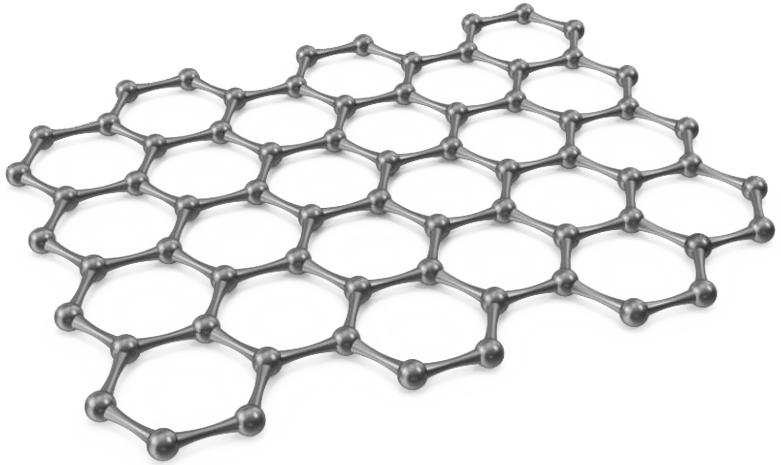
A tad better than previously – 5.5 GPa – but in general, fiber-reinforced composites are most effective when there is one direction of loading.

Another important composite: carbon fiber







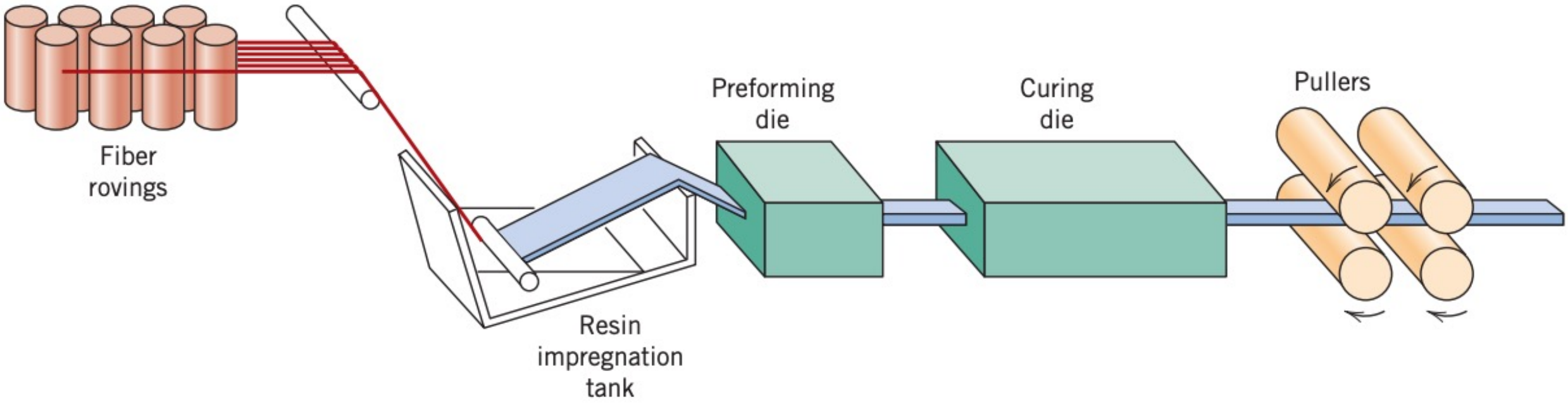


- Leverages the strong and **highly directional** nature of carbon-carbon bonding
- Mesh of carbon fibers are embedded in a polymer matrix

How do we make fiber-reinforced composites?

Producing fiber-reinforced composites: Poltrusion

1) Continuous, pre-rolled fibers are pulled through a heated resin tank
2) The coated fibers are passed through a curing die to solidify and shape
3) The aligned fiber-reinforced composites are cut after the rollers

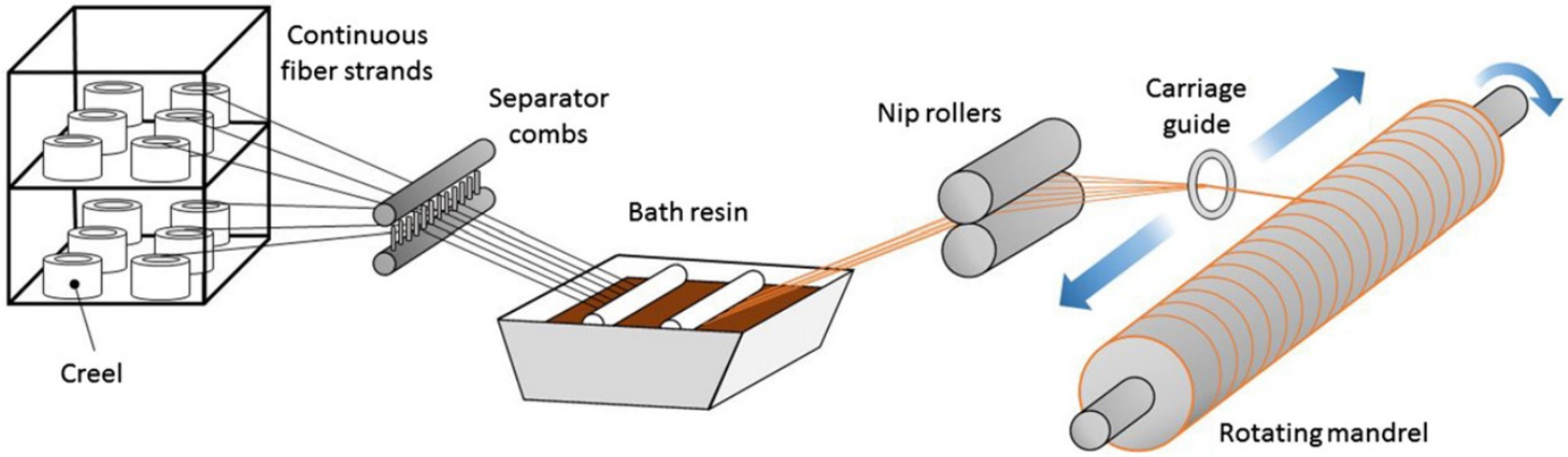


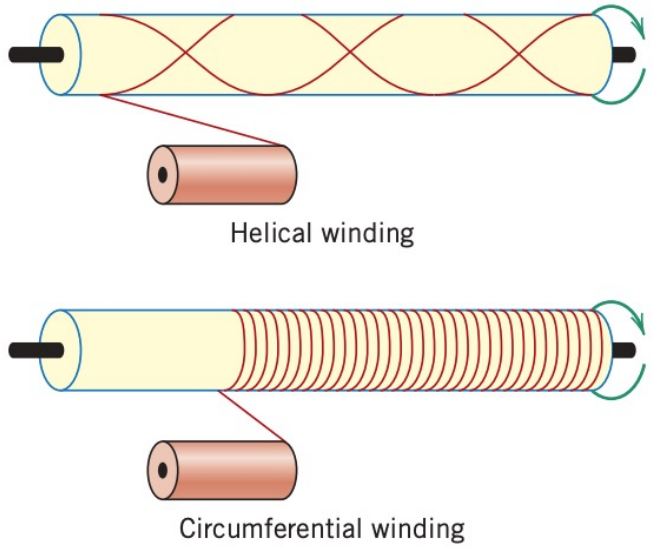
Producing fiber-reinforced composites: Poltrusion



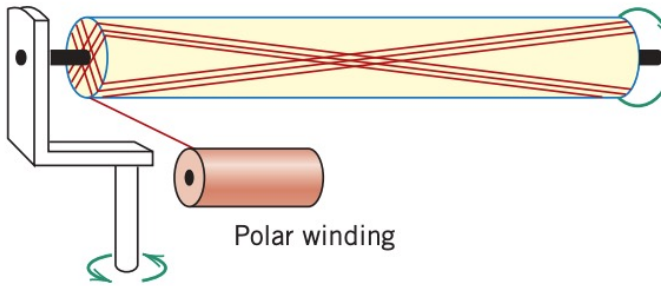
Producing fiber-reinforced composites: Filament winding

Poltrusion is used for aligned fibers (one direction). If we instead want multidirectional patterning of fibers, we can use **filament winding.**





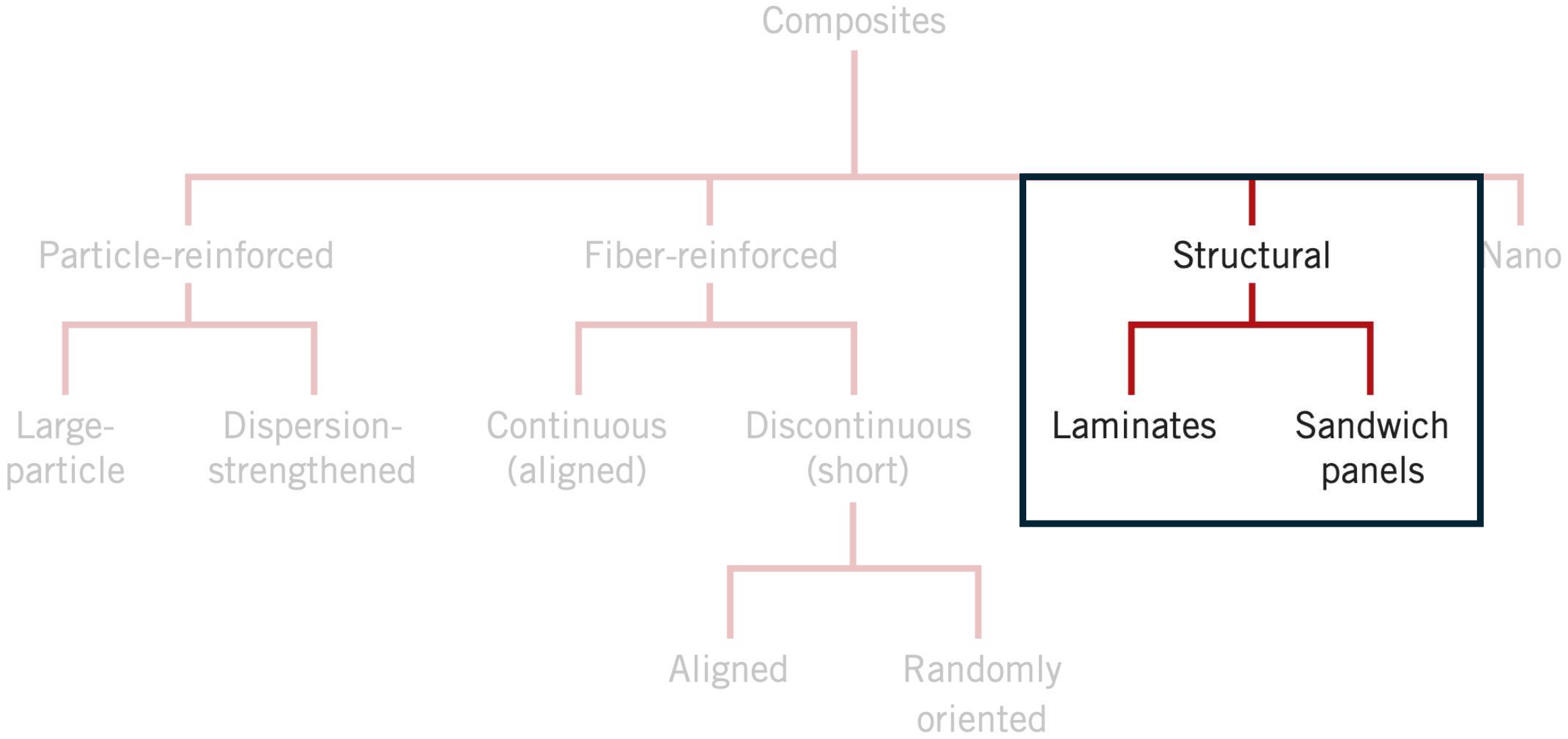
Curing is performed on the mandrel, resulting in a hollow cylinder composite that can then be removed



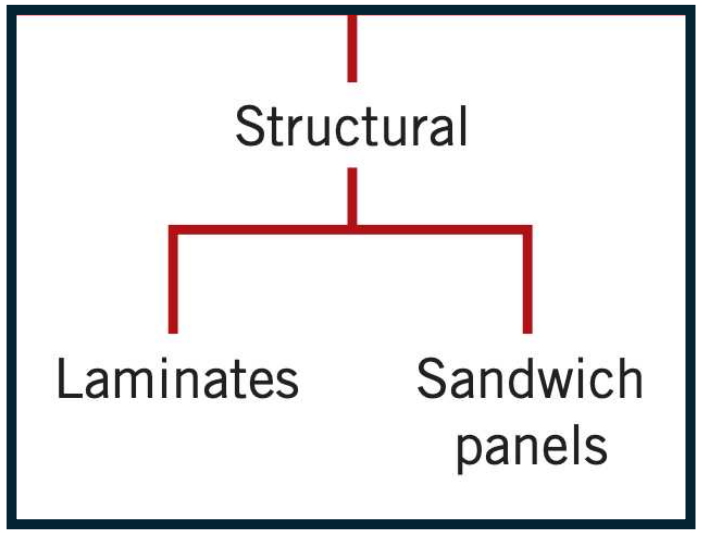
Producing fiber-reinforced composites: Filament winding



Structural composites

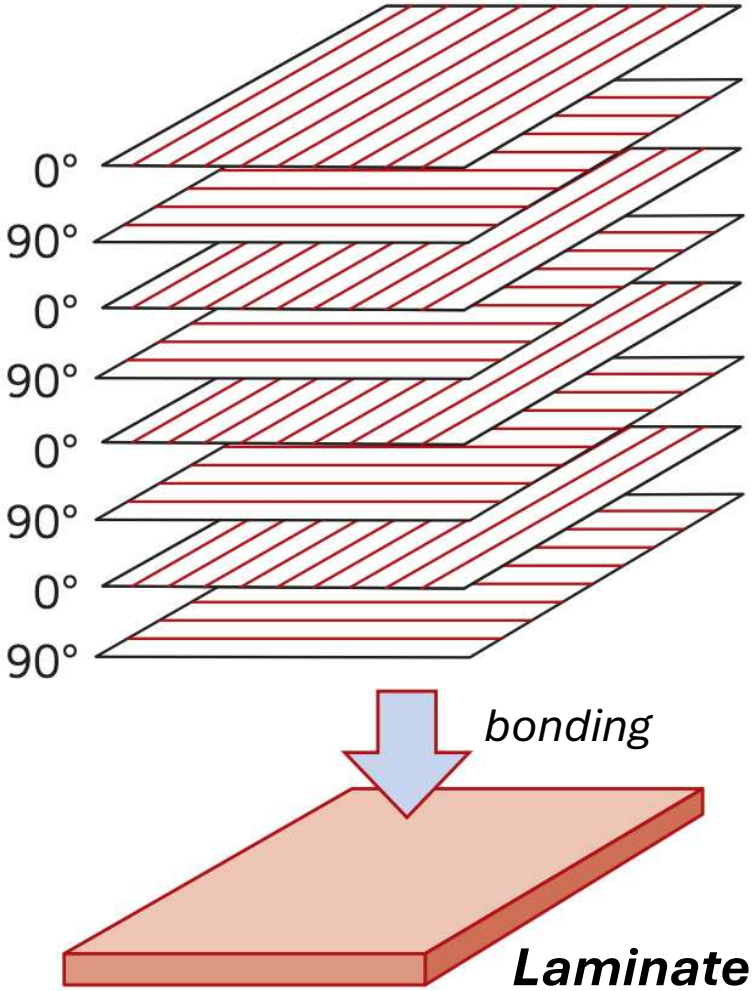


Structural composites



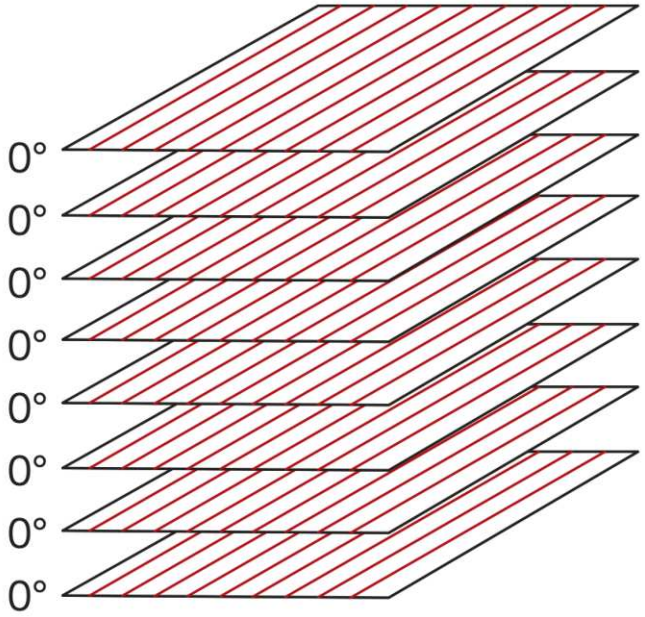
These are **layered** composites often used in structural applications.

A **laminar** composite is composed of 2D sheets (plies) that are stacked and bonded to one another.

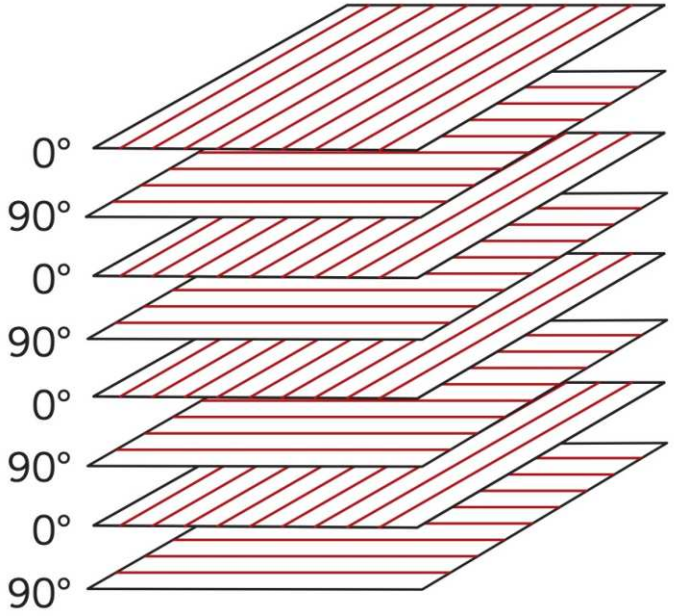


Oftentimes, each layer (ply) has some preferred strength direction – like we observed in aligned fiber-reinforced composites – and we stack these layers in such a way to leverage these strengths.

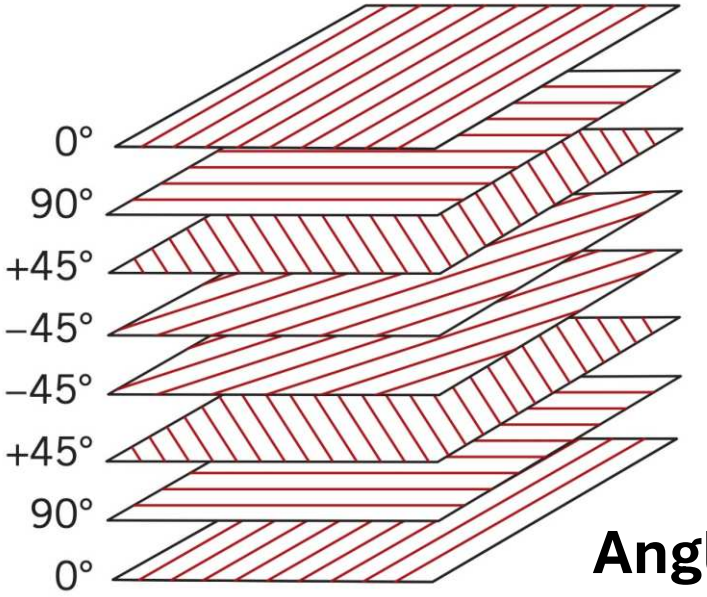
Structural composites



Unidirectional



Cross-Ply



Angle-Ply

Structural composites

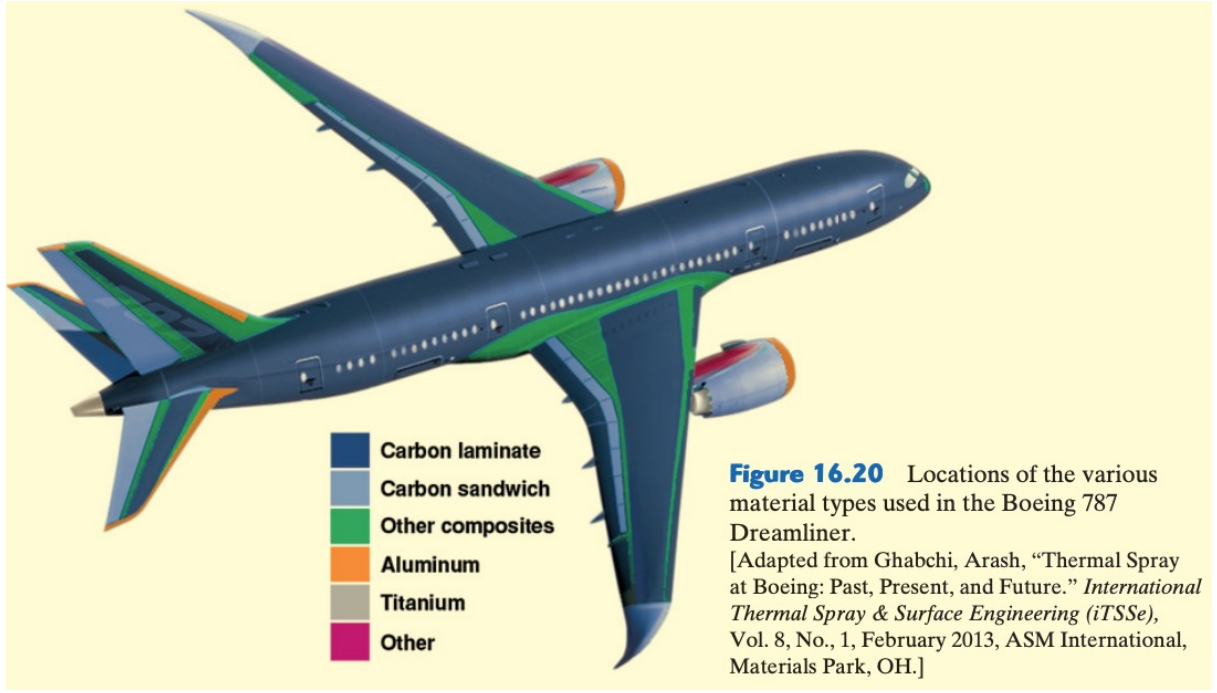
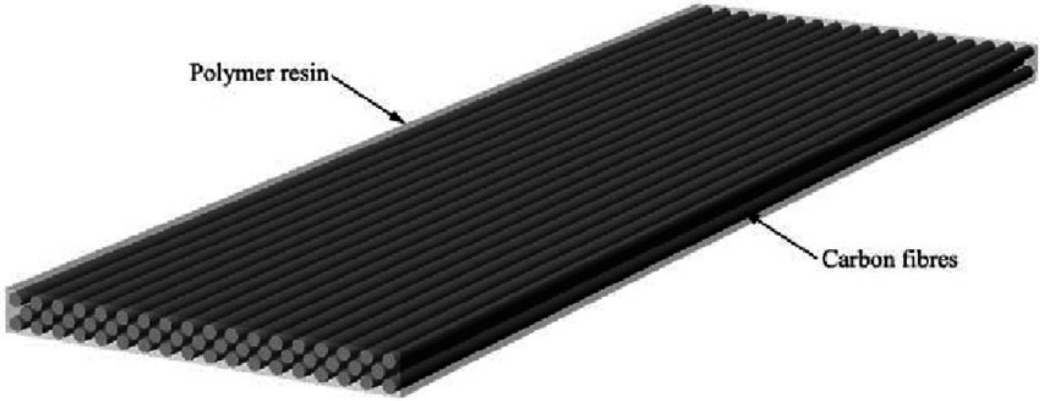
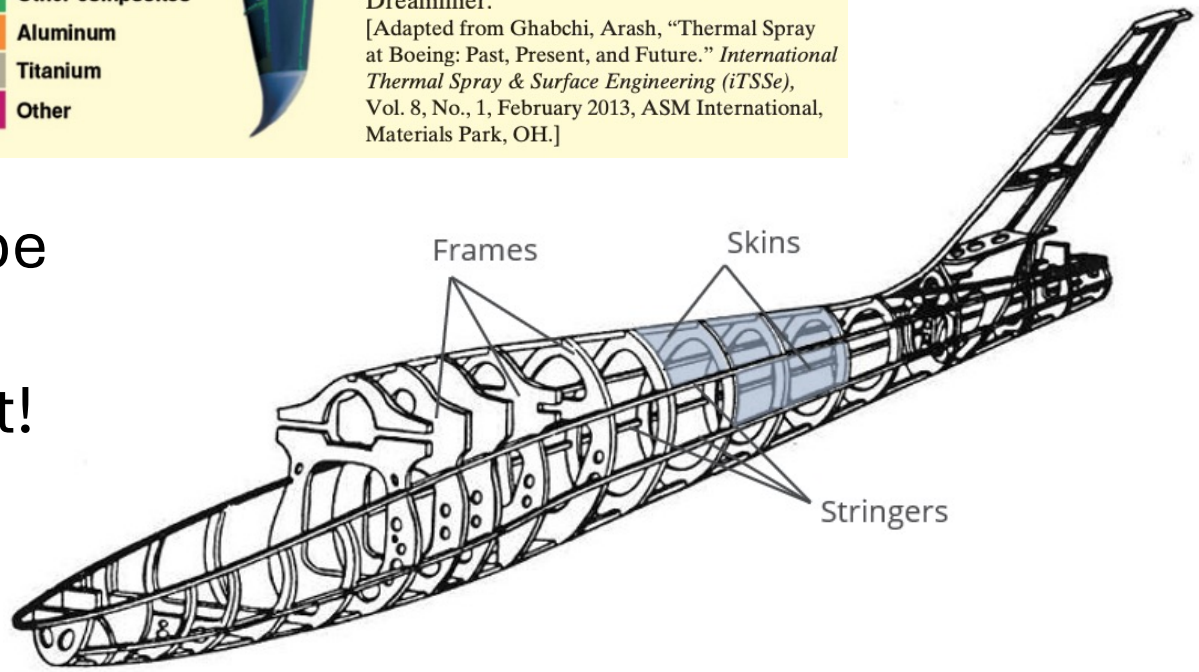


Figure 16.20 Locations of the various material types used in the Boeing 787 Dreamliner.
[Adapted from Ghabchi, Arash, "Thermal Spray at Boeing: Past, Present, and Future." *International Thermal Spray & Surface Engineering (iTSSe)*, Vol. 8, No., 1, February 2013, ASM International, Materials Park, OH.]

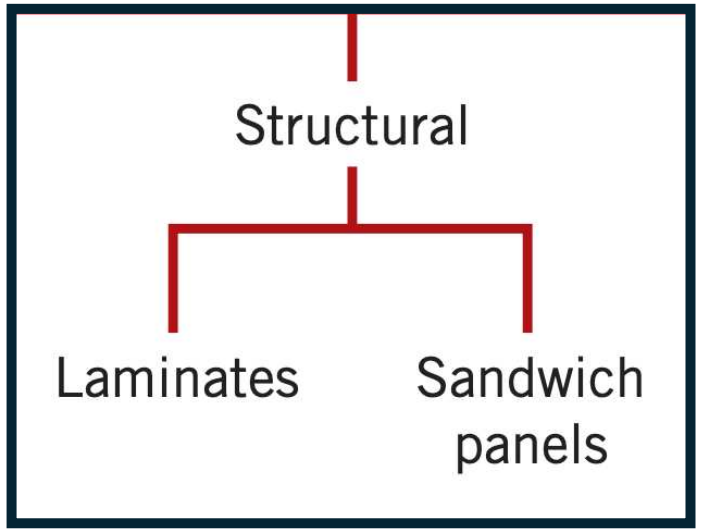


Needs to be strong but lightweight!

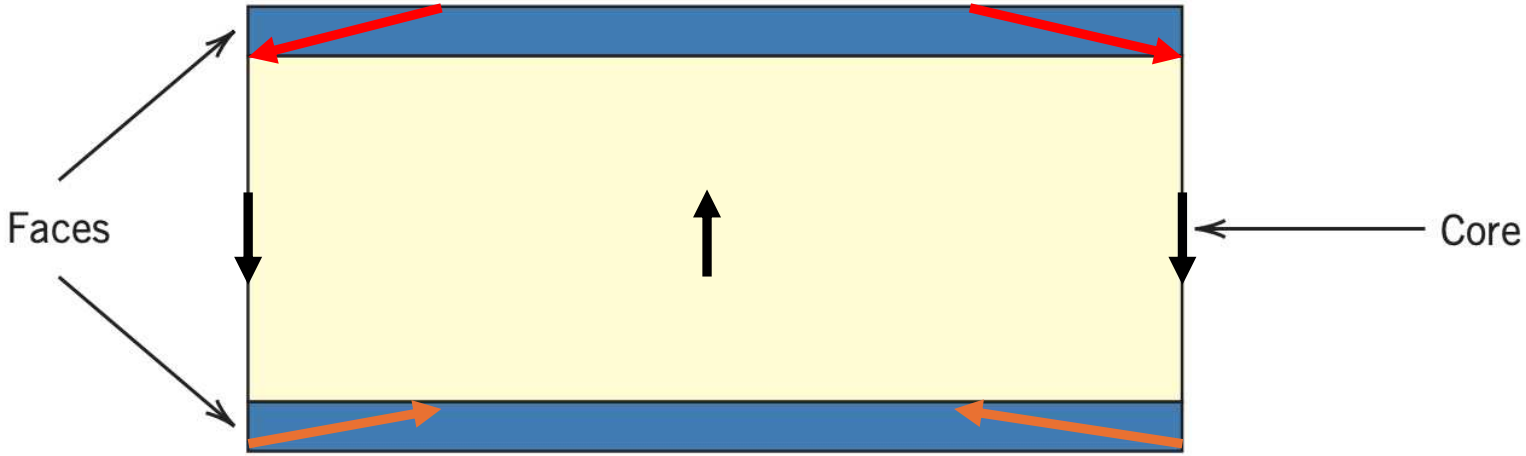


The fuselage and wings of often contain laminates of carbon fiber-reinforced polymers

Structural composites



Sandwich panels consist of two thin outer sheets bonded to a thicker core.

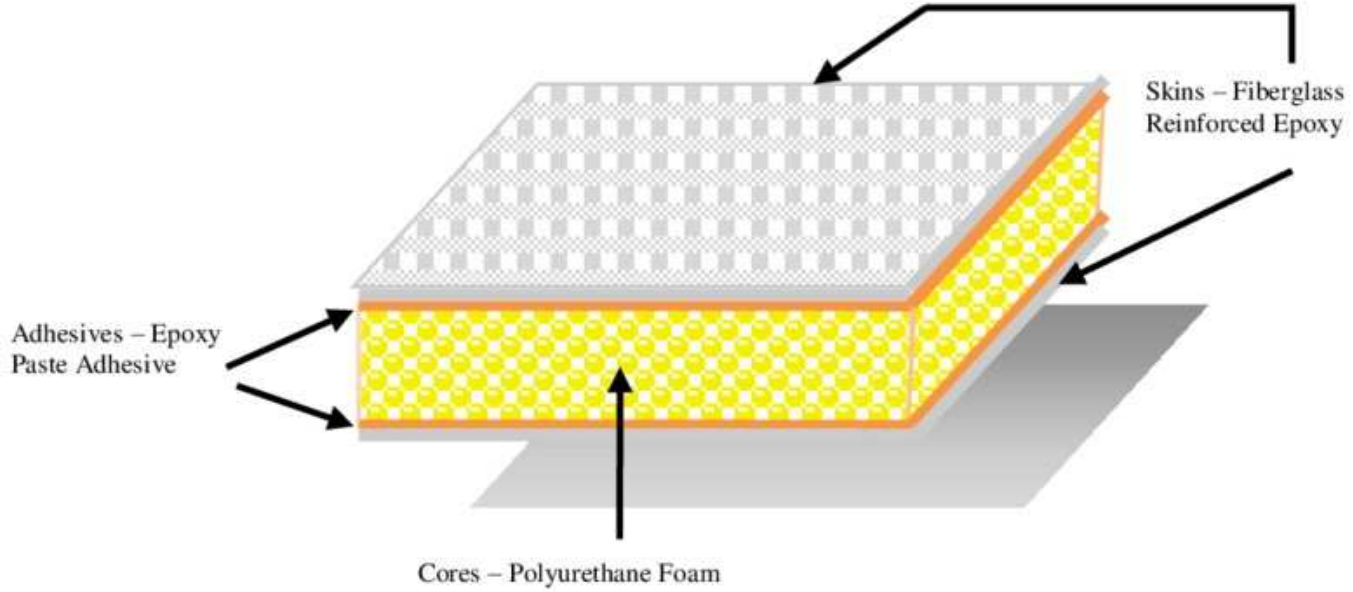


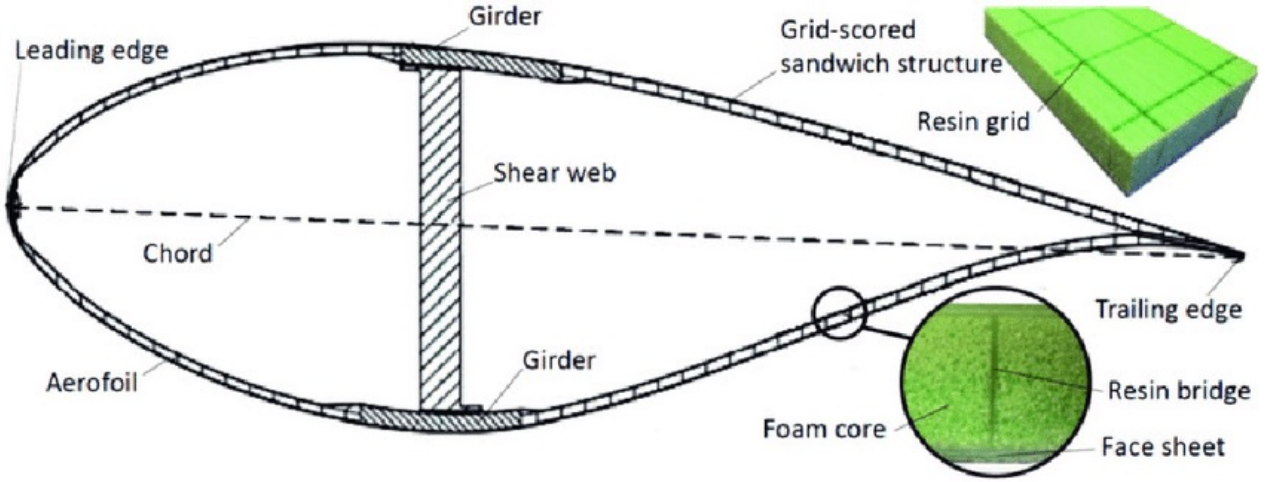
Typically, the **outer sheets are strong materials** (*e.g.*, metal alloys) while the **core is lightweight** (*e.g.*, plastic or wood). Attempting to bend the structure puts one outer sheet in tension and the other in compression – both will resist!

Structural composites

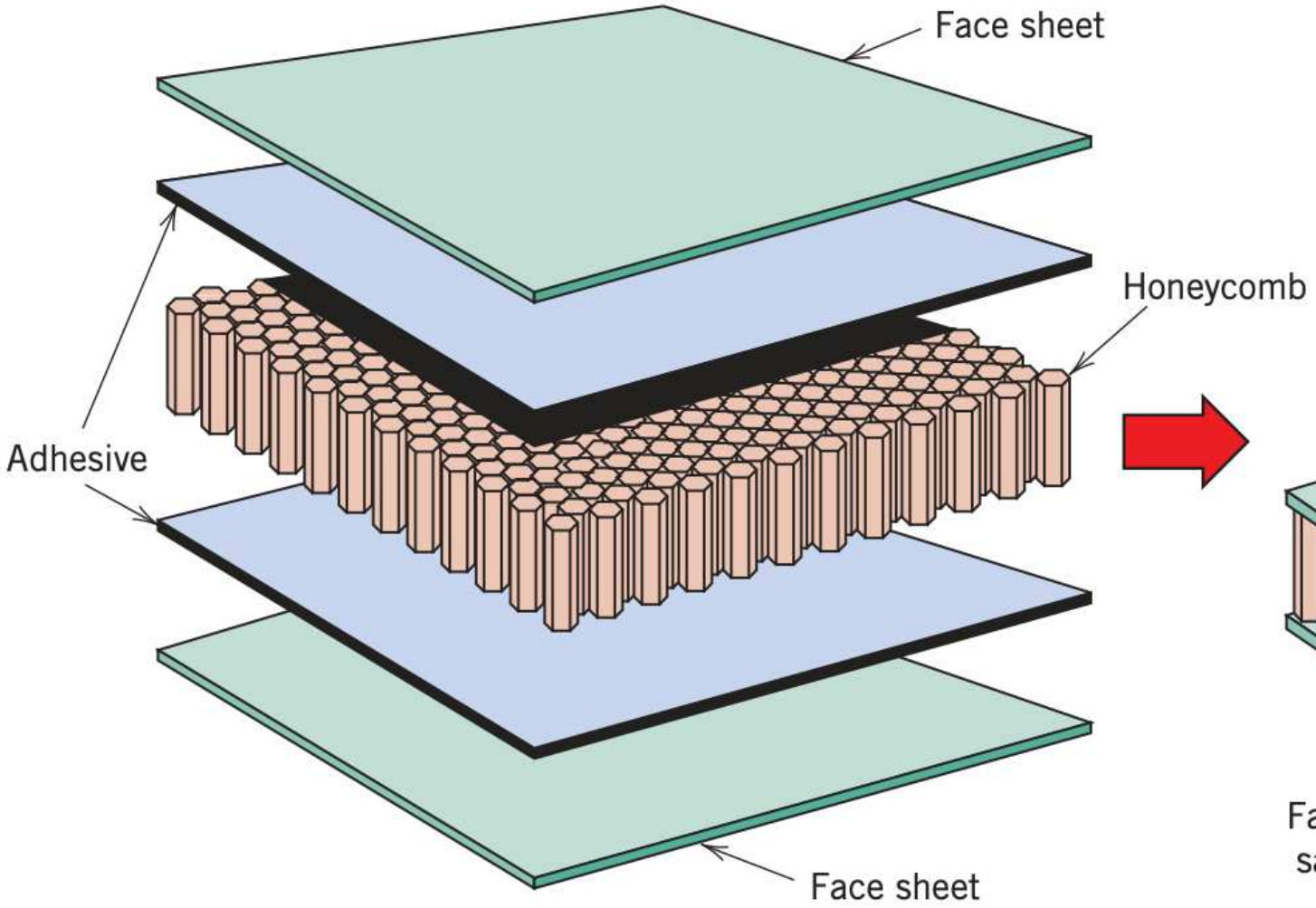
Turbine blades have layers of fiberglass with a foam core



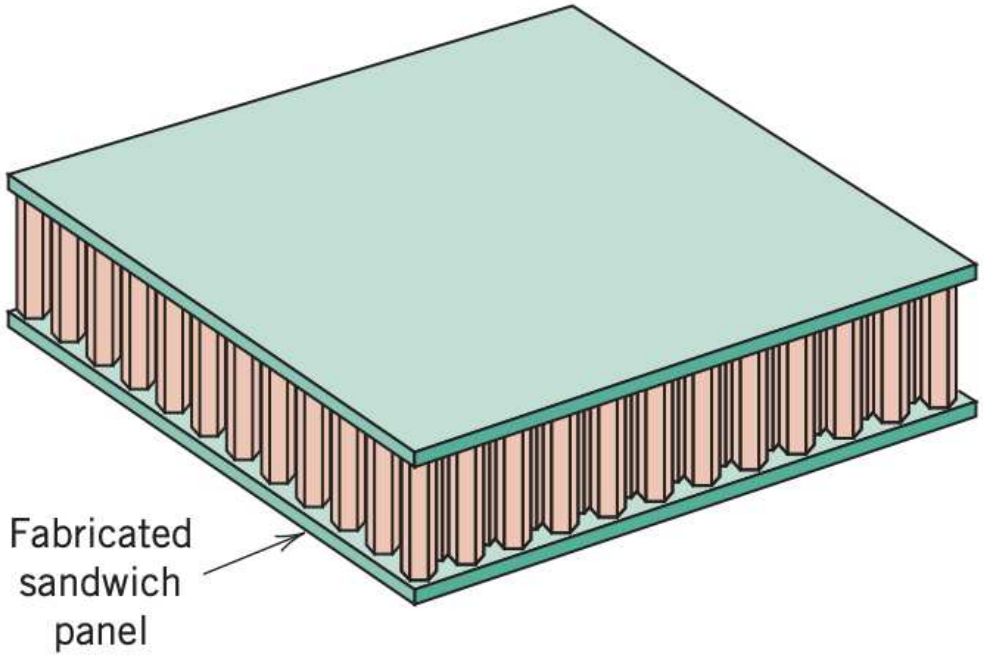




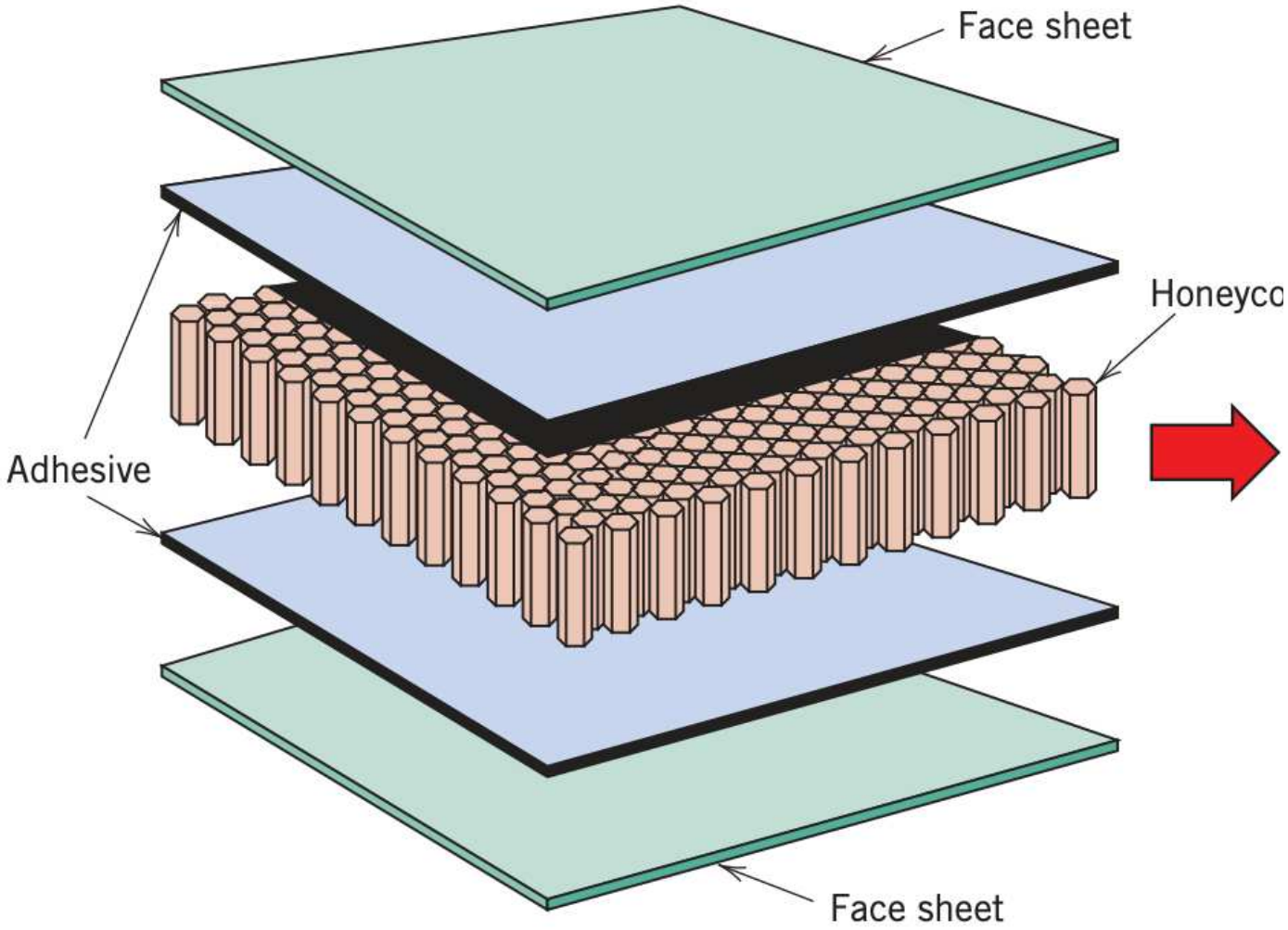
Structural composites

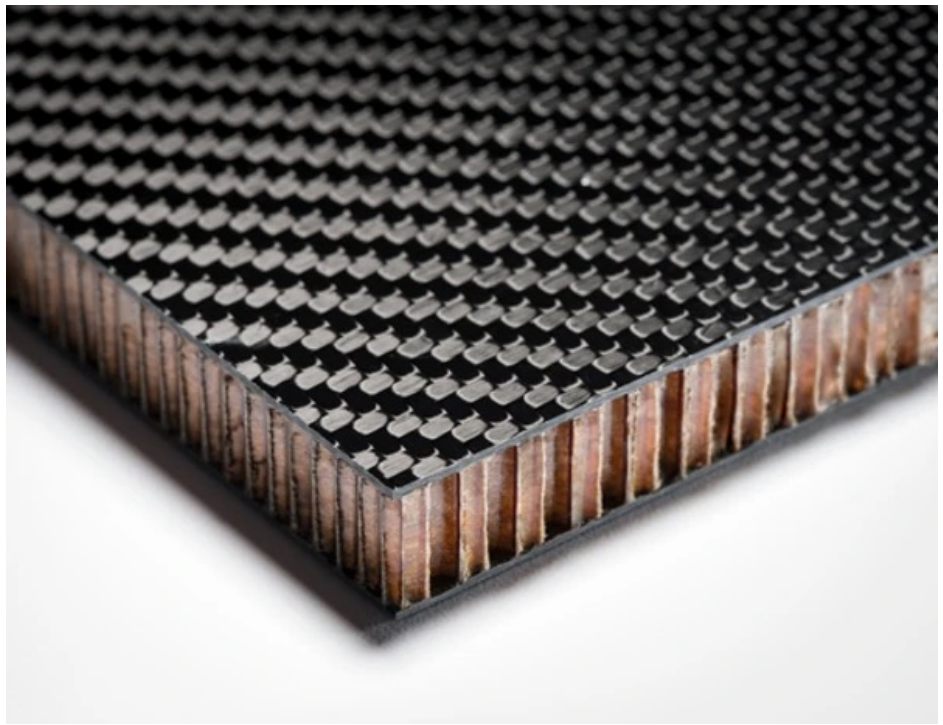


The core may also be composed of a partially hollow structure

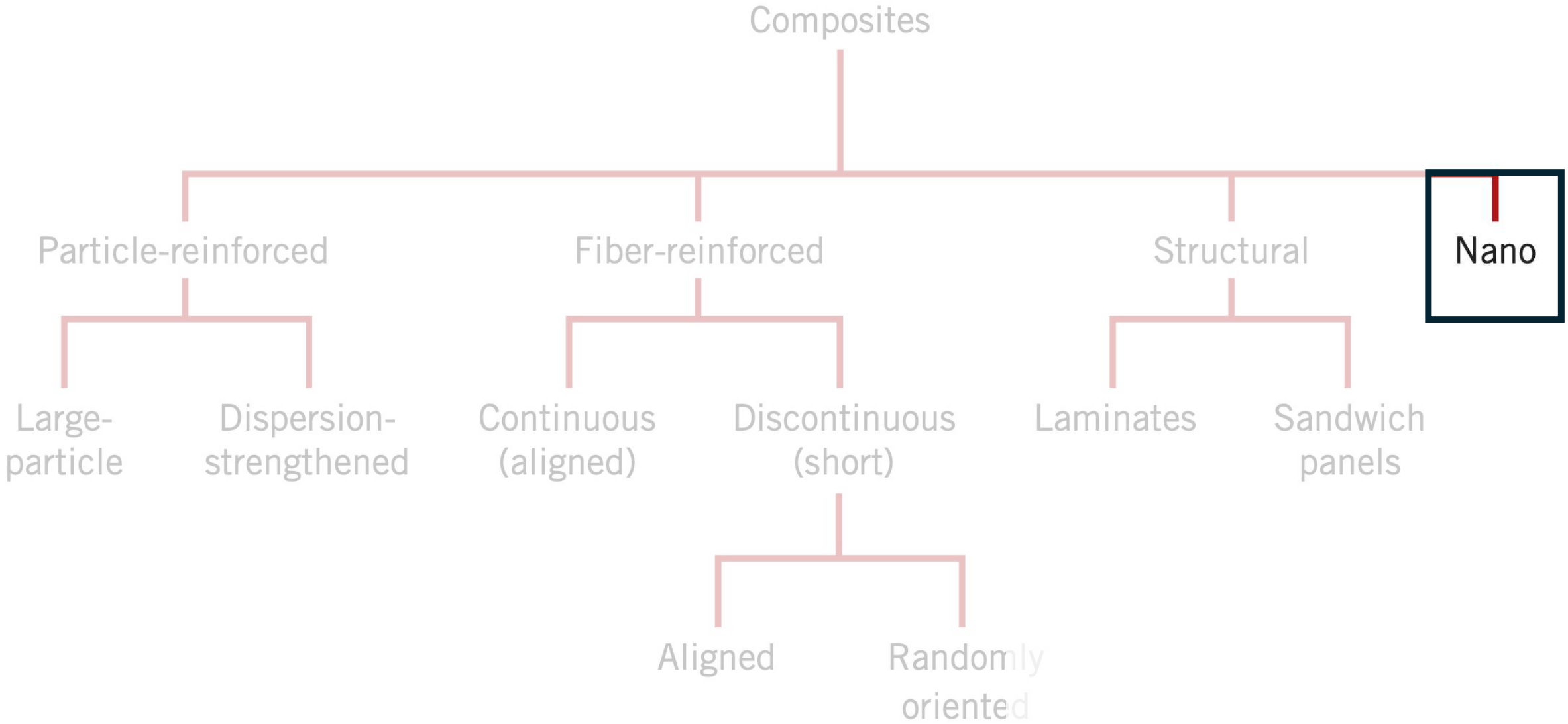


Structural composites

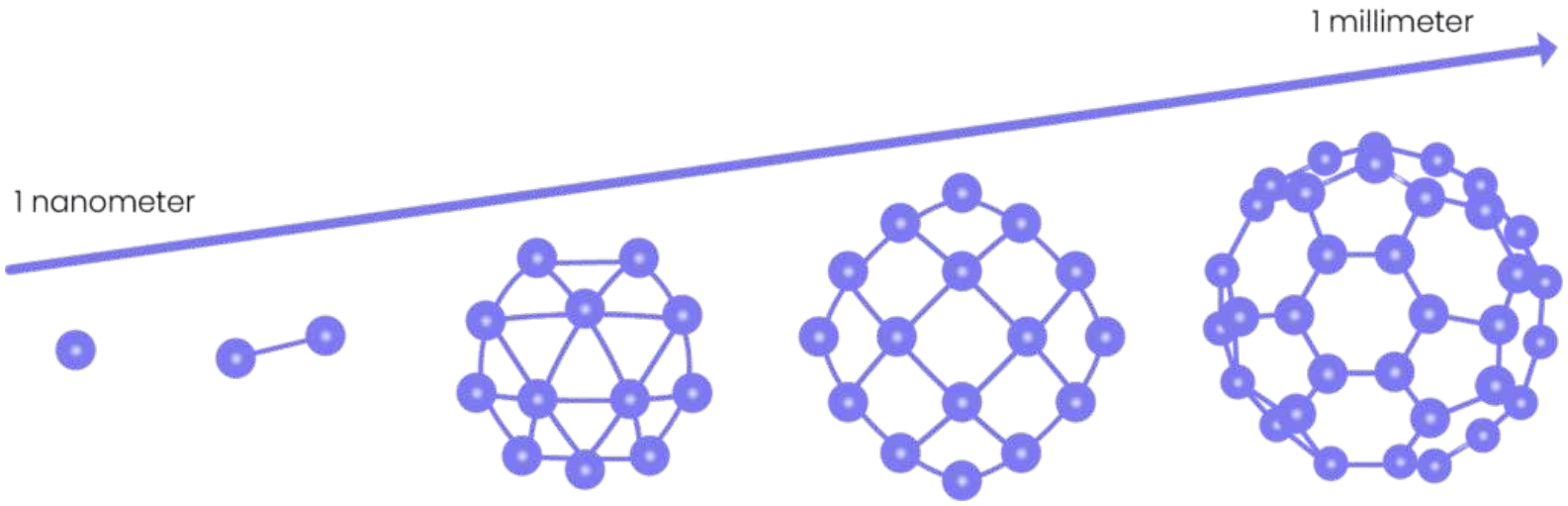




Nanocomposites

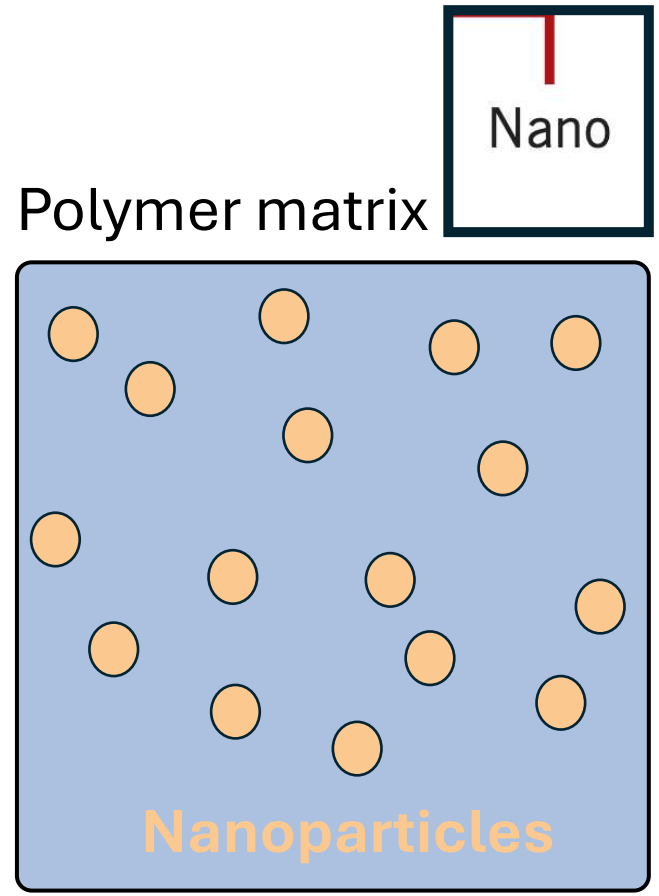


Nanocomposites

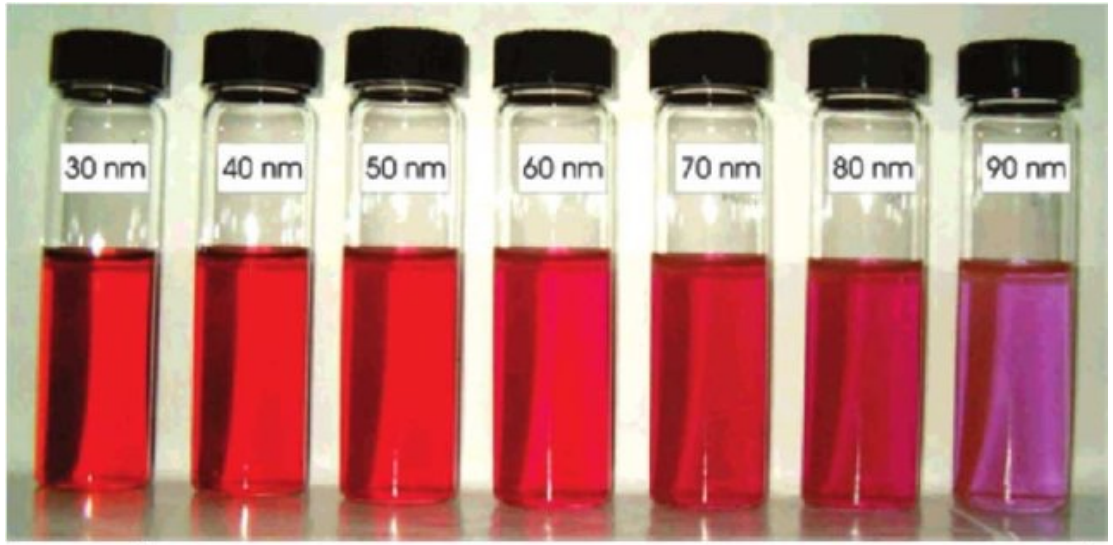


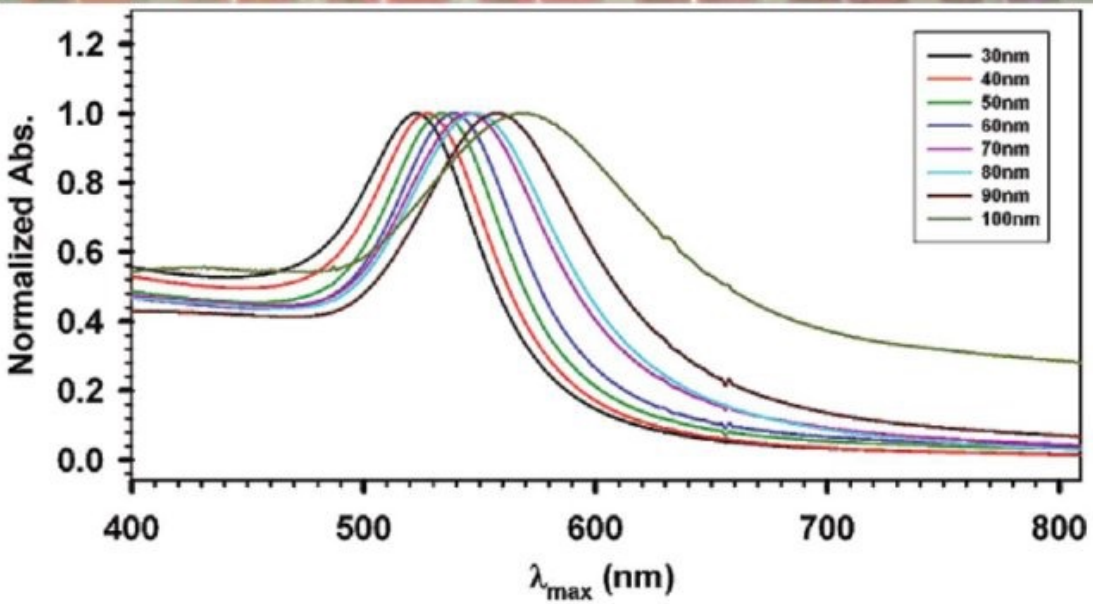
Think of this as an extreme case of particle reinforced composites, where the dispersed phase has an average particle **size on the order of nanometers (10^{-9} m)**

- **Quantum effects become important!**
- **Properties vary with particle size**

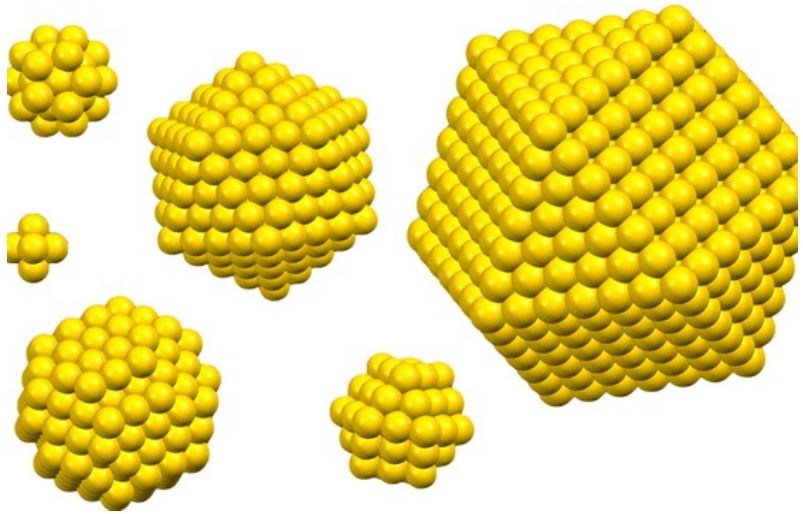


Nanocomposites





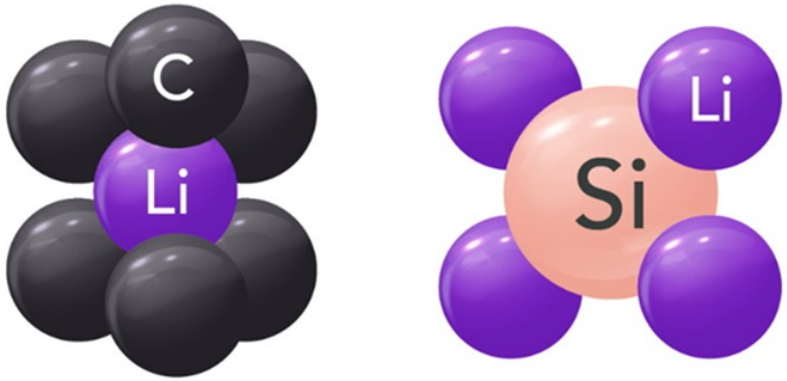
Gold nanoparticles are a classic example. They exhibit a visible color change as the particle diameter is reduced.



These are widely used for **catalysis** (*e.g.*, for CO oxidation)

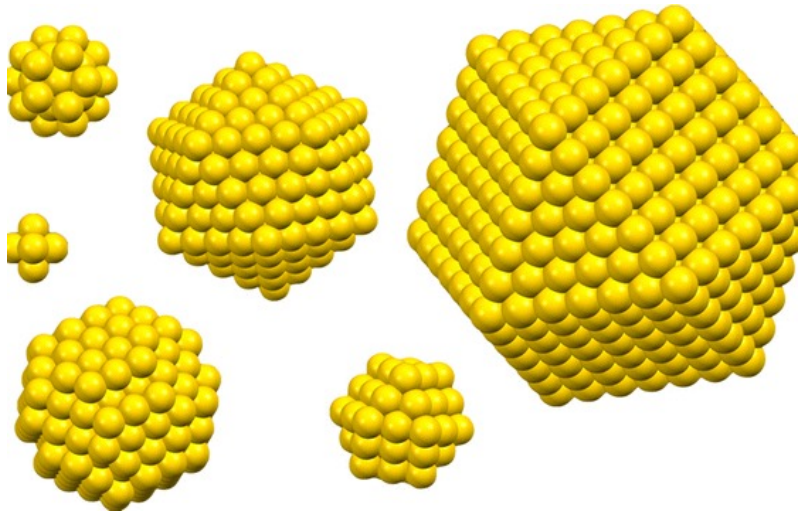
Nanocomposites

Example: Si-C nanocomposites for anodes in Li-ion batteries



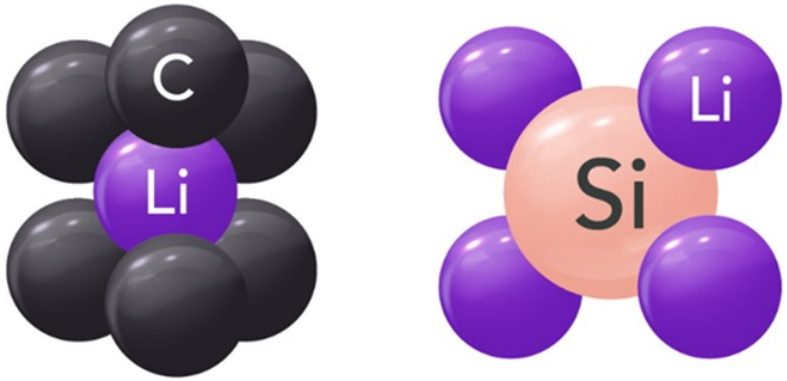
Si can store more Li per atom, but also exhibits huge volume change that leads to anode degradation

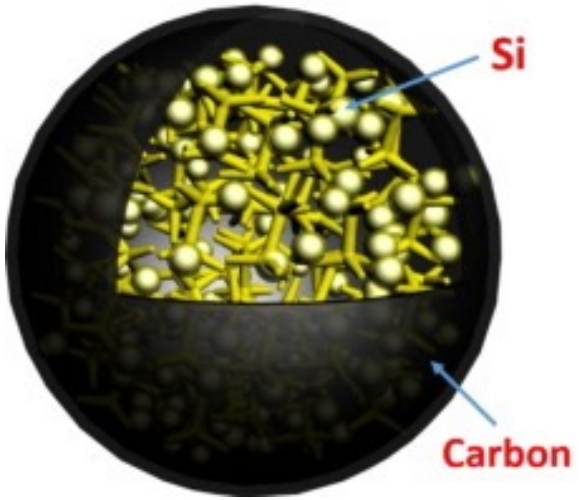
Nanocomposites embed these very small particles in a larger host matrix



Nanocomposites

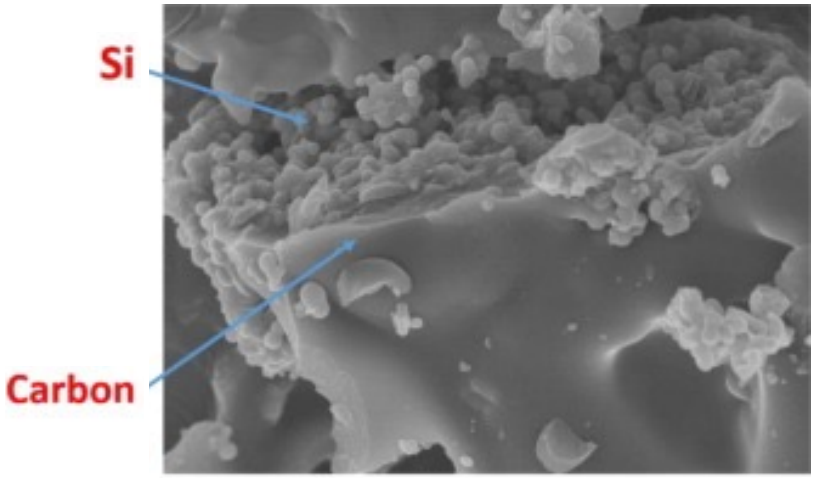
Example: Si-C nanocomposites for anodes in Li-ion batteries





Nanocomposites may offer a solution

Si can store more Li per atom, but also exhibits huge volume change that leads to anode degradation



What you need to know for the quiz on composites

- The different kinds: particulate, fiber-reinforced, and structural (layered)
- Know **fiber-reinforced composites** in detail
  - Influence of fiber *length* (continuous versus discontinuous)
  - Influence of fiber *orientation* (aligned versus random)
- Know how to use the **rule of mixtures** to compute properties

As usual, an equation sheet will be provided, but you need to know when to use which equation