Composites

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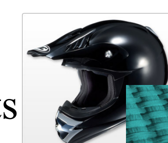
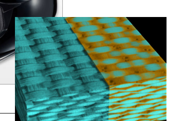
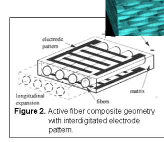
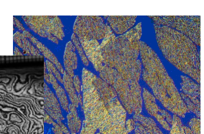
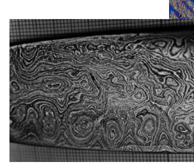
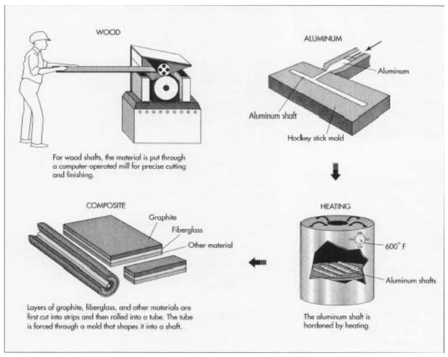
Composites

- Composite materials: materials containing multiple components that are mixed together
- Multiphase materials: materials containing multiple phases that are formed simultaneously as the materials are processed

Composites



Usually, a composite material consists of a matrix and one or more reinforcements (fibers, particles, layers, etc.).

The matrix and the reinforcement are synthesized separately.

By controlling the matrix/reinforcement content and species, the overall material properties can be adjusted in broad ranges.

Composites

The initial ideas was quite straightforward: as different materials are mixed together, advantages can cover shortages.

For example: glass fibers (strong but difficult to shape) in epoxy matrix (easy to shape but weak); steel rebars (strong but expensive) in concretes (cost-efficient but brittle), etc.

The actual strenghening mechanism is far more complicated by the simple rule of superposition.

Composite = reinforcements (hard fillers) + (interface) + matrix

Focus of this course

Composites

Filler / Matrix	Polymer	Ceramics	Metallic	Carbon
Polymer	Most Widely Used			
Ceramics				
Metallic				
Carbon				

Composites

- Usually, composites can be classified as:
  (1) *fibrous composites*, such as glass-fiber reinforced polymers (GFRP or fiberglass) and carbon-fiber reinforced polymers (CFRP);
  (2) *lamellar composites*, giving a material with uniform properties in the plane of the sheet, such as sandwich panels with stiff skins with a low-density core);
  (3) *particulate composites*, such as concrete, polymers filled with sand, silica flour, glass particles, and cemented carbide (hard metal) consisting of tungsten-carbide particles in cobalt that is the basis of the heavy-duty cutting tool industry; and
  (4) foams - composites of a solid and a gas.

Fibrous Composites

- Polymers are usually of low stiffness and quite ductile.
- Ceramics and glasses are stiff and strong, but catastrophically brittle.
- In fibrous ceramics/glass-polymer composites, the brittle failure of fibers leads to a progressive, but not sudden, failure.
- Along the fiber direction, the stiffness and the strength are the average of those of the matrix and the fibers, weighted by their volume fractions.
- However, the toughness is much higher than that of either the fiber or the matrix. This is due to the crack trapping effect or the pull-out effect.

Fibrous Composites

PROPERTIES OF SOME FIBRES AND MATRICES

Material	Density ρ(Mg m^{-3})	Modulus E(GPa)	Strength σ_f(MPa)
Fibres			
Carbon, Type1	1.95	390	2200
Carbon, Type2	1.75	250	2700
Cellulose fibres	1.61	60	1200
Glass (E-glass)	2.56	76	1400–2500
Kevlar	1.45	125	2760
Matrices			
Epoxies	1.2–1.4	2.1–5.5	40–85
Polyesters	1.1–1.4	1.3–4.5	45–85

Fibrous Composites

PROPERTIES, AND SPECIFIC PROPERTIES, OF COMPOSITES

Material	Density ρ (Mg m^{-3})	Young's modulus E(GPa)	Strength σ_y(MPa)	Fracture toughness K_{IC}(MPa $m^{1/2}$)	E/ρ	$E^{1/2}/\rho$	$E^{1/3}/\rho$	σ_y/ρ
Composites								
CFRP, 58% uniaxial C in epoxy	1.5	189	1050	32–45	126	9	3.8	700
GFRP, 50% uniaxial glass in polyester	2.0	48	1240	42–60	24	3.5	1.8	620
Kevlar-epoxy (KFRP), 60% uniaxial Kevlar in epoxy	1.4	76	1240	—	54	6.2	3.0	886
Metals								
High-strength steel	7.8	207	1000	100	27	1.8	0.76	128
Aluminium alloy	2.8	71	500	28	25	3.0	1.5	179

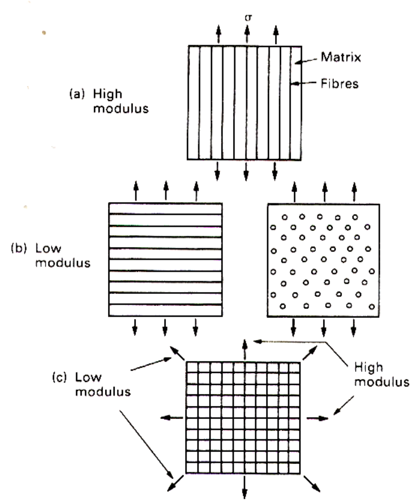
Fibrous Composites

- Polymer-matrix composites are often made by laying up glass, carbon or Kevlar fibers in an uncured mixture of resin and hardener.
- The resin cures, taking up the shape of the mold and bonding to the fibers.
- Many composites are based on epoxies or polyesters.
- Polymers can also be reinforced by chopped, short fibers in which the time-consuming fiber laying-up is avoided. The composites are usually isotropic.
- The short fibers can also be aligned through injection molding.

Fibrous Composites

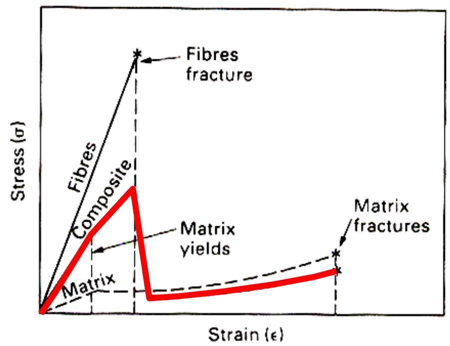
- Composites consisting of two linear-elastic components are also linear elastic. The **modulus** along the fiber direction can be estimated through
  $$E_{c\|} = V_f E_f + (1 - V_f) E_m$$
  where V is volume fraction; "f" stands for fiber and "m" stands for matrix.
- The modulus across the fibers is much less:
  $$E_{c\perp} = (V_f / E_f + (1 - V_f) / E_m)^{-1}$$
- By using a cross-weave of fibers the moduli in the 0 and 90° directions can be made equal, but those at 45° are still quite low.
- Isotropy can be restored by laminating sheets, rotated through 45°, to give a plywood-like *fiber laminate*.

Fibrous Composites



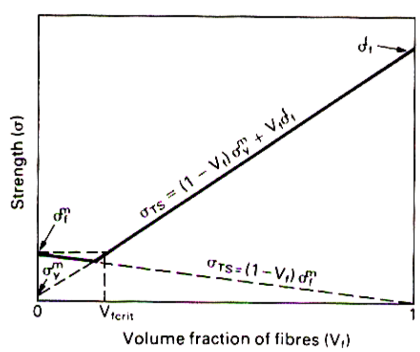
Fibrous Composites

- Many fibrous composites are made of strong, brittle fibers in a more ductile matrix.
- Under tensile stress, the matrix yields first.
- From then on, most of the load is carried by the fibers that continue to stretch elastically until they fracture.
- Then, the matrix dominates the overall **strength**.



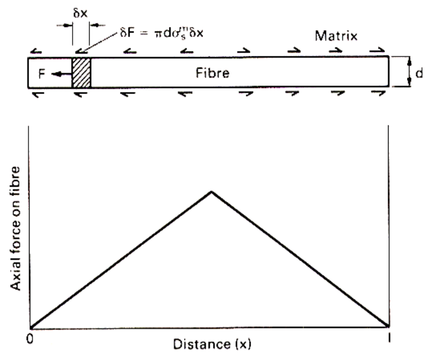
Fibrous Composites

- At peak stress, the fibers are about to break ($\sigma_f^{(f)}$) and the matrix has yielded ($\sigma_y^{(m)}$). Thus, the strength can be stated as
  $\sigma_{TS} = V_f\sigma_f^{(f)} + (1\text{-}V_f)\sigma_y^{(m)}$
- Once the fibers have fractured, the strength rises to a second maximum determined by the fracture strength of the matrix:
  $\sigma_{TS} = (1\text{-}V_f)\sigma_f^{(m)}$
- It can be seen that adding too few fibers does more harm than good. The fiber volume fraction should exceed V_{fcrit}.



Fibrous Composites

- If short fibers are used, the composites can be almost as strong as that of composites reinforced by continuous fibers, as long as the fiber length exceeds a *critical value*.
- Consider the peak stress that can be carried by a short fiber composite which has a matrix with a yield strength in shear of $\sigma_s^{(m)} \sim (1/2)\, \sigma_y^{(m)}$.



Effective bonding strength

Often: shear strength ≈ ½ of tensile strength ≈ ¼ of flexural strength

Fibrous Composites

- The axial force transmitted to a fiber of diameter *d* over a little segment δx of its length is

$$\delta F = \pi d \sigma_s^m \delta x.$$

- The force on the fiber thus increases from 0 at its end to (at *x*)

$$F = \int_0^x \pi d \sigma_s^m \mathrm{d}x = \pi d \sigma_s^m x$$

- The force which will just break the fiber is

$$F_c = \frac{\pi d^2}{4} \sigma_f^f.$$

- Hence, the fiber will break at a distance

$$x_c = \frac{d}{4} \frac{\sigma_f^f}{\sigma_s^m}$$

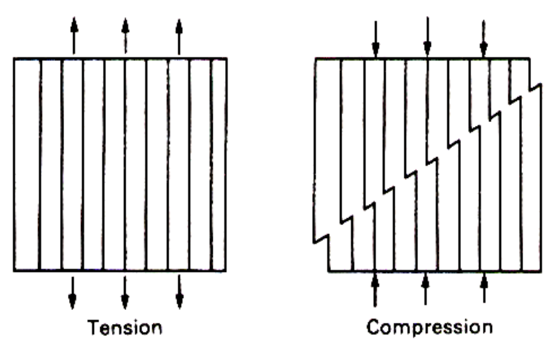
Fibrous Composites

- If the fiber is less than $2x_c$, the fiber does not break (it will be pulled out), but nor does it carry as much load as they could.
- If the fiber is longer than $2x_c$, nothing is gain by the extra length since the fiber breaks.
- The most efficient use of fibers is to chop them to the length $2x_c$. Then, the average stress carried by a fiber is simply $\sigma_f^{(f)}/2$, and

$$\sigma_{TS} = \frac{V_f \sigma_f^f}{2} + (1 - V_f)\sigma_y^m.$$

- For randomly oriented short fibers, the strength is lower than that given by the above equation. Only the fibers aligned with the load direction contribute the the overall strength.
- Compression strength is usually lower than that in tension since the fibers buckle, or, more precisely, *kink*.

Fibrous Composites



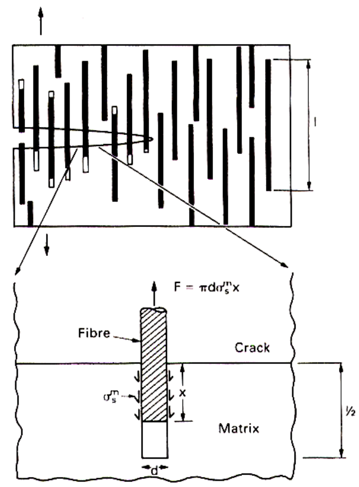
While ceramics and glasses are best in compression, composites are best in tension.

Fibrous Composites

- The **fracture resistance** G_c of a composite is a measure of the energy absorbed per unit crack area.
- If the fibers are pulled out, the fracture work due to a single fiber is:

$$\int_0^{l/2} F\mathrm{d}x = \int_0^{l/2} \pi d\sigma_s^m x\mathrm{d}x = \pi d\sigma_s^m \frac{l^2}{8}$$

- Fracture occurs in the tougher component (matrix)
- More importantly, the brittle component (fibers) toughens the tough component (matrix) – This is a very unique and brilliant arrangement!



Fibrous Composites

Fracture toughness, the critical stress intensity factor

- Since the number of fibers per unit crack area is $4V_f/\pi d^2$, the total fracture work is

$$G_c = \pi d\sigma_s^m \frac{l^2}{8} \times \frac{4V_f}{\pi d^2} = \frac{V_f}{2d}\sigma_s^m l^2.$$

$$K_{IC} = \sqrt{\frac{EG_{IC}}{1-\nu^2}}$$

- If the fibers are longer than $2x_c$, they will break.
- The optimum strength is obtained when $l = 2x_c$,

$$G_c = \frac{2V_f}{d}\sigma_s^m x_c^2 = \frac{2V_f}{d}\sigma_s^m\left(\frac{d}{4}\frac{\sigma_f^f}{\sigma_s^m}\right)^2$$

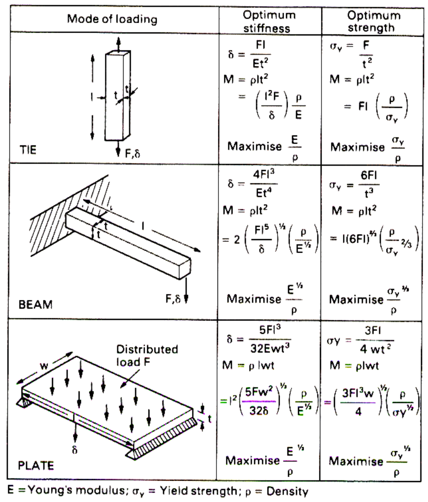
$$= \frac{V_f d}{8}\frac{(\sigma_f^f)^2}{\sigma_s^m}$$

Fracture resistance, the critical energy release rate

Matrix strength; effective fiber-matrix interfacial bonding strength

Fibrous Composites

- When structure weight is important, the component that gives lease deflection for a given weight is that made of a material with a maximum E/ρ (ties in tension; steel ~ Al ~ CFRP), $E^{1/2}/\rho$ (beam in bending; CFRP ~Al > Steel), or $E^{1/3}/\rho$ (plate in bending; CFRP best).



Particulate Composites

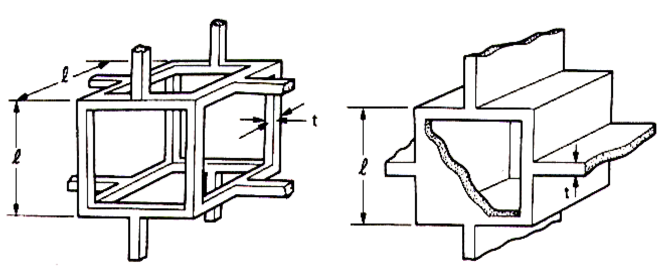
- They are made by blending silica flour, glass beads, even sand into a polymer during processing.
- They are much less efficient in the way that the filler contributes to the strength → Very often, the main purpose is to recycle waste powder/granular materials; or to use fillers to reduce the use of matrix material
- There is a small gain in stiffness, and sometimes in strength and toughness, but it is far less that in a fibrous composites.
- There attraction lies more in their low cost (e.g. use of waste powder materials; easy processing procedure…) and in the good wear resistance that a hard filler can give.

Cellular Solids, Foams

- Many natural materials are cellular: wood, bone, cork, coral…
- This structure permits an optimization of stiffness, strength, energy absorption, for a given weight.
- Foams, if combined with stiff skins to make sandwich panels, can be very stiff and light.
- Most polymers can be foamed easily by mechanical stirring or blowing a gas under pressure into melts.
- A more efficient way is to mix a chemical blowing agent with the granules of polymer before processing, which releases CO_2 when heated.
- The properties of foam is determined by the relative density ρ/ρ_s, which ~0.005-0.5. ("s" stands for solid material)

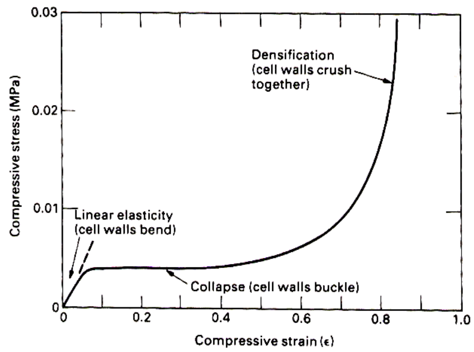
Cellular Solids, Foams

- The cells in foams are polyhedral, like grains in metal.
- The cell walls can be open (sponge) or closed (floating foam).
- They can be equiaxed or elongated (wood).



Cellular Solids, Foams

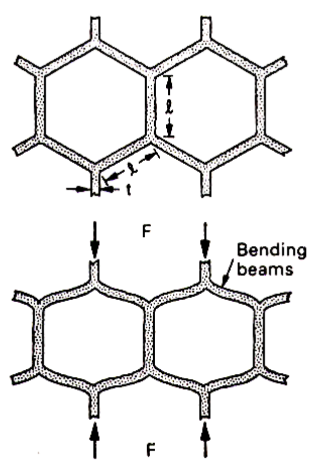
- When a foam is compressed, the stress-strain curve can be measured.
- There is a *plateau* of deformation at almost constant stress, followed by a *region of densification* as the cell walls crush together.



Cellular Solids, Foams

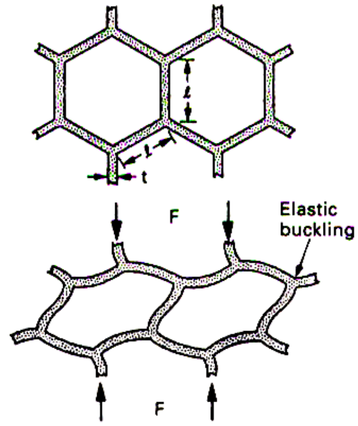
- At small strain (*linear-elastic* region), the *horizontal cell walls* are bent, like little beams of modulus E_s, built in at both ends, which can be calculated through basic beam theory:

  $E = E_s(\rho/\rho_s)^2$
- The linear elastic region ends at ~5% strain or less.



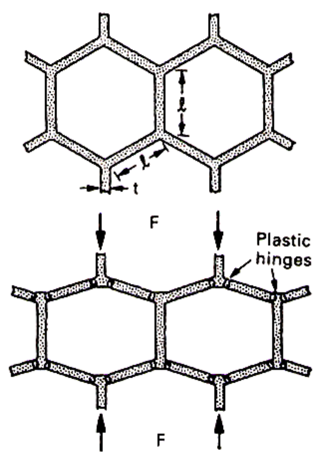
Cellular Solids, Foams

- As stain increases, the elastic buckling of the columns or plates that make up the cell edges or walls occurs.
- This causes the *plateau region*, in which the overall modulus is dominated by the *lateral cell walls*.
- The *elastic collapse stress* can be calculated using beam theory
  $\sigma_{el}^* = 0.05E_s(\rho/\rho_s)^2$



Cellular Solids, Foams

- The cell walls can also collapse through *plastic* behavior.
- The plastic collapse occurs when the moment exerted on the *horizontal cell walls* exceeds its fully plastic moment, creating plastic hinges.
- The plastic collapse stress can be estimated as
  $\sigma_{pl}^* = 0.3\sigma_y(\rho/\rho_s)^{3/2}$
- The plateau region can be beneficial to energy absorption (packaging, polyurethane automobile crash padding, polystyrene foam to protect TV...).



Materials That Can Be Engineered

- The stiffness, strength, and toughness of composites are controlled by the type and volume fraction of fibers.
- However, the materials engineering can go further than this, by orienting or laminating the fiber weave to
  (1) give directional properties, or
  (2) to reinforce holes or fixing points, or
  (3) to give a stiffness that varies in a controlled way across a component.
- Foaming also allows new degree of freedom to the designer.
- Composites are particularly suitable for *weight-optimal structure*, which is essential in aerospace and transport.

Homework

- A unidirectional fiber composite consists of 60% by volume of kevlar fibers in a matrix of epoxy. Assess the moduli $E_{c\parallel}$ and $E_{c\perp}$. Give the references of the data that you use in the calculation.
  (Answer: 77 GPa and 9 GPa)
- A unidirectional fiber composite consists of 60% by volume of continuous type-I carbon fibers in a matrix of epoxy. Estimate the maximum tensile strength of the composite. The yield strength of the matrix is around 40 MPa. Give the references of the data you use in the calculation.
  (Answer: 1.3 GPa)