Chapter 17 – Composites

composite material - a mixture of two or more material types

Why composites?

$\Downarrow$

limit on material properties available with conventional, unreinforced materials

$\Downarrow$

tailor material (and design)

$\Downarrow$

composite material

Typically stiffness, strength, and weight are the principal properties driving design of composites.

Classification by Form of Reinforcement

- Continuous Reinforcement
  - long fibers
  - layered reinforcements (e.g., sheet, cladding)

- Discontinuous Reinforcement
  - short fibers, whiskers
  - particles

Classification by Matrix

- polymer matrix
- metal matrix (MMC)
- ceramic matrix (CCM)

Reinforcement Modulus Selection

- Modulus basically related to atomic bonding strength:
  - covalent, ionic bonding

$\Downarrow$

high E, G

high T_{mp}

- Candidate materials:
  - B, C
  - B_4C, $B_{13}O_2$, B_6Si, AlB_3, BN
  - SiC
  - BeO

  - Al_2O_3
  - SiO_2
  - TiB_2
  - selected polymers (e.g., Kevlar)

  See Table 16.4 (Callister, 6th Ed.)

Above list comprised of elements from the first two rows of the period table (except Ti), due to density requirements.

Reinforcement Strength Selection

- In general, selection based on strength is secondary to modulus

- High strength is almost always desired

- Seek small size (diameter, thickness)
  - freedom from flaws
  - single crystals (whiskers) have higher strength

  See Appendix 12 and Table 16.4 (Callister, 6th Ed.)

Reinforcement Geometry & Distribution

- Reinforcement’s effectiveness related to:
  - concentration
  - size
  - shape
  - distribution
  - orientation
  - continuity

- Concentration: as % reinforcement ↑ composite stiffness and strength ↑

- Size: smaller size results in higher strength and lower tendency toward brittle failure

- Shape: fiber form most effective for providing stiffness and strength

- Distribution: homogeneous distribution required for best properties

- Orientation: preferred alignment of fibers and platelets result in anisotropic properties that can yield unique beneficial material behavior, if properly designed and applied

- Continuity: long continuous fibers more effective for stiffness and strength than short discontinuous fibers

Matrix Selection

- Principal factors influencing matrix selection:
  - density
  - thermal stability
  - environmental resistance

- Density: desire low density

- Thermal stability: match thermal stability with application temperature

- Environmental resistance: application may require higher resistance to environmental attack

- Matrix functions:
  - separates reinforcements
  - transfers load to reinforcements

- Interfacial strength between matrix and reinforcement is often key to properties

Density Considerations

- Most applications require low density

- E/ρ and σ/ρ ratios often used as criteria:
  - for many metals role of E/ρ less clear since E is roughly proportional to ρ: thus, E/ρ is approximately constant
  - for polymers and ceramics, other problems make E/ρ insufficient as a selection parameter
  - in flexural applications $E^{1/3}/\rho$ is the best measure for rigidity (want largest value)
  - σ/ρ ratio usually significant for selection

Reinforcement Volume Fraction

- Volume fraction of the reinforcement is a critical element in analysis, material configuration

- Typically 50-60 % for long continuous fiber reinforced systems

- Typically 10-40 % for discontinuous reinforced systems

- Rule of Mixtures often used for starting point in analysis

- Large-particulate composites:

$$E_{c(u)} = E_m V_m + E_p V_p \qquad \text{(upper limit)}$$

$$E_{c(l)} = E_m E_p / (V_m E_p + V_p E_m) \qquad \text{(lower limit)}$$

- Fiber-reinforced composites (and selected discontinuous particulate reinforced composites):

$\sigma_c = V_f \sigma_f + V_m \sigma_m$ (17-2)

$E_c = V_f E_f + V_m E_m = V_f E_f + (1 - V_f) E_m$ (17-6)

$1 / E_{ct} = V_f / E_f + (1 - V_f) / E_m$ (17-8)

Fiber-Reinforced Composites (Aligned, Continuous)

- Rule of Mixtures equations (17-2, 17-6, and 17-8) based on fiber (continuous, aligned) and matrix straining together elastically
- Note from Figure 17-6 and 17-7 stress/strain characteristics of individual constituents and composite
- Longitudinal strength predicted with modified Eq. 17-2 (when $e^*_f < e^*_m$):

$\sigma^*_{cl} = V_f \sigma^*_f + (1-V_f) \sigma'_m$

where: σ'_m is the matrix stress at fiber failure and failure is identified by *

- See Appendix 13 and Table 16.1 (Callister, 6th Ed.) for typical properties

Fiber-Reinforced Composites (Aligned, Discontinuous)

- Fibers carry no load at fiber ends; load carried by fibers entirely at some distance away from fiber ends ($l_c / 2$)
- Matrix carries load at fiber ends; load transferred entirely to fibers over a distance equal to $l_c / 2$
- See Figures 17-9 and 17-10
- Note derivations of Eq. 17-9, 17-10, 17-11, and 17-12

$l_c = \sigma^*_f d / 2 \tau_c$

$\sigma^*_{cd} = (1 - V_f)\sigma'_m + V_f \sigma^*_f (1 - l_c / 2l)$ (17-12) for $l > l_c$

$\sigma^*_{cd} = (1 - V_f) \sigma'_m + V_f \sigma^*_f (l / 2 l_c)$ (17-12) for $l < l_c$

or:

$\sigma^*_{cd} = (1 - V_f)\, \sigma'_m + l\, \tau_c V_f\ /\ d$ (17-12) for $l < l_c$

- Note Figure 17-12

Fiber-Reinforced Composites (Random, Discontinuous)

- To account for non-aligned (random oriented fibers), E_{cd} is sometimes estimated via:

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

- See Tables 16.2 and 16.3 (from Callister)

Table 16.1 Typical Longitudinal and Transverse Tensile Strengths for Three Unidirectional Fiber-Reinforced Composites. The Fiber Content for Each Is Approximately 50 Vol%.

Material	*Longitudinal Tensile Strength (MPa)*	*Transverse Tensile Strength (MPa)*
Glass–polyester	700	20
Carbon (high modulus)–epoxy	1000	35
Kevlar–epoxy	1200	20

Source: D. Hull and T. W. Clyne, *An Introduction to Composite Materials,* 2nd edition, Cambridge University Press, 1996, p. 179.

Table 16.2 Properties of Unreinforced and Reinforced Polycarbonates with Randomly Oriented Glass Fibers

		Fiber Reinforcement (vol%)		
Property	*Unreinforced*	*20*	*30*	*40*
Specific gravity	1.19–1.22	1.35	1.43	1.52
Tensile strength [MPa (ksi)]	59–62 (8.5–9.0)	110 (16)	131 (19)	159 (23)
Modulus of elasticity [GPa (10^6 psi)]	2.24–2.345 (0.325–0.340)	5.93 (0.86)	8.62 (1.25)	11.6 (1.68)
Elongation (%)	90–115	4–6	3–5	3–5
Impact strength, notched Izod (lb_f/in.)	12–16	2.0	2.0	2.5

Source: Adapted from Materials Engineering's *Materials Selector*, copyright © Penton/IPC.

Table 16.3 Reinforcement Efficiency of Fiber-Reinforced Composites for Several Fiber Orientations and at Various Directions of Stress Application

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	$\frac{1}{5}$

Source: H. Krenchel, *Fibre Reinforcement,* Copenhagen: Akademisk Forlag, 1964 [33].

Table 16.4 Characteristics of Several Fiber-Reinforcement Materials

Material	*Specific Gravity*	*Tensile Strength [GPa (10^6 psi)]*	*Specific Strength (GPa)*	*Modulus of Elasticity [GPa (10^6 psi)]*	*Specific Modulus (GPa)*
Whiskers					
Graphite	2.2	20 (3)	9.1	700 (100)	318
Silicon nitride	3.2	5–7 (0.75–1.0)	1.56–2.2	350–380 (50–55)	109–118
Aluminum oxide	4.0	10–20 (1–3)	2.5–5.0	700–1500 (100–220)	175–375
Silicon carbide	3.2	20 (3)	6.25	480 (70)	150
Fibers					
Aluminum oxide	3.95	1.38 (0.2)	0.35	379 (55)	96
Aramid (Kevlar 49)	1.44	3.6–4.1 (0.525–0.600)	2.5–2.85	131 (19)	91
Carbon[a]	1.78–2.15	1.5–4.8 (0.22–0.70)	0.70–2.70	228–724 (32–100)	106–407
E-Glass	2.58	3.45 (0.5)	1.34	72.5 (10.5)	28.1
Boron	2.57	3.6 (0.52)	1.40	400 (60)	156
Silicon carbide	3.0	3.9 (0.57)	1.30	400 (60)	133
UHMWPE (Spectra 900)	0.97	2.6 (0.38)	2.68	117 (17)	121
Metallic Wires					
High-strength steel	7.9	2.39 (0.35)	0.30	210 (30)	26.6
Molybdenum	10.2	2.2 (0.32)	0.22	324 (47)	31.8
Tungsten	19.3	2.89 (0.42)	0.15	407 (59)	21.1

[a] The term "carbon" instead of "graphite" is used to denote these fibers, since they are composed of crystalline graphite regions, and also of noncrystalline material and areas of crystal misalignment.