Chapter 1 – Introduction to Composite Materials

1.1 Introduction
1.2 Classification
1.3 Recycling (reading only)
1.4 Mechanics Terminology (review only)

1.1 Introduction

1) Four main categories of engineering materials
2) What's a composite?
3) Qualitive comparison of engineering materials
4) Quantitative comparison of engineering materials
5) Markets of composites

1) Four main categories of engineering materials

- Metals
- Plastics (or Engineering Polymers)
- Ceramics
- Composites

2) What's a composite? (p. 2)

A composite is a material that consists of 2 or more distinct constituent materials.

- Constituent materials have to be *significantly* different such that the properties of the composite are noticeably different from those of its constituents.
- Typically, one constituent is stiff and provides strength; the other is softer, and is to embed or support the stiff constituent.
- The stiff constituent is known as the reinforcing phase while the soft supporting constituent is known as the matrix.
- Reinforcing phase may take different forms: particles, flakes, fibers, etc.

3) Qualitative comparison of engineering

Metals:

- Dominate structural applications;
- Have the longest design & processing history;
- Have good stiffness, strength , thermal stability, temperature resistance, and high thermal and electrical conductivity;
- Are heavy compared with plastics and composites;
- Require several machining operations to obtain the final product;

Plastics:

- Became very common in the 1990's;
- Are light-weight, easy to process, and resistant to corrosion;
- Are not suitable for high-temperature (> 100 °C) applications.

Ceramics:

- Provide great thermal stability and very high hardness;
- Are best suited for high-temperature and high-wear applications;
- Are resistant to most forms of chemical attacks;
- Are very brittle;
- Are difficult to machine.

Composites:

- Natural composites have been utilized for a long time;
- Industrial applications started in the 1960's with the introduction of polymer-based composites;
- Applications include, to list just a few, auto parts, sporting goods, aerospace parts, consumer goods, marine and oil industries;
- They enable part integration;
- They enable in-service monitoring by embedding sensors;
- They enable DFM (design for manufacture) and DFA (design for assembly);
- Properties can be tailor-made (by selecting constituent materials and lay-up sequence, by optimization, for example);
- They have better impact properties;
- They have better NVH (noise-vibration-harshness) characteristics;
- There is a lack of design database, handbooks and history
- Resistance to temperature, solvents and chemicals varies;
- They absorb moisture, compromising or affecting composite's properties and dimensional stability;
- Composites may not be repaired or recycled, depending on the matrix.

4) Quantitative comparison of engineering materials

- In general, the specific strength (strength-to-density ratio) of composites is, approximately, 3 to 5 times that of steel and aluminum;
- Specific stiffness (stiffness-to-density ratio) of composites is ~5 times that of steel, and ~2 times that of aluminum;
- For example, carbon-fiber-reinforced polymers (CFRP's) and Titanium alloys have similar modulus (~130 GPA) and strength (~1000 MPa) but their densities are ~1400 kg/m^3 and ~4400 kg/m^3 respectively.
- Relative cost is defined as:

$$C_R = \frac{\$\, per\ kg\ of\ material}{\$\, per\ kg\ of\ mild\ steel\ rod}$$

- For example, relative costs are, ~20 for CFRPs and ~70 for Ti-alloys.
- Sec. 5.4 of text has 4 examples of laminated design, showing that the savings in mass or weight over metals range 50% to 75%

5) Markets of composites (pp. 16-17)

- The text has stats 1990-1995;
- 2004's market was as follows (U.S. stats):
    - Transport, 32%
    - Construction, 20%

- Corrosion-resistant apps, 12%
- Marine, 10%
- Electrical, 10%
- Consumer, 7%
- Appliance, 5%
- Aircraft, 1%
- Others, 3%

- Total consumption (in 2004) was 4.0 billion lbs.
- R. MacNeil, U.S. Composites Market Outlook for 2005 and Beyond, *Composites Manufacturing*, Jan. 16-29, 2005.

1.2 Classification

The sections covers classification as well as manufacture of gibers, and applications of composites **(pp. 16—50)**.

Manufacture of composites can be subject or course in itself.

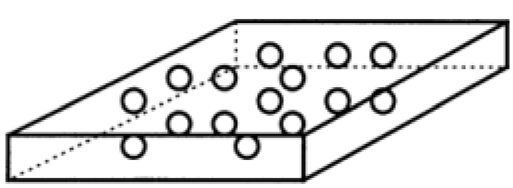
1. **Wood as a natural composite**
2. **Classification**
3. **Modern/Advanced/Man-made composites**
4. **Fibers used in advanced composites**
5. **Matrix materials**

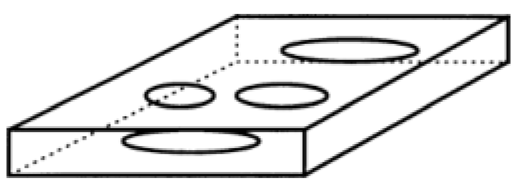
1. **Wood**

- Is the most commonly used natural composite;
- The 2 constituents are
  Fibers: long and stiff
  Cells: soft and to embed the fibers
- Modern/Advanced/Man-made composites imitate wood: strong reinforcing phase(s) embedded in softer supporting material(s).

2. **Classification based on the form of reinforcing phase (pp. 16-19 and Fig. 1.8)**

a. Particulate: randomly dispersed particles in a soft matrix. (like cement)
b. Flake: randomly dispersed flakes or aligned flakes in a soft matrix (like glass)

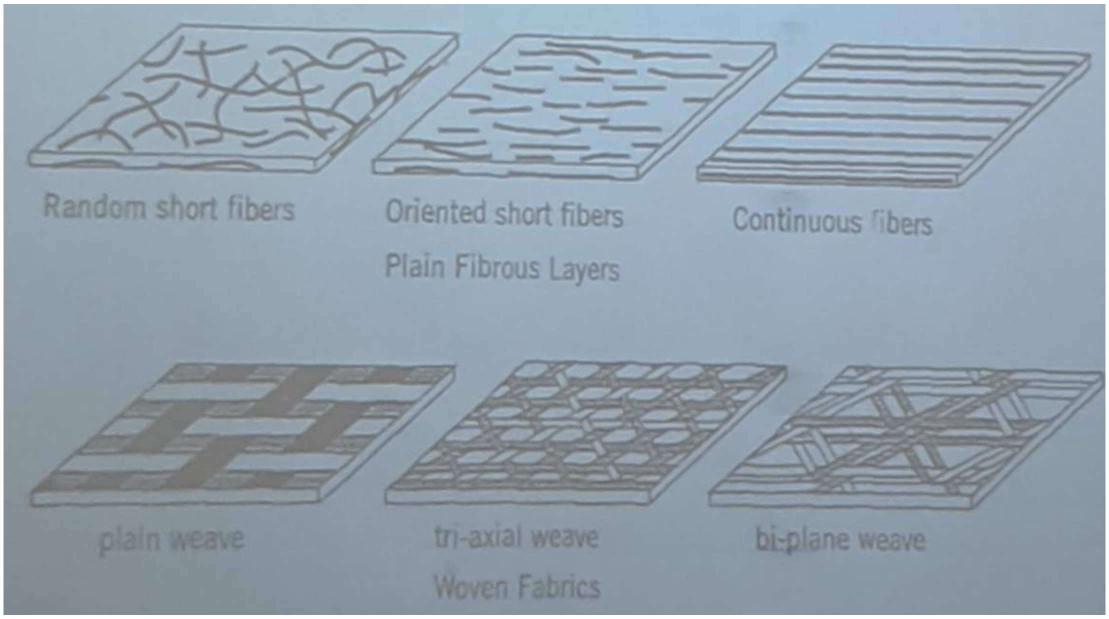

Particulate composites


Flake composites

c. Fiber-reinforced:
   Diameter: $0.0001'' \sim 0.005''$
   Length: $L \leq 100D$, short fibers
   Length: $L > 100D$, long fibers

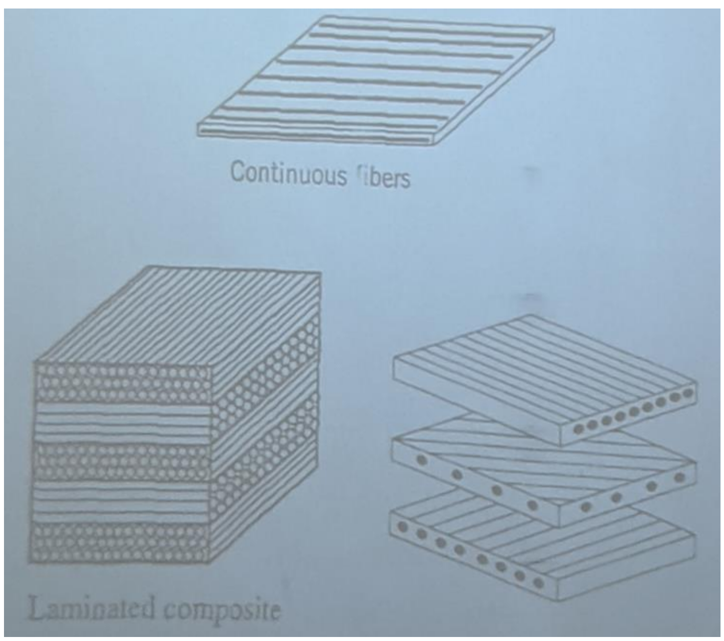
- Short fibers randomly oriented as in metals;

- Short gibers aligned in one direction;
- Long fibers aligned in one direction;
- Long fibers aligned in a few directions (weave).



d. Fiber-reinforced laminated:

- Thin layers of long and unidirectional fibers are the building blocks. A thin layer is known as a lamina or a ply;
- Layers of different materials, thicknesses and orientations are bonded together, as per the layup sequence. The result is the so-called laminate, or fiber-reinforced laminated composite;
- Fiber-reinforced laminated composites are commonly used in the design of the so-called high-performance components and structures.



3. Modern/Advanced/Man-made composites

- Imitating wood - strong fibers embedded in softer supporting materials
- Fibers:
    - Long (continuous) or short (discontinuous);
    - Aligned or random orientations
    - G – glass fibers;
    - C – carbon fibers including graphite fibers;
    - K – aramid fibers (Kevlar fibers; Kevlar is a trademark)
    - (…… etc)
- Matrix:
    - Polymers (→ PMCs polymer matrix composites);
    - Metals (→ MMCs);
    - Ceramics (→ CMCs);
    - (…… etc)

4. Fibers used in advanced composites

a. <u>Glass fibers:</u>

Most commonly used
High strength but low stiffness
Low cost
Insulating
Low CTE (coefficient of thermal expansion)
Poor abrasion resistance
(Manufacture of glass fibers: p. 22, Fig 1.9)
Types of glass fibers:
E – electrical (E-glass)
S – silica (S-glass)
C – corrosion
A – appearance
(…… etc) And their combinations
E-glass vs. S-glass

- They are more common than other glass fibers;
- E-glass is more common than S-glass;
- Compared with E-glass, S-glass has ~20 to 25% higher strength and stiffness, ~10% higher CTE, and is ~7 to 8 times as expensive;
- Table 1.6 (p. 21)

TABLE 1.6

Comparison of Properties of E-Glass and S-Glass

Property	Units	E-Glass	S-Glass
System of units: USCS			
Specific gravity	—	2.54	2.49
Young's modulus	Msi	10.5	12.4
Ultimate tensile strength	ksi	500	665
Coefficient of thermal expansion	μin./in./°F	2.8	3.1
System of units: SI			
Specific gravity	—	2.54	2.49
Young's modulus	GPa	72.40	85.50
Ultimate tensile strength	MPa	3447	4585
Coefficient of thermal expansion	μm/m/°C	5.04	5.58

b. Carbon and graphite fibers:

They are the so-called high-performance fibers (mainly for aerospace apps; lately used in auto-industry, civil infrastructures, offshore oil industry, etc.)

Carbon fibers are classified as, based on the precursors:

- PAN (poly-acrylo-nitrile, being most common)
- Pitch (bitumen)
- Rayon
- (……etc)

Manufacture of carbon fibers: p. 25, Fig. 1.11 (PAN-based carbon)

Table 1.8 (p. 25) compares PAN-based bs. Pitch-based carbon fibers.

CTE (coefficient of thermal expansion) is negative in longitudinal (axial) as well as radial directions.

Carbon fibers typically have a carbon content of 93-95%. If the carbon content gets to 99%, then carbon fibers become graphite fibers.

Graphite fibers vs. Carbon fibers;

- Graphite fibers have higher stiffness and strength, but higher cost as well.
- Processing temperature is 1900 $°C$ (3400 $°F$) compared with 1300 $°C$ (2400 $°F$) for carbon fibers.
- Graphite fibers are typically used in aircraft and aerospace applications.

c. Aramid fibers (Kevlar® fibers):

Kevlar® is the registered trademark of DuPont;

- Standard K-fibers include: K-29, K-49, K-129, and K-149 (or K29, K49, K129 and K149);
- Kevlar® 29 AP and Kevlar® 49 AP have higher performance than their respective standard counterparts;
- Kevlar® XP is the light weight version of the K-fibers, used for helmets and armors, for example.

Manufacture of Kevlar® fibers: ???

Table 1.9 (p. 26) compares K29 and K49

TABLE 1.9

Properties of Kevlar Fibers

Property	Units	Kevlar 29	Kevlar 49
System of units: USCS			
Specific gravity	—	1.44	1.48
Young's modulus	Msi	9	19
Ultimate tensile strength	ksi	525	525
Axial coefficient of thermal expansion	µin./in./°F	–1.111	–1.111
System of units: SI			
Specific gravity	—	1.44	1.48
Young's modulus	GPa	62.05	131.0
Ultimate tensile strength	MPa	3620	3620
Axial coefficient of thermal expansion	µm/m/°C	–2	–2

CTE is negative in longitudinal (axial) direction and positive in radial direction.

d. Other fibers:

Boron fibers:

- Strength and stiffness are at the same level as carbon;
- Fiber diameters (About 140 μm or 0.0055") are ~10 times those of carbon fibers;
- They are 300 times as expensive as E-glass;
- They can take higher buckling load.

5. Matrix materials

Functions of a matrix:

- Hold/embed fibers;
- Transmit forces between fibers;
- Protect fibers from the environment

a. Polymers

They are the common choice of a resin/matrix material.
When is a polymer a resin or a matrix?

- PMC's (Polymer-matrix-composites)
- Resin refers to polymer before and during processing
- Matrix refers to polymer after it is cured or solidified

Typical resins:

- Thermoset (e.g. epoxy, polyester, etc.);
- Thermoplastic (e.g. PEEK PPS, etc.).

Epoxy is the most commonly used resin/matrix.

b. Metals
Why metal matrix?

- MMCs (metal matrix composite)
- MMCs are insensitive to moisture
- MMCs have better resistance to wear and tear, to fatigue

Typical metals and fibers used in MCCs:

- Fibers: carbon, boron, SiC (silicon carbide)
- Metals: aluminum, magnesium, titanium
  - Boron-aluminum, for example

c. Ceramic

- CMCs (ceramic matrix composites)

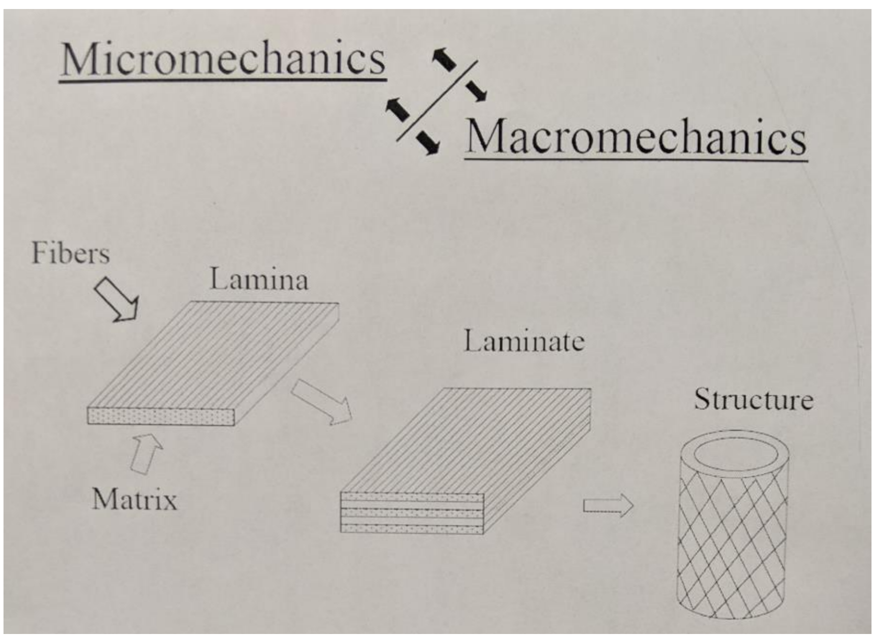
Typical CMCs:

- Carbon-ceramic
- SiC-ceramic

When ceramic is used as a material matrix to form CMCs fibers are to supplement ceramic, to reduce the brittleness of ceramics in particular.

Micromechanical Analysis (or Micromechanics – Chapter 3)

An analysis that starts with the properties (elastic moduli, strength, CTE, CME, etc.) of the constituent materials, and finds like properties of a unidirectional lamina.



Macromechanical Analysis (or Macromechanics)

A study of the stress-strain behavior of composites, using properties of unidirectional laminas found from micromechanics.

Level 1:
laminate level, Ch. 4

Level 2:
Structural level
beams (Ch. 6), plates (file on D2L), shells, etc.