Chapter 16
Part 1
Composite Materials

Introduction
• A composite material is a material system, a mixture or combination of two or more micro- or macro-constituents that differ in structure and composition and do not dissolve in each other.
• Properties of composite materials can be superior to its individual components
  – Metals: ductile, strong, high density
  – Ceramics: hard, brittle, corrosion resistance, thermal stability
  – Polymers: low density, ductile, inexpensive
• Composite materials: Judicious combination, trade offs
  – Usually structural applications
  – Exceptions – bimetal thermostats, superconducting wire

Introduction
• Examples: Fiber reinforced plastics, concrete, asphalt, wood etc.
• Generally, one constituent of the composite is continuous - The matrix phase, and the other phases are distributed in the matrix

  Matrix Phase:
  – The continuous phase
  – Purpose is to:
    • transfer stress to other phases
    • protect phases from environment
  – Classification: MMC, CMC, PMC

  metal ceramic polymer

Introduction
• Distributed or Dispersed phase:
  – Purpose: enhance matrix properties
    • MMC: increase $\sigma_y$, TS, creep resistance
    • CMC: increase fracture toughness ($K_{ic}$)
    • PMC: increase E, $\sigma_y$, TS, creep resistance
  – Classification: Particle, fiber, structural
Introduction

- Properties of a composite depend upon the properties of the individual phases, as well as:
  a) Volume fraction
  b) Size
  c) Shape
  d) Distribution
  e) Orientation of the distributed phase
- The limiting conditions are:
  - Iso-strain: matrix and reinforcement deform equally
  - Iso-stress: matrix and reinforcement are subject to the same stress

Iso-Stress Elastic Modulus of Lamellar Composite

- Iso-stress condition:
  \[ \sigma_c = \sigma_f = \sigma_m = \sigma \]

  Total change in length
  \[ \Delta l = \Delta l_f + \Delta l_m \]
  \[ \epsilon_c = \frac{\Delta l}{l} = \frac{\Delta l_f}{l_f} + \frac{\Delta l_m}{l_m} \]

  Since
  \[ \epsilon_c = \frac{\sigma}{E_c}, \epsilon_f = \frac{\sigma}{E_f}, \epsilon_m = \frac{\sigma}{E_m} \]

  Therefore
  \[ \frac{\sigma}{E_c} = \frac{\sigma V_f}{E_f} + \frac{\sigma V_m}{E_m} \]  
  Eq 16.16

Iso-Strain Elastic Modulus

- Isostrain condition:
  \[ \epsilon_c = \epsilon_f = \epsilon_m = \epsilon \]

  Total applied load
  \[ P_c = P_f + P_m \]  
  (1)

  Stress
  \[ \sigma = \frac{P}{A} \]
  \[ \sigma A_c = \sigma A_f + \sigma A_m \]  
  (2)

  Dividing (2) by \( \epsilon \) and \( A_c \), gives

  \[ E_c = E_f V_f + E_m V_m \]

  Rule of mixture of binary composites

Iso-Stress and Iso-Strain

- Iso-stress and iso-strain conditions represent limiting conditions for the composite behavior:
  - Iso-stress is the lower bound
  - Iso-strain is the upper bound

Modulus of Cu-W composites with different volume fractions of tungsten
Particle Reinforced Composites

- Cermet
  - Hard ceramic phase with a metallic binder
  - Cutting tools – WC or TiC in a Co or Ni matrix
    - Both need to be refractory to withstand high temperatures during cutting

- Automobile tires
  - Rubber (soft and compliant)
  - Carbon Black (stiffer)

Fine particle composites

- Spheroidite
  - Precipitation hardened or dispersion hardened
  - Precipitation strengthening was discussed with aluminum alloys
  - Dispersion strengthened alloys have hard oxides or carbide particles incorporated into a metallic matrix.
    - Typically used for high temperature applications.
    - TD nickel – thoria ThO₂ particles are mixed with nickel powder and consolidated by powder metallurgy techniques.

Large Particle Composites

- Concrete
  - Portland Cement concrete
    - Cement is the matrix – relatively expensive
    - Coarse and fine aggregates are used as fillers
    - Gravel and sand may up 60-80% by volume
  - Asphalitic cement concrete
    - Asphalt matrix – used in paving
  - Reinforced concrete
    - Portland cement concrete with steel reinforcing bars (rebars) introduced before the concrete sets
    - Concrete has poor tensile properties – the steel provides strength in tension

Portland Cement

- Production: Lime (CaO), Silica (SiO₂), alumina (Al₂O₃) and iron oxide (Fe₂O₃) are raw materials.
- Raw materials are crushed, ground and proportional for desired composition and blended.
- Mixture is fed into rotary kiln and heated to 1400-1650°C and then cooled and pulverized.
- Chemical Composition:

<table>
<thead>
<tr>
<th>Compound</th>
<th>Chemical formula</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tricalcium silicate</td>
<td>3CaO·SiO₂</td>
<td>C₃S</td>
</tr>
<tr>
<td>Dicalcium silicate</td>
<td>2CaO·SiO₂</td>
<td>C₂S</td>
</tr>
<tr>
<td>Tricalcium aluminate</td>
<td>3CaO·Al₂O₃</td>
<td>C₃A</td>
</tr>
<tr>
<td>Tetracalcium aluminoferrite</td>
<td>4CaO·Al₂O₃·Fe₂O₃</td>
<td>C₄AF</td>
</tr>
</tbody>
</table>
Hardening of Portland Cement

- Tricalcium silicate and dicalcium silicate constitute 75% of portland cement.
- Hydration reactions:
  \[ 2C_3S + H_2O \rightarrow C_3S_2\cdot 3H_2O + 3Ca(OH)_2 \]
  \[ 2C_2S + 4H_2O \rightarrow C_3S_2\cdot 3H_2O + Ca(OH)_2 \]
- Hydration of C\(_3\)S is responsible for early strength
- Most of compressive strength is developed in 28 days.
- Strengthening might continue for years

Prestressed Concrete

- Concrete has very poor strength in tension.
- Introduction of compressive stresses by \textit{tensioned reinforcements} (tendons) improves behavior in tension.
- \textit{Pretensioned concrete}: The tendon is first stretched and concrete is poured on the tendon.
- \textit{Post-tensioned concrete}: Steel reinforcements are used to improve tensile properties as in bending.

Fiber Reinforced Composites

- Fibers of a strong material distributed in a relatively soft and ductile matrix
  - The fibers carry most of the load
  - Under axial loading, equal strain hypothesis applies
  - Load transfer
    - The load on the fiber is tensile
    - The interface in under shear

  \[ \sigma_{\text{fiber}} = \frac{a l_f}{4} \sigma_f \]
  \[ l_c = \frac{\sigma_{\text{matrix}} d}{2 \tau} \]

  \( l_c > l_f \) - Fiber will fail first
  \( l_c < l_f \) - Fiber will get pulled out of the matrix
Longitudinal Deformation of a FR composite

- There are 4 distinct stages of the deformation behavior
  I. Both matrix and fiber undergo elastic def.
  II. Fiber def. is elastic, matrix def. is plastic
  IIIa. Both fiber and matrix undergo plastic def.
  III. Fiber fails resulting in composite failure

  If the fiber is brittle, stage IIIa above will not be observed

\[
\sigma_{\text{failure}} = \sigma_\text{m}(1 - V_f) + \sigma_f \text{ } V_f
\]

Short Fiber Reinforced Composites

- If the fiber length is greater than the critical length, then the composite is considered to be continuous fiber reinforced
  - If the fibers are all aligned in the same direction, then the properties in the longitudinal direction will obey the equal-strain hypothesis
  - In the perpendicular direction the properties will follow equal-stress hypothesis
    - Strength and elastic modulus will be very low
- To overcome this problem
  - Laminated composites – each layer may have fibers oriented in a different direction
    - 2D isotropy
    - Short fibers which are randomly oriented
      - 2D or 3D isotropy

Effect of Fiber Length and Orientation

- Long fibers provide highly efficient strengthening in the direction of the fiber
  - But properties are anisotropic
- Laminated (2D) or random short fiber (3D) provide isotropic properties but are less efficient in strengthening

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

<table>
<thead>
<tr>
<th>Fiber Orientation</th>
<th>Stress Direction</th>
<th>Reinforcement Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>All fibers parallel</td>
<td>Parallel to fibers</td>
<td>1</td>
</tr>
<tr>
<td>Fibers randomly and uniformly distributed within a specific plane</td>
<td>Any direction of the fibers</td>
<td>1/2</td>
</tr>
<tr>
<td>Fibers randomly and uniformly distributed within three dimensions in space</td>
<td>Any direction</td>
<td>1/3</td>
</tr>
</tbody>
</table>