Composite Materials

ISSUES TO ADDRESS...

• What are the classes and types of composites?
• Why are composites used instead of metals, ceramics, or polymers?
• How do we estimate composite stiffness & strength?

Composites Classification

• Composites: Multiphase material with significant proportions of each phase.

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

Dispersed phase:
- Purpose: enhance matrix properties.
  - MMC: increase $\sigma_y$, TS, creep resist.
  - CMC: increase $K_c$
  - PMC: increase $E$, $\sigma_y$, TS, creep resist.
- Classification: Particle, fiber, structural

Particulates Composites

• Examples:
  ✓ Spheroidite steel
  ✓ WC/Co cemented carbide
  ✓ Automobile tires

Properties of particulates composites depend on:
- concentration
- size
- distribution
Particulates Composites

- Elastic modulus of composites, $E_c$:
  > two approaches:
  
  ![Graph showing the relationship between $E_c$ and volume percentage of tungsten.]
  
  - Application to other properties:
    - Electrical conductivity, $\sigma_e$: Replace $E$ by $\sigma_e$.
    - Thermal conductivity, $k$: Replace $E$ by $k$.

Fiber Composites

(1) Aligned Continuous fibers

- Examples:
  - Metal: $\gamma'(\text{Ni}_3\text{Al})-\alpha(\text{Mo})$
    - Glass reinforced with SiC fibers
      formed by glass slurry
      $E_{\text{glass}} = 76\text{GPa}; E_{\text{SiC}} = 400\text{GPa}$.

(2) Discontinuous, random 2D fibers

- Example: Carbon-Carbon
  - Uses: disk brakes, gas turbine exhaust flaps, nose cones.

- Other variations:
  - Discontinuous, random 3D
  - Discontinuous, 1D

Fiber Composites

- Critical fiber length for effective stiffening & strengthening:
  
  $l_c = \frac{\sigma_f d}{2\tau_f}$
  
  For glass and carbon composites, $l_c$ is often around 1mm ($20 - 150 \times d_f$)

  Fibers need to be long enough to carry load.

  How does fiber strengthening work?
  
  Transfer load from matrix to strong/stiff fiber. Requires a good interface.
  
  No load is transferred at fiber ends
  
  Load is transferred along fiber sides
Fiber Composites

When:
- \( I > 15 \ l_c \) "continuous" fibers
- \( I \sim 10 \ l_c \) "discontinuous" fibers
- \( I < l_c \) not acting as fibers (particles).

Rule of Mixtures (RoM)

Volume of composite = Vol. of fibers + Vol. of matrix

Volume fraction of fibers: \( V_f = \frac{\text{vol. of fibers}}{\text{vol. of composite}} \)

Volume fraction of matrix: \( V_m = \frac{\text{vol. of matrix}}{\text{vol. of composite}} \)

\[ V_f + V_m = 1 \]

Thus density of composite can be written as:

\[ \rho_c = V_f \rho_f + V_m \rho_m \]

Elastic Properties: Longitudinal loading

Load carried by composite = loads carried by two phases:

\[ F_c = F_f + F_m \quad \text{since} \quad F = \sigma A \]

\[ \sigma A_f = \sigma_n A_n + \sigma_f A_f \quad \text{Divide by } A_c \]

Area fraction = vol. fraction (if all fibers have the same length)

\[ \sigma_c = \sigma_n V_n + \sigma_f V_f \]

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Elastic Properties: Transverse loading

Isostress case \( \sigma_c = \sigma_f = \sigma_m \)

\[ \epsilon_c A_c = \epsilon_f A_f \quad \text{From RoM} \]

but \( \epsilon = \sigma / E \)

\[ \frac{\sigma}{E_c} = \frac{\sigma_n V_n + \sigma_f V_f}{E_n} \]

(recall \( \sigma_c = \sigma_f = \sigma_m \))

\[ \frac{1}{E_c} = \frac{1}{E_n} V_n + \frac{1}{E_f} V_f \]

which can be rearranged to:

\[ E_c = \frac{E_n E_f}{V_n E_f + V_f E_n} = \frac{E_n E_f}{(1-V_f) E_f + V_f E_n} \]

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Strength of Aligned Cont. Fiber Composites

**Matrix**} \( \text{Fiber} \) \( \text{Same strain} \)

Composite will fail at lower fracture strain

So, either

Matrix fails first

\[ \text{Brittle matrices} \]

eg. epoxies

Or, fiber fails first

\[ \text{Ductile matrix} \]

eg. thermoplastic polymer

If we assume that strain-to-failure of fiber is less than strain-to-failure of matrix as is most common: i.e. \( \epsilon^*_{f} < \epsilon^*_{m} \)

Then we can estimate the longitudinal strength of the composite as:

\[ \sigma^*_{cl} = \sigma^*_{m}(1-V_f) + \sigma^*_{f}V_f \]

Where \( \sigma^*_{m} \) is the stress in the matrix when the fibers fail.

Discontinuous & Aligned Fiber Composites

Reinforcement efficiency is lower than that for continuous fibers but the composites are common for ……………….

- **Modulus of elasticity** can be up to ………. of continuous fiber composite
- **Tensile strength** can be up to ………. of continuous fiber composite

when \( \ell > \ell_c \), the longitudinal strength, \( \sigma^*_{cl} \) is given by:

\[ \sigma^*_{cl} = \sigma^*_{f}V_f \left( 1 - \frac{\ell}{2\ell_c} \right) + \sigma^*_{m}(1-V_f) \]

where \( \sigma^*_{f} \) and \( \sigma^*_{m} \) represent the fiber fracture strength and the matrix stress at fiber failure respectively.

If the fiber length is less than the critical length, \( \ell < \ell_c \), then:

\[ \sigma^*_{cl} = \frac{d}{d} \tau_c V_f + \sigma^*_{m}(1-V_f) \]

where,

\( d = \text{fiber diameter} \)

\( \tau_c = \text{the .......... of either fiber – matrix bond strength or matrix shear strength} \)

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Transverse Strength

Fiber-Matrix interface

- The transverse strength of unidirectional composites is usually very low.
- Fibers can actually act as ............ rather than as reinforcements.
- Transverse strength can be approximated as .......... the matrix strength in many cases.

<table>
<thead>
<tr>
<th>Material</th>
<th>Longitudinal Tensile Strength (MPa)</th>
<th>Transverse Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass-Polyester</td>
<td>700</td>
<td>20</td>
</tr>
<tr>
<td>Carbon (High Modulus)-Epoxy</td>
<td>1000</td>
<td>35</td>
</tr>
<tr>
<td>Kevlar-Epoxy</td>
<td>1200</td>
<td>20</td>
</tr>
</tbody>
</table>

Typical Longitudinal and Transverse Tensile Strengths for three Unidirectional Fiber-Reinforced Composites.

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Discontinuous & Randomly Oriented Fiber Composites

When fiber orientation is random and the fibers are short, a “RoM” expression is used for the elastic modulus using an .......... factor, K (which is less than unity- usually between 0.1 - 0.6).

\[ E_{cd} = K E_f V_f + E_m V_m \]

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Structural Composites

- Stacked and bonded fiber-reinforced sheets
  - stacking sequence: e.g., 0/90
  - benefit: balanced, in-plane stiffness

- Sandwich panels
  - low density, honeycomb core
  - benefit: small weight, large bending stiffness

Example
A continuous and aligned carbon fiber-epoxy composite consists of 60 vol% fibers. The moduli of elasticity are 700 GPa and 3 GPa for the fiber and the matrix respectively. Calculate the longitudinal and transverse composite modulus of elasticity? Compare the result with that of steel (E = 207 GPa)? Calculate the density of the composite if the density of carbon fiber is 1.8 g/cm³ and of the epoxy is 1.2 g/cm³?

Next time:
Fracture Mechanics