Chapter 3: Properties and Characteristics of Composite Materials

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3.1 Mechanical Properties of Composite Materials

The mechanical behaviour of a composite emerges from the interaction between matrix and reinforcement, and depends on the properties of each phase, the fibre volume fraction, fibre orientation, and interfacial bonding quality. A distinctive consequence is mechanical anisotropy: fibre-reinforced composites exhibit markedly different properties along and perpendicular to the fibre axis [3], [5].

A. Strength

Strength is the maximum stress a composite can sustain before failure. Along the fibre direction, strength is governed primarily by fibre properties and volume fraction. In the transverse direction, it depends on the weaker matrix and interfacial bond strength a directional dependence that requires engineers to align fibre orientations with expected loading paths [3], [5].

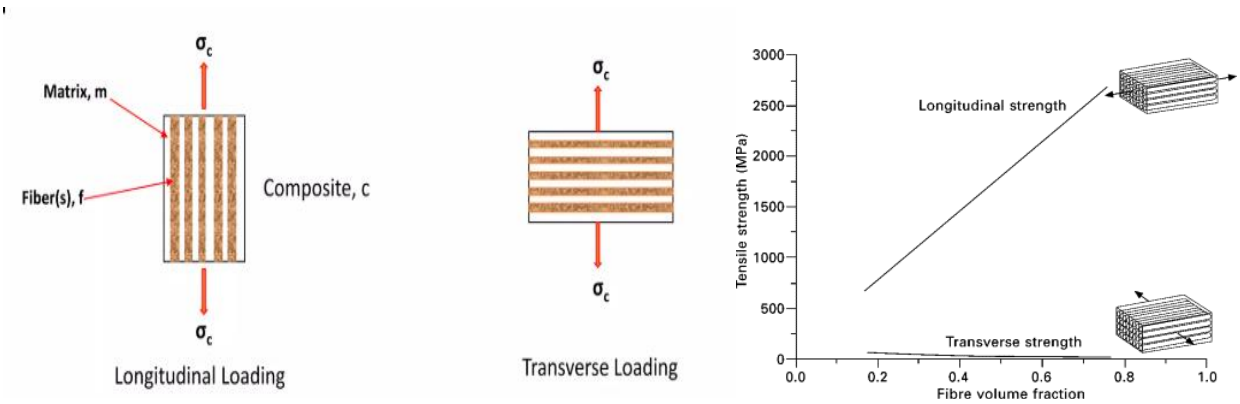

Figure 3.1 — Directional dependence of strength in a unidirectional composite: longitudinal versus transverse loading.

B. Stiffness

Stiffness is quantified by the elastic modulus. The longitudinal modulus follows the Rule of Mixtures:

$$\boldsymbol{E^1 = E_f \cdot V_f + E_m \cdot V_m}$$

- $\boldsymbol{E^1}$ = longitudinal modulus,
- $\boldsymbol{E_f}$ = fibre modulus,
- $\boldsymbol{E_m}$ = matrix modulus,
- $\boldsymbol{V_f}$= fibre volume fraction,
- $\boldsymbol{V_m}$ = matrix volume fraction.

The transverse modulus is substantially lower because the compliant matrix limits overall stiffness under iso-stress conditions [5].

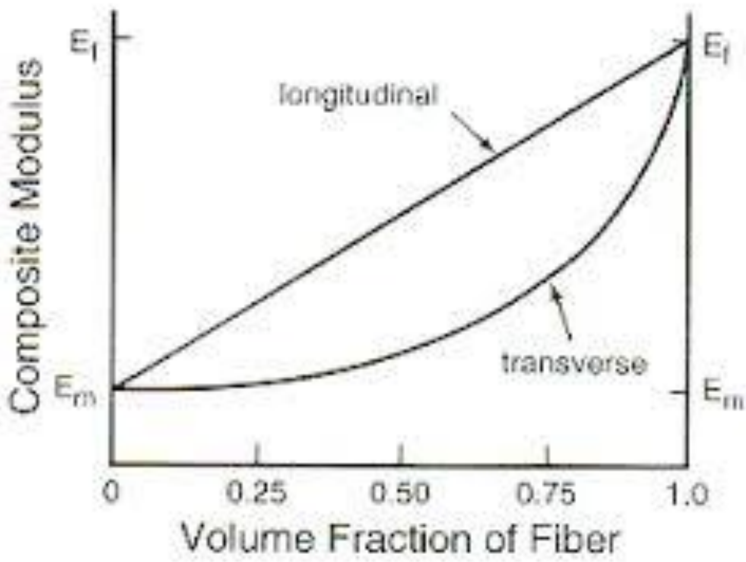

Figure 3.2 — Longitudinal and transverse elastic modulus as a function of fibre volume fraction.

C. Lightweight Advantage

One of the principal advantages of composite materials is their high strength and stiffness combined with low density.

This performance is commonly evaluated using:

$$Specific\ strength = \frac{Ultimate\ tensile\ strength}{Density}$$

$$Specific\ modulus = \frac{Elastic\ modulus}{Density}$$

Fibre-reinforced composites can provide higher specific strength and specific modulus compared with structural steel and aluminium alloys, making them particularly suitable for weight-sensitive applications in aerospace and transportation [1], [3].

These favourable mechanical characteristics account for the widespread use of composite materials in applications where high mechanical performance, low density, and design flexibility are required.

3.2 Thermal and Electrical Properties

The thermal and electrical behaviour of a composite depends on the nature of the matrix and reinforcement, their volume fractions, and the reinforcement architecture. As with mechanical properties, fibre-reinforced composites exhibit significant anisotropy in both thermal and electrical response [3], [6].

A. Thermal Properties

Thermal conductivity varies dramatically with constituent selection. Polymer matrices are poor conductors (<0.5 W/m·K), making PMCs effective thermal insulators, while metal matrices exploit the high conductivity of aluminium (~200 W/m·K) for thermal management applications. Carbon fibres conduct heat preferentially along their axis, creating significant directional anisotropy in carbon/polymer composites [3].

Thermal stability is governed primarily by the matrix: polymer matrices limit service to 250–350 °C, metal matrices extend this to 500–600 °C, and ceramic matrices maintain integrity above 1000 °C [3].

Thermal expansion in composites differs from monolithic materials because fibres and matrix have different coefficients of thermal expansion (CTE). Carbon fibres exhibit near-zero axial CTE while polymer matrices expand considerably, producing directional CTE that can be engineered to near zero in certain carbon/epoxy configurations — a critical advantage for dimensionally stable aerospace structures [5], [6].

B. Electrical Properties

Polymer matrices are electrically insulating; when combined with non-conductive glass or aramid fibres, the composite functions as an insulator. Carbon fibres, however, are moderately conductive along their axis, giving carbon/polymer composites directional electrical conductivity [3], [6].

This tailorability has practical consequences: GFRP composites are selected for electromagnetically transparent applications such as radomes, while CFRP composites provide a degree of electromagnetic shielding and lightning strike protection in aircraft structures [3].

3.3 Comparison with Traditional Materials

The selection between composites and traditional materials involves simultaneous evaluation of mechanical performance, density, environmental resistance, damage tolerance, manufacturability, and cost [7], [8].

A. Comparison with Metals

Composites offer lower density, higher specific strength and specific modulus, superior corrosion resistance, and directional property tailoring compared with steel and aluminium alloys. Metals, however, are isotropic, exhibit visible and predictable damage progression, and benefit from established low-cost manufacturing, joining, and recycling processes. Internal damage in composites, such as delamination, may remain undetected without specialised inspection [7], [8].

B. Comparison with Conventional Polymers

Composites provide substantially higher strength, stiffness, and dimensional stability than unreinforced polymers, but require more complex manufacturing, controlled curing, and quality inspection procedures that increase cycle time and production cost [7], [9].

References

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