Chapter 2: Composite Materials and Classification

Contents

2.1 Definition and Historical Evolution

A composite material is formed by combining two or more chemically distinct constituents at the macroscopic scale. These constituents remain physically identifiable within the final structure they do not dissolve into one another yet they cooperate to produce properties that neither can achieve alone (Figure 2.1) [3], [4].

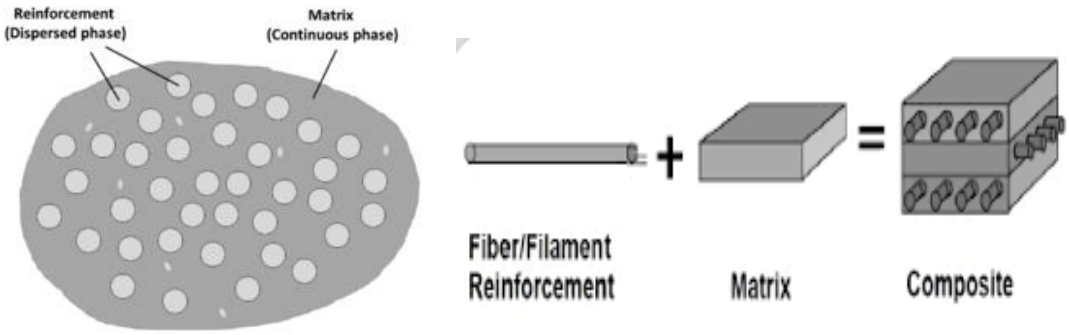

Figure 2.1 — Typical structure of a composite material showing matrix and reinforcement phases.

A composite material is mainly composed of two phases:

- **Matrix phase:** the continuous phase that surrounds and binds the reinforcement. It maintains the geometric arrangement of the reinforcement, transfers externally applied loads to it through the interface, and protects it from chemical and thermal degradation. Common matrix materials include polymers, metals, and ceramics, each defining a distinct class of composites with different operating capabilities [3].
- **Reinforcement phase:** the dispersed phase responsible for carrying the dominant share of the mechanical load. It governs the strength and stiffness of the composite system. Reinforcement can take the form of continuous fibres, short fibres, or particles, and its type, orientation, and volume fraction largely determine the resulting mechanical performance [4].

- The **interface** between matrix and reinforcement controls stress transfer between the two phases. The final performance of the composite is therefore governed not by the properties of its constituents in isolation, but by their nature, proportion, spatial arrangement, and interfacial bonding quality [3], [4].

2.2 Historical Evolution of Composite Materials

The principle of combining materials for improved performance is ancient. Wood is a natural composite of cellulose fibres embedded in a lignin matrix; bone combines collagen fibres with a hydroxyapatite mineral phase; and straw-reinforced mud bricks, used for thousands of years, follow the same matrix–reinforcement logic exploited in modern synthetic systems (Figure 2.2) [3], [4].

Figure 2.2 — Examples of natural and ancient composite materials.

The transition to engineered composites began in the 1930s when glass fibres were first combined with polymer resins to produce glass fibre reinforced polymers (GFRP). These materials offered reduced density, acceptable corrosion resistance, and improved specific mechanical properties compared with steel and aluminium alloys, establishing polymer matrix composites as a practical structural material class (Figure 2.3) [3], [5].

Figure 2.3 — Glass Fibre Reinforced Polymer (GFRP).

A second generation of composites emerged in the 1960s and 1970s with the development of carbon fibres and aramid fibres. Carbon fibres raised the attainable specific modulus and specific strength well beyond what glass fibres could provide, while aramid fibres introduced exceptional impact resistance and energy absorption capacity. These advances made composites viable for primary load-bearing structures in aerospace, where weight savings translate directly into fuel efficiency and payload capacity (Figure 2.4) [3], [4].

Figure 2.4 — Advanced composite materials used in aerospace and high-performance engineering applications.

More recent developments have broadened the field considerably. Ceramic matrix composites now operate in extreme thermal environments such as jet engine hot sections. Hybrid composites, combining two or more reinforcement types within a single matrix, allow engineers to optimise the balance between performance and cost. Smart composites integrate embedded sensors, actuators, or self-healing agents, enabling real-time structural health monitoring and adaptive response during service (Figure 2.5) [5].

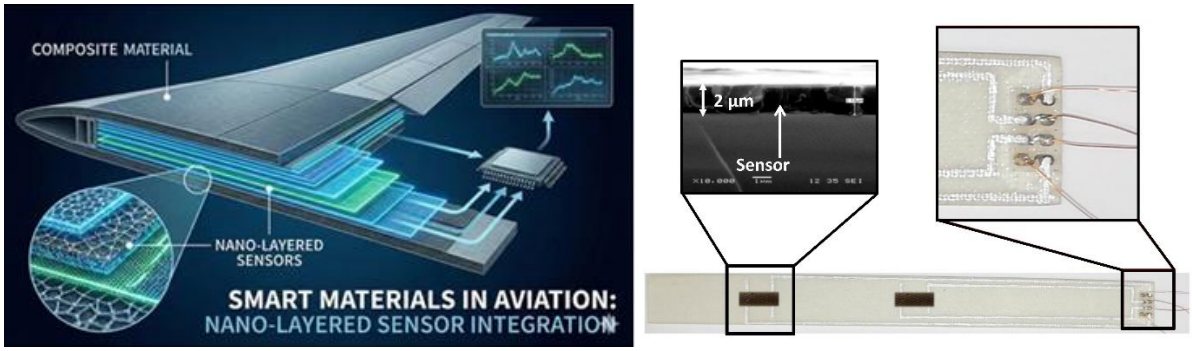

Figure 2.5 — Examples of advanced composite systems.

2.3 Constituents of Composite Materials

The engineering performance of a composite is determined by three elements: the reinforcement, the matrix, and the interface between them. This section examines each constituent and its contribution to the overall behaviour of the composite system [3], [4].

A. Reinforcement Materials

The reinforcement phase provides the primary contribution to strength and stiffness. It can take the form of continuous fibres, short fibres, or particles, depending on the application and manufacturing process Figure 2.6. The most common reinforcement materials differ significantly in their mechanical profiles, cost, and suitability for different service conditions [3], [4].

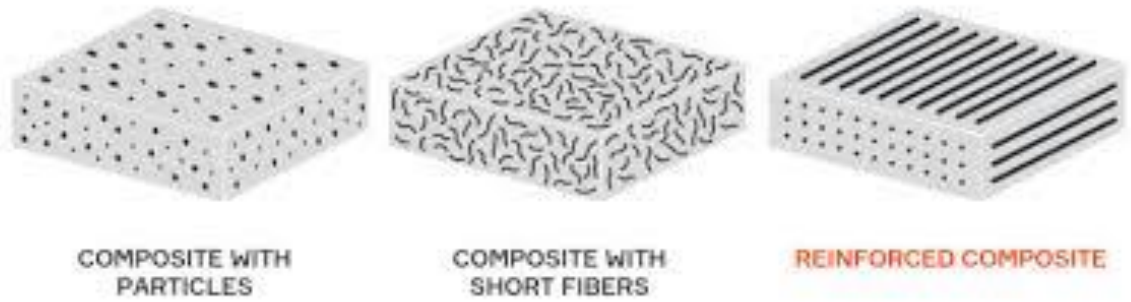

Figure 2.6 — Reinforcement forms in composite materials

- **Glass fibres** are the most widely used reinforcement in commercial composites. They offer high tensile strength (up to ~3500 MPa), moderate elastic modulus (~70 GPa), good corrosion resistance, and relatively low cost. These characteristics make glass fibres the standard choice for general-purpose polymer matrix composites in marine, automotive, and construction applications (Figure 2.7a) [3].
- **Carbon fibres** provide a combination of high specific strength and high specific modulus that no other commercial reinforcement can match. Their elastic modulus ranges from approximately 230 GPa for high-strength grades to over 500 GPa for ultra-high-modulus grades, at a density of only ~1.8 g/cm³. This performance comes at a higher cost, restricting carbon fibre use primarily to aerospace, motorsport, and high-performance structural applications (Figure 2.7b) [3].
- **Aramid fibres** (such as Kevlar) are distinguished by their exceptional impact resistance and energy absorption capacity at low density (~1.4 g/cm³). They are the preferred reinforcement in applications requiring ballistic protection, blast resistance, and lightweight damage-tolerant structures. Their compressive strength, however, is significantly lower than their tensile strength, which limits their use in compression-dominated loading situations (Figure 2.7c) [4].
- **Natural fibres** such as flax, hemp, jute, and bamboo are increasingly considered as renewable and biodegradable alternatives to synthetic reinforcements. They offer low density and acceptable specific mechanical properties for non-critical structural applications, with the additional advantage of reduced environmental impact during production and end-of-life disposal (Figure 2.7d) [3].

(a) (b) (c) (d)

Figure 2.7 — Principal reinforcement fibre types: (a) glass, (b) carbon, (c) aramid, (d) natural fibres.

B. Matrix Materials

The matrix binds the reinforcement, transfers applied loads through the interface, and protects the reinforcement from environmental degradation [3].

- **Polymer matrices** are the most widely used and are divided into two categories: *thermosets* (epoxy, polyester, vinyl ester), which undergo irreversible cross-linking during curing and offer high dimensional stability, and *thermoplastics* (polyamide, PEEK, polypropylene), which can be remelted and reshaped, providing better recyclability and impact toughness.

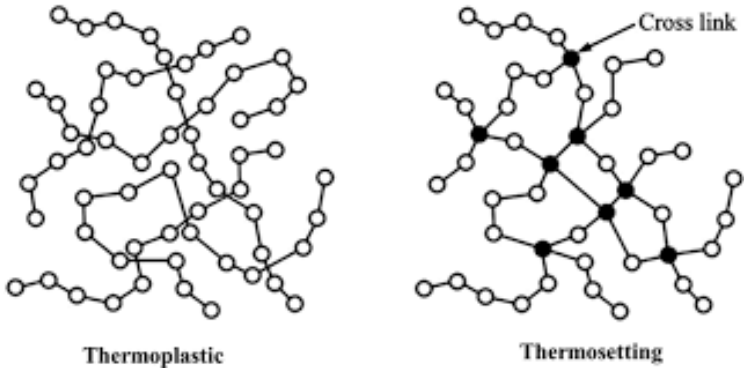

Figure 2.8 — Molecular structure comparison: thermoset (cross-linked network) versus thermoplastic (linear chains).

- **Metal matrices**, typically aluminium, magnesium, or titanium alloys, provide higher thermal conductivity, superior wear resistance, and greater operating temperatures than polymer matrices [4].

- **Ceramic matrices** are selected for extreme-temperature applications where neither polymer nor metal matrices can survive. The reinforcement in ceramic matrix composites primarily improves fracture toughness rather than strength [3].

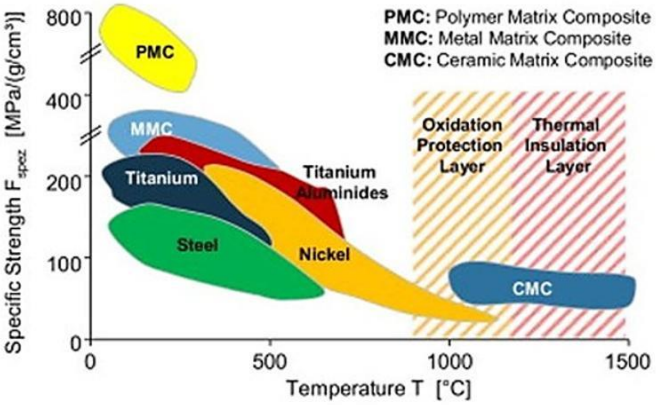

Figure 2.9 — Operating temperature ranges for polymer, metal, and ceramic matrix composites.

C. Fibre/Matrix Interface

The interface is the boundary region through which stress transfer between matrix and reinforcement occurs. A strong interface ensures efficient load transfer, enabling the composite to exploit the full mechanical potential of the fibres; however, an excessively strong bond promotes brittle fracture by forcing cracks through the fibres rather than deflecting along the interface. A weak interface, by contrast, permits fibre debonding and pull-out, which improves toughness at the cost of reduced strength. Composite design therefore requires optimising the interface to balance load transfer efficiency and damage tolerance [3], [4].

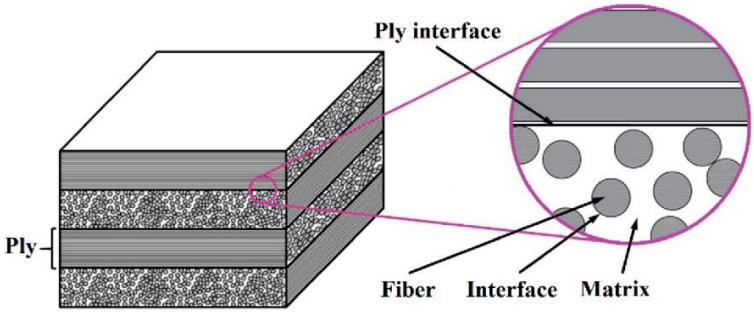

Figure 2.9 — Fibre/matrix interface: stress transfer mechanisms and the effect of interface strength on fracture behaviour.

D. Fibre Volume Fraction

The fibre volume fraction (V_f) is one of the most influential parameters in composite design: increasing V_f raises both stiffness and strength by placing a greater proportion of load-bearing reinforcement in any given cross-section [4].

The achievable V_f depends on the manufacturing process — hand lay-up typically reaches 30–40%, resin transfer moulding 50–55%, and filament winding or autoclave-cured prepreg 60–65%. Beyond approximately 70%, insufficient matrix remains to wet the fibres fully, producing voids and degraded bonding that reduce rather than improve performance [4].

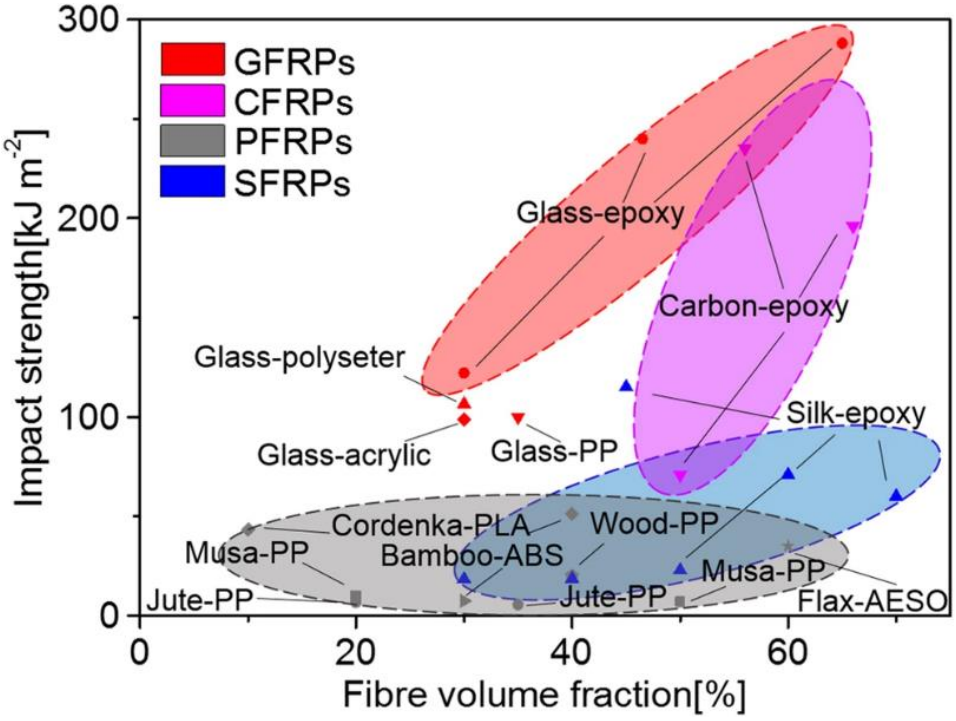

Figure 2.10 — Effect of fibre volume fraction on stiffness and strength of a unidirectional composite.

2.4 Classification of Composite Materials

Composite materials are classified primarily according to the type of matrix, because the matrix determines the processing conditions, the maximum operating temperature, the environmental resistance, and the range of compatible reinforcement forms. Three principal classes are recognised polymer, metal, and ceramic matrix composites together with hybrid composites, which combine elements from more than one class [3], [4].

A. Polymer Matrix Composites (PMC)

Polymer matrix composites are the most commercially widespread class. The polymer matrix provides low density, good chemical resistance, and relatively straightforward processing. Glass fibre reinforced polymers (GFRP) dominate cost-sensitive general engineering, while carbon fibre reinforced polymers (CFRP) serve weight-critical aerospace and motorsport applications. The principal limitation is their restricted thermal ceiling: most polymer matrices degrade above 250–350 °C (Figure 2.11a) [3].

B. Metal Matrix Composites (MMC)

Metal matrix composites use aluminium, magnesium, or titanium alloys reinforced with ceramic particles (SiC, Al_2O_3) or fibres. The metallic matrix extends the operating range to approximately 500–600 °C while providing superior thermal conductivity and wear resistance compared with PMCs. These characteristics suit automotive brake systems, engine components, and electronic packaging, though manufacturing is more complex and costly (Figure 2.11b) [4].

C. Ceramic Matrix Composites (CMC)

Ceramic matrix composites operate above 1000 °C, far beyond the limits of polymer and metal matrices. The role of the reinforcement in CMCs is primarily to improve fracture toughness rather than strength, transforming an inherently brittle matrix into

a damage-tolerant system. Applications include jet engine hot-section components and re-entry thermal protection systems (Figure 2.11c) [3].

D. Hybrid Composites

Hybrid composites combine two or more reinforcement types within a single matrix to optimise competing properties. A common example is the carbon/glass fibre hybrid: carbon fibres provide high stiffness in primary load paths, while glass fibres reduce cost and improve impact resistance in secondary regions (Figure 2.11d) [4].

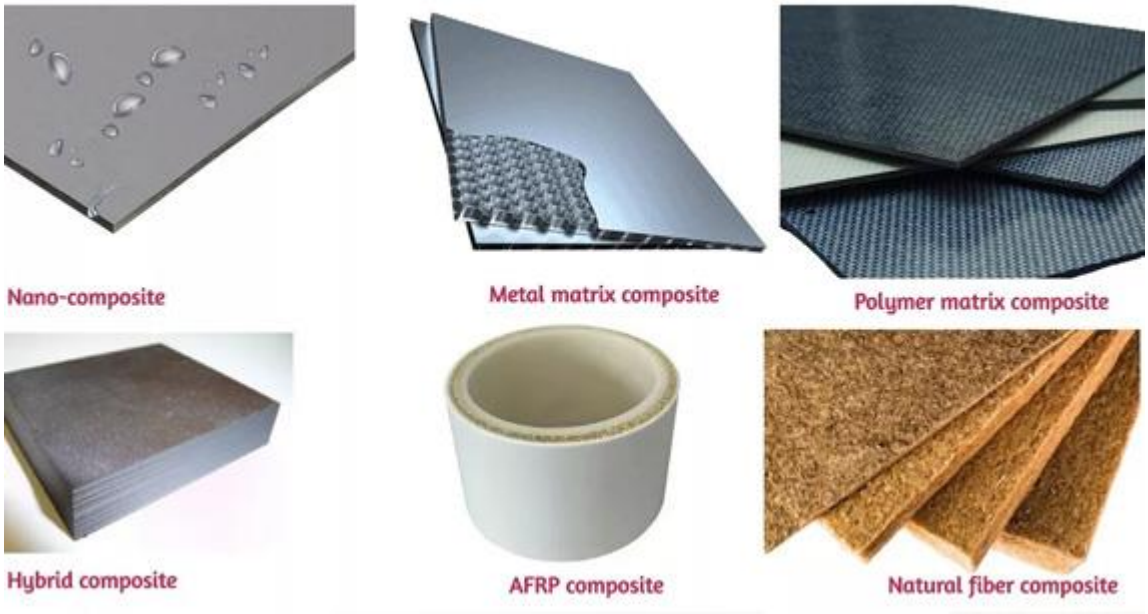

Figure 2.11 — The principal composite classes

2.4 Composite Reinforcement Architectures

The architecture of a composite describes the shape, size, and spatial distribution of the reinforcement within the matrix. This organisation directly governs the load transfer mechanism, the degree of anisotropy, and the overall mechanical efficiency of the composite system. As the reinforcement geometry progresses from equiaxed particles through short fibres to continuous fibres, the capacity for directional load bearing increases significantly [3], [4].

A. Particulate Composites

Particulate composites consist of small particles — ceramic, metalite, or mineral — distributed within a matrix. Particles improve properties such as hardness, wear resistance, and thermal behaviour, but their low aspect ratio limits directional reinforcement. These composites are generally easier and less expensive to manufacture than fibre-reinforced systems (Figure 2.12) [3].

B. Fibre-Reinforced Composites

Fibre-reinforced composites use high-aspect-ratio fibres to provide directional strength and stiffness. **Short-fibre composites** contain fibres of limited length, randomly or preferentially oriented, offering moderate and partially isotropic reinforcement. **Continuous-fibre composites** arrange long fibres along specific loading directions, maximising mechanical efficiency and producing strongly anisotropic properties. Continuous-fibre systems deliver the highest specific strength and modulus among all composite architectures, making them the standard for aerospace and high-performance structures (Figure 2.12) [4].

C. Laminated Composites

Laminated composites are produced by stacking multiple continuous-fibre laminae with different fibre orientations. By controlling the orientation and sequence of each ply, engineers can tailor directional properties to match complex multi-axial loading

conditions — a capability that single unidirectional layers cannot provide (Figure 2.12) [3].

D. Sandwich Structures

Sandwich composites separate two stiff, strong outer skins with a lightweight core — typically polymer foam, aluminium honeycomb, or balsa wood. This geometry produces high bending stiffness at very low weight by placing load-bearing material at maximum distance from the neutral axis, following the same structural principle as an I-beam (Figure 2.12) [4].

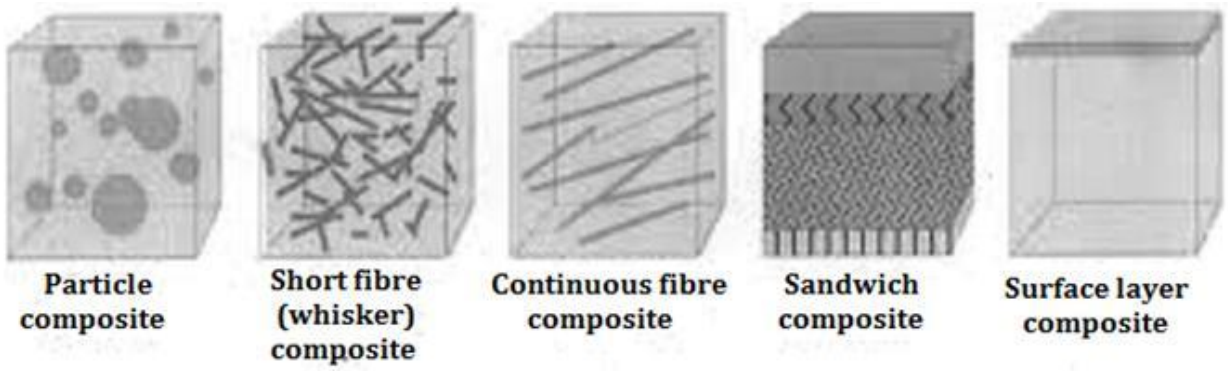

Figure 2.12 — Composite reinforcement architectures

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