University: University of Mohamed Kheider - Biskra

Faculty: Faculty of Science and Technology

Department: Common Core in Science and Technology

Composite Material

Pedagogical Handout

Dr. Toufik DJIMAOUI

Academic Year: 2025/2026

2nd Year Engineering students

Official Course Programs

Semestre: 3
Unité d'enseignement: UET 3.1
Matière : Matériaux composites
VHH : Cours: 1h30, VHS: 22h30
Crédits: 1 Coefficient: 1

Objectifs de l'enseignement :

Ce cours consacré aux matériaux composites : définition, historique, utilisation, fabrication

Connaissances préalables recommandées :

Ce cours requiert des connaissances de base sur le calcul matriciel, élasticité, mécanique de la rupture, résistance des matériaux et structures mécaniques

Contenu de la matière :

Chapitre 1 : Introduction

- Définition et historique d'un matériau composite.
- Evolution des composites.
- Intérêt et applications dans différents domaines :
  - Aéronautique (fuselages, ailes).
  - Automobile (pièces structurelles, carrosserie).
  - Génie civil (béton armé de fibres, structures marines).
  - Sport et biomédical (prothèses, raquettes, vélos).
  - ….

Chapitre 02 : Matériaux composites

A. Constituants d'un composite

- **Renforts** : fibres de verre, carbone, aramide, fibres naturelles.
- **Matrices** : polymères (thermodurcissables, thermoplastiques), métaux, céramiques.
- Interfaces fibre/matrice et rôle de l'adhésion.

B. Types de composites

- Composites à matrice polymère (CMP).
- Composites à matrice métallique (CMM).
- Composites à matrice céramique (CMC).
- Hybrides.

C. Autres types

- Matériaux composites
- Matériaux multimatériaux
- Panneaux sandwichs
- Matériaux intelligents et adaptroniques
- Nanomatériaux
- Comportements mécaniques et rupture

Chapitre 03 : Propriétés et caractéristiques

- Propriétés mécaniques : résistance, rigidité, légèreté.
- Propriétés thermiques et électriques.
- Comparaison avec les matériaux traditionnels (métaux, polymères classiques).

Chapitre 04 : Méthodes de fabrication

- Stratification manuelle, moulage sous vide.
- Pultrusion, enroûlement filamentaire.
- Injection, infusion, impression 3D.
- Techniques industrielles modernes.

Chapitre 05 : Sélection des matériaux

- Propriétés d'usage
- Adéquation matériau-fonction
- Adéquation matériau-Procédé
- Fabrication additive
- Sélection multicritère
- Choix entre alliage d'aluminium et composites organiques
- Renforcement et réparation des structures endommagées

Mode d'évaluation:

Examen: 100 %.

Références :

1. Kittel C., « Physique de l'état solide », Dunod, 1998.
2. Boch P., « Matériaux et processus céramiques », Hermès Science Publications, 2001.
3. Haussonne J.-M. et al., « Céramiques et verres, Principes et techniques d'élaboration », Traité des Matériaux, vol 16, Presses Polytechniques et Universitaires Romandes, 2005.
4. Cornet A.et Deville J.P, « Physique et Ingénierie des surfaces », Monographie de Matériologie, EDP Sciences, 1998
5. Gourgues-Lorenzon A. F. et Naze L., Matériaux pour l'ingénieur, comportement, endommagement et rupture par fatigue 2008.
6. Jefferson Andrew, J. Arumugam, V., Saravanakumar, K., Dhakal, H.N. and Santulli, C., 2015. Compression after impact strength of repaired GFRP composite laminates under repeated impact loading. Composite Structures, 133: 911-920.
7. Aggelopoulos, E.S., Righiniotis, T.D. and Chryssanthopoulos, M.K., 2014. Composite patch repair of steel plates with fatigue cracks growing in the thickness direction. Composite Structures, 108:729-735.

General Introduction

Conventional engineering materials metals, polymers, and ceramics each satisfy a limited set of performance requirements. Metals such as steel and aluminium alloys provide high strength and stiffness, but their elevated density penalises applications where weight reduction is critical. Polymers offer low density and good corrosion resistance, yet they cannot sustain the mechanical loads demanded by primary structural components. Ceramics withstand extreme temperatures but are inherently brittle and prone to catastrophic fracture under impact. This fundamental trade-off between competing properties drives the need for a different class of engineering materials capable of combining advantages that no single conventional material can deliver simultaneously [1], [3].

Composite materials address this need. A composite is an engineered material formed by combining two or more chemically distinct constituents at the macroscopic scale. These constituents remain physically identifiable within the final structure and do not dissolve into one another, yet they work together to produce enhanced or tailored properties unattainable by any constituent alone. This capacity for property combination enables composites to achieve high specific strength, high specific modulus, corrosion resistance, and thermal stability that surpass those of conventional metals and unreinforced polymers [3], [4].

The use of composite materials dates back thousands of years through natural examples such as wood, bone, and straw-reinforced mud bricks. Modern synthetic composites emerged in the 1930s with glass fibre reinforced polymers (GFRP), followed by higher-performance carbon and aramid fibre systems in the 1960s–1970s. The field has since expanded to include ceramic matrix composites, hybrid composites, and smart composites with embedded sensing capabilities [3], [5].

Today, composites are widely used in aerospace primary structures, automotive body panels, wind turbine blades, marine hulls, civil infrastructure retrofitting, sports equipment, and biomedical implants. Their growing adoption is driven by the demand for lightweight, durable, and efficient engineering solutions where reducing structural mass translates directly into improved performance and reduced operational cost [1], [4].

This course is organised in five chapters. Chapter 1 reviews the principal classes of engineering materials and the structure–property–processing–performance relationships. Chapter 2 defines composite materials, their constituents, and classification systems. Chapter 3 the physical and mechanical properties of composites. Chapter 4 covers the main manufacturing processes and associated quality control methods. Chapter 5 addresses material selection for practical engineering design.

Contents

Chapter 1: Generalities on Engineering Materials

Contents

1.1 Introduction to Materials Science

materials science investigates the relationship between the internal organization of a material (such as atomic bonding, crystal structure, and grain morphology) and its actual engineering behavior. This field relies on the interaction among four key variables represented by the "materials science tetrahedron": processing, structure, properties, and performance (Figure 1.1) [1], [2]. Consequently, selecting materials for engineering applications requires a careful balance between the material's properties, its operating conditions, and its manufacturing costs [1].

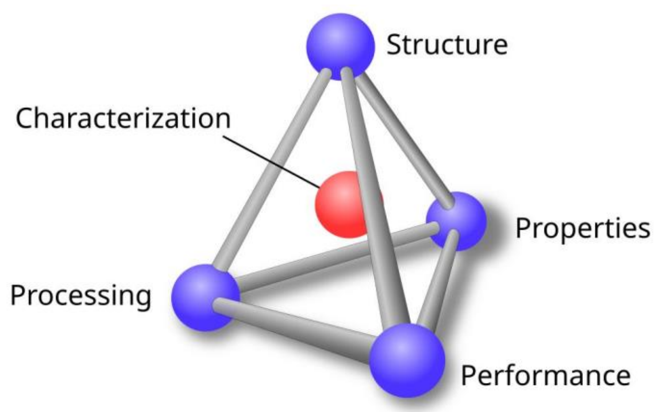


Figure 1.1 Materials Science Tetrahedron showing the interconnected relationship between Processing, Structure, Properties, and Performance

In composite materials engineering, this framework acquires additional complexity. The performance of a composite depends not only on the intrinsic properties of its constituents but also on design variables absent in monolithic materials: reinforcement type and form, volume fraction, stacking sequence, and interfacial bonding quality. This allows the engineer to construct the property set itself rather than select from pre-existing options [1], [3].

1.2 Classification of Engineering Materials

Engineering materials are commonly classified into four major families (Figure 1.2): metals and alloys, polymers, ceramics and glasses, and composite materials. This classification is based primarily on the nature of atomic bonding, chemical composition, and the resulting physical and mechanical properties [1], [2].

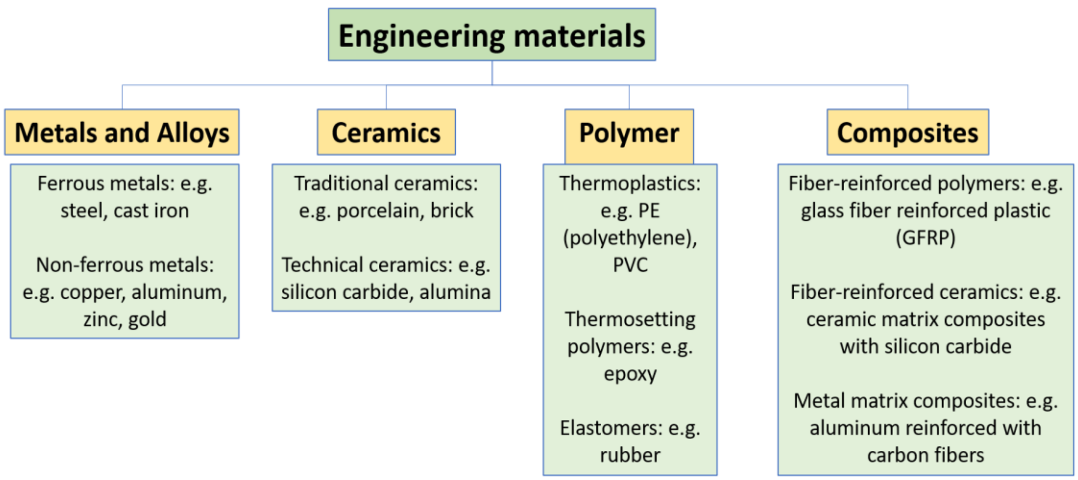


Figure 1.2 — General classification of engineering materials

Metals and alloys are held together by metallic bonding Figure 1.3, in which positively charged ions share a delocalised electron cloud. This structure gives metals their characteristic high strength, stiffness, electrical and thermal conductivity, and capacity for plastic deformation. Steel, aluminium alloys, and titanium alloys are the most widely used structural metals, though their relatively high

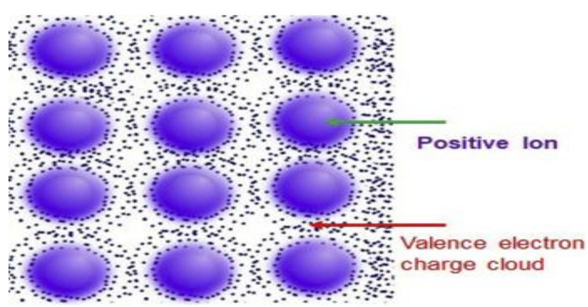


Figure 1.3 Metallic Bonding

density and susceptibility to corrosion remain persistent limitations [2].

Polymers consist of long molecular chains with strong covalent bonds along the backbone and weaker secondary bonds between chains Figure 1.4 . They offer low density, good chemical resistance, and ease of processing, but at significantly lower strength, stiffness, and operating temperatures compared with metals. They are classified as thermoplastics, which can be reshaped by reheating, or thermosets, which undergo irreversible cross-linking during curing [2].

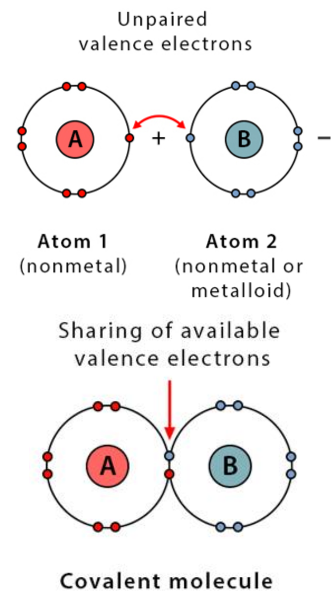


Figure 1.4 Covalent Bonding

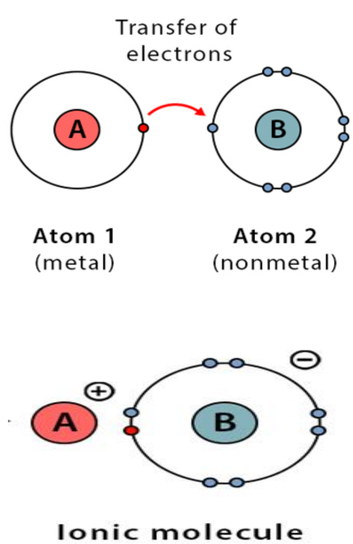


Figure 1.5 Ionic Bonding

Ceramics and glasses are formed by ionic or covalent bonding Figure 1.5, producing materials with high hardness, excellent thermal stability, and strong chemical resistance. They can operate at temperatures far exceeding the limits of metals and polymers; however, their inherent brittleness and low tolerance to tensile or impact loading restrict their use to applications where these weaknesses can be managed through design [1].

Composite materials combine constituents from two or more of the preceding families to achieve property combinations that no single material class can provide alone. Their position in this classification is unique because their properties are not fixed by composition alone but can be engineered through the selection of matrix and reinforcement types, their proportions, and the architecture of the reinforcement phase [1], [3].

1.3 Properties of Engineering Materials

The selection and application of engineering materials depend strongly on their physical, mechanical, thermal, electrical, and chemical properties. These properties describe how a material responds to external conditions and determine its suitability for a specific engineering application [1], [2].

A. Physical Properties

Physical properties describe the intrinsic characteristics of a material that are independent of applied loading or external fields [1], [2].

- **Density** is the mass per unit volume and directly influences the weight of structural components. As shown in Figure 1.6, engineering materials span a wide density range: metals such as steel (~7.8 g/cm^3) and aluminium (~2.7 g/cm^3) are considerably denser than polymers (~0.9–1.4 g/cm^3), which explains the growing interest in lightweight alternatives for transportation and aerospace applications.

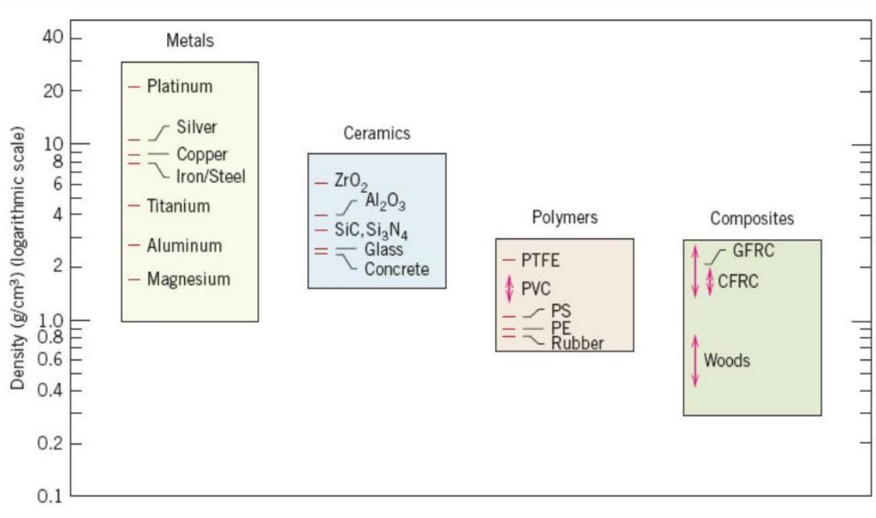


Figure 1.6 — Density ranges for the principal engineering material families.

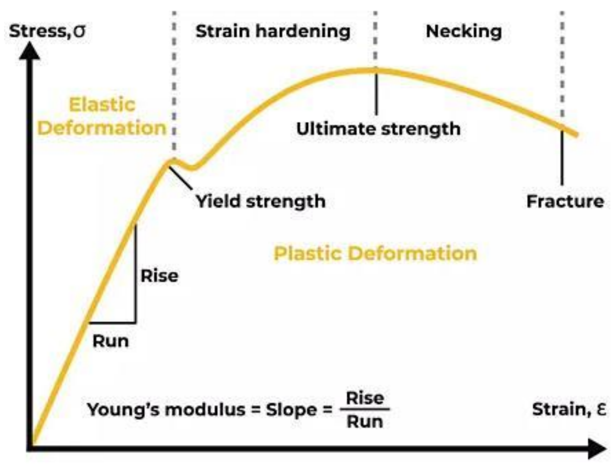
- **Melting point** determines the maximum temperature at which a material retains its solid-state integrity. Refractory ceramics and tungsten alloys melt above 2500 °C, whereas most thermoplastics soften below 300 °C [2].

B. Mechanical Properties

Mechanical properties characterise how a material responds to externally applied forces and are the primary criteria in structural design [2].

- **Strength** is the maximum stress a material can sustain before failure, measured under tension, compression, or shear depending on the service mode. As illustrated in Figure 1.7, the stress–strain curve provides valuable information about strength, stiffness, and ductility.

- **Stiffness**, quantified by the elastic modulus (Young's modulus), describes the resistance to elastic deformation; the slope of the linear elastic region shown in Figure 1.7 corresponds to the elastic modulus of the material.



Tensile test results.

Figure 1. 7— Stress–strain behaviour and mechanical testing of engineering materials.

- **Toughness** is the total energy absorbed before fracture and reflects the combined effect of strength and ductility. As shown in Figure 1.8, ceramics exhibit high strength but fail abruptly with minimal plastic deformation (brittle fracture), whereas metals such as low-carbon steel undergo significant plastic deformation before failure (ductile fracture), resulting in considerably higher toughness. Unreinforced polymers, by contrast, display large strains at relatively low stress levels, with toughness that varies widely depending on the polymer type and testing conditions

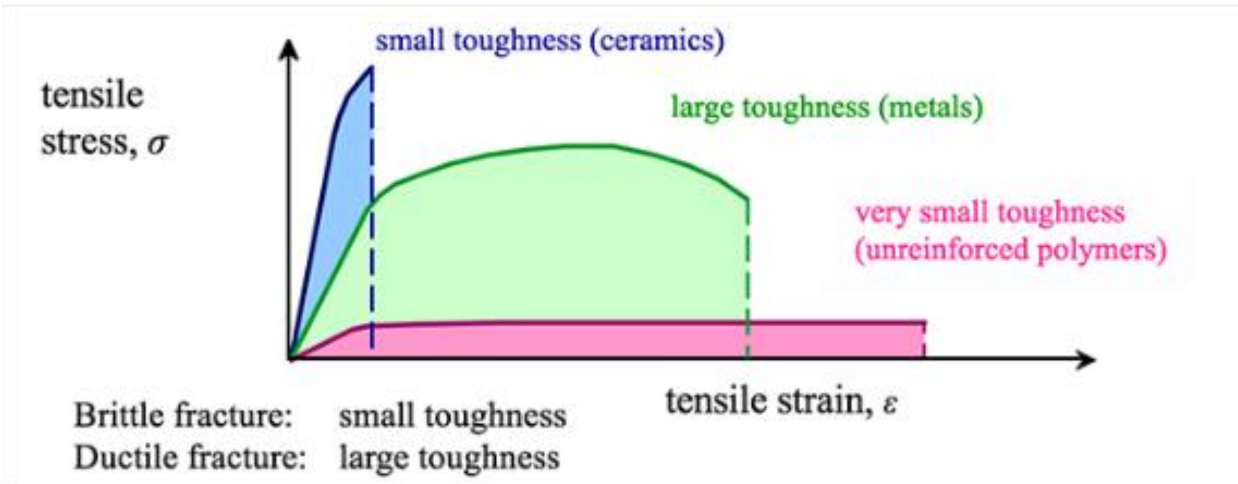


Figure 1.8 Comparative stress–strain curves for ceramics, metals, and unreinforced polymers, illustrating the contrast between brittle and ductile fracture behaviour.

- **Hardness** measures resistance to localised surface deformation and correlates directly with wear resistance *Figure 1.9*.

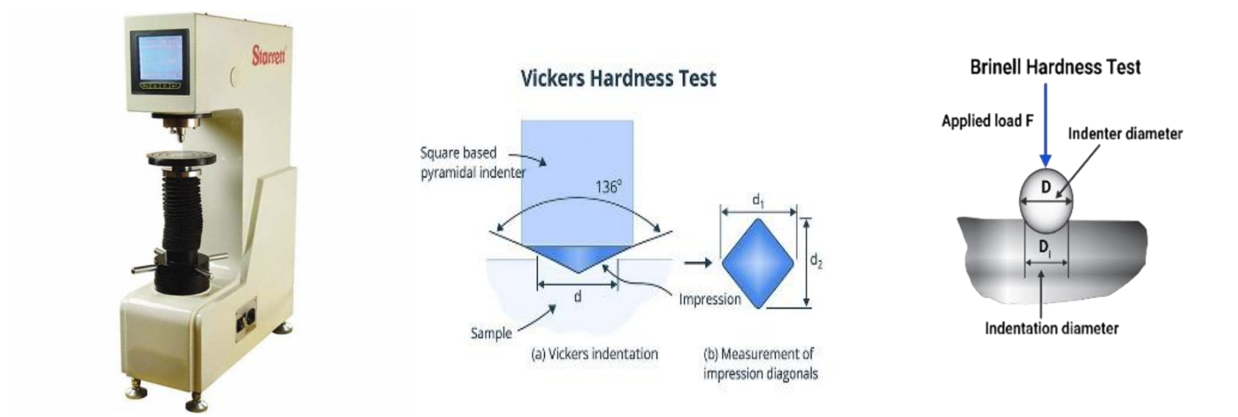


Figure 1.9 Common hardness testing methods used in materials engineering.

- **Fatigue resistance** describes the ability of a material to endure repeated cyclic loading without crack initiation and propagation to failure. As illustrated in Figure 1.10, the S–N curve (stress versus number of cycles) characterises the fatigue behaviour of a material: some metals, such as steel, exhibit a distinct endurance limit below which failure does not occur, whereas aluminium alloys and most polymers show a continuous decline in allowable stress with increasing cycle count.rotating shafts, bridges, and mechanical springs [2].

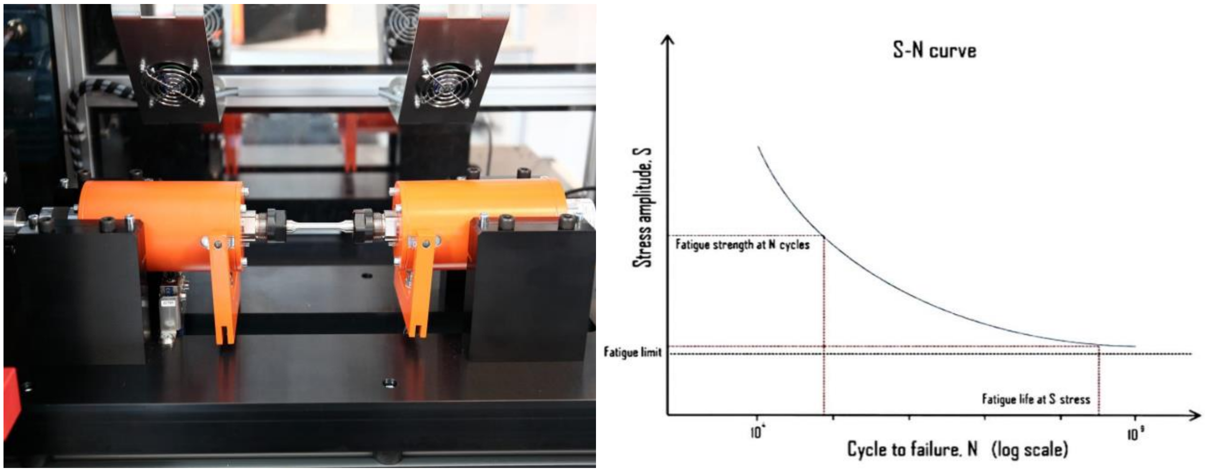


Figure 1.10 Typical S–N fatigue curves and rotating beam fatigue testing setup.

C. Thermal Properties

Thermal properties govern how a material responds to temperature variations and heat flow [1].

- **Thermal conductivity** quantifies the rate of heat transfer under a temperature gradient. As shown in Figure 1.11.

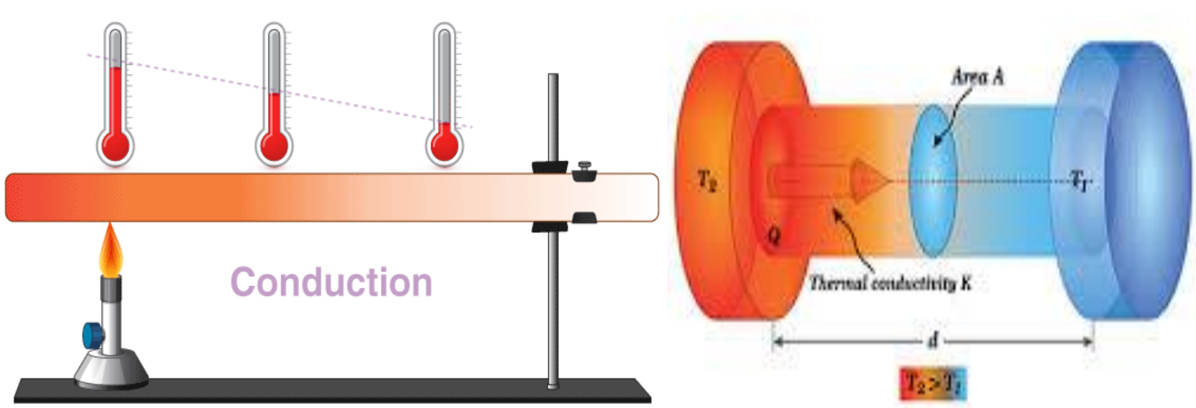


Figure 1.11 Thermal conductivity.

- **Thermal stability** refers to the ability of a material to retain its properties at elevated temperatures. Ceramics maintain structural integrity well above 1000 °C, whereas most polymers degrade between 100 °C and 300 °C *Figure 1.11*.

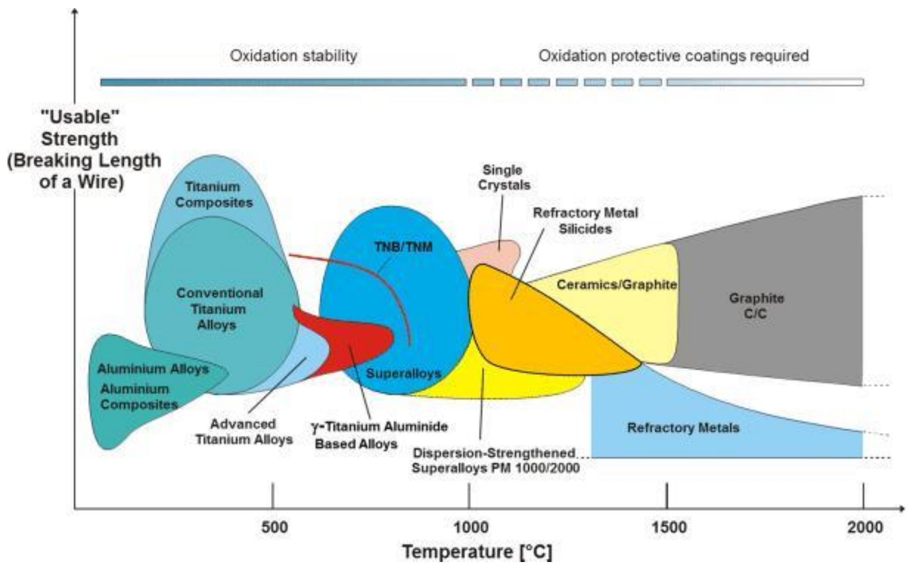


Figure 1.11 — Temperature operating limits for the principal engineering material families.

- **Thermal expansion** is the dimensional change caused by temperature variation *Figure 1.12*. Mismatched expansion coefficients between joined materials can generate internal stresses leading to distortion or interfacial failure [1].

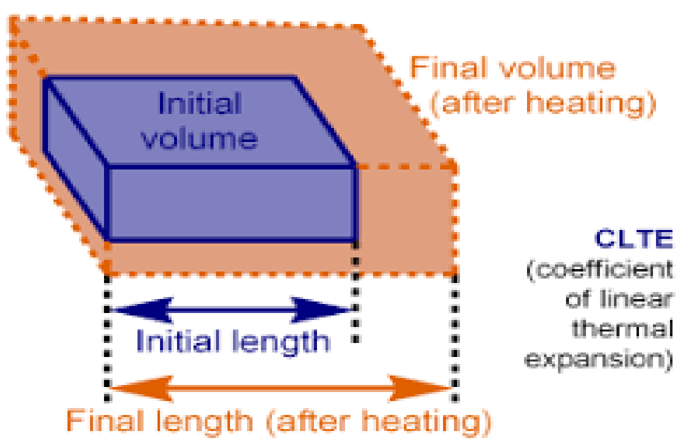


Figure 1.12 — Thermal expansion

D. Electrical Properties

Electrical properties define how a material interacts with electric fields and current flow [2].

- **Electrical conductivity** measures the capacity to transport charge carriers,
- **electrical resistivity** quantifies the opposition to that transport.

As shown in Figure 1.13, these properties span a vast range across material families: metals exhibit high conductivity ,semiconductors occupy an intermediate range, and ceramics and polymers function as electrical insulators.

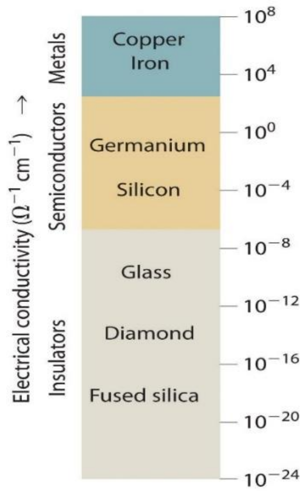


Figure 1.13 — Electrical conductivity spectrum for metals, semiconductors, and insulators.

- **Dielectric behaviour** describes the response of a non-conducting material to an applied electric field and determines its suitability as an electrical insulator or capacitor medium. This property is particularly relevant in electronic packaging, power transmission insulation, and sensor applications *Figure 1.14*.

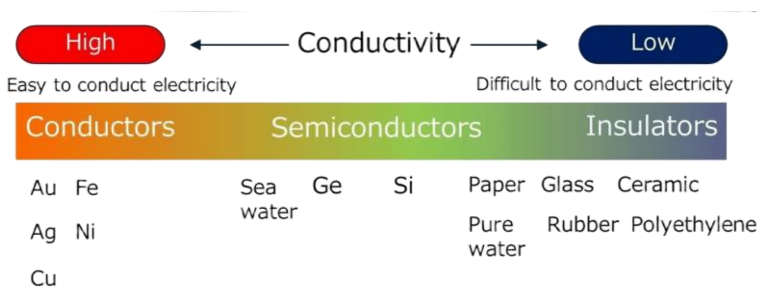


Figure 1.14 — Classification of materials based on electrical behaviour: conductors, semiconductors, and insulators.

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].

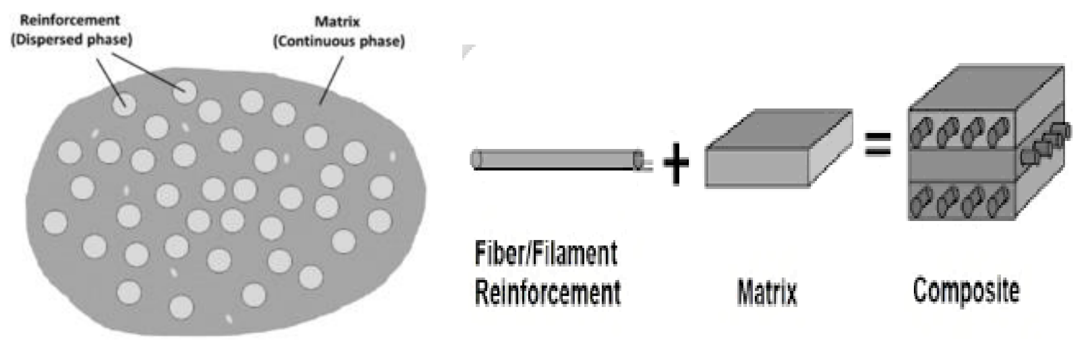


Figure 2.1 Typical structure of a composite material showing matrix and reinforcement phases.

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].

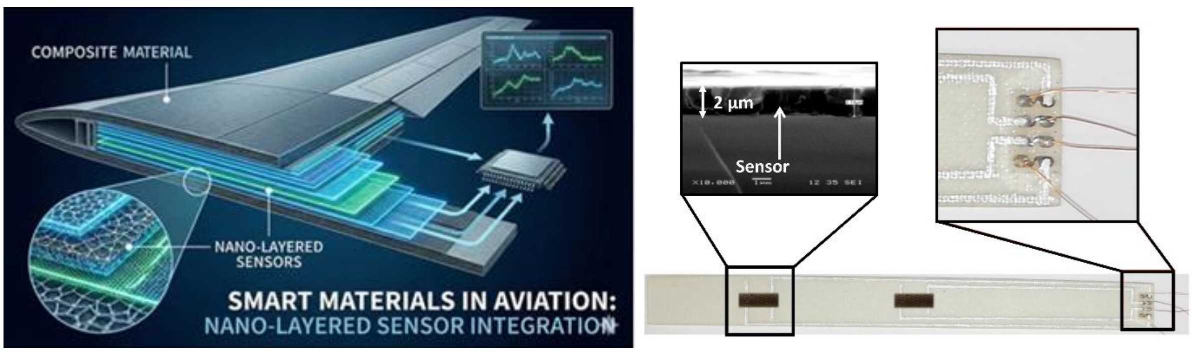


Figure 2.5 Examples of advanced composite systems.

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].

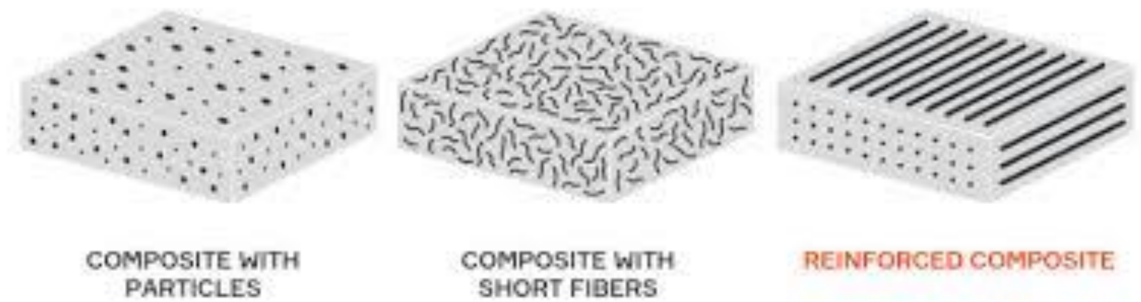


Figure 2.6 Reinforcement forms in composite materials

- **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/cm^3. 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/cm^3). 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.

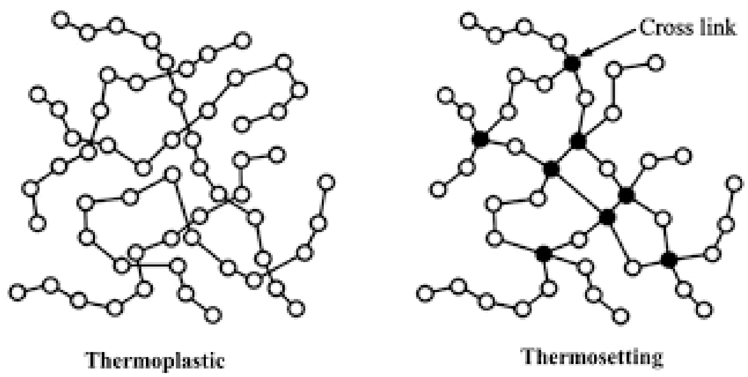


Figure 2.8 Molecular structure comparison: thermoset (cross-linked network) versus thermoplastic (linear chains).

- **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].

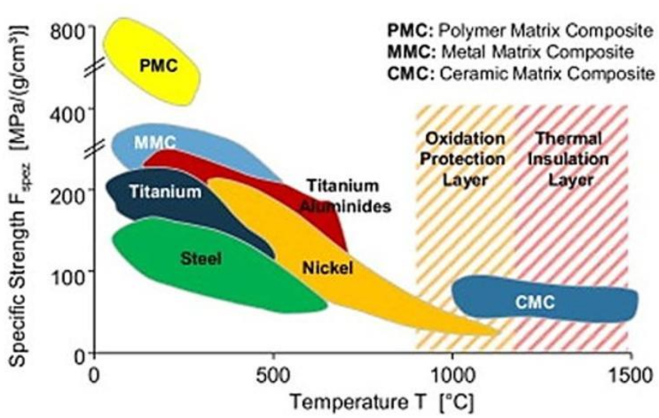


Figure 2.9 Operating temperature ranges for polymer, metal, and ceramic matrix composites.

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].

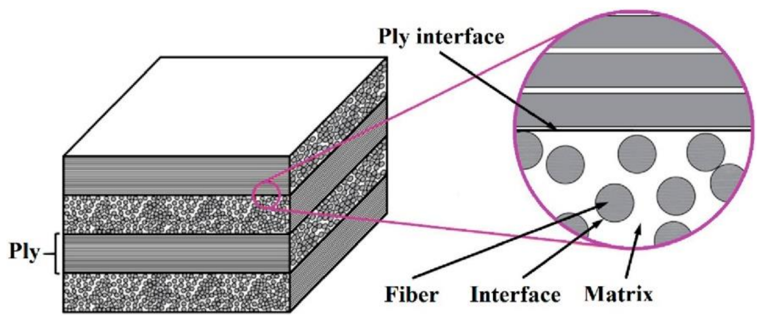


Figure 2.9 Fibre/matrix interface: stress transfer mechanisms and the effect of interface strength on fracture behaviour.

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].

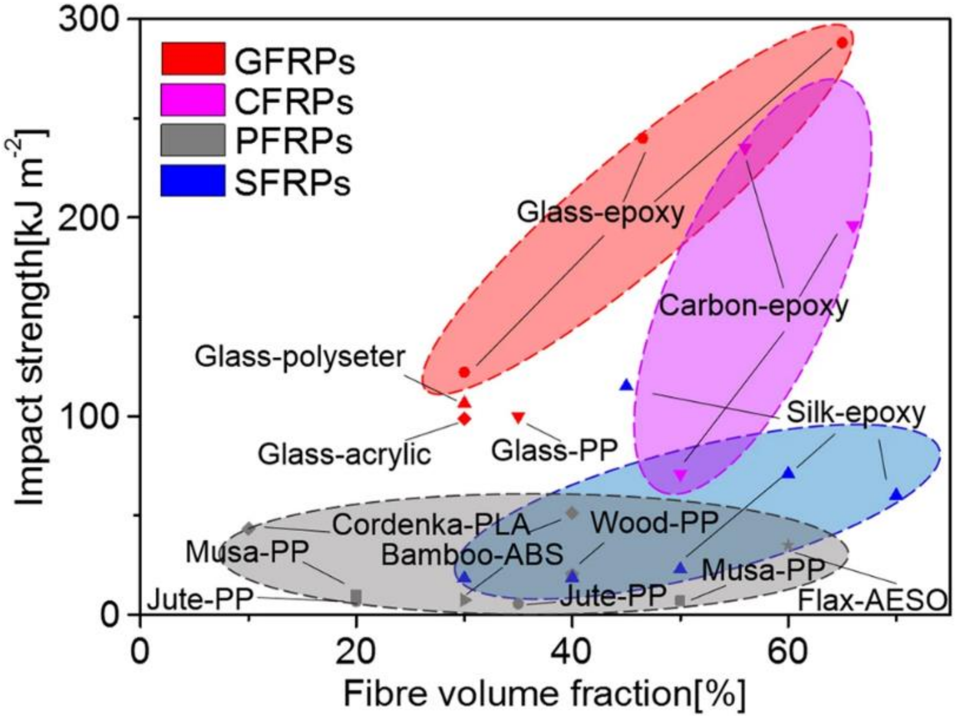


Figure 2.10 Effect of fibre volume fraction on stiffness and strength of a unidirectional composite.

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].

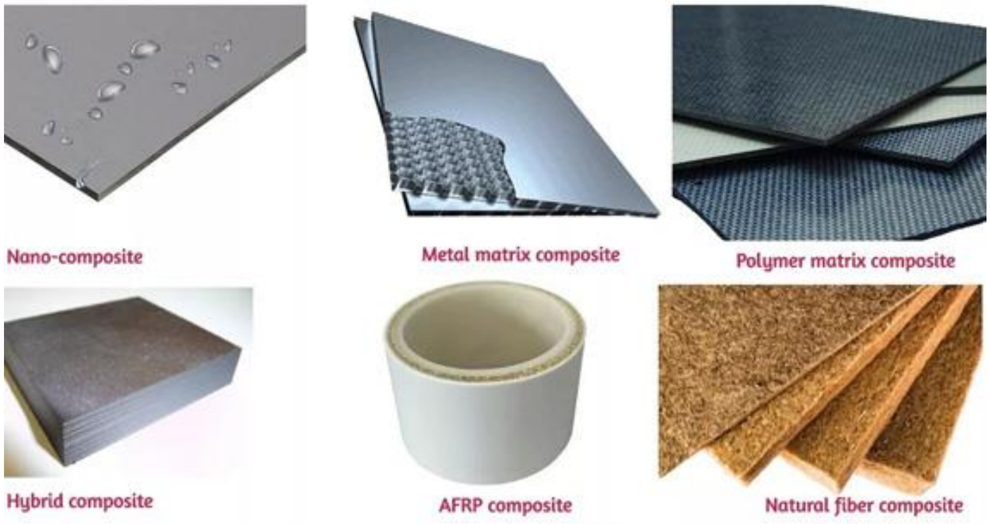


Figure 2.11 The principal composite classes

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].

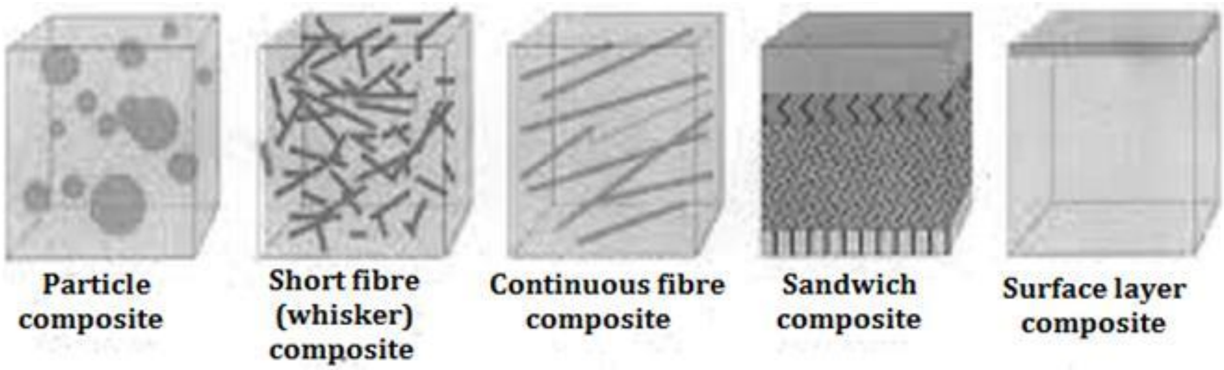


Figure 2.12 — Composite reinforcement architectures

Chapter 3: Properties and Characteristics of Composite Materials

Contents

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].

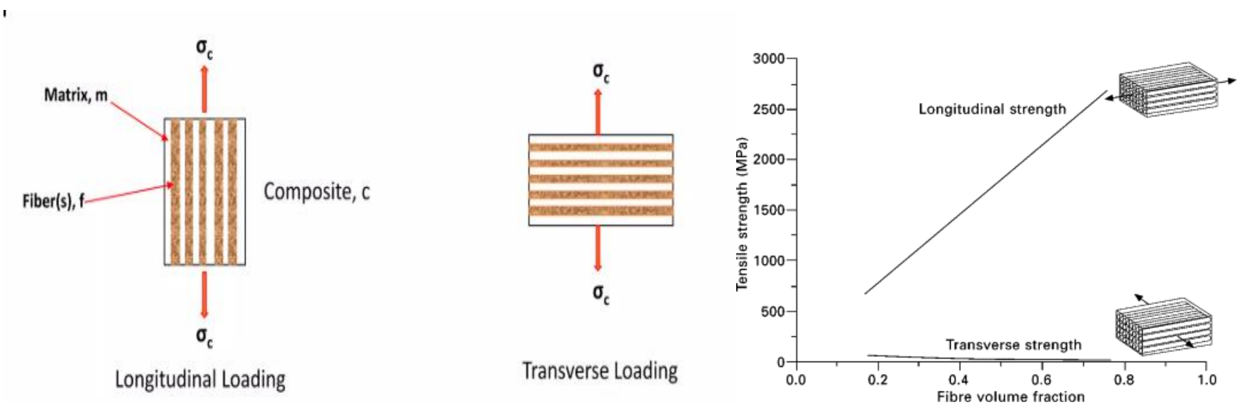


Figure 3.1 — Directional dependence of strength in a unidirectional composite: longitudinal versus transverse loading.

B. Stiffness

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

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

- E^1 = longitudinal modulus,
- E_f = fibre modulus,
- E_m = matrix modulus,
- V_f= fibre volume fraction,
- V_m = matrix volume fraction.

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

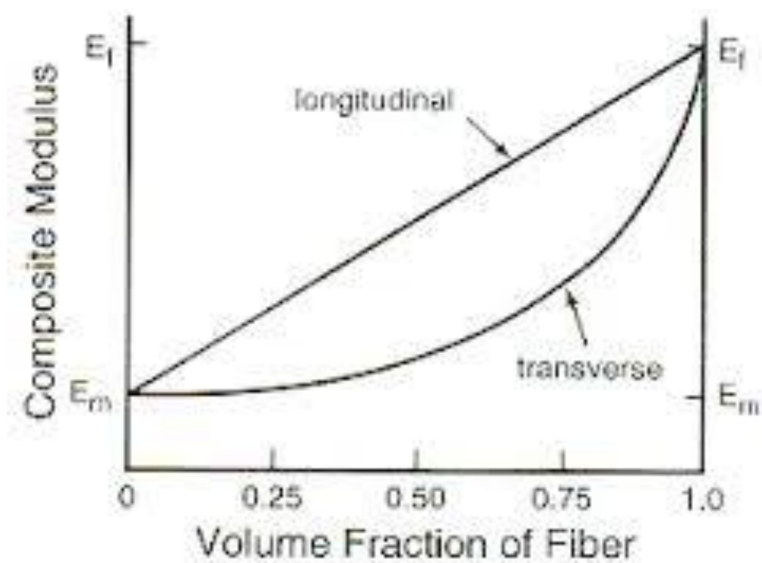


Figure 3.2 — Longitudinal and transverse elastic modulus as a function of fibre volume fraction.

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].

Chapter 4: Manufacturing Processes of Composite Materials

Contents

Introduction

The manufacturing process determines not only the shape of a composite component but also its internal quality fibre volume fraction, void content, fibre alignment, and interfacial bonding all of which directly govern mechanical performance. Selecting an appropriate process requires matching the matrix and reinforcement type, component geometry, production volume, and required quality level to the capabilities and constraints of available techniques [10], [11].

This chapter presents the principal manufacturing methods organised by increasing process complexity and automation, followed by common manufacturing defects and quality control methods.

4.1 Open-Mould Processes

Open-mould processes are the simplest composite manufacturing methods, in which the reinforcement and matrix are combined on an open mould surface without external pressure from a matched mould. They offer low tooling cost and geometric flexibility but provide limited control over fibre content and part consistency [11], [9].

A. Hand Lay-Up

Hand lay-up is the most basic composite fabrication technique. Reinforcement layers are placed onto a mould surface and manually impregnated with liquid resin using rollers or brushes. The laminate cures at ambient temperature or under controlled thermal conditions [11].

The simplicity of this process low equipment cost, no size limitation, and suitability for complex geometries makes it widely used for prototypes, low-volume production, and large structures such as boat hulls. Its principal limitations are low production rate, dependence on operator skill, and variability in fibre volume fraction and void content between parts [11].

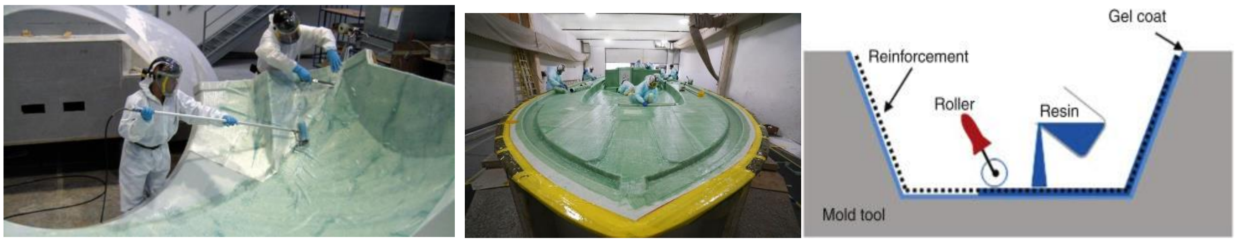


Figure 4.1 Schematic illustration of the hand lay-up process.

B. Vacuum Bagging

Vacuum bagging improves upon hand lay-up by sealing a flexible membrane over the laminate and applying vacuum pressure. The vacuum extracts entrapped air, compacts the laminate, and improves fibre wet-out, producing lower void content and more consistent mechanical properties than hand lay-up alone [9].

This technique is widely employed in aerospace and high-performance applications where the quality improvement over basic hand lay-up justifies the additional processing step, but full autoclave consolidation is not required [9].

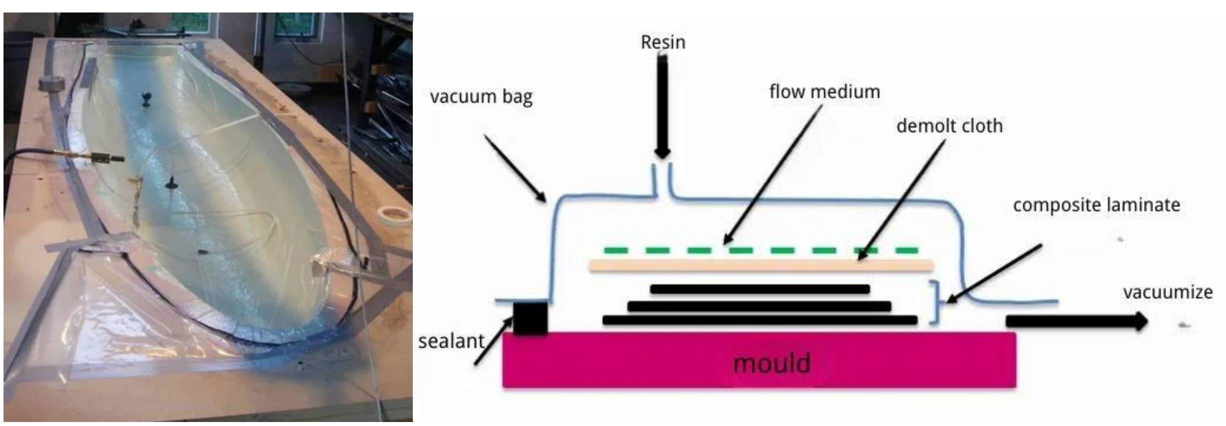


Figure 4.2 Schematic illustration of the vacuum bagging process.

4.2 Closed Mould Processes

Closed mould processes use matched moulds or sealed systems to apply controlled pressure during manufacturing, providing improved dimensional accuracy, surface finish, and fibre content control compared with open mould methods [10], [11].

A. Resin Transfer Moulding (RTM)

In RTM, dry fibre preforms are placed into a rigid mould cavity, the mould is closed, and liquid resin is injected under controlled pressure to impregnate the reinforcement. This approach provides good control over fibre volume fraction, consistent part quality, and reduced void content compared with open mould processes. RTM is suited to moderate complexity structural parts in automotive, aerospace, and marine applications, though tooling costs are higher than for open mould methods [10].

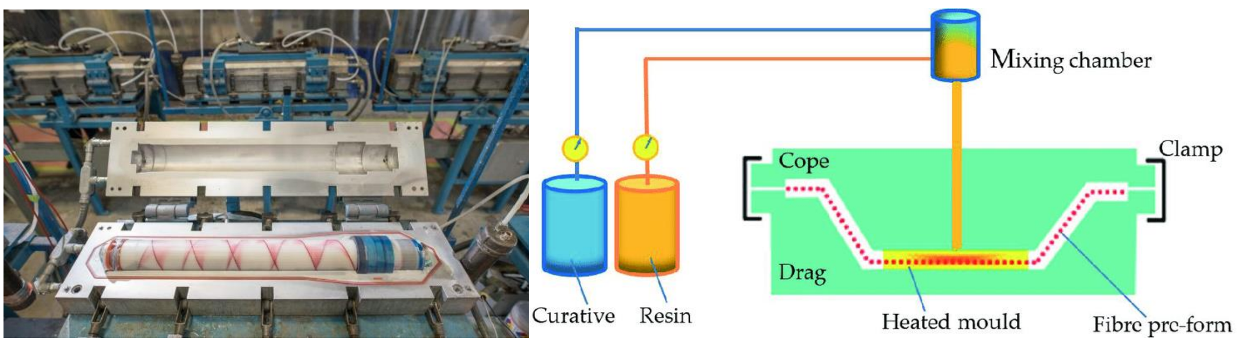


Figure 4.3 Schematic illustration of the RTM process.

B. Vacuum Assisted Resin Infusion (VARI)

VARI uses vacuum pressure rather than positive injection pressure to draw resin through dry reinforcement placed on an open mould sealed with a flexible membrane. This reduces tooling cost relative to RTM and is particularly suited to large components such as wind turbine blades, marine hulls, and infrastructure elements. The trade off is longer cycle time and less precise control over fibre volume fraction [11].

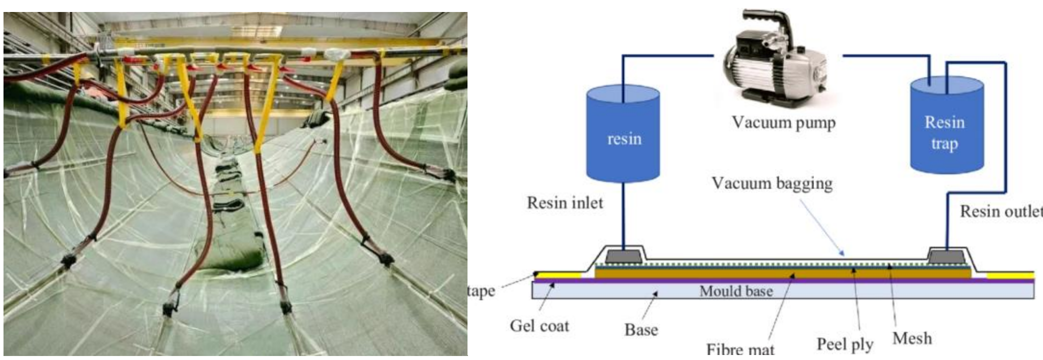


Figure 4.4 Schematic illustration of the VARI process.

C. Injection Moulding (SMC/BMC)

Injection moulding processes manufacture composite parts reinforced with short fibres or particulate fillers at high production rates. Two material forms are processed by this route: **Sheet Moulding Compound (SMC)**, pre impregnated sheets of chopped fibres compression moulded under heat and pressure, and **Bulk Moulding Compound (BMC)**, a dough like mixture of short fibres and resin injected or compression moulded into a heated cavity [10], [11].

These processes offer high dimensional accuracy, good surface finish, and cost effectiveness for mass production. The principal limitation is restriction to short fibre reinforcement, which produces lower mechanical performance than continuous fibre composites. SMC/BMC moulding is widely used in automotive and electrical industries for structural and semi structural components [10].

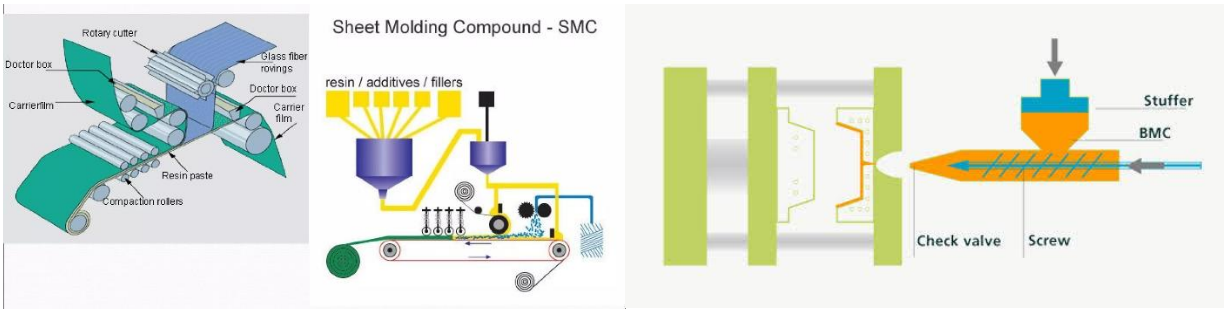


Figure 4.5 Schematic illustration of SMC/BMC injection moulding.

4.3 Continuous and Semi Automated Processes

Continuous processes produce composite components with constant cross sections or controlled fibre placement at high efficiency, combining automated fibre handling with continuous curing [5], [9].

A. Pultrusion

Pultrusion produces composite profiles with constant cross section by pulling continuous fibres through a resin bath, then through a heated die that shapes and cures the composite in a single continuous operation. The cured profile is cut to length as it exits the die [5].

This process achieves consistent fibre alignment, high volume fraction, and good longitudinal mechanical properties at high production rates. It is restricted, however, to components with uniform cross section — beams, rods, channels, and structural profiles for civil engineering and industrial applications [5].

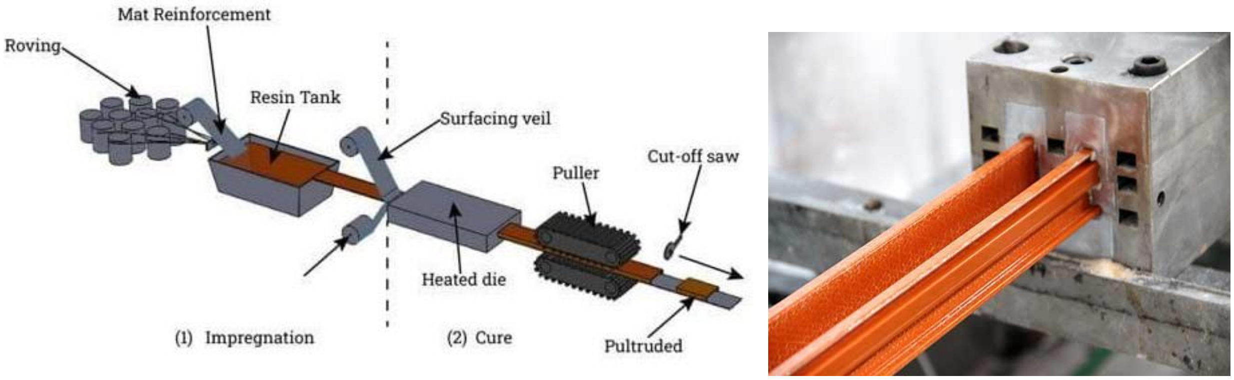


Figure 4.6 Schematic illustration of the pultrusion process.

B. Filament Winding

Filament winding is a semi automated process in which continuous resin impregnated fibre tows are wound onto a rotating mandrel at controlled angles following a predetermined pattern. The wound structure is then cured and the mandrel removed [9].

The process provides precise control over fibre orientation and achieves high fibre volume fractions, making it the standard method for manufacturing pressure vessels, pipes, rocket motor casings, and cylindrical storage tanks. Its principal limitation is restriction to primarily convex and axially symmetric geometries [9].

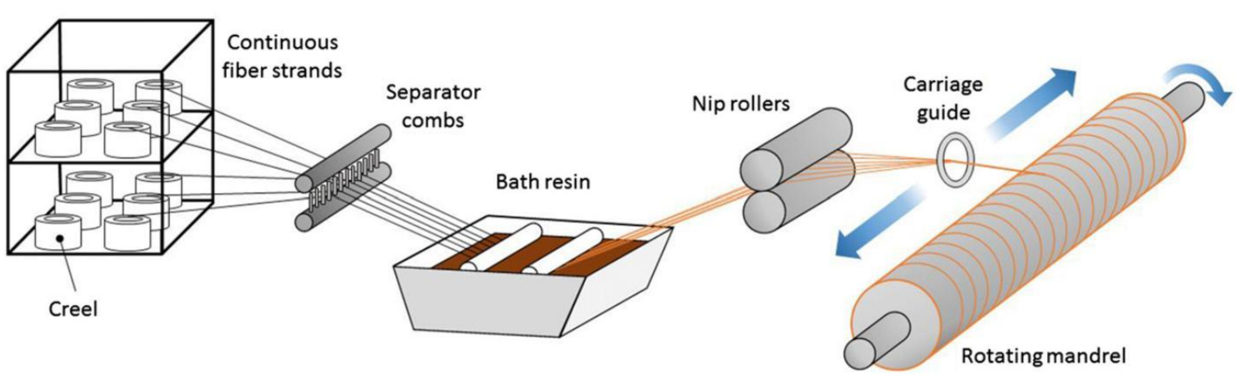


Figure 4.7 Schematic illustration of the filament winding process.

4.4 Modern Industrial Techniques

Modern manufacturing techniques improve production efficiency, reproducibility, and the capability to produce complex geometries beyond the reach of conventional methods [10], [11].

A. Automated Fibre Placement (AFP)

AFP is a computer-controlled process in which a robotic head places narrow strips of pre impregnated fibre (prepreg tapes or tows) onto a mould surface with high positional precision. The process offers precise fibre orientation control, reduced material waste, and the ability to manufacture large complex curved structures such as fuselage sections and wing skins. The principal barrier is high capital investment and the need for advanced programming and process control [10].

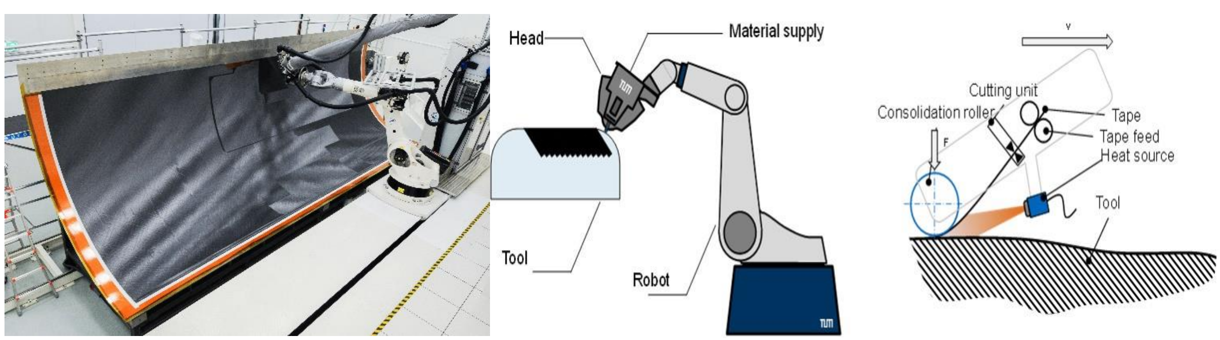


Figure 4.8 Automated Fibre Placement (AFP) robotic system.

B. Prepreg Processing

Prepreg processing uses pre impregnated reinforcement layers — fibres already combined with a controlled amount of partially cured resin — which are laid onto a mould in the required orientation and stacking sequence, then consolidated under heat and pressure, typically in an autoclave [11].

This method provides the most precise control over resin content and fibre volume fraction among all composite manufacturing techniques, producing high quality laminates with minimal void content and consistent mechanical properties. It is the standard method for high performance aerospace and motorsport structures. The trade offs are high material and processing cost, and the requirement for refrigerated storage to prevent premature curing of the prepreg material [11].

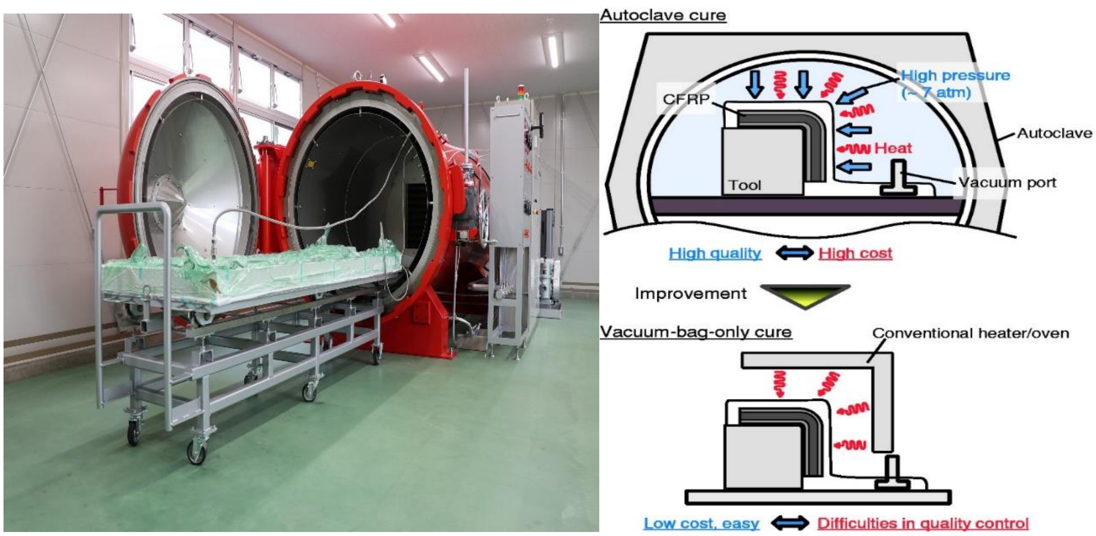


Figure 4.9 Prepreg lay up and autoclave curing process.

C. Additive Manufacturing of Composites (3D Printing)

Additive manufacturing enables composite part fabrication by depositing material layer by layer from a digital model. The two principal approaches are **Fused Deposition Modelling (FDM)**, which extrudes thermoplastic filaments reinforced with short fibres, and **Continuous Fibre Printing**, which deposits continuous fibres within a thermoplastic matrix during the printing process [10].

The technology offers high design freedom, rapid prototyping capability, and reduced material waste. Current limitations include lower mechanical performance compared with conventional methods, restricted build volume, and a limited range of compatible materials. Additive manufacturing is an active area of development with growing applications in aerospace, biomedical, and custom engineering components [10].

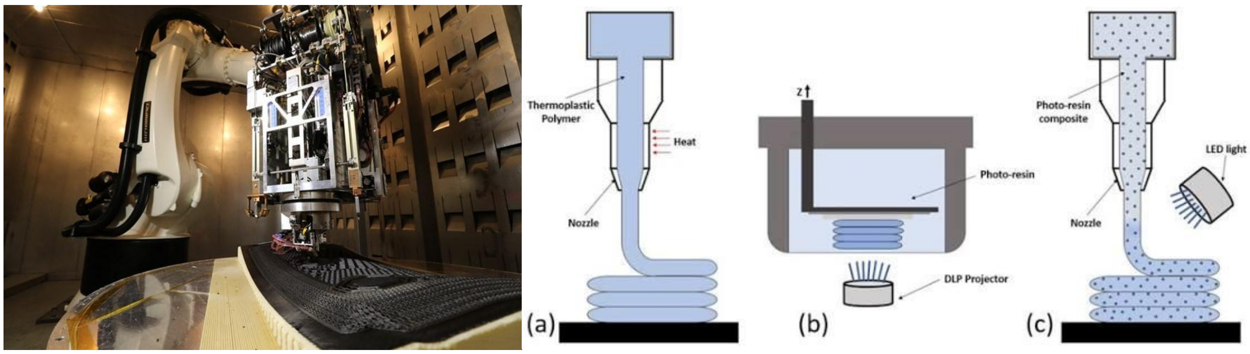


Figure 4.10 Additive manufacturing of composite materials.

4.5 Manufacturing Defects and Quality Control

The manufacturing process significantly affects the structural reliability of composite components. Defects introduced during processing can degrade mechanical performance and compromise service life [4], [10].

A. Common Manufacturing Defects

The principal defects encountered in composite manufacturing are:

- **Voids** entrapped air or gas pockets within the laminate that reduce mechanical strength and interfacial stress transfer efficiency. Void content is influenced directly by the consolidation pressure and degassing effectiveness of the manufacturing process.
- **Fibre misalignment** deviation from the intended fibre orientation, which reduces strength and stiffness in the designed loading direction. This defect is particularly critical in processes relying on manual fibre placement.

- **Incomplete curing** insufficient or non-uniform resin cross linking, leading to reduced mechanical properties and dimensional instability. It results from inadequate temperature control or premature interruption of the cure cycle.
- **Weak interfacial bonding** insufficient adhesion between reinforcement and matrix, reducing stress transfer efficiency and promoting premature failure under loading [4], [10].

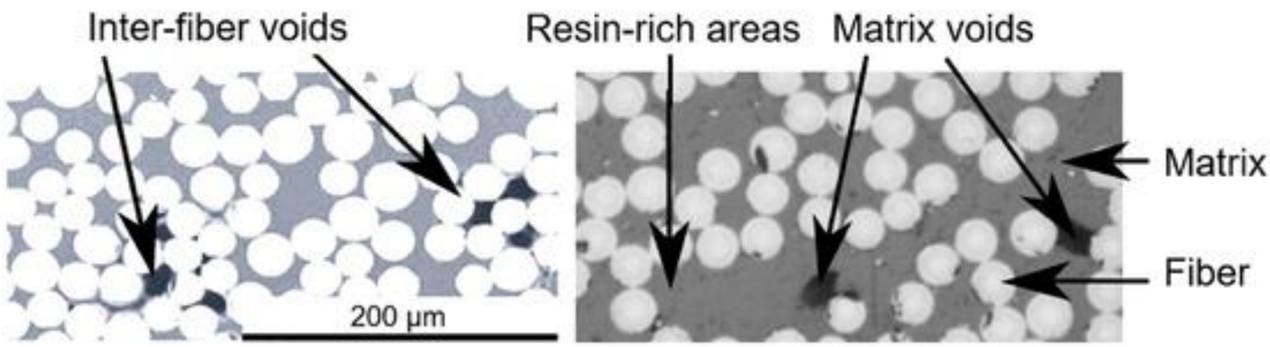


Figure 4.11 Common manufacturing defects in composite laminates: voids, fibre misalignment, incomplete curing, and interfacial debonding.

B. Quality Control and Inspection

Quality control methods verify that composite components conform to specified performance and reliability standards. Process monitoring tracks key parameters — temperature, pressure, and cure cycle duration — during manufacturing. Visual inspection identifies surface defects in finished components [11].

For internal defects that are not visible on the surface, Non-Destructive Testing (NDT) techniques are employed:

- **Ultrasonic inspection** detects delamination's, voids, and variations in laminate thickness by analyzing the propagation of sound waves through the material.
- **X ray inspection** reveals internal voids, fibre misalignment, and foreign inclusions.
- **Infrared thermography** identifies subsurface defects by detecting thermal anomalies on the component surface during controlled heating [11].

Quality control is essential in aerospace and high-performance applications where undetected defects can lead to catastrophic structural failure during service [11].

Figure 4.12 Non-destructive testing methods for composite inspection

Chapter 5: Material Selection

Contents

Introduction

The selection of composite materials for engineering applications requires a systematic evaluation that connects service requirements, material capabilities, manufacturing constraints, and economic factors into a coherent decision framework. This chapter presents the principal concepts and methods used in composite material selection, from defining functional requirements through multi-criteria evaluation to practical case studies and repair considerations [1], [3].

5.1 Service Properties and Functional Compatibility

The first step in material selection is to identify the properties the component needs during its operational life. These typically include [1], [3]:

- **Mechanical:** strength, stiffness, fatigue resistance, and impact tolerance.
- **Thermal:** thermal stability, conductivity, and resistance to elevated temperatures.
- **Chemical:** corrosion resistance and compatibility with the operating environment.
- **Physical:** density, dimensional stability, and surface finish.
- **Durability:** long-term performance under sustained loading, environmental exposure, and ageing.

Once these requirements are defined, the engineer matches them against available materials. This process asks four basic questions [1]:

- What is the component's primary function?
- What type of loading will it experience?
- What environment will it operate in? How long must it last?

Composites hold a particular advantage at this stage because their properties are not fixed they can be adjusted by changing the matrix, the reinforcement type, the fibre direction, or the layer stacking sequence to match the specific needs of the application [3].

5.2 Material–Process Compatibility

A material that meets all functional requirements may still be unsuitable if no manufacturing process can shape it into the required geometry at reasonable cost. Hand lay-up and VARI are suited to large simple shapes using thermoset matrices with glass or carbon fibres. RTM handles moderate-complexity parts with fibre preforms, while SMC/BMC injection moulding produces complex high-volume components using short-fibre reinforcement. Pultrusion is restricted to constant cross-section profiles with continuous fibres, and filament winding to axially symmetric geometries. AFP and prepreg processing accommodate large curved structures using either thermoset or thermoplastic matrices with continuous fibres. Additive manufacturing works with thermoplastic matrices and short or continuous fibres for complex low-volume parts [10], [11].

5.3 Multi-Criteria Selection

In practice, no material is best in every category. A material may be strong but expensive, or light but difficult to manufacture. Multi-criteria methods help engineers weigh these trade-offs systematically [1].

A. Ashby Charts

Ashby charts are graphs that plot one property against another for example, stiffness versus density. Each material occupies a region on the chart, and the engineer draws a selection line representing the design target. Materials above the line meet the requirement; those below do not. This visual approach makes it easy to compare dozens of materials at a glance and to identify which composites outperform metals for a given design objective [1].

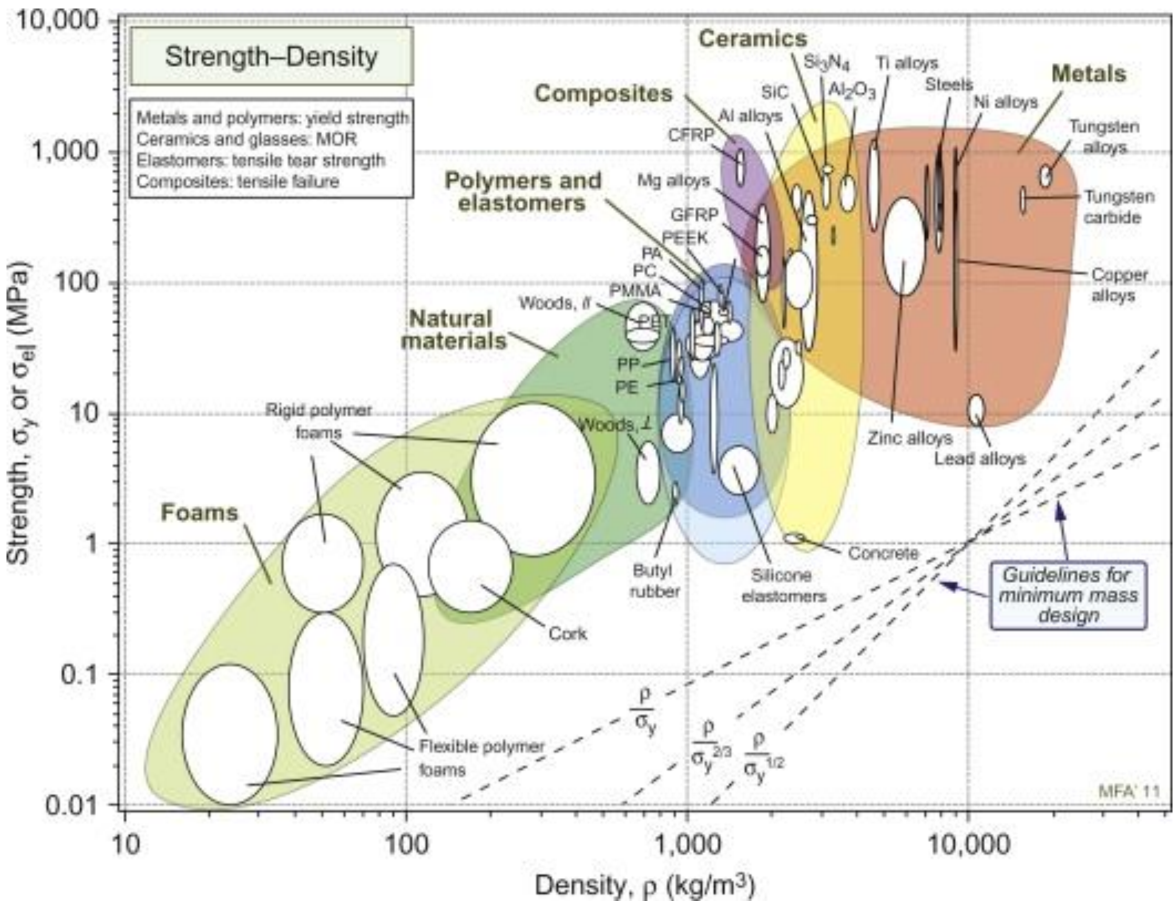


Figure 5.2 Ashby chart: strength-density, showing where composites, metals, and polymers fall.

B. Weighted Scoring Method

When several criteria matter at the same time, a scoring method can be used:

- List the criteria that matter (strength, density, cost, corrosion resistance, etc.).
- Give each criterion a weight reflecting how important it is for this particular application.
- Score each candidate material on every criterion.
- Multiply each score by its weight and add the results.
- The material with the highest total score is the best overall candidate.

This approach forces the engineer to make priorities explicit rather than relying on intuition [1], [7].

5.4 Aluminium Alloys versus CFRP Composites

The choice between aluminium and CFRP is one of the most common selection decisions in modern structural engineering. CFRP offers significantly lower density (~1.6 versus ~2.7 g/cm^3), higher specific strength and specific modulus, inherent corrosion resistance without surface treatment, and superior fatigue performance. Aluminium, however, retains advantages in manufacturing cost, recyclability, damage visibility surface damage in metals is immediately apparent whereas internal damage in composites may remain undetected and repairability through conventional techniques rather than the specialised methods composites require [1], [3], [7].

In aerospace, CFRP has progressively replaced aluminium in primary structures because the weight savings reduce fuel consumption significantly. The Boeing 787 and Airbus A350 are both over 50% composite by structural weight. Aluminium remains the better choice when cost, easy inspection, and simple repair are the priorities [1], [7].

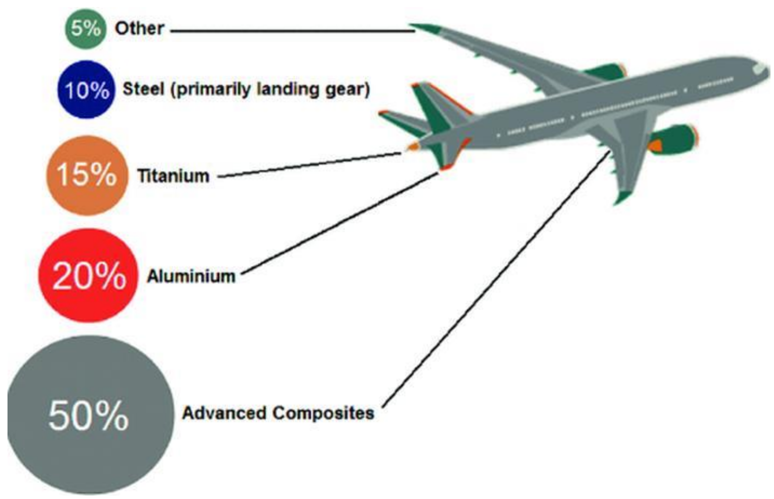


Figure 5.3 Composite content evolution in commercial aircraft structures.

5.5 Reinforcement and Repair of Damaged Structures

A. Structural Reinforcement

Composite patches and laminates (CFRP or GFRP) can be bonded onto the outside of existing structures concrete beams, bridge columns, metallic frames to restore or increase their load-carrying capacity. This technique is widely used for seismic retrofitting and for extending the life of ageing infrastructure [4], [15].

B. Repair of Composite Structures

When a composite component is damaged in service, three main repair methods are available:

- **Patch repair:** a composite patch is bonded over the damaged area simple and effective for surface damage.

- **Scarf repair:** the damaged zone is cut away at a tapered angle and replacement layers are bonded in this gives better load transfer and is used for structural repairs.
- **Injection repair:** resin is injected into delaminated zones to re-bond the separated layers used for internal damage that has not broken through the surface [3], [15].

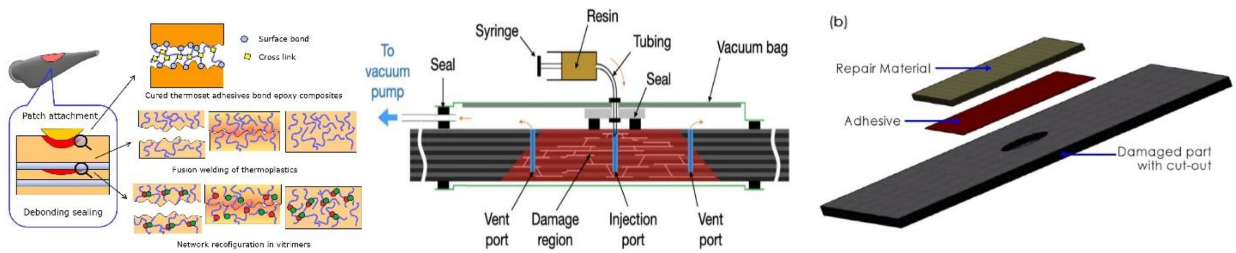


Figure 5.2 The three composite repair methods: patch, scarf, and injection.

The choice of method depends on how severe the damage is, whether the area is accessible, how critical the component is structurally, and how much strength needs to be restored [3], [15].

References

[1] M. F. Ashby, Materials Selection in Mechanical Design, 5th ed., Oxford, UK: Butterworth-Heinemann, 2016.

[2] W. D. Callister Jr. and D. G. Rethwisch, Materials Science and Engineering: An Introduction, 10th ed., Hoboken, NJ, USA: John Wiley & Sons, 2018.

[3] K. K. Chawla, Composite Materials: Science and Engineering, 4th ed., New York, NY, USA: Springer, 2019.

[4] D. Hull and T. W. Clyne, An Introduction to Composite Materials, 2nd ed., Cambridge, UK: Cambridge University Press, 1996.

[5] R. M. Jones, Mechanics of Composite Materials, 2nd ed., Boca Raton, FL, USA: CRC Press, 2018.

[6] I. M. Daniel and O. Ishai, Engineering Mechanics of Composite Materials, 2nd ed., New York, NY, USA: Oxford University Press, 2006.

[7] F. L. Matthews and R. D. Rawlings, Composite Materials: Engineering and Science, Boca Raton, FL, USA: CRC Press, 1999.

[8] D. R. Askeland and W. J. Wright, The Science and Engineering of Materials, 7th ed., Boston, MA, USA: Cengage Learning, 2016.

[9] A. B. Strong, Fundamentals of Composites Manufacturing: Materials, Methods, and Applications, 2nd ed., Dearborn, MI, USA: Society of Manufacturing Engineers, 2008.

[10] P. K. Mallick, Fiber-Reinforced Composites: Materials, Manufacturing, and Design, 3rd ed., Boca Raton, FL, USA: CRC Press, 2007.

[11] S. K. Mazumdar, Composites Manufacturing: Materials, Product, and Process Engineering, Boca Raton, FL, USA: CRC Press, 2002.

[12] J.-M. Berthelot, Matériaux composites : Comportement mécanique et analyse des structures, 5e éd., Paris, France: Lavoisier, 2012.

[13] D. Gay, Matériaux composites, 6e éd., Paris, France: Lavoisier — Hermès, 2015.

[14] B. D. Agarwal, L. J. Broutman, and K. Chandrashekhara, Analysis and Performance of Fiber Composites, 4th ed., Hoboken, NJ, USA: John Wiley & Sons, 2017.

[15] L. P. Kollár and G. S. Springer, Mechanics of Composite Structures, Cambridge, UK: Cambridge University Press, 2003.