

The background features a collage of architectural and design-related illustrations. In the top left, there's a blue pen, a yellow ruler, and an orange pencil on a light blue grid. In the top center, a light blue pencil and a yellow and grey marker are shown. On the right, a large teal protractor and a blue pencil are depicted. The bottom left shows a dark teal architectural floor plan on a grid. The bottom center and right contain line drawings of classical and modern buildings, including a domed structure and several skyscrapers.

Composite Materials Reinforcements & Interfaces

Sweshareefa Mahakul | Assistant Prof. ME

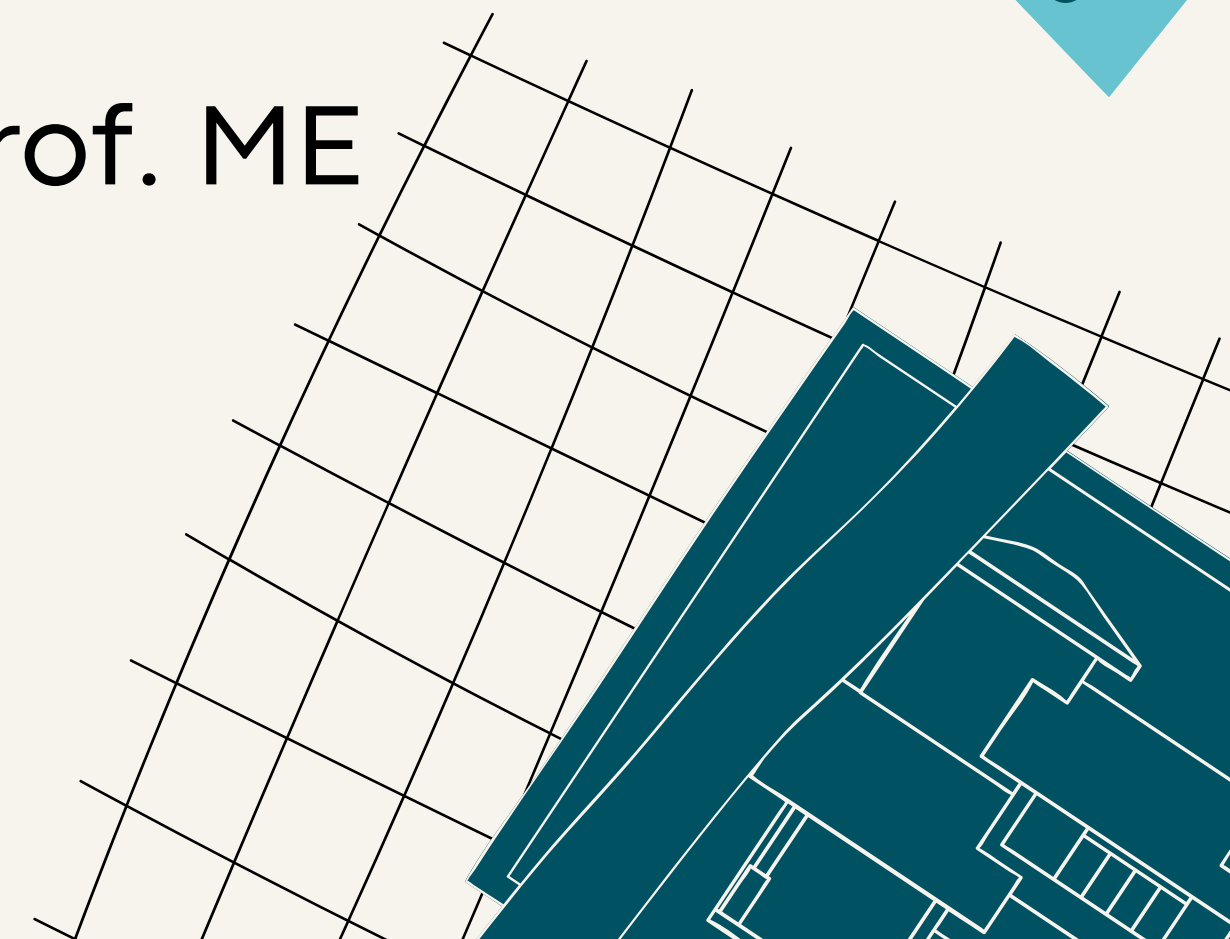
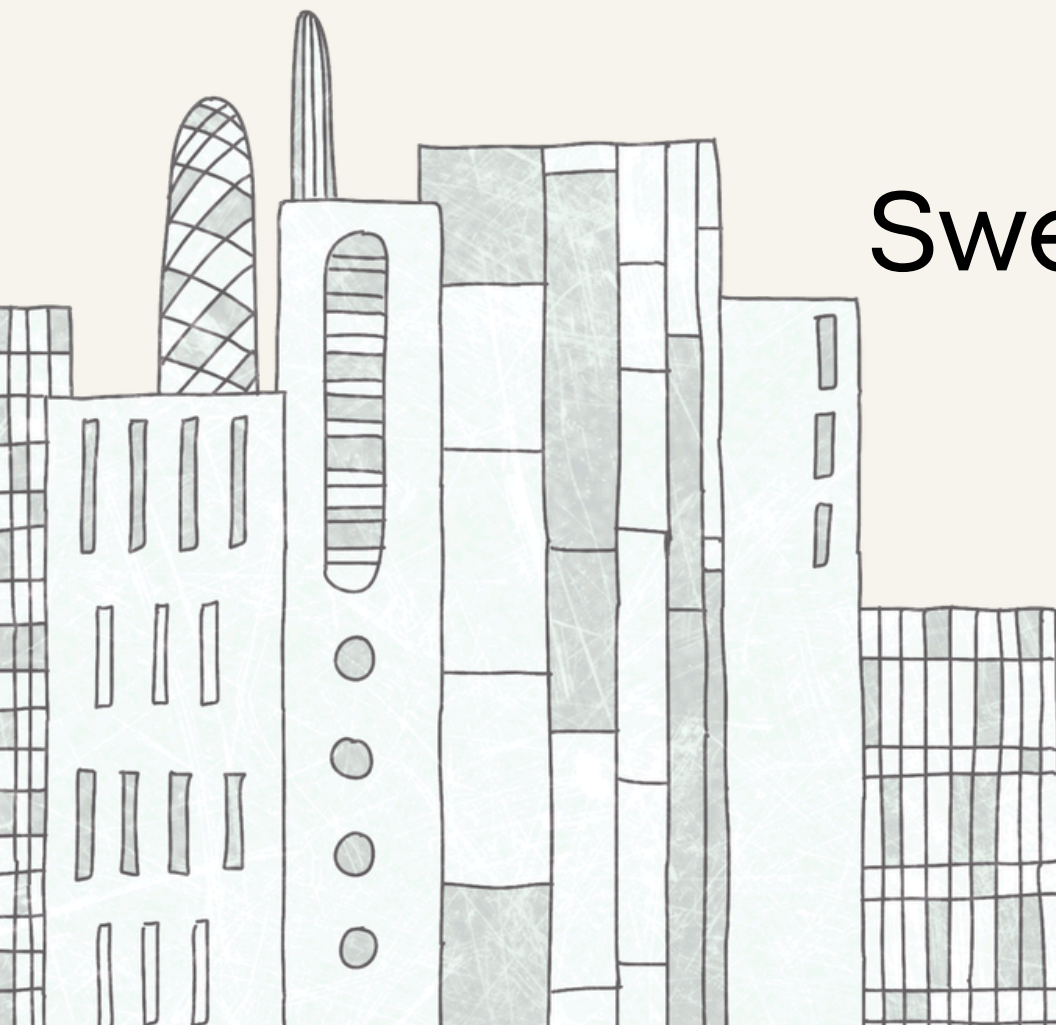


Key Reinforcement Fibers

Carbon · Boron · Glass

Aramid · Al_2O_3 · SiC

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Glass Fibers

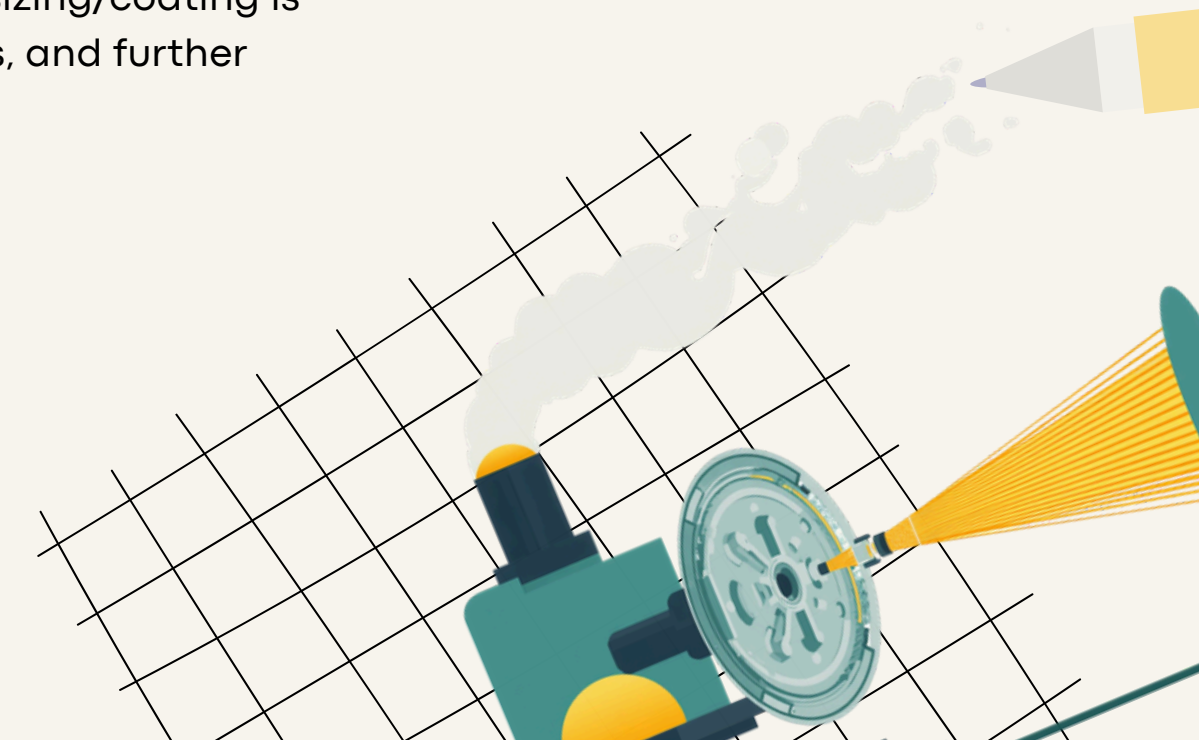
Nature & Composition

Glass fibers are amorphous, inorganic materials primarily composed of silica (SiO_2) along with oxides of calcium, boron, sodium, and aluminum. E-glass (electrical grade) is the most widely used, offering good tensile strength (~ 3.5 GPa), low cost, and excellent electrical insulation. S-glass has higher silica content ($\sim 65\%$) providing superior strength and stiffness. Glass fibers are isotropic, non-crystalline, and exhibit brittle fracture behavior with density ~ 2.5 g/cm³.

Manufacturing Process

Glass fibers are manufactured by the melt-drawing process: raw materials (silica sand, limestone, boric acid) are melted at $\sim 1260^\circ\text{C}$ in a furnace. Molten glass flows through platinum-rhodium bushings with hundreds of fine orifices (1–2 mm dia.). Filaments are drawn at high speed (~ 3 km/min), rapidly cooling and solidifying. A chemical sizing/coating is applied for protection and matrix adhesion. Fibers are gathered into strands, wound onto bobbins, and further processed into rovings, mats, or woven fabrics.

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Carbon Fibers

Nature & Structure

Carbon fibers consist of long, thin strands of carbon atoms arranged in a crystalline graphite-like structure aligned parallel to the fiber axis. This hexagonal layered arrangement (turbostratic graphite) gives carbon fibers exceptional stiffness and strength. They exhibit high tensile strength (3.5–7 GPa), high modulus of elasticity (200–800 GPa), low density ($\sim 1.75\text{--}2.0\text{ g/cm}^3$), excellent thermal and chemical resistance, and near-zero coefficient of thermal expansion. Carbon fibers are classified as High Strength (HS), High Modulus (HM), and Ultra-High Modulus (UHM) based on their mechanical properties.

Manufacturing Process

Carbon fibers are manufactured primarily from Polyacrylonitrile (PAN) precursor ($\sim 90\%$ of production) or pitch-based precursors. PAN Process: (1) Stabilization – PAN fibers are oxidized at $200\text{--}300^\circ\text{C}$ in air to form a ladder polymer structure. (2) Carbonization – Heated to $1000\text{--}1500^\circ\text{C}$ in inert atmosphere (N_2), removing non-carbon elements. (3) Graphitization – Optional heating to $2000\text{--}3000^\circ\text{C}$ to increase modulus. (4) Surface Treatment – Oxidation to improve fiber-matrix adhesion. (5) Sizing – Protective coating applied before final use. Pitch-based fibers offer higher modulus but lower strength compared to PAN-based fibers.

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Aramid Fibers

Nature & Properties

Aramid fibers (Aromatic Polyamide) are synthetic organic fibers known for exceptional strength-to-weight ratio. They exhibit high tensile strength (~ 3.6 GPa), low density (1.44 g/cm³), and excellent thermal stability up to 500°C . Aramid fibers are resistant to impact, fatigue, and organic solvents. Two main types: Kevlar (para-aramid) and Nomex (meta-aramid). Para-aramid offers superior mechanical properties; meta-aramid excels in thermal resistance.

Manufacturing Process

Aramid fibers are produced via dry-jet wet spinning (solution spinning). The polymer is dissolved in sulfuric acid to form a liquid crystalline solution. This solution is extruded through a spinneret into an air gap, then into a coagulation bath (water). The air gap allows molecular alignment, imparting high orientation and strength. Fibers are washed, dried, and heat-treated. The rigid rod-like polymer chains align parallel to the fiber axis, giving outstanding tensile properties.

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Comparison of Fibers

Mechanical Properties

Carbon Fiber: Highest stiffness & strength-to-weight ratio; $E = 230\text{--}700$ GPa.

Boron Fiber: High stiffness, used in aerospace; $E \approx 400$ GPa.

Glass Fiber: Moderate strength, low cost; $E \approx 70$ GPa.

Aramid (Kevlar): High tensile strength, excellent toughness; $E \approx 70\text{--}125$ GPa.

Al_2O_3 : High temp resistance, moderate stiffness.

SiC: Superior hardness & thermal stability.

Applications & Characteristics

Carbon: Aerospace, automotive, sporting goods — lightweight structures.

Boron: Military aircraft, sporting equipment.

Glass: Construction, marine, automotive — cost-effective reinforcement.

Aramid: Ballistic armor, cables, pressure vessels.

Al_2O_3 : High-temp metal matrix composites.

SiC: Ceramic matrix composites, turbine blades.

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The background features several decorative elements: a blue pen and yellow ruler on a grid in the top left; a blue ruler and yellow triangle on a grid in the top right; a blue pencil and yellow pencil in the middle right; a blue architectural drawing on a grid in the bottom left; and a line-art illustration of a classical building with a dome and a modern city skyline in the bottom right.

Role of Interfaces in Composite Materials

Wettability & Bonding

Surface Energy & Wettability:

- Wettability describes the ability of a liquid matrix to spread over a solid fiber surface, governed by surface energy.
- High wettability (low contact angle $< 90^\circ$) ensures intimate fiber-matrix contact, promoting strong adhesion.
- Surface energy of fibers: Carbon ($\sim 40 \text{ mJ/m}^2$), Glass ($\sim 50 \text{ mJ/m}^2$), Aramid ($\sim 35 \text{ mJ/m}^2$) — determines spreading behavior.
- Young's equation: $\gamma_{SV} = \gamma_{SL} + \gamma_{LV} \cdot \cos\theta$ relates solid-vapor, solid-liquid, and liquid-vapor interfacial energies.

Adhesion Mechanisms at the Interface:

- Mechanical interlocking: Matrix penetrates fiber surface roughness, creating physical grip.
- Chemical bonding: Covalent/ionic bonds formed via coupling agents (e.g., silanes on glass fibers) enhance adhesion.
- Interdiffusion: Polymer chain entanglement across the interface improves bond strength in thermoplastic composites.
- Electrostatic attraction: Charge differences between fiber and matrix contribute to adhesive forces.
- Surface treatments (oxidation, sizing, plasma) increase surface energy and reactive sites for stronger bonding.



The Interface in Composites

The interface (or interphase) in composite materials is the boundary region between the reinforcing fiber and the surrounding matrix. Unlike a simple 2D boundary, it is a distinct 3D zone with unique chemical, physical, and mechanical properties. The interphase governs stress transfer from matrix to fiber, dictates failure modes, and controls overall composite performance. Its thickness can range from a few nanometers to several microns depending on fiber treatment and matrix chemistry.

The structural integrity of the interphase is critical: a strong, well-bonded interface ensures efficient load transfer and enhanced stiffness, while a weak interface leads to debonding and delamination. Surface treatments such as sizing, coupling agents (e.g., silanes), and oxidative etching are applied to fibers to optimize interfacial adhesion. The interphase also plays a key role in toughness — a controlled weak interface can deflect cracks and improve damage tolerance in brittle matrix composites.

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Bonding at Interfaces

Mechanical Bonding: Occurs due to physical interlocking between fiber surface roughness and the matrix material. Surface irregularities, pits, and grooves on fiber surfaces provide anchorage points, enabling load transfer through frictional resistance. This bonding type is prominent in carbon and glass fiber composites and is highly dependent on fiber surface texture and processing conditions.

Chemical & Physical Bonding: Chemical bonding involves covalent or ionic bonds formed at the fiber-matrix interface, often enhanced by coupling agents (e.g., silanes for glass fibers). Physical bonding includes van der Waals forces and electrostatic interactions arising from molecular attraction. Aramid and boron fibers rely significantly on these mechanisms. Combined bonding modes govern interfacial shear strength and composite durability.

Fiber-Matrix Interface Bonding





Tests for Measuring Interfacial Strength

The interfacial strength between fiber and matrix is critical to composite performance. Several experimental methods are used to evaluate this bond:

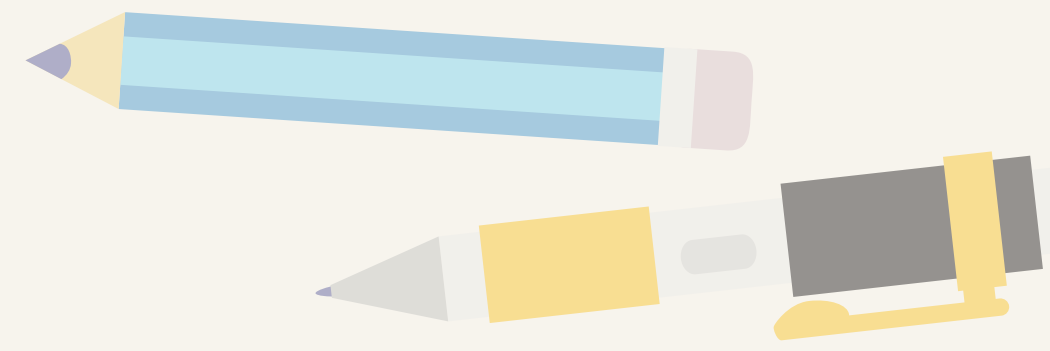
- Pull-Out Test: A single fiber is embedded in a matrix block and pulled axially. The force required to debond and extract the fiber is measured, providing the interfacial shear strength (IFSS).
- Fragmentation Test: A single fiber is embedded in a dog-bone shaped matrix specimen. Under tensile loading, the fiber fractures into progressively smaller fragments until a saturation length is reached, allowing IFSS calculation via shear-lag analysis.

- Microbond (Microdroplet) Test: A small droplet of matrix resin is cured onto a single fiber. The droplet is then sheared off using a microvise, and the debonding force is recorded to determine IFSS.

- Indentation (Push-In/Push-Out) Test: A fiber cross-section is loaded with a nanoindenter to push the fiber into or through the matrix, measuring frictional and adhesive interfacial properties.

Comparison: Each test offers unique insights — pull-out and microbond are suited for single-fiber studies, fragmentation captures statistical behavior, and push-out is ideal for ceramic and metal matrix composites.

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Thank You!
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