Composite - An Introduction

Issues to address…

- What are composites?
- Classification of composites.
- Why composites?
- Mechanical properties of composites.
- Applications.

Composite materials – Definition

- Definition: a material composed of 2 or more constituents
  - Reinforcement phase (e.g., Fibers)
  - Binder phase (e.g., compliant matrix)

- Advantages
  - High strength and stiffness
  - Low weight ratio
  - Material can be designed in addition to the structure

Classification of Composite Materials

1. *Metal Matrix Composites* (MMCs) - mixtures of ceramics and metals, such as cemented carbides and other cermets

2. *Ceramic Matrix Composites* (CMCs) - Al_2O_3 and SiC imbedded with fibers to improve properties, especially in high temperature applications
   The least common composite matrix

3. *Polymer Matrix Composites* (PMCs) - thermosetting resins are widely used in PMCs
   Examples: epoxy and polyester with fiber reinforcement, and phenolic with powders

Polymer matrix composite combinations

Fibre

E-glass
S-glass
carbon (graphite)
aramid (eg Kevlar)
boron

Matrix

epoxy
polyimide
polyester
thermoplastics (PA, PS, PEEK…)

Ceramic matrix composite combinations

Fibre	*Matrix*
SiC	SiC
alumina	alumina
SiN	glass-ceramic
	SiN

Metal matrix composite combinations

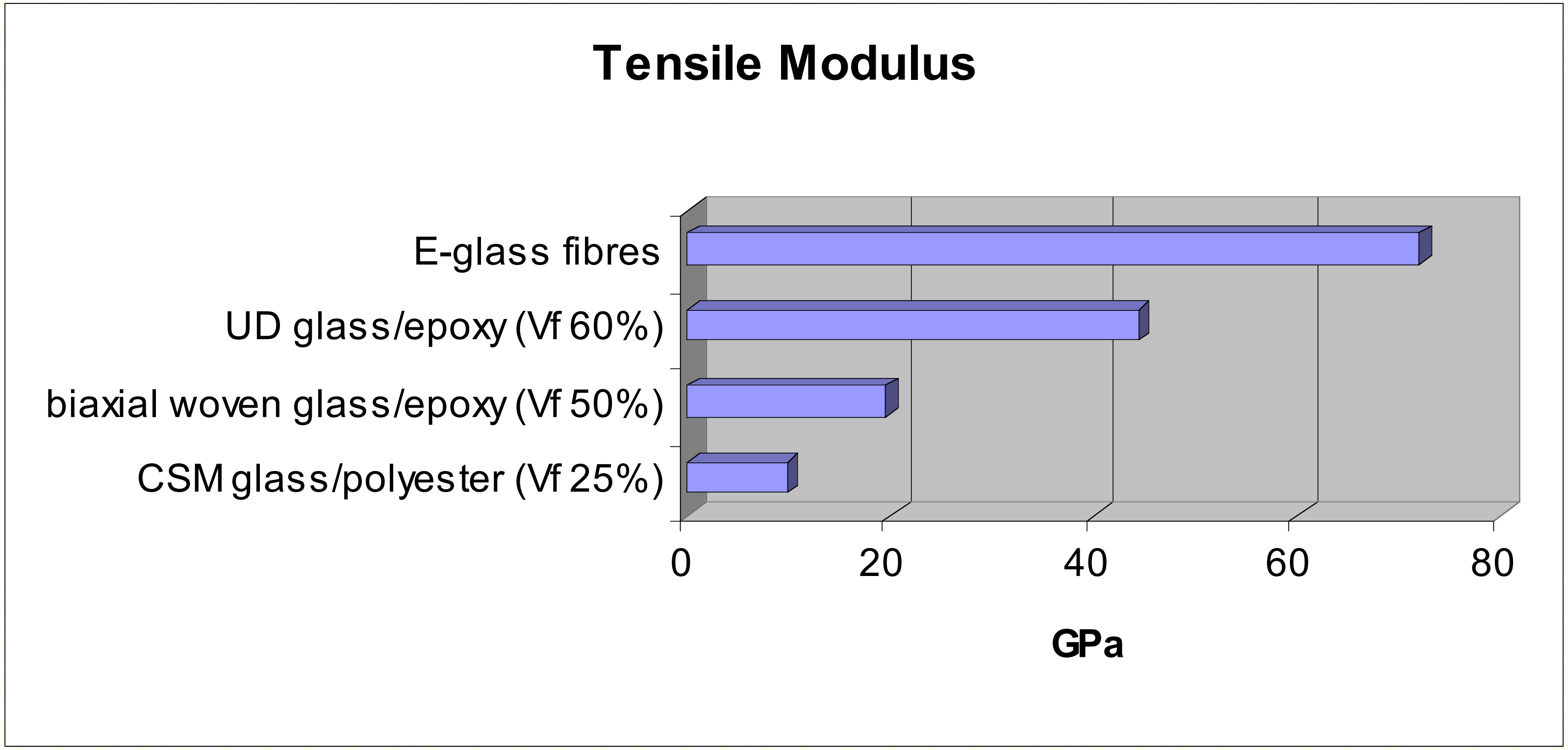
Fibre

boron
Borsic
carbon (graphite)
SiC
alumina (Al_2O_3)

Matrix

aluminium
magnesium
titanium
copper

Composite property might be only 10% of the fibre property:



Where?

Composites in sports

fiberglass
carbon/epoxy laminates

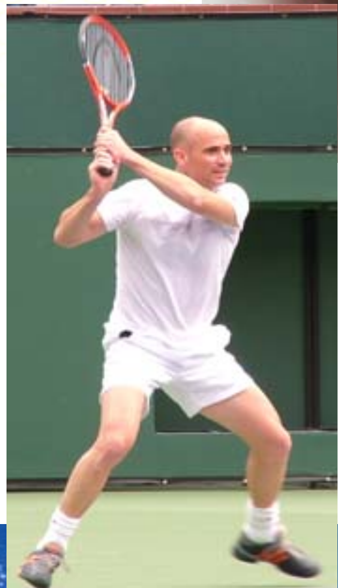
Concrete

- The classical example of a composite is concrete.

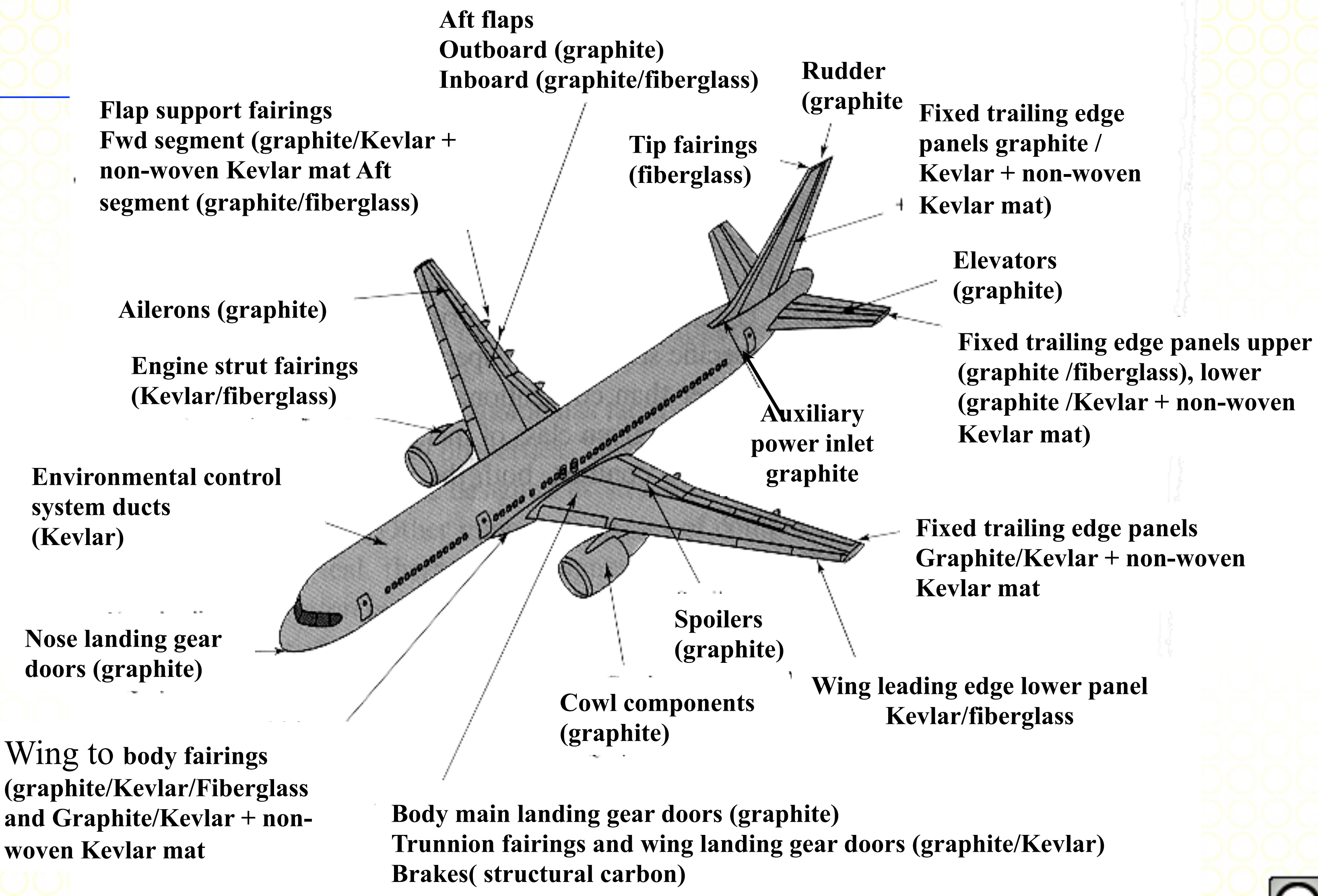
- It is more complex than it appears. There are typically coarse and fine particles (rocks!) embedded in a matrix of silicates and sulfates. There is a high fraction of pores of all sizes. This is an example of a *particulate composite*.

- Ordinary concrete (properly made) has excellent compressive strength but poor tensile strength. Thus reinforced concrete was invented to combine the tensile strength of steel with the compressive strength of concrete. This is an example of a *fiber reinforced composite*.

Composites in Action



Boeing 757-200



From http://matse101.mse.uiuc.edu/

Why Composites are Important

- Composites can be very strong and stiff, yet very light in weight, so ratios of strength-to-weight and stiffness-to-weight are several times greater than steel or aluminum
- Fatigue properties are generally better than for common engineering metals
- Toughness is often greater too
- Composites can be designed that do not corrode like steel
- Possible to achieve combinations of properties not attainable with metals, ceramics, or polymers alone

Disadvantages and Limitations of Composite Materials

- Properties of many important composites are anisotropic
- Many of the polymer-based composites are subject to attack by chemicals or solvents, just as the polymers themselves are susceptible to attack
- Composite materials are generally expensive
- Manufacturing methods for shaping composite materials are often slow and costly

Why are composites used in engineering?

- Weight saving (high *specific* properties)
- Corrosion resistance
- Fatigue properties
- Manufacturing advantages:
    - reduced parts count
    - novel geometries
    - low cost tooling
- Design freedoms
    - continuous property spectrum
    - anisotropic properties

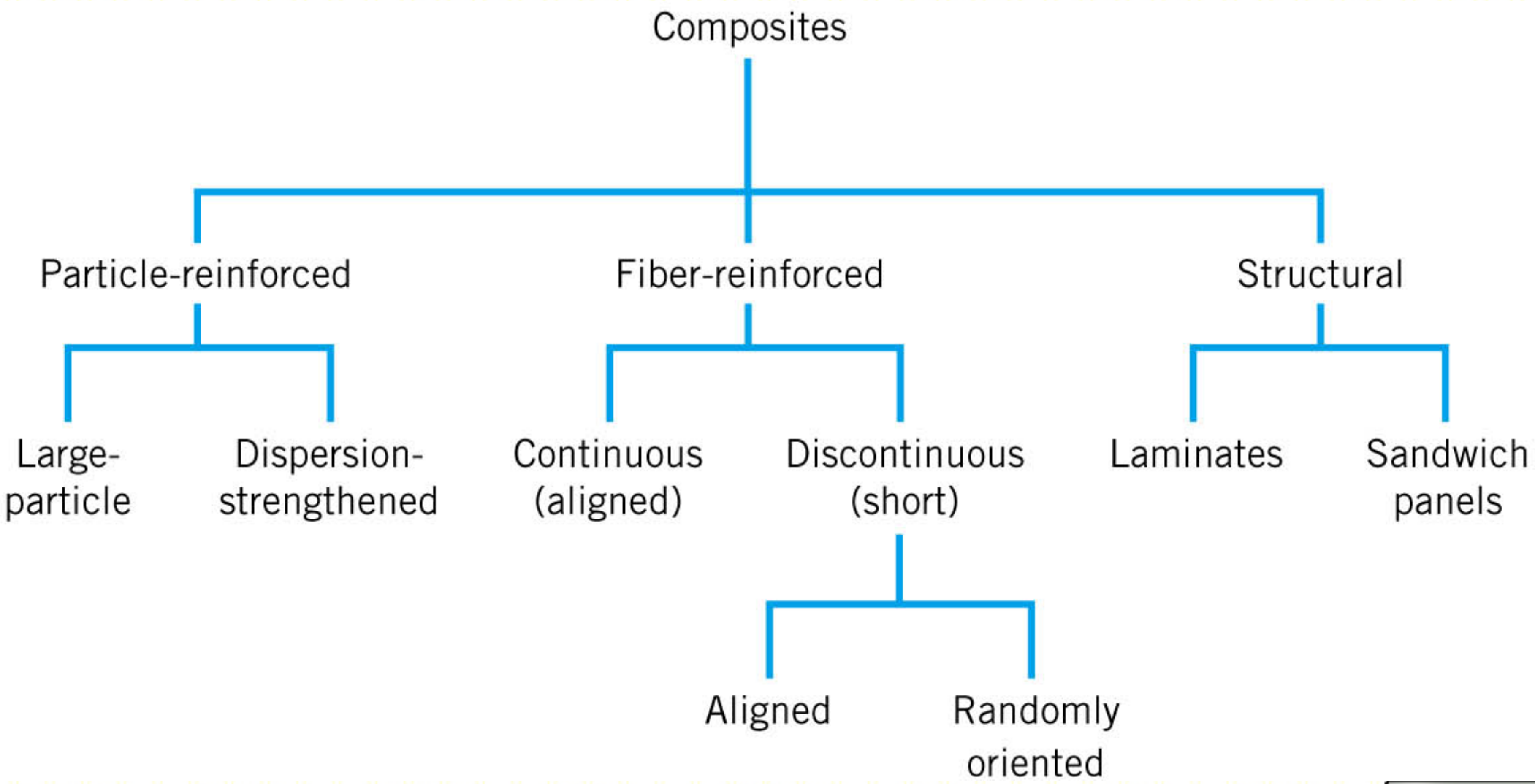
Why aren't composites used **more** in engineering?

- High cost of raw materials
- Lack of design standards
- Few 'mass production' processes available
- Properties of laminated composites:
  - low through-thickness strength
  - low interlaminar shear strength
- No 'off the shelf' properties - performance depends on quality of manufacture

Costs of composite manufacture

- Material costs -- higher for composites
  - Constituent materials (e.g., fibers and resin)
  - Processing costs -- embedding fibers in matrix
    - not required for metals Carbon fibers order of magnitude higher than aluminum
- Design costs -- lower for composites
  - Can reduce the number of parts in a complex assembly by designing the material in combination with the structure
- Increased performance must justify higher material costs

Types of composites



The Reinforcing Phase

- Function is to reinforce the matrix phase

- Imbedded phase is most commonly one of the following shapes:
    - Fibers
    - Particles
    - Flakes

- In addition, the phase can take the form of an infiltrated phase in a skeletal or porous matrix
    - Example: a powder metallurgy part infiltrated with polymer

Forms of Reinforcement Phase

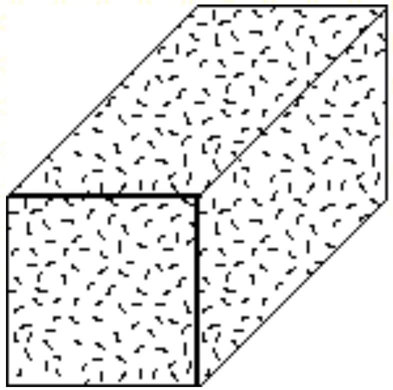
- Fibers
  - cross-section can be circular, square or hexagonal
  - Diameters --> 0.0001" - 0.005 "
  - Lengths --> L/D ratio
    - 100 -- for chopped fiber
    - much longer for continuous fiber
- Particulate
  - small particles that impede dislication movement (in metal composites) and strengthens the matrix
  - For sizes > 1 μm, strength of particle is involves in load sharing with matrix
- Flakes
  - flat platelet form

Composite characteristics

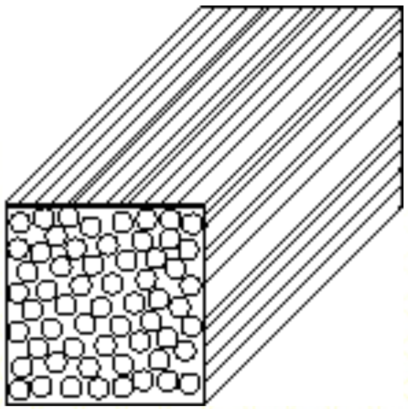
Depends on:

- properties of the matrix material.
- properties of reinforcement material.
- ratio of matrix to reinforcement.
- matrix-reinforcement bonding/adhesion.
- mode of fabrication.

Fibers as a reinforcement



Random fiber (short fiber) reinforced composites



Continuous fiber (long fiber) reinforced composites

Particles and Flakes

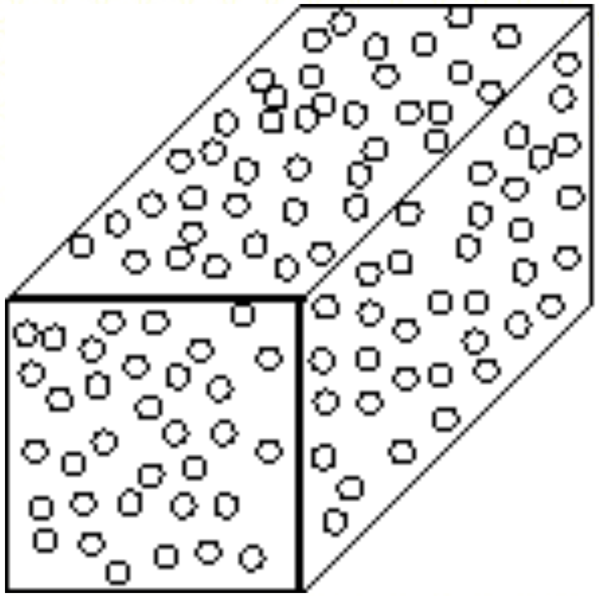
- A second common shape of imbedded phase is *particulate*, ranging in size from microscopic to macroscopic

- *Flakes* are basically two-dimensional particles - small flat platelets

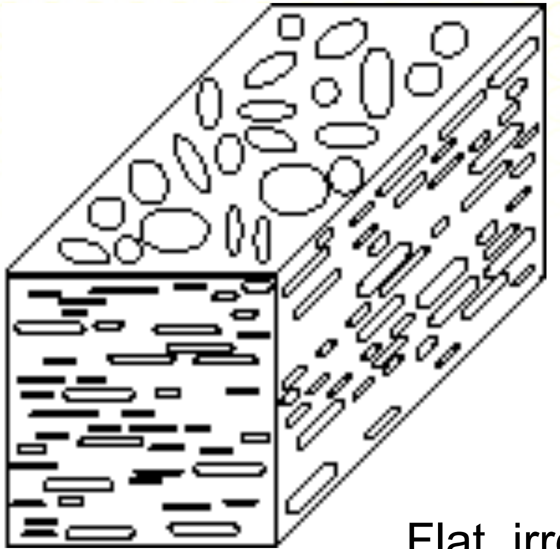
- The distribution of particles in the composite matrix is random, and therefore strength and other properties of the composite material are usually isotropic

- Strengthening mechanism depends on particle size

Particles as the reinforcement



Flat flakes as the reinforcement



Flat, irregularly shaped pieces of material.

Fibers

- Filaments of reinforcing material, usually circular in cross-section
- Diameters range from less than 0.0025 mm to about 0.13 mm, depending on material
- Filaments provide greatest opportunity for strength enhancement of composites
  - The filament form of most materials is significantly stronger than the bulk form
  - As diameter is reduced, the material becomes oriented in the fiber axis direction and probability of defects in the structure decreases significantly

Continuous vs. Discontinuous Fibers

Continuous fibers - very long; in theory, they offer a continuous path by which a load can be carried by the composite part

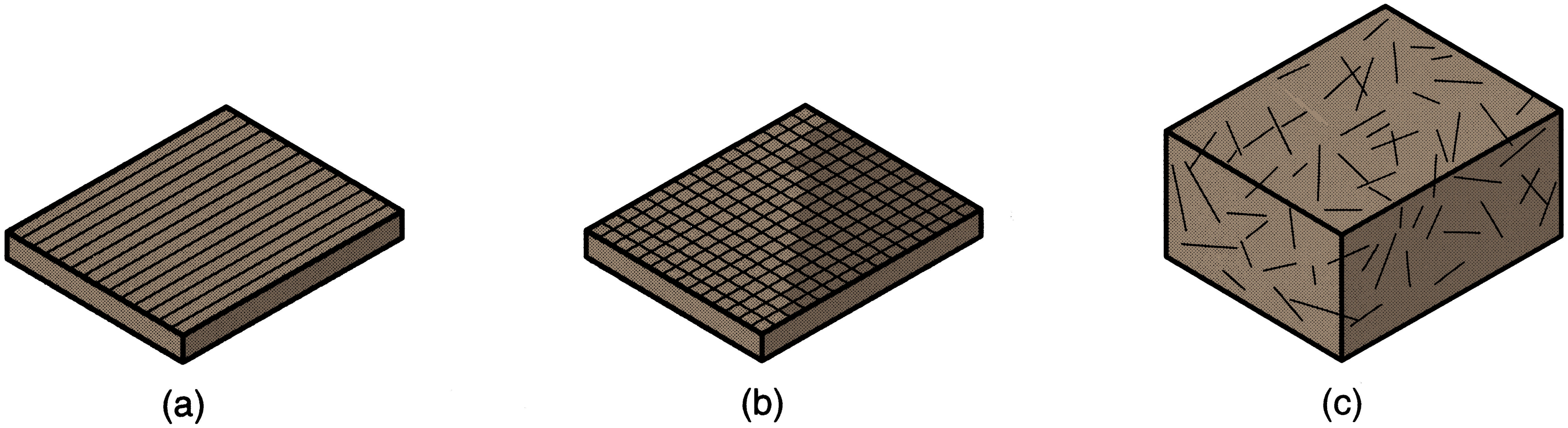
Discontinuous fibers (chopped sections of continuous fibers) - short lengths (L/D = roughly 100)

Fiber Orientation – Three Cases

One-dimensional reinforcement, in which maximum strength and stiffness are obtained in the direction of the fiber

Planar reinforcement, in some cases in the form of a two-dimensional woven fabric

Random or three-dimensional in which the composite material tends to possess isotropic properties



Fiber orientation in composite materials:
(a) one-dimensional, continuous fibers; (b) planar, continuous fibers in the form of a woven fabric; and (c) random, discontinuous fibers

Materials for Fibers

Fiber materials in fiber-reinforced composites:

- Glass – most widely used filament
- Carbon – high elastic modulus
- Boron – very high elastic modulus
- Polymers - Kevlar
- Ceramics – SiC and Al_2O_3
- Metals - steel

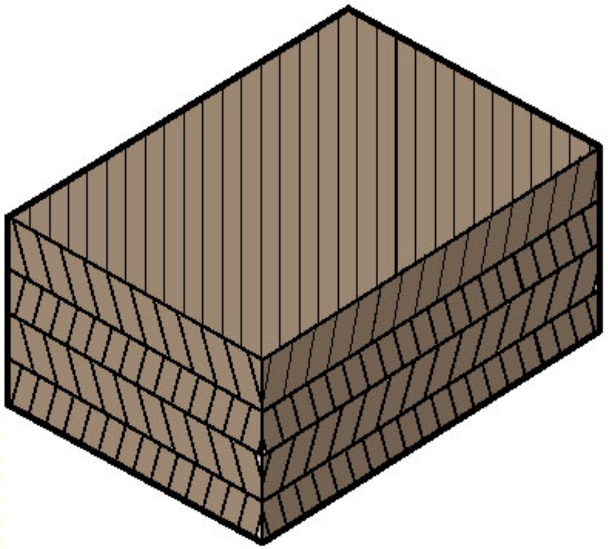
The most important commercial use of fibers is in polymer composites

Other Composite Structures

- Laminar composite structure – conventional
- Sandwich structure
- Honeycomb sandwich structure

Laminar Composite Structure

Two or more layers bonded together in an integral piece
Example: *plywood* in which layers are the same wood, but grains are oriented differently to increase overall strength of the laminated piece

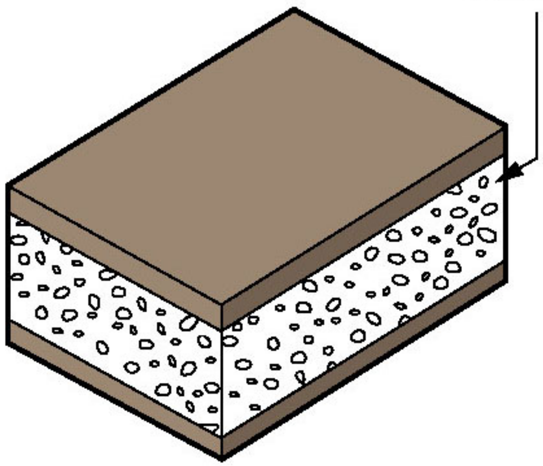


(a)

Laminar composite structures: conventional laminar structure

Sandwich Structure – Foam Core

Consists of a relatively thick core of low density foam bonded on both faces to thin sheets of a different material

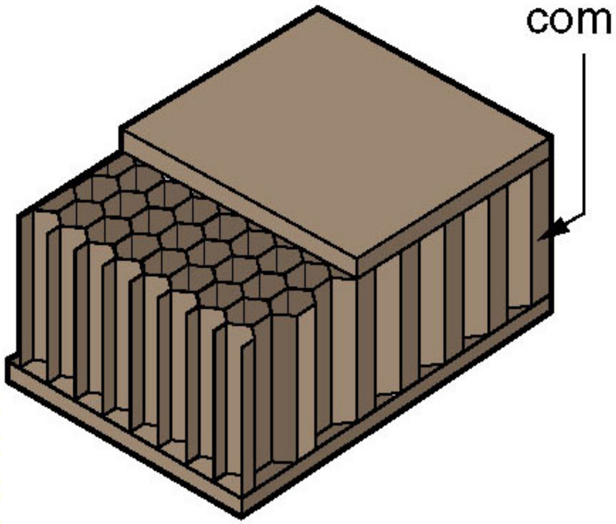


(b)

Laminar composite structures: sandwich structure using foam core

Sandwich Structure – Honeycomb Core

An alternative to foam core
Either foam or honeycomb achieves high strength-to-weight and stiffness-to-weight ratios



(c)

Laminar composite structures: sandwich structure using honeycomb core

Fibers - Glass

- Most widely used fiber
- Uses: piping, tanks, boats, sporting goods
- Advantages
  - low cost
  - Corrosion resistance
  - Low cost relative to other composites:
- Disadvantages
  - Relatively low strength
  - High elongation
  - Moderate strength and weight
- Types:
  - E-Glass - electrical, cheaper
  - S-Glass - high strength

E glass

- the lowest cost of all commercially available reinforcing fibres
- widespread use in the FRP industry
- excellent electrical properties and durability
- Relatively poor impact resistance

S glass

- improved stiffness and strength
- high-temperature tolerance
- S glass is considerably more expensive than E glass
- Developed for aerospace and defence industries
- Used in some hard ballistic armour applications

Continuous Strand Roving

- is a collection of parallel filaments coaled with a suitable sizing
- bonded together into a single strand (end) or multiple strands (ends) having little or no twist
- wound into a cylindrical supply package.

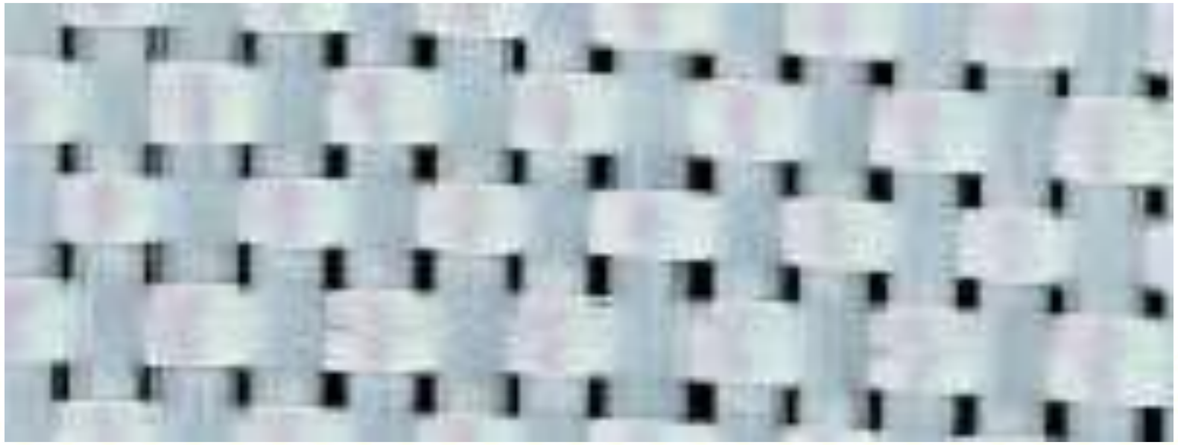
Roving may be applied as continuous reinforcement in woven roving, filament winding, pultrusion, prepregs, or chopped into sheet molding compounds, preforms, mats, spray-up, centrifugal casting, extrusion compounding and continuous laminating processes.

Chopped Strand Mat

Chopped strand mat is the most extensively used reinforcement in the fiberglass industry. The advantages of mat versus fabrics are their low cost and how easily they conform to contours. They do not offer the strength characteristics of fabrics, but are ideal for low cost, rapid build ups.

Woven roving

Woven Roving is used in laminating large fiberglass parts such as boats and tanks where an inexpensive, high impact, high strength reinforcement is required. Woven roving should be used with mat whenever bonding to plywood or making repairs.



Mat Tape

Like Chopped Strand Mat described above, available in a 4" width for selective reinforcement of seams, corners or edges of large parts.

Continuous Strand Veil Surfacing

This lightweight mat is typically used as a surfacing layer on laminations to improve surface finish and to provide a resin rich area in corrosion resistant tank linings.

Unidirectional E-Glass

Unidirectional fabrics are used to strengthen in one direction and save weight in the less critical orientation. This fabric permits a part's strength to be tailored to any orientation or stiffness with little weight penalty.

Bi-directional E-Glass

This high performance, loose weave, 2 x 2 twill fabric is both strong and formable. When cut off the roll on a 45 degree bias, it will drape over virtually any contour. It was developed for the light aircraft market, but it can be used anywhere high strength, fast wet-out, and drapability are desired.

Fiber- Aramid

Aramid (e.g. Kevlar) fiber-reinforced polymer composites:

- High strength, high modulus.
- Much better strength-to-weight than metals.
- Stable to relatively high T (high mechanical properties maintained from ~ - 200 to 200^{o}C).
- Relatively inert chemically (except strong acids).
- Uses: bullet-proof vests, tires, ropes, missile cases, parts for automotive brake, clutch lining and gaskets…

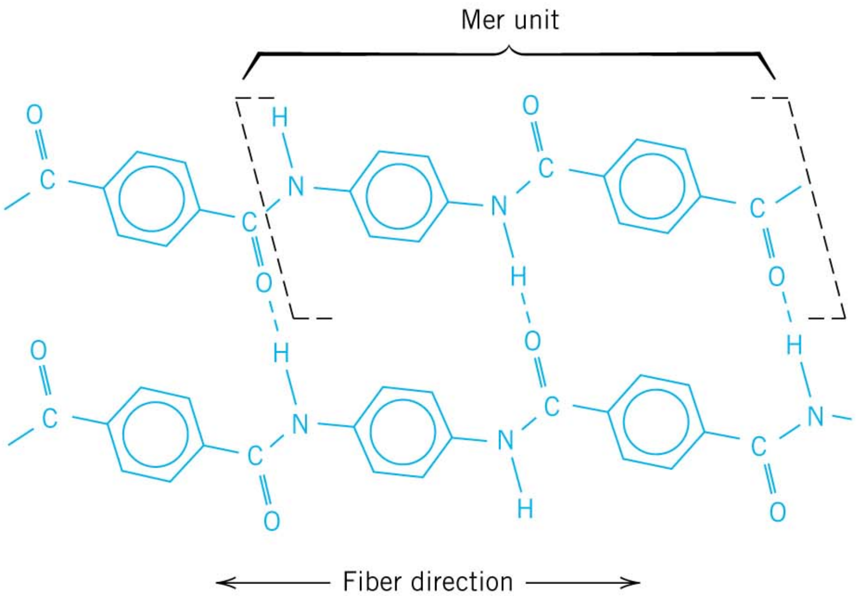
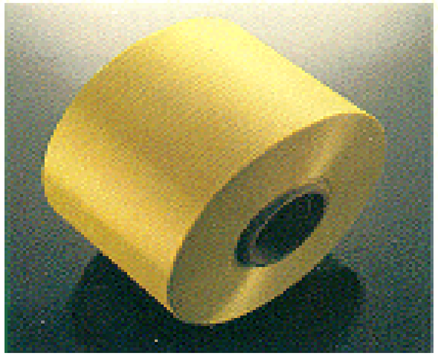


FIGURE 16.10 Schematic representation of mer and chain structures for aramid (Kevlar) fibers. Chain alignment with the fiber direction and hydrogen bonds that form between adjacent chains are also shown. [From F. R. Jones (Editor), *Handbook of Polymer-Fibre Composites.* Copyright © 1994 by Addison-Wesley Longman. Reprinted with permission.]

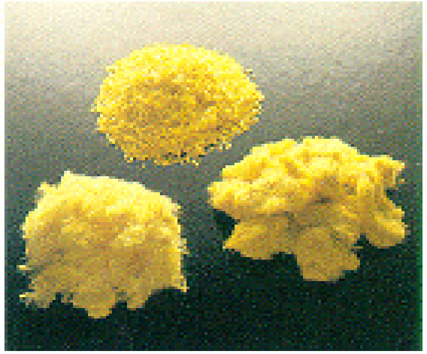
Fibers - Aramid (kevlar, Twaron)

- Uses:
  - high performance replacement for glass fiber
- Examples
  - Armor, protective clothing, industrial, sporting goods
- Advantages:
  - higher strength and lighter than glass
  - More ductile than carbon

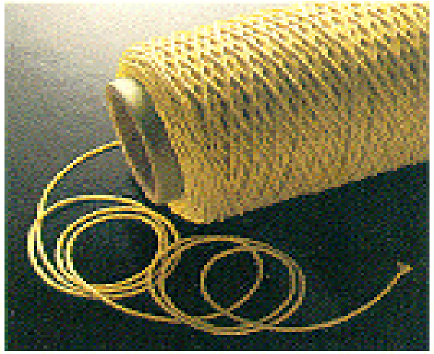
Different kinds of Kevlar fibres



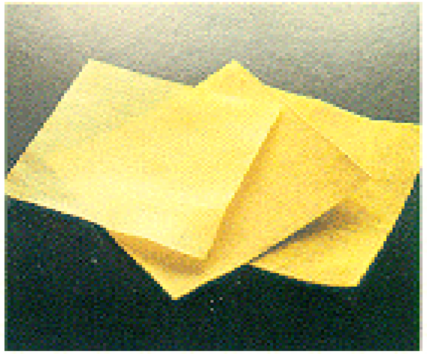
Tapes



Short fibres



Rovings



Fabric

Applications

Fiber- carbon

Some reason for using Carbon fibers:

- Highest specific modulus and specific strength of all reinforcing fiber materials.
- Retain high modulus and tensile strength at elevated temperature (chemical oxidation may be a problem).
- At or near Room Temp., very inert.

Some applications: fishing rods, golf clubs, bicycles, military and commercial aircraft structural components…

Fibers - Carbon

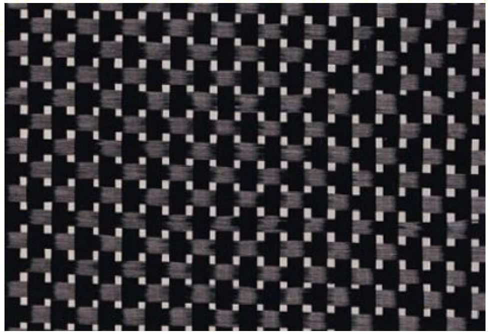
- 2nd most widely used fiber
- Examples
  - aerospace, sporting goods
- Advantages
  - high stiffness and strength
  - Low density
  - Intermediate cost
  - Properties:
    - Standard modulus: 207-240 GPPa
    - Intermediate modulus: 240-340 GPa
    - High modulus: 340-960 GPa
    - Diameter: 5-8 microns, smaller than human hair

Fibers -- Carbon

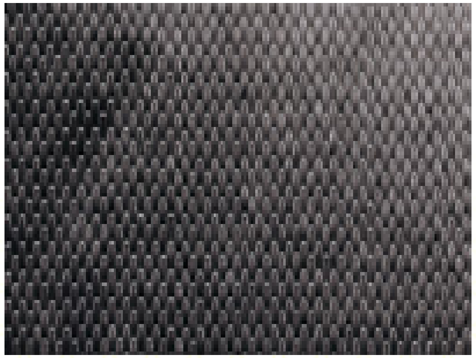
- Types of carbon fiber
  - vary in strength with processing
  - Trade-off between strength and modulus
- Intermediate modulus
  - PAN (Polyacrylonitrile)
    - fiber precursor heated and stretched to align structure and remove non-carbon material
- High modulus
  - made from petroleum pitch precursor at lower cost
  - much lower strength

Different types of carbon fibres

Roving



Woven fabric I

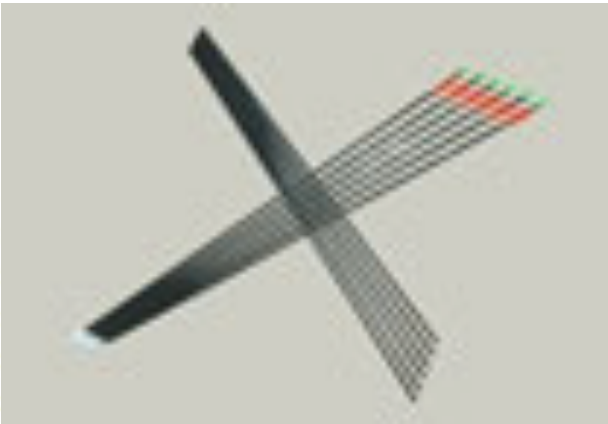


Woven fabric II

Preform

Bicycle Fork

Mountain Stick



Golf and Arrow Shafts

Fiber - Others

- Boron
  - High stiffness, very high cost
  - Large diameter - 200 microns
  - Good compressive strength
- Polyethylene - trade name: Spectra fiber
  - Textile industry
  - High strength
  - Extremely light weight
  - Low range of temperature usage

Fibers -- Others

- Ceramic Fibers (and matrices)
  - Very high temperature applications (e.g. engine components)
  - Silicon carbide fiber - in whisker form.
  - Ceramic matrix so temperature resistance is not compromised
  - Infrequent use

Fiber Material Properties

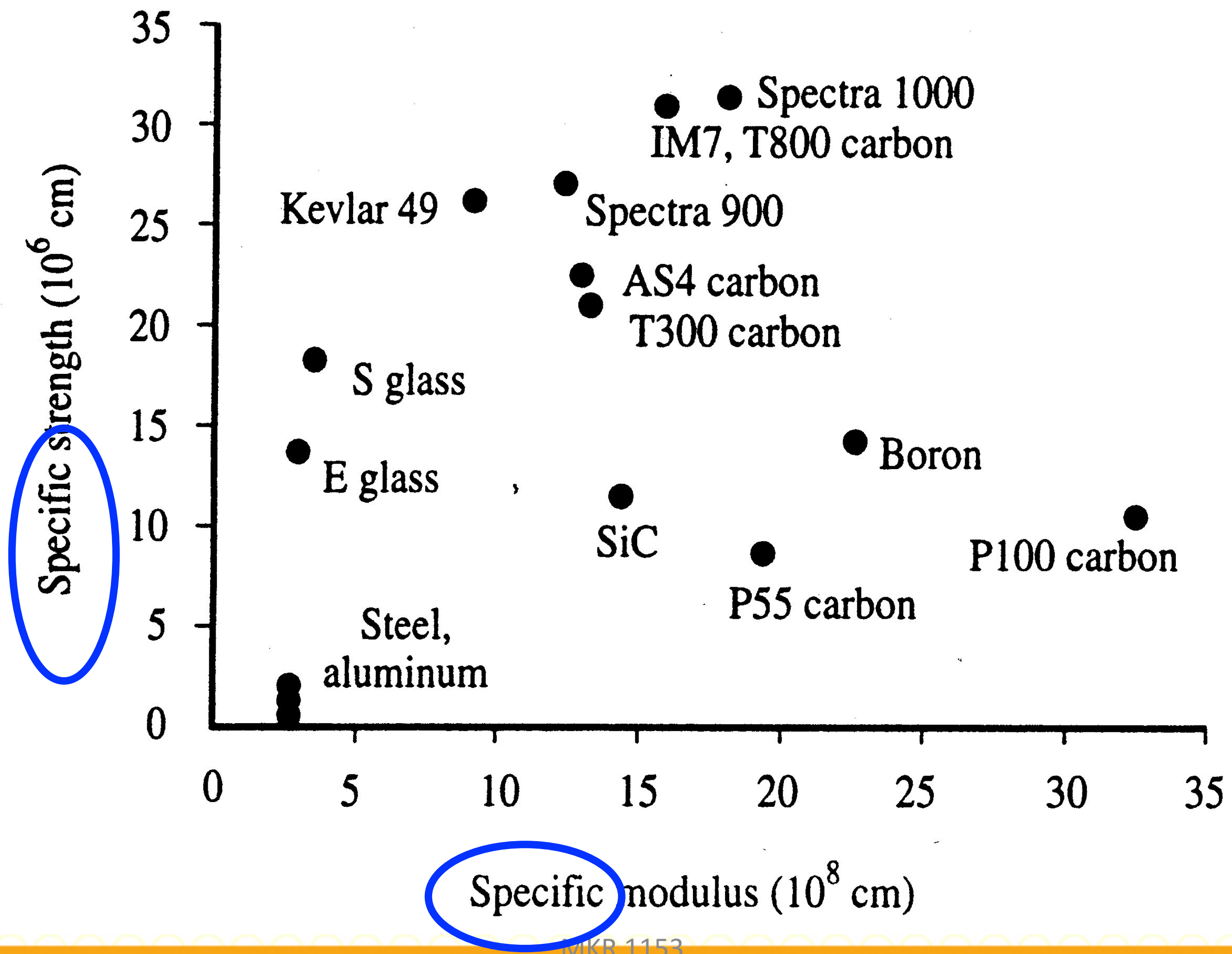
Table 1.1 Mechanical Properties of Typical Fibers

Fiber	Fiber Diameter (μm)	Fiber Density (lb/in³)	Fiber Density (g/cc)	Tensile Strength (ksi)	Tensile Strength (GPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)
E-glass	8–14	0.092	2.54	500	3.45	10.5	72.4
S-glass	8–14	0.090	2.49	665	4.58	12.5	86.2
Polyethylene	10–12	0.035	0.97	392	2.70	12.6	87.0
Aramid (Kevlar 49)	12	0.052	1.44	525	3.62	19.0	130.0
HS Carbon, T300	7	0.063	1.76	514	3.53	33.6	230
AS4 Carbon	7	0.065	1.80	580	4.00	33.0	228
IM7 Carbon	5	0.065	1.80	785	5.41	40.0	276
XUHM Carbon	—	0.068	1.88	550	3.79	62.0	428
GY80 Carbon	8.4	0.071	1.96	270	1.86	83.0	572
Boron	50–203	0.094	2.60	500	3.44	59.0	407
Silicon Carbide		0.115	3.19	220	1.52	70.0	483

Sources: From [1.1, 1.2] and product literature.

Steel: density (Fe) = 7.87 g/cc;TS=0.380 GPa; Modulus=207 GPa
Al: density=2.71 g/cc; TS=0.035 GPa; Modulus=69 GPa

Fiber Strength



Functions of the Matrix Material

- Provides the bulk form of the part or product made of the composite material
- Holds the imbedded phase in place, usually enclosing and often concealing it
- When a load is applied, the matrix shares the load with the secondary phase, in some cases deforming so that the stress is essentially born by the reinforcing agent

Matrix Materials

- Demands on matrix
  - Interlaminar shear strength
  - Toughness
  - Moisture/environmental resistance
  - Temperature properties
  - Cost

Matrices - Polymeric

- Thermosets
  - cure by chemical reaction
  - Irreversible
  - Examples
    - Polyester, vinylester
      - Most common, lower cost, solvent resistance
    - Epoxy resins
      - Superior performance, relatively costly

Matrices - Thermoplastics

- Formed by heating to elevated temperature at which softening occurs
  - Reversible reaction
  - Can be reformed and/or repaired - not common
  - Limited in temperature range to 150^{o}C
- Examples
  - Polypropylene
    - with nylon or glass
    - can be injected-- inexpensive
  - Soften layers of combined fiber and resin and place in a mold -- higher costs

Matrices - Others

- Metal Matrix Composites - higher temperature
  - e.g., Aluminum with boron or carbon fibers
- Ceramic matrix materials - very high temperature
  - Fiber is used to add toughness, not necessarily higher in strength and stiffness

Important Note

- Composite properties are less than that of the fiber because of dilution by the matrix and the need to orient fibers in different directions.

Prepregs

- Prepreg and prepreg layup
  - "prepreg" - partially cured mixture of fiber and resin
    - Unidirectional prepreg tape with paper backing
      - wound on spools
      - Cut and stacked
  - Curing conditions
    - Typical temperature and pressure in autoclave is 120-200^{o}C, 100 psi

Fabric effects on material properties

Table 1.2 Typical Properties of Glass–Polyester Composites in Various Forms

Form	Density (g/cc)	Tensile Strength		Tensile Modulus	
		(ksi)	(MPa)	(Msi)	(GPa)
Unidirectional roving	2.0	100	690	6.0	40
Woven glass fabric	1.9	48	330	3.8	26
Chopped strand mat	1.7	42	290	2.4	16.7
Sheet molding compound R50	1.87	24	164	2.3	16

Sources: From [1.4, 1.5].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GREAT LAKES

Boron/epoxy horizontal and vertical stabilizers (F-15)

Carbon/epoxy wing, fuselage panels, control surfaces (AV-8B)

Carbon/epoxy wingskins with integral titanium splice plates, carbon/epoxy control surfaces and stabilizers (horizontal and vertical)

C/E wing skins, stabilizers, fuselage skins, control surfaces, internal structure (F-22)

Fiber placed C/E landing gear fairings, C/E control surfaces, research on C/E horizontal tail and rear access panel.