PART I

PRINCIPLES OF CONSTRUCTION

1

COMPOSITE MATERIALS, INTEREST, AND PROPERTIES

1.1 WHAT IS COMPOSITE MATERIAL?

As the term indicates, *composite material* reveals a material that is different from common heterogeneous materials. Currently *composite materials* refers to materials having strong fibers—continuous or noncontinuous—surrounded by a weaker matrix material. The matrix serves to distribute the fibers and also to transmit the load to the fibers.

Notes: Composite materials are not new. They have been used since antiquity. Wood and cob have been everyday composites. Composites have also been used to optimize the performance of some conventional weapons. For example:

- In the Mongolian arcs, the compressed parts are made of corn, and the stretched parts are made of wood and cow tendons glued together.
- Japanese swords or sabers have their blades made of steel and soft iron: the steel part is stratified like a sheet of paste, with orientation of defects and impurities in the long direction[1] (see Figure 1.1), then formed into a U shape into which the soft iron is placed. The sword then has good resistance for flexure and impact.

One can see in this period the beginning of the distinction between the common composites used universally and the high performance composites.

The composite material as obtained is

- Very heterogeneous.
- Very "anisotropic." This notion of "anisotropy" will be illustrated later in Section 3.1 and also in Chapter 9. Simply put this means that the mechanical properties of the material depend on the direction.

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[1] In folding a sheet of steel over itself 15 times, one obtains 2^{15} = 32,768 layers.

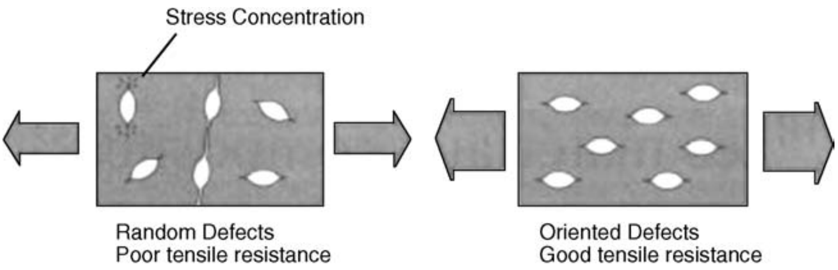

Figure 1.1 Effect of the Orientation of Impurities

1.2 FIBERS AND MATRIX

The bonding between fibers and matrix is created during the manufacturing phase of the composite material. This has fundamental influence on the mechanical properties of the composite material.

1.2.1 Fibers

Fibers consist of thousands of filaments, each filament having a diameter of between 5 and 15 micrometers, allowing them to be producible using textile machines;[2] for example, in the case of glass fiber, one can obtain two **semi-products** as shown in Figure 1.2. These fibers are sold in the following forms:

- Short fibers, with lengths of a few centimeters or fractions of millimeters are **felts, mats**, and short fibers used in injection molding.
- Long fibers, which are cut during time of fabrication of the composite material, are used as is or woven.

Principal fiber materials are

- Glass
- Aramid or **Kevlar**® (very light)
- Carbon (high modulus or high strength)
- Boron (high modulus or high strength)
- Silicon carbide (high temperature resistant)

In forming fiber reinforcement, the assembly of fibers to make fiber forms for the fabrication of composite material can take the following forms:

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[2] One wants to have fibers as thin as possible because their rupture strength decreases as their diameter increases, and very small fiber diameters allow for effective radius of curvature in fiber bending to be on the order of half a millimeter. However, exception is made for boron fibers (diameter in the order of 100 microns), which are formed around a tungsten filament (diameter = 12 microns). Their minimum radius of curvature is 4 mm. Then, except for particular cases, weaving is not possible.

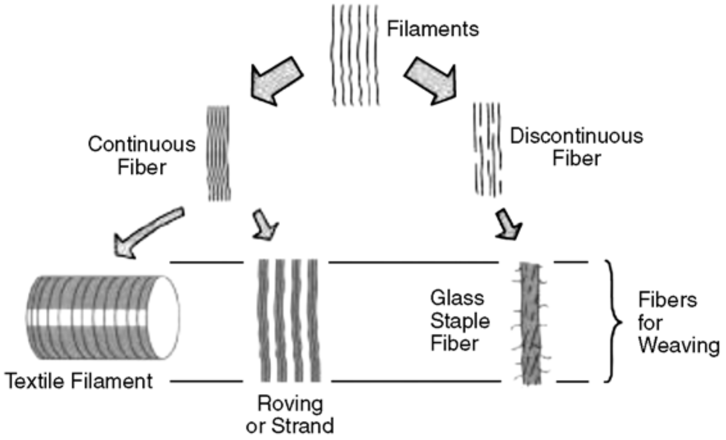

Figure 1.2 Different Fiber Forms

- **Unidimensional:** unidirectional tows, yarns, or tapes
- **Bidimensional:** woven or nonwoven fabrics (felts or mats)
- **Tridimensional:** fabrics (sometimes called *multidimensional fabrics*) with fibers oriented along many directions (>2)

Before the formation of the reinforcements, the fibers are subjected to a surface treatment to

- Decrease the abrasion action of fibers when passing through the forming machines.
- Improve the adhesion with the matrix material.

Other types of reinforcements, full or empty spheres (microspheres) or powders (see Section 3.5.3), are also used.

1.2.1.1 Relative Importance of Different Fibers in Applications

Figure 1.3 allows one to judge the relative importance in terms of the amount of fibers used in the fabrication of composites. One can immediately notice the industrial importance of fiber glass (produced in large quantities). Carbon and Kevlar fibers are reserved for high performance components.

Following are a few notes on the fibers:

- Glass fiber: The filaments are obtained by pulling the glass (silicon + sodium carbonate and calcium carbonate; $T > 1000°C$) through the small orifices of a plate made of platinum alloy.
- Kevlar fiber: This is an aramid fiber, yellowish color, made by DuPont de Nemours (USA). These are aromatic polyamides obtained by synthesis at –10°C, then fibrillated and drawn to obtain high modulus of elasticity.
- Carbon fiber: Filaments of polyacrylonitrile or pitch (obtained from residues of the petroleum products) are oxidized at high temperatures (300°C), then heated further to 1500°C in a nitrogen atmosphere. Then only the hexagonal

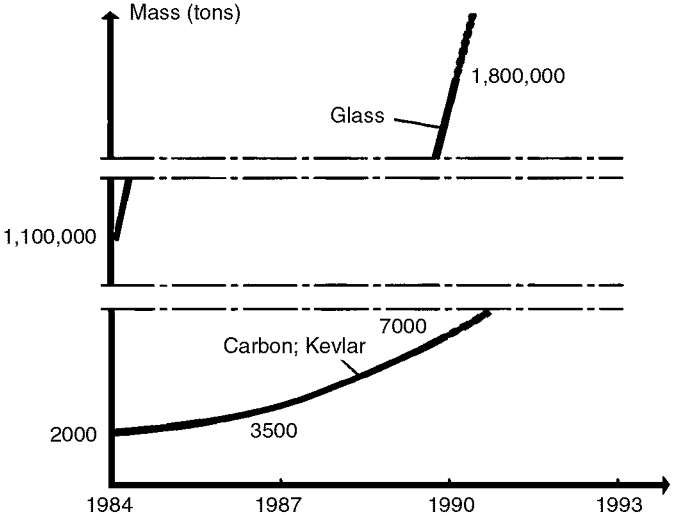

Figure 1.3 Relative Sale Volume of Different Fibers

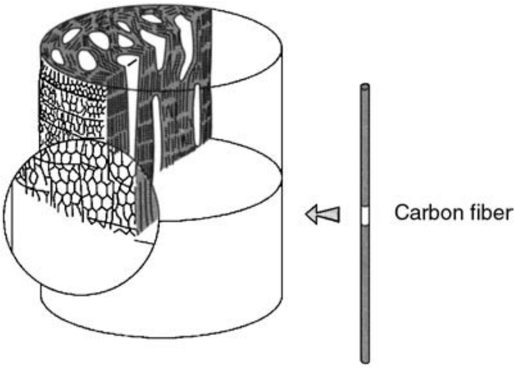

Figure 1.4 Structure of Carbon Fiber

carbon chains, as shown in Figure 1.4, remain. Black and bright filaments are obtained. High modulus of elasticity is obtained by drawing at high temperature.

- Boron fiber: Tungsten filament (diameter 12 μm) serves to catalyze the reaction between boron chloride and hydrogen at 1200°C. The boron fibers obtained have a diameter of about 100 μm (the growth speed is about 1 micron per second).
- Silicon carbide: The principle of fabrication is analogous to that of boron fiber: chemical vapor deposition (1200°C) of methyl trichlorosilane mixed with hydrogen.

The principal physical–mechanical properties of the fibers are indicated in Table 1.3. Note the very significant disparity of the prices per unit weight.

1.2.2 Matrix Materials

The matrix materials include the following:

- **Polymeric matrix:** thermoplastic resins (polypropylene, polyphenylene sulfone, polyamide, polyetheretherketone, etc.) and thermoset resins (polyesters, phenolics, melamines, silicones, polyurethanes, epoxies). Their principal physical properties are indicated in the Table 1.4.
- **Mineral matrix:** silicon carbide, carbon. They can be used at high temperatures (see Sections 2.2.4, 3.6, 7.1.10, 7.5).
- **Metallic matrix:** aluminum alloys, titanium alloys, oriented eutectics.

1.3 WHAT CAN BE MADE USING COMPOSITE MATERIALS?

The range of applications is very large. A few examples are shown below.

- Electrical, Electronics
  - Insulation for electrical construction
  - Supports for circuit breakers
  - Supports for printed circuits
  - Armors, boxes, covers
  - Antennas, radomes
  - Tops of television towers
  - Cable tracks
  - Windmills
- Buildings and Public Works
  - Housing cells
  - Chimneys
  - Concrete molds
  - Various covers (domes, windows, etc.)
  - Swimming pools
  - Facade panels
  - Profiles
  - Partitions, doors, furniture, bathrooms
- Road Transports
  - Body components
  - Complete body
  - Wheels, shields, radiator grills,
  - Transmission shafts
  - Suspension springs
  - Bottles for compressed petroleum gas
  - Chassis
  - Suspension arms
  - Casings
  - Cabins, seats
  - Highway tankers, isothermal trucks
  - Trailers

- Rail transports:
  - Fronts of power units
  - Wagons
  - Doors, seats, interior panels
  - Ventilation housings
- Marine Transports:
  - Hovercrafts
  - Rescue crafts
  - Patrol boats
  - Trawlers
  - Landing gears
  - Anti-mine ships
  - Racing boats
  - Pleasure boats
  - Canoes
- Cable transports:
  - Telepherique cabins
  - Telecabins
- Air transports
  - All composite passenger aircrafts
  - All composite gliders
  - Many aircraft components: radomes, leading edges, ailerons, vertical stabilizers
  - Helicopter blades, propellers
  - Transmission shafts
  - Aircraft brake discs
- Space Transports
  - Rocket boosters
  - Reservoirs
  - Nozzles
  - Shields for atmosphere reentrance
- General mechanical applications
  - Gears
  - Bearings
  - Housings, casings
  - Jack body
  - Robot arms
  - Fly wheels
  - Weaving machine rods
  - Pipes
  - Components of drawing table
  - Compressed gas bottles
  - Tubes for offshore platforms
  - Pneumatics for radial frames
- Sports and Recreation
  - Tennis and squash rackets
  - Fishing poles
  - Skis

- Poles used in jumping
- Sails
- Surf boards,
- Roller skates
- Bows and arrows
- Javelins
- Protection helmets
- Bicycle frames
- Golf clubs
- Oars

1.4 TYPICAL EXAMPLES OF INTEREST ON THE USE OF COMPOSITE MATERIALS

In the domain of commercial aircraft, one can compare the concerns of manufacturers with the principal characteristic properties of composite materials. The concerns of the manufacturers are performance **and** economy. The characteristics of composite components include the following:

- Weight saving leads to fuel saving, increase in payload, or increase in range which improves performances.
- Good fatigue resistance leads to enhanced life which involves saving in the long-term cost of the product.
- Good corrosion resistance means fewer requirements for inspection which results in saving on maintenance cost.

Moreover, taking into account the cost of the composite solution as compared with the conventional solution, one can state that composites fit the demand of aircraft manufacturers.

1.5 EXAMPLES ON REPLACING CONVENTIONAL SOLUTIONS WITH COMPOSITES

Table 1.1 shows a few significant cases illustrating the improvement on price and performance that can be obtained after replacement of a conventional solution with a composite solution.

1.6 PRINCIPAL PHYSICAL PROPERTIES

Tables 1.2 through 1.5 take into account the properties of only individual components, reinforcements, or matrices. The characteristics of composite materials resulting from the combination of reinforcement and matrix depend on

- The proportions of reinforcements and matrix (see Section 3.2)
- The form of the reinforcement (see Section 3.2)
- The fabrication process

Table 1.1 Properties of Commonly Used Resins

Application	*Price of Previous Construction*	*Price of Composite Construction*
65 m^3 reservoir for chemicals	Stainless steel + installation: 1.	0.53
Smoke stack for chemical plant	Steel: 1.	0.51
Nitric acid vapor washer	Stainless steel: 1.	0.33
Helicopter stabilizer	Light alloys + steel (16 kg): 1.	Carbon/epoxy (9 kg): 0.45
Helicopter winch support	Welded steel (16 kg): 1.	Carbon/epoxy (11 kg): 1.2
Helicopter motor hub	(Mass: 1): 1.	Carbon/Kevlar/epoxy (mass: 0.8): 0.4
X–Y table for fabrication of integrated circuits	Cast aluminum: Rate of fabrication: 30 plates/hr	Carbon/epoxy honeycomb sandwich: 55 plates/hr
Drum for drawing table	Speed of drawing: 15 to 30 cm/sec	Kevlar/epoxy: 40 to 80 cm/sec
Head of welding robot	Aluminum: Mass = 6 kg	Carbon/epoxy: Mass = 3 kg
Weaving machine rod	Aluminum: Rate = 250 shots/minute	Carbon/epoxy: Rate = 350 shots/minute
Aircraft floor	(Mass = 1): 1.	Carbon/Kevlar/epoxy (mass: 0.8): 1.7

These characteristics may be observed in Figure 1.5, which shows the tensile strength for different fiber fractions and different forms of reinforcement for the case of glass/resin composite, and Figure 1.6, which gives an interesting view on the specific resistance of the principal composites as a function of temperature. (The specific strength is defined as the strength divided by the density σ_{rupt}/ρ.)

Other remarkable properties of these materials include the following:

- Composite materials **do not yield** (their elastic limits correspond to the rupture limit; see Section 5.4.5).
- Composite materials are very **fatigue resistant** (see Section 5.1).
- Composite materials **age** subject to humidity (epoxy resin can absorb water by diffusion up to 6% of its mass; the composite of reinforcement/resin can absorb up to 2%) and heat.
- Composite materials **do not corrode**, except in the case of contact "aluminum with carbon fibers" in which case galvanic phenomenon creates rapid corrosion.
- Composite materials are not sensitive to the common chemicals used in engines: grease, oils, hydraulic liquids, paints and solvents, petroleum. However, paint thinners attack the epoxy resins.
- Composite materials have medium to low level impact resistance (inferior to that of metallic materials).
- Composite materials have excellent fire resistance as compared with the light alloys with identical thicknesses. However, the smokes emitted from the combustion of certain matrices can be toxic.

Table 1.2 Properties of Commonly Used Metals and Alloys and Silicon

Metals and Alloys	*Density* ρ *(kg/m^3)*	*Elastic Modulus* E *(MPa)*	*Shear Modulus* G *(MPa)*	*Poisson Ratio* ν	*Tensile Strength* σ_{ult} *(Mpa)*	*Elongation (%)*	*Coefficient of Thermal Expansion at 20°C* α *(°C^{-1})*	*Coefficient of Thermal Conductivity at 20°C* λ*(W/m°C)*	*Heat Capacity c(J/kg°C)*	*Useful Temperature Limit* T_{max} *(°C)*
Steels	7800	205,000	79,000	0.3	400 to 1600	1.8 to 10	1.3×10^{-5}	20 to 100	400 to 800	800
Aluminum Alloy 2024	2800	75,000	29,000	0.3	450	10	2.2×10^{-5}	140	1000	350
Titanium Alloy TA 6V	4400	105,000	40,300	0.3	1200	14	0.8×10^{-5}	17	540	700
Copper	8800	125,000	48,000	0.3	200 to 500		1.7×10^{-5}	380	390	650
Nickel	8900	220,000			500 to 850			70	500	900
Beryllium	1840	294,000		0.05	200		1.2×10^{-5}	150 (20°C) 90 (800°C)	1750 (20°C) 3000 (800°C)	900
Silicon	2200	95,000				5		1.4 (20°C) 3 (1200°C)	750 (20°C) 1200(500°C)	1300

Table 1.3 Properties of Commonly Used Reinforcements

Reinforcements	*Fiber Diameter* $d(\mu m)$	*Density* $\rho(kg/m^3)$	*Modulus of Elasticity* $E(Mpa)$	*Shear Modulus* $G(Mpa)$	*Poisson Ratio* ν	*Tensile Strength* σ_{Ult} *(Mpa)*	*Elongation* $E(\%)$	*Coefficient of Thermal Expansion* $\alpha(°C^{-1})$	*Coefficient of Thermal Conductivity* $\lambda(W/M°C)$	*Heat Capacity* $c(J/kg°C)$	*Useful Temperature Limit* T_{max} *(°C)*	*Price 1993 ($/kg)*
"R" glass, high performance	10	2500	86,000		0.2	3200	4	0.3×10^{-5}	1	800	700	14
"E" glass, common applications	16	2600	74,000	30,000	0.25	2500	3.5	0.5×10^{-5}	1	800	700	2
Kevlar 49	12	1450	130,000	12,000	0.4	2900	2.3	-0.2×10^{-5}	0.03	1400		70
"HT" graphite, high strength	7	1750	230,000	50,000	0.3	3200	1.3	0.02×10^{-5}	200 (20°C) 60 (800°C)	800	>1500	70
"HM" graphite, high modulus	6.5	1800	390,000	20,000	0.35	2500	0.6	0.08×10^{-5}	200 (20°C) 60 (800°C)	800	>1500	140
Boron	100	2600	400,000			3400	0.8	0.4×10^{-5}			500	500
Aluminum	20	3700	380,000			1400	0.4		50 (20°C) 7 (800°C)	900	>1000	
Aluminum silicate	10	2600	200,000			3000	1.5					
Silicon carbide	14	2550	200,000			2800	1.3	0.5×10^{-5}			1300	600
Polyethylene		960	100,000			3000					150	

Table 1.4 Properties of Commonly Used Resins

Resins	*Density* ρ *(kg/m^3)*	*Elastic Modulus E(Mpa)*	*Shear Modulus G(Mpa)*	*Poisson Ratio* ν	*Tensile Strength* σ_{Ult} *(Mpa)*	*Elongation E%*	*Coefficient of Thermal Expansion* α *(°C^{-1})*	*Coefficient of Thermal Conductivity* λ*(W/m°C)*	*Heat Capacity C(J/kg°C)*	*Useful Temperature Limit* T_{max} *(°C)*	*Price 1993 ($/kg)*
Thermosets											
Epoxy	1200	4500	1600	0.4	130	2 (100°C) 6 (200°C)	11×10^{-5}	0.2	1000	90 to 200	6 to 20
Phenolic	1300	3000	1100	0.4	70	2.5	1×10^{-5}	0.3	1000	120 to 200	
Polyester	1200	4000	1400	0.4	80	2.5	8×10^{-5}	0.2	1400	60 to 200	2.4
Polycarbonate	1200	2400		0.35	60		6×10^{-5}		1200	120	
Vinylester	1150	3300			75	4	5×10^{-5}			>100	4
Silicone	1100	2200		0.5	35					100 to 350	
Urethane	1100	700 to 7000			30	100				100	4
Polyimide	1400	4000 to 19,000	1100	0.35	70	1	8×10^{-5}	0.2	1000	250 to 300	
Thermoplastics											
Polypropylene (pp)	900	1200		0.4	30	20 to 400	9×10^{-5}		330	70 to 140	
Polyphenylene sulfone (pps)	1300	4000			65	100	5×10^{-5}			130 to 250	
Polyamide (pa)	1100	2000		0.35	70	200	8×10^{-5}		1200	170	6
Polyether sulfone (pes)	1350	3000			85	60	6×10^{-5}			180	25
Polyetherimide (pei)	1250	3500			105	60	6×10^{-5}	0.2		200	20
Polyether-ether-ketone (peek)	1300	4000			90	50	5×10^{-5}	0.3		140 to 250	96

Table 1.5 Properties of Commonly Used Core Materials

Cores	*Density* $\rho(Kg/M^3)$	*Modulus of Elasticity* $E(Mpa)$	*Shear Modulus* $G(Mpa)$	*Poisson Ratio* ν	*Compressive Strength* $\sigma_{Ult}(Mpa)$	*Elongation* $E\%$	*Coefficient of Thermal Expansion* $\alpha(°C^{-1})$	*Coefficient of Thermal Conductivity* $\lambda(W/M°C)$	*Heat Capacity* $C(J/Kg°C)$	*Useful Temperature Limit* T_{max} (°C)	*Price 1993* (\$/Kg)
Balsa	100 to 190	2000 to 6000	100 to 250		8 to 18			0.05			11
Polyurethane foam	30 to 70	25 to 60		0.4						75	
Polystyrene foam	30 to 45	20 to 30		0.4	0.25 to 1.25					75	
Honeycombs											
Impregnated carton			50 to 350								
Impregnated glass fabric			100 to 600								
Aluminum	15 to 130		130 to 910		0.2 to 8						
Steel			550 to 1250								
Nomex®	25 to 50		10 to 40		0.2 to 2.5						

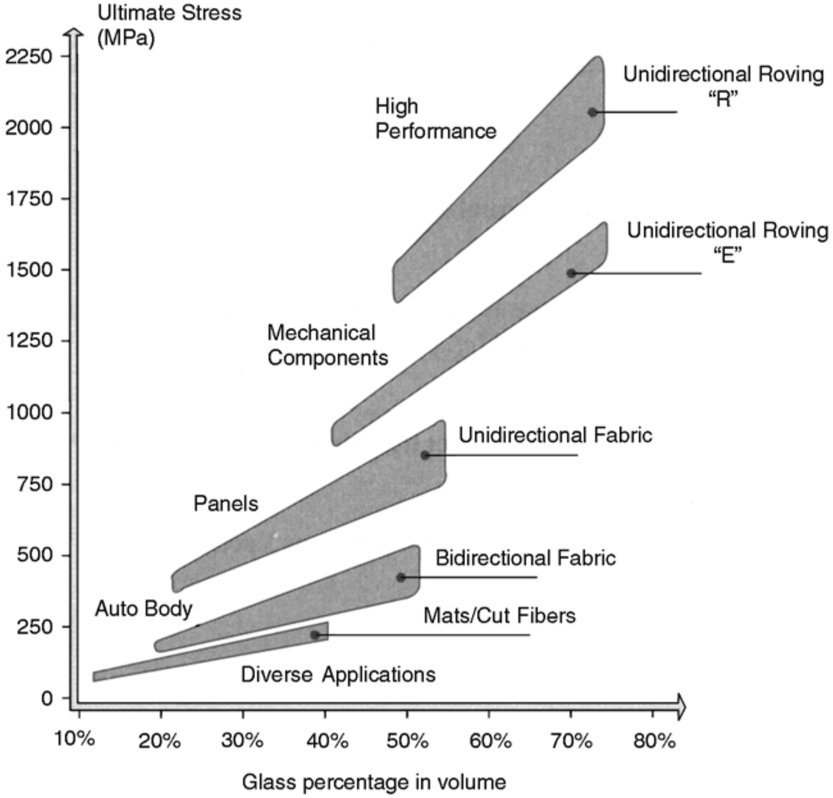

Figure 1.5 Tensile Strength of Glass/Resin Composites

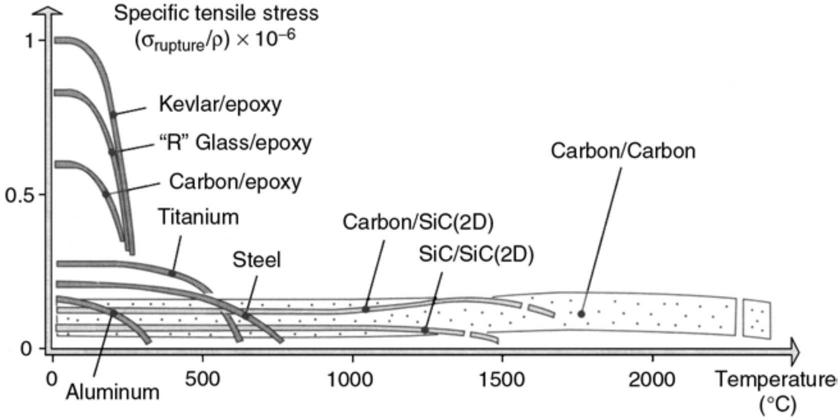

Figure 1.6 Specific Strength of Different Composites