Introduction to composites

A composite is a structural material that consists of two or more combined constituents that are combined at a macroscopic level to form a useful third material. One constituent is called the *reinforcing phase* and the one in which it is embedded is called the *matrix*. The reinforcing phase material may be in the form of fibers, particles, or flakes. The matrix phase materials are generally continuous. Examples of composite systems include concrete reinforced with steel and epoxy reinforced with graphite fibers, etc. (1).

Properties that can be improved by forming a composite materials: (2)

- strength
- stiffness
- corrosion resistance
- wear resistance
- attractiveness
- weight
- fatigue life
- temperature-dependent behavior
- thermal insulation
- thermal conductivity
- acoustical insulation

What are the advantages of using composites over metals? (1)

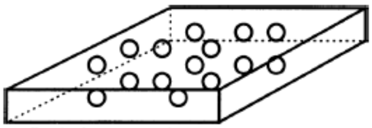
Monolithic metals and their alloys cannot always meet the demands of today’s advanced technologies. Only by combining several materials can one meet the performance requirements. For example, trusses and benches used in satellites need to be dimensionally stable in space during temperature changes between –256° F (–160° C) and 200°F (93.3°C). Limitations on coefficientof thermal expansion thus are low and may be of the order of ±1 X 10^{-7} in./in./°F (±1.8×10^{-7}m/m/°C). Monolithic materials cannot meet these requirements; this leaves composites, such as graphite/epoxy, as the only materials to satisfy them. In many cases, using composites is more efficient. For example, in the highly competitive airline market, one is continuously looking for ways to lower the overall mass of the aircraft without decreasing the stiffness and strength of its components. This is possible by replacing conventional metal alloys with composite materials. Even if the composite material costs may be higher, the reduction in the number of parts in an assembly and the savings in fuel costs make them more profitable. Reducing 1 kg of mass in a commercial aircraft can save up to 2720 l of fuel per year; Fuel expenses are 25% of the total operating costs of a commercial airline. Composites offer several other advantages over conventional materials. These may include improved strength, stiffness, fatigue and impact resistance, thermal conductivity, corrosion resistance, etc.

Classification of composites

Composites are classified by

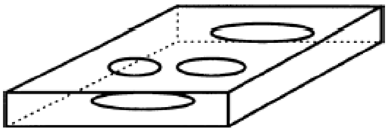
1. the geometry of the reinforcement - particulate, flake, and fibers or
2. by the type of matrix - polymer, metal, ceramic, and carbon.

Particulate composites consist of particles immersed in matrices such as alloys and ceramics. They are usually isotropic because the particles are added randomly. Particulate composites have advantages such as improved strength, increased operating temperature, oxidation resistance, etc. Typical examples include use of aluminum particles in rubber; silicon carbide particles in aluminum; and gravel, sand, and cement to make concrete.



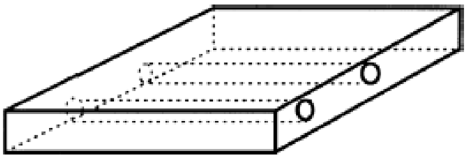
Particulate composites

Flake composites consist of flat reinforcements of matrices. Typical flake materials are glass, mica, aluminum, and silver. Flake composites provide advantages such as high out-of-plane flexural modulus, higher strength, and low cost. However, flakes cannot be oriented easily and only a limited number of materials are available for use.



Flake composites

Fiber composites consist of matrices reinforced by short (discontinuous) or long (continuous) fibers. Fibers are generally anisotropic and examples include carbon and aramids. Examples of matrices are resins such as epoxy, metals such as aluminum, and ceramics such as calcium–alumino silicate. The fundamental units of continuous fiber matrix composite are unidirectional or woven fiber laminas. Laminas are stacked on top of each other at various angles to form a multidirectional laminate.



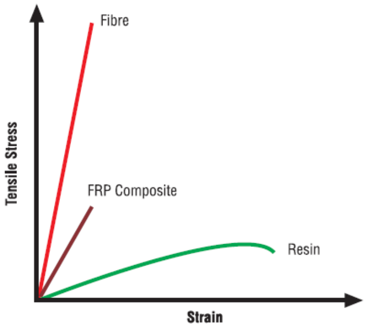
Fiber composites

Nanocomposites consist of materials that are of the scale of nanometers (10^{-9} m). The accepted range to be classified as a nanocomposite is that one of the constituents is less than 100 nm. At this scale, the properties of materials are different from those of the bulk material. Generally, advanced composite materials have constituents on the microscale (10^{-6} m). By having materials at the nanometer scale, most of the properties of the resulting composite material are better than the ones at the microscale. Not all properties of nanocomposites are better; in some cases, toughness and impact strength can decrease. Applications of nanocomposites include packaging applications for the military in which nanocomposite films show improvement in properties such as elastic modulus, and transmission rates for water vapor, heat distortion, and oxygen.

Polymer matrix composites (4)

Resin systems such have limited use for the manufacture of structures on their own, since their mechanical properties are not very high when compared to most metals. However, they have desirable properties, most notably their ability to be easily formed into complex shapes. Materials such as glass, aramid and boron have extremely high tensile and compressive strength but in 'solid form' these properties are not readily apparent. This is due to the fact that when stressed, random surface flaws will cause each material to crack and fail well below its theoretical 'breaking point'. To overcome this problem, the material is produced in fibre form, so that, although the same number of random flaws will occur, they will be restricted to a small number of fibres with the remainder exhibiting the material's theoretical strength. Therefore a bundle of fibres will reflect more accurately the optimum performance of the material. However, fibres alone can only exhibit tensile properties along the fibre's length, in the same way as fibres in a rope. It is when the resin systems are combined with reinforcing fibres such as glass, carbon and aramid, that exceptional properties can be obtained. The resin matrix spreads the load applied to the composite between each of the individual fibres and also protects the fibres from damage caused by abrasion and impact. High strengths and stiffnesses, ease of moulding complex shapes, high environmental resistance all coupled with low densities, make the resultant composite superior to metals for many applications.

Since PMC's combine a resin system and reinforcing fibres, the properties of the resulting composite material will combine something of the properties of the resin on its own with that of the fibres on their own.



Overall, the properties of the composite are determined by:

i) The properties of the fibre

ii) The properties of the resin

iii) The ratio of fibre to resin in the composite (Fibre Volume Fraction)

iv) The geometry and orientation of the fibres in the composite

Designing with composites

Loading - There are four main direct loads that any material in a structure has to withstand: ***tension, compression, shear and flexure.***

Tension

Fig. 1 shows a tensile load applied to a composite. The response of a composite to tensile loads is very dependent on the tensile stiffness and strength properties of the reinforcement fibres, since these are far higher than the resin system on its own.

Figure 1 – Tensile loading

Compression

Figure 2 shows a composite under a compressive load. Here, the adhesive and stiffness properties of the resin system are crucial, as it is the role of the resin to maintain the fibres as straight columns and to prevent them from buckling.

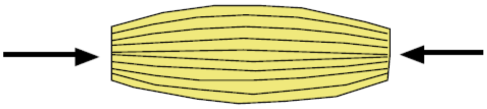


Figure 2 – Compressive loading

Shear

Figure 3 shows a composite experiencing a shear load. This load is trying to slide adjacent layers of fibres over each other. Under shear loads the resin plays the major role, transferring the stresses across the composite. For the composite to perform well under shear loads the resin element must not only exhibit good mechanical properties but must also have high adhesion to the reinforcement fibre. The interlaminar shear strength (ILSS) of a composite is often used to indicate this property in a multi-layer composite (‘laminate’).

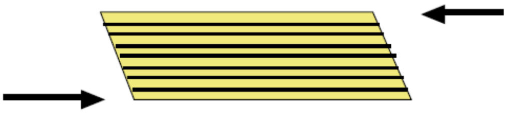


Figure 3 – Shear loading

Flexure

Flexural loads are really a combination of tensile, compression and shear loads. When loaded as shown, the upper face is put into compression, the lower face into tension and the central portion of the laminate experiences shear.

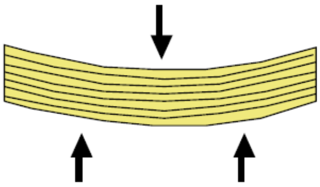


Figure 4 – Flexural loading

Stress strain behavior

The strength of a laminate is usually decided by how much load it can withstand before it suffers complete failure. This ultimate or breaking strength is the point at which the resin exhibits catastrophic breakdown and the fibre reinforcements break. However, before this ultimate strength is achieved, the laminate will reach a stress level where the resin will begin to crack away from those fibre reinforcements not aligned with the applied load, and these cracks will spread through the resin matrix. This is known as **‘transverse micro-cracking’** and, although the laminate has not completely failed at this point, the breakdown process has commenced. Consequently, while designing a long-lasting structure, one must ensure that their laminates do not exceed this point under regular service loads.

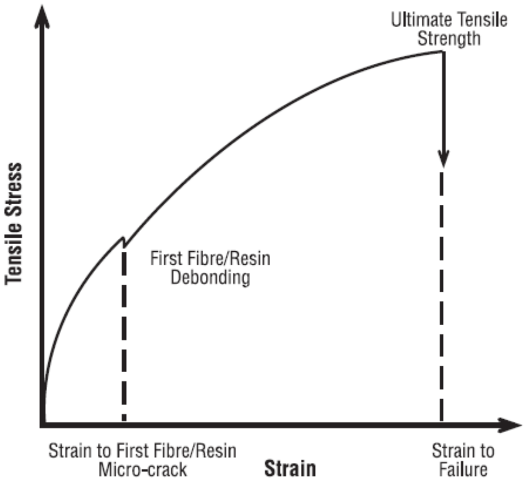


Figure 5 – Typical FRP stress/strain graph

The strain that a laminate can reach before microcracking depends strongly on the toughness and adhesive properties of the resin system. For brittle resin systems, such as most polyesters, this point occurs a long way before laminate failure, and so severely limits the strains to which such laminates can be subjected. As an example, tests have shown that for a polyester/glass woven roving laminate, micro-cracking typically occurs at about 0.2% strain with ultimate failure not occurring until 2.0% strain. This equates to a usable strength of only 10% of the ultimate strength. As the ultimate strength of a laminate in tension is governed by the strength of the fibres, these resin micro-cracks do not immediately reduce the ultimate properties of the laminate. However, in an environment such as water or moist air, the micro-cracked laminate will absorb considerably more water than an uncracked laminate. This will then lead to an increase in weight, moisture attack on the resin and fibre sizing agents, loss of stiffness and, with time, an eventual drop in ultimate properties. Increased resin/fibre adhesion is generally derived from both the resin's chemistry and its compatibility with the chemical surface treatments applied to fibres. Here the well-known adhesive properties of epoxy help laminates achieve higher microcracking strains. Resin toughness can be hard to measure, but is broadly indicated by its ultimate strain to failure. A comparison between various resin systems is shown in Figure 6

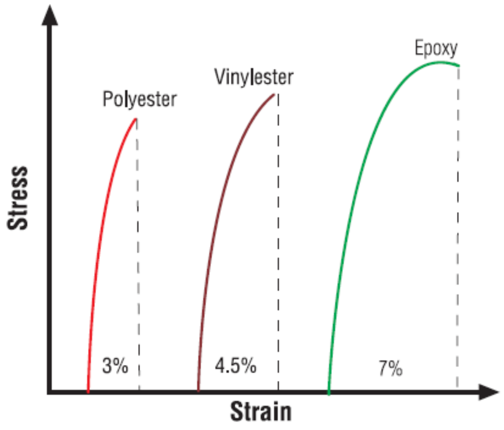


Figure 6 - Typical Resin Stress/Strain Curves (Post-Cured for 5 hrs @ 80°C

It should also be noted that when a composite is loaded in tension, for the full mechanical properties of the fibre component to be achieved, the resin must be able to deform to at least the same extent as the fibre. Figure 7 gives the strain to failure for E-glass, S-glass, aramid and high-strength grade carbon fibres on their own (i.e. not in a composite form). Here it can be seen that, for example, the S-glass fibre, with an elongation to break of 5.3%, will require a resin with an elongation to break of at least this value to achieve maximum tensile properties.

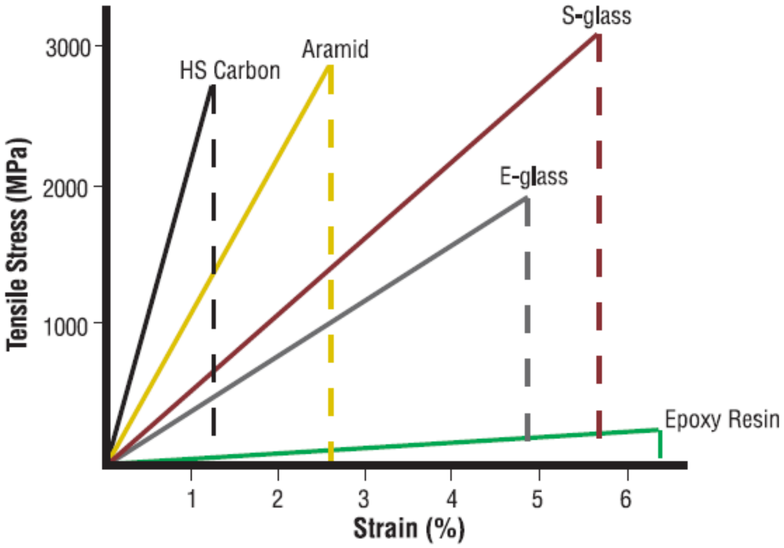
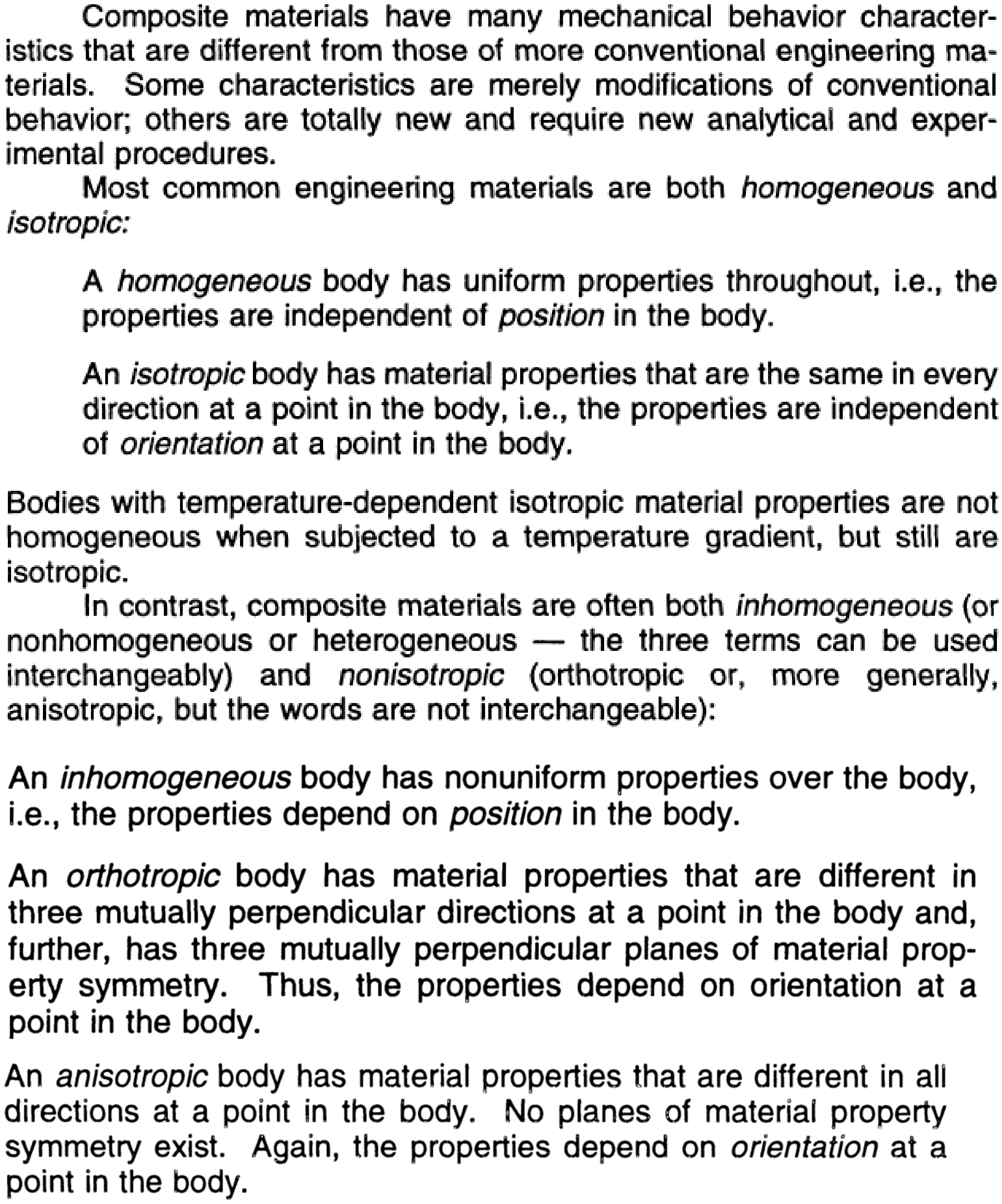


Figure 7 - Typical strains to failure

Mechanical behavior of composite materials (2)

Fundamentals of the mechanical behavior of composites.



Composite materials have many mechanical behavior characteristics that are different from those of more conventional engineering materials. Some characteristics are merely modifications of conventional behavior; others are totally new and require new analytical and experimental procedures.

Most common engineering materials are both *homogeneous* and *isotropic:*

> A *homogeneous* body has uniform properties throughout, i.e., the properties are independent of *position* in the body.
>
> An *isotropic* body has material properties that are the same in every direction at a point in the body, i.e., the properties are independent of *orientation* at a point in the body.

Bodies with temperature-dependent isotropic material properties are not homogeneous when subjected to a temperature gradient, but still are isotropic.

In contrast, composite materials are often both *inhomogeneous* (or nonhomogeneous or heterogeneous — the three terms can be used interchangeably) and *nonisotropic* (orthotropic or, more generally, anisotropic, but the words are not interchangeable):

An *inhomogeneous* body has nonuniform properties over the body, i.e., the properties depend on *position* in the body.

An *orthotropic* body has material properties that are different in three mutually perpendicular directions at a point in the body and, further, has three mutually perpendicular planes of material property symmetry. Thus, the properties depend on orientation at a point in the body.

An *anisotropic* body has material properties that are different in all directions at a point in the body. No planes of material property symmetry exist. Again, the properties depend on *orientation* at a point in the body.

Lamina (1) - A lamina (also called a ply or layer) is a single flat layer of unidirectional fibers or woven fibers arranged in a matrix.

Laminate - A laminate is a stack of plies of composites. Each layer can be laid at various orientations and can be made up of different material systems.

Hybrid laminate - Hybrid composites contain more than one fiber or one matrix system in a laminate. The main four types of hybrid laminates follow.

- *Interply hybrid laminates* contain plies made of two or more different composite systems. Examples include car bumpers made of glass/ epoxy layers to provide torsional rigidity and graphite/epoxy to give stiffness. The combinations also lower the cost of the bumper.
- *Intraply hybrid composites* consist of two or more different fibers used in the same ply. Examples include golf clubs that use graphite and aramid fibers. Graphite fibers provide the torsional rigidity and the aramid fibers provide tensile strength and toughness.
- An *interply–intraply hybrid* consists of plies that have two or more different fibers in the same ply and distinct composite systems in more than one ply.
- *Resin hybrid laminates* combine two or more resins instead of combining two or more fibers in a laminate. Generally, one resin is flexible and the other one is rigid. Tests have proven that these resin hybrid laminates can increase shear and work of fracture properties by more than 50% over those of all-flexible or all-rigid resins.

Mechanics (3)

The mechanics of materials deal with stresses, strains, and deformations in engineering structures subjected to mechanical and thermal loads. A common assumption in the mechanics of conventional materials, such as steel and aluminum, is that they are homogeneous and isotropic continua. For a homogeneous material, properties do not depend on the location, and for an isotropic material, properties do not depend on the orientation. Fiber-reinforced composites, on the other hand, are microscopically inhomogeneous and nonisotropic (orthotropic). As a result, the mechanics of fiber-reinforced composites are far more complex than that of conventional materials. The mechanics of fiber-reinforced composite materials are studied at two levels:

1. The micromechanics level, in which the interaction of the constituent materials is examined on a microscopic scale. Equations describing the elastic and thermal characteristics of a lamina are, in general, based on micromechanics formulations. An understanding of the interaction between various constituents is also useful in delineating the failure modes in a fiber-reinforced composite material.
1. The macromechanics level, in which the response of a fiber-reinforced composite material to mechanical and thermal loads is examined on a macroscopic scale. The material is assumed to be homogeneous. Equations of orthotropic elasticity are used to calculate stresses, strains, and deflections.

References:

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