# Chapter 1

# Basic Principles of Composites

## Composite Materials

***A composite material is a mixture of at least two components.*** One component must be "strong" and stiff and the second component (the "matrix") must be somewhat less stiff, and surrounds the "strong" particles with an intimate bond. In general, the best performing composite materials contain the largest proportion of the "strong" component and the least amount of the "softer" matrix, preferably just enough to wet the fibers and fill the voids. The entire large mass then ***approaches the strength and properties of the strong material alone***.

For our purposes, the ***"strong" component is nearly always in the form of fibers,*** which are very long compared with their diameter. Some practical stiff fibers are glass, cotton (cellulose), and graphite. The ***matrix can be any material which can completely wet and surround the fibers***, bonding them securely. In this book, we will be almost exclusively concerned with the epoxy family of plastics, that is applied as a thin fluid which hardens in place to bond the structure. Practical structures are then built up from as many layers of composite material as needed to carry the design load.

## Composite Skins

For aircraft applications, we will make much use of composite materials which are fabricated into thin sheets, roughly similar to familiar sheets of thin aluminum.  These sheets may be quite strong in tension (like a rope), but, like any thin sheet (or a rope), they bend easily under load and usually require additional support in a practical structure. ***A thin sheet of any practical material cannot support significant compression*** or bending loads.

## *Advanced Composite Techniques*

In this book, we will use thin composite sheets as load-carrying surfaces, or ***skins***, where the thin sheets are bonded to a thick ***core*** of light-weight material to make a ***sandwich***. ***The core acts to constrain the thin skin from buckling under compression. If a thin strong skin is bonded to each side of a thick core, the resulting light-weight panel will be found to be highly resistant to bending and twisting, while the tensile strength remains the same.***

### *A Brief Digression on "Stiffness"*

*Practical materials typically used in successful aircraft structures cover quite a wide range of "stiffness." The reader will repeatedly find discussions in the aviation literature where authors have observed that aluminum has approximately twice the stiffness (modulus) of glass composite and so reach the generalized conclusion that a composite structure must always be more flexible than a corresponding aluminum structure. The fact is that properly designed structures do* ***not*** *correspond and therefore* ***different designs must be used for different materials.*** *An argument based solely on the differences in modulus does not account for the wide success of low-modulus wooden aircraft. The WW II German V-2 rocket successfully used a skin of very thin high modulus steel welded to a dense mesh of supporting stiffeners. We do not see steel aircraft today.*

# *Composite Structures*

Large hollow ***structures***, like wings, cowl covers, and fuselages, can be assembled from a few sandwich panels which may be accurately formed into large subassemblies. Usually, adhesive bonding of the subassemblies is used, so ***loads are distributed*** over large bonding areas, not concentrated as when rivets or bolts are used.

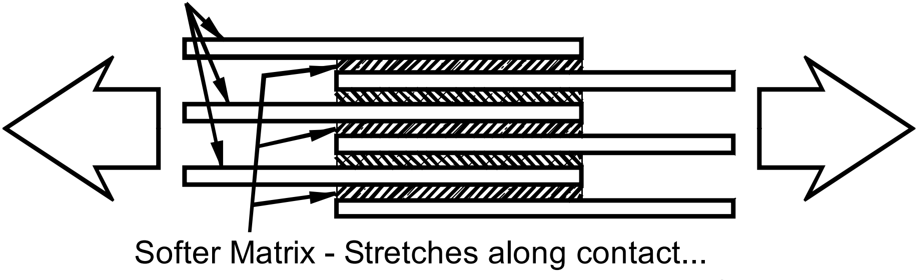
***When a load force is applied to any practical object, the object must elongate or deflect, however slightly. The movement due to the deforming force is called STRAIN.*** If a fly walks over a steel rail, the steel rail must deflect just enough (strain) to develop a counterforce to carry the weight of the fly. With very sensitive instruments, we can weigh the fly by measuring the strain.

If a load force is applied to an area, the ***force per unit area is called STRESS.*** If a tensile force of 2,000 pounds is applied to a shaft with an area of 2 square inches, the ***stress*** is 1,000 pounds per square inch.

We will refer to stress in structures a very great deal in this book, but we should keep in mind that we can ***only measure strain*** when we apply a test force to an object.

The ***ratio of unit stress to unit strain*** is a characteristic of a material and is called the ***modulus of elasticity***, often called ***Young's Modulus***, the ***"stiffness"*** of the material, or just the "modulus." Diamond is a material with a very high "modulus" indeed. Rubber has a very low modulus. Spring steel is stiffer than hardened aluminum, which is stiffer than cured fiberglass. The characteristic is very widely published in engineering handbooks.

Assume for discussion that the "strong" fiber chosen for a composite is an ideal material which has ***infinite stiffness and therefore does not deform under load,*** so that ***all*** of the deflection (strain) must be passed to the matrix that grips the fiber. Assume further that the structure is made up mostly of "ideal" fibers, packed closely. The less-stiff matrix, then, will form a thin film which completely fills the small spaces between fibers. As the surrounding matrix deforms all along the ideal stiff fibers, it passes shear forces to neighboring ideal fibers, which, in turn, pass this strain throughout the structure. ***All of the displacement (strain) in the loaded object then occurs in the matrix,*** but is distributed throughout the huge area of contact between the fiber and the matrix.



How Fiber Composites Work

In a practical composite, the fibers cannot be ideal, and must deform under load to some extent; but the principle works if the fibers are stiffer than the matrix. In practical composites, the strong component is typically at least two to four times stiffer than the matrix.

## Examples of Composites

Composites are very common. Concrete is a composite. The very best concrete consists of a densely packed array (no voids) of nearly round, flawless, granite stones and pebbles, graded down to sand, surrounded by a matrix of Portland cement. Ideally, there will be a minimum thickness of Portland cement required to completely cover every granite particle, so that the well-mixed concrete will have the most granite and the least cement. The resulting structure then approaches the properties of solid granite, except that it has the considerable advantage of being able to be poured into place!

Tough metal alloys and abrasive grinding wheels are composites. In both cases, crystals of extremely hard material are bound in a less-stiff matrix. Asbestos fibers have very high tensile strength and, when mixed in a matrix of Portland cement, make a very good composite that was used for many years in furnace flues until the toxic effects of asbestos became known.

For aircraft applications, we will be mainly concerned with composites made of finely drawn glass fibers (fiberglass) embedded in a matrix of epoxy resin. Other fibers and matrix materials are also important.

## Wood as a Composite

Wood is both a composite and a structure. Under a microscope, wood is seen to be a complex structure of tiny hollow cells. The cell walls are mostly made of strong cellulose fibers embedded (with air and water) in a resinous matrix called lignin. Wood has “grain”; we know that wood is much stronger “with” the grain than “across” it. Bamboo is an excellent example of nature’s efficiency at making very long cellulose columns with a minimum of material. Bamboo is a complex structure of highly oriented fibers, embedded in lignin, and arranged into a hollow tube, with stiffening “panels” at regular intervals.

# Panels

## Thin Panels

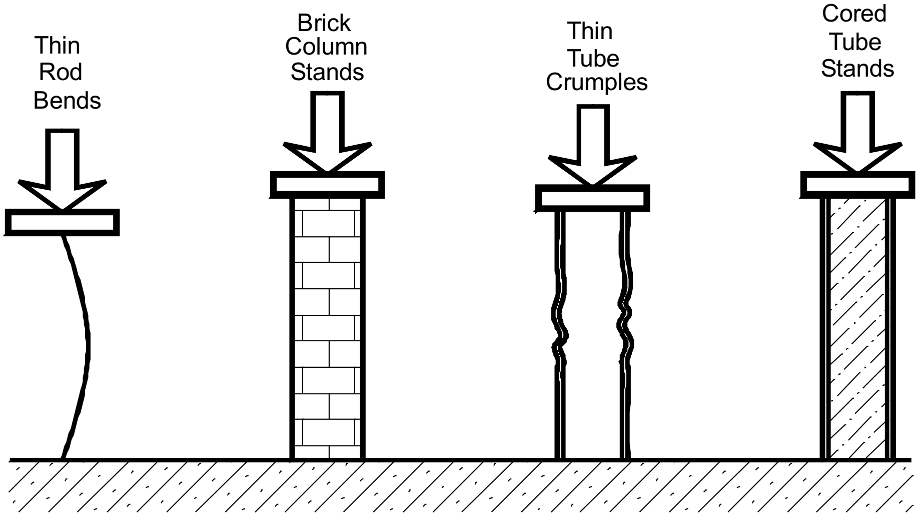
Light-weight aircraft structures require much use of thin panels that cover large areas. In general, some kind of supporting structure is required that collects and concentrates the loads. This is evident in classic fabric-covered aircraft, where most of the skin area of the aircraft consists of strong cloth stretched tightly between rigid supports. Flight loads impressed on the fabric are concentrated and transferred to a system of formers, ribs, bulkheads, and spars. ***A sheet of stretched fabric, like a rope, cannot support a compression load, only tension,*** so necessary compression loads must be carried elswhere by the supporting structure.

***All forces at any point on a free body, including an entire aircraft, must balance to zero***. This means that any ***tensile forces in the body must be balanced somewhere in the structure by resulting compression forces.*** In the case of aircraft with wing struts, like the smaller *Cessnas* or the homebuilt *Tailwind*, flight loads will tend to pull the wings up, placing a lifting load on the strut attachment, so the ***lifting force produces tension in the strut***. The strut is connected to the attachment point at an angle, so there must then be a resulting compression load in the wing (spar), pushing in toward the cabin.

Similarly, where there is a pure bending load, such as outboard of the strut attachment, this bending must be opposed by compression in the top surface of the wing (or spar) and by tension in the bottom surface. The designer must provide sufficient material in the right places and with the right properties to carry all these loads. It happens that ***wood is quite weight-efficient in carrying compression***, which accounts in part for the success of the highly-evolved wood-frame aircraft designs of World War I.

## The Buckling Problem

We know that if we push on the ends of a long, thin, column (like a bamboo stick or a long piece of steel piano wire) it will bend out of the way with a very small load, long before the inherent compression strength of the material is reached. Similarly, if we place a piece of cardboard on a flat surface and push the edges together, the cardboard sheet will wrinkle or bend off of the table easily. This is ***buckling.***



Essentially the same argument can be made for modern light aircraft, which use thin aluminum skins over an aluminum supporting structure: The thin metal skin cannot carry significant compression without buckling, hence the designer must use stiffeners (like "hat sections") to reduce the effective panel size or must carry the compression load elsewhere than in the skin, as with fabric-covered aircraft.

One obvious way to deal with compression buckling is to make the skin thicker. Unfortunately, this adds weight very quickly if the same material is used throughout the thickness of the skin.

***We can make very useful "thin" skins from composite materials,*** and we will give quite a bit of attention to that very goal in this book. These composite thin skins approximately correspond to thin aluminum and, like aluminum, are ***subject to buckling*** when compressed in thin, long sections. Practical structures using thin composite skins can be - and are - designed, but only for applications without compression.

## Torsion

We “wring out” (twist) a wet towel because we wish to generate a high ***compressive*** force on the fabric and drive out the unwanted water. We could squeeze the wet fabric directly between our fingers, but we soon learn that ***twisting generates more compression*** throughout the volume.

***Twisting, or torsion, must be dealt with frequently in aircraft applications and is often the limiting factor in a practical design.*** In fabric-covered aircraft wings, the designer may choose to carry torsion with a series of internal steel bracing wires which run diagonally between the top and bottom of adjacent ribs. In aluminum aircraft, the designer may use stiffening members attached to the thin skin, so that local compression forces will not cause it to buckle.

> ***Torsional rigidity of a structure is sharply dependent on the cross-sectional area of the structure. Therefore, it is beneficial to make as much use as possible of the material at the periphery of the structure — the skin — and that the skin must be capable of carrying a compression load.***

## Sandwich Structures

A ***sandwich structure is a beam*** or panel which uses a thin, strong, skin on ***both*** sides of a core, which is typically of a much lighter material. Modern high-performance skis and snowboards are examples of sandwich construction. Most present-day skis use non-metallic composite skins over a variety of light cores. The first successful “composite” ski, by Head, used aluminum skins bonded to a lighter wooden core, a valid sandwich. (It is interesting that Mr. Head, a non-skier, was an aircraft engineer.)

For aircraft design, the use of sandwich construction gets around the buckling problem by making the effective panel thickness very large without significantly increasing the weight. Basically, the “thin” panel is made “thick” in a very weight-efficient way.

***The essential point of the sandwich is that a very thin (strong) skin is supported by the light-weight core over a very large span so that the skin does not buckle under compression.*** This allows the designer to use sandwich panels in many places in an aircraft where compression loads must be carried, usually simplifying the structure. The effectiveness of this design strategy is generally surprising to the newcomer, who may be familiar only with conventional thin materials. (See Appendix 2 for a discussion of elementary beam theory and an explanation of the theory of the sandwich.)

In this book, most of the attention will be given to the many applications of the sandwich principle and how very well adapted it is to the use of composite materials.

## Attachments - Distributed Loads

The use of composite construction allows the builder to think about the problem of attaching parts in a different way. In a practical aircraft, there are many areas where large subassemblies must be attached to each other: like wings to wingtips or doors to hinges. The ***classical builder thinks in terms of highly stressed parts*** passing concentrated loads, like high-grade bolts in bushings, lines of rivets, and small-area welds. The ***composite builder can often distribute a load over a wide area, greatly reducing local stresses*** and usually avoiding complexity.

***Composite designs lend themselves to the use of very large one-piece subassemblies,*** such as half of an entire fuselage or a control surface which contains no intermediate fasteners at all. These subassemblies may be joined by adhesive bonding over very large areas which permit low stresses.

# Environmental Factors - Postcuring

Composite materials have the great added advantage of being essentially immune to corrosion. They do not rust. They do not absorb water to a significant degree (hence their great success in boats). They are dimensionally stable. They do, however, have lower temperature limits than metals and may be subject to deterioration due to ultraviolet light, unless simple precautions are taken.

The composite materials to be described in this book for use by the home builder require an awareness of temperature limitations. Modern composite materials, ***post-cured*** as described below, retain safe strength in very hot environments, as long as the aircraft is not stored at a temperature which approaches the softening temperature of the matrix. In practice, this would allow storage up to about 140 degrees F. Most builders will agree that this is not an important limitation.

## *Importance of Postcuring*

The home builder will not have access to the expensive tooling and curing ovens used by the mainline aircraft industry. Layups must be made and cured at room temperature. Fortunately, the amateur can get almost as good properties in a cured composite as can the well-tooled professionals by heating the finished part in a temporary home-made oven for several hours, even using solar heating. Postcuring can be done at any time after the initial room-temperature cure, so builders usually find it convenient to postcure several previously cured parts at one time.

Briefly: the process of curing a two-part resin never quite completes over time. Toward the end of the curing process, as the matrix becomes quite solid, any remaining unreacted molecules of the two parts find it much harder to move to combine with a partner. The initially-cured matrix, like most non-crystalline plastics, will have a temperature at which it just begins to flow. Materials scientists call this the ***glass transition temperature***, or tg, comparing the effect to the softening of glass. For the epoxies typically used in aircraft, tg will be about 40 degrees F higher than the temperature at which the sample was cured. ***Postcuring consists of raising the temperature of the workpiece to just below the tg point and holding it for several hours.*** The additional curing that takes place at the higher temperature raises the tg to a new, higher level. (During postcure, the part is softened, so it is subject to deformation and must be held in position by appropriate means.)

# *Basic Materials*

In this book, all of the Exercises and most of the discussion will involve the following materials, all currently widely used for the light-weight structures typical of composite aircraft home building:

## Reinforcing Fibers

The most widely-used fiber is common bottle glass, known as “E-glass,” which is drawn into very fine fibers, then specially coated for adhesion with the matrix, grouped into yarns, and delivered as woven cloth in various weights and types of weave. (See Appendix 3 for a detailed discussion of the fibers and weaves used, including special high-performance fibers, such as S-glass and carbon.)

## Matrix Materials

We will use one of the several two-part epoxy products sold by the aircraft supply houses for the homebuilder trade. (See Appendix 3 for a detailed discussion of matrix materials, including a comparison with the polyester matrix materials widely used in boatbuilding, but not used here.)

## Core Materials

***Foams:*** We will use very light-weight rigid foams as the primary core materials in a structural sandwich. These foams will be used in two ways: (1) to serve as forms that define a shape for a skin which is added after the foam is shaped, and (2) included as a core when forming a sandwich skin, using a mold or “tool”.

### Other Mixes

***Syntactic foam*** is a mixture of the “regular” matrix material used and tiny hollow glass “microballoons,” usually called “glass bubbles” in catalogs. The builder first mixes up a batch of epoxy matrix and stirs it well, then adds several volumes of the extremely light microballons, depending on the application. Builders refer to both the balloons themselves and the mixture as “micro,” for short. Essentially, the microballoons act to dilute and extend the liquid matrix while displacing the much heavier epoxy. The epoxy hardens to create the equivalent of a foam. ***Slurry*** is a thin mixture of epoxy and micro, about 1:1 by volume, which is used to fill and bond the interface between the core and the skin. Slurry can be applied with a paint brush. ***Medium or wet micro,*** 1:2 to 4 by volume, is a mixture with about the consistency of heavy cream which is used to bond pieces of foam as needed. ***"Dry" micro*** or "***paste*** ," 1:5 to 6 by volume, is a thick mixture which will stand up in the mixing cup like peanut butter and is used to repair foam and to fill any voids in a core. It also may be used as a surface filler. (See ***Fillers***, below.) Dry micro may be applied with a trowel or squeegee.

***"Flox"*** is a special case of a core material which is made by mixing cotton linters (essentially individual cellulose fibers) into premixed epoxy to the consistency of peanut butter. The result is a true composite which may be troweled into position and which hardens to form a very strong and tough structure. (Again, builders refer to both the raw, unmixed fibers, and the material when mixed with epoxy, as "flox.") Flox is much too heavy for general use as a core, but is used in special applications, such as pass-throughs for bolts, or for high stress corners. In some applications, weight can be traded for strength by mixing an equal volume of micro with the cotton flox.

## Adhesives

Structural adhesive is a specially formulated two-part epoxy which has the property of extremely good adhesion to cured epoxy. It is also somewhat less stiff than the glass structure it bonds, so that the shearing stress on the joint can be passed into the bonding area. (Chapter 7 explains why this is important.)

## Fillers

***The cured surface of an open layup always leaves the rough pattern of the cloth weave*** and has high and low areas that need to be filled and adjusted to level with a light-weight, easily sanded filling material. The automotive industry offers a wide range of surface filling systems, some of which are applicable to aircraft finishing. Aircraft supply houses offer filling systems specifically designed for composite aircraft.

We will make extensive use of ***automotive polyester body filler***, sold everywhere under the "Bondo" brand, but we ***will not use this material to carry structural loads.*** We will use it ***only*** for temporary jigging and clamping of parts. Variations, which are easier to sand out, are sold as "Non-Clog Lightweight Filler" or "Finishing Paste." The unmixed material is a paste about the consistency of peanut butter, to be mixed with a small amount of catalyst in very small batches, as needed. Setting time is about three minutes after mixing. ***All these materials are styrene-based and will dissolve polystyrene foam core material if they come in direct contact.*** They are entirely satisfactory on poly***urethane*** foam. Polystyrene foam must first be coated with epoxy, to avoid attack by the styrene.

Very dry micro, briefly described above, is an excellent filler, and is light and cheap, but it is quite difficult to handle as a surface filler and most builders try to use some other filling method for surfaces.

## Mold-making Plasters

We need a quick, cheap way to form complex shapes like wingtips and fairings. This shape can then be used to support a layup directly or to make an accurate mold to shape the part. Home supply stores carry a wide range of water-catalyzed products like plaster of paris and its derivatives, patching plaster and drywall compound. Generally, the mold builder will want to use a fast-setting, non-sandable, stable material like plaster of paris or Fixall which has a good proportion of sand in it as a first rough approximation to the desired surface. This surface will be followed by a layer of ***drywall compound, which is readily sandable.*** The expensive auto body finishing materials can then be used to form the final surface.

## Gelcoats: Why Everybody Else Uses Them

In the main-line world of high-production commercial molded composites of such products as boats, shower stalls, car bodies, trash bins, and pretty colors, what the buyer sees as “fiberglass” is the surface ***gelcoat.***

In commercial production, the gelcoat is a ***non-reinforced*** layer, almost always polyester, which is sprayed into the mold as a liquid and forms what will be the finished outside surface. After an initial setup, whatever fiber-reinforced structure  required by the design is added. The gelcoat is usually a special formulation and contains color pigments and ultra-violet inhibitors as well as fillers to reduce cost and increase “stickiness.”

***The advantages of the gelcoat are so great that its use is almost universal in commercial production.*** Any dust or dead bugs that may be around can be safely incorporated in the gelcoat. The fragile mold release film is protected from any shop damage which might be caused by adding the fiber layers. In fact, a large part of commercial fiberglass production is made by "chopper gun," in which chopped glass fiber and catalyzed resin is sprayed into the mold, much like making a gunite swimming pool. Craftsmanship may not be the first priority and weight saving is not thought of. The molding process produces a smooth surface with very low labor cost. Shop manuals for the general trade describe gelcoat tools and techniques at great length.

Gelcoats are used in some kit aircraft production, but with greater attention paid to thickness control and a higher level of craftsmanship.

***We choose not to use gelcoats*** for high-quality homebuilt aircraft for several equally important reasons: weight being one. A small aircraft has a lot of surface area and a 12-mil gelcoat will add about fifty pounds of essentially non-structural weight. Another reason is that we use the epoxy family of matrix materials - rarely polyester - and most available gelcoats are not compatible.

The "price" paid for not using gelcoat is basically more work. Mold release is not as easy and we don't get a "free" finished surface. The reward is lighter, stronger, accurate structures.

The following chapters will describe the special techniques useful in high-performance gelcoat-free homebuilt structures.