Overview of Fiber-Reinforced Composites

1.1 What is a "Composite" Material?

It is reasonable to begin an introduction to composite materials by defining just what these materials are. It turns out, however, that materials technologists are always arguing about such definitions. What is a ceramic, for instance? Ceramists, like most of us always wanting as much turf as possible, sometimes say a ceramic is anything that isn't a metal or an organic. They call silicon carbide (SiC) a ceramic, and most engineers agree – it's hard, brittle, and infusible: these are properties we associate with ceramics. But it's full of carbon. Does this make it an organic? No; even organic chemists who define their field as the chemistry of carbon call SiC a ceramic, feeling in this case that properties outweigh chemical composition in assigning titles. There are a lot of gray areas in materials nomenclature.

Nowhere is this ambiguity more evident than in the modern materials category titled "composites." The name implies that the material is composed of dissimilar constituents, and that is true of composites. But isn't it true of all materials? Even a material as simple as pure hydrogen has a composite chemical constitution of protons and electrons, which in turn are composed of still smaller and dissimilar entities. A certain degree of arbitrariness is required in settling on a working definition for most materials classes, and certainly for composites.

In this text, we will follow a common though far from universal convention that takes "composites" to be materials in which a homogeneous "matrix" component is "reinforced" by a stronger and stiffer constituent that is usually fibrous but may have a particulate or other shape. For instance, the term "FRP" (for Fiber Reinforced Plastic) usually indicates a thermosetting polyester matrix containing glass fibers[1], and this particular composite has the lion's share of today's commercial market. Figure 1 shows a FRP laminate fabricated by "crossplying" unidirectionally-reinforced layers in a 0o-900 stacking sequence.

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[1] The width of the fiber in modern composites is usually in the range of 10-100 μ. (μ, or "micron," is 10^{-6} m. A "mil," or 0.001 inches, is 25.4 μ.) The width scale differentiates composites from reinforced concrete, in which the steel rods reinforcing the cement is approximately ¼".

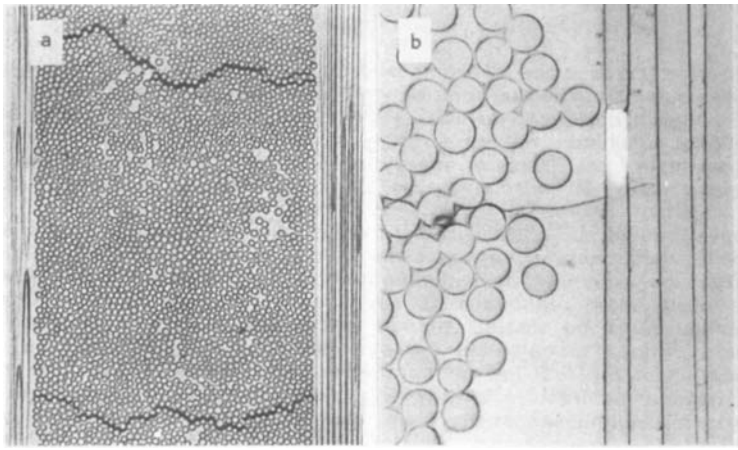

Fig. 1 - A crossplied FRP laminate, showing nonuniform fiber packing and microcracking (from B. Harris, Engineering Composite Materials, The Institute of Metals, London, 1986).

This text will concentrate primarily on fiber-reinforced polymer-matrix composites, with less attention to materials such as rubber reinforced with carbon black or Portland cement reinforced with rock or steel. Both of these are definitely considered to be composites by the communities dealing with them, but they lie outside the arena of composite materials as the term has come to be used today by many practitioners.

As seen in Table 1[2,] the fibers used in modern composites have strengths and stiffnesses far above those of traditional bulk materials. The high strengths of the glass fibers are due to processing that avoids the internal or surface flaws which normally weaken glass, and the strength and stiffness of the polymeric aramid fiber is a consequence of the nearly perfect alignment of the molecular chains with the fiber axis.

Table 1 - Properties of Composite Reinforcing Fibers.

Material	***E*, GPa**	**σ_b, GPa**	**ρ, kg/m^3**	**E/ρ, MJ/kg**	**σ_b/ρ, MJ/kg**	**cost, $/kg**
E-glass	72.4	2.4	2,540	28.5	0.95	1.1
S-glass	85.5	4.5	2,490	34.3	1.8	22-33
aramid	124	3.6	1,440	86	2.5	22-33
boron	400	3.5	2,450	163	1.43	330-440
HS graphite	253	4.5	1,800	140	2.5	66-110
HM graphite	520	2.4	1,850	281	1.3	220-660

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[2] F.P. Gerstle, "Composites," *Encyclopedia of Polymer Science and Engineering,* Wiley, New York, 1991. Here E is the modulus of elasticity, σ_b is the tensile strength, and ρ is the density.

Of course, these materials are not generally usable as fibers alone, and typically they are impregnated by a matrix material that acts to transfer loads to the fibers. The matrix also protects the fibers from abrasion and environmental attack. The matrix dilutes the properties to some degree, but even so very high specific (weight-adjusted) properties are available from these materials. Metal and glass are available as matrix materials, but these are currently very expensive and largely restricted to R&D laboratories. Polymers are much more commonly used, with unsaturated styrene-hardened polyesters having the majority of low-to-medium performance applications and epoxy or more sophisticated thermosets having the higher end of the market. Thermoplastic matrix composites are increasingly attractive materials, with processing difficulties being perhaps their principal limitation.

1.2 Types of Composites

Composites can be categorized using the processing and manufacturing methods used to fabricate them, and this section will give a brief overview of these.

Composites are popular for making prototype parts because a wide variety of shapes can be created quickly and inexpensively. It is required only to configure a bed of fibers in the desired shape, and then impregnate them with a curable thermosetting polymer. Figure 2 illustrates how this might be done simply by placing a woven fabric on a mold constructed from wood or other convenient material. The polymer resin is then rolled or squeegeed into the fabric, and the resin allowed to react chemically ("cure") to a hard matrix. The application of an uncured resin to a dry fabric of fiber preform is called wet hand lay-up. The curing reaction may require elevated temperature, but resins capable of curing at room temperature are widely available. This technique can make a large and complete article, such as a canoe or auto body panel, or also make repairs as filling in a rusted-out portion of a car body.

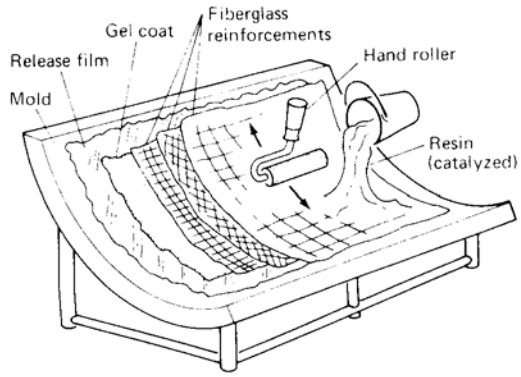

Fig. 2 - Wet hand lay-up process (Lubin, p. 346)

Even in such a simple process, the fabricator quickly learns several points of art: some sort of "release" film or layer must be placed between the mold and the part, since otherwise the part will be glued to the mold and perhaps impossible to remove. A nonreinforced polymer layer, often called a "gel[3] coat" might also be put at the mold side of the part; this creates a smooth surface that may be more attractive than the fiber-containing material. The gel coat might contain a decorative film, such as the logo for a ski or skateboard manufacturer.

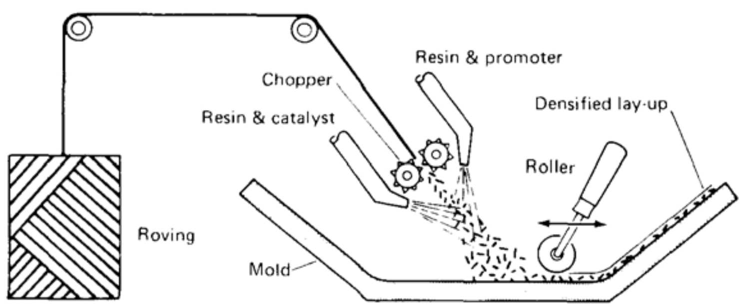

Fig. 3 - Spray-up process (Lubin, p. 351)

The wet hand layup process is uneconomical if many parts are to be manufactured, and an extension of the layup idea leads to the "spray-up" processing shown in Fig. 3. Here resin and curing catalyst is delivered continuously to a nozzle that can be hand-held or moved by suitable machinery. Glass (typically) or other continuous fibers are delivered from creels and chopped to a desired length (usually ~1″) and mixed into the resin. The mixture is then sprayed onto the

[3] The term "gel" appears often in materials engineering, with differing meanings. It usually indicates a material that is insoluble in the other constitutents present.

mold, giving a short-fiber composite with random fiber orientation. Many successful components, such as the body of the famous early Corvette sports car (Fig. 4) used this process.

Fig. 4 – Circa '53 corvette (http://www.glassmandan.com/graphics/05.jpg)

The sprayup process offers little control over fiber placement, and in some applications it is desirable or even necessary to place fibers to achieve a match between the stress within a part – which in general is different in different directions – with the anisotropic strengths offered by composites. One way to do this is by procuring sheets (called "lamina," or "plies") of oriented and collimated fibers that have been "preimpregnated" by uncured resin. This material, termed "prepreg," is manufactured by firms that have developed specialized and often proprietary equipment for this purpose. Prepreg material can be obtained in both a unidirectionally reinforced form (called prepreg tape) and prepreg fabric.

Since the prepreg resin is reactive, the material is kept in a freezer to suppress cure until the part is to be produced. At the appropriate time, prepreg is removed from the freezer, usually allowed to warm (moisture condensation is often a problem), cut into pieces of the needed size, and then "laid up" to produce a "laminate" in which each lamina is oriented in the appropriate direction (see Fig. 5). The procedure for determining the layup sequence (how many layers, of which material, in what direction) will be presented in later lectures.

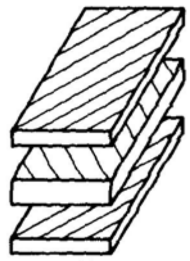

Fig. 5 – A multi-ply laminate composed of individual laminae, each possibly of a different material and oriented in different directions.

The laid up but uncured laminate, which by now may represent a substantial monetary investment, must then be cured. This generally requires raising the temperature to cause the chemical curing reaction to proceed at reasonable speed, and in addition pressure must usually be applied to the laminate in order to drive out entrapped air and to suppress bubble formation by volatiles (water in particular) that are also entrapped within the laminate. The development of the appropriate "cure cycle" (the time dependence of temperature and pressure needed to give a fully cured and void-free laminate) is a vital but often difficult part of composites processing.

Equipment capable of controlling the temperature and pressure applied to a laminate might be quite simple or terrifically complex and expensive. At the simple end of the expense spectrum, cure can be achieved by constructing a frame capable of holding the part, electrical resistive heating tape, and a fire hose. When pressure is needed, water is admitted to the fire hose, giving approximately 50 psig consolidation pressure. At the expensive end of the spectrum – and widely used in aircraft manufacturing – the part is placed in a bag that can be connected to a vacuum. This gives atmospheric pressure only, but can be augmented by pressure supplied by an autoclave. Figure 6 shows a schematic of the autoclave process, which also shows some of the auxiliary components such as a coarse-weave "bleeder" fabric that can help remove volatiles and excess resin from the laminate.

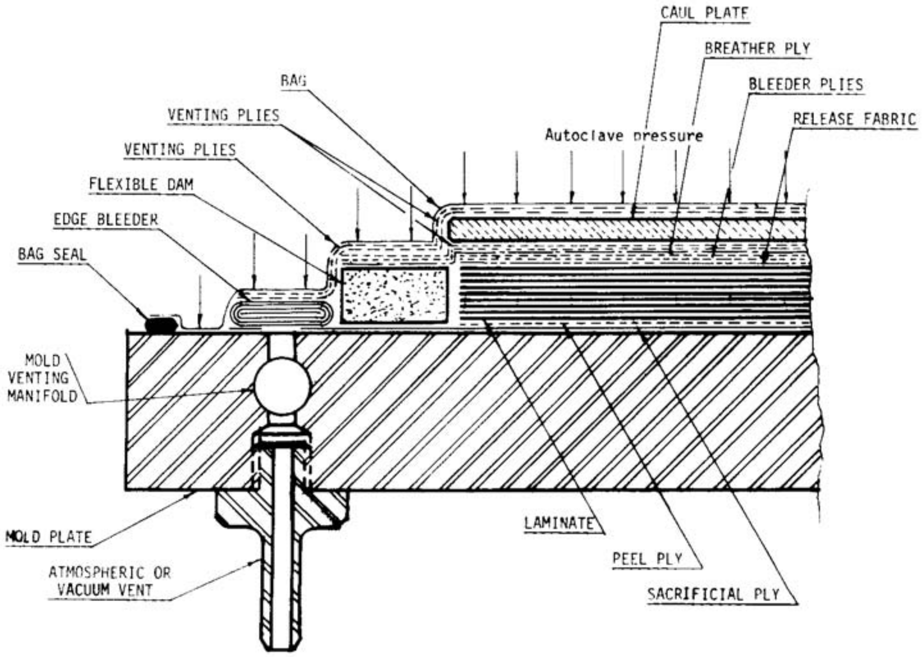

Figure 6 - Autoclave molding (G. Lubin, ed., *Handbook of Composites*, Van Nostrand, New York, 1982, p. 370

Autoclaves large enough to hold a part as large as an aircraft wing are a multimillion-dollar investment, and it is important to schedule its use optimally. The arrival of prepreg must be scheduled carefully to avoid excess freezer costs caused by too-early delivery, or autoclave costs when a delay from too-late arrival occurs. Clearly, this is an important area for modern industrial engineering management methods.

Another way to get fibers placed in a polymer matrix is to put them there one at a time – or almost, anyway. If the part to be made is circular or oval in cross-section, this can be done by "winding" fibers around a "mandrel" of the desired shape as shown if Figure 7.

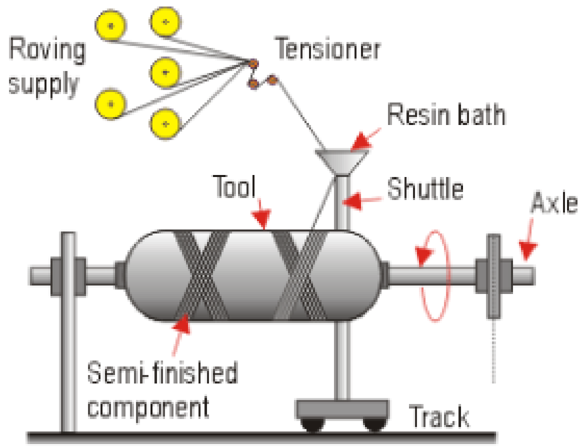

Figure. 7 – from Azom.com web site

This is obviously a rather expensive process also, but less so than running a large autoclave. Filament winding has been used for large rocket motor cases since shortly after World War II, including the Polaris submarine-launched ballistic missiles (Figure 8). It has also proven competitive in the manufacture of drive shafts in large truck tractors.

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Figure 8 - Lockheed Martin Missiles & Space/ US NAVY Polaris A3 in Highbay, Lockheed Martin Missiles & Space, Sunnyvale, Ca.

1.3 Why Use Composites?

Materials are selected for a given application based principally on the material's *properties*. Most engineering structures are required to bear loads, so the material property of greatest interest is very often its *strength*. Strength alone is not always enough, however, as in aircraft or many other structures a great penalty accompanies weight. It is obvious an aircraft must be as light as possible, since it must be able to fly. As another example, a bicyclist wants her bicycle to be light, since that makes it easier to climb hills (and to carry it upstairs to keep it from being stolen).

In some other applications, the importance of light weight is not so obvious: consider an energy-storage flywheel (see Figure 9), which can store energy in a kinetic form via the inertia of a rotating mass. Some subway cars use this approach in regenerative braking: as the car brakes to a stop at the station, motor/generators driving the wheels are used in a generator mode to supply current to the flywheel motor. This causes the generator shaft to apply a braking resistance to the wheel, and the generated current speeds up the flywheel and raises its kinetic energy. When the subway car wishes to accelerate back up to speed, the flywheel motor is switched to generator mode and used to supply current back to the wheel motors; the original kinetic energy of the car is thus saved for later reuse rather than dissipating it as heat in conventional braking.

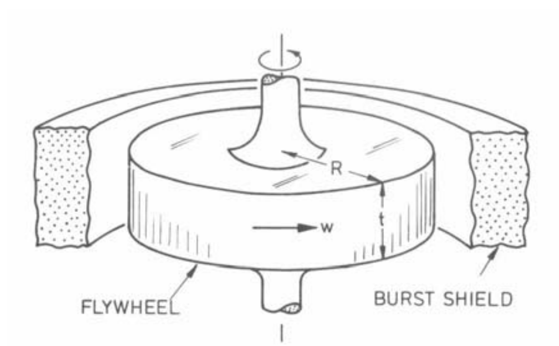

Figure 9 – An energy-storage flywheel (Ashby).

For the highest electromechanical efficiency, we wish to select a flywheel material that maximizes the stored kinetic energy per unit mass of the wheel. The kinetic energy U of a rotating mass is given by

$$U = \frac{1}{2} I \omega^2 = \frac{1}{2}\left(\frac{\pi}{2}\rho R^4 t\right)\omega^2$$

where I is the flywheel's polar moment of inertia, ρ is the material's mass density, R is the outer radius, t is the thickness, and ω is the rotational speed. The mass m is the flywheel volume times the density:

$$m = \pi R^2 \cdot t \cdot \rho$$

so the energy per unit mass is

$$\frac{U}{m} = \frac{1}{4} R^2 \omega^2$$

It appears that maximum energy efficiency is obtained by making both R and ω as large as possible. However, both of these factors also increase the stress within the wheel, as given by the relation

$$\sigma_p = \left(\frac{3+\nu}{8}\right)\rho R^2 \omega^2$$

where σ_p is the maximum principal stress and ν is the material Poisson ratio, near 0.3 for many materials. Hence R and ω cannot be increased arbitrarily, since eventually the stress will exceed the failure stress σ_f of the material and the flywheel will fail. If the principal stress is set equal to the failure stress and the factors $R\omega$ are eliminated between the two previous expressions, the maximum energy density available for a homogeneous isotropic material is

$$\frac{U}{m} = \frac{\sigma_f}{\rho} \cdot \left(\frac{2}{3+\nu}\right).$$

Considering ν to be approximately constant for materials of consideration, it is evident that a material should be selected to give as high a ratio of σ_f/ρ as possible.

High strength at low weight is perhaps the principal advantage of fiber composites, as shown in the "Ashby Plot" of Fig. 10. Note the line labeled σ_f/ρ in this plot of strength vs. density; materials lying along this line all have equal strengths per unit weight. Materials having the greatest strength-weight advantage are those as far as possible to the upper left of the plot, perpendicularly to the σ_f/ρ line. Ceramics excel if the loads are compressive, but these materials are brittle and have low tensile strengths. Hence we disregard ceramics for flywheels, and then engineering composites are the champions with regard to tensile strength per unit weight.

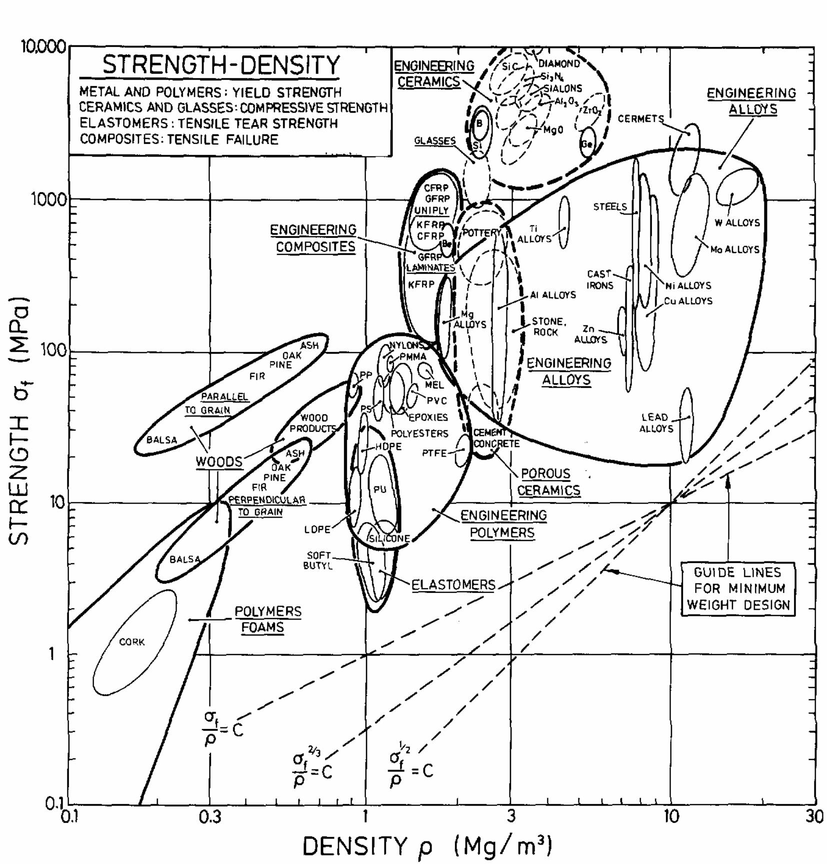

Fig. 10 - M.F. Ashby, *Materials Selection in Mechanical Design*, Pergamon Press, Oxford, 1992.

1.4 The Market for Composites

Many composites used today are at the leading edge of materials technology, with performance and costs appropriate to ultrademanding applications such as spacecraft. But heterogeneous materials combining the best aspects of dissimilar constituents have been used by nature for millions of years – trees employ cellulosic fibrous components to reinforce a lignin matrix, and arrange the strong fibers in just the correct direction to withstand loads from wind and other environmental sources. Ancient society, imitating nature, used this approach as well: the Book of Exodus speaks of using straw to reinforce mud in brickmaking, without which the bricks would have almost no strength.

The modern use of fiber-reinforced polymer composites began in the years near World War II, with early applications being rocket motor cases and radomes using glass fibers. The Chevrolet Corvette of the 1950's had a fiberglass body (they still do), which wasn't always easy to repair after a collision but did offer an escape from the rusting that afflicts most car bodies.

Growth of the market for composites has been very good overall since the 1960's, averaging around 15% per year (compared with 11% for plastics, 6½% for chemicals, and 3½% for the Gross Domestic Product)[4]. By 1979 composites of all types totaled approximately 8 billion pounds, with a value of about 6 billion dollars.

Materials selection has always involved a number of compromises for the engineering designer. Of course, the material's properties are extremely important, since the performance of the structure or component to be designed relies in the properties of the material used in its construction. However, properties come at a cost, and the engineer must balance cost factors in making a materials selection. Cost includes not only the base cost of the material itself, but also factors that affect cost indirectly. Advanced materials almost always cost more: they are more expensive on a per-pound basis, they can require extra training to learn new design procedures, the processing can require new tooling and personnel training, and there may be expensive safety and environmental-impact procedures. The improved properties of the material must be able to justify these additional costs, and it is common for the decision to be a difficult one.

In the years following their expansion into mainline engineering applications, composites' cost has been dominated by economies of scale: materials produced in relatively small quantities require more expensive handwork and specialty tooling than traditional materials such as steel and aluminum, and are more expensive for this reason alone. This leads to a chicken-and-egg situation in which a new material is not used because it is too expensive, but its costs remain high largely because it is not produced in sufficient quantities. Partly as a result of this, the composites community has had a kind of evangelical outlook, with materials entrepreneurs touting the many advantages composites could bring to engineering design if they were used more aggressively. The drawbacks of composites, most of which result in increased costs of one sort or another, have kept the material from revolutionizing engineering design. At the same time, the advantages of composites are too compelling to ignore, and they have continued to generate good though not superlative growth rates, on the order of 10-15% per year.

1.5 When to Consider Composites

Composites bring many performance advantages to the designer of structural devices, among which we can list:

[4] Lubin, *Handbook of Composites*

- Composites have high stiffness, strength, and toughness, often comparable with structural metal alloys. Further, they usually provide these properties at substantially less weight than metals: their “specific” strength and modulus per unit weight is near five times that of steel or aluminum. This means the overall structure may be lighter, and in weight-critical devices such as airplanes or spacecraft this weight savings might be a compelling advantage.

- Composites can be made *anisotropic*, i.e. have different properties in different directions, and this can be used to design a more efficient structure. In many structures the stresses are also different in different directions; for instance in closed-end pressure vessels – such as a rocket motor case – the circumferential stresses are twice the axial stresses. Using composites, such a vessel can be made twice as strong in the circumferential direction as in the axial.

- Many structures experience *fatigue* loading, in which the internal stresses vary with time. Axles on rolling stock are examples; here the stresses vary sinusoidally from tension to compression as the axle turns. These fatigue stresses can eventually lead to failure, even when the maximum stress is much less than the failure strength of the material as measured in a static tension test. Composites of then have excellent fatigue resistance in comparison with metal alloys, and often show evidence of accumulating fatigue damage, so that the damage can be detected and the part replaced before a catastrophic failure occurs.

- Materials can exhibit *damping*, in which a certain fraction of the mechanical strain energy deposited in the material by a loading cycle is dissipated as heat. This can be advantageous, for instance in controlling mechanically-induced vibrations. Composites generally offer relatively high levels of damping, and furthermore the damping can often be tailored to desired levels by suitable formulation and processing.

- Composites can be excellent in applications involving sliding friction, with tribological (“wear”) properties approaching those of lubricated steel.

- Composites do not rust as do many ferrous alloys, and resistance to this common form of environmental degradation may offer better life-cycle cost even if the original structure is initially more costly.

- Many structural parts are assembled from a number of subassemblies, and the assembly process adds cost and complexity to the design. Composites offer a lot of flexibility in processing and property control, and this often leads to possibilities for part reduction and simpler manufacture.

Of course, composites are not perfect for all applications, and the designer needs to be aware of their drawbacks as well as their advantages. Among these cautionary notes we can list:

- Not all applications are weight-critical. If weight-adjusted properties not relevant, steel and other traditional materials may work fine at lower cost.

- Anisotropy and other "special" features are advantageous in that they provide a great deal of design flexibility, but the flip side of this coin is that they also complicate the design. The well-known tools of stress analysis used in isotropic linear elastic design must be extended to include anisotropy, for instance, and not all designers are comfortable with these more advanced tools.

- Even after several years of touting composites as the "material of the future," economies of scale are still not well developed. As a result, composites are almost always more expensive – often much more expensive – than traditional materials, so the designer must look to composites' various advantages to offset the extra cost. During the energy-crisis period of the 1970's, automobile manufacturers were so anxious to reduce vehicle weight that they were willing to pay a premium for composites and their weight advantages. But as worry about energy efficiency diminished, the industry gradually returned to a strict lowest-cost approach in selecting materials. Hence the market for composites in automobiles returned to a more modest rate of growth.

- Although composites have been used extensively in demanding structural applications for a half-century, the long-term durability of these materials is much less certain than that of steel or other traditional structural materials. The well-publicized separation of the tail fin of an American Airlines A300-600 Airbus (see Fig. 12) after takeoff from JFK airport on November 12, 2001 is a case in point. It is not clear that this accident was due to failure of the tail's graphite-epoxy material, but NASA is looking very hard at this possibility. Certainly there have been media reports expressing concern about the material, and this points up the uncertainty designers must consider in employing composites.

Fig. 12 – the A300-600 Airbus.