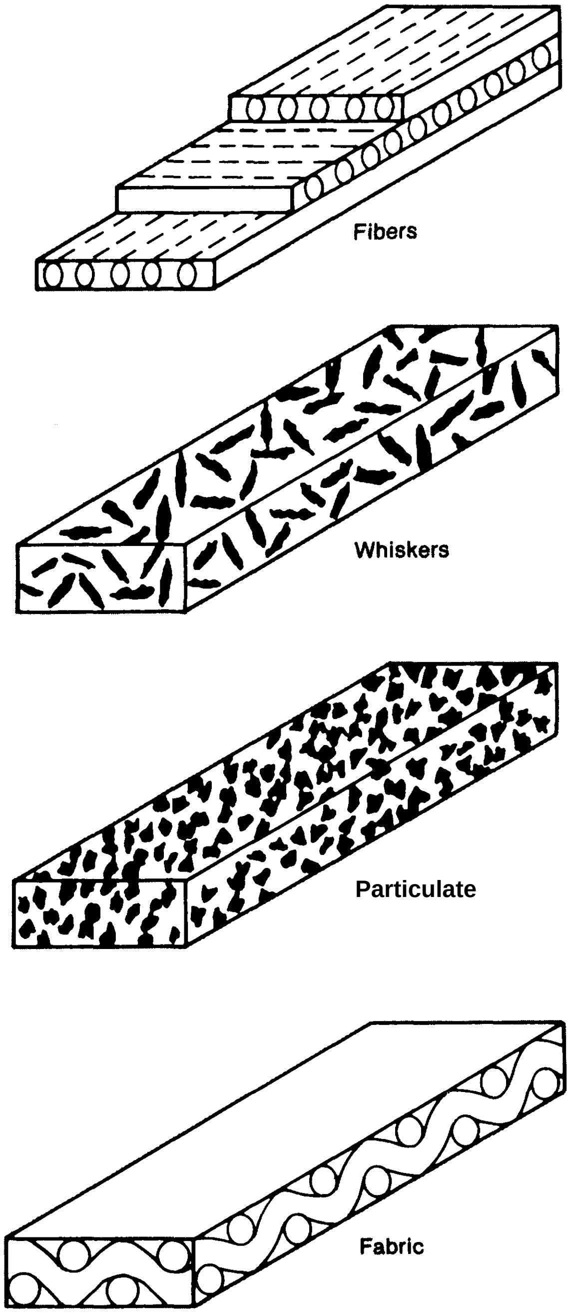
POLYMER MATRIX COMPOSITES

Unlike a ceramic matrix composite, in which the reinforcement is used primarily to improve the fracture toughness, the reinforcement in a polymer matrix composite (PMC) lends strength and stiffness to the relatively weak matrix. The composite is designed so that the mechanical loads to which the structure is subjected in service are supported by the reinforcement. The function of the matrix is to bond the fibers together and to transfer loads between them. As with ceramic matrix composites, the reinforcement may consist of particles, whiskers, fibers, or fabrics, as shown in figure ***6.***

Polymer matrix composites are often divided into two categories: reinforced plastics, and "advanced composites. " The distinction is based on the level of mechanical properties (usually strength and stiffness); however, there is no unambiguous line separating the two. Reinforced plastics, which are relatively inexpensive, typically consist of polyester resins reinforced with low-strength glass fibers (E-glass); they have been in use for ***30*** to ***40*** years in applications such as boat hulls, corrugated sheet, pipe, automotive panels, and sporting goods. Advanced composites, which have been in use for only about 15 years, primarily in the aerospace industry, consist of fiber and matrix combinations which yield superior strength and stiffness. They are relatively expensive and typically contain a large percentage of high-performance continuous fibers, such as high-strength glass (S-glass), graphite, aramid, or other organic fibers. In this report, market opportunities for both reinforced plastics and advanced composites are considered.

The properties of the composite depend *on* the matrix, the reinforcement, and the boundary layer between the two, called the "interphase." Consequently, there are many variables to consider when designing a composite. These include the type of matrix, the type of reinforcement, their relative proportions, the geometry of the reinforcement, and the nature of the interphase. Each of these variables must be carefully controlled in order to produce a structural material optimized for the conditions under which it is to be used.

Figure 6.—Composite Reinforcement Types



SOURCE: Carl Zweben, General Electric Co

The use of continuous fiber reinforcement confers a directional character (“anisotropy”) to the properties of composites. PMCs are strongest when stressed parallel ***(O o)*** to the direction of the fibers (longitudinal direction), and weakest when stressed perpendicular ***(90°)*** to the fibers (transverse direction). In practice, most structures are subjected to complex loads, necessitating the use of fibers oriented in several directions (e. g., 0°, + / ***–45°, 900).*** However, PMCs are most efficiently used in applications which can take advantage of the inherent anisotropy of the materials, as shown in figure 7, which compares the strength and stiffness of composites with various metals.

When discontinuous fibers or particles are used for reinforcement, the properties tend to be more isotropic, since the reinforcement direction is not as well defined. Such composites lack the outstanding strength of continuous fiber PMCs, but they can be produced more cheaply, using the technologies developed for unreinforced plastics, such as extrusion, injection molding, and compression molding. Sheet molding compound (SMC, figure 7) is such a material, which is widely used in the automotive industry.

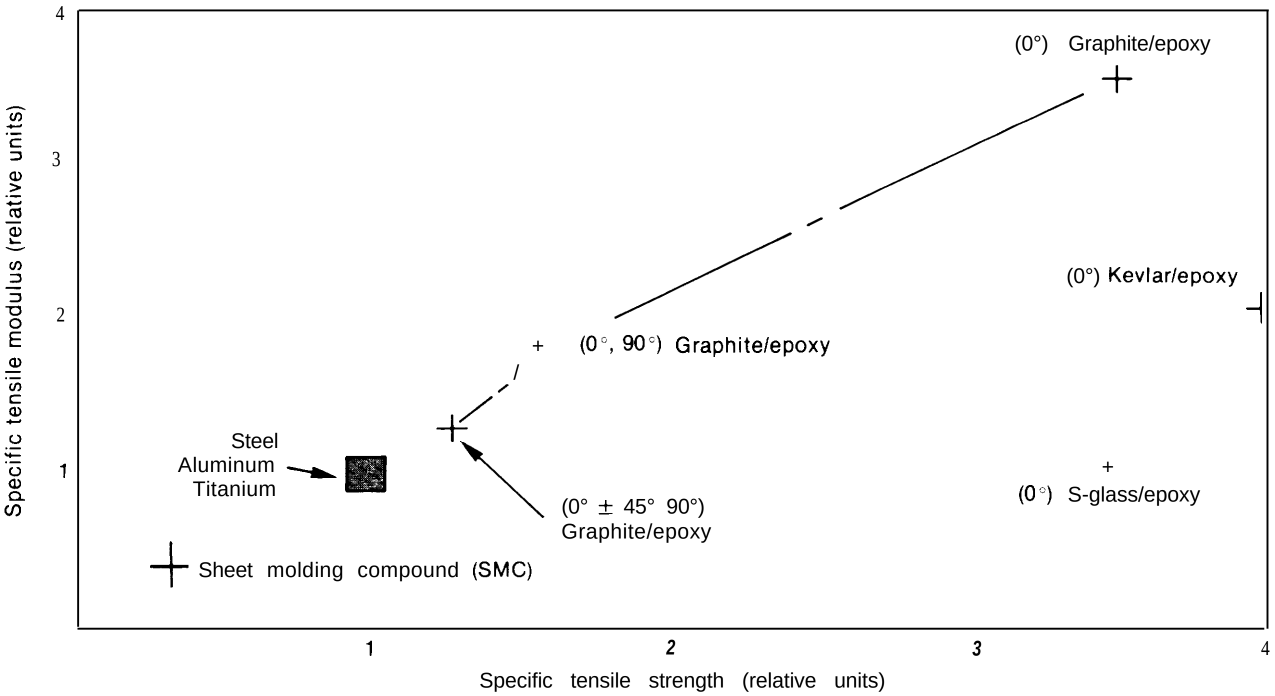
The Polymer Composites Industry

The reinforced plastics/composites industry today encompasses a very broad range of materials, products, and manufacturing processes. About ***85*** percent of the material used is glass fiber-reinforced polyester resin (often called fiber-reinforced plastic, or FRP).[1] FRP is fabricated by a number of processes to produce a great variety of products, some of which are noted above.

Less than 2 percent of the material used in the reinforced plastics/composites industry goes into

[1] Reginald B. Stoops, R.B. Stoops & Associates, Newport, RI, “Manufacturing Requirements of Polymer Matrix Composites, ” contractor report prepared for the Office of Technology Assessment, December 1985.

Figure 7.–Comparison of the Specific Strength and Stiffness of Various Composites and Metals (Steel: AISI 4340; Aluminum: 7075-T6; Titanium: Ti-6A1-4V) Specific Properties are Ordinary Properties Divided by Density. Angles Refer to the Directions of Fiber Reinforcement



SOURCE Carl Zweben, General Electric Co

"advanced composites" for use in "high-tech" applications such as aircraft and aerospace.[2] In 1984, the world produced some 22 million pounds of advanced composite materials, mostly in the United States. The total value of fabricated parts was about $1.3 billion split among four major consuming industries: aerospace (60 percent), sports equipment (20 percent), and industrial and automotive (15 percent).[3]

It has been estimated that advanced polymer composites will grow at the relatively high rate of about 15 percent per year in the next few years, with the fastest growing sector being the aerospace industry at 22 percent. By 1995, consumption is forecast to be 110 million pounds with a value in 1985 dollars of about $6.5 billion. By the year 2000, consumption is estimated to be 200 million pounds valued at about $12 billion.[4]

If we divide these numbers to get a rough idea of the cost per pound of advanced composite material, we find a value of about $60/pound. This compares with a value of about $1/pound for steel or $1 .50/pound for FRP. If these forecasts are correct, it is clear that over this period advanced composites will be used primarily in high value-added applications which can support this level of material costs. However, we shall see that use of composites can lead to cost savings in manufacturing and service. Thus, the per-pound cost is rarely a useful standard for comparing advanced composites with traditional materials.

[2]Ibid, These are primarily epoxy matrices reinforced with carbon fibers.

[3]According to the market research firm, Strategic Analysis (Reading, PA) as reported in *High Technology,* May 1986, p. 72. Advanced composites were defined as those reinforced with S-glass or superior fibers.

[4]"Industry News, " *SAMPE Journal,* July August 1985, p. 89.

Composite Constituents

Matrix

The matrix determines the resistance of the composite to most of the degradative processes which eventually cause failure of the structure, including impact damage, delamination, water absorption, chemical attack, and high-temperature creep. Thus, the matrix is typically the "weak link" in the composite structure.

The matrix phase of commercial composites can be classified as either "thermoset" or "thermoplastic. " The general characteristics of each matrix type are shown in figure 8; however, recently developed matrix resins have begun to change this picture, as noted below.

Thermosets. -Thermosetting resins include polyesters, vinylesters, epoxies, bismaleimides, and polyamides. Thermosetting polyesters are commonly used in FRPs, and epoxies make up most of the current market for advanced composite resins. Initially, the viscosity of these resins is low; however, these matrix materials undergo chemical reactions which crosslink the polymer chains, and thus connect the entire matrix together in a three-dimensional network. This process is called "curing. " Thermoses, because of their three-dimensional crosslinked structure, tend to have high dimensional stability, high temperature resistance, and good resistance to solvents. Recently, considerable progress has been made in improving the toughness of thermosets.[5]

[5]Norman J. Johnston, "Synthesis and Toughness Properties of Resins and Composites, " CP 2321, National Aeronautics and Space Administration, 1984.

Figure 8.—Comparison of General Characteristics of Thermoset and Thermoplastic Matrices

Resin type	Process temperature	Process time	Use temperature	Solvent resistance	Toughness
Thermoset	Low	High	High	High	Low
Toughened thermoset	↑			↑	
Lightly crosslinked thermoplastic		1	t		1
Thermoplastic	High	Low	Low	Low	High

SOURCE Darrel R Tenney NASA Langley Research Center

Thermoplastics.—Thermoplastic resins, sometimes called engineering plastics, include some polyesters, polyetherimide, polyamide imide, polyphenylene sulfide, polyether ether ketone (PEEK), and liquid crystal polymers. They consist of long, discrete molecules which melt to a viscous liquid at the processing temperature, typically **5000** to **700°** F **(260°** to 3710 C), and, after forming, are cooled to an amorphous, semicrystalline, or crystalline solid. The degree of crystallinity has a strong effect on the final matrix properties. Unlike the curing process of therrnosetting resins, the processing of thermoplastics is reversible, and, by simply reheating to the process temperature, the resin can be formed into another shape if desired. Thermoplastics, while generally inferior to thermosets in high-temperature strength and chemical stability, are more resistant to cracking and impact damage. However, it should be noted that recently developed high-performance thermoplastics such as PEEK, which have a semicrystalline microstructure, exhibit excellent high-temperature strength and solvent resistance.

Thermoplastics offer great promise for the future from a manufacturing point of view, since it is easier and faster to heat and cool a material than it is to cure it. This makes thermoplastic matrices attractive to high-volume industries such as the automotive industry. Currently, thermoplastics are used primarily with discontinuous fiber reinforcements such as chopped glass or carbon/graphite. However, there is great potential for high-performance thermoplastics reinforced with continuous fibers. For example, thermoplastics could be used in place of epoxies in the composite structure of the next generation of fighter aircraft.

Reinforcement

The continuous reinforcing fibers of advanced composites are responsible for their high strength and stiffness. The most important fibers in current use are glass, graphite, and aramid (other organic fibers, such as oriented polyethylene, are also becoming important). Advanced composites contain about **60** percent of reinforcing fiber by volume. The strength and stiffness of some continuous fiber composites are compared with those of sheet molding compound and various metals in figure 7. For example, unidirectional, high strength graphite/epoxy has over three times the specific strength and stiffness of common metal alloys.

Of the continuous fibers, glass has a relatively low stiffness; however, its tensile strength is competitive with the other fibers and its cost is dramatically lower. This combination of properties is likely to keep glass fibers the most widely used reinforcement for high-volume commercial composite applications. Only when stiffness or weight are at a premium will aramid and graphite fibers be used.

Interphase

The interphase of composites is the region where loads are transmitted between the reinforcement and the matrix. The extent of interaction between the reinforcement and the matrix is a design variable, and may vary from strong chemical bonding to weak frictional forces. This can often be controlled by using an appropriate coating on the reinforcing fibers. Generally, a strong interracial bond makes the composite more rigid, but brittle; a weak bond decreases stiffness, but enhances toughness. If the interracial bond is not at least as strong as the matrix, fracture and delamination will occur at the interphase under certain loading conditions. Frequently, the most desirable coupling is intermediate between the strong and weak limits. The bond is also critical to the long-term stability of the composite, playing a key role in fatigue properties, environmental behavior, and resistance to hot-wet conditions.

Properties of Polymer Composites

Composites are designed materials. This is really the fact that underlies their usefulness. Given the spectrum of matrix and reinforcement materials available, the composite properties can be optimized for a specific application. A composite can be designed to have zero coefficient of thermal expansion. It can be reinforced with combinations of fiber materials (hybrid composites) and geometries in order to optimize performance and minimize cost. The inherent anisotropy of the material means that the composite can have different properties in different directions. The design opportunities of PMC materials are just beginning to be realized.

Design, Processing, and Testing of Polymer Matrix Composites

Composites Design

Because of their larger number of components and anisotropic properties, polymer composites are inherently more complex than metals. In fact, composites are more accurately characterized as customized structures rather than materials. While the engineering properties of the homogeneous resins and fibers can be determined, the properties of the composite depend on the composition, fiber geometry, and the nature of the interphase. The categories of mechanical and physical properties used to characterize composites are carried over from the long engineering experience with metals. In many cases, however, properties which are meaningful in metals are not meaningful in composites. “Toughness” is such a property. In metals, where the dynamics of crack propagation and failure are relatively well understood, toughness can be defined relatively easily. In a composite, however, toughness is a complicated function of the matrix, fiber, and interphase, as well as the reinforcement geometry. The shear and compression properties of composites are also poorly defined.

In spite of many years of discussion about standardized test methods for measuring engineering properties, the composites community has not been able to reach a consensus on what it is that the existing tests actually measure. The Army’s Materials Technology Laboratory (Watertown, Massachusetts) is currently developing MIL-17, a handbook on advanced composites which will begin to address the questions of how data on composites can be obtained and reported. At present, each company qualifies its material for each separate aerospace or defense application according to its own individual tests and procedures. Data on material properties are often developed under government contract (costing $100,000 to $200,000 and taking about 1 year), and companies are reluctant to share the results. Even when data are reported in the literature, the type of test used and the statistical reliability of the results are not reported with the data. While the lack of standards probably does not inhibit the expert designer of composite aerospace structures, standards could encourage the use of composites in industries such as construction, where designers have no familiarity with the materials.

Computer-Aided Design.—Inasmuch as composites are tailored to meet the design requirements of a particular structure, designers must rely on computer models to analyze and predict the behavior of composite structures using a database containing the properties of the resins, fibers, and unidirectional composites. Such models presuppose a scientific understanding of the underlying physical, chemical, and mechanical processes within the composite at a microscopic level, and the relations between these and the macroscopic properties. In general, this understanding does not exist; the most critical needs in this area are discussed below in the section on research and development priorities.

A number of models exist today to address the needs of composites designers. Elastic behavior modeling is fairly advanced, with programs available to analyze stress distributions and elastic deformation in complex three-dimensional shapes. Several models exist to predict failure in composite structures where the characteristics of the critical flaws are known. These are based on Linear Elastic Fracture Mechanics (LEFM), a body of theory developed to predict fracture in metals. Extension of LEFM to composites is controversial today, because the failure modes of composites are more complex than metals. Very little work has been done in modeling the long-term behavior of composites; for example, in the areas of fatigue, creep, and environmental degradation. Part of the reason for this is the lack of data on which to test and validate models.

In spite of the lack of modeling capability, experience to date has shown that designers and manufacturers can produce reliable composite structures. This is no doubt due to two factors. First, in the face of uncertainty, designers tend to “overdesign”; that is, to be too conservative in their use of material, to avoid any possibility of material failure. Second, composite structures have been extensively tested before use, ensuring that any potential problems show up during the tests. Thus, the composite materials themselves have been proven, in the sense that structures can be fabricated which are reliable and meet all design criteria. However, both overdesign and empirical testing are costly and drive up the prices of composites. The principal benefit of enhanced modeling capability will be to help to make composites more cost competitive.

Manufacturing of Polymer Composite Structures

Given the many different fibers and matrices from which composites can be made, the subject of PMC manufacturing is an extremely broad one. However, more than any other single area, low cost manufacturing technologies are required before composites can be utilized more widely. The basic steps include: impregnation of the fiber with the resin; forming of the structure; curing (thermoset matrices) or thermal processing (thermoplastic matrices); and finishing. Depending on the process, these steps may occur separately or simultaneously. For example, the starting material for many composites is a “prepreg”; i.e., a fiber tape or cloth which has been preimpregnated with resin and partially cured. Therrnoset prepregs may be stored in the freezer for up to 12 months prior to use. Some of the more important fabrication processes for composites are listed in table 12.

Nondestructive Evaluation (NDE) of Polymer Matrix Composites

In general, polymer composites do not have as great a tendency to brittle fracture as do ceramics. This means that the critical flaw size in large PMC structures may be of the order of centimeters, while in ceramics it is some tens of micrometers. PMC structures are increasingly used in life-critical structures such as aircraft wings and fuselages.

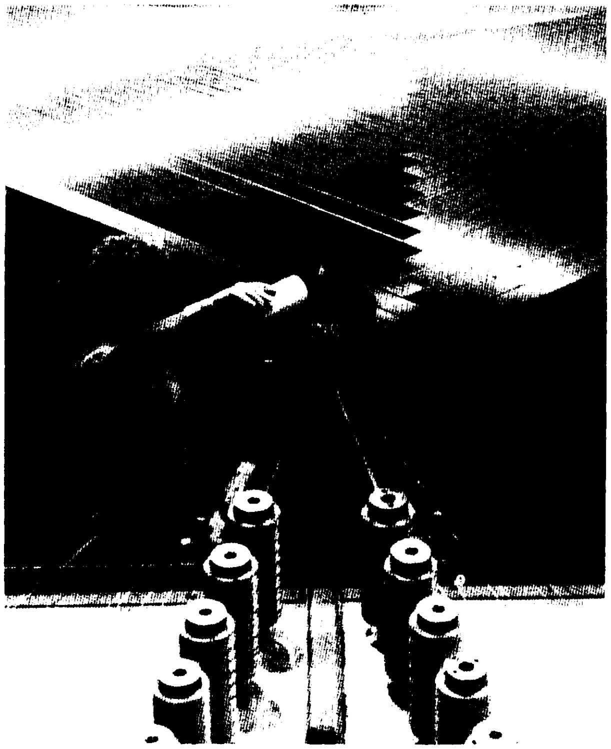


Photo credit: Hercules, Inc.

Filament winding of a rocket motor case.

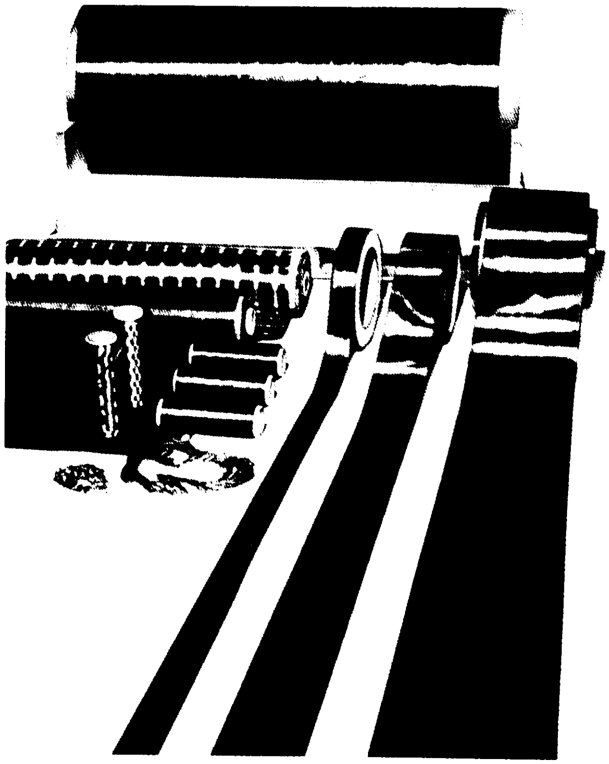


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Table 12.— Production Techniques for Polymer Composites

Technique	Characteristics	Examples
Sheet molding	Fast, flexible, 1 -2" fiber	SMC automotive body panels
Injection molding	Fast, high volume very short fibers, thermoplastics	Gears, fan blades
Resin transfer molding	Fast, complex parts, good control of fiber orientation	Automotive structural panels
Prepreg tape layup	Slow, laborious, reliable, expensive (speed improved by automation)	Aerospace structures
Pultrusion	Continuous, constant cross-section parts	I-beams, columns
Filament windlng	Moderate speed, complex geometries, hollow parts	Aircraft fuselage, pipes, drive shafts
Thermal forming (future)	Reinforced thermoplastic matrices, fast, easy repair, joining	All of above

SOURCE Off Ice of Technology Assessment

This places a special burden on NDE, both in the factory and in the field.

Although NDE is now used primarily for the detection of defects in finished structures, in the future it will be used increasingly for monitoring the status of composites at intermediate steps in the production process. Progress in this field will require development of sophisticated sensors and feedback control systems.

Requirements for NDE of composites differ somewhat from those of ceramics. While the flaw sizes to be detected are not as small, the area of structure to be investigated is frequently much larger, up to hundreds of square feet. Thus, techniques are required which can rapidly scan large areas for flaws or damage. While there are numerous NDE techniques which may be useful in the laboratory for testing of small specimens for research purposes, relatively few are appropriate to production or field-level inspection. Several of the more important NDE techniques which are relevant to production, end product, and field level inspection are listed in table 13. Excellent progress has been made in production-level techniques such as ultrasonics, and manufacturers are confident that large composite surface areas can be inspected reliably and economically for such flaws as bulk delaminations.

The inspection and repair of composite structures (e.g., aircraft components) at the depot and field levels will require a substantial training program for inspectors unfamiliar with composites. All procedures must be standardized and straightforward, since in general composite experts will not be available. In the future, as inspection processes become fully computerized, this will be an excellent application for expert systems which can guide the operator through the process and alert him to any detected anomalies.

Table 13.—NDE Techniques Appropriate for Production, Finished Product, Depot, and Field-Level Inspections of Polymer Matrix Composite Structures

N DE technique	Flaw type	Sensitivity	Complex shapes	Development for commercialization
Production:				
Visual (remote) ... ... , . .	Fiber orientation Foreign material	good	good	none
Ultrasonic ., ...	Porosity, viscosity during cure	good	poor	extensive
Dielectrometry	Degree of cure	good	good	some
End product:				
Visual	surface	good	good	none
Ultrasonic	bulk	good	poor	some
Radiographic	bulk	fair	excel lent	none
Acoustic emission ., ...	bulk	fair	good	extensive
Depot level:				
Ultrasonic ., ...	bulk delamination	good	poor	some
Field level:				
Ultrasonic	bulk delamination	fair	Door	extensive

SOURCE Joseph A. Moyzis, et al , "Nondestructive Testing of Polymer Matrix Composites," a contractor report prepared for OTA, December 1985

Health and Safety

There are a number of unique health and safety issues associated with the manufacture of composite materials. The health hazards stem from the fact that chemically active materials are used and workers handling them may breathe harmful fumes or come in contact with irritating chemicals. The chemical of greatest concern is the styrene monomer used in polyester resins. The problem is most severe when the resin is sprayed, and the monomer evaporates into the air. Inhalation of styrene monomer can cause headaches, dizziness, or sore throat; some people become sensitized to the vapors and can no longer work in a reinforced plastics plant.

The Occupational Safety and Health Administration has specified that styrene monomer concentrations in a plant should not exceed 100 parts per million.[6] In a plant where spray systems are used, extensive air handling equipment, spray booths, and air masks are required to maintain these standards. Where polyester resins are used for compression molding, resin transfer molding, or other enclosed mold systems, the problem can be dealt with by simple exhaust systems.

A new safety hazard was introduced with the advent of carbon fibers, which tend to float around a plant where they are used and, because they are electrical conductors, can get into unprotected electrical devices to cause short circuits. The fiber concentration in the air can be controlled by a negative pressure exhaust system in the area where they are used, but all electrical devices in the area should be sealed (explosion proof).

Recycling and Disposal of Composites

Most polymer composite materials in use today have thermosetting matrices, and after they have been cured, have no apparent scrap value. Although attempts have been made to grind them up and use them as fillers, this has not proven to be economically practical. The reuse of uncured FRP composites offers little economic incentive. Most scrap is simply discarded. One of the potential advantages of composites with thermoplastic matrices is that the scrap can be recycled.

[6]*World of Composites,* quarterly publication of the SPI Reinforced Plastics/Composites Institute, winter 1986.

Cured composites present no particular problem with disposal; they are chemically inert and can be used for land fill. Burning them can generate toxic smoke, and so is generally avoided.

The principal problem of disposal arises with uncured composites. Wet lay-ups, prepregs, SMC, etc., are still chemically active and pose both health and safety problems. If used in landfill, the active chemicals can leach out and cause contamination of the soil or water. A more serious problem is that the catalyzed resins may go on to cure and generate an exotherm that causes spontaneous combustion or self-ignition. The safe way to dispose of uncured composite material is to first bake it until it is cured and then dispose of it.

Applications of Polymer Matrix Composites

Polymer matrix composites are a more mature technology than structural ceramics. With the experience gained in military applications such as fighter aircraft and rocket motor casings beginning in the 1970s, composites now have a solid record of exceptional performance and reliability, They are rapidly becoming the baseline structural material of the defense aerospace industry.

Becaues of their high cost, diffusion of advanced composites into the civilian economy is likely to be a "top-down" process, progressing from relatively high value-added applications such as aircraft to automobiles and then to the relatively "low-tech" applications such as construction. On the other hand, there is also a "bottom-up" process at work in which savings in manufacturing costs permit unreinforced engineering plastics and short fiber-reinforced composites to replace metals in applications where high strength and stiffness are not required. Use of sheet molding compound for automobile body panels is one example of this phenomenon.

Markets for Advanced Polymer Matrix Composites

Aerospace.—This sector has been estimated to consume as much as 80 percent of all high-performance PMCs.[7] Growth projections for aero-

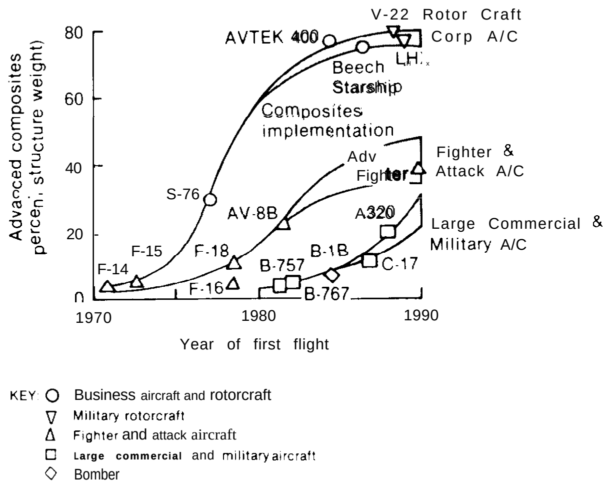
[7]According to the market study conducted by Business Communications Co., "Advanced Composites: An Evaluation of Commercial Prospects, " Stamford, CT, as reported in *World of Composites,* a publication of the Society of Plastics Industries, winter 1986, p. 4.

space usage of composites have ranged from 8.5 percent per year[8] to 22 percent per year.[9] The primary matrix materials in aerospace applications are epoxies, and the most common reinforcements are carbon/graphite, aramid (e. g., Du Pent's "Kevlar 49"), and high-strength glass fibers. However, high-temperature thermoplastics such as PEEK are considered by many to be the matrices of choice for future aerospace applications. Composites are used extensively today in small military aircraft, military and commercial rotorcraft, and prototype business aircraft. The next major aircraft market opportunity for composites is in large military and commercial transport aircraft.

The principal advantages of PMCs in aerospace applications are their superior specific strength and stiffness compared with metals, resulting in weight savings of 10 to **60** percent over metal designs, with **20** to **30** percent being typical.[10] This weight reduction can be used to increase range, payload, maneuverability and speed, or reduce fuel consumption. It has been estimated that a pound of weight saved on a commercial transport aircraft is worth $100 to **$300** over its service life, depending on the price of fuel, among other factors.[11] This high premium for weight saved is unique to this sector, and explains why it leads all others in growth rate. Additional advantages of PMCs are their superior fatigue and corrosion resistance, and vibration damping properties.

Military *Aircraft.—Advanced* composites have become essential to the superior performance of a large number of fighter and attack aircraft (figure 9). Indications are that composites may account for up to 40 percent of the structural weight of the Advanced Technology Fighter (ATF), which is still in the design phase. Because the performance advantages of composites in military aircraft more than compensate for their high cost,

Figure 9.—Composite Aircraft Structure (by **percent)**



SOURCE. Richard N Hadcock, Grumman Aircraft Systems Division, "Status and Viability of Composite Materials in Structure of High Performance Aircraft, " a presentation to the National Research Council, Aeronautics and Space Engineering Board Naval Postgraduate School, Monterey, CA, Feb 10, 1986

this is likely to be the fastest growing market for advanced composites over the next decade. One estimate, which assumes only existing production plus the ATF, projects a growth from about **0.3** million pounds per year in 1985 to 2 million pounds per year in 1995. '2

Commercial Aircraft. —If glass fiber reinforced composites are included, the volume of composites used in commercial and business aircraft is about twice that used in military aircraft.[13] In *current* commercial transport aircraft, such as the Boeing **767,** composites make up about **3** percent of the structural weight, and are used exclusively in the secondary (not flight-critical) structure. 14 However, several companies, including Beech and Avtek, are awaiting FAA approval of "all composite" business aircraft prototypes, which utilize composites in the wings, empennage, and fuselage.[15]

'According to the market study conducted by Frost & Sullivan, 'Worldwide High Performance Composites, " New York, as reported in *World of Composites,* a publication of the Society of Plastics Industries, winter 1986, p. *4.*

'According to a market study by Charles H. Kline & Co., "Advanced Polymer Composites, " Fairfield, NJ, as reported in *Plastics Engineering,* June 1985, p. 62.

[10] Carl Zweben, "polymer Matrix Composites, " *Frontiers in Materials Technologies,* M.A. Meyers and O.T. Inal (eds.) (The Netherlands: Elsevier Science Publishers, 1985), p. 365.

[11] Bob Hammer, Boeing Commercial Aircraft Co., personal communication, August 1986.

[12] Richard N, Hadcock, Grumman Aircraft Systems Division, "Status and Viability of Composite Materials in Structures of High Performance Aircraft, " a presentation to the National Research Council, Aeronautics and Space Engineering Board, Naval Postgraduate School, Monterey, CA, Feb. 10, 1986.

[13] Ibid.

[14] Darrel R, Tenney, NASA Langley Research Center, "Advanced Composite Materials: Applications and Technology Needs, " presentation to the Metal Properties Council, Inc., Miami, FL, Dec. 5, 1985.

[15] Hadcock, op. cit. , Feb. 10, 1986.

Photo credit" Hercules, Inc.

A modern lightweight fighter incorporating 64 different components—more than 900 pounds of composite structure per airplane.

Although growth of the business aircraft fleet over the next 5 years is expected to be only around 10 percent, two categories (turboprops and turbojets) are expected to grow significantly. " These aircraft are also the best candidates for composite fuselages. The estimated value (derived from cost and volume estimates) of composite fuselages, assuming all business aircraft manufacturers adopt this technology, is about $100 million a year.[17] These fuselages could account for 1.2 million pounds of graphite/epoxy consumption annually. Large transport or commercial aircraft fuselages will probably not be made from advanced composites until the technology is demonstrated in business aircraft.

By the year **2000,** composites could make up 65 percent of the structural weight of commercial transport aircraft.[18] Estimating a structural weight of 75,000 pounds per aircraft and production of 500 aircraft per year, this application alone should account for 24 million pounds of advanced composite per year. Assuming a starting material value of $60/lb, the market in the year **2000** is valued at about $1.5 billion for the composite material alone. A more conservative estimate, which assumes that no new commercial aircraft will be built by 1995, has placed the U.S. composite commercial airframe production at between 1 and 2 million pounds in that year.[19]

Helicopters.–With the exception of the "all-composite" business aircraft prototypes, which are still awaiting certification, composites have been used more extensively in helicopters than in aircraft. Military applications have led the way, and the advantages of composites are much the same as in aircraft: weight reduction, parts consolidation, and fatigue and corrosion resistance. Over the past 15 years, composites have become the baseline materials for rotors, blades, and tail assemblies. Sikorsky's **S-76** commercial model, which is about **25** percent composite by weight (figure 9), was certified in the late 1970s. Future military helicopters, such as the Army's LHX (with major airframe design teams at Bell/McDonnell Douglas and Boeing/Sikorsky), or the Navy's tilt-rotor V-22 "Osprey" (designed by Bell/Boeing), have specifications which force designers to consider composites, which are likely to comprise up to 80 percent of the structural weight (figure 9). Materials such as graphite/epoxy are likely to be used in the airframe, bulkheads, tail booms, and vertical fins, while the less stiff glass/epoxy composites will be used in the rotor systems. As with aircraft, there could be a long-term trend away from epoxy resins and toward thermoplastic resins.

Automotive Industry .—The automotive industry is widely viewed as being the industry in which the greatest volume of advanced PMC materials will be used in the future. Because the industry is mature and highly competitive, the principal motivation for introducing composites is cost savings. In contrast to the aircraft industry, there is no clear-cut premium associated with a pound of weight saved. Nevertheless, Detroit continues to be interested in saving weight as it pursues the conflicting goals of larger automobiles and higher fuel efficiency. Automakers are looking to the vehicle skin/frame systems to provide the next big leap in weight reduction. Other potential advantages of composites, such as corrosion resistance, appear to be secondary to the cost issue.

"Materials Modeling Associates, "Properties, Costs, and Applications of Polymeric Composites, " Massachusetts Institute of Technology, a contractor report prepared for the Office of Technology Assessment, December 1985.

[17]Ibid.

[18]Tenney, op. cit. , Dec. 5, 1985.

[19]Hadcock, op. cit., Feb. 10, 1986.

By far the greatest volume of composite material is sheet molding compound (SMC) used in exterior panels .20 The most visible automotive use of SMC in recent years is the Pontiac Fiero, which has an all composite exterior. The Fiero is constructed with a steel "space frame" superstructure to which the composite body panels are attached. By using different composite exterior panels, automakers can achieve model differentiation for limited production runs (100,000 to **200,000** units) while avoiding the prohibitive tooling costs which would be involved with use of steel. Automobile companies have adopted the space frame concept and will be using PMC materials for exterior panels in the future. In the short run, these will be mostly SMC.

The next major opportunity for composites in automobiles is in structural components,[21] Two structural components currently in service are the composite drive shaft and leaf spring. Some **3,000** drive shafts manufactured by filament winding graphite and E-glass fibers in a polyester resin are used annually in the Ford Econoline van. 22 Also, glass fiber reinforced plastic leaf springs in the Corvette and several other models are in production at the rate of approximately **600,000** per year. Leaf springs are regarded as a very promising application of composites, and are expected to show strong growth, especially in light trucks. Prototype primary body structures have been constructed with weight savings of **20** percent or more.

Advance engineering groups within the Big Three automobile producers are targeting the mid-1990s to launch composite unibody vehicles .23 Initially, composite unibodies will appear in limited production, in models like the Corvette or Fiero. Annual production should be in the range of **25,000** to 100,000 vehicles. It is likely that a composite unibody would not look like a conventional metal unibody, but would have a shape more consistent with the requirements of the manufacturing process used; resin transfer molding or filament winding would be two candidate Drocesses. However, an estimate of the amount of composite material required can be obtained from the following. A typical mid-size, stamped steel unibody weighs between 500 and **600** pounds. It is expected that the equivalent composite system will weigh **25** to **45** percent less. Based on these assumptions, consumption of composites will amount to about 12,000 tons in the first full year, which represents about 10 percent of current reinforced plastic consumption in the domestic automotive sector. Estimating the value of composite unibodies at $6/lb, the estimated market would be about **$150** million for these components alone.[24]

The automakers are exploring composite unibodies for a variety of reasons. Composite vehicles would enable designers to reduce the number of parts required in assembly; some manufacturers are looking into a one-piece composite structure. By reducing the number of parts, better consistency of parts can be achieved at considerably reduced

Photo credit *Ford* Motor Co

Compression molded composite rear floor pan prototype for the Ford Escort. Ten steel components were consolidated into a single molding, with 15 percent weight savings.

[20] Materials Modeling Associates, op. cit., December 1985.
[21] P. Beardmore, "Composite Structures for Automobiles," *Composite Structures* 5:163-176, *1986.*
[22] Although composite drive shafts are technicall, successful, Ford will take them out of production in 1987 in favor of a new aluminum design
"Materials Modeling Associates, op. cit., December *1985.*
[24] Ibid.

assembly costs. Composites also offer substantial improvements in specific mechanical properties, with the possibility of reducing weight while increasing strength and stiffness. Finally, PMCs offer greatly improved corrosion resistance over steel or galvanized steel, since they do not rust. Observers have estimated that composite automobiles could last **20** or more years, compared to the current average vehicle lifetime of 10 years.[25]

Without question, the major technical barrier to use of PMCs in the automotive industry is the lack of manufacturing technologies capable of matching the high production rates of metal stamping technology. The fact that steel parts can be stamped in seconds while plastics mold in minutes has led to lower production costs for steel. A major reason behind the increased use of plastics in automobiles is that the time of manufacture has fallen, not the cost of the equipment, tools, or materials. The fastest current technologies can process material at the rate of tens of pounds per minute, while true economy will require rates of 100 pounds per minute or more.[26] Thus, there is a gap of roughly an order of magnitude between current and economical rates.

If composites are used extensively in automobile unibodies, there could be large, secondary economic effects. These would involve the automobile producers and suppliers, the service network, and those involved in disposal of automobiles.

Auto producers will have to build new facilities or modify existing physical plant in order to fabricate composite unibodies in-house. Alternatively, they may elect to outsource the molding operations. This would lead to the creation of new specialized composites molding businesses, similar to the custom molders of plastics which now serve Detroit. Production lines would have to be altered to accommodate different processes for joining components together. Segments of the automobile service network would be directly affected by a change to composite unibodies. Body shops would have to change their repair procedures, or switch from repairing to replacing damaged parts. Rust-proofing services might be eliminated altogether.

Finally, an all-composite unibody will greatly reduce the supply of steel scrap and may render the recycling of automobiles unprofitable. Should this occur, disposing of millions of auto hulks per year could become a national problem. In addition, since steel minimills use steel scrap as their starting material, they might be placed in jeopardy.

Reciprocating Equipment.—PMC materials have considerable potential for use in many different kinds of high-speed industrial machinery. Current applications include such components as centrifuge rotors, weaving machinery, hand-held tools, and robot arms. All of these applications take advantage of the low inertial mass, but they also benefit to various extents from the tailorable anisotropic stiffness, superior strength, low thermal expansion, fatigue life, and vibration damping characteristics of composites.

The productivity of robotic work stations and flexible manufacturing cells could be improved if robots could operate at higher speeds with more accurate endpoint positioning, Stiffness is the key mechanical property, since the endpoint accuracy is limited by bending deflections in the beam-shaped robot members. With metal designs, stiffness is obtained at the cost of higher mass, which limits the robot response time. Consequently, the ratio of the weight of the manipulator arm to that of the payload is rarely lower than 10:1.[27] Because of their superior stiffness per unit weight, composites are a promising solution to this problem. At present, only one U.S. company[28] has marketed a robot incorporating composites, although there are several Japanese models and a number of other countries are funding research.

Although the benefits of using composites in reciprocating equipment are clear, initial attempts to penetrate this market have been disappointing. The market is a highly fragmented one, and equipment manufacturers, who tend to be oriented

[25]Ibid.

[26]Charles Segal, President, Omnia, Raleigh, NC, in OTA workshop on "Future Applications of Advanced Composites," Dec. 10, 1985.

[27]B.S. Thompson and C.K. Sung, "The Design of Robots and Intelligent Manipulators Using Modern Composite Materials," *Mechanism & Machine Theory* 20: 471-482, 1985.

[28]Graco Robotics of Lavonia, Michigan manufactures a spray painting robot with a hollow graphite/epoxy arm. However, this arm is being phased out in favor of a new aluminum design.

toward metals, have shown a reluctance to consider the use of a higher cost material (particularly when its use requires new processes and tooling) even when performance advantages are demonstrated. No attempt has been made to quantitatively estimate future markets. Composite penetration is likely to be slow but steady.

Shipping and Storage.—Plastics have long been known to be inert to chemical attack from a wide variety of substances. This has made them useful as containers for many corrosive chemicals. With the addition of fiber reinforcement, the increased strength makes them suitable for large structures such as large diameter pipe, holding tanks, and pressure vessels. One generic limitation of composites for these applications is temperature. As the structures are generally made out of glass fiber reinforced polyester or epoxy, the maximum service temperature is about **3000** F **(1490 C).** A further potential problem is that the glass fibers are subject to corrosive attack if the matrix cracks and exposes them to water or other chemicals. Assuming fiber cost reductions can be achieved, use of corrosion-resistant graphite or ceramic fiber reinforcement could be a promising solution to this problem in the future.

Pipe. -Glass fiber reinforced plastic (FRP) pipes have major applications in the oil and the chemical process industry. The demand for composite pipe is directly affected by the level of economic activity within these industries. Chemical manufacturing expenditures have been decreasing over the past few years, and low oil prices have brought acquisition of new oil field equipment to a halt. Consequently, the demand for fiberglass-reinforced pipe in these sectors has been declining. 29

Industry sources predict that any growth in the demand for composite pipe will come from the petroleum industry. One high-volume application which has shown strong growth is pipe used in pumping of gasoline. It is expected that fiberglass-reinforced pipe will penetrate 15 to 30 percent of the oil field market in such applications as sucker rods, downhole tubing, and casing, However, growth in these areas is predicated on rising oil prices. The FRP pipe industry is approximately 30 years old. It saw tremendous growth until 1980, but is now leveling off. A maximum of **5** percent annual growth is expected .30

Storage Tanks.—FRP has captured about 40 percent of the market for underground tanks for storing fuel and corrosive chemicals and could increase its market share to about 80 percent over the next 5 to 10 years.[31] FRP underground tanks are expected to last at least 30 years, compared with 13 to 15 years for bare steel.

Above-ground tanks for storage of oil, chemicals, and food represent a large potential market for FRP. Above-ground tanks smaller than about 12 feet in diameter or less than 30 feet high are predominantly FRP, but for larger tanks, the difficulty of manufacturing, handling, and shipping with FRP makes steel the more economical material.

Composites could be used widely in the future for portable storage tanks and pressure vessels. The two properties of greatest importance are corrosion resistance and light weight. In Europe today there are currently some 20,000 tanker trucks which use an FRP shell reinforced by a steel frame. In the United States there is one prototype tanker which utilizes a reinforcement combination of chopped glass fiber and glass filament wound layers.[32] The standaard tanker design for hauling corrosive chemicals (a business which accounts for about 5 percent of the total shipping market), is stainless steel lined with rubber, epoxy, or glass. These liners must be replaced every 1 to 5 years, at considerable expense. The composite tanker can be produced for approximately the same price as the steel design, and, based on the European experience and the performance record of underground composite tanks, it is expected to last longer, reduce costs, and increase safety. As of September **1984,** composite tanker trucks were approved by the Department of Transportation for travel on U.S. roads; however, the difficulty of obtaining insurance continues to be a serious barrier to use of composite tankers .33

Material Modeling Associates, op. cit., December 1985.

[30]Ibid.

[31]*World of* Composites, o. cit,, winter 1986, P. 8.

[32]Joseph M. Plecnik, et al., "Composite Tanker Trucks Have Made the Grade, " Plastics Engineering 41(3):63-65, March 1985.

[33]Joseph M. Plecnik, Department of Civil Engineering, Long Beach State University, personal communication, August 1986.

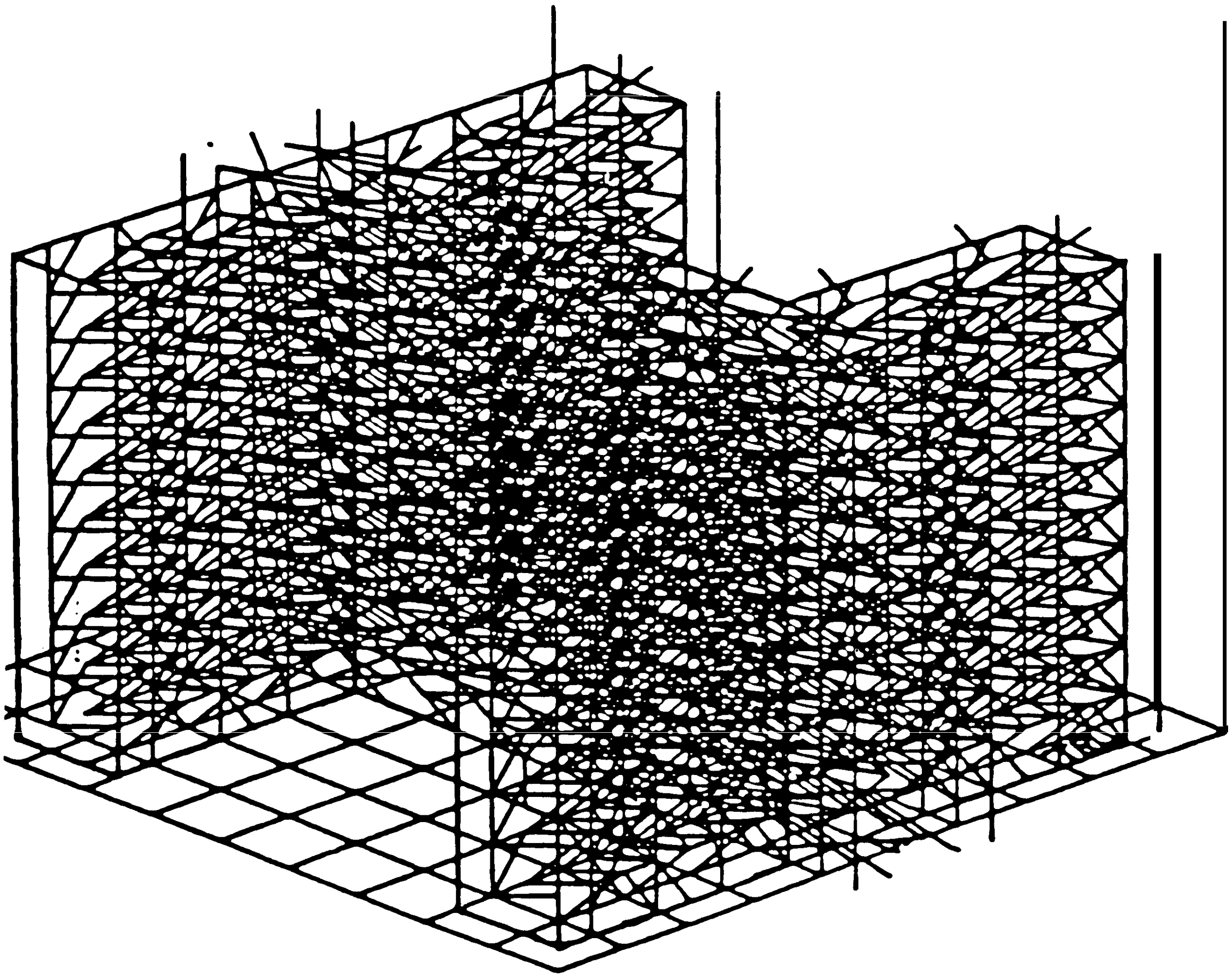


Photo credit: The CUMAGNA Corp.

Computer trace of fiber paths in a three-dimensional braided I-beam. This process yields a composite I-beam which is strong in all directions, but which weighs much less than steel.

Construction.—Construction applications are potentially a very significant opportunity for composites. For example, most highway bridges in the United States are over 35 years old, and most railroad bridges are over 70 years old.[34] Replacing or refurbishing even a small fraction of these with composite materials would involve a substantial volume of fiber and resin. However, significant technical, economic, and institutional barriers exist to the implementation of this technology, such that construction opportunities should be viewed as long term.

[34] John Scalzi, National Science Foundation, persona] communication, August 1986.

A potentially high-volume market for composites is in construction of buildings, bridges, and housing. Additional applications include lamp posts, smokestacks, and highway culverts. Construction equipment, including cranes, booms, and outdoor drive systems, could also benefit from use of composites. Because of the many inexpensive alternative building materials currently being used, cost of the PMC materials will be the key to their use in this sector. The chief advantage of composites would be reduced overall systems costs for erecting the structure, including consolidation of fabrication operations, reduced transportation and construction costs due to lighter weight structures, and reduced maintenance and lifetime costs due to improved corrosion resistance.[35]

Bridges are likely to be the first large scale construction application for polymer composites. The U.S. Department of Transportation is currently evaluating composites for use in bridge decking and stay cables.[36] Fiberglass tendons are also being used in place of steel in prestressed concrete bridge structures. ” Other countries which have active programs in this area include the Peoples' Republic of China, England, West Germany, Israel, and Switzerland. Because the largest load which must be supported by the bridge is its own dead weight, use of light weight composites would allow the bridge to accommodate increased traffic or heavier trucks. Decking materials are likely to be relatively inexpensive vinylester or epoxy resins reinforced with continuous glass fibers. Cables would probably be reinforced with graphite or aramid fibers, because of the high modulus and low creep requirements.

The manufactured housing industry is an especially intriguing potential opportunity for composite materials. In 1984, almost half of all new housing units were partially manufactured; i.e., large components were built in factories, rather than assembled onsite.[38] In the future, factory manufacture of housing promises to reduce housing costs while still maintaining options for distinctive designs. Composite manufacturing techniques such as pultrusion and transfer molding could be used to fabricate wall structures containing structural members and panels in a single step, Components such as I-beams, angles, and channels can also be economically produced by these techniques. In spite of the opportunities, however, Japan and several countries in Europe are far ahead of the United States in composite housing construction technologies.

An important research need affecting the use of composites in construction applications has to

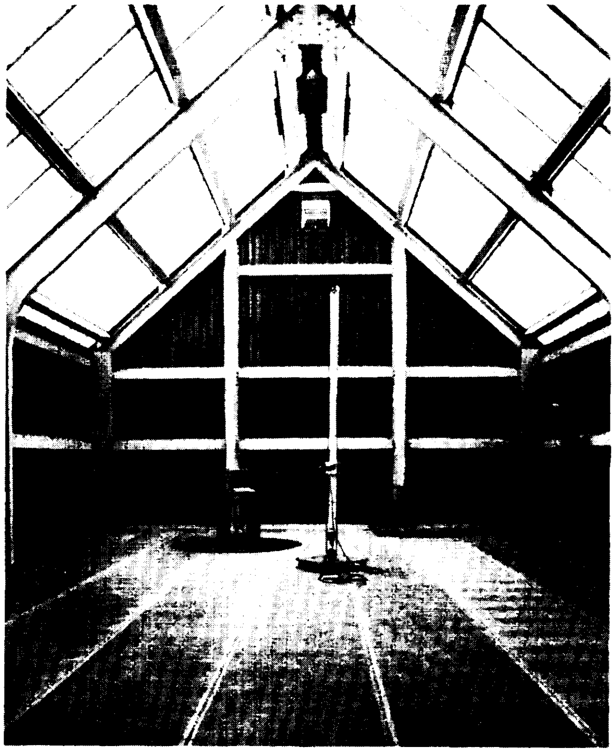


Photo credit: Composite Technology, Inc

Interior of a nonmetallic, nonmagnetic structure built for Apple Computer, Inc., to house a microwave device testing facility. The building components, including fasteners, are entirely made of fiber-reinforced composites.

do with adhesion and joining. The joining of composite materials to other materials for the purpose of load transfer, or to themselves for the purpose of manufacturing components, requires advances in technology beyond present levels. This is a particular obstacle when joining may be done by unskilled labor.

An additional technical barrier is need for development of design techniques for integrated, multifunctional structures. Window frames, which are made by joining together several pieces of wood, can be replaced by molded plastic and composite structures having many fewer pieces, lower assembly costs, and better service performance. The flexibility of the design and manufacture of composite materials could also be used to integrate a window frame into a larger wall section, again reducing the number of parts and the cost of manufacture, This has been done for certain experimental bathroom structures where lavato-

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[35] Howard Smallowitz, "Reshaping the Future of Plastic Buildings," *Civil Engineering*, May *1985*, pp. 38-41.

[36] According to information provided by Craig A. Ballinger, Federal Highway Administration, August 1986.

[37] *Engineering News Record*, Aug. 29, 1985, p. 11.

[38] Thomas E. Nutt-Powell, "The House That Machines Built," *Technology Review, Nov. 1985*, p. *31*.

ries, shower rooms, and other structural components have been integrated in a single molding.[39]

The principal barriers to the adoption of new materials technologies in the construction industry in the United States are not so much technological as institutional and economic. Like the highway construction industry discussed above, the housing construction industry is highly fragmented. This makes the rate of R&D investment and adoption of new technology very low. The performance of housing materials is regulated by thousands of different State and local building and fire safety codes, all written with conventional materials in mind. Further, engineers and contractors lack familiarity with the composite materials and processes. Finally, composites must compete with a variety of low-cost housing materials in current use. As a result, composites used in manufactured housing are not likely to be "advanced"; rather, they might consist of wood fibers pressed with inexpensive resins or laminated structures involving FRP skin panels glued to a foam or honeycomb core.

Medical Devices.—PMC materials are currently being developed for medical prostheses and implants. The impact of composites on orthopedic devices is expected to be especially significant. While medical devices are not likely to provide a large volume market for composites, their social and economic value are likely to be high. The total estimated world market for orthopedic devices such as hips, knees, bone plates, and intramedullary nails is currently about 6 million units with a total value of just over $500 million.[40] Estimates of the U.S. market for all biocompatible materials by the year 2000 have been quoted above as up to $3 billion per year.[41] Polymer composites could capture a substantial portion of that, sharing the market with ceramics and metals.

Metallic implant devices of this type, such as the total hip unit which has been used since the early *1960s*, suffer a variety of disadvantages: difficulty in fixation, allergic reactions to various metal ions, poor matching of elastic stiffness, and mechanical (fatigue) failure. Composite materials have the potential to overcome many of these difficulties. Not only can the problem of metal ion release be eliminated, but composite materials can be fabricated with stiffness which is tailored to the stiffness of the bone to which they are attached, so that the bone continues to bear load, and does not resorb (degenerate) due to absence of mechanical loading. This is a persistent problem with metal implants. It is also possible to create implants from biodegradable composite systems which would provide initial stability to a fracture but would gradually resorb over time as the natural tissue repairs itself. Finally, composites can be designed to serve as a scaffold for the invasive growth of bone tissue as an alternative to cement fixation. This leads to a stronger and more durable joint.

Research in composite orthopedic devices is currently being carried out on a relatively small scale in the labs of orthopedic device manufacturers. Further research is required to improve in situ strength and service life, stress analysis, and fabrication and quality control technologies.

In order to overcome the remaining technical barriers, a cooperative effort of an interdisciplinary team is required. At a minimum, the team must include expertise in design, engineering, manufacturing, and orthopedic surgery. Significant strides in this field are being made in Japan, the United Kingdom, France, Germany, Italy, Canada, and Australia, as well as in the United States.[42]

Future Trends in Polymer Matrix Composites

Novel Reinforcement Types

Rigid Rod Molecules.—Composites can be reinforced with individual rigid rod-like molecules or fibers generated from these molecules. One example is poly (phenylbenzobisthiazole), or PBT. Experimental fibers made from this material have specific strength and modulus on a par with the most advanced fibrous reinforcement, exceeding the properties of commercially available metals,

[39] Kenneth L. Reifsnider, Materials Response Group, Virginia Polytechnic Institute, "Engineering Research Needs of Polymer Composites," a contractor report prepared for the Office of Technology Assessment, December *1985*.

[40] Ibid.

[41] Hench and Wilson, op. cit.

[42] Reifsnider, op. cit., December 1985.

including titanium, by over a factor of 10.[43] A particularly exciting possibility is dissolving the molecular rods in a flexible polymer, and thus creating a composite reinforced by individual molecules. Such a homogeneous composition would mitigate the problem of matching the thermal expansion coefficient between the reinforcement and the matrix, and would virtually eliminate the troublesome interface between them. The future of this technology will depend on solving the problems of effectively dissolving the rods in the "matrix" and on orienting them once dissolved.

Novel Matrices

Because the matrix largely determines the environmental durability and toughness, the greatest improvements in the performance of polymer composites in the future will come from new matrices, rather than new fibers. Perhaps the most significant opportunities lie in the area of molecular design; chemists will be able to design polymer molecules to have the desired flexibility, strength, high-temperature resistance, and adhesive properties.[44] Some of the more promising directions are discussed below.

Oriented Molecular Structures. -At present the anisotropic properties of most composites are determined by the directions of fiber orientation. In the future, it may be possible to orient the individual polymer molecules during or after polymerization to produce a "self-reinforced" structure. The oriented polymers will serve the same reinforcing function as fibers do in today's composites. In effect, today's organic fibers (e.g., Du Pent's Kevlar or Allied's Spectra **900),** which consist of oriented polymers and which have among the highest specific stiffness and strength of all fibers, provide a glimpse of the properties which tomorrow's matrices might have.

Recently developed examples of oriented polymer structures are the liquid crystal polymers (LCPs). They consist of rigid aromatic chains modified by thermoplastic polyesters (e.g., poly - ethyleneterephthalate, or PET), or polyaramids, and have a self-reinforcing fibrous character which imparts strength and modulus comparable to those of reinforced thermoplastic molding compounds, such as **30** percent glass reinforced nylons." The fiber orientations of current LCPS are hard to control (current applications include microwave cookware and ovenware, which require high-temperature resistance but not high strength) and this represents a challenge for the future.

High-Temperature Matrices.—The maximum continuous service temperature of organic polymers in an oxidizing atmosphere is probably around **7000** F,[46] although brief exposures to higher temperatures can be tolerated. Currently, the most "refractory" matrices are polyamides, which can be used at temperatures of **600°** F (316° C), although slow degradation occurs." If stable, high-temperature matrices could be developed, they would find application in a variety of engine components and advanced aircraft structures.

Thermotropic Thermosets. -These hybrid matrices are designed to exploit the processing advantages of thermoplastics and the dimensional stability and corrosion resistance of thermoses. The molecules are long, discrete chains which have the latent capacity to form crosslinks. Processing is identical to thermoplastics in that the discrete polymers are formed at high temperatures to the desired shape. Then, however, instead of cooling to produce a solid, the structure is given an extra "kick," with additional heat or ultraviolet light, which initiates crosslinking between the polymer chains. Thus, the finished structure has the dimensional stability characteristic of a thermoset.[48]

[43] Thaddeus Helminiak, "Hi-Tech Polymers From Ordered Molecules, " Chemical *Week,* Apr. 11, 1984.

[44] Charles p, West, Resin Research Laboratories, Inc., Newark, NJ, personal communication, August 1986.

[45] Reginald B, Stoops, R.B. Stoops & Associates, Newport, RI, "Ultimate Properties of Polymer Matrix Materials, " a contractor report prepared for the Office of Technology Assessment, December 1985.

[46] Paul McMahan, Celanese Research Corp., in an OTA workshop, "Future Opportunities for the Use of Composite Materials, " Dec. 10, 1985.

[47] *Aerospace America,* May 1986, p. 22.

[48] John Riggs, Celanese Research Corp. in OTA workshop cited in footnote 46.

The Composites Factory of the Future

It is in the nature of advanced composites that they do not lend themselves to standard processes or manufacturing procedures. The very concept of tailoring a material to each specific application militates against standardization. It is therefore unlikely that we will see completely automated factories in the near future in which manufacturing instructions are fed in at one end and a composite part pops out the other, untouched by human hand.

Computer-Aided Design.—Computer-aided design (CAD) systems currently focus on three-dimensional graphics, and are often coupled with the capability for stress analysis of a structure. However, a comprehensive CAD system which would facilitate the process of choosing suitable materials, reinforcement geometry, and method of fabrication is still far in the future. Such a system would require an extensive database on fiber and resin properties, as well as a processing database which would permit modeling of the manufacturing steps necessary to fabricate the part, including the costs of those operations. The principal advantage of an integrated CAD system would be to clearly define the options and tradeoffs associated with various production strategies.

Computer-Aided Manufacturing.—Computer-aided manufacturing (CAM) would alter the processing of composites in several ways. Based on the instructions generated by the CAD system, numerically controlled machine tools would automatically machine molds contoured to the precise outline of the part. CAD instructions would guide automated lay-up of the part, and sensors embedded in the molds or in the materials themselves would make the entire manufacturing process an interactive one in which the computer controller would automatically adjust the processing variables based on real-time information about the state of the structure being fabricated. With the advent of robot-assisted manufacturing, NDE during the production cycle, performed with prcbes manipulated by the robot and analyzed by artificial intelligence, could become the way all high-value composite components are produced. Integration and miniaturization of sensors will lead to improvements in the quality and reliability of the information obtained from a nondestructive test.

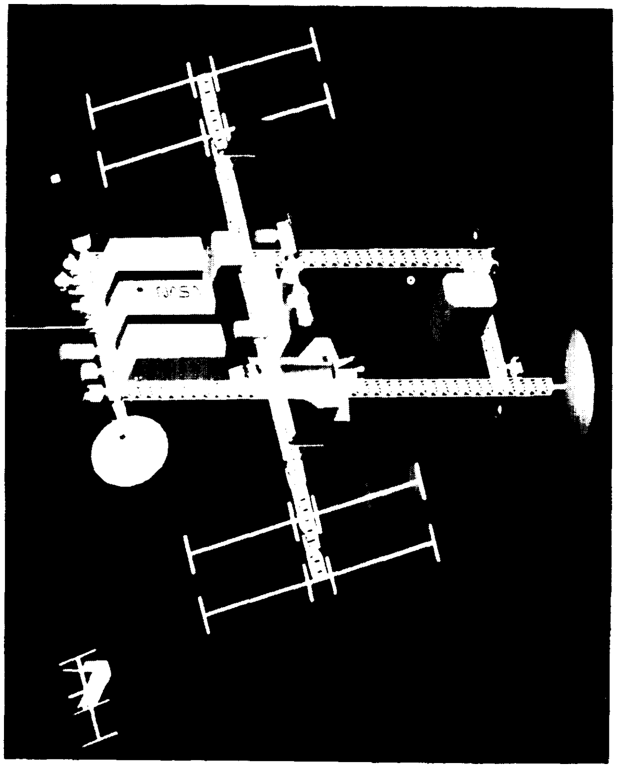
Nondestructive Evaluation.—Experience to date gives no indication that composite structures in service will require more frequent inspection than metal structures. In the future, it will be judged inconvenient to take composite systems out of service merely to inspect them for structural integrity. For such cases it will be necessary to have NDE performed continuously by devices that can sense changes in the mechanical properties which would precede a structural failure. These sensors would be included in the critical components during manufacture, and their signals would be examined regularly by a computer which would integrate the data, using AI, and decide whether to alert a human operator. A candidate NDE test for such a system is acoustic emission, in which the sound emitted by a composite structure under stress can be used to characterize the flaw population. Another possibility would be to include optically or electrically conducting fibers with the structural reinforcement; the degree of transmission of light or electric current by these fibers could be related to fiber breakage in the overall structure.

Thermal Forming.—With the increased use of advanced thermoplastic composites in the future, new thermal forming technologies will become important. The thermoplastic could be applied either as a hot melt or as a prepreg, which is relatively fast and easy to make with thermoplastics. Either method will require the development of new equipment capable of placing the fibers and compacting the structure while maintaining the process temperature.

Space

Space Transportation Systems.—over 10,000 pounds of advanced composites are used on the NASA space shuttle. ” Polymer composites are also being considered in designs for the proposed aerospace plane, although such an aircraft probably will not be available until after the year 2000. The primary limitation on the use of polymer composites in this application is high tempera-

‘* Tenney, op. cit. , Dec. 5, 1985.



Reference configuration for the NASA manned space station. Composites could be used in the tubular struts which make up the frame.

ture.[50] Flying at speeds exceeding Mach 7, the lower surfaces and leading edges would experience temperatures of **2,000°** to 3,000° F (1,093° to 1,649° C).[51] If PMC materials were available which could retain high strength and stiffness up to 800° F (427° C), they could be used extensively for the cooler skin structure and most of the substructure.

Space Station.—Graphite/epoxy composites and aluminum are both being considered for the tubular struts in the space station reference design. The goal of reducing launch weight favors the use of composites; however, their lower thermal conductivity compared with aluminum could create problems in service. The most serious environmental problem faced by the composite is temperature swings between –250° F (–121° C) and +200° F (+93° C) caused by periodic exposure to the sun. This thermal cycling produces radial cracks in graphite/epoxy tubes which can reduce the torsional stiffness by as much as **30** percent after only **500** cycles.[52] To reduce the effects of thermal cycling, the composite tubes would be coated with a reflecting, thermally conducting layer to equalize the temperature throughout the tube. The layer would also protect the composite from atomic oxygen, which is a major cause of material degradation in low earth orbit, as well as from solar ultraviolet radiation.

Military.—Composites of all types, including ceramic, polymer, and metal matrix composites, are ideal materials for use in space-based military systems, such as those associated with the Strategic Defense Initiative (SDI).[53] Properties such as low density, high specific stiffness, low coefficient of thermal expansion, and high temperature resistance are all necessary for structures which must maneuver rapidly in space, maintain high dimensional stability, and withstand hostile attack. A program devoted to the development of new materials and structures has recently been established within the SDIO.[54]

Bioproduction

Living cells can synthesize polymeric molecules with long chains and complex chemistries which cannot be economically reproduced in the laboratory. For example, crops and forests are an important source of structural materials and chemical feedstocks. A number of crops such as crambe, rapeseed, and various hardwood trees are now being evaluated for commercial production of lubricants, engineering nylons, and composites.[55] For some materials, such as natural rubber, the United States is totally dependent on foreign sources. Congress has mandated ("Critical Agricultural Materials Act," Public Law 98-284, 1984) that the Department of Agriculture estab-

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[50] Hadcock, op. cit., Feb. 10, 1986.

[51] Ibid.

[52] Tenney, op. cit., Dec. 5, 1985.

[53] Jerome Persh, "Materials and Structure, Science and Technology Requirements for the DOD Strategic Defense Initiative," *American Ceramic Society Bulletin* 64(4):555-559, 1985.

[54] The effort includes: lightweight structures, thermal and electrical materials, optical materials and processes, tribological materials, and materials durability. Current budgets are about $2 million and are projected to reach $50 million in 1989.

[55] According to information supplied by the USDA's Office of Critical Materials.

lish an Office of Critical Materials to evaluate the potential of industrial crops to replace key imported materials. Several demonstration projects of 2,000 acres or more are planned for 1987.

With the possible exception of wood, it is unlikely that biologically produced materials will compete seriously with polymer matrix composites in the structural applications discussed in this report. Although natural polymers such as cellulose, collagen, or silk can have remarkably high strength, their low stiffness is likely to limit their use in many structures. Nevertheless, their unique chemical and physical properties make them appropriate for certain specialty applications. For example, collagen is a biologically compatible material which is being used to generate artificial skin.[56]

Biotechnology may offer a novel approach to the synthesis of biological polymers in the future. Genetically engineered bacteria and cells have been used to produce proteins related to silk.[57] In the future, production rates could be accelerated by extracting the protein synthetic machinery from the cells and driving the process with an external energy source, such as a laser or electric current.[58] The flexibility inherent in such a scheme would be enormous; by simply altering the genetic instructions, new polymers could be produced.

Research and Development Priorities for Polymer Matrix Composites

Federal R&D spending for polymer matrix composites in fiscal years 1985 and 1986 is shown in table 14; roughly 65 to 70 percent in each year was spent by the Department of Defense. The large drop in Federal expenditures from 1985 to 1986 does not reflect a sharp cut in composites R&D; rather, it can be attributed to the completion of large research programs in 1985 and the transitioning of the technology (particularly for

Table 14.—Budgets for Polymer Matrix Composite R&D in Fiscal Years 1985 and 1986 (millions)

Agency	FY 1985	FY 1986
Department of Defense[a] (6.1, 6.2, 6.3A),	55.9	29.2
National Aeronautics Space Agency[b]	23	8.7
National Science Foundation[c] ., ...,	1-2	1-2
National Bureau of Standards[d] . . ., .,	0.4	0.4
Department of Transportation[e] ., .,	—	0.4
Total . . ., .,	80-81	40-41

SOURCES [a]Jerome Persh, DOO
[b]Michael Greenfield, NASA
[c]Ranga Komanduri, NSF
[d]Leslie Smith, NBS
[e]Craig Ballinger, FHWA

carbon fiber composites) to private industry. Defense applications continue to drive the development of advanced composites, which are used in an estimated $80 billion of weapons systems.[59]

Reliable composite structures can now be designed which satisfy all of the engineering requirements of a given application. However, scientific understanding of composites has lagged behind engineering practice; in order to design more efficiently and cost effectively, and to develop improved materials, it will be necessary to understand and model several important aspects of composites. Based on the opportunities outlined above, some research and development priorities for composites are suggested below.

Very Important

Processing Science.—The primary goal of processing science is to be able to control the fabrication process to assure complete and uniform cure, minimize thermal stresses, control resin content, and assure accurate fiber placement. This requires a model which can predict the influences of key process variables and techniques for monitoring these variables so that pressure and temperature can be adjusted accordingly. Such models would also provide useful guidelines for tool design. At present, modeling is in a very early stage of development.

The existence of low-cost fabrication processes will be critical to the use of new composite systems, such as low-cost, high-performance thermoplastics reinforced with continuous fibers. For

[56] J. Burke, et al., "The Successful Use of Physiologically Acceptable Artificial Skin in the Treatment of Extensive Bum In jury," *Annals of Surgery* 194:413-428, 1982.
[57] Dennis Lang, Syntro Corp., La Jolla, CA, personal communication, August 1986.
[58] Terence Barrett, National Aeronautics and Space Administration, persona] communication, August 1986.
[59] Kenneth Foster, Assistant for Materials Policy, Department of Defense, personal communication, August 1986.

example, methods for fabricating shapes with double curvature are needed. Another important problem is the impregnation and wetting of fiber bundles by these relatively viscous plastics. The effect of processing on microstructure requires further study, as does the influence of residual thermal stresses. The latter is a particular concern for resins processed at high temperatures. Finally, as for thermoses, process models are required.

Impact Damage.—The impact damage resistance of a composite structure has a critical effect on its reliability in service. It has been shown that impact damage that is barely visible to the naked eye can cause a reduction in strength of as much as 40 percent.[60] Impact resistance is especially important in primary aircraft structures and other safety-critical components. Tougher thermoplastic matrix materials promise to improve the impact resistance of aircraft structures now made with epoxy matrices.

The complexity of the impact damage process makes modeling very difficult. However, it would be very desirable to be able to relate the extent of damage to the properties of the matrix, fiber, and interphase, along with factors like reinforcement form. This would facilitate the development of more reliable materials and structures. In addition, an understanding of impact damage mechanisms would aid in developing protocols for repair of composite structures, a field which largely relies on empirical methods.

Delamination. -There is a strong body of opinion that delamination is the most critical form of damage in composite structures (particularly those produced from prepregs). As noted above, impact damage barely visible on the surface can cause dramatic reductions in strength through local delamination. Delamination may prove to be a problem of increasing severity in the future, because of the trend toward higher working strains that tend to accentuate this mode of failure.

Analyses to date have concentrated on growth and failure associated with compressive loading. These need to be verified and refined. In addition, the effects of combined loading, resin fracture toughness, reinforcement form, and environment need to be investigated.

[60] Carl Zweben, General Electric Co., "Assessment of the Science Base for Composite Materials, " a contractor report prepared for the Office of Technology Assessment, December 1985.

Interphase.—The interphase has a critical influence on the composite, since it determines how the reinforcement properties are translated into the composite properties. The characteristics of this little-studied region merit thorough investigation. The objective would be to develop a body of knowledge that would guide the development of fiber surface treatments, matrices, and fiber coatings that will optimize composite mechanical properties and provide resistance to environmental degradation.

Important

Strength.—The excellent strength properties of composites are one of the major reasons for their use. However, as with many properties of composites, their strong heterogeneity makes strength characteristics very complex. This heterogeneity gives rise to failure modes that frequently have no counterpart in homogeneous materials. Even in the simplest composites, unidirectional laminates, the relationships between axial and transverse loading (parallel and perpendicular to the fiber direction) and failure are not well understood. In more complex composites, containing several fiber orientations and various flaw populations, efforts to model strength have been largely empirical. It will be important in the future to have analytical models for the various failure modes of unidirectional composites and laminates that relate strength properties to basic constituent properties.

Fatigue.—Fatigue of composites is an important design consideration. Fatigue resistance is a major advantage which composites enjoy over metals; however, the traditional models for analyzing fatigue in metals do not apply to composites. The risks associated with fatigue failure are likely to increase because of the trend toward use of fibers with higher failure strains, and the desire to use higher design allowable for existing materials. Ideally, it would be desirable to be able to predict composite fatigue behavior based on constituent properties. A more realistic near-term objective is to understand fatigue mechanisms, and how they are related to the properties of fibers, matrix, interphase, loading, and environment of the composite. Important topics which have not received adequate attention are the fatigue properties of the reinforcements and matrix resins, and compression fatigue of unidirectional composites. In view of the increasing interest in thermoplastics, fatigue of these materials also deserves study.

Fracture.—One of the most important modes of failure in metals is crack propagation. Arising at regions of high stress, such as holes, defects, or other discontinuities, cracks tend to grow under cyclic tensile load. When cracks reach a critical size, they propagate in an unstable manner, causing failure of the part in which they are located. This, in turn, may result in failure of the entire structure. In contrast, failure of composites often results from gradual weakening caused by the accumulation of dispersed damages, rather than by propagation of a single crack.

In view of the significant differences in failure modes between metals and composites, use of linear elastic fracture mechanics (LEFM) to describe fracture in these complex materials is controversial. It is open to question whether there are unique values of fracture toughness or critical stress intensity that describe the fracture characteristics of composites. In order to develop reliable design methods and improved materials in the future, it will be necessary to develop a body of fracture analysis which is capable of accounting for the more complex failure mechanisms.

Environmental Effects.—The environments to which composites are subjected can have a significant effect on their properties. Environments that are known to be especially damaging are those of high temperature and moisture under load, ultraviolet radiation, and some corrosive chemicals. The key need in the environmental area is to develop a thorough understanding of degradation mechanisms for fibers, resins, and interphases in the environments of greatest concern. This knowledge will lead to more reliable use of existing materials and provide the information required to develop new, more degradation-resistant ones.

Reinforcement Forms and Hybrid Composites.—There are two main reasons for the interest in new reinforcement forms: improved through-the-thickness properties, and lower cost. A pervasive weakness of composite laminates of all kinds is that the out-of-plane strength and stiffness, being dependent primarily on the matrix, are much inferior to the in-plane properties. This is because in convertional laminates there is no fiber reinforcement in the thickness direction.

New reinforcement forms under development include triaxial fabrics, multilayer fabrics, two-dimensional braids, three-dimensional braids, and various kinds of knits. In addition, laminates have been reinforced in the thickness direction by stitching. From an analytical standpoint, the major drawback to fabrics, braids, and knits is that they introduce fiber curvature, which can cause significant loss of strength, compared to a unidirectional laminate. However, multidirectional reinforcement appears to confer increased fracture toughness on the composite.

Use of several types of fibers to reinforce composites will be driven by the desire to obtain properties that cannot be achieved with a single fiber, and to reduce cost. For example, glass fibers, which are cheap but have a relatively low tensile modulus, can be mixed with more costly, high modulus graphite fibers to achieve a composite which is both stiff and relatively cheap.

With both new reinforcement forms and hybrid reinforcement, there is a great need for analytical methods to identify the configurations required to produce desired properties. Without such tools, it will be necessary to rely on intuition and time-consuming, costly empirical approaches.

Test Methods.—Reliable and standardized test methods are critical to the evaluation of all materials. For homogeneous materials such as metals, such methods are fairly straightforward. In composites, however, the macroscopic mechanical behavior is a complex summation of the behavior of the microconstituents. Consequently, there has been great difficulty in achieving a consensus on what properties are actually being measured in a given test, let alone what test is most appropriate for a given property. There are currently numerous test methods in use throughout the industry, and numerous private databases. This has resulted in considerable property variability appearing in papers and reports. The problem is particularly severe for toughness, bending, shear, and compression properties.

The movement to standardize composites testing began in ***1969,*** but has stalled in recent years. [61] Standardized methods of testing and reporting results are a prerequisite to the establishment of composite properties databases for design and process modeling. The lack of standards is also a significant barrier to the transfer of test results from one structural application to another.

Desirable

Creep Fracture.—Materials subjected to sustained loading fail at stress levels lower than their static strengths. This is called creep fracture. Topics which require study include tensile and compressive loading of both unidirectional composites and laminates, and the influence of temperature and environment. Since the time-dependent degradation of the matrix and interphase properties are typically greater than those of the fibrous reinforcements, particular attention should be paid to transverse matrix cracking and delamination.

Viscoelastic and Creep Properties.—The occurrence of significant deformation resulting from sustained loading can have an adverse effect on structural performance in some applications, such as reciprocating equipment, bridges, and buildings. Consequently, creep behavior is an important material characteristic. This subject could benefit from development of a database for creep properties of various fibers, matrices, and composites, especially for compressive loading, which has received relatively little attention.

“Kenneth L. Reifsnider, Virginia Polytechnic Institute, personal communication, August 1986.