# Chapter 3

# Polymer Matrix Composites

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Chapter 3

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## FINDINGS

Polymer matrix composites (PMCs) are comprised of a variety of short or continuous fibers bound together by an organic polymer matrix. Unlike a ceramic matrix composite (CMC), in which the reinforcement is used primarily to improve the fracture toughness, the reinforcement in a PMC provides high strength and stiffness. The PMC 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.

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-stiffness glass fibers. Advanced composites, which have been in use for only about 15 years, primarily in the aerospace industry, have superior strength and stiffness, and are relatively expensive. Advanced composites are the focus of this assessment.

Chief among the advantages of PMCs is their light weight coupled with high stiffness and strength along the direction of the reinforcement. This combination is the basis of their usefulness in aircraft, automobiles, and other moving structures. Other desirable properties include superior corrosion and fatigue resistance compared to metals. Because the matrix decomposes at high temperatures, however, current PMCs are limited to service temperatures below about 600° F (316° C).

Experience over the past 15 years with advanced composite structures in military aircraft indicates that reliable PMC structures can be fabricated. However, their high cost remains a major barrier to more widespread use in commercial applications. Most advanced PMCs today are fabricated by a laborious process called lay-up. This typically involves placement of sequential layers of polymer-impregnated fiber tapes on a mold surface, followed by heating under pressure to cure the lay-up into an integrated structure. Although automation is beginning to speed up this process, production rates are still too slow to be suitable for high-volume, low-cost industrial applications such as automotive production lines. New fabrication methods that are much faster and cheaper will be required before PMCs can successfully compete with metals in these applications.

### Applications and Market Opportunities

Aerospace applications of advanced composites account for about 50 percent of current sales. Sporting goods, such as golf clubs and tennis rackets, account for another 25 percent. The sporting goods market is considered mature, with projected annual growth rates of 3 percent. Automobiles and industrial equipment round out the current list of major users of PMCs, with a 25 percent share.

The next major challenge for PMCs will be use in large military and commercial transport aircraft. PMCs currently comprise about 3 percent of the structural weight of commercial aircraft such as the Boeing 757, but could eventually account for more than 65 percent. Because fuel savings are a major reason for the use of PMCs in commercial aircraft, fuel prices must rise to make them competitive.

The largest volume opportunity for PMCs is in the automobile. PMCs currently are in limited production in body panels, drive shafts, and leaf springs. By the late 1990s, PMC unibody structures could be introduced in limited production. Additional near-term markets for PMCs include medical implants, reciprocating industrial machinery, storage and transportation of corrosive chemicals, and military vehicles and weapons.

Beyond the turn of the century, PMCs could be used extensively in construction applications such as bridges, buildings, and manufactured housing. Because of their resistance to corrosion, they may also be attractive for marine structures. Realization of these opportunities will depend on development of cheaper materials and on designs that take advantage of compounding benefits of PMCs, such as reduced weight and increased durability. In space, a variety of composites could be used in the proposed aerospace plane, and PMCs are being considered for the tubular frame of the NASA space station.

### Research and Development Priorities

Unlike most structural ceramics, PMCs have compiled an excellent service record, particularly in military aircraft. However, in many cases the technology has outrun the basic understanding of these materials. To generate improved materials and to design and manufacture PMCs more cost-effectively, the following needs should be addressed:

- **Processing Science:** Development of new, low-cost fabrication methods will be critical for PMCs. An essential prerequisite to this is a sound scientific basis for understanding how process variables affect final properties.
- **Impact Resistance:** This property is crucial to the reliability and durability of PMC structures.
- **Delamination:** A growing body of evidence suggests that this is the single most important mode of damage propagation in PMCs with laminar structures.
- **Interphase:** The poorly understood interfacial region between the fiber and matrix has a critical influence on PMC behavior.

## INTRODUCTION

Unlike a ceramic matrix composite, in which the reinforcement is used primarily to improve the fracture toughness, the reinforcement in a polymer matrix composite provides strength and stiffness that are lacking in the 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 relatively weak matrix is to bond the fibers together and to transfer loads between them, As with CMCs, the reinforcement may consist of particles, whiskers, fibers, or fabrics, as shown in figure 3-1.

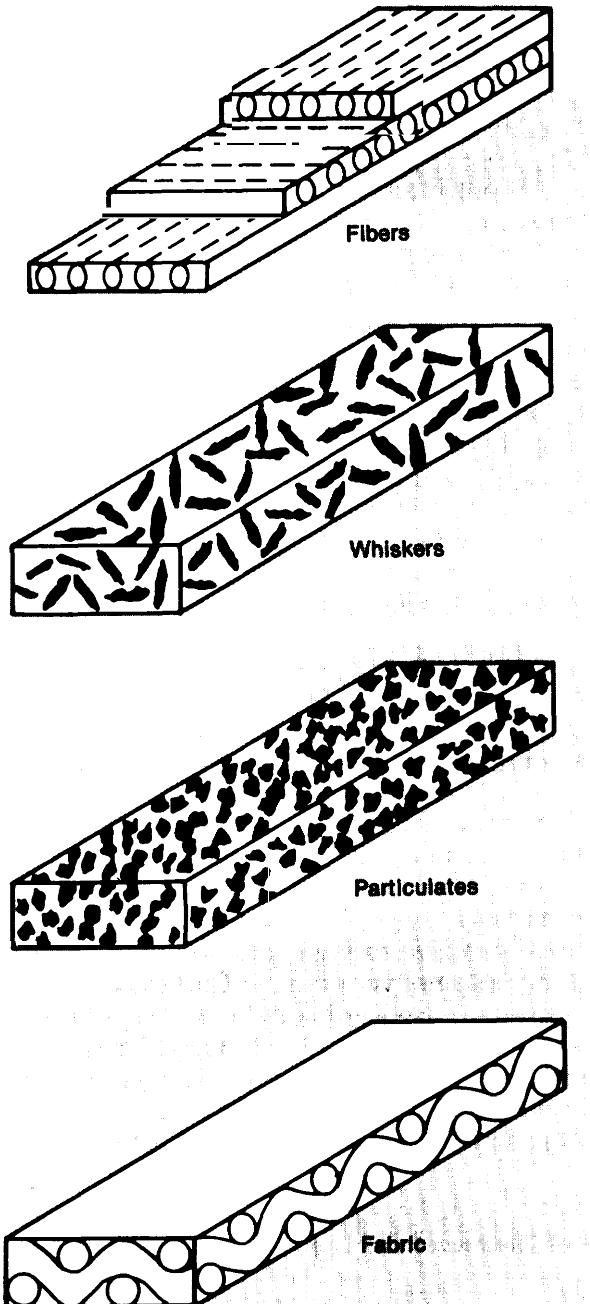
PMCs are often divided into two categories: reinforced plastics, and so-called advanced composites, The distinction is based on the level of mechanical properties (usually strength and stiffness); however, there is no unambiguous line separating the two. Reinforced plastics, which are relatively inexpensive, typically consist of polyester resins reinforced with low-stiffness 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 that yield superior strength and stiffness. They are relatively expensive and typically contain a large percentage of high-performance continuous fibers, such as high-stiffness glass (S-glass), graphite, aramid, or other organic fibers. This assessment primarily focuses on market opportunities for advanced composites.

Less than 2 percent of the material used in the reinforced plastics/PMCs industry goes into advanced composites for use in high-technology applications such as aircraft and aerospace.[1] In

[1]These advanced composites are primarily epoxy matrices reinforced with carbon fibers. Reginald B. Stoops, R.B. Stoops& Associates, Newport, RI, "Manufacturing Requirements of Polymer Matrix Composites, " contractor report for OTA, December 1985.

**Figure 3-1.—Composite Reinforcement Types**




SOURCE: Carl Zweben, General Electric Co

**1985, the worldwide sales of advanced composite materials reached over $2 billion.** The total value of fabricated parts in the United States was about $1.3 billion split among three major industry categories: 1) aerospace (50 percent), 2) sports equipment (25 percent), and 3) industrial and automotive (25 percent).[2]

It has been estimated that advanced composites consumption could 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 forecast to be 200 million pounds, valued at about $12 billion.[3]

Based on these forecasts, it is evident that the current and near-term cost per pound of advanced composite structure is roughly $60 per pound. This compares with a value of about $1 per pound for steel or $1.50 per pound for glass fiber-reinforced plastic (FRP). If these forecasts are correct, it is clear that over this period (to the year 2000), advanced composites will be used primarily in high value-added applications that can support this level of material costs. However, use of PMCs can lead to cost savings in manufacturing and service. Thus, the per-pound cost is rarely a useful standard for comparing PMCs with traditional materials.

[2]Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, March 1987.

J"Industry News," *SAMPE Journal,* July/August 1985, p. 89.

# CONSTITUENTS OF POLYMER MATRIX COMPOSITES

## Matrix

The matrix properties determine the resistance of the PMC to most of the degradative processes that eventually cause failure of the structure. These processes include impact damage, delamination, water absorption, chemical attack, and high-temperature creep. Thus, the matrix is typically the weak link in the PMC structure.

The matrix phase of commercial PMCs can be classified as either thermoset or thermoplastic. The general characteristics of each matrix type are shown in figure 3-2; however, recently developed matrix resins have begun to change this picture, as noted below.

### Thermoses

Thermosetting resins include polyesters, vinylesters, epoxies, bismaleimides, and polyamides. Thermosetting polyesters are commonly used in fiber-reinforced plastics, and epoxies make up most of the current market for advanced composites resins. Initially, the viscosity of these resins is low; however, thermoset resins undergo chemical reactions that 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 and maximum operating temperatures of thermosets. A

[4]See, for instance, *Aerospace America,* May 1986, p. 22.

### Thermoplastics

Thermoplastic resins, sometimes called engineering plastics, include some polyesters, poly-etherimide, polyamide imide, polyphenylene sulfide, polyether-etherketone (PEEK), and liquid crystal polymers. They consist of long, discrete molecules that melt *to* a viscous liquid at the processing temperature, typically 500” 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 thermosetting 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, although generally inferior to thermoses 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, because 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, thermoplas-

**Figure 3-2.—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. . . . . | | | | | |
| Thermoplastic. . . . . . . . . . . . . . . . . . . . . . | High | Low | Low | Low | High |

SOURCE: Darrel R. Tenney, NASA Langley Research Center.

tics could be used in place of epoxies in the composite structure of the next generation of fighter aircraft.

## Reinforcement

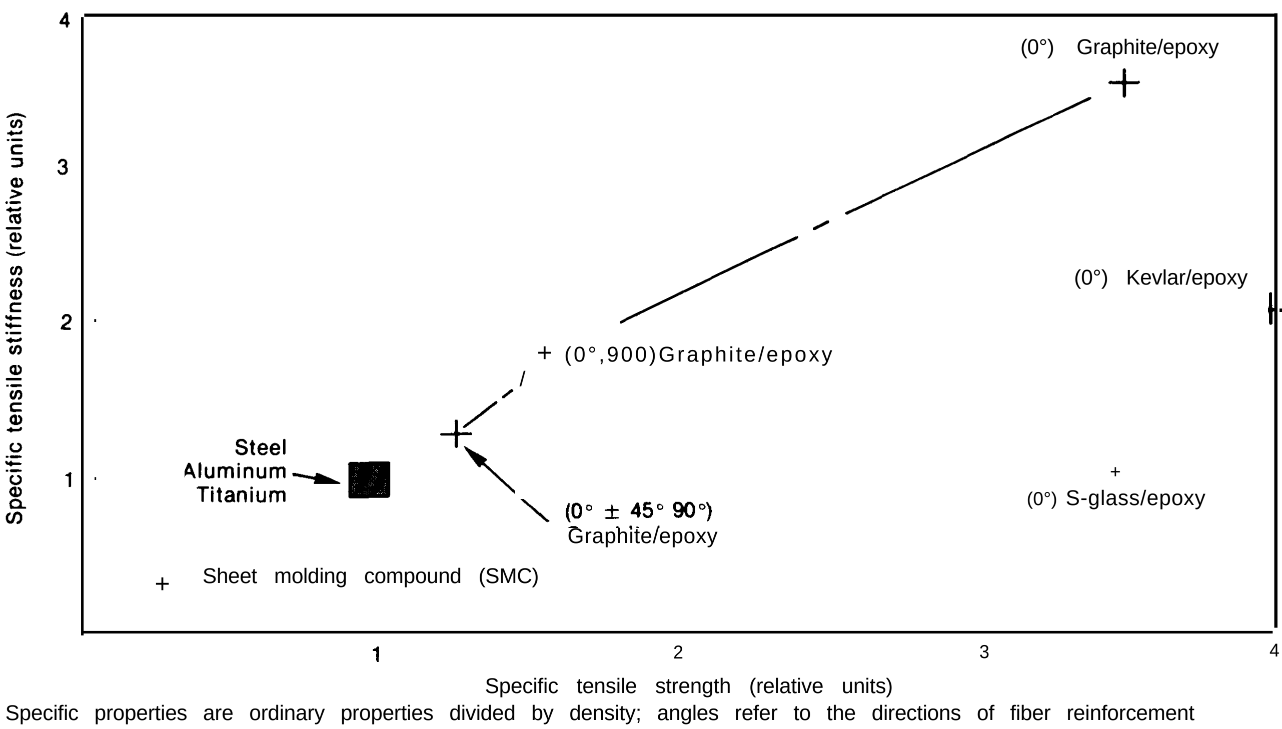
The continuous reinforcing fibers of advanced composites are responsible for their high strength and stiffness. The most important fibers in current use are glass, graphite, and aramid. Other organic fibers, such as oriented polyethylene, are also becoming important. PMCs contain about 60 percent reinforcing fiber by volume. The strength and stiffness of some continuous fiber-reinforced PMCs are compared with those of sheet molding compound and various metals in figure 3-3. For instance, unidirectional, high-strength graphite/epoxy has over three times the specific strength and stiffness (specific properties are ordinary properties divided by density) 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 ensure that glass fibers remain the most widely used reinforcement for high-volume commercial PMC applications. Only when stiffness or weight are at a premium would aramid and graphite fibers be used.

## Interphase

The interphase of PMCs is the region in which loads are transmitted between the reinforcement and the matrix. The extent of interaction between the reinforcement and the matrix is a design variable, and it may vary from strong chemical bonding to weak frictional forces. This can often be controlled by using an appropriate coating on the reinforcing fibers.

**Figure 3-3.—Comparison of the Specific Strength and Stiffness of Various Composites and Metals[a]**




Specific properties are ordinary properties divided by density; angles refer to the directions of fiber reinforcement

[a]Steel: AISI 4340; Aluminum: 7075-T6; Titanium: Ti-6Al-4V.

SOURCE: Carl Zweben, General Electric Co.

Generally, a strong interracial bond makes the PMC 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, debonding can occur at the interphase under certain loading conditions. To maximize the fracture toughness of the PMC, the most desirable coupling is often intermediate between the strong and weak limits. The character of the interracial bond is also critical to the long-term stability of the PMC, playing a key role in fatigue properties, environmental behavior, and resistance to hot/wet conditions.

## PROPERTIES OF POLYMER MATRIX COMPOSITES

The properties of the PMC depend on the matrix, the reinforcement, and the interphase. Consequently, there are many variables to consider when designing a PMC. These include not only the types of matrix and reinforcement but also their relative proportions, the geometry of the reinforcement, and the nature of the interphase. Each of these variables must be carefully *con*trolled to produce a structural material optimized for the conditions for which it is to be used.

The use of continuous-fiber reinforcement confers a directional character, called an isotropy, to the properties of PMCs. PMCs are strongest when stressed parallel to the direction of the fibers (0°, axial, or longitudinal, direction) and weakest when stressed perpendicular to the fibers (90°, transverse direction). In practice, most structures are subjected to complex loads, necessitating the use of fibers oriented in several directions (e.g., 0, ±45, 90°). However, PMCs are most efficiently used in applications that can take advantage of the inherent anisotropy of the materials, as shown in figure 3-3.

When discontinuous fibers or particles are used for reinforcement, the properties tend to be more isotropic because these reinforcements tend to be randomly oriented, Such PMCs 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) is such a material, widely used in the automotive industry; see figure 3-3.

The complexity of advanced composites can complicate a comparison of properties with conventional materials. Properties such as specific strength are relatively easy to compare, Advanced composites have higher specific strengths and stiffnesses than metals, as shown in figure 3-3. In many cases, however, properties that are easily defined in metals are less easily defined in advanced composites. Toughness is such a property. In metals, wherein the dynamics of crack propagation and failure are relatively well understood, toughness can be defined relatively easily. I n an advanced composite, however, toughness is a complicated function of the matrix, fiber, and interphase, as well as the reinforcement geometry.[5] Shear and compression properties of advanced composites are also poorly defined.

Another result of the complexity of PMCs is that the mechanical properties are highly interdependent. For instance, cracking associated with shear stresses may result in a loss of stiffness. Impact damage can seriously reduce the compressive strength of PMCs. Compressive and shear properties can be seen to relate strongly to the toughness of the matrix, and to the strength of the interfacial bond between matrix and fiber.

‘Given that perfect composite toughness cannot be attained, in some cases a material with lower toughness may be preferable to one with higher toughness. A brittle composite with low impact resistance may shatter upon impact, while a slightly tougher composite may suffer cracking. For some applications, even slight cracking may be unacceptable, and impossible to repair. If the composite shatters in the region of impact, but no cracking occurs in the surrounding material, the damage may be easier to repair.

# DESIGN, PROCESSING, AND TESTING

## Design

Advanced composites are designed materials. This is really the fact that underlies their usefulness. Given the spectrum of matrix and reinforcement materials available, properties can be optimized for a specific application. An advanced composite can be designed to have zero coefficient of thermal expansion. It can be reinforced with combinations of fiber materials (hybrid PMCs) and geometries to maximize performance and minimize cost. The design opportunities of PMC materials are only beginning to be realized.

The enormous design flexibility of advanced composites is obtained at the cost of a large number of unfamiliar design variables. In fact, composites are more accurately characterized as customized structures, rather than materials. Although the engineering properties of the homogeneous resins and fibers can be determined, the properties of each composite depend on the composition, fiber geometry, and the nature of the interphase. However, the categories of mechanical and physical properties used to characterize PMCs are carried over from long engineering experience with metals.

A major need in advanced composites technology is a better capability for modeling structure-property relationships (discussed in more depth in ch. 5). In spite of this lack, however, experience to date has shown that designers and manufacturers can produce reliable PMC structures. This is probably due to two factors. First, in the face of uncertainty, designers tend to overdesign; that is, they are conservative in their use of material, to avoid any possibility of material failure. Second, PMC structures are extensively tested before use, ensuring that any potential problems show up during the tests. Thus, the PMC materials themselves have been proven, in the sense that structures can be fabricated that are reliable and meet all design criteria. However, both overdesign and empirical testing are costly and drive up the prices of PMCs. Thus, a principal benefit of enhanced modeling capability will be to help make advanced composites more cost-competitive.

## Manufacturing

Given the many different fibers and matrices from which PMCs 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 advanced composites can be used more widely. The basic steps include: 1 ) impregnation of the fiber with the resin, 2) forming of the structure, 3) curing (thermoset matrices) or thermal processing (thermoplastic matrices), and 4) finishing.

Depending on the process, these steps may occur separately or continuously. For instance, the starting material for many PMCs is a prepreg; i.e., a fiber tape or cloth that has been preimpregnated with resin and partially cured. In pultrusion, by contrast, impregnation, forming, and curing are done in one continuous process. Some of the more important fabrication processes for PMCs are listed in table 3-1.

In the aerospace sector, advanced composite structures are commonly fabricated by the slow and labor-intensive process of hand lay-up of

**Table 3-1 .—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 lay-up | Slow, laborious, reliable, expensive (speed improved by automation) | Aerospace structures |
| Pultrusion | Continuous, constant cross-section parts | I-beams, columns |
| Filament winding | 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: Office of Technology Assessment, 1988.

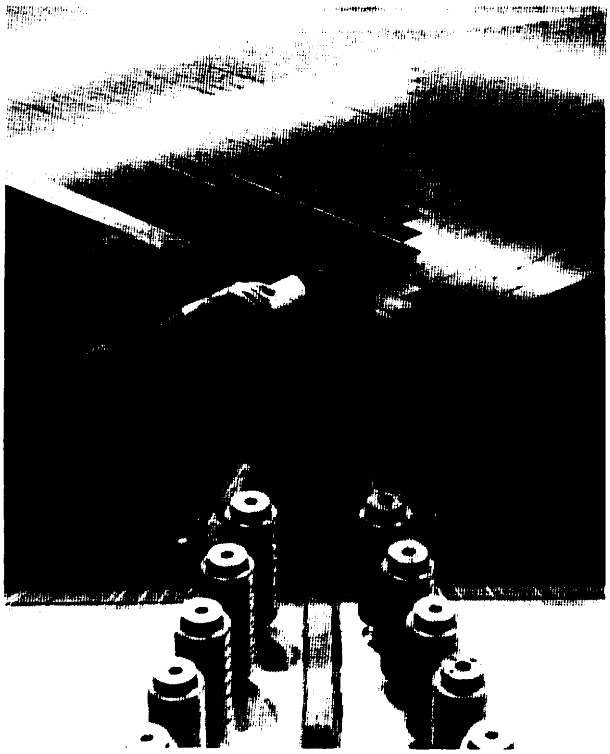


*Photo credit: Hercules, Inc.*

Filament winding of a rocket motor case.

prepreg tapes. Hand lay-up involves placement of sheets or tapes of prepreg on a tool (the contoured surface that defines the shape of the finished part). Labor costs often dominate the production costs of these PMC structures. In the case of a business aircraft fuselage, material costs have been estimated at about$13,000 per unit; labor costs, about $21,000 per unit; and capital costs, about $1,400 per unit.[6] These labor cost estimates include 1,154 person-hours for hand lay-up of the stiffeners and honeycomb core of the fuselage; only 35 person-hours are required to produce the inner and outer advanced composite skins, which can be fabricated by the automated filament winding process. '

New, more automated processes are now available that offer dramatic increases in productivity over hand lay-up. One project underway in-house at an airframe manufacturer can lay up to 100 feet of **3- or 6-inch** wide prepreg tape per minute, in complex shapes of variable thickness.[8] **At** least one machine tool manufacturer is developing a system of automated tape laying that takes into account the specified contour of the mold, and aligns the tape according to tape width and desired gap between strips, laying the tape along a precomputed path.

Most of these processes have been explored for thermosetting advanced composites for aircraft applications such as ailerons, stabilizers, flaps, fins, and wing skins; in addition there has also been some work done in the area of auto-

[6] Materials Modeling Associates, "Properties, Costs, and Applications of Polymeric Composites," in conjunction with Massachusetts Institute of Technology, a contractor report prepared for OTA, December 1985.

[7] 1 bid.

[8] "Rockwell Team Demonstrates Automatic Construction of Large Composite Wings," *Aviation Week & Space Technology,* June 15, 1987, p. 336.

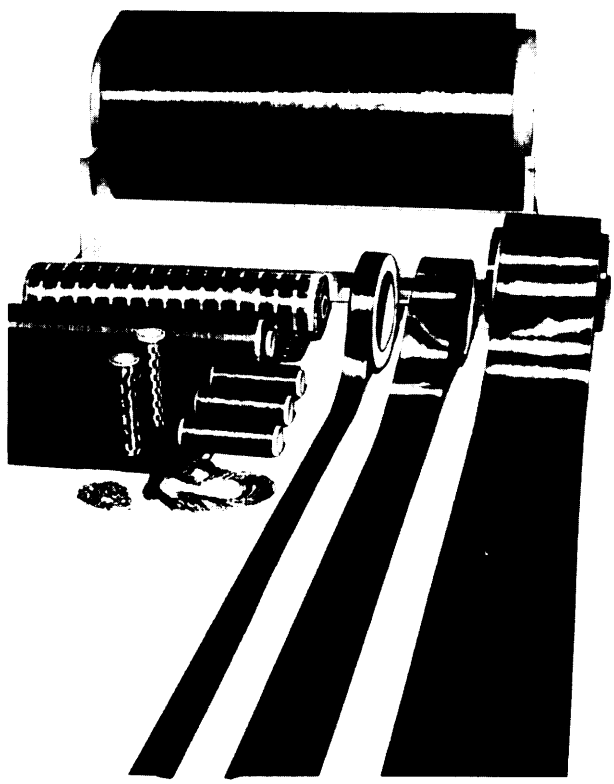


*Photo credit: Hercules Inc.*

Graphite fiber reinforcement forms. Top: broadgoods; right: prepreg tape; left (front): chopped fiber and carbon fiber rope; left (rear): fabric and fabric prepreg.

mated tape laying for continuous fiber-reinforced thermoplastic sheets, laid in parallel strips and continuously fused as they are placed.[9]

## Nondestructive Evaluation

In general, PMCs 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, whereas in ceramics, it is some tens of microns. Advanced composite structures are increasingly used in life-critical structures such as aircraft wings and fuselages. This places a special burden on nondestructive evaluation (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 could be used increasingly for monitoring the status of PMCs 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 PMCs differ somewhat from those for ceramics. Although 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, NDE techniques are required that can rapidly scan large areas for flaws or damage. Even though there are numerous techniques that may be useful in the laboratory for testing small specimens for research purposes, relatively few are appropriate to production or field-level inspection.

Several of the more important NDE techniques that are relevant to production, end product, and field level inspection are listed in table 3-2. Excellent progress has been made in production level techniques such as ultrasonics, and manufacturers are confident that large PMC surface areas can be inspected reliably and economically for such flaws as bulk delamination.

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

[9] Roger Seifried, Cincinnati Miliacron, personal communication, June 1, 1987.

**Table 3-2.—NDE Techniques Appropriate for Production, Finished Product, Depot-, and Field-Level Inspections of Polymer Matrix Composite Structures**

| NDE 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 | excellent | none |
| Acoustic emission | Bulk | fair | good | extensive |
| Depot level: | | | | |
| Ultrasonic | Bulk delamination | good | poor | some |
| Field level: | | | | |
| Ultrasonic | Bulk delamination | fair | poor | 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 PMC materials. The health hazards associated with the manufacture of PMC materials stem from the fact that chemically active materials are used and workers handling them may breathe harmful fumes or come into 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. In fact, some people become sensitized to the vapors and they can no longer work in a reinforced plastics plant.

The Occupational Health and Safety Administration (OSHA) has specified that styrene monomer concentrations in a plant should not exceed 100 parts per million.[10] In a plant in which 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 use of simple exhaust systems.

A new safety hazard was introduced with the advent of carbon fibers. They tend to float around the plant in which they are used. Because they are electrical conductors, they can get into unprotected electrical devices and cause short circuits. The fiber concentration in the air can be controlled by a negative pressure exhaust system in the area in which they are used, but all electrical devices in the area should be sealed to make them explosion proof. Because most factories using carbon fibers are generally involved with advanced composites and are more sophisticated than most reinforced plastics plants, they are able to handle this hazard without undue difficulty.

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

## Recycling and Disposal

Most PMC materials in use today have thermosetting matrices; consequently, after they have been cured, they 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 PMCs offers little economic incentive; most scrap is simply discarded, By contrast, one of the potential advantages of PMCs with thermoplastic matrices is that the scrap can be recycled,

Cured PMCs present no particular disposal problem; they are chemically inert and can be used for landfill. Incineration is generally avoided because it can generate toxic smoke.

The principal problem associated with PMC disposal arises with uncured PMCs. 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 PMC material is to bake it until it is cured and then dispose of it.

# APPLICATIONS AND MARKETS

PMCs area 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, advanced composites now have a good record of performance and reliability. They are rapidly becoming the baseline structural material of the defense/aerospace industry.

Because 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-technology applications such as construction, which generally requires standardized shapes such as tubes, bars, beams, etc. 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 PMCs to replace metals in applications in which high strength and stiffness are not required, such as use of SMC for automobile body panels.

Applications and markets for PMCs are discussed according to end-user industry below.

## Aerospace

The aerospace industry is estimated to consume about 50 percent of advanced composites production in the United States.[11] Growth projections for aerospace usage of advanced composites have ranged from 8.5 percent per year[12] to 22 percent per year.[13] Advanced Composites are used extensively today in small military aircraft, military and commercial rotorcraft, and prototype business aircraft. The next major aircraft market opportunity for advanced composites is in large military and commercial transport aircraft.

The primary matrix materials used in aerospace applications are epoxies, and the most common reinforcements are carbon/graphite, aramid (e.g., Du Pont's Kevlar), and high-stiffness glass fibers. However, high-temperature thermoplastics such as PEEK are considered by many to be the matrices of choice for future aerospace applications.

Compared with metals, the principal advantages of advanced composites in aerospace applications are their superior specific strength and stiffness, resulting in weight savings of 10 to 60 percent over metal designs, with 20 to 30 percent being typical.[14] This weight reduction can be used to increase range, payload, maneuverability and speed, or to 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.[15] This high premium for weight saved is unique to this aerospace sector, and explains why it leads all others in advanced composite market growth rate. Additional advantages of advanced composites 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 3-4). Because the performance advantages of advanced composites in military aircraft more than compensate for their high cost, this is likely to be the fastest growing market for advanced composites over the next decade. Indications are that composites may account for up to 40 percent of the struc-

[11] Strategic Analysis, Inc., op. cit., March 1987.

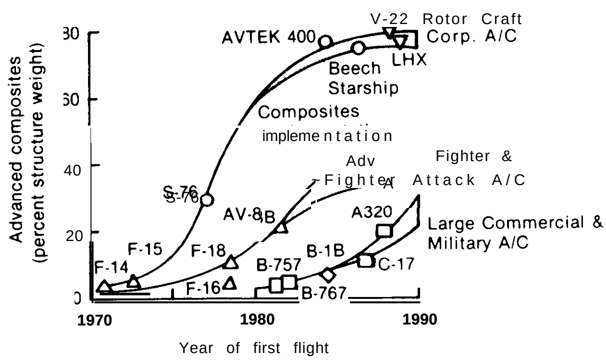
[12] According to "Worldwide High Performance Composites," a market study conducted by Frost & Sullivan, New York, NY, as reported in *World of Composites,* a publication of the Society of Plastics Industries, winter 1986, p. 4.

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

[14] Carl Zweben, "Polymer Matrix Composites," *Frontiers in Materials Technologies,* M.A. Meyers and O.T. Inal (eds.) (The Netherlands: Elsevier Science Publishers, 1985), ch. 12, p. 365.

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

**Figure 3-4.—Composite Aircraft Structure** (by **percent)**




KEY O Business aircraft and rotorcraft
v Military rotorcraft
A Fighter and attack aircraft
❑ Large commercial and military aircraft
**O** Bomber

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, 1966.

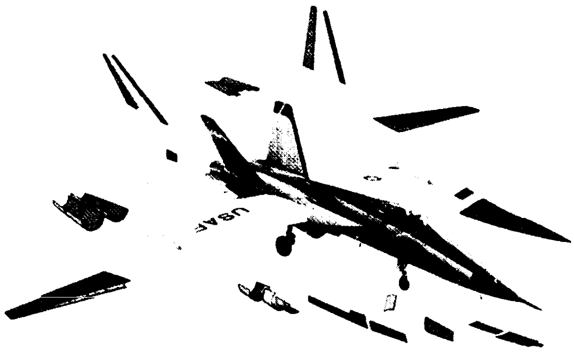


Photo credit: Hercules, Inc.

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

tural weight of the Advanced Tactical Fighter (ATF), which is still in the design phase. 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.[16]

## Commercial Aircraft

If aramid and glass fiber-reinforced composites are included, the volume of composites used in commercial and business aircraft is about twice that used in military aircraft.[17] In current commercial transport aircraft, such as the Boeing 767, advanced composites make up about 3 percent of the structural weight, and are used exclusively in the secondary (not flight-critical) structure.[18] However, two companies, Beechcraft and Avtek, are anticipating Federal Aviation Administration (FAA) certification of "all-composite aircraft prototypes for business use in 1988 and 1990, respectively. [19]

Although overall growth of the business aircraft fleet through the early 1990s is expected to be only around 10 percent, two categories (turboprop and turbojets) are expected to grow significantly.[20] 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 per year.[21] 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, PMCs could make up 65 percent of the structural weight of commercial transport aircraft.[22] 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 composites per year. Assuming a starting material value of $60 per pound, the market in the year 2000 is projected to be worth about $1.5 billion for the composite materials alone. A much 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 only 1 million to 2 million pounds in that year.[23]

### Helicopters

With the exception of the all-composite business aircraft prototypes, which are still awaiting certification, advanced composites have been used more extensively in helicopters than in aircraft. Military applications have led the way, and the advantages of advanced composites are much the same as in aircraft: weight reduction, parts consolidation, and resistance to fatigue and corrosion,

Over the past 15 years, advanced composites have become the baseline materials for rotors, blades, and tail assemblies. Sikorsky's S-76 com-

[16] 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.

[17] Ibid.

[18] 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.

[19] According t. information supplied by Beechcraft and Avtek.

[20] Materials Modeling Associates, op. cit., footnote 6, 1985.

[21] Ibid.

[22] Tenney, op. cit., footnote [1]8.

[23] Hadcock, op. cit., footnote 16.

mercial model, which is about 25 percent advanced composite by weight (figure 3-4), was certified in the late 1970s. Future military helicopters, such as the Army's proposed 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 that require designers to consider advanced composites. In these helicopters, composites are likely to comprise up to **80 percent of the structural weight (figure 3-4).**

Materials such as graphite/epoxy are likely to be used in the airframe, bulkheads, tail booms, and vertical fins, while glass/epoxy PMCs of lesser stiffness could 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 composite materials could be used in the future. (See ch. 7 for a case study examining the use of PMCs for automobile body structures.) Because the industry is mature and highly competitive, the principal motivation for introducing PMCs is cost savings.

In contrast to the aircraft industry, there is no clear-cut premium associated with a pound of weight saved. Nevertheless, the automotive industry 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 technical advantages of PMCs, such as corrosion resistance, appear to be secondary to the cost issue.

By far the greatest volume of PMC material in use is sheet molding compound (WK), used in nonstructural parts such as exterior panels. The most visible automotive use of SMC in recent years has been in the Pontiac Fiero, which has an all-PMC exterior.[24]

24 The Fiero will be cancelled at the end of 1988.

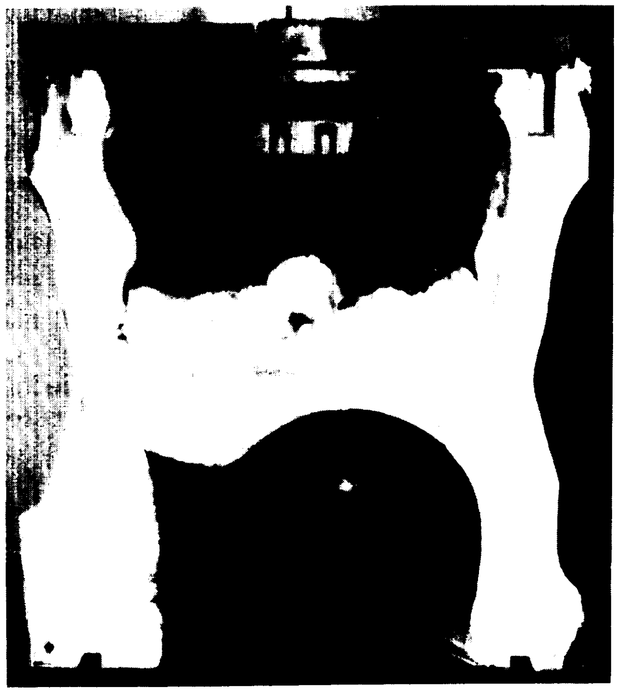


*Photo credit: Ford Motor Co.*

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.

The next major opportunity for PMCs in automobiles is in structural components.[25] Two structural components currently in service are the advanced composite drive shaft and leaf spring. Some 3,000 drive shafts, manufactured by filament winding of graphite and E-glass fibers in a polyester resin, were used annually in the Ford Econoline van.[26] Meanwhile, glass FRP 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 PMCs, and they 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.

Engineering groups within the Big Three U.S. automobile producers are considering advanced

25P. Beardmore, "Composite Structures for Automobiles," *Composite Structures,* vol. *5, 1986,* pp. 163-176.

26Although composite drive shafts are technically successful, Ford took them out of production in 1987 in favor of a new aluminum design.

composite unibody vehicle designs for the late *1990s.*[27] The automakers are exploring PMC frames for a variety of reasons. PMC vehicles would enable designers to reduce the number of parts required in assembly; some manufacturers are looking into a one-piece advanced composite body. By reducing the number of parts, better consistency of parts can be achieved at considerably reduced assembly costs.

Advanced composites also offer substantial improvements in specific mechanical properties, with the possibility of reducing weight while increasing strength and stiffness. Finally, because they do not rust, PMCs offer greatly improved corrosion resistance over steel or galvanized steel. Analysts have estimated that PMC automobiles could last 20 or more years, compared to the current average vehicle lifetime of 10 years .[28]

The major technical barrier to use of PMCs in the automotive industry is the lack of manufacturing technologies capable matching the high production rates of metal-stamping technology (see ch. 7). The fastest current technologies can process material at the rate of tens of pounds per minute, but true economy will require rates of a hundred pounds per minute or more.[29] Thus, there is a gap of roughly an order of magnitude between current and economical rates.

## 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 varying degrees from the tailorable an isotropic stiffness, superior strength, low thermal expansion, and fatigue-life and vibration-damping characteristics of PMCs.

In robotic applications, increasing both the speed and the endpoint accuracy of the robot are desired improvements. Stiffness is the key mechanical property in that 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's response time. Consequently, the ratio of the weight of the manipulator arm to that of the payload is rarely lower than 10:1.30 Because of their superior stiffness per unit weight, PMCs are a promising solution to this problem. At present, only one U.S. company has marketed a robot incorporating PMCs,[31] although there are several Japanese models on the market and a number of other countries are funding research.

Although the benefits of using PMCs 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 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. PMC penetration is likely to be slow but steady.

## Naval Applications

The light weight and corrosion resistance of PMCs makes them attractive for a number of naval applications. Advanced composites are currently in production in molded propeller assemblies for the Mark 46 torpedo, at a cost savings of 65 to 70 percent over the previous aluminum design .32 The Navy is also evaluating PMCs for hatch doors, bulkheads, and propeller shafts. PMC components in the ship superstructure have the dual advantage of lowering the center of mass (and therefore increasing the stability) and pro-

[27] Materials Modeling Associates, op. cit., footnote 6, 1985.

[28] Ibid.

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

[30] B. S. Thompson and C.K. Sung, "The Design of Robots and Intelligent Manipulators Using Modern Composite Materials," *Mechanism and Machine Theory* 20:471-*82,* 1985.

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

[32] Ronald L. pegg and Herbert Reyes, "Progress i n Naval Composites," *Advanced Materials and Processes,* March 1987, p. 35.

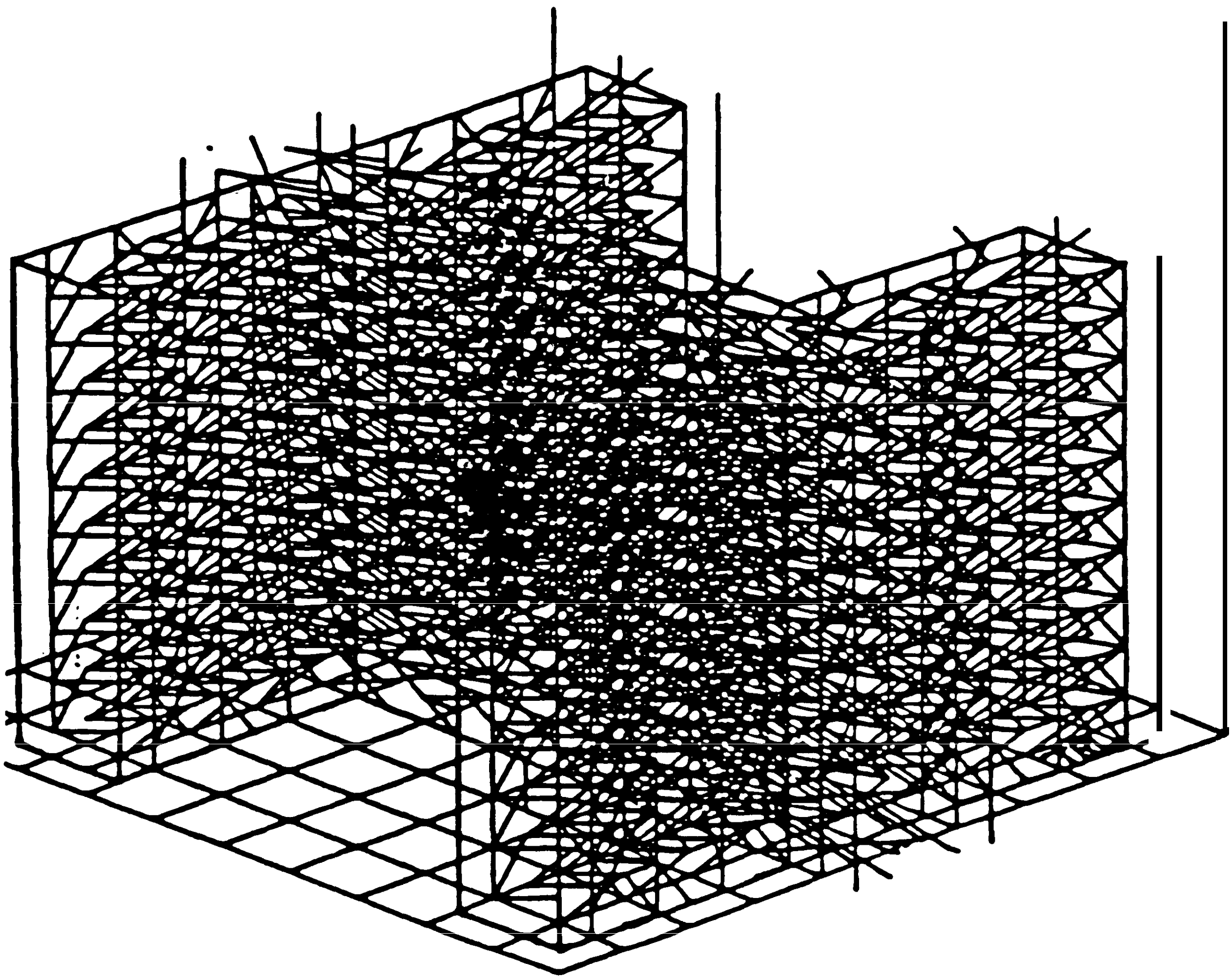


*Photo credit: The CUMAGNA Corp.*

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

vialing better protection against shrapnel fragments in combat. PMCs have also been in use for years as sonar domes on submarines, and radomes for surface ships.

Future applications for PMCs on surface ships include antenna masts and stacks (due to reduced weight and radar cross section), and valves, pipes, and ducts (due to lower weight and corrosion resistance). PMCs could also be used for an advanced technology submarine hull, providing weight savings and thus speed advantages over metal hulls currently in use.

## Construction

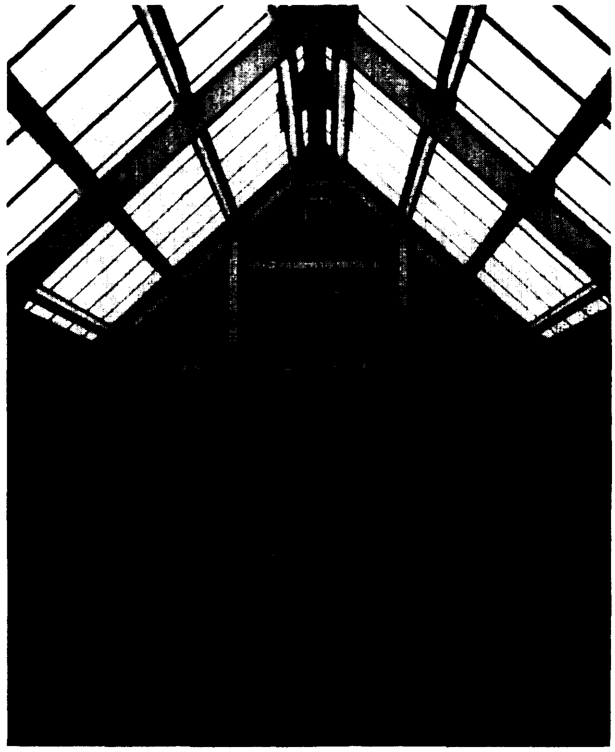
A potentially high-volume market for PMCs lies in construction applications, especially in construction of buildings, bridges, and housing. Additional applications include lampposts, smokestacks, and highway culverts. Construction equipment, including cranes, booms, and outdoor drive systems, could also benefit from use of PMCs. Because of the many inexpensive alternative building materials currently being used, the cost of PMC materials will be the key to their use in this sector.

The chief advantage of using PMCs in construction 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.[33]

Bridges are likely to be the first large-scale construction application for PMCs in the United States. Because the largest load that must be supported by the bridge is its own dead weight, use of lightweight advanced 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 stiffness and low creep requirements.

The opportunities for use of PMCs in bridges are considerable: 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** PMC 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. Nevertheless, the U.S. Department of Transportation is currently evaluating PMCs for use in bridge decking and stay cables.[35] Fiberglass tendons are also being used in place of steel in prestressed concrete bridge structures.[36] Other countries that have active programs in this area include China, Great Britain, West Germany, Israel, and Switzerland.

The manufactured housing industry is an especially intriguing potential opportunity for PMC materials. In 1984, almost half of all new housing units were partially manufactured; that is, large components were built in factories, rather



*redI Co Tec ology,*

**e a me a mag e re b App e C mp e e a m wav d e g ac e b d g mp d g a e e are e made b mp**

than assembled on site.[37] In the future, factory manufacture of housing promises to reduce housing costs while still maintaining options for distinctive designs. PMC manufacturing techniques such as pultrusion and transfer molding could be used to fabricate integral wall structures containing structural members and panels constructed 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 housing construction technologies.

One important research need affecting the use of PMCs in construction applications has to do

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

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

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

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

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

with adhesion and joining. The joining of PMC 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. A second need for PMCs use in the construction industry involves the availability of standardized shapes of standard PMC materials to be purchased much the way metal shapes are currently sold for construction use.

An additional technical barrier is need for development of design techniques for integrated, multifunctional structures. Window frames made by joining together several pieces of wood can be replaced by molded plastic and PMC structures having many fewer pieces, lower assembly costs, and better service performance. The flexibility of the design and manufacture of PMC 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 already been done for certain experimental bathroom structures in which lavatories, shower rooms, and other structural components have been integrated in a single molding.[38]

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, the housing construction industry is highly fragmented. This makes the rate of research and development 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 PMC materials and processes. Finally, PMCs must compete with a variety of low-cost housing materials in current use. As a result, PMCs used in manufactured housing are not likely to be advanced; rather, they are likely to 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 PMCs on orthopedic devices is expected to be especially significant. Although medical devices are not likely to provide a large volume market for PMCs, 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.[39] Estimates of the U.S. market for all biocompatible materials by the year 2000 range up to $3 billion per year.[40] PMCs could capture a substantial portion of that, sharing the market with ceramics and metals.

Metallic implant devices, such as the total hip unit that 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.

PMC materials have the potential to overcome many of these difficulties. Not only can the problem of metal ion release be eliminated, but PMC materials can be fabricated with stiffness that 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 PMC systems that would provide initial stability to a fracture but would gradually resorb over time as the natural tissue repairs itself. In addition, PMCs can be designed to serve as

[38]Kenneth L. Reifsnider, Materials Response Croup, Virginia Polytechnic Institute, "Engineering Research Needs of Polymer Composites, " a contractor report prepared for OTA, December 1985.

[39]Ibid.

[40]Larry L. Hench and June Wilson, "Biocompatibility of Silicates for Medical Use, " *Silicon Blochemlstry,* CIBA Foundation Symposium No. 121 (Chichester, England: John Wiley & Sons, 1986), pp. 231-246.

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

To overcome the remaining technical barriers, a cooperative effort of interdisciplinary teams is required. At a minimum, a team must include expertise in design, engineering, manufacturing, and orthopedic surgery. Significant strides in this field are being made in Japan, Great Britain, France, West Germany, Italy, Canada, and Australia, as well as in the United States.[41]

41 Reifsnider, op. cit., footnote 38.

# FUTURE TRENDS IN POLYMER MATRIX COMPOSITES

## Novel Reinforcement Types

### Rigid Rod Molecules

PMCs can be reinforced with individual, rigid rod-like molecules or with fibers generated from these molecules. One example is poly (phenylbenzobisthiazole), or PBT. Experimental fibers made from this material have specific strength and stiffness on a par with the most advanced fiber reinforcement, exceeding the properties of commercially available metals, including titanium, by more than a factor of 10.[42] One particularly promising possibility is to dissolve the molecular rods in a flexible polymer and thus create a PMC 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 it 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 of orienting them once dissolved.

### Novel Matrices

Because the matrix largely determines the environmental durability and toughness, the greatest improvements in the performance of future PMCs 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.[43] Some of the more promising directions are discussed below.

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

## Oriented Molecular Structures

At present the anisotropic properties of most PMCs 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 could serve the same reinforcing function as fibers do in today's PMCs. 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 of tomorrow's matrices.

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., polyethyleneterephthalate, or PET), or polyaramids. They have a self-reinforcing fibrous character that imparts strength and stiffness comparable to those of reinforced thermoplastic molding compounds, such as 30 percent glass-reinforced nylons.[44] The fiber orientations of current LCPs are hard to control (current applications include microwave cookware and ovenware that require high-temperature resistance but not high strength) and this represents a challenge for the future.

43 Charles P. West, Resin Research Laboratories, Inc., Personal communication, August 1986.

44 Reginald B. Stoops, "Ultimate Properties of Polymer Matrix Materials," contractor report prepared for OTA, December 1985.

## High-Temperature Matrices

The maximum continuous service temperature of organic polymers in an oxidizing atmosphere is probably around 700° F,[45] although brief exposures to higher temperatures can be tolerated. Currently, the most refractory matrices are polyamides, which can be used at a maximum temperature of 600° F (316° C), although slow degradation occurs.[46] If stable, high-temperature matrices could be developed, they would find application in a variety of engine components and advanced aircraft structures.

## Thermotropic Thermoses

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 that 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.[47]

## Space Applications

### Space Transportation Systems

Over 10,000 pounds of advanced composites are used on the space shuttle. da Advanced composites are also being considered in designs for a proposed National Aerospace Plane (NASP), although such an aircraft probably will not be available until after the year 2000. The primary limitation on the use of advanced composites in this application would be high temperature.[49] 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).[so] If advanced composites were available that 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.

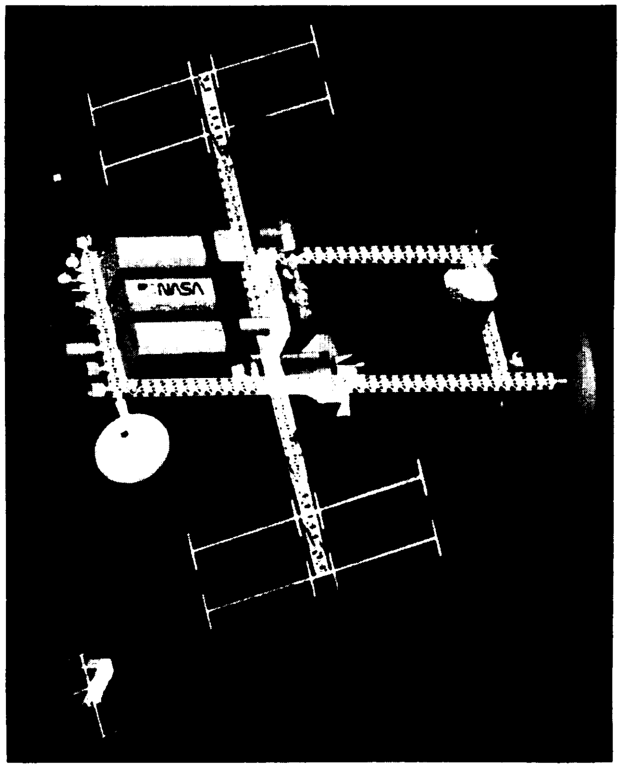



*Photo credit: National Aeronaut/es and Space Administration*

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

### Space Station

Graphite/epoxy advanced 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 advanced composites; however, their lower thermal conductivity (compared with aluminum) could create problems in service. The most serious environmental problem faced by advanced composites is temperature swings between — 250°

[45] Paul McMahan, Celanese Research Corp., in an OTA workshop, "Future Opportunities for the Use of Composite Materials," Dec. 10, 1985.
[46] *Aerospace America,* May 1986, p. 22.
[47] John Riggs, Celanese Research Corp., in an OTA workshop, "Future Opportunities for the Use of Composite Materials, " Dec. 10, 1985.
[48] Tenney, op. cit., footnote 18.
[49] Hadcock, op. cit., footnote 16.

50Ibid.

F (– 1210 C) and +200° F (+93° C) caused by periodic exposure to the Sun. This thermal cycling produces radial cracks in graphite/epoxy tubes that can reduce the torsional stiffness by as much as 30 percent after only 500 cycles.[51] To reduce the effects of thermal cycling, advanced composite tubes would be coated with a reflecting, thermally conducting layer to equalize the temperature throughout the tube. The layer would also protect the PMC from atomic oxygen (a major cause of material degradation in low-Earth orbit), and 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 envisioned for the Strategic Defense Initiative.[52] Properties such as low density, high specific stiffness, low coefficient of thermal expansion, and high temperature resistance are all necessary for structures that 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 been established within the Strategic Defense Initiative Office.[53]

## Bioproduction

Living cells can synthesize polymeric molecules with long chains and complex chemistries that cannot be economically reproduced in the laboratory. For instance, crops and forests are an important source of structural materials and chemical feedstocks. Several plants such as cram be and rapeseed, and certain hardwood trees, are now being evaluated for commercial production of lubricants, engineering nylons, and PMCs.[54] For some materials, such as natural rubber, the United States is totally dependent on foreign sources. In the Critical Agricultural Materials Act of 1984 (Public Law 98-284), Congress mandated that the Department of Agriculture establish 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 were started in 1987.

With the possible exception of wood, it is unlikely that biologically produced materials will compete seriously with PMCs in the structural applications discussed in this report. Although natural polymers such as cellulose, collagen, and 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 instance, collagen is a biologically compatible material that is used to generate artificial skin.[55]

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.[56] 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.[57] The flexibility inherent in such a scheme would be enormous; by simply altering the genetic instructions, new polymers could be produced.

51 Tenney, op. cit., footnote 18.

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

53 The effort includes: lightweight structures; thermal and electrical materials; optical materials and processes; tribological materials; and materials durability. In 1988, budgets for these materials programs were about $26 million, and are projected to reach $54 million in 1989.

54 According to information supplied by the USDA'S Office of Critical Materials.

55 J. Burke, et al., "The Successful Use of Physiologically Acceptable Artificial Skin in the Treatment of Extensive Burn In jury," *Annals of Surgery*, vol. 194, 1982, pp. 413-28.

56 Dennis Lang, Syntro Corp., personal communication, August 1986.

57 Terrence Barrett, National Aeronautics and Space Administration, personal communication, August 1986.

# RESEARCH AND DEVELOPMENT PRIORITIES

Federal R&D spending for PMCs in fiscal years 1985 to 1987 is shown in table 3-3; roughly 70 to 80 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 PMC R&D; rather, it can be attributed to the completion of large research programs in 1985 and the transitioning of the technology (particularly for carbon fiber PMCs) out of the basic and applied research categories of the DoD budget (6. 1, 6.2, and 6.3A). Defense applications continue to drive the development of PMCs, which are used in an estimated $80 billion of weapons systems.[58]

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

## Very Important

### Processing Science

The primary goal of processing science is to be able to control the fabrication process to ensure complete and uniform cure, minimize thermal stresses, control resin content, and ensure accurate fiber placement. This requires models that 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, though, modeling is in a very early stage of development.

The existence of low-cost fabrication processes will be critical to the use of new PMC systems, such as low-cost, high-performance thermoplastics reinforced with continuous fibers. For instance, 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 effects of processing on microstructure require further study. Similar knowledge is needed of the influence of residual thermal stresses, a particular concern for resins processed at high temperatures. Finally, as for thermoses, process models are required.

### Impact Damage

The resistance to impact damage of a PMC structure has a critical effect on its reliability in service. Impact damage barely visible to the naked eye can cause a reduction in strength of as much as 40 percent.[59] 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 such as rein-

[58]Kenneth Foster, Assistant for Materials Policy, Department of Defense, personal communication, August 1986.

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

**Table 3-3.—Budgets for Polymer Matrix Composite R&D in Fiscal Years 1985 to 1987 (millions of dollars)**

| Agency | FY 1985 | FY 1986 | FY 1987 |
|---|---|---|---|
| Department of Defense (6.1, 6.2, 6,3A) | $55.9 | $29.2 | $33.8 |
| National Aeronautics and Space Administration | 23 | 8.7 | 5.0 |
| National Science Foundation | 1-2 | 1-2 | 3.0 |
| National Bureau of standards | 04 | 04 | 0.5 |
| Department of Transportation | · | 0.4 | 0.2 |
| Total | $80-81 | $40-41 | $42.5 |

SOURCE OTA survey of agency representatives forcement 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 PMC structures, a field that still relies largely on empirical methods.

### Delamination

There is a strong body of opinion that delamination is the most critical form of damage in PMC 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. Voids and pores between layers can also pose serious problems to the integrity of the PMC. 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 crack 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.

### Interphase

The interphase has a critical influence on the PMC in that it determines how the reinforcement properties are translated into the properties of the composite structure. 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 mechanical properties and provide resistance to environmental degradation.

## Important

### Strength

The excellent strength properties of PMCs are one of the major reasons for their use. However, as with many properties of PMCs, their heterogeneity makes strength characteristics very complex. This heterogeneity gives rise to failure modes that frequently have no counterpart in homogeneous materials. Even for the simplest PMCs, unidirectional laminates, there is an inadequate understanding of the relationships between axial and transverse loading (parallel and perpendicular to the fiber direction) and failure. In more complex PMCs, 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 PMCs and laminates that relate strength properties to basic constituent properties.

### Fatigue

Fatigue of PMCs is an important design consideration. Fatigue resistance is a major advantage that PMCs enjoy over metals; however, the traditional models for analyzing fatigue in metals do not apply to PMCs. The risks associated with fatigue failure are likely to increase because of the trend toward use of fibers with higher failure strains, plus the desire to use higher design allowable for existing materials.

Ideally, it would be desirable to be able to predict PMC 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 PMC. Important topics that have not received adequate attention are the fatigue properties of the reinforcements and matrix resins, and compression fatigue of unidirectional PMCs. 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 PMCs 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 PMCs, use of linear elastic fracture mechanics 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 PMCs. To develop reliable design methods and improved materials in the future, it will be necessary to develop a body of fracture analysis that is capable of accounting for the more complex failure mechanisms.

### Environmental Effects

The environments to which PMCs are subjected can have a significant effect on their properties. Environments 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 PMCs

There are two main reasons for the interest in new reinforcement forms: improved through-the-thickness properties, and lower cost. A pervasive weakness of PMC 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 conventional 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 that can cause significant loss of strength compared to a unidirectional laminate. However, multidirectional reinforcement appears to confer increased fracture toughness on the PMC.

Use of several types of fibers to reinforce PMCs will be driven by the desire to obtain properties that cannot be achieved with a single fiber, and to reduce cost. For instance, glass fibers, which are cheap but have a relatively low tensile stiffness, can be mixed with more costly, high-stiffness graphite fibers to achieve a PMC that 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 human intuition and time-consuming, costly empirical approaches.

## Desirable

### Creep Fracture

Materials subjected to sustained loading fail at stress levels lower than their static strengths. This phenomenon is called creep fracture. Topics that require study include tensile and compressive loading of both unidirectional PMCs and laminates, and the influence of temperature and environment. Because the time-dependent degradation of the matrix and interphase properties are typically greater than those of the fiber 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 PMCs, especially for compressive loading, which has received relatively little attention.