# Fiber-Reinforced Composites: Engineered Structural Materials

P. Beardmore, J. J. Harwood, K. R. Kinsman, R. E. Robertson

*Summary.* Fiber-reinforced composites are an emerging new class of engineering materials. The ability to tailor-make composite materials and structures offers exciting opportunities for a broad spectrum of industrial applications. This article reviews the nature of fiber-reinforced polymer composites, their characteristics and properties, and the manufacturing and fabrication processes involved in composite production. The automotive industry is used as an example of the striking potential of composites as structural materials and the issues involved in bringing this potential into reality.

We are on the verge of witnessing the widespread introduction of a new major class of engineering materials in the industrial marketplace. It has long been the aspiration of materials scientists and engineers to reproduce in tailor-made, engineered materials the intricate structural networks so often found in nature's products and the human body which give rise to such remarkable functional characteristics. This long-sought goal seems to be approaching realization through the incorporation of a variety of fine fibers or filaments into appropriate matrices for the achievement of engineering properties not easily attained, if at all, in conventional bulk materials. In particular, continuous fiber-reinforced plastic (FRP) composites are close at hand as competitive classes of materials for structural and engineering applications.

Over the past decade there has been a remarkable growth in the use of plastics in the United States and in the rate of their acceptance for a broad range of industrial and consumer products. The polymer science and technologies which underlay these developments are described by Anderson *et al.* (*1*) and by Alfrey and Schrenk (*2*). But it has been claimed that a "second revolution" in the plastics industry and technology will come from the large-scale industrial applications of FRP's. The features of the fiber composites that make them so promising as industrial and engineering materials are their low density, high specific strength (strength/density), and high specific stiffness (modulus/density), and the opportunities to tailor the materials properties through the control of fiber and matrix combination and fabrication processing.

A most familiar use of FRP's is in recreation products involving largely glass fiber-resin systems in a variety of forms typically assembled by hand-labor-intensive processes. Fiberglass boats and other recreation vehicles, either all or in part, are commonly constructed of chopped glass on woven glass fiber mats held in resin matrices. But applications involving more demanding performance and more innovative use of continuous fiber reinforcement are evolving. An early example is rod forms, most familiarly fiberglass fishing rods. Today, even lighter and more responsive rods are filament wound with graphite and Kevlar fibers. Golf club shafts, tennis rackets, skis, ship masts are other products in which the advantages of lightness and the ability to tune the response of the component through manipulation of fiber placement are being tested in the marketplace.

But the most sophisticated use of the advantages offered by composites always has been pursued in high-performance aircraft and in military and space vehicle applications, where the premium on weight reduction supported the associated high cost. This application experience fostered sufficient confidence in design, engineering, performance, and reliability of certain composites that selected control surfaces in current-generation commercial aircraft are being retrofitted with these lighter materials in the interest of increased fuel efficiency. Boeing recently publicized plans to use significant quantities of advanced graphite and graphite/Kevlar composites in their next generations of planes, such as the Boeing 757 and Boeing 767 (Fig. 1). Advanced communication satellites, such as Intelsat V (Fig. 2), make extensive use of graphite fiber-reinforced composites for the truss structure and the large dish antennas. Not only are these designed for strength, stiffness, and lightness, but the composites provide the dimensional (thermal) stability critical to the communications task performed.

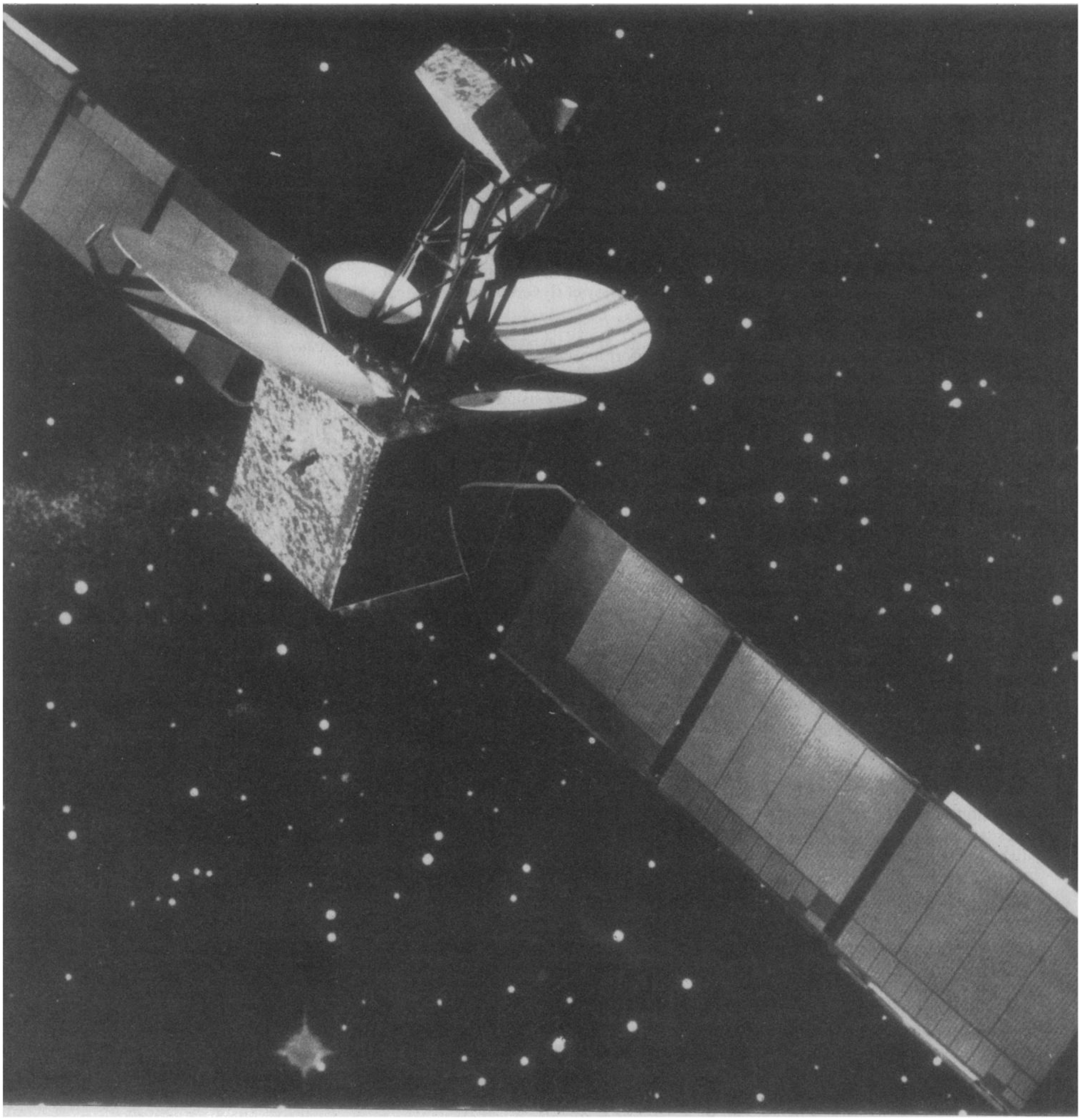
Of more impact on the consumer marketplace are the composite materials developments taking place in the automotive industry. Some 600 million pounds of fiberglass-reinforced plastics were used by the transportation industry in 1979. It has been projected that this amount may grow to more than 1 billion pounds per year over the next 5 years. Moreover, the intensive commitment on the part of the automotive industry to develop and produce new generations of vehicles with significantly improved fuel economy has brought lightweight, high-strength materials into key roles. Analyses based on expectations of technological and manufacturing developments indicate that fiber-reinforced polymer composites have a real potential as a next-generation class of materials for vehicle applications. Within this class, hybrid graphite fiber composite systems offer dramatic weight-saving opportunities—perhaps up to 70 percent weight reduction on a materials basis and more than 30 percent reduction in vehicle weight. These are the stimuli that have led to aggressive exploration and development of new classes of composite materials for advanced vehicle applications.

In this article we will review briefly the nature of fiber-reinforced polymer composites, the types of fibers currently being utilized for reinforcement, the requirements and functions of the resin matrix, the manufacturing and fabrication processes involved in composites production, and the properties and engineering advantages of composites. Using the automotive industry as an example, we will indicate the striking potential of composites as structural materials and the issues involved in bringing this potential into reality.

---

J. J. Harwood is director of the Materials Sciences Laboratory; P. Beardmore is principal research scientist, and K. R. Kinsman and R. E. Robertson are staff scientists in the Metallurgy Department, Ford Research Laboratory, Dearborn, Michigan 48121.

0036-8075/80/0523-0833$02.00/0



*One of the Intelsat V series of advanced communication satellites. The first satellite in this series is scheduled to be launched by NASA for the International Telecommunications Satellite Organization later in 1980. The satellite will carry telephone calls, television, telex, and telegrams; it can simultaneously handle 12,000 telephone calls and two TV channels. Graphite fiber-reinforced composites are used for the truss structure and large dish antennas of the satellite. [C. K. H. Dharan, Ford Aerospace and Communications Corp., Western Development Laboratories, Palo Alto, California]*

## Fiber Composites

Is a fiber composite simply a mass of fibers dispersed in some polymer or metal matrix? Polymer engineers have viewed composites as fiber-reinforced plastics—an upgrading of the polymer's stiffness and strength by fibers without a significant loss in resilience or toughness, and often without a large decrease in the ease of processing. Ceramists have viewed composites as a clever way (and it is) to utilize the high stiffness and high intrinsic strength of lightweight, brittle ceramics. The cleverness is in isolating the surface flaws that are catastrophic in a monolith by subdividing the ceramic into a very large number of fibers separated by a crack-stopping matrix. And metal physicists have viewed composites as a way of utilizing metal whiskers so defect-free that the strengths approach theoretical estimates.

For structural designers and materials engineers, fiber composites have become more than any of the above concepts. With the advent of graphite (carbon) and aramid (Kevlar) fibers, fiber composites have become a means for tailor-making "engineered," mechanically anisotropic materials that have superior properties in selected directions. With the reinforcement of plastics with glass fibers, for example, the composite is often anisotropic but at least the constitutents are isotropic. With Kevlar and graphite fibers, the molecular arrangement within the fiber is highly oriented, with the strongest covalent bonds along the fiber axis and weaker covalent and even van der Waals bonds in the transverse direction. The fibers, then, mirror internally the properties of the composite in which they are used—high stiffness and strength, including fatigue and creep resistance, along the fiber axis, with much lower transverse stiffness and strength. Optimum utilization of such oriented materials requires matching the direction-controlled properties of the composite to the service load conditions.

Table 1. Fiber properties.

| Fiber | Density (g/cm$^3$) | Tensile strength (MPa) | Modulus (GPa) | Cost ($/lb) |
|---|---|---|---|---|
| Graphite-I | 1.75 | 2760 | 235 | 20-32 |
| Graphite-II | 1.85 | 2415 | 220 | 75 |
| S-Glass | 2.63 | 3450 | 90 | 2.3 |
| E-Glass | 2.63 | 2415 | 72 | 0.50 |
| Kevlar | 1.45 | 2760 | 130 | 9 |

## Fibers

A variety of fibers is available for use in composites. Table 1 summarizes the major types currently used in engineering structural plastics. Not included are boron fibers, which are considered too expensive for anything but aerospace and military applications, and alumina and silicon carbide fibers, which are newer types being developed for composite reinforcements. Some of the fibers, such as graphite, can be fabricated with a wide range of properties. Table 2 lists mechanical properties of fiber-reinforced composites with epoxy matrices. (Also included in Table 2 are comparative properties for steel and aluminum.) It is the unique combinations of properties available in these fibers that provide the outstanding structural characteristics of fiber-reinforced composites. The key features of low density and high strengths and moduli give rise to high specific strengths and specific stiffness properties. Graphite fiber composites are particularly outstanding in this respect (Fig. 3).

All the fibers listed in Table 1 are used commercially, the selection of any particular fiber being dependent on the required combination of properties in the composite and cost considerations. The use of these fibers stems, of course, from the capability of producing the outstanding properties in the fiber form—it is important to emphasize that equivalent properties cannot be produced in the bulk form. Thus, it is the specific conditions used in generating the fiber that dictate the properties; development of successful fiber technology has been the key to advanced composite technology.

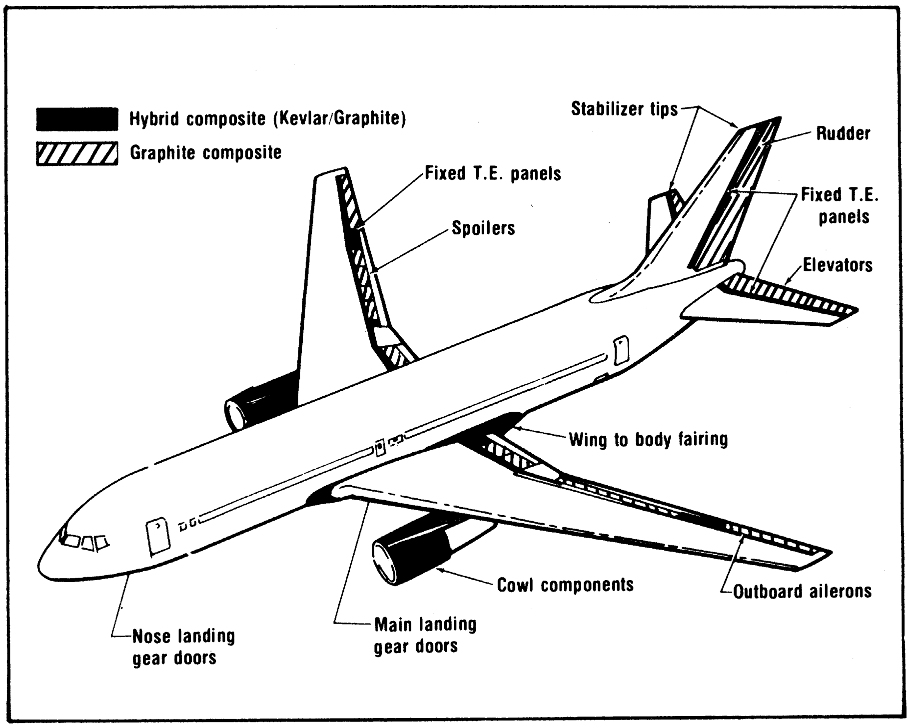


Fig. 1. Advanced composites on the Boeing 767 (5).

The fiber-producing process is unique for each different fiber. For example, for aramid fibers such as Kevlar the polymer is drawn into fiber form under the appropriate set of conditions (stress, temperature, and so on) to generate and retain an extremely high degree of orientation in the polymeric chains. For graphite fibers, a two-stage heating process is involved, as summarized in Fig. 4. The major manufacturing process for graphite fibers involves the generation of the fibers from a precursor fiber; the predominant precursor fiber is polyacrylonitrile (PAN), although other polymeric fibers such as rayon have been used. The PAN fiber is pulled under tension through the first heating stage, at 250° to 400°C, in which it is oxidized to produce a stable state. The fiber is then pyrolized to drive off all the atoms except a carbon ladder backbone; in this stage the temperature varies between 1500° and 2500°C depending on the degree of graphitization required. The properties of the resulting graphite fibers depend on the amount of graphite crystal structure in the fiber and the degree of orientation of the basal plane of the graphite crystallites along the fiber axis. Both of these are a function of the tension applied during heating and the temperature of conversion. Control of these two variables allows a family of graphite fibers to be commercially produced with a range of properties.

Also under industrial development is a new technology for making graphite fibers using pitch as the precursor material. The pitch process has the potential for significantly reducing the cost of graphite fibers.

Table 2. Typical properties of fiber-reinforced composites.

| Material | Weight of fiber (%) | Tensile strength (MPa) | Modulus (GPa) |
|---|---|---|---|
| Graphite-I/epoxy | 65 continuous | 1380 | 124 |
| Graphite-II/epoxy | 65 continuous | 1100 | 180 |
| S-glass/epoxy | 65 continuous | 1660 | 48 |
| E-Glass/epoxy | 65 continuous | 1100 | 35 |
| Kevlar/epoxy | 65 continuous | 1240 | 62 |
| SMC-30 | 30 chopped | 140 | 10 |
| SMC-65 | 65 chopped | 280 | 13 |
| Steel (5160) |  | 1380 | 200 |
| Aluminum |  | 560 | 70 |

## Matrix

The resin matrix performs several functions in FRP composites. (We use the term matrix here to include the material between the fiber surfaces, both the matrix resin and any coating previously applied to the fibers.) First, the matrix must keep the fibers separated so they cannot abrade each other during any periodic straining or deflection of the composite. Second, the matrix must be mechanically coupled to the fibers so that it can bear loads. Ideally, the fibers should carry the total load. The fibers are generally much stiffer, stronger, and more fatigue and creep resistant. But even in ideal cases when the fiber orientations are well matched to the applied stress, the matrix is needed to transfer externally applied loads into and out of the fiber composite as well as to transfer internal loads around fiber breaks in continuous fiber composites and between fibers in chopped fiber and whisker composites. In less ideal cases where loads are complex, the composite may even have to bear loads transverse to the fiber axis. Not only must the matrix resin and its coupling to the fibers be able to bear these loads, the loads often must be sustained under conditions of changing temperature and moisture.

Although it is clear that the matrix must be coupled to the fibers, there has been considerable discussion over the years about just how much strength and stiffness is desirable for the matrix and coupling. If they approach those of the fiber too closely, the composite will behave like the brittle monolithic material. Although there is still no completely satisfactory answer, an empirical rule that is followed for polymeric matrices is a strength and coupling to the fibers that allows stubs of fibers roughly five to ten times their diameter to be pulled from the matrix when the composite is stretched to failure along the fiber axis.

There are many combinations of fibers and matrices that yield desirable composite properties. The key to the appropriate combination is the ability to manufacture it. Composites, perhaps more than other structural materials, are manufacturing process-dominated; that is, the properties are a direct consequence of the method of preparation. In general, the matrix should be derivable from a liquid precursor. The transverse strength requirement means that the liquid precursor must wet the surface of the fibers. Wetting is needed to bring the matrix and fiber into proximity for covalent, dipolar, or van der Waals bonding to occur, as desired. Although various flow patterns and pressure applications can be used to speed the mixing and wetting of the fibers by the matrix resin, the local rate of wetting is governed by the parameter $\gamma \cos \theta/\eta$, where $\gamma$ is the surface tension of the matrix precursor liquid, $\theta$ is the advancing contact angle of the liquid on the fiber surface, and $\eta$ is the viscosity of the liquid (*3*). Since $\gamma \cos \theta$ is usually small, the viscosity must also be small for reasonable processing speeds. General methods for increasing the matrix liquid viscosity after wetting are cooling the liquid, thereby inducing crystallization; inducing a chemical reaction like polymerization; or evaporating a low-viscosity solvent. In certain processes for manufacturing fiber composites, such as pultrusion (like extrusion in metals), some filament winding, and matched die molding from preforms, the low-viscosity resin is brought to the rigid state in a single step by polymerization. In other processes, an intermediate matrix state is utilized, obtained by one or more of the viscosity-increasing mechanisms above. The intermediate viscous or leathery state is desired because it makes the handling of the composite before final curing much simpler and cleaner.

Coatings are often applied to the fibers prior to mixing with the matrix resin to

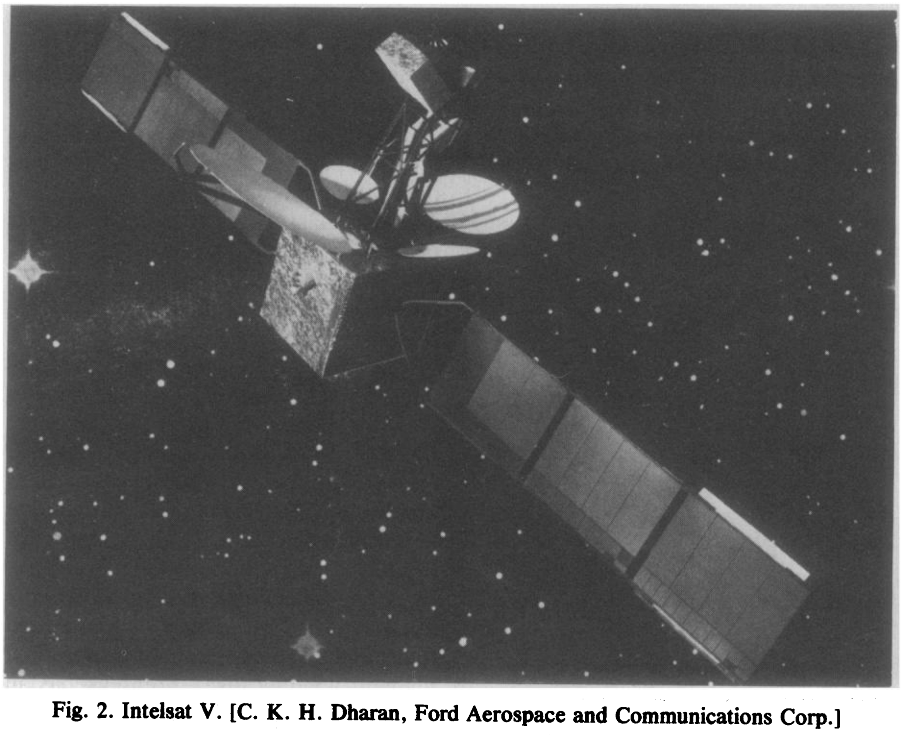


Fig. 2. Intelsat V. [C. K. H. Dharan, Ford Aerospace and Communications Corp.]

prevent the fibers from abrading one another during subsequent processing and to aid adhesion between fiber and matrix. When $\gamma \cos \theta$ for the matrix liquid against the fibers is particularly small, the rate of wetting, or the quality of the wetting in a fixed process, can be greatly enhanced by spreading a thin layer of the matrix on the fibers. Sometimes a monolayer bridging link is employed between the specific chemical functionalities of the fiber and matrix. Thus, practically all glass fibers for composites are treated with silanes, in which one end of the molecule can form up to three Si-O bonds with the glass surface while the other end can chemically join to the matrix.

Table 3. Organic matrices and maximum use temperatures.

| Matrix | Maximum use temperature (°C) |
|---|---|
| Thermosetting | |
| Polyester | 95 |
| Vinyl ester | 95 |
| Epoxy | 175 |
| Polyimide | 315 |
| Thermoplastic | |
| Nylon 66 | 140 |
| Poly(butylene terephthalate) | 180 |
| Polysulfone | 150 |
| Poly(amide-imide) | 260 |

A list of polymeric matrix resins of current automotive interest is given in Table 3 along with the maximum continuous-use temperatures. The resins of greatest current interest are the polyesters. Although they are called *poly*esters, the ester linkage is used to produce only short chains of roughly 20 monomers. The monomers consist of dibasic acids and glycols. Typical acids include maleic anhydride, fumaric acid, phthalic anhydride, and isophthalic acid. Typical glycols include ethylene glycol, propylene glycol, and diethylene glycol. These are then combined to give oligomers with molecular weights of 1500 to 3500. To reduce the viscosity and enhance the subsequent reactivity of the unsaturated backbone, these polyesters are dissolved in unsaturated monomers like styrene. Concentrations of 30 to 50 percent styrene are common. It should be clear that the term polyester refers to a class of materials and not to a particular compound. After the polyester-monomer mixture is applied to the fibers and they are shaped in the desired form, the resin can be cured by an addition-type polymerization in about 2 minutes at 150°C, using a peroxide initiator such as *t*-butyl perbenzoate. The final polymer network thus consists of the original polyester oligomer intersecting or interconnecting polystyrene chains, which typically consist of two styrene monomers between polyester backbone junctions. Polyester matrix formation is seen to involve a two-step polymerization: an esterification or condensation polymerization followed by an addition polymerization.

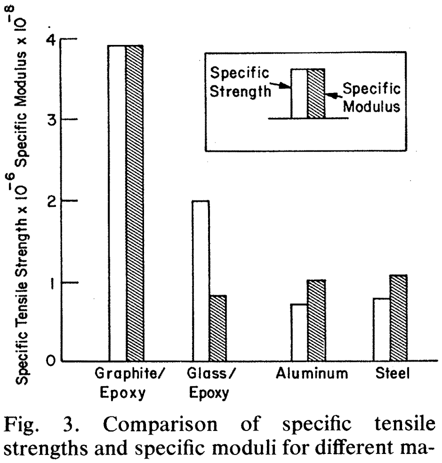


Fig. 3. Comparison of specific tensile strengths and specific moduli for different materials.

A three-step polymerization is used for the commercially important SMC process to avoid handling problems. In this process, the mixture of resin, fibers, and a particulate filler, if desired, is held between sheets of polyethylene film until it thickens to a leathery sheet molding compound (SMC). Thickening is obtained by making the polyester with excess acid and including in the fiber mixture a divalent metal oxide like magnesium oxide. The reaction between these produces, after a day or two, the desired change from a soft, sticky mass to a handleable sheet. The original formulation for SMC, and perhaps still the most important commercially, is 30 percent chopped glass fiber, 30 percent ground limestone, and the rest resin, by weight. The same process is useful for many different combinations of chopped and continuous fibers.

The fiber composites exhibiting perhaps the best mechanical performance to date are those made from epoxy resins. Most of the aerospace composites have epoxy matrices, although these matrices are less attractive for most automotive applications because of their long cure times. Although there are a few processes in which the liquid resin applied to the fibers is cured in a single step to a rigid matrix, most processes, including most filament winding, use "prepregs" as an intermediate state. That is, the fibers are impregnated by the resin and the resin thickened to facilitate subsequent handling. In some cases, a solid novolac epoxy resin is applied to the fibers in a solvent and then dried. In other cases, part of the epoxy curing reaction is allowed to occur. Epoxy resins often used for composites are the diglycidyl ether of bisphenol A, dimers of this, the tetraglycidyl ether of tetraphenolethane, tetraglycidylmethyldianiline, and the epoxies derived from the novolacs. Most epoxy systems for prepregging involve mixtures of the epoxy resins to achieve a balance of properties. There are many agents for curing at elevated temperatures; important agents are diaminodiphenyl sulfone and dicyanodiamide, which with accelerators cure with the diglycidyl ether of bisphenol A after 30 to 60 minutes at 165° to 175°C (*4*).

The good mechanical performance of epoxy matrices arises from their general toughness and their good adhesion to the fiber surface through hydroxyl groups formed when the oxirane ring is opened on curing. As a way of taking advantage of the mechanical performance of epoxies and the rapid cure of polyesters, unsaturated acids such as methacrylic acid can be reacted with the glycidyl ethers of bisphenol A to form vinyl esters. Like the polyesters, monomers such as styrene are added to the vinyl ester to reduce viscosity. As a result, the curing behavior of the vinyl ester is essentially the same as that of the polyes-

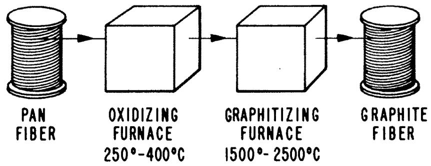


Fig. 4. Schematic of graphite fiber production from polyacrylonitrile.

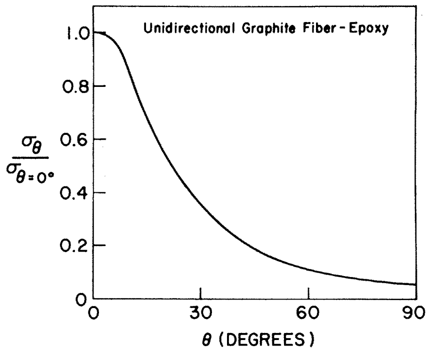


Fig. 5. Decrease in tensile strength away from the fiber direction in a continuous fiber-reinforced composite. $\theta$ is the angle with the fiber alignment direction.

ters. In general, the mechanical properties of composites with vinyl ester matrices are intermediate between those with polyester and epoxy matrices.

Thermoplastic matrix resins are of interest because they should be formable by a hot stamping process. This would allow shorter processing times than are possible even with the vinyl esters and polyesters. Except for two stampable materials of moderately low stiffness and strength, PPG's Azdel with polypropylene and Allied Chemical's STX with nylon 6, reinforced thermoplastic composites are still in an early stage of development.

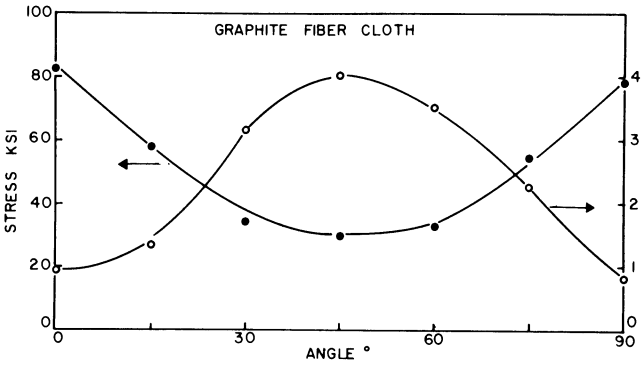


Fig. 6. Variation in properties as a function of testing angle in a graphite fiber cloth in which alternate layers of fibers are aligned in the 0° and 90° directions.

### Types of Fiber Composites

The useful properties of the fiber-reinforced composites are the end result of the combined properties of the fiber and the supporting matrix. Key features of composite technology are the availability of matrix resins and fabrication processes that do not significantly degrade the intrinsic properties of the fiber. A realistic target is to have the strength and modulus properties of the composite roughly follow the law of mixtures of the fiber/resin two-component system.

In principle, there is an infinite gradation of fiber composite types ranging from chopped fiber composites at the low properties end to a continuous, unidirectional fiber composite at the high properties end. Essentially, the composites differ in the amount of fiber, fiber length, and fiber type (Table 2). In general, the chopped fiber systems are used in lightly loaded or, at best, semistructural applications, whereas the continuous fiber-reinforced composites are high-performance structural materials. By their very nature, continuous fiber-reinforced composites are highly anisotropic. If all the fibers are aligned in one direction, maximum properties are achieved in that direction. However, the properties decrease rapidly in directions away from the fiber direction, as illustrated in Fig. 5. To generate more orthotropic properties, alternate layers of fibers are frequently alternated between 0° and 90° directions, resulting in less directionality but at the expense of absolute properties in the 0° direction (Fig. 6). Because of such marked directionality of properties, it is extremely important to have a good definition of the total stress environment under which a composite component operates. Accurate knowledge of the variations and types of stresses acting on the component enable the rational selection of design methodologies and the critical orientation of laminate and fiber arrays to provide for structural design optimization.

The types of composites and composite design technologies employed by different industries can be quite specific to the particular requirements and practice of the individual industry. For aerospace, the criticality of minimizing weight at (virtually) any cost combined with low-volume production allows the most exotic and expensive fibers to be used, combined with long matrix cure times and hand-layup fabrication procedures. In mass-production, consumer-oriented industries such as the automotive industry, the high volume and high production rates demand automated fabrication, short matrix cure times, and minimization of cost. Such demands suggest that for highly stressed structural application, fiber hybrids are the most likely candidates, with a large fraction of the fibers being continuous. As the name suggests, hybrid fiber composites contain mixed fibers, tailored to optimize properties and minimize cost. The hybrids of perhaps greatest promise are E-glass composites containing appropriate amounts of graphite fiber, but other combinations are being considered. Particular hybrid combinations will be determined by the appropriate property-cost trade-offs for any given application. It is significant that cost pressures are also stimulating the development of hybrid composites for aeronautical applications.

### Composite Processing

There are basically two types of processing for converting the raw fiber into the finished product:

1) Direct processes. In these processes, the fiber is combined with the matrix polymer and formed into the finished part in one continuous operation.

2) Indirect processes. In these processes, the combining of the fiber and matrix polymer takes place in a separate, preliminary stage, and the conversion of this preform to the finished product takes place in a subsequent, physically separate fabrication procedure.

*Direct processes*. The attraction of direct-process fabrication lies in the simplicity and cost effectiveness of such operations. Starting with the raw fiber, the fabrication process is continuous through the final product. The disadvantage of such processes lies in the restricted geometric shapes that can be fabricated. Examples of such processes are injection molding, pultrusion, and filament winding. Pultrusion is particularly applicable to parts that are straight or only slightly curved. It consists of pulling a bundle of fibers through a resin bath and subsequently through a heated die in which the matrix is cured. Production rates in the range of 2 to 5 feet per minute are currently achievable.

Filament winding is an important, high-speed process for manufacturing tubes. The fibers are prewet by a technique similar to pultrusion and then wrapped around a mandrel at precisely determined orientations and subsequently cured either in a continuous or batch-heating process. Production rates greater than 6 feet per minute are achievable in this process. Filament winding is also suitable as a high-speed fabrication process for making preforms with controlled orientations and amounts of fiber. Large-diameter filament-wound tubes can be slit before curing into preform sheets for fabrication into shapes by other methods.

Perhaps the most rapid polymer processing is injection molding of thermoplastic parts, both short glass fiber-reinforced and unreinforced. Molding cycle times are measured in fractions of minutes and multiples of the part are made at the same time. The fluid polymer is injected into a closed, cooled mold. After the polymer has cooled enough for the part to become rigid, the mold opens for the part or parts to be ejected and then closes again to begin the next cycle. The process is rapid and inexpensive enough to be used for many small parts on the car as well as for a wide variety of everyday consumer plastic items.

*Indirect processes*. The indirect processes involve an intermediate step in the transition from the raw fibers to the finished product. All the processes involve the preparation of some kind of preform in which the fiber is intermixed with the matrix resin and treated so that the preform is handleable. For thermoset matrices, such a step involves partial curing to allow handling of the preform; the preform must then be storable for up to 6 months without a further significant amount of curing. For thermoplastic matrices, the preform is rigid and stable at room temperature with infinite storage time.

Examples of indirect processes are compression molding and vacuum bag curing for the thermoset matrix composites. In compression molding, the preform is pressed into final shape in a matched metal die and heated in the die to fully cure the matrix. The cycle time depends on the thickness of the part and the particular resin employed, but typically varies between 2 and 3 minutes for the faster-curing polyester systems. Vacuum bag curing is generally a much slower process in which the preform is "sucked" against a female mold by evacuation of a plastic bag around the mold, and subsequently cured in an autoclave. This process is normally restricted to low-volume applications, such as in aerospace use, and tends to use longer-cure, epoxy-type matrices.

Table 4. Summary of weights of GrFRP components. Vehicle weights: Ford LTD 1979, 3740 pounds; lightweight concept vehicle, 2504 pounds.

| Component | Weight (pounds) | | |
|---|---|---|---|
| | In steel | In graphite | Savings |
| Body-in-white* | 461.0 | 208.0 | 253.0 |
| Frame | 282.8 | 207.2 | 75.6 |
| Front end | 96.0 | 29.3 | 66.7 |
| Hood | 49.0 | 16.7 | 32.3 |
| Deck lid | 42.8 | 13.9 | 28.9 |
| Bumpers | 123.1 | 44.4 | 78.7 |
| Wheels | 92.0 | 49.3 | 42.7 |
| Doors | 155.6 | 61.1 | 94.5 |
| Miscellaneous† | 69.3 | 35.8 | 33.5 |

*Complete body structure without closure panels (doors, deck lid, etc.) and trim (seats, etc.). †Bracketry, seat frame, and other items.

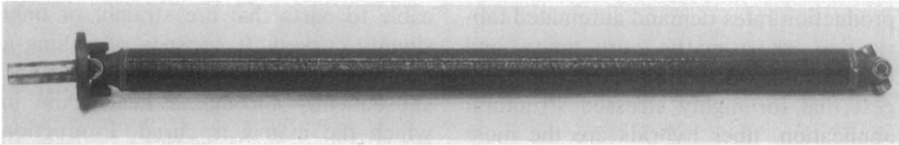


Fig. 7. Typical GrFRP drive shaft for a medium-sized automobile. The tube was manufactured by filament winding, using an epoxy matrix, and was adhesively bonded onto steel yokes. The weight saving compared to the same component made with steel was 5 pounds.

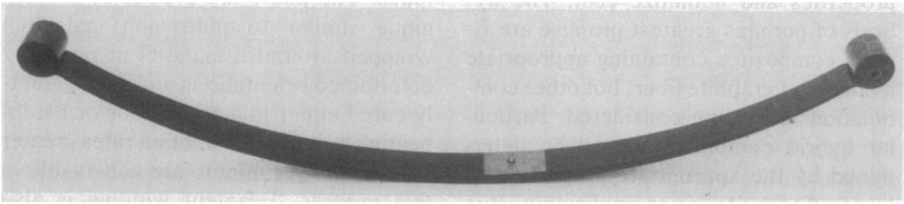


Fig. 8. Automobile leaf spring made of GrFRP. This component weighs 7 pounds, compared to 28 pounds in steel.

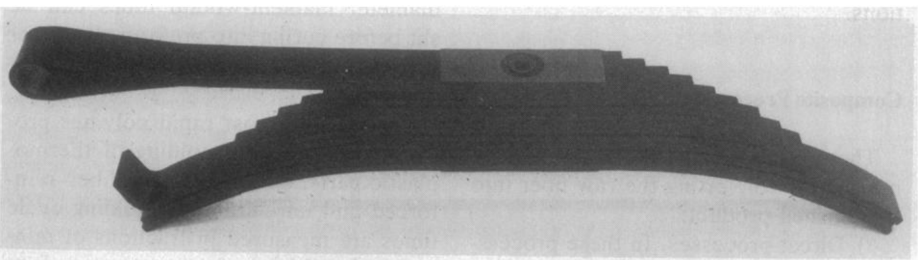


Fig. 9. Experimental GrFRP heavy truck spring. The weight is 30 pounds compared to 125 pounds in steel. With four springs per rear truck suspension, the potential weight saving per truck is nearly 400 pounds.

Warm stamping of thermoplastic matrix composites is not as well developed as the thermoset matrix procedures, but is appealing because of the infinite shelf life and handleability. Basically, it consists of preheating the sheet, forming to final shape in a die, and then cooling to retain the shape before removal from the die. The rheological behavior of fiber-containing thermoplastic resin and the mobility of the fibers during the stamping operations are key process features that require control for the successful development of thermoplastic stamping as a composite material fabrication process.

## Composites in the Automotive Industry

Except for a few specialized applications, the development of glass fiber-reinforced plastics (GlFRP) for the auto industry has concentrated primarily on manufacturing techniques that can economically turn out large numbers of parts and only secondarily on strength properties. However, attempts are now being made to improve properties, by replacing particulate fillers with glass fibers and by lengthening the fibers, while trying to retain some of the rapid fabricating techniques.

*Current and near-term automotive uses for glass fiber-reinforced plastics*. The best known example of GlFRP usage in automobiles is the Chevrolet Corvette. Since its introduction in the mid-1950's, the Corvette has had a GlFRP exterior body fabricated by compressive molding of SMC. Practically all grille opening panels on American-made cars are fabricated from glass-reinforced SMC materials; in such applications, the final component is less expensive to manufacture from SMC because numerous steel stampings can be integrated into one molding with a consequent reduction in labor and assembly costs. A continuing problem that has compromised other sheet metal replacement (outer panels of doors, hoods, and so on) has been the inability to produce a high-quality exterior surface in SMC, especially where there is much variation of thickness. This results in an undesirable finished paint appearance. It seems likely that a newly developed in-mold urethane coating process may solve this problem and open the way for large-scale application of SMC in exterior components.

To date, most automotive usage of plastics has been in relatively non-load-bearing applications. The next step is to apply composites in components bearing moderate loads. For example, a radiator support with an integral fan shroud is being evaluated for automotive companies. To meet the load requirements, an SMC formulation with increased glass fiber content (60 percent by weight) must be used and the glass fibers must be a mix of continuous or relatively long (4 to 12 inch) unidirectionally oriented fibers and short (1 inch) randomly oriented fibers. GlFRP composite bumper reinforcements and leaf springs are also beginning to appear in production vehicles. GlFRP composites are competing effectively in the heavy truck market because of their weight-saving and cost features. Heavy truck cabs and related exterior components are becoming frequent choices for composite applications.

*Advanced composites—graphite and hybrid graphite composite.* Intensified concern about energy and current shifts in the marketplace have accelerated efforts to reduce vehicle size and weight, and applications of lightweight materials have assumed a key role in advanced fuel-efficient vehicle designs. Materials are critical to the design of vehicles with optimum capacity and utility at minimum weight. In looking beyond 1985, it has become clear that the dramatic weight reduction potential of the advanced graphite fiber composites (developed initially for military and aerospace applications) offers opportunities to achieve further improvements in fuel economy. This recognition has been a driving force for the exploration and development of graphite fiber-reinforced plastic (GrFRP) composites for future vehicle application that is now taking place almost worldwide.

Engineering data on the characterization and engineering properties of the GrFRP's are being generated, and numerous prototype components are being extensively evaluated. However, the design methodology needed for continuous fiber composite components is radically different from that for isotropic metals. The fiber composite components consist of discrete layers, or laminae, and the properties of individual layers may be completely different, depending on the material (type of fiber) and fiber orientation. The resulting laminate is usually anisotropic, and the design analysis must examine every layer for potential failure. Finite-element analysis, computer-aided design, and computer graphics and modeling techniques have become essential features of the development and design of these new materials.

The principles of this design methodology have been used in the development of a number of GrFRP experimental components. In particular, drive shafts and leaf springs were used as initial examples of the potential for GrFRP composites in automobiles. Among the more promising of these experimental components are a typical automobile drive shaft (Fig. 7), an automobile leaf spring (Fig. 8), and a truck spring (Fig. 9).

### The Ford GrFRP Concept Vehicle

This promising developmental experience with graphite fiber composite components led Ford Motor Company in 1977 to undertake the building of an experimental car with body, chassis, and power train components to be made of graphite fiber composites to the maximum extent possible. The 1979 Ford was selected as the design to demonstrate the potential of graphite fiber composite technology for making a lightweight six-passenger car with good fuel economy while retaining the performance and characteristics of larger vehicles. The project was intended to demonstrate concept feasibility and design and materials feasibility and to identify the critical issues related to production feasibility for future vehicles. Manufacturing and cost feasibility were not program objectives.

A schematic of the GrFRP vehicle is shown in Fig. 10, where the shaded areas represent the parts of the vehicle fabricated in GrFRP. The completed experimental vehicle with a 2.3-liter engine weighed 2504 pounds—1246 pounds less than 1979 production Ford LTD with the standard 5.0-liter engine. The fuel economy was projected to be 33 percent, or 6 miles per gallon, better than the base production car. Virtually all of the body, frame, and chassis parts—about 160 parts—are made of graphite fiber-reinforced composites. Only the power train, trim, and some chassis components were not converted. However, most of these (for instance, engine, brakes, transmission) were downsized or downgaged for secondary weight reductions.

Some 600 pounds of graphite composites was used, containing about 400 pounds of graphite fiber. The primary weight saving—by direct materials substitution—was 706 pounds; the remaining 540 pounds saved was the result of secondary weight reductions. A summary of the weight savings achieved in key components is given in Table 4. For

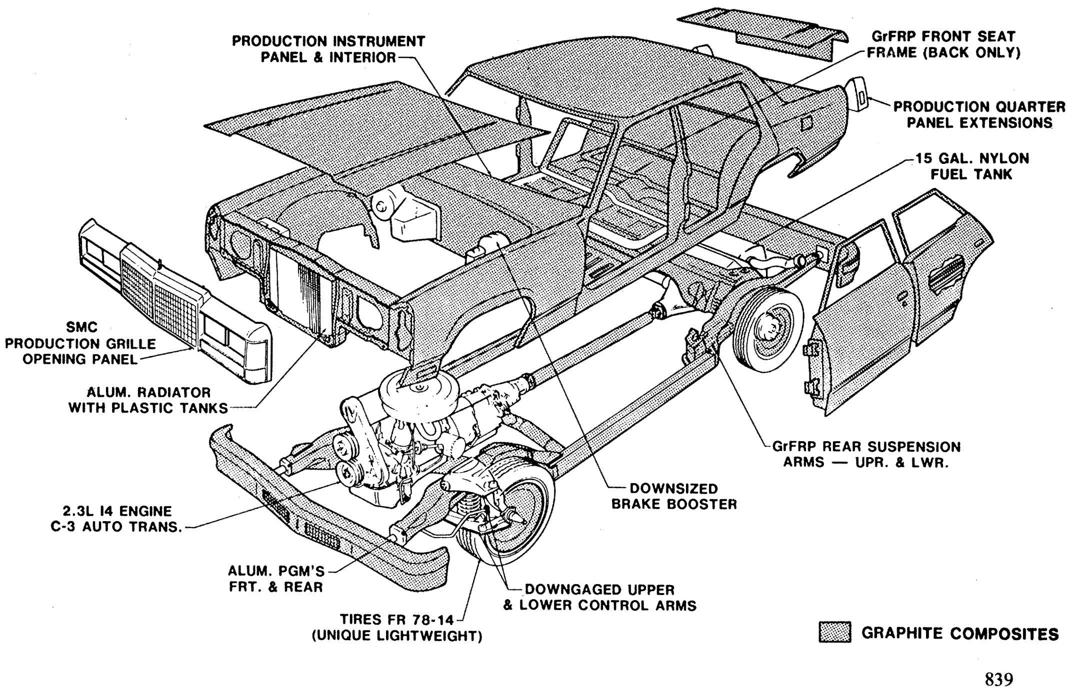


Fig. 10. Schematic of experimental car with body, chassis, and power train components made of GrFRP.

the hood, front end, deck lid, bumpers, and door, part weight savings ranged from 61 to 69 percent—gratifyingly close to our design expectations. For the wheels and miscellaneous brackets, a 45 to 50 percent weight reduction was achieved.

The weight and design targets were successfully achieved and, in its preliminary evaluation, the experimental vehicle exhibited an initial ride quality equivalent to that of production vehicles in the same stage of development.

The experience gained in this car program underscored the two key issues that will determine large-scale future applications: materials cost and manufacturing feasibility. The fiber industry indicates that the price of graphite fibers will come down dramatically as capacity and markets increase. A price of $6 per pound of fiber in the middle to late 1980's appears to be a reasonable projection, compared with the current price of $20 per pound. However, on a materials basis, all-graphite composites will not approach the more favorable economics of automotive materials such as steel or aluminum. The automotive industry, together with the composites and resin industry, must develop hybrid composites containing graphite, glass, and other fibers, to improve the economic effectiveness of such composites.

Equally important is the need for low-cost manufacturing processes for producing both preforms and components compatible with automotive industry practice. Hand-layup techniques obviously are not economically feasible. High-speed manufacturing processes, perhaps involving new resins and processing techniques, are required.

The automotive industry needs to have in hand well-characterized and tested classes of materials, more understanding of performance characteristics in service and failure modes, design methodologies compatible with new materials and manufacturing processes, bonding and joining methods, and methods of nondestructive evaluation and quality control.

One long-range issue critical to the future automotive application of composites is related to crashworthiness and durability. The ability to design and integrate composite materials and composite structures to ensure vehicle safety and integrity must be fully demonstrated before we can move toward large-scale production considerations.

In our view, the graphite fiber composite experimental car marks the end of a phase in graphite fiber composite technology—a phase in which conceptual feasibility was the predominant focus. We now face the hard tasks of bringing to reality the potential demonstrated to date. Hybridization, formability, and low-cost, high-rate manufacturing processes emerge as the targets for the next round of materials manufacturing R & D programs.

## Future

The future picture for composites will involve the aggressive pursuit of every application where they are thought to be of advantage. This spans a wide range of materials and economics of application. New product opportunities will continue to be coupled to developments in the technology of composite fabrication and design. Larger-scale structural use of composites will be constrained by the challenges of rapid and automated processing, the reliability of mass-produced structures, material cost, and more efficient design.

Aerospace use of composites will continue to be the proving ground for high-performance and exotic fiber-matrix combinations and for design methodology. Such structures have been labor-intensive handcrafted articles. But the development of next-generation combat aircraft, which could be 50 percent composite materials, will also be more cost-constrained and automation will be required to adequately fabricate the increasingly larger and more complex components while remaining competitive in cost.

The advantages of tailored high-performance products will always support specialized applications, as in sports equipment and in certain advanced technologies. But composite use continues to expand into more highly cost-constrained sectors. Perhaps the automobile industry's need for high-rate automated processing will encourage development of more know-how and the ability to control the compromises between performance and reliability. As in aerospace, progress will likely include a tailoring of material form and shape to an automated industry, but it will take a different form and include more variety. Optimized design will afford cost-effective use, which will probably include hybrid composites and composite structures of various forms. Reliable prediction and control of fiber distribution in complex structures formed by machines will open new opportunities for optimal use of composite materials.

If indeed the R & D activities during the next decade realize the promise of composite materials in consumer market applications, we will have provided a stimulus for a quantum increase in the output of the plastics industry for the 1990's and perhaps a realistic basis for the coming of a second revolution in plastics.

### References and Notes

1. B. C. Anderson, L. R. Bartron, J. W. Collette, *Science* **208**, 807 (1980).
2. T. Alfrey and W. Schrenk, *ibid*., p. 813.
3. H. van Oene *et al.*, *J. Adhes.* **1**, 54 (1969).
4. J. Delmonte, in *Epoxy Resins: Chemistry and Technology*, C. A. May and Y. Tanaka, Eds. (Dekker, New York, 1973), pp. 589-631.
5. R. H. Wehrenberg II, *Mater. Eng.* (January 1980), p. 33.