

**MECHANICAL  
BEHAVIOR AND  
PROPERTIES OF  
COMPOSITE  
MATERIALS**





# **MECHANICAL BEHAVIOR AND PROPERTIES OF COMPOSITE MATERIALS**

**VOLUME 1**

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## Delaware Composites Design Encyclopedia—Volume 1

a TECHNOMIC publication

*Published in the Western Hemisphere by*  
Technomic Publishing Company, Inc.  
851 New Holland Avenue  
Box 3535  
Lancaster, Pennsylvania 17604 U.S.A.

*Distributed in the Rest of the World by*  
Technomic Publishing AG

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Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Main entry under title:

Delaware Composites Design Encyclopedia—Volume 1/Mechanical Behavior and Properties of Composite Materials

A Technomic Publishing Company book  
Bibliography: p.

Library of Congress Card No. 89-51098  
ISBN No. 8762-684-7

# FORWARD

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*The Delaware Composites Design Encyclopedia* provides users with basic knowledge about the design and analysis of composite materials and structures. The six-volume indexed set is an ongoing series to which new volumes will be added as new needs arise and new knowledge is gained about this rapidly growing field of composites. Unlike many other guides on this subject, the encyclopedia emphasizes the underlying fundamental science base—documenting the high-quality research in the various disciplines that contribute to the field—in addition to engineering solutions to specific problems. It is intended for use by engineers, materials scientists, designers, and other technical personnel involved in the applications of composite materials to industrial products.

The material contained in the encyclopedia was written by international experts in the field and compiled at the University of Delaware's Center for Composite Materials (CCM). Established in 1974, CCM began its University-Industry Consortium, "Applications of Composite Materials to Industrial Products," in 1978 to meet the needs of the aerospace, automotive, electronics, and consumer products industries. Now regarded as an international leader in composites research and education, the Center continues to be supported by the Consortium as well as by the National Science Foundation, the United States Army Research Office-University Research Initiative Program, other federal agencies, and the State of Delaware.

The first version of the *Delaware Composites Design Encyclopedia* was published in 1981 and offered as a

special benefit to Consortium members. It has since grown in size and scope and is now being offered to the composites community at large for the first time. The current volumes cover the following subjects:

Volume 1—Mechanical Behavior and Properties of Composite Materials

Volume 2—Micromechanical Materials Modeling

Volume 3—Processing and Fabrication Technology

Volume 4—Failure Analysis of Composite Materials

Volume 5—Design Studies

Volume 6—Test Methods

*Index to Volumes 1-6*

Dr. John W. Gillespie, Jr. and Dr. Leif A. Carlsson, review editors of the *Delaware Composites Design Encyclopedia*, have incorporated the most recent references relevant to the subject matter to maintain the highest quality, up-to-date encyclopedia of this type.

Volume 1, authored by international experts Carl Zweben, H. Thomas Hahn and Tsu-Wei Chou, begins with a basic introduction to roles and properties of the constituents and their relationship to the mechanics of composites. These sections provide the background information for more detailed subject matter on static strength and fatigue and elastic properties of continuous, discontinuous and woven fabric composites. By emphasizing the fundamentals that affect material performance, engineers and scientists will be able to select the types of fibers, matrices and fiber architectures that will best fulfill the processing and performance requirements of the composites application.

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# C O N T E N T S

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Foreword vii

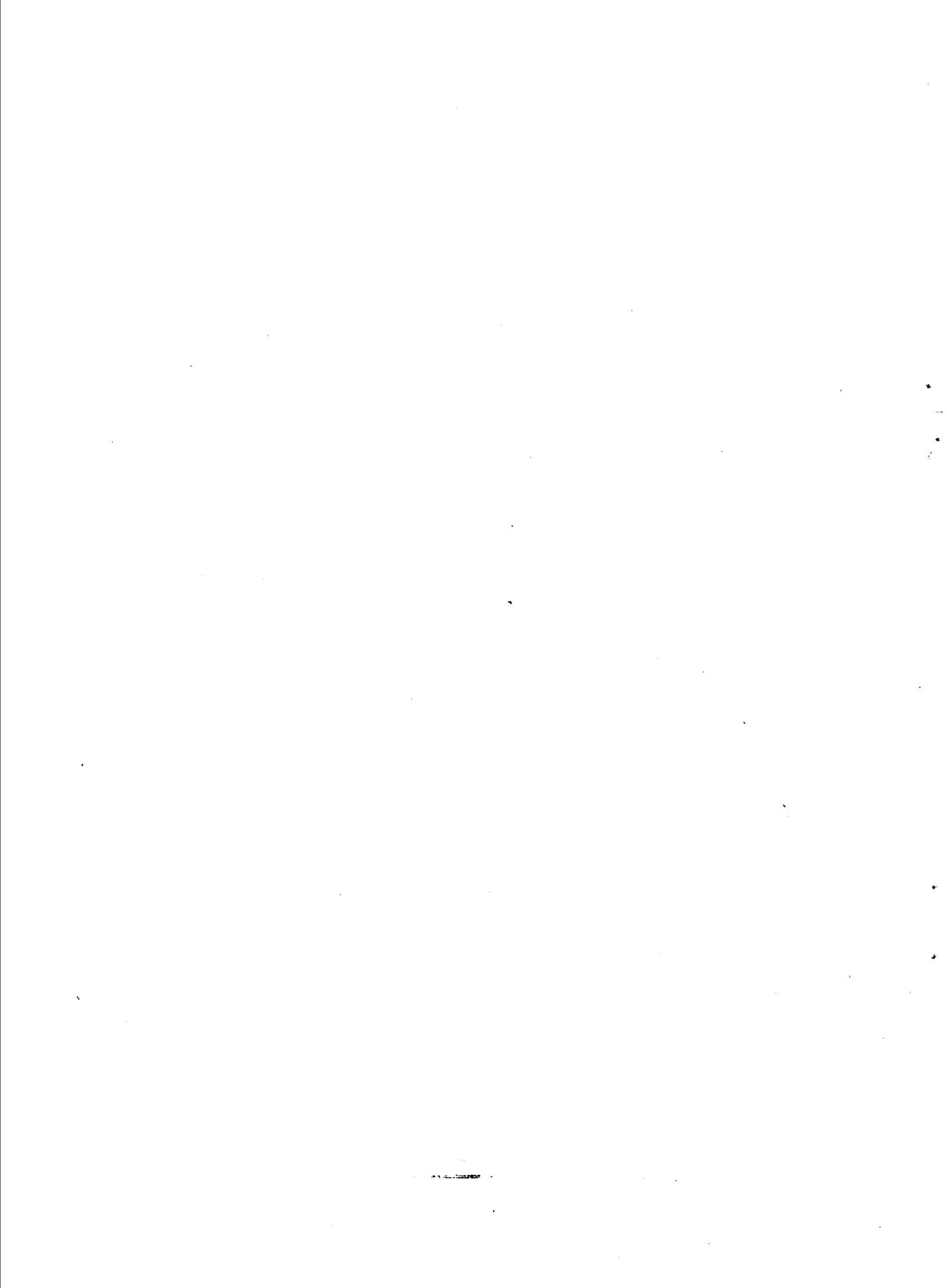
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## **SECTION 1.1**

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### *Introduction*



This volume is intended to help the designer to answer the following questions:

- Which composite material system should I use?
- How do the properties of composites differ from those of metals and unreinforced plastics?
- What are the properties of the most important composites?
- What are the phenomenological aspects of fatigue properties of composites?

Solids are commonly divided into four classes: metals, ceramics, glasses and polymers [1]. Fibrous composites have been made using fibers and matrix materials from all of these groups of materials. The most important category of composites at present uses polymers for the matrix phase combined with graphite, glass, ceramic or polymeric fibers. The scope of this section is limited to these materials. As fillers are frequently used in polymeric-matrix composites, these constituents will also be considered.

### 1.1.1 General Characteristics of Composite Materials

Resin-matrix composites are a rapidly expanding class of materials made by combining polymeric matrices with various forms of fibrous reinforcements. Particulates and other types of fillers are sometimes added as well. Composite properties depend on many factors, among which are the properties of the constituents; the form of fibrous reinforcement used (chopped, woven, etc.); fiber volume fraction, length, distribution and orientation; interfacial bond strength; and void content. Many of these factors depend strongly on the fabrication process used. Therefore, it is important that values used in design reflect the process by which the structural component is manufactured.

Because of the vast array of composite materials available, it is difficult to generalize when discussing mechanical properties. However, there are some common features: composites are all heterogeneous, most are anisotropic, and they generally display considerable properties' variability compared to most structural metallic alloys.

Heterogeneous composites have properties that vary from point-to-point throughout the material. For example, when a point inside the material is selected at random, the properties at that point can be very different depending on whether it falls in the matrix or one of the fibers. While it is true that all materials are heterogeneous on the microscopic level, the degree of heterogeneity is generally more severe for composites than for metals. This is because the two primary phases, fiber and matrix, have radically different properties and geometries.

Heterogeneity contributes to another important composite material characteristic, property variability. As mentioned earlier, composite strength and stiffness characteristics depend strongly on fiber orientation, fiber spatial distribution, and the variability of fiber properties. Since it is impossible to position each fiber individually, there is an inherent property variability in composites. Composites reinforced with discontinuous fibers, such as bulk molding compounds and sheet molding compounds, are particularly prone to property nonuniformity because it is difficult to control local fiber content and orientation in the face of material flow. As a result, material stiffness and strength properties vary from point-to-point throughout the material.

Resin properties are strongly dependent on processing conditions, such as temperature and pressure, which can vary significantly throughout a component during its fabrication. Where two regions of material flow come together, there is a "knit line" which is not crossed by any fibers. This knit line is a weak region and a frequent cause of part failure.

Other major items contributing to property variation throughout a part include the following: the material may contain voids, which serve as local stress concentrations, and the important fiber-matrix interfacial bond may vary, as it depends on many factors, including the level and type of applied surface finish [2].

Anisotropy is another property common to most composites. An anisotropic material is one whose properties vary with direction. For example, a composite reinforced with straight, parallel continuous fibers is significantly stronger and stiffer in the direction parallel to the fibers than it is in the transverse direction [2].

In the following discussion we consider the properties of the important fibers, matrix materials and fillers. We then describe characteristics of composites with different forms of reinforcement. Finally we consider mechanical property data and the tests by which they are determined.

## 1.1.2 Fibers

### *General Characteristics of Reinforcing Fibers*

There are several major categories of man-made reinforcing fibers: glass, graphite (carbon), organic, boron, and ceramic. This subsection considers the properties of these fibers, emphasizing the most important ones: glass, graphite, and organic.

The most important naturally occurring reinforcing fiber is asbestos. In recent years there have been several studies linking asbestos fibers to health disorders. As a result, many users are attempting to convert their products to other reinforcements. For comparative purposes, we will include the properties of asbestos fibers.

Although their properties are extremely different, man-made fibers have some common characteristics. As a rule, the fibers are rather fine, with diameters ranging from about 2 to  $13 \times 10^{-6}$  m (1 to  $5 \times 10^{-4}$  in). The main exceptions are boron fibers which are available in diameters of 1 to  $2 \times 10^{-4}$  m (4 to  $8 \times 10^{-3}$  in). Man-made fibers are generally produced in continuous processes, although later they may be chopped, cut or milled into short lengths. It is difficult to measure fiber properties directly because they are extremely fine and generally quite brittle. As a rule, the only mechanical properties that are routinely determined are extensional tensile modulus and tensile

strength. The breaking load of a particular filament can be determined relatively easily. However, definition of a cross-sectional area, which may vary along the length of the fiber, is not simple, and this can affect reported values for breaking stress (breaking load divided by cross-sectional area) and modulus [3].

The subject of fiber tensile strength is important and deserves some consideration. The major reinforcing fibers have tensile stress-strain curves that are linear to failure. One exception is Kevlar<sup>1</sup> 29 aramid which has a modulus that increases somewhat with increasing stress. The absence of yielding makes fibers sensitive to imperfections, which has two important effects on tensile strength: there is considerable scatter at a given gage length, and mean strength decreases with increasing gage length [4]. Therefore, a reported value of mean fiber strength requires the associated test length to be specified. Further, the amount of scatter is important in evaluating fiber strength. Ideally, fiber strength properties should be measured at several lengths.

The problem of understanding fiber tensile strength is complicated by the fact that fiber tensile strength is measured using single fibers, untwisted bundles of fibers (ends), impregnated ends, twisted ends (yarns), and composite tensile coupons. As a rule, each one gives a different strength value. The reasons for this are discussed in the subsections dealing with the properties of unidirectional composites (composites reinforced with continuous straight, parallel fibers) and test methods. Fiber strength values reported in this subsection are based on single filament tests and unidirectional composite coupon tests. The latter data are of greatest relevance to designers.

The subject of composite impact resistance is extremely complex, and there is no one number that can be used to characterize completely the damage resistance of a given material. However, the area under a fiber stress-strain curve, which is the energy it absorbs in failing, provides some useful information about its contribution to the impact resistance of a composite. When fibers have different compressive and tensile strengths, or when these stress-strain curves are non-linear as in the case of Kevlar 49 in compression [5], compressive and tensile energies to failure are different.

<sup>1</sup>Registered trademark of E. I. du Pont de Nemours & Co., Inc.

## Glass Fibers

Glass fibers are the cheapest and most widely used man-made composite reinforcements. They are also the oldest, dating back to the period of World War II. Glass fibers generally have high strength-to-weight ratios, but their elastic moduli, which are in the range of those of aluminum alloys, are low compared to the newer fibers such as graphite and aramid [2]. The internal structure of glass fibers is amorphous (noncrystalline) and they are generally regarded to be isotropic. As fibers comprise only a part of the composite, and as they are generally oriented in several directions, the modulus-to-density ratios of glass fiber-reinforced plastics are substantially lower than those of metals [2]. This is one of their major limitations as a structural material.

The increase of deformation with time when a material is subjected to a constant load is called creep. The creep resistance of glass fibers at room temperature is substantially better than that of plastics, but not as good as that of structural metals like aluminum and steel. The addition of glass fibers to plastics greatly reduces their tendency to creep.

The failure of a material after a period of time under constant load is referred to as creep rupture or static fatigue [1]. As in the case of creep, the properties of glass at room temperature fall between those of plastics and metals, but much closer to the latter [2].

Glass fibers generally have good chemical resistance and are noncombustible. They do not absorb water, but their tensile strength is substantially reduced by the presence of moisture.

The coefficient of thermal expansion of glass is an order of magnitude lower than that of most plastics and is lower than most aluminum and steel alloys [2]. Reduction of coefficient of thermal expansion is an important reason for the addition of glass fibers to plastics for many applications. A material with a low coefficient of expansion is frequently said to be dimensionally stable, but other factors enter into resistance to dimensional changes including creep and swelling from moisture absorption.

The strength, modulus and creep rupture resistance of glass fibers decrease with increasing temperature. Conversely, creep rate increases. However, the useful temperature range is quite large. Glass does not soften substantially until temperatures over 500°C (1000°F) are reached.

Table 1.1-1. Representative properties of E glass and S glass fibers.

	E Glass	S Glass
Density, $\delta$ (g/cm <sup>3</sup> )	2.60	2.50
Young's Modulus, $E$ (GPa)	72	87
Tensile Strength,* $\sigma_T$ (GPa)	1.72	2.53
Tensile Elongation,* %	2.4	2.9
Specific Modulus, $E/\delta$ (MNm/kg)	27.7	34.8
Specific Strength,* $\sigma_T/\delta$ (MNm/kg)	0.66	1.01
Longitudinal CTE (10 <sup>-6</sup> /°C)	5.0	5.6

\*In a typical composite.

Glass fibers are extremely sensitive to abrasion damage, and they are coated with protective sizings during their production. The sizings also serve as a lubricant and promote adhesion between the fibers and the resins. It is important to select fibers with sizings that are compatible with the matrix with which they are to be used.

When fibers are to be woven into fabric, they are coated with special textile sizings which are removed by heating or "burned off" after weaving. Subsequently, they are treated with another finish to reduce abrasion damage and promote resin adhesion.

There are two important types of glass reinforcing fibers, *E* and *S*. A third type, *C* glass, is used where corrosion resistance is particularly important [2]. The most widely used reinforcing fiber, by far, is *E* glass, where the *E* designates electrical grade. This lime-alumina-borosilicate glass does not have a fixed composition. Producers vary constituents based on raw material costs and process considerations. Within prescribed ranges, variations in glass formulation are not thought to affect mechanical properties substantially. However, the user should be alert to the fact that producers use different compositions from time to time and should assure themselves that these differences do not affect product performance in their applications.

Table 1.1-1 presents properties of *E* glass fibers. The tensile strength value is based on what is obtained in a representative unidirectional composite. Figure 1.1-1 shows how the mean tensile strength of single filaments varies with gage length [6]. As discussed earlier, mean strength decreases significantly with increasing length. *E* glass fibers have relatively high energies to failure, providing their composites with relatively good impact resistance compared to those of other fibers.

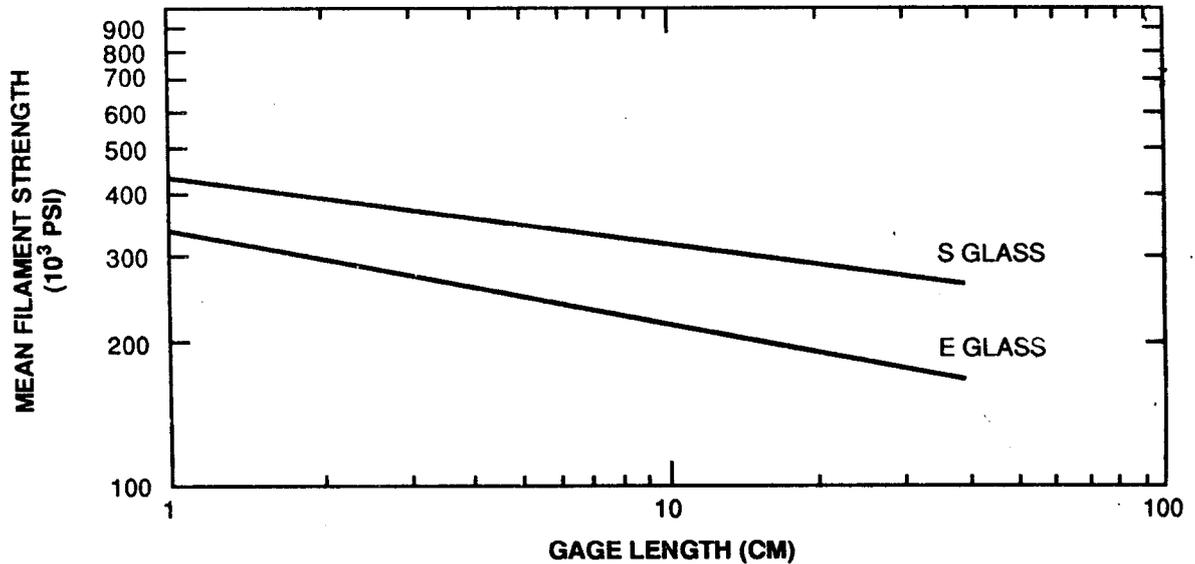


FIGURE 1.1-1.

Composites reinforced with *E* glass fibers are employed in an enormous number of applications. Their uses are so broad that they are generally grouped into several major categories. Some typical examples are listed below:

- automotive: grill opening panels, fender extenders, cab and body components
- agricultural: tractor hoods, fenders, seats, feed troughs
- appliances: air conditioner cases, fans, washing machine tubs, gears
- aerospace: radomes, aircraft fairings and interiors
- business machines: housing, gears, circuit boards, frames
- chemical: pipes, tanks, ducts, filters
- construction: concrete forms, translucent skylights, curtain walls
- electrical/electronic: electric pole crossarms, insulators, electronic components
- marine: boats, water tanks, barge covers
- recreational: motor homes, trailers, campers, snowmobiles
- transportation: truck trailer panels, rapid transit car ends, seating

*S* glass is a high-strength glass initially developed for military applications. Its modulus is about twenty per-

cent greater than that of *E* glass and it is about one-third stronger. Table 1.1-1 presents the properties of this material. As for *E* glass, the reported value of tensile strength is based on composite strength data. Figure 1.1-1 shows the decrease in mean filament strength with increasing gage length.

The failure energy of *S* glass fibers is high, and the impact resistance of composites made from them is among the highest of all fiber-reinforced materials. The creep rupture resistance of this material is significantly better than that of *E* glass. Despite its generally better properties, the use of *S* glass is far more limited than *E* glass because of its higher cost.

### Graphite (Carbon) Fibers

Graphite fibers, sometimes referred to as carbon fibers, comprise one of the most important classes of reinforcement with enormous potential for future growth. Their primary advantages over glass fiber are higher modulus, lower density, much better fatigue properties, improved creep rupture resistance, and lower coefficient of thermal expansion [2]. Creep at room temperature is generally considered to be negligible. On the negative side, because of their low strain-to-failure ratio, failure energies are relatively low. As a

result, the impact resistance of graphite fiber composites is generally lower than that of glass fiber composites. However, it should be emphasized that the subject of impact resistance is very complex, and generalizations can sometimes be misleading.

Graphite fibers of commercial importance are currently made from three precursors: polyacrylonitrile (PAN) fiber [7], rayon fiber, and petroleum pitch [8], a residue of the refining process. Production of high-modulus graphite fibers by pyrolysis of rayon and PAN fibers dates back to the 1960s. (Low-modulus carbon fibers produced by pyrolysis of rayon cloth, used for re-entry vehicles and rocket nozzles, were introduced in the 1950s.) Spinning of graphite fibers from pitch is a more recent development. Some believe that, because of lower raw material costs, pitch fibers are likely to be less expensive than those using fiber precursors. However, to date, pitch fibers have been able to match the moduli that can be obtained with PAN- and rayon-based fibers, but their strength properties have been substan-

tially lower. The high strength and moduli of graphite fibers, regardless of precursor, result from their high degree of crystallinity and orientation. Because of their high degree of internal structure orientation, graphite fibers are strongly anisotropic. Transverse extensional modulus and shear moduli for most fibers are generally an order of magnitude lower than axial modulus [9].

The most important graphite fibers at the present time are PAN-based, and these will be considered in this section. There are many graphite fibers on the market. They can be divided, somewhat arbitrarily, into three major categories: high-strength, high-modulus and ultrahigh-modulus. Table 1.1-2 presents representative properties of these materials. The tensile strengths reported are effective values that would be obtained in representative unidirectional composite specimens. Figure 1.1-2 shows the considerable amount of scatter and decrease in mean strength for high-modulus graphite fibers reported by Diefendorf and Tokarsky [10]. According to the authors, this results from local

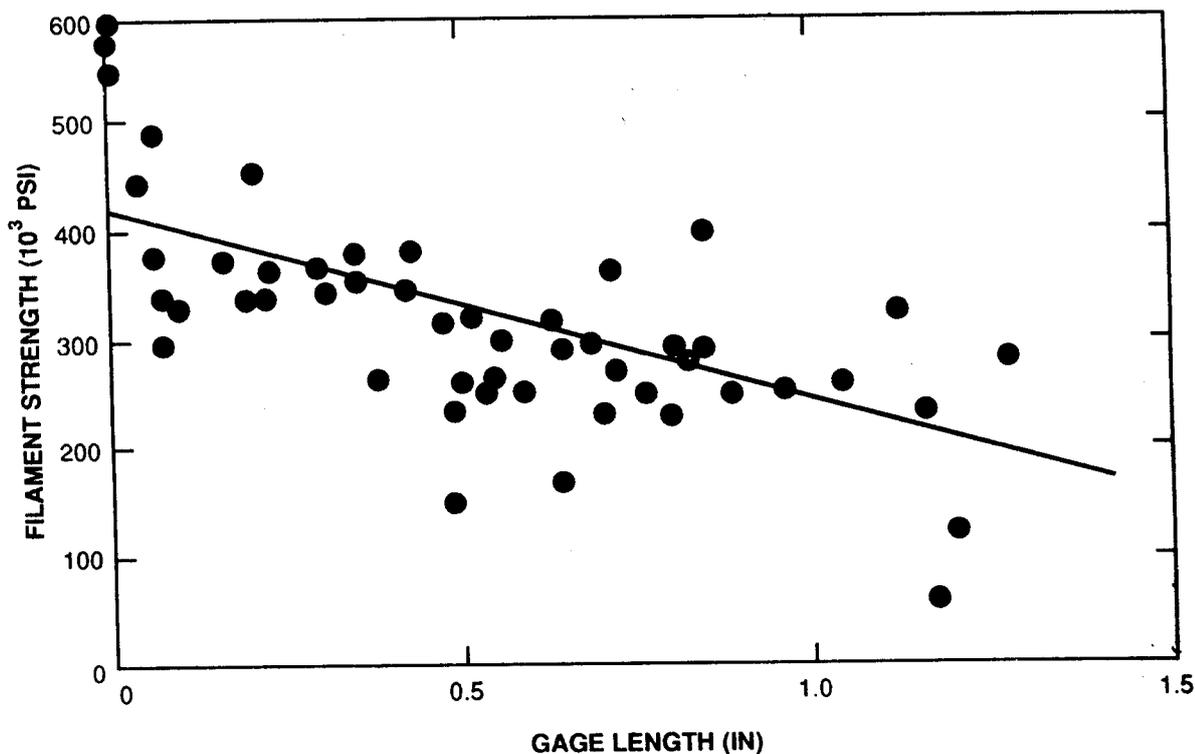


Table 1.1-2. Representative properties of graphite (carbon) fibers.

	High-Strength	High-Modulus	Ultrahigh-Modulus
Density, $\delta$ (g/cm <sup>3</sup> )	1.8	1.9	2.0-2.1
Young's Modulus, $E$ (GPa)	230	370	520-620
Tensile Strength,* $\sigma_T$ (GPa)	2.48	1.79	1.03-1.31
Tensile Elongation,* %	1.1	0.5	0.2
Specific Modulus, $E/\delta$ (MNm/kg)	128	195	260-295
Specific Strength,* $\sigma_T/\delta$ (MNm/kg)	1.38	0.94	0.52-0.62
Longitudinal CTE (10 <sup>-6</sup> /°C)	-0.4	-0.5	-1.1**

\*In a typical composite.

\*\*Estimated.

microcompressive buckling imperfections that are created during the cool down phase of fiber production. High-modulus fibers are more prone to this kind of imperfection because of their greater internal orientation.

As the tensile stress-strain curve of graphite fibers is linear to failure, ultimate strain is simply equal to tensile strength divided by modulus. Since tensile strength decreases with increasing modulus, the failure strain of high-modulus fibers is considerably lower than that of high-strength fibers. As a result, composites made from high-modulus and ultrahigh-modulus fibers tend to be more brittle than those reinforced with high-strength fibers. This makes them more sensitive to stress concentrations such as those that occur around joints and cutouts.

Table 1.1-3. Representative properties of Kevlar 29 and Kevlar 49 aramid fibers.

	Kevlar 29	Kevlar 49
Density, $\delta$ (g/cm <sup>3</sup> )	1.44	1.44
Young's Modulus, $E$ (GPa)	83	124
Tensile Strength,* $\sigma_T$ (GPa)	2.27	2.27
Tensile Elongation,* %	2.8	1.8
Specific Modulus, $E/\delta$ (MNm/kg)	57.6	86.1
Specific Strength,* $\sigma/\delta$ (MNm/kg)	1.58	1.58
Longitudinal CTE (10 <sup>-6</sup> /°C)	-	-2

\*In a typical composite.

## Organic Fibers

Some natural organic fibers, such as cotton, jute and sisal, are used as reinforcements. However, because of their low modulus, the mechanical properties they provide are modest, and they are of little interest for structural applications. The same is true of synthetic organic fibers, with the exception of aromatic polyamides (aramids).

There are several commercial aramid fibers: Nomex,<sup>2</sup> Kevlar, Kevlar 29 and Kevlar 49. Applications of Nomex include high-temperature fabrics, filters and structural honeycomb for sandwich-core laminates. Kevlar is used for tire cord. The two fibers of interest for reinforcing plastics are Kevlar 49 and, to a lesser extent, Kevlar 29. Table 1.1-3 presents representative properties of these two fibers. While the tensile stress-strain curve of Kevlar 49 is linear to failure, that of Kevlar 29 is slightly concave upward. The modulus of Kevlar 29 increases from an initial value of 83 GPa (12 × 10<sup>6</sup> psi) to a value at failure of about 100 GPa (15 × 10<sup>6</sup> psi). Kevlar 49 has an axial modulus of 124 GPa (18 × 10<sup>6</sup> psi) and a specific gravity of 1.44, about the same as Kevlar 29. Because of its higher stiffness, Kevlar 49 is used more widely as a reinforcement, and the remainder of this subsection will be devoted to a discussion of this fiber.

Figure 1.1-3 shows the tensile strength and strain to failure of Kevlar 49 aramid fibers as a function of gage length [11]. As for glass and graphite, mean strength decreases as test length increases. The line representing ultimate strain roughly parallels that of strength. The slight difference in slope is probably the result of experimental uncertainty in determination of ultimate strains.

The modulus of Kevlar 49 is between that of  $E$  glass, 72 GPa (10.5 × 10<sup>6</sup> psi), and high-strength graphite, 230 GPa (34 × 10<sup>6</sup> psi). Because its density is much lower than that of  $E$  glass (1.44 compared to 2.6), the specific modulus of Kevlar 49, 86 GPa (12.5 × 10<sup>6</sup> psi), is three times that of  $E$  glass, but it is significantly lower than that of high-strength graphite, 130 GPa (19 × 10<sup>6</sup> psi).

The tensile stress-strain curve of composites reinforced with aligned Kevlar 49 fibers (unidirectional composites) is linear to failure when they are loaded in the fiber direction. In this respect they are similar to the

<sup>2</sup>Registered trademark of E. I. du Pont de Nemours & Co., Inc.

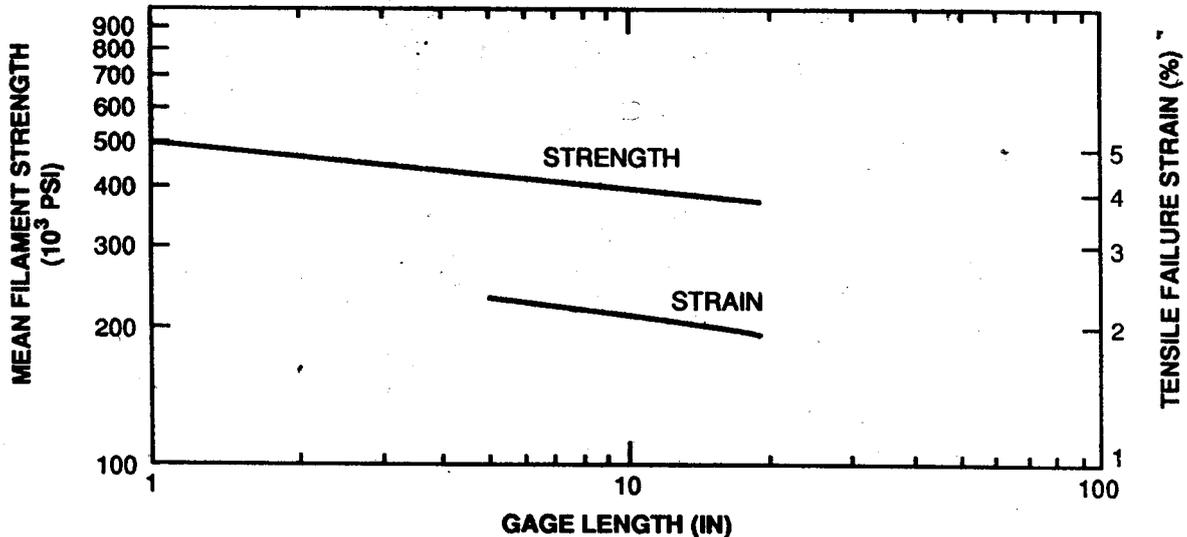


FIGURE 1.1.3.

other composites discussed in this section. However, their compressive behavior is unique. The compressive stress-strain curve resembles that of an elastic-plastic material [12]. This nonlinearity results from a fiber failure mode which appears to be associated with an instability or kinking of the fiber microstructure. The onset of compressive nonlinearity occurs at a fiber stress of about 440 MPa ( $65 \times 10^3$  psi), which corresponds to a strain of 0.35%. Because of these properties, the compressive strengths of composites reinforced with Kevlar 49 aramid fibers are, in many cases, significantly lower than those using other reinforcements such as glass and graphite.

Kevlar 49 fibers have excellent tensile-tensile fatigue resistance. Their compressive fatigue characteristics have not been studied extensively, but appear to be good within the proportional limit. The resistance to creep of Kevlar 49 fibers is significantly better than that of other organic fibers. Room temperature creep rates as a function of stress are of the same order of magnitude as those of glass and should be considered in design. The creep rupture resistance of Kevlar 49 falls between those of *S* glass and graphite.

Kevlar 49 fibers are strongly anisotropic, a property they share with graphite. Transverse extensional modulus and shear moduli are about an order of magnitude lower than axial extensional modulus. Kevlar 49 has the highest specific strength (strength divided by density)

of any commercial material. As a result it is the material of choice for high-performance rocket motor cases and pressure vessels.

The tensile energy to failure of Kevlar 49 is much greater than that of high-strength graphite, about the same as *E* glass and significantly lower than *S* glass. Although the area under the compressive stress-strain curve of Kevlar 49 is very large, the energy to the proportional limit is relatively low compared to other fibers. Because of these and other factors, the impact behavior of composites reinforced with Kevlar 49 is particularly complex. As a rule of thumb the impact resistance of these materials falls between those of *E* glass and high-strength graphite composites.

Applications of Kevlar 49 composites include aircraft fairings, wing trailing edges, interiors and other semi-structural applications, high-performance boats and sports equipment such as golf club shafts, skis and tennis rackets. Kevlar 49 is frequently used in combination with other fibers, such as graphite and *E* glass to obtain a balance of properties and cost that cannot be obtained with a single fiber.

### 1.1.3 Resins

In this subsection, we consider the mechanical and physical properties of the most common resins which

Table 1.1-4. Common thermosetting resins.

Alkyds
Diallyl Phthalates (DAP)
Epoxies
Furans
Melamines
Phenolics
Polybutadienes
Polyesters (thermosetting)
Polyimides (thermosetting)
Polyurethanes
Silicones
Ureas
Vinyl Esters

are used with reinforcing fibers. Resins (also called polymers and plastics) are generally divided into two main classes, thermosets and thermoplastics. We consider the general characteristics of these types of resins and discuss their use in composites. For a more detailed discussion of resin chemistry, see section 3.3 in Volume 3.

### Thermosets

Thermosetting resins (thermosets) are materials which are cured, or hardened into a permanent shape by an irreversible chemical reaction known as cross-linking. Thermosets may soften at elevated temperatures, but they cannot be reformed [13]. Although the first thermoset resins required heat for curing, hence the name, many others in this category undergo cross-linking in the presence of a catalyst, without the addition of heat. Thermosetting polyesters are a prime example. In the curing process, linear polymer chains are joined to form a rigidized three-dimensional structure.

Thermosets are generally brittle and are rarely used without some form of filler or reinforcement. Because of their cross-linked structure, thermosetting plastics have relatively good creep resistance and elevated temperature properties, although modulus and strength do decrease with increasing temperature. The chemical resistance of these materials is relatively good. In particular, thermosetting polyesters and vinyl esters are widely used in applications where corrosion resistance is important.

Table 1.1-4 lists the most important thermosetting resins. The major polymers used in composites are epoxies, vinyl esters and polyesters. Epoxy-matrix composites generally have the best mechanical proper-

ties. These resins are relatively expensive and have long cure cycles, although some more rapid-cure systems have been recently introduced. Polyester composites tend to have elastic properties similar to those of epoxy, but lower strength characteristics. The elastic properties of reinforced vinyl esters are like those of reinforced epoxies and polyesters, and their strengths fall somewhere in between.

Table 1.1-5 presents representative properties of some thermosetting resins. Elastic moduli and strengths are typically an order of magnitude lower than those of metals.

### Thermoplastics

Thermoplastic resins are solid at room temperature. They soften or melt when heated and re-harden when cooled [13]. These long-chain polymers do not cross-link as do thermosets, and they can be repeatedly reformed by application of heat, although this may eventually result in material degradation. Table 1.1-6 lists some of the more common thermoplastic polymers.

Thermoplastics generally are tough compared to thermosets and are widely used without reinforcement. However, their stiffness and strength properties, although similar to those of thermosets, are low compared to other structural materials, as Table 1.1-5 shows, so that use of reinforcements is desirable. Thermoplastics can be formed into complex shapes easily and economically by processes such as injection molding, extrusion, and thermoforming. The creep resistance of many thermoplastics, particularly at elevated temperature, is significantly lower than that of thermosets, and this has been a serious impediment to their wider use in structural applications. As a class of materials, thermoplastics are also more susceptible to attack by solvents than are thermosets.

Earlier, thermoplastics were reinforced primarily with discontinuous glass fibers and particulate fillers; however, recently there has been much work with continuous fibers in the area of relatively high-temperature resins like polyetheretherketone, polysulfones and thermoplastic polyimides [14,15]. The elastic and strength properties obtained with composites using these matrices are similar to or better than those employing epoxies, and their impact resistance is significantly better. The good moisture resistance and high temperature range of polyimides makes them particularly attractive, although they are more difficult to process than ep-

Table 1.1-5. Typical resin properties at room temperature (unfilled).

Resin	Type	Density g/cm <sup>3</sup>	Tensile Modulus GPa (10 <sup>4</sup> PSI)	Tensile Strength MPa (10 <sup>4</sup> PSI)
Epoxy	Thermoset	1.1-1.4	2.1-5.5 (0.3-0.8)	40-85 (6-12)
Phenolic	Thermoset	1.2-1.4	2.7-4.1 (0.4-0.6)	35-60 (5-9)
Polyester	Thermoset	1.1-1.4	1.3-4.1 (0.2-0.6)	40-85 (6-12)
Acetal	Thermoplastic	1.4	3.5 (0.5)	70 (10)
Nylon	Thermoplastic	1.1	1.3-3.5 (0.2-0.5)	55-90 (8-13)
Polycarbonate	Thermoplastic	1.2	2.1-3.5 (0.3-0.5)	55-70 (8-10)
Polyethylene	Thermoplastic	0.9-1.0	0.7-1.4 (0.1-0.2)	20-35 (3-5)
Polyester	Thermoplastic	1.3-1.4	2.1-2.8 (0.3-0.4)	55-60 (8-9)
PEEK	Thermoplastic	1.3-1.4	3.5-4.4 (0.5-0.6)	100 (15)
PPS	Thermoplastic	1.3-1.4	3.5 (0.5)	78 (15)

oxies. Polysulfone composites are easier to fabricate than polyimides, but their relatively poor solvent resistance is a severe limitation. PEEK is a relatively new semi-crystalline matrix polymer with excellent solvent resistance and mechanical properties [15].

It appears likely that high-performance thermoplastic-matrix composites will become an important class of high-performance structural materials.

#### 1.1.4 Fillers

Fillers are small organic and inorganic particulate materials mixed with plastics to modify their properties, extend resins in short supply, and reduce cost. There are many fillers available with a variety of shapes: spherical, plate-like, fibrous and irregular. The distinction between short fibers and fibrous particulates is blurred. We arbitrarily define the maximum dimension for a filler to be less than 1 mm (0.04 in). The principal reasons for using fillers are summarized in Table 1.1-7.

#### Discussion

Many fillers are abundant, naturally occurring materials, which are far cheaper than petroleum-based resins. The dramatic rise in the price of oil has made filler use increasingly attractive for economic reasons. Additionally, occasional resin shortages provide strong motivation for use of fillers to extend resins without adversely affecting product performance.

Filled plastics are *particulate composites* whose properties depend on the following:

- resin properties
- filler properties
- internal geometry, including filler shape, volume fraction, distribution, and orientation (for non-spherical particles)

The wide variety of fillers available makes it possible to modify properties in opposite directions. For example, some fillers produce composites with thermal conductivities that are greater than the resin, others lower. The same holds for electrical conductivity.

Table 1.1-6. Common thermoplastic resins.

Acrylonitrile-butadiene-styrenes (ABS)
Acetals
Acrylics
Cellulosics
Fluoropolymers
Nylons (polyamides)
Polyamide-imide
Polyaryl ether
Polyarylsulfone
Polycarbonates
Polyesters (thermoplastic)
Polyetheretherketone (PEEK)
Polyethersulfones
Polyethylenes
Polyimides (thermoplastic)
Polyphenylene oxides (PPO)
Polyphenylene sulfides (PPS)
Polyphenylquinoxalines (PPQ)
Polypropylenes
Polystyrenes
Polysulfones
Polyvinyl chlorides (PVC)
Styrene-acrylonitriles (SAN)