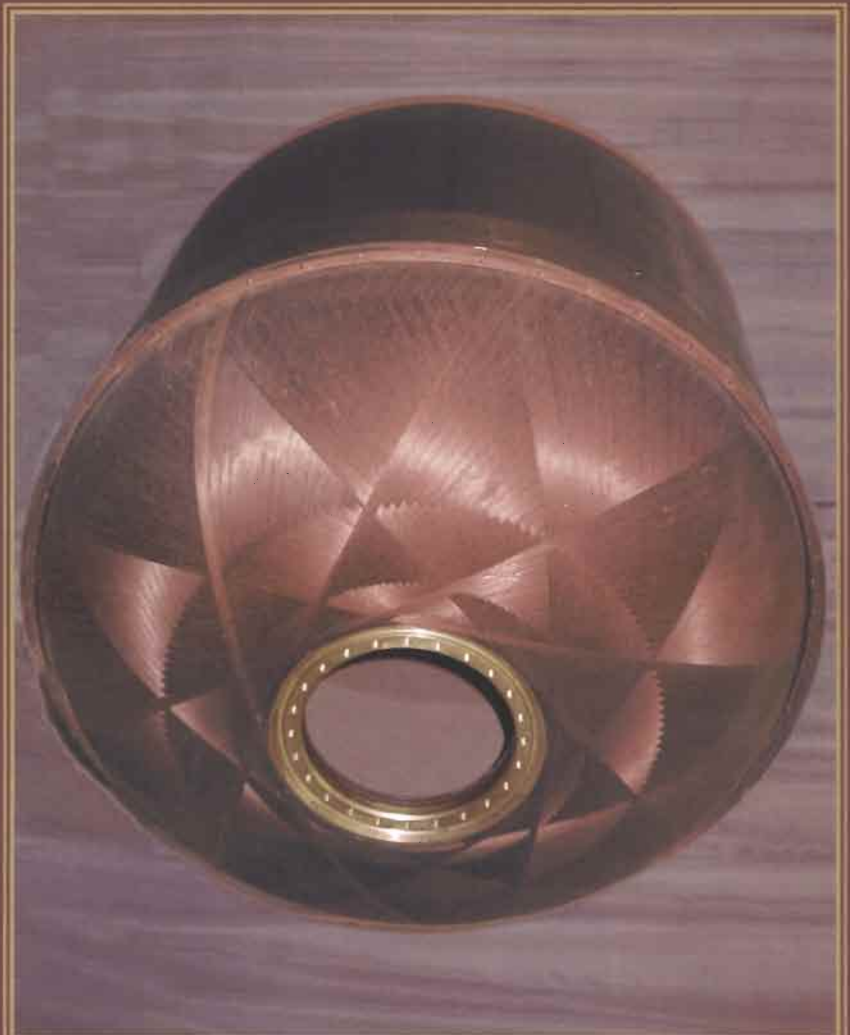

Mechanics and Analysis of Composite Materials

Valery V. Vasiliev & Evgeny V. Morozov

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PREFACE

This book is concerned with the topical problems of mechanics of advanced composite materials whose mechanical properties are controlled by high-strength and high-stiffness continuous fibers embedded in polymeric, metal, or ceramic matrix. Although the idea of combining two or more components to produce materials with controlled properties has been known and used from time immemorial, modern composites have been developed only several decades ago and have found by now intensive application in different fields of engineering, particularly, in aerospace structures for which high strength-to-weight and stiffness-to-weight ratios are required.

Due to wide existing and potential applications, composite technology has been developed very intensively over recent decades, and there exist numerous publications that cover anisotropic elasticity, mechanics of composite materials, design, analysis, fabrication, and application of composite structures. According to the list of books on composites presented in Mechanics of Fibrous Composites by C.T. Herakovich (1998) there were 35 books published in this field before 1995, and this list should be supplemented now with at least five new books.

In connection with this, the authors were challenged with a natural question as to what causes the necessity to publish another book and what is the difference between this book and the existing ones. Concerning this question, we had at least three motivations supporting us in this work.

First, this book is of a more specific nature than the published ones which usually cover not only mechanics of materials but also include analysis of composite beams, plates and shells, joints, and elements of design of composite structures that, being also important, do not strictly belong to mechanics of composite materials. This situation looked quite natural because composite science and technology, having been under intensive development only over several past decades, required the books of a universal type. Nowadays however, application of composite materials has reached the level at which special books can be dedicated to all the aforementioned problems of composite technology and, first of all, to mechanics of composite materials which is discussed in this book in conjunction with analysis of composite materials. As we hope, thus constructed combination of materials science and mechanics of solids has allowed us to cover such specific features of material behavior as nonlinear elasticity, plasticity, creep, structural nonlinearity and discuss in detail the problems of material micro- and macro-mechanics that are only slightly touched in the existing books, e.g., stress diffusion in a unidirectional material with broken fibers, physical and statistical aspects of fiber strength, coupling effects in anisotropic and laminated materials, etc.

Second, this book, being devoted to materials, is written by designers of composite structures who over the last 30 years were involved in practically all main

Soviet and then Russian projects in composite technology. This governs the list of problems covered in the book which can be referred to as material problems challenging designers and determines the third of its specific features – discussion is illustrated with composite parts and structures built within the frameworks of these projects. In connection with this, the authors appreciate the permission of the Russian Composite Center – Central Institute of Special Machinery (CRISM) to use in the book the pictures of structures developed and fabricated in CRISM as part of the joint research and design projects.

The book consists of eight chapters progressively covering all structural levels of composite materials from their components through elementary plies and layers to laminates.

Chapter 1 is an Introduction in which typical reinforcing and matrix materials as well as typical manufacturing processes used in composite technology are described.

Chapter 2 is also a sort of Introduction but dealing with fundamentals of mechanics of solids, i.e., stress, strain, and constitutive theories, governing equations, and principles that are used in the next chapters for analysis of composite materials.

Chapter 3 is devoted to the basic structural element of a composite material – unidirectional composite ply. In addition to traditional description of micromechanical models and experimental results, the physical nature of fiber strength, its statistical characteristics and interaction of damaged fibers through the matrix are discussed, and an attempt is made to show that fibrous composites comprise a special class of man-made materials utilizing natural potentials of material strength and structure.

Chapter 4 contains a description of typical composite layers made of unidirectional, fabric, and spatially reinforced composite materials. Traditional linear elastic models are supplemented in this chapter with nonlinear elastic and elastic–plastic analysis demonstrating specific types of behavior of composites with metal and thermoplastic matrices.

Chapter 5 is concerned with mechanics of laminates and includes traditional description of the laminate stiffness matrix, coupling effects in typical laminates and procedures of stress calculation for in-plane and interlaminar stresses.

Chapter 6 presents a practical approach to evaluation of laminate strength. Three main types of failure criteria, i.e., structural criteria indicating the modes of failure, approximation polynomial criteria treated as formal approximations of experimental data, and tensor-polynomial criteria are analyzed and compared with available experimental results for unidirectional and fabric composites.

Chapter 7 dealing with environmental, and special loading effects includes analysis of thermal conductivity, hydrothermal elasticity, material aging, creep, and durability under long-term loading, fatigue, damping and impact resistance of typical advanced composites. The influence of manufacturing factors on material properties and behavior is demonstrated for filament winding accompanied with nonuniform stress distribution between the fibers and ply waviness and laying-up processing of nonsymmetric laminate exhibiting warping after curing and cooling.

The last Chapter 8 covers a specific for composite materials problem of material optimal design and presents composite laminates of uniform strength providing high weight efficiency of composite structures demonstrated for filament wound pressure vessels.

The book is designed to be used by researchers and specialists in mechanical engineering involved in composite technology, design, and analysis of composite structures. It can be also useful for graduate students in engineering.

Valery V. Vasiliev *Evgeny V. Morozov*

CONTENTS

Chapter 1

INTRODUCTION

1.1. Structural materials

Material is the basic element of all natural and man-made structures. Figuratively speaking it materializes the structural conception. Technological progress is associated with continuous improvement of existing material properties as well as with expansion of structural material classes and types. Usually, new materials emerge due to necessity to improve the structure efficiency and performance, but as a rule, new materials themselves in turn provide new opportunities to develop updated structures and technology, while the latter presents material science with new problems and tasks. One of the best manifestations of this interrelated process in development of materials, structures, and technology is associated with composite materials to which this book is devoted.

Structural materials should possess a great number of physical, chemical and other types of properties, but there exist at least two principal characteristics that are of primary importance. These characteristics are stiffness and strength that provide the structure with the ability to maintain its shape and dimensions under loading or any other external action.

High stiffness means that material exhibits low deformation under loading. However, saying that stiffness is an important property we do not mean that it should be necessarily high. Ability of structure to have controlled deformation (compliance) can be also important for some applications (e.g., springs; shock absorbers; pressure, force, and displacement gauges).

Shortage of material strength results in uncontrolled compliance, i.e., in failure after which a structure does not exist any more. Usually, we need to have as high strength as possible, but there are some exceptions (e.g., controlled failure of explosive bolts is used to separate rocket stages).

Thus, without controlled stiffness and strength the structure cannot exist. Naturally, both properties depend greatly on the structure design but are determined by stiffness and strength of the structural material because a good design is only a proper utilization of material properties.

To evaluate material stiffness and strength, consider the simplest test – a bar with cross-sectional area A loaded with tensile force F as shown in Fig. 1.1. Obviously,

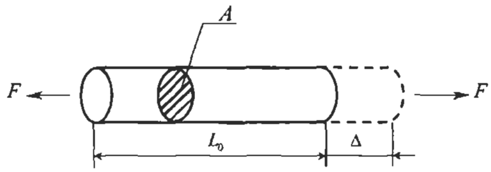


Fig. 1.1. A bar under tension.

the higher is the force causing the bar rupture the higher is the bar strength. However, this strength depends not only on the material properties – it is proportional to the cross-sectional area A. Thus, it is natural to characterize material strength with the ultimate stress

$$\bar{\sigma} = \frac{\bar{F}}{A} \ , \tag{1.1}$$

where $\bar{F}$ is the force causing the bar failure (here and further we use the overbar notation to indicate the ultimate characteristics). As follows from Eq. (1.1), stress is measured in force divided by area, i.e., according to international (SI) units, in pascals (Pa) so that 1 Pa = 1 N/m^2. Because loading of real structures induces relatively high stresses, we also use kilopascals (1 kPa = 10^3 Pa), megapascals (1 MPa = 10^6 Pa), and gigapascals (1 GPa = 10^9 Pa). Conversion of old metric (kilogram per square centimeter) and English (pound per square inch) units to pascals can be done using the following relations: 1 kg/cm^2 = 98 kPa and 1 psi = 6.89 kPa.

For some special (e.g., aerospace or marine) applications, i.e., for which material density, ρ, is also important, a normalized characteristic

$$k_\sigma = \frac{\bar{\sigma}}{\rho} \tag{1.2}$$

is also used to describe the material. This characteristic is called "specific strength" of the material. If we use old metric units, i.e., measure force and mass in kilograms and dimensions in meters, substitution of Eq. (1.1) into Eq. (1.2) yields k_σ in meters. This result has a simple physical sense, namely k_σ is the length of the vertically hanging fiber under which the fiber will be broken by its own weight.

Stiffness of the bar shown in Fig. 1.1 can be characterized with an elongation Δ corresponding to the applied force F or acting stress $\sigma = F/A$. However, Δ is proportional to the bar length L_0. To evaluate material stiffness, we introduce strain

$$\varepsilon = \frac{\Delta}{L_0} \ . \tag{1.3}$$

Since ε is very small for structural materials the ratio in Eq. (1.3) is normally multiplied by 100, and ε is expressed as a percentage.

Naturally, for any material, there should exist some interrelation between stress and strain, i.e.

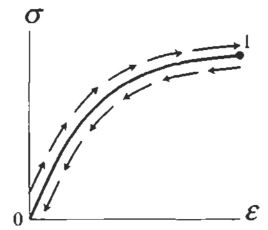
$$\varepsilon = f(\sigma) \quad \text{or} \quad \sigma = \varphi(\varepsilon). \tag{1.4}$$

These equations specify the so-called constitutive law and are referred to as constitutive equations. They allow us to introduce an important concept of the material model which represents some idealized object possessing only those features of the real material that are essential for the problem under study. The point is that performing design or analysis we always operate with models rather than with real materials. Particularly, for strength and stiffness analysis, this model is described by constitutive equations, Eqs. (1.4), and is specified by the form of function $f(\sigma)$ or $\varphi(\varepsilon)$.

The simplest is the elastic model which implies that $f(0) = 0$, $\varphi(0) = 0$ and that Eqs. (1.4) are the same for the processes of an active loading and an unloading. The corresponding stress–strain diagram (or curve) is presented in Fig 1.2. Elastic model (or elastic material) is characterized with two important features. First, the corresponding constitutive equations, Eqs. (1.4), do not include time as a parameter. This means that the form of the curve shown in Fig. 1.2 does not depend on the rate of loading (naturally, it should be low enough to neglect the inertia and dynamic effects). Second, the work performed by force F is accumulated in the bar as potential energy, which is also referred to as strain energy or elastic energy. Consider some infinitesimal elongation $d\Delta$ and calculate elementary work performed by the force F in Fig 1.1 as $dW = F\,d\Delta$. Then, work corresponding to point 1 of the curve in Fig. 1.2 is

$$W = \int_0^{\Delta_1} F\,d\Delta\ ,$$

where Δ_1 is the elongation of the bar corresponding to point 1 of the curve. The work W is equal to elastic energy of the bar which is proportional to the bar volume and can be presented as



$$E = L_0 A \int_0^{\varepsilon_1} \sigma \, d\varepsilon \ ,$$

where $\sigma = F/A$, $\varepsilon = \Delta/L_0$, and $\varepsilon_1 = \Delta_1/L_0$. Integral

$$U = \int_0^{\varepsilon_1} \sigma \, d\varepsilon = \int_0^{\varepsilon_1} \varphi(\varepsilon) d\varepsilon \tag{1.5}$$

is a specific elastic energy (energy accumulated in the unit volume of the bar) that is referred to as an elastic potential. It is important that U does not depend on the history of loading. This means that irrespective of the way we reach point 1 of the curve in Fig 1.2 (e.g., by means of continuous loading, increasing force F step by step, or using any other loading program), the final value of U will be the same and will depend only on the value of final strain ε_1 for the given material.

A very important particular case of the elastic model is the linear elastic model described by the well-known Hooke's law (see Fig. 1.3)

$$\sigma = E\varepsilon \ . \tag{1.6}$$

Here, E is the modulus of elasticity. As follows from Eqs. (1.3) and (1.6), $E = \sigma$ if $\varepsilon = 1$, i.e. if $\Delta = L_0$. Thus, modulus can be interpreted as the stress causing elongation of the bar in Fig. 1.1 as high as the initial length. Because the majority of structural materials fails before such a high elongation can occur, modulus is usually much higher then the ultimate stress $\bar{\sigma}$.

Similar to specific strength k_σ in Eq. (1.2), we can introduce the corresponding specific modulus

$$k_E = \frac{E}{\rho} \tag{1.7}$$

determining material stiffness with respect to material density.

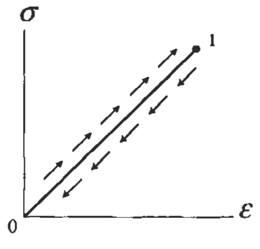


Fig. 1.3. Stress–strain diagram for a linear elastic material.

Absolute and specific values of mechanical characteristics for typical materials discussed in this book are listed in Table 1.1.

After some generalization, modulus can be used to describe nonlinear material behavior of the type shown in Fig. 1.4. For this purpose, the so-called secant, E_s, and tangent, E_t, moduli are introduced as

$$E_s = \frac{\sigma}{\varepsilon} = \frac{\sigma}{f(\sigma)}, \quad E_t = \frac{d\sigma}{d\varepsilon} = \frac{d\varphi(\varepsilon)}{d\varepsilon} \ . \tag{1.8}$$

While the slope α in Fig. 1.4 determines modulus E, the slopes β and γ determine E_s and E_t, respectively. As it can be seen, E_s and E_t, in contrast to E, depend on the level of loading, i.e., on σ or ε. For a linear elastic material (see Fig. 1.3), $E_s = E_t = E$.

Hooke's law, Eq. (1.6), describes rather well the initial part of stress–strain diagram for the majority of structural materials. However, under relatively high level of stress or strain, materials exhibit nonlinear behavior.

One of the existing models is the nonlinear elastic material model introduced above (see Fig. 1.2). This model allows us to describe the behavior of highly deformable rubber-type materials.

Another model developed to describe metals is the so-called elastic–plastic material model. The corresponding stress–strain diagram is shown in Fig. 1.5. In contrast to elastic material (see Fig. 1.2), the processes of active loading and unloading are described with different laws in this case. In addition to elastic strain, ε_e, which disappears after the load is taken off, the residual strain (for the bar shown in Fig. 1.1, it is plastic strain, ε_p) retains in the material. As for an elastic material, stress–strain curve in Fig. 1.5 does not depend on the rate of loading (or time of loading). However, in contrast to an elastic material, the final strain of an elastic–plastic material can depend on the history of loading, i.e., on the law according to which the final value of stress was reached.

Thus, for elastic or elastic–plastic materials, constitutive equations, Eqs. (1.4), do not include time. However, under relatively high temperature practically all the materials demonstrate time-dependent behavior (some of them do it even under room temperature). If we apply to the bar shown in Fig. 1.1 some force F and keep it constant, we can see that for a time-sensitive material the strain increases under constant force. This phenomenon is called the creep of the material.

So, the most general material model that is used in this book can be described with the constitutive equation of the following type:

$$\varepsilon = f(\sigma, t, T) \ , \tag{1.9}$$

where t indicates the time moment, while σ and T are stress and temperature corresponding to this moment. In the general case, constitutive equation, Eq. (1.9), specifies strain that can be decomposed into three constituents corresponding to elastic, plastic and creep deformation, i.e.

$$\varepsilon = \varepsilon_e + \varepsilon_p + \varepsilon_c \ . \tag{1.10}$$

Table 1.1
Mechanical properties of structural materials and fibers.

Material	Ultimate tensile stress, $\bar{\sigma}$ (MPa)	Modulus, E (GPa)	Specific gravity	Maximum specific strength, $k_\sigma \times 10^3$ (m)	Maximum specific modulus, $k_E \times 10^3$ (m)
Metal alloys					
Steel	770–2200	180–210	7.8–7.85	28.8	2750
Aluminum	260–700	69–72	2.7–2.85	26.5	2670
Titanium	1000–1200	110	4.5	26.7	2440
Magnesium	260	40	1.8	14.4	2220
Beryllium	620	320	1.85	33.5	17300
Nickel	400–500	200	8.9	5.6	2250
Metal wires (diameter, μm)					
Steel (20–1500)	1500–4400	180–200	7.8	56.4	2560
Aluminum (150)	290	69	2.7	10.7	2550
Titanium (100–800)	1400–1500	120	4.5	33.3	2670
Beryllium (50–500)	1100–1450	240–310	1.8–1.85	80.5	17200
Tungsten (20–50)	3300–4000	410	19–19.3	21.1	2160
Molybdenum (25–250)	1800–2200	360	10.2	21.5	3500
Thermoset polymeric resins					
Epoxy	60–90	2.4–4.2	1.2–1.3	7.5	350
Polyester	30–70	2.8–3.8	1.2–1.35	5.8	310
Phenol–formaldehyde	40–70	7–11	1.2–1.3	5.8	910
Organosilicone	25–50	6.8–10	1.35–1.4	3.7	740
Polyimide	55–110	3.2	1.3–1.43	8.5	240
Bismaleimide	80	4.2	1.2	6.7	350
Thermoplastic polymers					
Polyethylene	20–45	6–8.5	0.95	4.7	890
Polystyrene	35–45	30	1.05	4.3	2860
Teflon	15–35	3.5	2.3	1.5	150
Nylon	80	2.8	1.14	7.0	240
Polyester (PC)	60	2.5	1.32	4.5	190
Polysulfone (PSU)	70	2.7	1.24	5.6	220
Polyamide–imide (PAI)	90–190	2.8–4.4	1.42	13.4	360
Polyetheretherketone (PEEK)	90–100	3.1–3.8	1.3	7.7	300
Polyphenylenesulfide (PPS)	80	3.5	1.36	5.9	250
Synthetic fibers					
Capron	680–780	4.4	1.1	70	400
Dacron	390–880	4.9–15.7	1.4	60	1430
Teflon	340–440	2.9	2.3	190	130
Nitron	390–880	4.9–8.8	1.2	70	730
Polypropylene	730–930	4.4	0.9	100	480
Viscose	930	20	1.52	60	1300
Fibers for advanced composites (diameter, μm)					
Glass (3–19)	3100–5000	72–95	2.4–2.6	200	3960
Quartz (10)	6000	74	2.2	270	3360
Basalt (9–13)	3000–3500	90	2.7–3.0	130	3300
Aramid (12–15)	3500–5500	140–180	1.4–1.47	390	12800

Table 1.1 (Contd.)

Material	Ultimate tensile stress, $\bar{\sigma}$ (MPa)	Modulus E (GPa)	Specific gravity	Maximum specific strength, $k_\sigma \times 10^3$ (m)	Maximum specific modulus, $k_E \times 10^3$ (m)
Polyethylene (20–40)	2600–3300	120–170	0.97	310	17500
Carbon (5–11)					
High-strength	7000	300	1.75	400	17100
High-modulus	2700	850	1.78	150	47700
Boron (100–200)	2500–3700	390–420	2.5–2.6	150	16800
Alumina – Al_2O_3 (20–500)	2400–4100	470–530	3.96	100	13300
Silicon Carbide – SiC (10–15)	2700	185	2.4–2.7	110	7700
Titanium Carbide – TiC (280)	1500	450	4.9	30	9100
Boron Carbide – B_4C (50)	2100–2500	480	2.5	100	10000
Boron Nitride – BN (7)	1400	90	1.9	70	4700

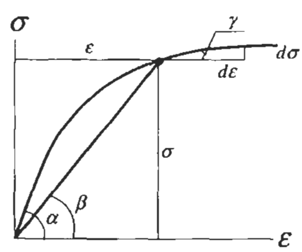


Fig. 1.4. Introduction of secant and tangent moduli.

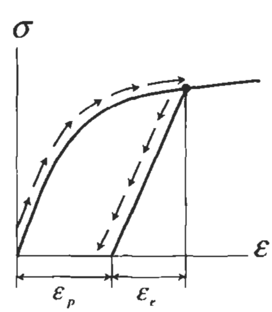


Fig. 1.5. Stress–strain diagram for elastic–plastic material.

However, in application to particular problems, this model can be usually substantially simplified. To show this, consider the bar in Fig. 1.1 and assume that force F is applied at the moment $t=0$ and is taken off at moment $t=t_1$ as shown in Fig. 1.6(a). At the moment $t=0$, elastic and plastic strains that do not depend on time appear, and while time is running, the creep strain is developed. At

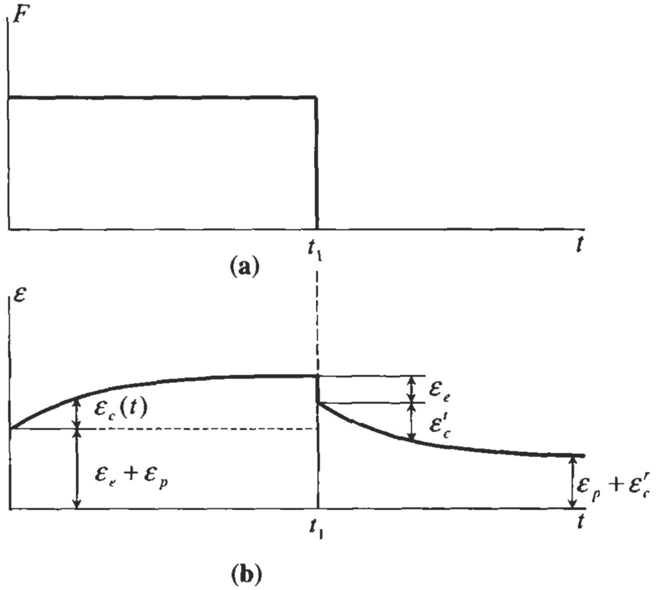


Fig. 1.6. Dependence of force (a) and strain (b) on time.

the moment $t = t_1$ elastic strain disappears, while reversible part of the creep strain, ε_c^t, disappears in time. Residual strain consists of the plastic strain, ε_p, and residual part of the creep strain, ε_c^r.

Now assume that $\varepsilon_p \ll \varepsilon_c$ which means that either material is elastic or the applied load does not induce high stress and, hence, plastic strain. Then we can neglect ε_p in Eq. (1.10) and simplify the model. Furthermore let $\varepsilon_c \ll \varepsilon_c$ which in turn means that either material is not susceptible to creep or the force acts for a short time (t_1 is close to zero). Thus we arrive at the simplest elastic model which is the case for the majority of practical applications. It is important that the proper choice of the material model depends not only on the material nature and properties but also on the operational conditions of the structure. For example, a shell-type structure made of aramid–epoxy composite material, that is susceptible to creep, and designed to withstand the internal gas pressure should be analyzed with due regard to the creep if this structure is a pressure vessel for long term gas storage. At the same time for a solid propellant rocket motor case working for seconds, the creep strain can be ignored.

A very important feature of material models under consideration is their phenomenological nature. This means that these models ignore the actual material microstructure (e.g., crystalline structure of metals or molecular structure of polymers) and represent the material as some uniform continuum possessing some effective properties that are the same irrespective of how small the material volume is. This allows us, first, to determine material properties testing material samples (as in Fig. 1.1). Second, this formally enables us to apply methods of Mechanics of

Solids that deal with equations derived for infinitesimal volumes of material. And third, this allows us to simplify the strength and stiffness evaluation problem and to reduce it to a reasonable practical level not going into analysis of the actual mechanisms of material deformation and fracture.

1.2. Composite materials

This book is devoted to composite materials that emerged in the middle of the 20th century as a promising class of engineering materials providing new prospects for modern technology. Generally speaking any material consisting of two or more components with different properties and distinct boundaries between the components can be referred to as a composite material. Moreover, the idea of combining several components to produce a material with properties that are not attainable with the individual components has been used by man for thousands of years. Correspondingly, the majority of natural materials that have emerged as a result of a prolonged evolution process can be treated as composite materials.

With respect to the problems covered in this book we can classify existing composite materials (composites) into two main groups.

The first group comprises composites that are known as "filled materials". The main feature of these materials is the existence of some basic or matrix material whose properties are improved by filling it with some particles. Usually the matrix volume fraction is more than 50% in such materials, and material properties, being naturally modified by the fillers, are governed mainly by the matrix. As a rule, filled materials can be treated as homogeneous and isotropic, i.e., traditional models of Mechanics of Materials developed for metals and other conventional materials can be used to describe their behavior. This group of composites is not touched on in the book.

The second group of composite materials that is under study here involves composites that are called "reinforced materials". The basic components of these materials (sometimes referred to as "advanced composites") are long and thin fibers possessing high strength and stiffness. The fibers are bound with a matrix material whose volume fraction in a composite is usually less than 50%. The main properties of advanced composites due to which these materials find a wide application in engineering are governed by fibers whose types and characteristics are considered below.

The following sections provide a concise description of typical matrix materials and fiber-matrix compositions. Two comments should be made with respect to the data presented in those sections. First, only a brief information concerning material properties that are essential for the problems covered in this book is presented there, and, second, the given data are of a broad nature and are not expected to be used in design or analysis of particular composite structures. More complete description of composite materials and their components including the history of development and advancement, chemical compositions, physical characteristics, manufacturing, and applications can be found elsewhere (Peters, 1998).

1.2.1. Fibers for advanced composites

Continuous glass fibers (the first type of fibers used in advanced composites) are made by pulling molten glass (at a temperature about 1300°C) through 0.8–3.0 mm diameter dies and further high-speed stretching to a diameter of 3–19 μm. Usually glass fibers have solid circular cross sections. However there exist fibers with rectangular (square or plane), triangular, and hexagonal cross sections, as well as hollow circular fibers. Typical mechanical characteristics and density of glass fibers are listed in Table 1.1, while typical stress–strain diagram is shown in Fig. 1.7.

Important properties of glass fibers as components of advanced composites for engineering applications are their high strength which is maintained in humid environments but degrades under elevated temperatures (see Fig. 1.8), relatively low stiffness (about 40% of the stiffness of steel), high chemical and biological resistance, and low cost. Being actually elements of monolithic glass, the fibers do not absorb water and change their dimensions in water. For the same reason, they are brittle and sensitive to surface damage.

Quartz fibers are similar to glass fibers and are obtained by high-speed stretching of quartz rods made of (under temperature of about 2200°C) fused quartz crystals or sand. Original process developed for manufacturing of glass fibers cannot be used

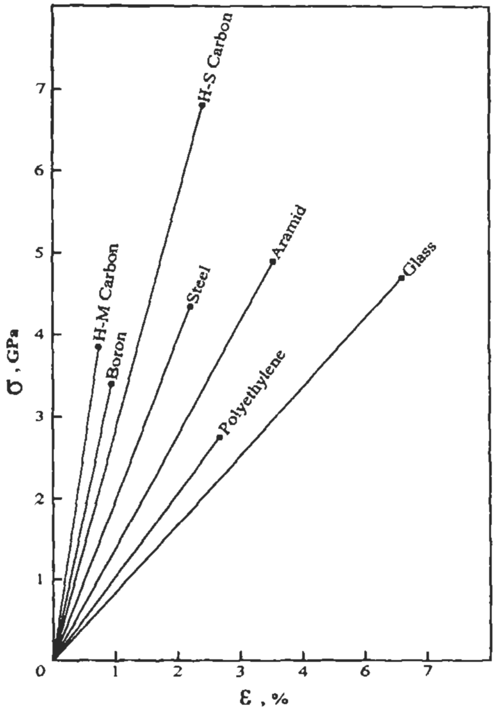


Fig. 1.7. Stress–strain diagrams for typical fibers of advanced composites.