High-Performance Fibre Composites

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Preface

The aim of this book is to provide engineers, designers and materials scientists with some insight into the nature and potential of high-performance fibre composites. The characteristics of these materials are governed primarily by the properties of the reinforcing fibres, which have high strengths and high stiffness values and occupy a large proportion of the volume of the composite. Advanced composite materials are fabricated in ways that enable the advantageous characteristics of the fibres to be exploited as effectively as possible in an engineering structure. The book therefore deals both with reinforcing fibres and with the physical principles of reinforcement. To provide some measure of perspective, brief mention is made of the characteristics of traditional structural metals and of composites that utilize a small admixture of fibres to enhance the strength and toughness of a matrix.

The processes used in the manufacture of various reinforcing fibres are outlined and an account is given of the more important factors that govern their characteristics. Reinforcement is considered both from the point of view of the elastic characteristics of the composites and of the mechanics of failure. These issues are central to a basic understanding of advanced fibre composites.

Since the early 1960s a very considerable world-wide investment has been made in research and in the engineering applications of fibre composites. This is reflected in the large numbers of research papers and technical reports that have been published. A multiplicity of engineering applications has developed with specialized design requirements and material properties. Although this book deals only with the fundamental characteristics of high-performance composites, a fairly extensive list of references to research papers, review articles and books dealing with specialized aspects of the field is included. It is hoped that these will provide convenient points of departure for readers wishing to explore particular aspects of the subject in greater depth, but a fully comprehensive treatment of all aspects of high-performance composites has not been attempted. The reinforcing fibres described have been chosen primarily to illustrate fundamental principles and to give some insight into the various manufacturing routes that can be taken. The composite properties described are related to the physical processes occurring at the microstructural level and deal primarily with polymeric matrix systems. The major points of difference with metal matrix systems are discussed where appropriate.

The plan of the book is as follows. In Chapter 1 the general characteristics required of a structural material are outlined and an introduction given to the advantages of metals and fibrous composites in this context. Some of the processes used in the fabrication of fibrous composites are also outlined.

Chapter 2 deals with a wide range of reinforcing fibres including continuous fibres such as glass, boron, carbon, silicon carbide and aromatic polyamide fibres. Various types of discontinuous reinforcing fibres are also described.

Chapter 3 deals with the elastic properties of fibre composites. The relationships between the elastic constants of an isotropic material are first developed and methods of computing the various elastic moduli of fibre composites from the properties of their component parts are then outlined. The elastic properties of laminae and laminates are discussed at an elementary level; the mathematical development of the theory of anisotropic elasticity is kept to a minimum. Finally in this chapter the relative behaviours of continuous and discontinuous fibres are compared.

Chapter 4 deals with the development of matrix cracks in brittle matrix composites. Simple unidirectionally reinforced materials and also laminates are considered. Comparisons are made between theoretical predictions and experimental results.

Chapter 5 is concerned with the fracture of fibrous composites under tensile loading and deals primarily with unidirectionally reinforced systems. Various processes that inhibit failure, such as interfacial debonding and fibre "pull-out" are described. Composite failure is considered, both in terms of the statistics of fibre failure and from the viewpoint of the micromechanics of crack growth, and this is extended to cover hybrid systems.

Chapter 6 deals with fracture under more complex off-axis and compressive loading conditions. The behaviour of laminates is considered, including the effects of combined in-plane stresses.

Chapter 7 is concerned with some aspects of the long-term strength of fibrous composites. An account is given of the factors controlling the damage tolerance of laminates. The mechanisms of fatigue damage in unidirectional systems and laminates are also outlined. Finally, a brief mention is made of environmental effects on the mechanical properties of polymeric matrix composites.

I am grateful for assistance from many sources in the preparation of this book. Photographs of manufacturing processes and composite engineering components have been generously provided. I would like to thank all who have allowed me to reproduce photographs and diagrams from their published work and to their publishers for permission to use them. My understanding of composite materials has developed over many years during contact with many colleagues, initially in Rolls Royce Ltd. and subsequently in the University of Nottingham, and their contributions are much appreciated. I would like to thank the Wolfson Foundation and the Science Research Council for their generous support of my work in Nottingham.

It is apparent that a book of this nature must draw extensively on the published work of many authors. References are made in the text to specific contributions and these are warmly acknowledged.

J. G. MORLEY

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1
Outline of the General Characteristics of Structural Materials and the Fabrication and Applications of Fibre Composites

1.1 GENERAL REQUIREMENTS OF STRUCTURAL MATERIALS

A structural material is required to be strong and stiff enough to carry loads without being deformed significantly by them. For most applications a low-density material has obvious advantages. At the same time it should be easily shaped and joined to other components so as to form an engineering structure. It should be resistant to a range of corrosive environments and it should provide all these facilities as inexpensively as possible. For a considerable period of time metals provided the best compromise in meeting these requirements but, over the last few years, they have been supplanted for many applications by fibre-reinforced composite materials. There are now many types of composite materials in commercial use that show particular advantages in certain applications.

Fibre-reinforced composites also have their limitations. A simple composite consisting of unidirectionally aligned fibres in a matrix has highly anisotropic characteristics, since the fibres contribute to the strength and stiffness primarily in the direction of fibre alignment. For most engineering applications a structural material has to support loads applied in a variety of directions. It then becomes necessary to design a composite structure so that the optimum proportion of fibres is aligned in the necessary directions. Efficient composite structures can be manufactured, but correspondingly greater complexity is introduced into the design process. The elastic characteristics of fibre-reinforced composites can now be predicted with reasonable accuracy, but their various failure processes are not yet fully understood.

1.2 STRENGTH AND TOUGHNESS IN ENGINEERING MATERIALS

Strength and toughness are primary requirements in structural materials. The toughness of metals is achieved by a quite different process from that used in the design of fibre composites. Before outlining means by which the toughness and the resistance of a material to crack propagation are obtained, we first consider the theoretical strength of an ideal solid.

The tensile fracture of an ideal homogeneous elastic solid should occur by the pulling apart of adjacent planes of atoms. The force of attraction between the atomic planes varies with their distance of separation, being zero when the atoms occupy their equilibrium positions. For small deformations the force increases approximately linearly with increasing separation (Hooke's Law). The attractive force between the atoms must eventually reach a maximum value, corresponding to an applied stress of σ_{max}, and then decrease with increasing separation of the atomic planes (Orowan, 1949). This relationship can be represented approximately by a sign curve (see for example, Cottrell, 1964). Hence the external applied stress σ will be given (see Figure 1.1) by

$$\sigma = \sigma_{max} \sin (2\pi x/\lambda) \tag{1.1}$$

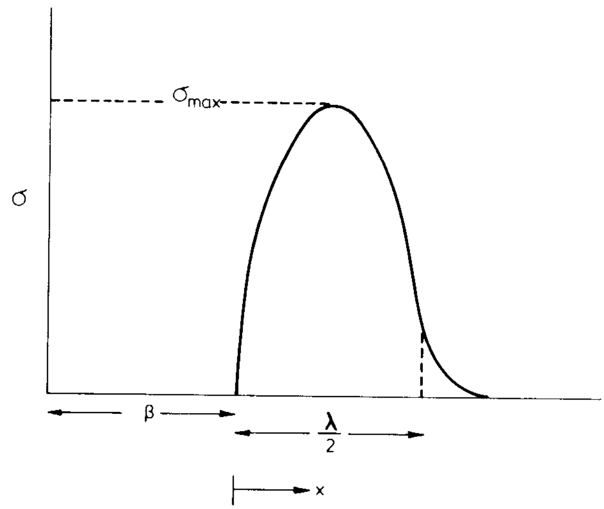

Figure 1.1. Tensile fracture of an ideal solid. (Redrawn from Cottrell, 1964.)

where x is the displacement from the equilibrium separation β and $\lambda/2$ represents the limiting displacement for interatomic cohesion. For small values of x,

$$\sigma = \sigma_{max} 2\pi x/\lambda \qquad (1.2)$$

and from Hooke's Law,

$$\sigma = Ex/\beta \qquad (1.3)$$

where E is the Young's modulus of the material. From equations (1.2) and (1.3):

$$\sigma_{max} = \lambda E/2\pi\beta \qquad (1.4)$$

We now assume that the work done in separating two planes of atoms is equal to the surface energy γ of the newly created surfaces, so that

$$2\gamma = \int_0^{\lambda/2} \sigma_{max} \sin(2\pi/\lambda)\, dx = \sigma_{max}\lambda/\pi \qquad (1.5)$$

From equations (1.4) and (1.5), we have

$$\sigma_{max} = (E\gamma/\beta)^{1/2} \qquad (1.6)$$

Inserting appropriate values for λ and β in equation (1.6) gives

$$\sigma_{max} \simeq E/10 \qquad \text{or} \qquad \varepsilon_{max} \simeq 0.1$$

where ε_{max} is the maximum theoretical elastic strain shown by a solid at fracture.

These values are about an order of magnitude greater than present day strong elastic reinforcing fibres and about two orders of magnitude greater than conventional materials in bulk form. This discrepancy is due to the presence of cracks and flaws in practical materials. It is convenient to represent a crack as an elliptical cavity within an elastic plate (see Figure 1.2). The stresses round such a cavity have been calculated by various people, following the original work of Inglis (1913) (see e.g. Timoshenko and Goodier, 1951). The stress σ_y developed at the tip of the ellipse in the direction of loading when a unidirectional tensile stress σ is applied to the plate is given by

$$\sigma_y = \sigma(1 + 2a/b) = \sigma[1 + 2(a/\rho)^{1/2}] \qquad (1.7)$$

where a and b are the semi-major and semi-minor axes of the ellipse and ρ is the radius of curvature of the ellipse at the tip of its major axis (crack tip). The applied stress is thus increased locally by a factor of three due to the presence of a circular hole. Also the local stress enhancement at the tip of a crack increases as the length of the crack increases and the radius of curvature of its tip decreases.

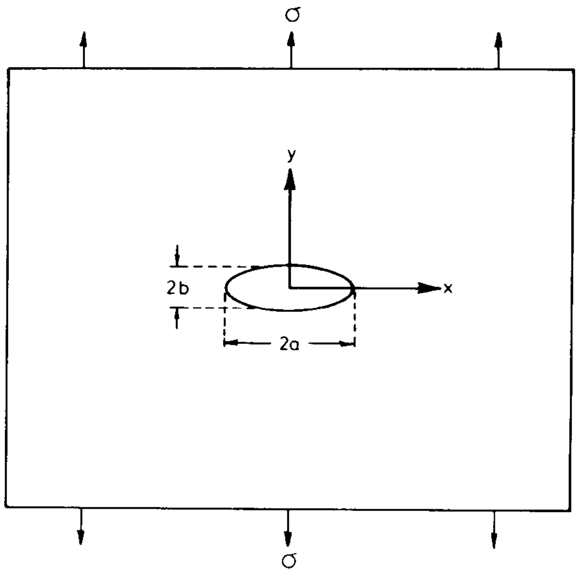

Figure 1.2. Representation of a crack by an elliptical cavity.

In addition to the stress σ_y acting in the direction of loading, a stress σ_x also acts perpendicular to the direction of loading. This is zero at the crack tip, increases to a maximum value of short distance from the crack tip and then falls progressively at increasing distances. Values of σ_y and σ_x calculated for an elliptical crack for which $a = 100b$ are shown in Figure 1.3. The maximum value of σ_x is about one-fifth of the maximum value of σ_y and this is reached at a distance from the crack tip roughly equal to the radius of curvature of the crack tip. It is apparent that stresses exceeding the theoretical strength of a solid can be generated by cracks of suitable geometry. When the material is homogeneous and elastic, the stress-raising ability of a crack is independent of its absolute size.

If a crack in a brittle material is to extend, energy must be supplied at least equal to surface energy of the newly created surfaces. This energy can be provided by the elastic relaxation of a stressed solid as the crack extends. Griffith (1920) showed that, for the situation illustrated in Figure 1.2, the amount of energy supplied by elastic relaxation is equivalent to the complete relaxation of an elliptical zone around the crack having an area equal to twice that of a circle whose diameter is the crack length. If the plate is assumed to have unit thickness the amount of energy released is therefore given by $2\pi a^2(\sigma^2/2E)$ and the rate of release of strain energy with increasing crack length is given by $\mathrm{d}/\mathrm{d}a\,(\pi a^2\sigma^2/E)$. Since two surfaces are

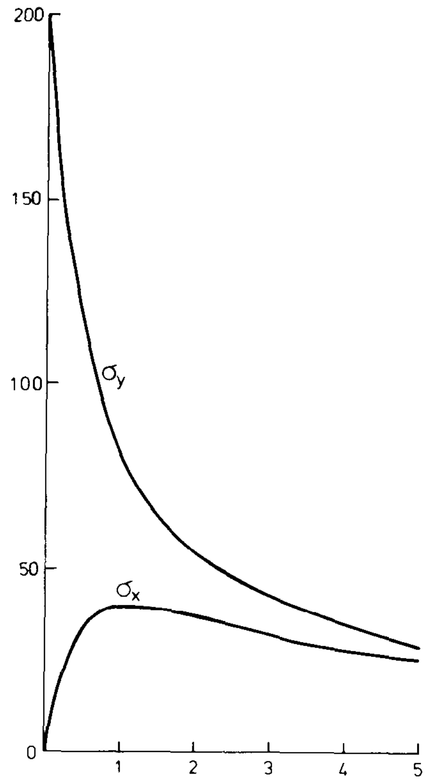

Figure 1.3. Local stress enhancement near the crack tip calculated for points on the *x* axis. Distances are expressed in terms of the radius of curvature of the crack tip. (Redrawn from Cook and Gordon, 1964.)

produced at each end of the crack, the minimum rate of absorption of energy is given by $d/da\,(4\gamma a)$, where γ is the surface energy. The crack becomes unstable when the rate of release of strain energy with increasing crack length equals the rate of energy absorption. Thus the critical condition for crack growth is given by

$$\pi a \sigma^2 / E = 2\gamma \quad (1.8)$$

so that

$$\sigma = (2\gamma E / \pi a)^{1/2} \quad (1.9)$$

Equation (1.9) applies to plane stress (thin sheet) conditions. For plane strain conditions the stress for unstable crack growth is given by

$$\sigma = \left(\frac{2E\gamma}{\pi(1-v^2)a}\right)^{1/2} \tag{1.10}$$

where v is the Poisson ratio of the material.

When a crack becomes unstable its rate of growth increases up to a limiting value which is about one-half of the velocity of transverse elastic waves in the material. In brittle materials, internal flaws, caused for example by foreign inclusions, can initiate fracture at points ahead to the main crack on planes different from that in which the main crack is propagating. Where the crack faces intersect, a step is formed that has a quasi-parabolic shape in the plane of the primary crack face. These effects produce essentially linear topographical features that radiate out from the point of initial fracture.

In the case of metals, plastic deformation occurs at the tip of a crack as a result of the high stresses developed there. When the zone of plastic deformation is small compared with the length of the crack, the bulk of the material behaves elastically and equation (1.9), suitably modified, can be applied. We now have to include the work done in deforming the material at the crack tip prior to fracture occurring there by plastic flow. In practice the surface energy term can be neglected, since the work done during plastic deformation is typically greater by several orders of magnitude. If we replace 2γ by G_c, the total resistance of the material to crack extension, we can write equation (1.9) as

$$\pi a\sigma^2/E = G_c \tag{1.11}$$

A crack may propagate by a crack opening (Mode I), forward shear (Mode II) or by parallel shear (Mode III); see Figure 1.4. It is convenient to substitute $K_{1c}^2 = G_{1c}E$ for the crack opening mode of failure (for plane stress conditions) so that $K_{1c} = \sigma(\pi a)^{1/2}$ and is termed the critical stress intensity factor. This relationship between K_{1c} and G_{1c} applies only when the crack length is small compared with the dimensions of the material and requires modification to deal with other stress conditions (see e.g. Paris and Sih 1965).

The large amount of work required to cause a metal to fracture by crack propagation makes metal alloys, in general, insensitive to damage during monotonic loading and is a basic reason for their widespread use as structural materials. Under cyclic loading, however, cracks can propagate incrementally at relatively low stress levels until they reach the critical size for unstable extension. This is termed fatigue failure and can be atmosphere-dependent. It is the source of most of the failures in service of metal structures and sets a primary limitation on the use of metals in highly

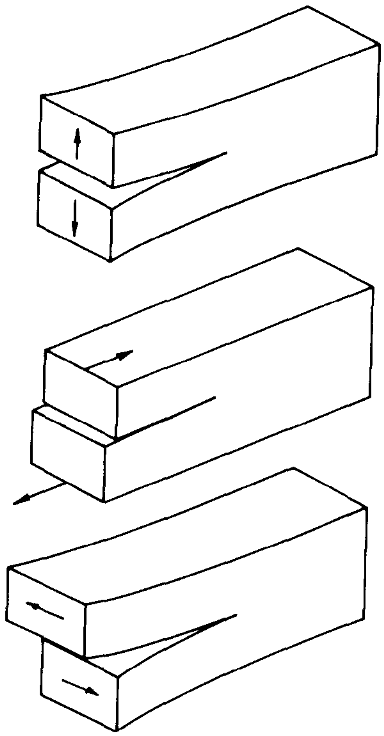

Figure 1.4. Crack extension modes. (*a*) (Mode I) crack opening mode; (*b*) (Model II), forward shearing mode; (*c*) (Mode III), parallel shearing mode.

stressed cyclically loaded structures. Other limitations of metals are due to their relatively high densities, which for practical alloys increase in proportion to the elastic modulus of the material. The ratio of elastic modulus to density is therefore sensibly constant for most metal alloys and this sets a limitation on the use of metals where movement (oscillatory, rotational or translational) is required of a structure.

Fibre-reinforced composites offer certain advantages over metals. This is because they employ a mechanism different from ductility to resist failure by the growth of a crack from a region of damage. Because ductility is not required of the load-bearing fibres they can be formed from brittle materials that have high elastic moduli and low densities. These materials, when in the form of thin fibres, can be made very strong in general, although weak regions will exist as a consequence of surface damage or the presence of flaws. Although failure may occur in the fibres at widely spaced flaws, these failures do not cause immediate failure of the composite structure. This is