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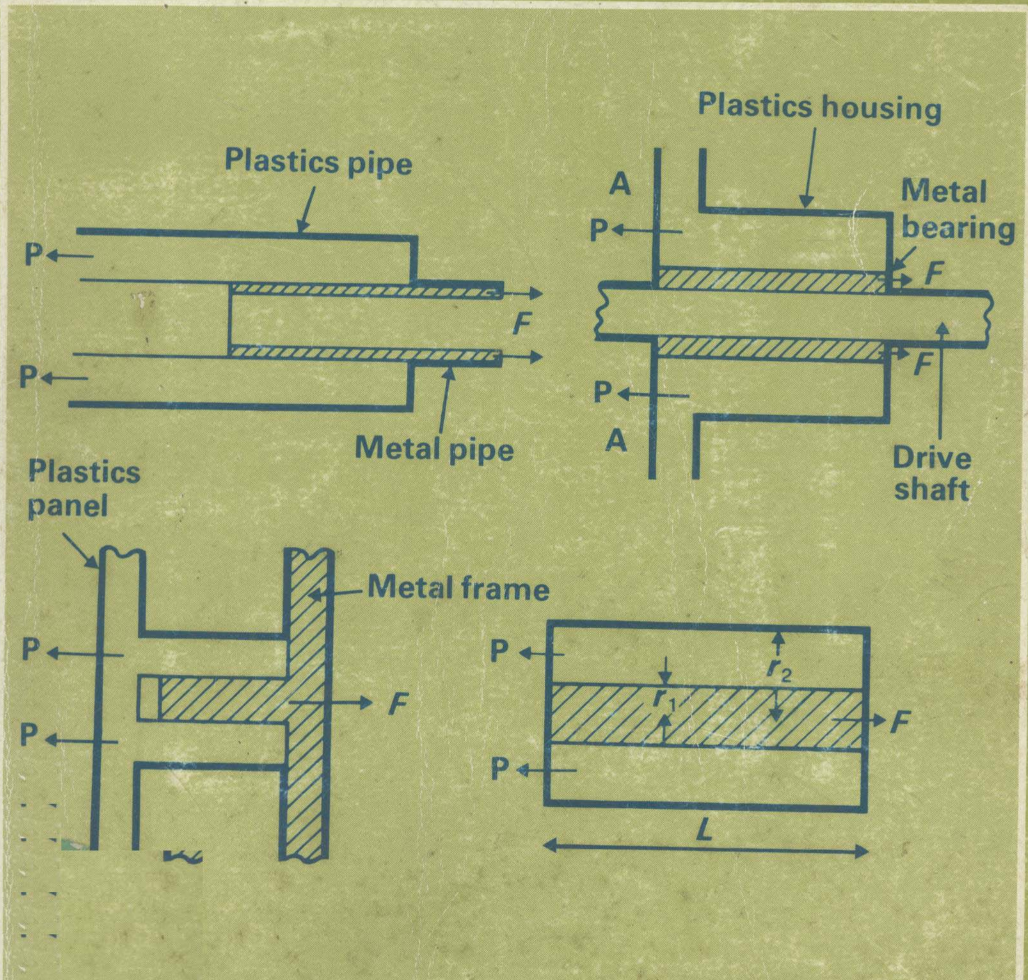

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Foreword

This book complements the materials data provided by the major polymer suppliers. It is concerned with the manipulation of these data to predict the in-service performance of plastics products or to optimize product design. The book is concerned with products used in engineering applications, and the design calculations are properly the responsibility of the plastics design engineer. Thus, the presentation inevitably involves a certain amount of engineering mathematics, but this has been kept as simple as possible.

Although the ideal reader of this book is the plastics design engineer, it is recognized that there are very few workers with this title in industry. In the past, plastics product design has often been carried out by workers in materials suppliers' and processors' organizations, and often by non-engineers. In the future it is likely that plastics design will be performed by design engineers, many of whom presently have little familiarity with plastics properties, and there is evidence that this trend is already happening. Thus, this book has been written with the design engineer in mind, but other workers will find much of interest to them provided that they recognize the need for some engineering theory and are willing to come to terms with it.

The book will be useful in education, in training courses and for the individual reader, and will serve to provide a basis of understanding of the principles involved in plastics design calculations. It will also stimulate developments towards more precise methods for specific plastics products.

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Part 1
Introduction

1.1 Product design

Product design must take account of a wide range of factors including cost, aesthetic appeal, method of manufacture, materials availability, and intended use and likely abuse of the product. In practice, a general appraisal of these factors leads to a preliminary design involving a tentative choice of material, and of product dimensions and fabrication method. The design is then refined by giving detailed consideration to factors such as materials selection, mould design and local product geometry. In many cases, plastics products have been successfully designed by matching material selection with product requirements, and by ensuring that mould design gives rapid processing with acceptable product appearance. Often engineering design of the product, to ensure fitness for purpose, is confined to suitable radiusing of corners, etc. This book is concerned with design applications where more detailed engineering design is necessary, or where it can provide worthwhile benefits.

1.2 Who needs engineering design?

Engineering design is necessary when the product will encounter during its service lifetime, loads of sufficient magnitude as to threaten the satisfactory performance of the product. These loads may arise as a result of the primary product requirements (for example, in a pressurized container), as loads encountered during transport or installation, or accidental loads or overloads (for example, normal wear and tear in use).

The need for engineering design can be overcome by over-design, and this is probably the main reason why many existing plastics products have undergone little detailed design. However there are a number of strong pressures against over-design and in favour of detailed engineering design. These are the conflicting requirements for efficient use of polymer feedstock and energy on the one hand, and for product reliability on the other, particularly in the context of product liability legislation.

There is a consensus view[1] that plastics have an important role to play in the future, and they may be in a more favourable position than traditional materials. In applications in which they can be used, their total energy requirements (for feedstock and for material and product processing) can be lower than for metals, and they can give further savings through lower weight in transport and other applications employing moving parts. However, the continued use of plastics will depend on more efficient use of materials and on the choice of products for which there is significant added value (that is, engineered products). In applications such as transport (particularly motor vehicle), building, domestic appliances and consumer durables, plastics must move towards a situation in which they are considered as engineering materials, comparable with metals in their respective applications, and capable of being treated accordingly.

1.3 Who carries out engineering design?

Engineering design is carried out in industry by a range of people with varying backgrounds and expertise. This arises because the production of a major plastics product involves a technical input from the materials supplier, from the manufacturer (for example, a trade moulder) and from the customer for the plastics product. The latter may be a user industry, such as a motor vehicle company, and in this case, the level of technical contribution will be relatively high.

The customer's specification for an engineering product may vary between the extremes of a detailed description of the required product, including its method of manufacture, and a simple statement of the function that the product must perform in service. In the former case, it is likely that the customer or a design consultant has carried out a detailed design exercise, and the materials supplier and manufacturer then take little or no part in the design and accept a lower level of responsibility for the satisfactory performance of the product. In the latter case, the customer's end-use requirements have to be translated into a detailed product design, and this may be done by the processor, the materials supplier or a design consultant. In practice, a well designed product will require a team effort between the supplier, processor and customer but, depending on the nature of the companies involved, the main effort and responsibility may be taken at any point along that spectrum of activities.

As a result of the factors discussed above, and the fact that different products require different levels of design expertise, any design aid cannot hope to cater precisely for the specific needs of all designers. The type and level of presentation which is most acceptable for an engineer who is familiar with engineering design in traditional materials is unlikely to be appropriate for the majority of personnel in supplier or processor companies with chemical or process engineering backgrounds. Further, within the former group, the requirements of the designer who is involved with the overall design are different from those of the design analyst who is responsible for the detailed engineering calculations.

Because of the fragmented nature and relatively low level of expertise of current engineering design practice for plastics products, there is a need for improvement, but this cannot be provided uniformly over all sectors. It is the author's view that improvement will be achieved most effectively by increasing the familiarity with plastics design of the engineer who is already familiar with design with traditional materials, and this book has been written with this in mind. This will have the greatest initial impact on user industries, such as motor vehicle, and on some manufacturers of plastics products, but it is hoped that it will have some interest for suppliers and trade moulders, and will eventually have more relevance for their activities. The presentation of this book is aimed somewhere between the designer and the design analyst.

1.4 The nature of engineering design

The main purposes of engineering design are to predict the likely performance of the product in service and to optimize this performance within the constraints of cost, weight, etc. Detailed design of a product for load-bearing applications requires some form of analysis relating applied loads, component geometry, materials properties and service requirements. Essentially this involves three main steps:

(a) Assessment of stress and strain levels in the proposed design,

(b) comparison of critical stress and/or deformation values with design criteria to ensure that the proposed design will satisfy product requirements and materials limitations, and

(c) modification of the proposed design to obtain optimum satisfaction of product requirements.

The first step is given a good deal of attention in this book because of its importance, and because it often receives inadequate consideration in current design practice for plastics products.

The design criteria involved in the second step may be concerned with avoiding excessive deformation, component breakage, cracking, crazing, fatigue, etc. and they may be affected by the service environment and by ageing of the material. The first of these criteria is a purely geometric condition based on product requirements, whereas the other criteria are essentially material-property conditions specifying the ability of the material to remain serviceable under the existing conditions. It is important to note that steps (a) and (b) are essentially independent, and they are treated accordingly here (in Parts 2 and 3 and Part 4, respectively).

1.5 The mechanical properties of plastics

The nature of plastics properties differs in some respects from that of traditional engineering materials. In many situations plastics can be treated as though they were traditional materials, with appropriate 'effective' values for properties such as Young's modulus and Poisson's ratio, and this is the basis for much of current design practice. However, more effective and confident design will be achieved by recognition of the differences between the properties of the two classes of materials, and by modifications to traditional design procedures where this is appropriate. This is the purpose of the present book, but a single illustration is appropriate here.

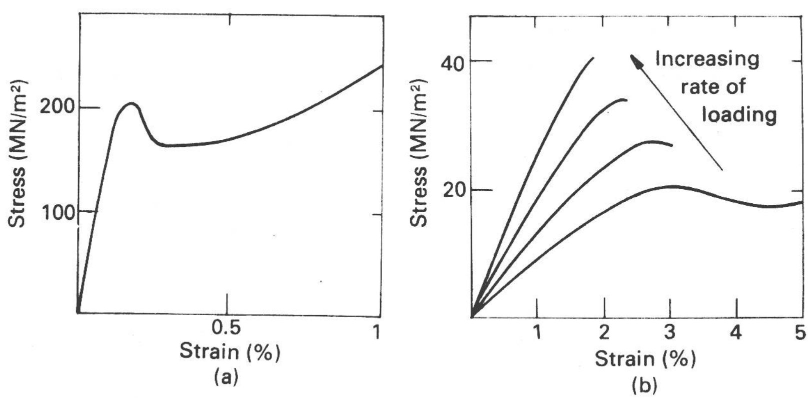

Figure 1.1 *Schematic stress/strain curves for* (*a*) *metal and* (*b*) *plastics. Axes indicate orders of magnitude.*

A typical stress/strain curve for a metal is shown in Figure 1.1 (a). It exhibits elastic behaviour at small strains, followed by yield, plastic flow and ultimate failure. A significant difference in the behaviour of plastics is that it is not possible to talk about *the* stress/strain curve for a plastics material. A typical *set* of stress/strain curves is shown in Figure 1.1(b), and this behaviour arises from the viscoelastic nature of plastics properties, whereby the stress depends not only on the strain in the material, but also on the rate or frequency of loading, or on the length of time for which the load has been applied. These unfamiliar concepts are described in simple terms in Sections 2.11, 2.9 and 2.2, respectively, and it is shown in subsequent sections that this behaviour can be readily incorporated into design calculations. Metals exhibit these types of behaviour to only a limited degree and under extreme conditions, and the mechanisms are different.

In engineering applications metals are designed to behave elastically in service, with only local plastic flow to relieve stress concentrations during shakedown. Since strains are usually small, linear elastic behaviour can be assumed, and classical 'Strength of Materials' formulae[2,3] can be used in design. However, plastics exhibit viscoelastic properties, and modifications to classical elastic formulae may be required. Further, the relatively lower stiffness of plastics may involve large deformations resulting in nonlinear behaviour, and the design may be deformation-controlled in a plastics material whereas it was strength-controlled in a metal.

1.6 The effects of processing and environment

In addition to the viscoelastic properties, plastics materials may exhibit significant anisotropy and inhomogeneity. The former is more important in materials reinforced with long fibres (for example, glass reinforced plastics (GRP)[4]), but it can occur in unreinforced plastics due to molecular orientation during processing. Inhomogeneity is particularly important in sandwich materials where it can be used to advantage[5], but it can occur in sheet moulding compound (SMC) and short fibre filled thermoplastics, again due to processing.

These effects of processing on materials properties can be important factors in plastics product design. Unfortunately, they cannot yet be treated rationally, and the design calculations must use estimates of the properties of processed material. In order to overcome the difference between data from test specimens provided by suppliers and data for material processed into a particular product form, it has been suggested[6] that data could be provided in future for typical moulded sub-components, and this could be coupled with a form of sub-component design[7] approach. Although this may be a viable proposition in the future, the author believes that progress in plastics design will come from appropriate modifications to existing design procedures for traditional materials. Thus the design calculations will be based on the ideas presented in this book, and the design data will be chosen as far as possible to represent processed material.

Like other engineering materials, plastics properties can be affected by the environment in which they have to operate. Plastics are often chosen in preference to metals because of their anti-corrosion properties. Nevertheless, their properties are influenced by environmental exposure (water, light, heat, acid, etc) and this may be a principal factor in materials selection at the preliminary design stage. In the subsequent design calculations, the materials data should be relevant to the appropriate environment, where this is thought to be significant. Plastics properties are particularly dependent on temperature variations, and this can be handled adequately in design, as indicated in Sections 2.13–2.15.

1.7 Current design information

Design information is available on a variety of topics, in various forms and from a number of different sources. The nature of plastics properties is described in design guides, in materials suppliers' technical booklets and in the technical literature[8–22]. The principles of good mould design in order to avoid detrimental effects due, for example, to stress concentrations, sink marks and weld lines, are likewise presented in these three forms of publications. Test methods for the acquisition of design data are covered by British[23] and international standards and by the technical literature[24,25], and at least one standard[26] recommends the forms in which design data should be presented. Graphs and tables of data for specific materials are provided by materials suppliers.

Information on the use of design data in design calculations for plastics products is scattered over a number of sources. It is contained to some extent in design guides[8,9,15], codes of practice[27], suppliers' general data handouts[13–16], suppliers' booklets for specific product areas[14], and in the technical literature[17–22]. However, these fragmented contributions do not provide an adequate and convenient basis for the wider use of engineering design methods for plastics products, and this was the motivation for the present book.

1.8 Formulae, design sheets or computers?

Provision of design methods for plastics products needs to employ a form which is recognizable to designers in traditional materials, and design formulae[2,3], design sheets[28] and computer programs have all been used. However, most existing design aids have been developed for metals, and modifications need to be made, where necessary, to make them applicable to plastics. It is obviously foolish to use a sophisticated computer technique, such as the finite element method, to handle the complex geometry of a component, if the program has inadequate representation of material properties. Since plastics do not always behave like metals, some changes of principle may be necessary in addition to the substitution of different values for materials parameters.

This book cannot provide a full set of modified formulae, design sheets and computer programs. But it can make the designer aware of the relevant factors to be considered when designing for plastics. In this way he may adapt and use modified design formulae, and be in a position to demand the provision of design sheets and computer packages which incorporate the features that he needs.

1.9 Scope and nature of this book

For many current and potential engineering uses of plastics the main non-traditional characteristic is that of viscoelasticity, rather than anisotropy or inhomogeneity. This book concentrates on the various facets of viscoelastic behaviour and the consequent design implications. A treatment of anisotropy will be given in a separate book devoted more specifically to GRP. The present book is particularly relevant to engineering design with thermoplastics, including particle and short-fibre filled materials. However, it will also be useful in some aspects of design with thermosets, including sheet and dough moulding compounds and GRP.

This book is concerned firstly with the various aspects of assessing stress and deformation levels in plastics product design, and then with the specification and application of design criteria. These various aspects are discussed in separate brief sections and, in most cases, they are followed by an illustration of how they occur in practical design and how they are treated. An impression of the range of factors which are considered, and the types of illustrative example, can be obtained by studying the contents pages.

Part 2
Assessment of stress and deformation in one dimension

2.1 Introduction

In general, plastics products are three-dimensional objects in the sense that they have length, width and depth or thickness. However, there is an important class of situations in which product geometry and applied loading induce only a single non-zero stress component, at least to an engineering approximation. For example, extension of a simple beam induces only longitudinal stresses, and flexure of a long beam does likewise, although there is a through-thickness variation of that stress in the latter case. Similarly, internal pressure within a thin tube induces hoop stresses, and torsion of a shaft causes shear stresses.

In all of the examples given above, the single applied stress component may induce strains in more than one direction due to Poisson's ratio effects. However, there is one particular strain or deformation measure in each case which is of special interest for the designer. This would be the amount of longitudinal extension in the case of a beam under a tensile load, or its lateral deflection under flexural load. For the pressurized tube, the hoop strain is the important quantity and, for the shaft, it is the amount of twist for a given applied moment.

The single strain component of interest ε is related to the single non-zero applied stress σ through an appropriate constitutive (stress/strain) relation for the material. For a linear elastic material this relation takes the form

$$\varepsilon = \frac{\sigma}{E} \qquad [2.1]$$

and E is an elastic modulus. In the beam and tube examples given above, E is the Young's modulus for the material, but in the case of torsion of a shaft it must be replaced by the shear modulus. In the subsequent discussion, other relations between ε and σ will be discussed, and it should be remembered that the numerical values of materials parameters should relate to the particular form of loading (extension, compression, shear) being considered.

For a linear elastic material, the single relation [2.1] is adequate no matter whether the loads are applied in a steady fashion, at high rates, as dynamic vibrations, or in a more general time-dependent manner. For a viscoelastic material, it is more convenient to use a different form of constitutive relation for each of these classes of loading situation. The purpose of this Part of the book is to introduce these relations and to show how they are applied in design.

2.2 Creep under constant stress

Creep is the phenomenon whereby the strain in a material due to a constant applied stress varies with time. In metals, creep is usually only significant at elevated temperatures, although some metals such as lead show appreciable creep over long periods at ambient temperatures. A typical strain/time curve for a metal under constant stress and at elevated temperature[29] is shown in Figure 2.1. It is composed of primary, secondary and tertiary stages, and in practice it is often possible to restrict attention to the dominant secondary stage in which the strain

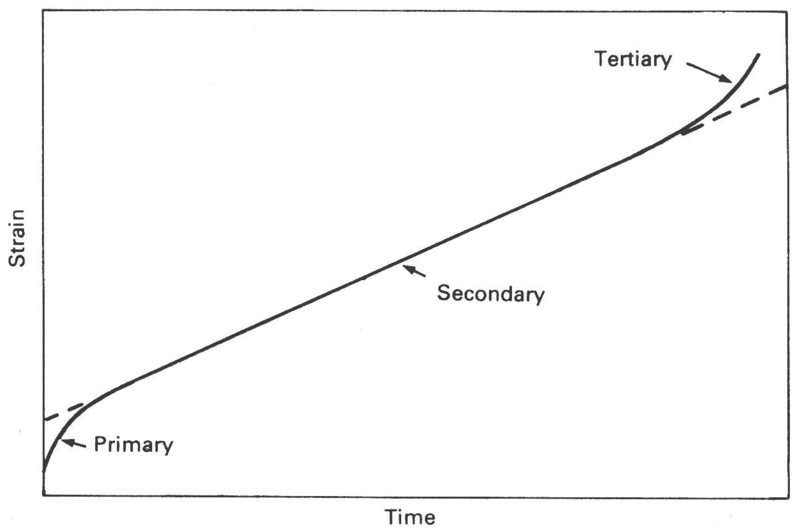

Figure 2.1 *The three phases of creep for a metal under constant stress and at elevated temperature*[29] *(Note linear axes).*

rate is approximately constant. In this case, the creep behaviour can be represented by a formula relating strain rate $\dot{\varepsilon}$ to the applied stress σ, and the strain ε and time t do not appear explicitly in this formula. For example, it is often adequate to use a power-law relation[29]

$$\dot{\varepsilon} = A\sigma^n \qquad [2.2]$$

where A and n are constants for the particular material.

Plastics differ from metals in that creep at ambient temperatures is the rule rather than the exception, and it may be very significant at elevated temperatures. The form of the creep curve (strain/time at constant stress) for a plastics material is basically different from that for a metal since the secondary phase is rarely significant. Consequently the creep behaviour in service is of the primary type, and it is usual to plot these creep data versus the logarithm of time. A typical set of creep data at room temperature (for polypropylene[13c]) is shown in Figure 2.2, where the different curves correspond to different applied stress levels, the loads having been applied at time $t = 0$. Thus the strain may typically

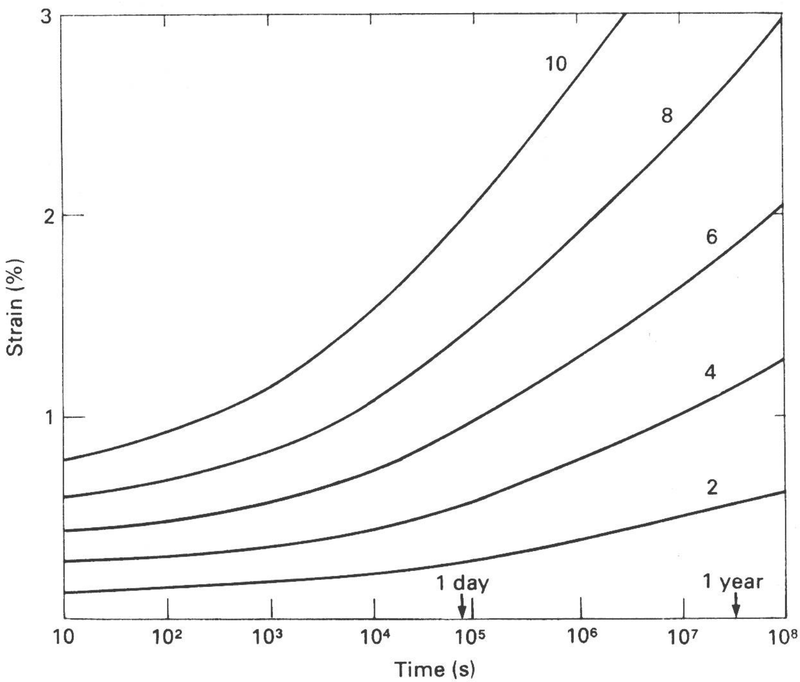

Figure 2.2 *Tensile creep curves for a grade of polypropylene at 20°C and at different stress levels.*[13c] *Numbers refer to stress level in MN/m².* (*Note logarithmic time axis*)