DESIGN
— FOR —
CREEP

second edition

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CHAPMAN & HALL

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CHAPMAN & HALL
London · Glasgow · Weinheim · New York · Tokyo · Melbourne · Madras

Published by Chapman & Hall, 2–6 Boundary Row, London SE1 8HN, UK

Chapman & Hall, 2–6 Boundary Row, London SE1 8HN, UK

Blackie Academic & Professional, Wester Cleddens Road, Bishopbriggs,
Glasgow G64 2NZ, UK

Chapman & Hall GmbH, Pappelallee 3, 69469 Weinheim, Germany

Chapman & Hall USA, 115 Fifth Avenue, New York, NY 10003, USA

Chapman & Hall Japan, ITP-Japan, Kyowa Building, 3F, 2-2-1 Hirakawacho,
Chiyoda-ku, Tokyo 102, Japan

Chapman & Hall Australia, 102 Dodds Street, South Melbourne,
Victoria 3205, Australia

Chapman & Hall India, R. Seshadri, 32 Second Main Road, CIT East,
Madras 600 035, India

First edition 1971

Second edition 1995

Typeset in 10/12 pt Times by Thomson Press (India) Ltd, Madras
Printed in Great Britain by T.J. Press, Padstow, Cornwall

ISBN 0 412 59040 9

A catalogue record for this book is available from the British Library

Library of Congress Catalog Card Number: 95-67608

∞ Printed on acid-free text paper, manufactured in accordance with
ANSI/NISO Z39.48-1992.

Design for Creep

Preface

Our rationale for the second edition remains the same as for the first edition, which appeared over twenty years ago. This is to offer simplified, useful and easily understood methods for dealing with the creep of components operating under conditions met in practice. When the first edition was written, we could not claim that the methods which were introduced were well-tried. They were somewhat conjectural, although firmly based, but not sufficiently well developed. Since that time, the Reference Stress Methods (RSM) introduced in the book have received much scrutiny and development. The best recognition we could have of the original methods is the fact that they are now firmly embedded in codes of practice. Hopefully, we have now gone a long way towards achieving our original objectives.

There are major additions to this second edition which should help to justify our claims. These include further clarification regarding Reference Stress Methods in Chapter 4. There are also new topics which depend on RSM in varying degrees:

- Creep fracture is covered in Chapter 7, where methods for assessing creep crack initiation and crack growth are fully described. This chapter starts with a review of the basic concepts of fracture mechanics and follows with useful, approximate methods, compatible with the needs of design for creep and the availability of standard data.
- Creep/fatigue interactions and environmental effects appear in Chapter 8.
- High-temperature design procedures are described in Chapter 9, which includes the British R5 Code of Practice now wholly based on RSM. This chapter also offers commentary on the ASME approach through Code Case N47 and the French RCC-MR rules for mechanical components.

Another feature of design methods for creep which has emerged strongly since the first edition is Kachanov's ideas of damage. These have enabled enlargement and strengthening of guidelines for conditions leading to rupture and they are described in Chapter 5. They have also enabled techniques for the quantification of creep strains, in which it is presumed that 'damage' occurs from the early stages of creep. These techniques are outlined in extensions to the original Chapter 2, as well as in a new Appendix 6, which concentrates exclusively on practical use of the Kachanov damage concepts in some detail and their relevance to topics such as life assessment.

Chapters 1, 2, 3 and 6 remain essentially the same so far as their emphases are concerned: information, its sensible distillation and use in design analysis and extrapolation. There has, of course, been some revision and reorganization of these chapters in seeking improvements of description and updating of information. The original appendices have passed the tests of time so are included and enlarged where necessary. The chapter on materials development in the first edition was felt to be too skimpy considering the importance of the subject. Although it has been discarded in the second edition, the themes discussed are still considered useful and this is particularly so where polymeric materials are concerned.

Throughout the book, we have tried to emphasize the need for utility of purpose against much-needed physical understanding and formulation of problems involved in creep. To this end, the computer has played an important role as a tool in providing solutions to problems. The solutions so obtained have helped in the extraction of themes of general importance which can often be presented nondimensionally in graphical form as aids for initial design purposes.

The second edition contains mixed units of measurement. Much of the data in Imperial units used in the first edition were quite old, but all of this is still highly relevant. It seemed inappropriate to make arithmetic conversions which would result in peculiar numbers to suit an international system, which is not in full operation anyway. Later data which have been used follow the SI system.

In addition to the authors, several colleagues and former students on each side of the Atlantic Ocean have contributed valuable ideas directly or indirectly for the presentation of our work and for this we thank them. The unstinting cooperation of Charmaine Venter in processing our joint efforts in the production and editing of what you now read cannot pass without us expressing our deep gratitude.

R. K. Penny
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Introduction

Engineering design is concerned mainly with planning and problem solving. What *is* the problem? What useful information about it is available? If more information is needed, how can it be generated? How can the information best be used in proposing alternative paths to achieving a useful and reliable end product? These are some of the questions a designer has to answer. In so doing, programmes of *necessary* research and development often have to be formulated. At all times, the designer is subjected to the constraints of time and cost: how soon? how much? Primarily because of these constraints, the designer is required to make decisions on the basis of incomplete information and this takes a considerable amount of judgement to be gained only from experience and guidance from codes of practice. As an aid to decision making, rational analysis, which attempts to take into account the most important features of the problem, is an essential part of the design process. Of course what constitutes the most important features will not be revealed until some results of this analysis are available and so the process is an iterative one. Bearing in mind the approximate and sparse nature of the information which is usually available, it would be pointless to start with a sophisticated analysis. Otherwise a futile incompatibility would exist between input and output; in addition, the most important results are usually obscured by a proliferation of detail when the general is sought before the particular.

The preceding remarks are quite general. As it happens though, they are particularly relevant when it comes to design for creep. Within the confines of a book of this size, however, it is impracticable to consider all aspects of design to meet all eventualities. Instead, it is intended to concentrate primarily on two areas of great importance: information and its effective use.

1.1 DEFINITION OF THE PROBLEM

The phenomenon of creep is the source of many problems in design. Foremost amongst these is the need for the generation of ways of predicting whether components operating in the creep range will sustain the life required of them. The useful life could be terminated:

- when the deformation become excessive;
- when rupture occurs;
- when latent flaws or initiated cracks grow at unacceptable rates by creep or creep/fatigue.

For most practical applications, predictive methods must be capable of accounting for complex loadings which vary with time.

1.2 INFORMATION AVAILABLE

Ever since the recognition of creep as a problem in the design of high-temperature components, the constant tensile load creep test has been, and is likely to remain, the most important means of providing creep data. The information gained from this test reveals, in a simplified way, how a given material will act under different combinations of loading and temperature. Most frequently, the creep test is performed at constant temperature and constant load and from this the data extracted are:

- deformation data usually presented in terms of a strain, measured over a gauge length, at various times. This gives the *creep curve* which generally takes the form shown schematically in Fig. 1.1;
- rupture data. This amounts to the measurement of one coordinate – t_r, the time at which rupture occurs – of the last point in Fig. 1.1. Sometimes, but all too rarely, attempts to measure the other coordinate of this point are also made. Generally, rupture data are presented in graphic form portraying variations in rupture time with stress.

Whatever data are presented, it is well known that large variations in it – scatter – are usually present. This arises from a variety of sources and the designer must heed this fact in the use of the information and in the search for better information when the need arises.

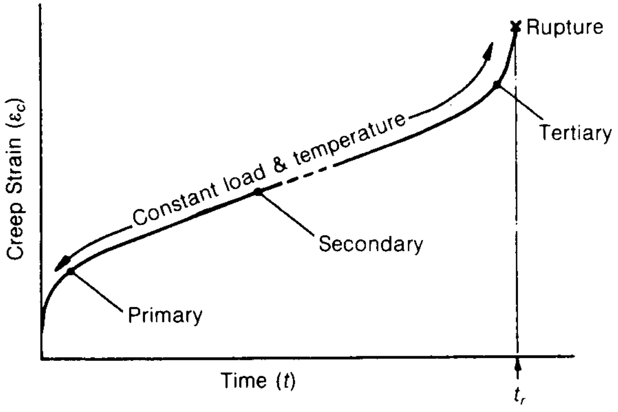

Fig. 1.1 Strain accumulation during the standard creep test.

In Chapter 2, various methods of expressing creep deformation data in suitable mathematical form are reviewed as a prelude to its use in component analysis. Wherever possible, attempts are made to attach physical interpretations to the data, in order that an understanding of underlying mechanisms can eventually be added to the store of knowledge. In this way, the engineer can also contribute to the *design of materials*, a field traditionally the province of the metal physicist and metallurgist. At the same time, the simplest phenomenological descriptions of materials have been sought as an expedient to component design. In this Chapter, most emphasis is placed on the effect of stress: constant uniaxial stress, variable uniaxial stress and the effects of multiaxiality of stress. It has only been possible to conjecture about the effect of temperature on creep accumulation for the simple reason that so little *information* is available. The duality of stress and temperature effects on damage leading to rupture is considered in more detail in Chapter 5.

Chapter 5 is the counterpart of Chapter 2 so far as damage and rupture are concerned. Once again, emphasis is placed on the need for understanding the mechanisms which can contribute to this form of failure, whether they occur in the tensile test or in components.

References [1], [3] and [6] have been particularly useful sources of information on all of these topics.

1.3 THE USE OF DATA IN COMPONENT ANALYSIS AND LIFE ASSESSMENT

A major object of this book is to offer simplified, useful and easily understood, well-tried methods which are linked with the simple tension test for dealing with creep of components under general loading conditions.

It seems logical, in the first place, to seek methods of analysis for components subjected to steady loading and this is done in Chapter 3. Over the last few decades, the ready availability of computers has given rise to optimism that numerical methods of analysis can solve most nonlinear problems through the use of commercially available software. However, it has also been apparent that validation of this software is still essential and that a thorough knowledge of the assumptions involved in the programs is important. Cost is still an inhibition to wide-scale use of the technology whilst the needed input data from creep tests are rarely available. Finally, there is no evidence that growth in computer power has brought about a corresponding growth of understanding of creep problems or design methodologies.

In Chapter 3, some general guidelines are given on methods of analysis of creep problems involving constant loading which are based on numerical analysis. No attempt is made to aim for explicit analytical solutions, but the guidelines given also emphasize the need to extract general themes, wherever possible, which can often be based on simplified constitutive equations. For example, our own early experiences in obtaining results for beams, plates and multiple shell components, have been invaluable and are reviewed in Chapter 3. In addition, early hand calculations were essential to us in rationalizing time-stepping algorithms used in numerical programs. These experiences are retained in this edition rather than giving expositions on numerical analysis. In Chapter 3 we also exhort all workers in the field to disseminate their methods and results in usable ways as aids towards better understanding, better design practice and contributions towards the development of usable codes of practice.

Chapter 4 discusses the more practical cases of variable loading and temperature conditions. A particular feature here is the adaptation of solution methods generated in Chapter 3, together with a prescription of the further manipulation and testing needed to evolve procedures for dealing with variable conditions. Although it is recognized that the methods outlined are not always completely rigorous mathematically, it is clear that some form of approximation is needed in order to progress beyond other methods in current use, which are invariably lacking in any rationale or are not justified through the lack of data or of high cost. This viewpoint is taken on the grounds that an 'exact' method would require data to cover every combination of variable stress and temperature – an impossible task – and a combination of materials data and a generation of computers not presently available. Another important tool available to the designer is physical experimentation, so a brief section of Chapter 4 is devoted to this with a view to justifying some of the methods which are being proposed. The power of the so-called *Reference Stress Method*, which has emerged over the years as the most effective method in the tool kit needed by designers for creep, is reviewed. The methods involved are virtually unrivalled in their ability to solve complex problems whilst avoiding the awesome, costly task of cyclic inelastic calculation.

Another aspect of creep, which is vital to the designer and requires much skill in analysis, derives from the extrapolation of relatively short-term rupture data to the predictions of realistic component lifetimes. This need arises from the usual constraints of time and cost. Clearly, it is not practicable to wait ten years or so for data before being able to size and manufacture components needed within a few years. Thus, techniques have been developed which allow estimates to be made from realistic times. The hazards in such procedures are extensively reviewed in Chapter 6, where recommendations for particular cases are also made.

In the last 10–20 years, much has been said and much money has been spent on studies of failure resulting from crack growth, caused by a variety of possible mechanisms. Amongst these are fast, unstable propagation mechanisms initiated from the presence of a defect, by cyclic loading, stress corrosion, creep deformation or any combination of them. The whole situation surrounding these topics is one of confusion, which is not surprising since the topics are difficult enough at room temperature, let alone in the creep range. It has been commonplace to label the various studies which have been performed as 'fundamental' or 'empirical', 'mechanistic', 'phenomenological' and so on by specialists in this field. It is not our mission in this book to add further to the confusion or labels, but rather to provide some guidance for designers in the hope that our synthesis of available information will be useful. This is not to provide a current statement of the art, but rather to provide simplifications that designers need and usually do not have the time to unravel.

Chapter 7 on creep fracture starts by reviewing the conventional concepts of fracture mechanics as a basis for the formulation of simplifying approaches to creep cracking. Perhaps not too surprisingly, some of the principles which were derived earlier, from the Reference Stress Method for describing creep deformation, have been extended to cover creep fracture. The major contributions to this are described in Chapter 7 and are illustrated with worked examples. Whilst the subject is still in a state of flux, it now seems that routine design parameters for creep fracture can be well defined. This encouraging state of maturity in the development of usable methods in design has not yet been reached in problems in which there are creep, fatigue and environmental interactions. Chapter 8 sets out to review what can be done in assessing these complex interactions and, stripped to the essentials of all the current theories, a basis which we call the 'damage counter' needs to be resorted to. The basic reason for this is that the behaviour of materials at high temperature is dictated by damage caused on account of the amplitude and duration of the cyclic loading (and/or temperature). The robust methods revealed in this chapter are about the only ones currently useful for design. They are not validated, nor are they necessarily accurate, but in view of the information available, it will be for the designer to decide whether they are applicable to his particular problem.

Chapter 9 presents a summary of a basic, high-temperature design procedure. This is drawn up as an extension of low-temperature procedures by the factor of time. By this is meant the provision of an articulated series of steps to be checked against time-independent and time-dependent criteria. Most of these steps, in current use internationally, are based upon ASME code formulations such as Code Case N47. Some of the features of the British R5 Code which are based on the Reference Stress Method are also reviewed and optimism is expressed about the emergence of a solid foundation for a systematic high temperature design methodology.

Our review of the available literature mentioned in this section has revealed that the classical work of Bailey [2] is one which has the most in common with our aims. The proceedings of international conferences [1, 3, 4] are also of general interest while those of another [5] introduced some themes which have since proved to be of lasting value. Long term data, such as those presented in [6], have proved invaluable in enabling validation of results.

1.4 SOME BASIC DEFINITIONS OF TERMS USED

The literature on creep behaviour contains a confusing amount of ambiguity in terminology which is capable of causing much misunderstanding. In order that we should not add to the confusion it is considered necessary to define some of the basic terms which are used in the book.

- *Primary, secondary, and tertiary creep*
  Those stages associated with the constant load creep test when the creep rate is decelerating, is constant, or is accelerating respectively (Fig. 1.1). It is not suggested that these are necessarily mechanistically different regions.
- *Recovery*
  The loss of effective strain hardening due to thermal softening.
- *Reverse creep*
  The reversal of creep strain on unloading.
- *Transient creep*
  Creep deformation occurring in a component during stress redistribution under steady load and temperature.
- *Stationary state*
  The state of a component when stress redistribution is complete. 'Completion' is defined in the text. This state is comparable to the so-called *steady state* which is usually derived from an analysis in which stress redistribution is ignored.

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2

Factors affecting strain accumulation

One of the primary aims of a designer of equipment operating in the creep range is to off-set the possibilities of failure by excessive deformation. Dimensional changes with time, even of the order of a few millimetres, leading to mismatch of components or contact between moving parts, could lead to serious damage to plant, not to mention loss of human life and revenue. Such conditions must obviously be considered as a failure criterion, even though there had been no material failure by cracking.

In order to be able to predict the deformation of components in the creep range, it is necessary firstly to study the factors affecting the accumulation of strain in a simple tensile specimen. The constitutive relations needed for such calculations can then be formed. As one might expect, these are considerably more complex than the simple formulation in the linear elastic region in which strain is directly proportional to the applied stress.

Any method of predicting the behaviour of a component must be capable of calculating strain accumulation under variable loading and temperature. Stresses will be redistributed by the process of creep. At the same time, the service conditions – the applied loadings by steam pressure and inertia, for example, and temperature – will usually be changing. In addition, the stress system will be multidimensional in most practical situations.

In the first part of this chapter, we review strain accumulation in a tensile specimen under constant load, with the specimen maintained at constant temperature. This is done for a number of reasons. Firstly, information obtained from this simple and seemingly artificial state is relatively easy to collect by careful laboratory testing. The stress in the specimen is taken to be constant at a value equal to the applied load, divided by the original cross-section area. The consequences of significant changes in the area, for whatever reason, can only be calculated since they cannot be measured. Ways of doing this follow later. Secondly, and partly because such tests are easily performed, this is practically the only information available for covering a wide range of materials and temperatures. Reliable data on the effects of stress variation and multiaxiality and temperature variation are extremely sparse. Clearly, if the simple isothermal, constant load test is the easiest way of gathering relevant data, then it is desirable that all other effects be related to this test if it is possible to do so. Thirdly, it is more instructive to eliminate some of the variables in the first instance, in order to separate the most important features of the creep process.

2.1 CREEP UNDER CONSTANT UNIAXIAL STRESS

During creep, a tensile specimen under a constant load will continually deform with time. This deformation depends on three main parameters: stress, time and temperature. The most general creep equation is therefore

$$\varepsilon_c = f(\sigma, t, T) \tag{2.1}$$

A useful first approximation is to limit this general function to a commutative law of the form

$$\varepsilon_c = f_1(\sigma) f_2(t) f_3(T) \tag{2.2}$$

The separation of the functions $f_1(\sigma)$ and $f_2(t)$ has been implicit in most of the work on creep and appears to be generally acceptable for the purpose of component design analysis.

The use of a separate function of stress, $f_1(\sigma)$, emerged from early studies of secondary creep in the 1930s. Further encouragement came from similar investigations concerned primarily with the 'time laws' of creep (e.g. Andrade [1], McVetty [15]).

Separation of the function of temperature, $f_3(T)$, is not as easily acceptable as the separation of $f_1(\sigma)$ and $f_2(t)$. Many workers combine time and temperature in a single parameter (e.g. Dorn [5]), which would not always be consistent with a separate function $f_3(T)$. However, it is possible that an approximation of this kind will be reasonable in many cases, especially when considering a component with thermal gradients.

2.1.1 The stress function $f_1(\sigma)$

The function $f_1(\sigma)$ has been chosen in many different ways. Kennedy [13] gives a full summary; of course, there are others. The most common forms are given below.

Norton [19] 1929	$f_1(\sigma) = K\sigma^m$	(2.3)
Soderberg [26] 1936	$f_1(\sigma) = B\{\exp(\sigma/\sigma_0) - 1\}$	(2.4)
McVetty [15] 1943	$f_1(\sigma) = A\sinh(\sigma/\sigma_0)$	(2.5)
Dorn [15] (high stress) 1955	$f_1(\sigma) = C\exp(\sigma/\sigma_0)$	(2.6)
Johnson, Henderson and Kahn [11] 1963	$f_1(\sigma) = D_1\sigma^{m_1} + D_2\sigma^{m_2}$	(2.7)
Garofalo [8] 1965	$f_1(\sigma) = A\{\sinh(\sigma/\sigma_0)\}^m$	(2.8)

where K, A, B, C, D, m, m_1, m_2 and σ_0 are material constants.