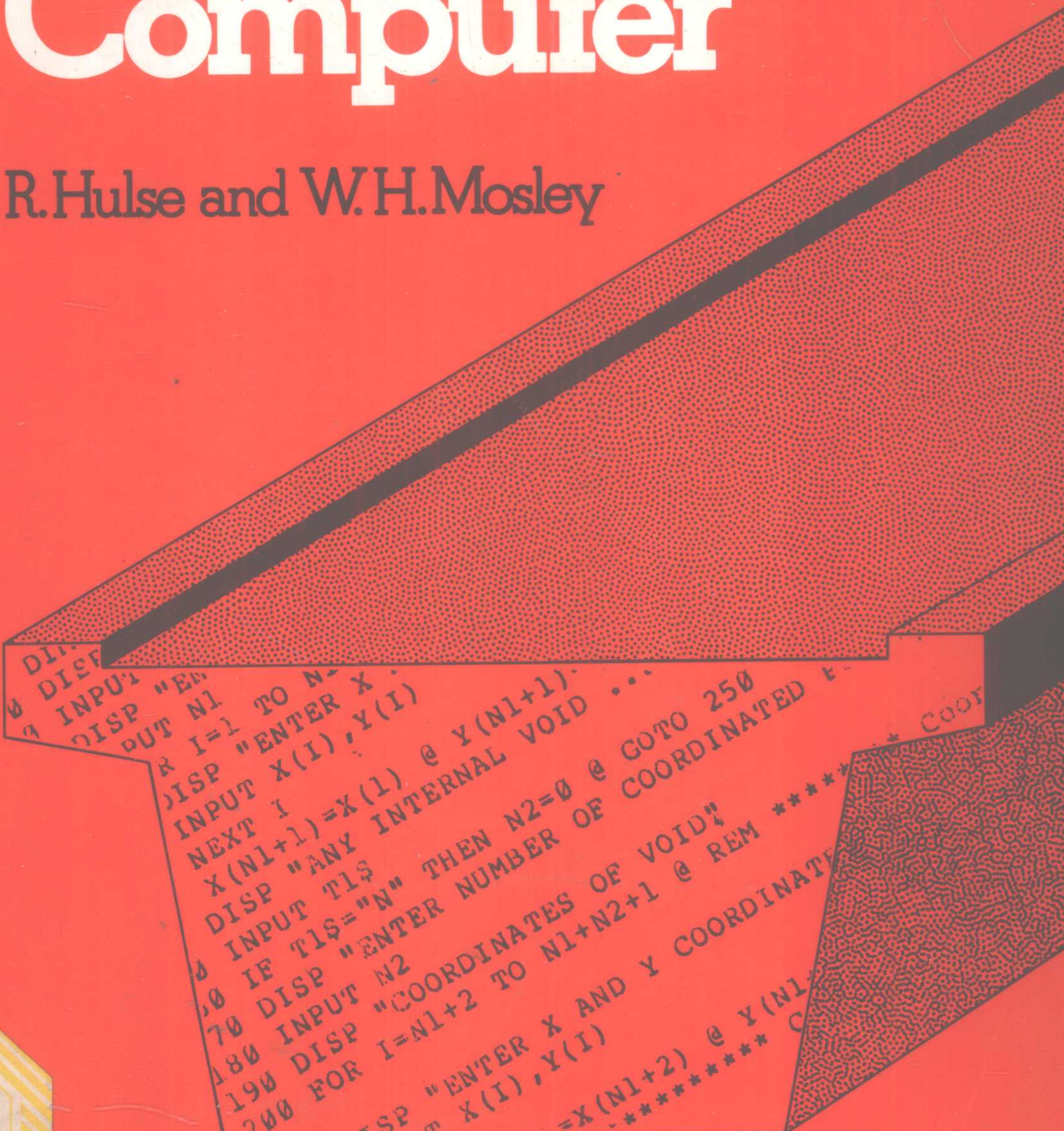
Prestressed Concrete Design by Computer

R. Hulse and W. H. Mosley



PRESTRESSED CONCRETE DESIGN BY COMPUTER

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The programs in this book are available on disc for IBM PC compatible or Hewlett Packard 86 computers. For further information write to:

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The programs in the book *Reinforced Concrete Design by Computer* by the same authors are also available on disc from the above address.

Preface

Following the introduction in September 1985 of the British Standard BS 8110 *The Structural Use of Concrete*, the authors published their book *Reinforced Concrete Design by Computer* which contained a large number of computer programs relevant to the design of reinforced concrete structures. *Reinforced Concrete Design by Computer* was written to demonstrate how the principles and practices of limit state reinforced concrete design could be incorporated into simple, easy-to-use computer programs and it aimed to provide an understanding of the role of the small computer in the design and detailing of reinforced concrete structures.

Although the second chapter of *Reinforced Concrete Design by Computer*, which is concerned with the analysis of the continuous beam and substitute frame, is equally applicable to prestressed concrete structures, no further programs are given which are specifically applicable to prestressed design. This book is intended to rectify that omission and to act as a companion volume to the first book.

The aims of the two books are identical, and the style and presentation of the first book have been maintained in this volume. For those areas of prestressed concrete design where the use of the computer can be advantageous, the principles of analysis and design are presented and explained with written text, flow charts and examples, together with the requirements of the British Standard BS 8110. Program listings are given in the BASIC language.

It is hoped that those readers who used our first text to develop their own suite of programs for reinforced concrete design will be sufficiently encouraged to use the programs in this book to develop a matching suite of programs for prestressed concrete analysis and design.

R. Hulse
W. H. Mosley

Notation

The notation used throughout the book is in accordance with BS 8110, and symbols used are defined in the text. In the programs a set of variable names has been adopted which generally reflects this notation. For example, all stresses have variable names commencing with the letter 'F' to reflect the use of the lower case 'f'.

As many variables, such as the characteristic strength of concrete, are common to a number of programs, a set of variable names has been 'reserved' to have the meanings given in the list below. Other variable names unique to a particular program are given in the description of that program. For the sake of conciseness, variables used only as, for example, loop counters are not given in the description.

'Reserved' variable name	*BS 8110*	*Description*
A or AC	A_c	Area of concrete
AS	A_s	Area of tension reinforcement
AV	—	A_{sv}/s_v ratio for shear links
B	b	Breadth of section
BF	—	Breadth of flange
BW	b_w	Breadth of web
CM	—	Minimum cover to reinforcement
D	d	Effective depth of tension reinforcement

D1	d'	Depth to compression reinforcement
DI	θ	Bar diameter
E	ϵ	Strain
EC	E_c	Modulus of elasticity: concrete
ES	E_s	Modulus of elasticity: steel
FU	f_{cu}	Characteristic concrete cube strength
FV	f_{yv}	Characteristic strength of link reinforcement
FY	f_y	Characteristic strength of reinforcement
GK	G_k	Characteristic dead load
H	h	Overall depth of section
HF	h_f	Thickness of flange
I2	I	Second moment of area
L	l	Length
M	M	Bending moment
MR	α_e	Modular ratio
MU	M	Ultimate moment of resistance
N	N	Axial load at section
QK	Q_k	Characteristic imposed load
RO	ρ	$= 100A_s/bd$
SV	s_v	Spacing of links along a member
T	T	Torsional moment due to ultimate loads
T$	—	Title used as first item of input data to each program
X	x	Neutral axis depth

Contents

1

Introduction — Prestressed Concrete

1.1 Background

Prestressed concrete construction is an alternative technique to that of conventional steel reinforcement. It has developed from the early pioneering days of the 1930s to 1940s, when engineers such as Freysinnet and Magnel developed the initial concepts, to become a widely used technique applicable to all types of structures and structural components. These can range from simple beams and floor slabs to large oil platform structures and innovative bridge forms.

In the early days of prestressed construction the available steel was not suitable for prestressing work but the development of high-strength, high-tensile reinforcement soon led to a more widespread acceptance of this constructional material. The availability of better quality steel was also matched by improvements in concrete technology, resulting in the availability of higher strengths of concrete which again are more suited to prestressing work.

Following the development of initial concepts and availability of suitable materials the theory of prestressing has been well researched, and methods of analysis and design are now well understood and incorporated in modern design standards such as BS 8110 (see reference 1). It is not the intention of this book to give a comprehensive coverage of the theory as this is already given in a number of excellent textbooks, some of which are given in a list of Further Reading at the end of this book. The intention is, however, to highlight those areas of prestressed design where design methods can be incorporated into simple, easy-to-use computer programs which will act as aids in the numerically orientated techniques associated with prestressed concrete design.

1.2 Simple Concepts of Prestressed Concrete

Prestressing is a technique for inducing a state of pre-compression in a concrete section. Concrete is inherently weak in tension although strong in compression; a concrete beam, for example, would fail in flexure under relatively low loads, owing to the development of excessive tensile stresses (figure 1.1(a)).

In reinforced concrete construction strength is provided by the addition of reinforcing bars in the tension zone of the beam, resulting in a composite action between the reinforcement in tension and the area of concrete acting in compression. In prestressed construction the concept is somewhat different, as the intention of prestressing is to induce a state of initial precompression in the beam of sufficient magnitude and distribution to counteract the tensile stresses which arise from the external loading system (figure 1.1(b)).

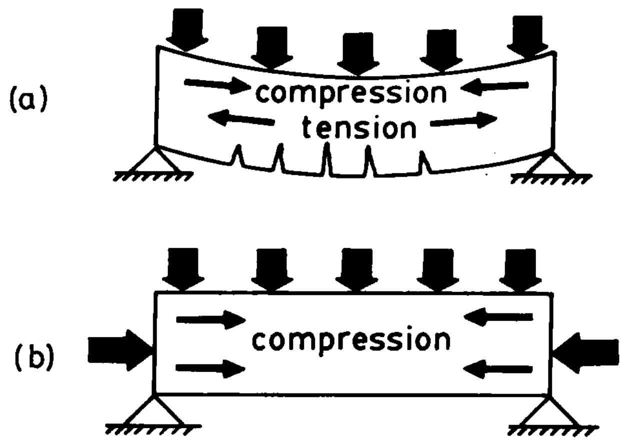

Figure 1.1 *Action of prestressing on a concrete beam*

As a result of prestressing, the concrete section will invariably be in a state of full compression under serviceability load conditions and flexural cracking will not occur at the underside of the beam.

Prestressing also helps to control and minimise the development of shear cracks. As in reinforced concrete construction, a beam under load will be subjected to vertical and complementary horizontal shear stresses which give rise to diagonal tension shear cracks developing in the concrete. The precompression stresses help to resist the development of the cracks although usually additional shear reinforcement will also be required.

1.3 Techniques of Prestressing

There are two broad categories of prestressed construction, referred to as either *pre-tensioning* or *post-tensioning*.

1.3.1 Pre-tensioned Construction

In pre-tensioned construction, high tensile steel wires or tendons are tensioned and anchored between some form of anchorage abutments. The concrete, contained within a mould, is cast around the tendons and when hardened the tendons are released from the abutments. The subsequent contraction of the tendons and the fact that they are bonded to the concrete result in a contraction of the concrete section and a state of compressive stress being induced in the concrete.

Generally this type of construction lends itself to factory production where a set of tendons is stressed over a long stressing bed and several beams or slabs can be simultaneously cast along the length of the bed. Tendons are invariably straight, although at pre-determined locations they can be encased in tubing to break the bond between the tendon and the concrete. In this way the prestressing force can be varied along the length of the beam.

1.3.2 Post-tensioned Construction

In post-tensioned construction the prestressing tendons are located within ducts at the required pre-determined positions. The concrete is cast around the ducts, and when cured to achieve sufficient strength the tendons are tensioned and locked in place using an anchorage system which is cast into, and forms an integral part of, the end of the structural section. The anchorage system is usually one of the several patented systems but typically will consist of a wedge and barrel system which will grip and hold the tendons.

Again, pre-compression is induced in the concrete as a result of contraction of the tendons, but in this case it is dependent on the efficiency of the anchorage system at the end of the unit. To give additional bond between the tendons and the concrete, and to provide corrosion protection, grout may be injected under pressure into the void between the tendon and the duct.

One particular advantage of post-tensioned construction is that the duct, and hence the tendons, can be located with a varying profile along the length of the concrete unit. In this way the amount of pre-compression can be varied and controlled to match the variation of bending stresses arising from the varying bending moments along the length of the unit.

1.4 Advantages of Prestressed Concrete

No one type of structural medium can offer the perfect solution to all design situations. However, prestressed concrete does offer a number of distinct advantages over reinforced concrete and these advantages do lead to the choice of prestressing as a viable design solution.

Perhaps the most important advantage is that in a fully prestressed section the whole of the concrete area acts to resist bending, unlike reinforced concrete where the concrete in the tension zone is cracked and provides negligible contribution to the stiffness of the section. Hence for a given span and loading it is possible to design a beam or slab of shallower depth if prestressed construction is used. This leads to aesthetic advantages, a saving in materials and a reduction in weight of the structure which can result in further savings in foundation requirements. In tall buildings a reduction in the depth of floor construction will also result in a cumulative saving in the height of the building.

The fact that a prestressed section is in compression means that under serviceability load conditions cracking will not take place. The problem of corrosion is therefore minimised. Prestressing also ensures that, in the event of cracking under unintentional overload conditions, when the overload is removed the cracks will close up again. Provided that the overload is not excessive, this resilience ensures that the prestressed unit will continue to perform satisfactorily.

Full compression over the whole section also ensures that the gross concrete section is effective in providing stiffness to resist deflection. In addition, by adjusting the level of the tendons it is possible to provide deflections due to prestress which can fully or partially nullify the downward deflections due to live and dead loading. Deflection control is therefore assured.

Weighed against these advantages is the fact that higher-strength concrete and higher-grade steels are used in prestressed construction. Hence, although less material may be used, the unit cost of the materials will be relatively high. In addition, the cost of ducting, end anchors, barrels and wedges will add to the overall cost. The prestressing operation also necessitates a reasonable level of site skills and supervision than is otherwise necessary in conventional reinforced concrete construction.

1.5 Prestressed Concrete Design

Modern prestressed design methods follow the limit state design philosophy of BS 8110. It is necessary to ensure that in any design both serviceability and ultimate limit states are satisfied.

1.5.1 Serviceability Limit States

The principal serviceability limit state is that of cracking and this is controlled by limiting the flexural tensile stresses under service load conditions. BS 8110 recognises three classes of prestressing.

CLASS 1: No flexural tensile stresses allowed
CLASS 2: Flexural tensile stresses allowed but no visible cracking permitted
CLASS 3: Flexural tensile stresses allowed but the maximum surface crack width must not exceed 0.1 mm for severe environmental exposure and 0.2 mm in other cases

The calculations associated with this limit state are based on the application of simple bending theory (see later chapters) using the section properties of the gross concrete section. BS 8110 gives guidance on the acceptable levels of both tension and compression stresses for all three classes of structure. The Standard also differentiates between stress conditions at transfer (when the unit is stressed) and those under normal service conditions.

In the former case a typical prestressed beam would be subject to the stresses due to the initial prestressing force together with its own self-weight as shown in figure 1.2(a). The critical surface for tensile cracking to take place will be along the top of the beam. Under full service conditions (figure 1.2(b)) the tendency will be for tension to develop on the underside surface when the superimposed live load is acting.

Account should also be taken of any loss of prestress force that will have taken place subsequent to transfer because of factors such as elastic shortening of the concrete, creep and shrinkage. BS 8110 gives guidance on

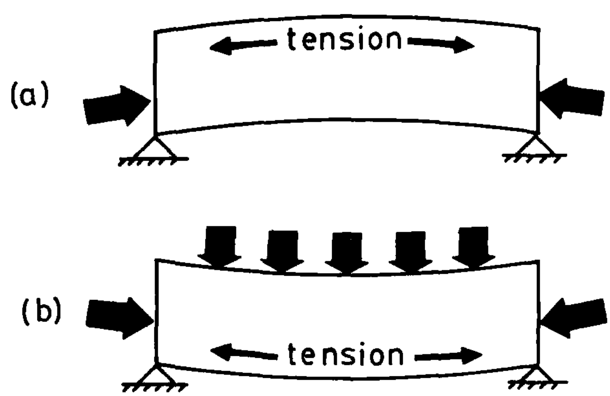

Figure 1.2 *Prestressed beam: (a) at transfer; (b) under service load conditions*

methods of calculating these losses but typically the total loss will be in the range of 25–30 per cent.

In the case of the serviceability limit state of deflection, BS 8110 gives some limited guidance on acceptable levels of deflection. These limits on deflection in the Standard are based on experience and to check compliance it is usually only necessary to carry out a simple elastic analysis using the gross concrete section properties. However, the elastic properties of concrete are time-dependent and, because of the effects of creep, it is usually necessary to calculate both instantaneous and long-term deflections using, in the latter case, an effective modulus of elasticity which allows for creep effects.

1.5.2 Ultimate Limit States

The two principal ultimate limit states are those of flexure and shear. In both cases the design loads are obtained by multiplying the characteristic loads by the appropriate partial safety factors for loads given in Clause 2.4.3 of BS 8110. In the case of design for dead and imposed loading, the partial safety factors are taken as 1.4 and 1.6 for dead and imposed load respectively.

For flexural design, the ultimate moment of resistance can be obtained by reference to tables and equations given in Clause 4.3.7 of BS 8110 or more generally by the application of a strain compatibility analysis which forms the basis of the ultimate moment analysis program in chapter 3.

In designing for shear it is necessary to consider sections which are either uncracked or cracked in flexure at ultimate load conditions. Clause 4.3.8 of BS 8110 gives design equations to deal with both situations. The equations given enable the shear strength of the concrete to be determined and shear reinforcement may then be provided to give additional shear resistance.

1.5.3 The Stages in Design

Limit state design requires that all limit states should be checked and designed for. Generally, for Class 1 and Class 2 members the critical design condition will be that of cracking at transfer or service load conditions. The design is usually based on elastic conditions and the ultimate strength of the section is subsequently checked.

In the case of Class 3 members the ultimate limit state will usually be critical and should be considered first. Serviceability stress conditions should be subsequently checked.