STRUCTURAL CONCRETE

C B WILBY

Structural concrete

Materials; mix design; plain, reinforced and prestressed concrete; design tables

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Structural concrete

To

Jean,

Charles (Anthony),

Chris and

Mark

Preface

This book includes:

1. The design and analysis of reinforced and prestressed concrete structural components (or members or elements) and structures.
2. The basic theories required for (1).
3. The properties and behaviour of plain concrete, and of the steel used for reinforcing and prestressing concrete.
4. Cement manufacture.
5. Properties of cement and fine and coarse aggregates.
6. The design of concrete mixes and properties of fresh (or wet) concrete.
7. Numerous design tables and graphs, both for general use and for aiding design with British Standard CP 110. (These are listed in Appendix 1 to assist location.)
8. The use of limit state design and British Standard CP 110 in connection with the above.
9. Various British Standard CP 110 clauses, figures and tables used or referred to in the text, or otherwise useful, are given in Appendix 4. (The structural concrete engineer will undoubtedly acquire CP 110, Parts 1, 2 and 3, sometime in his career. However, Appendix 4 may be adequate for his needs as a student and save him the considerable expense of these documents.)

It has been written primarily as a good course for University (or C.N.A.A.) bachelor degree students of civil and/or structural engineering. It has everything and more than required by a bachelor degree student in architecture and by students on non-degree courses in civil and structural engineering, architecture and building. The book is also useful to a student on an M.Sc. or post-graduate diploma course in concrete technology or structural engineering, as a basis for his more advanced work (Chapters 4 and 8 may provide some of the course material).

The book should be a useful addition to the design offices of practising engineers, with its numerous design tables and graphs. It will help an experienced CP 114 designer to convert to CP 110 as it collects together the CP 110 clauses, figures and tables most useful for most designs, and gives the information required for designing concrete mixes.

A special feature which should appeal to students and practising engineers internationally is the explanation with the use of examples of Hillerborg's methods (particularly his advanced method) for designing any type of indeterminate slab (see later and Chapter 4). The method is lower bound and produces very sensible practical reinforcement systems.

A special feature which should appeal to students beginning design is that the author teaches the student how to create practical structures (see Chapter 7 and Section 2.5). Competitive books sometimes give designs of structures of known geometry, which check the strength of the given structure and design the reinforcement for those sections requiring the most. No explanation is given of how to decide upon the geometry of the structure, yet this is the first thing a beginner has to obtain. An example is given in this book of how to decide upon a reasonable structural system from a rectangular layout of column positions. This is usually the starting point as the architect will have planned his client's requirements to suit a certain layout of columns. The example (Chapter 7) shows speedily that all the members will meet with CP 110 requirements; in particular their sizes are adequate with regard to limit states and reasonably economic and adequate to contain practical reinforcement systems. Then a summary is given showing how to set out calculations in practice for submission for checking by other professionals.

With regard to two-way and flat slabs of complicated shapes which cannot be designed by the use of tables, this is the first book of its type to give useful design examples using Hillerborg's advanced method. They stand on their own and are completely explained. The many advantages of Hillerborg's methods are outlined. It is also the first book of its type (that is not a specialist book devoted to yield-line analysis only) to give useful examples using the equilibrium method of yield-line analysis and the most effective combined equilibrium and virtual-work method, topics which are, at best, scantily covered in most student texts. Yet lecturers often teach students these methods and the method of affine slab transformations (required for skew slabs, for example sometimes required for bridge decks). This method, generally omitted by competitive books, is included in this book, which also gives examples using the virtual-work method (the only method usually covered adequately by competitive books).

A history of the design and analysis of these slabs and a review of useful design tables put the various designs and analyses into perspective.

A very special feature of the book is the wide range of topics covered, and for this the author is indebted to the following for their assistance and comments. Thanks go to

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Extracts from the D.O.E.'s *Design of Normal Concrete Mixes* included in Chapter 2 are contributed by courtesy of the Director, Building Research Establishment. Crown Copyright reproduced by permission of the Controller H.M.S.O., and extracts from CP 110 in Appendix 4 and elsewhere in this book, are included by kind permission of the British Standards Institution, 2 Park Street, London W1A 2BS from whom complete copies of the documents can be obtained.

The author thanks Mrs H. Mahoney, Photographs Librarian, Cement and Concrete Association, for her efficient help and permission to reproduce the photographs in Chapter 7.

Contents

Chapter 1

Serviceability and safety

1.1 Serviceability and safety

A structure or any part of it, such as a beam, column, slab, etc., must be serviceable in use and safe against collapse. Serviceability requires that, at the kind of loads likely to occur during use, everything will be satisfactory, for example, deflections will be adequately small, vibrations will be tolerable, the maximum width of cracks will be no greater than specified, etc. For example, for prestressed concrete no cracks may be specified whatsoever, whilst for reinforced concrete design the maximum size of crack might be specified as small enough not to admit rainwater (about 0.25 mm) or, if inside a building, not to be visually unacceptable.

Safety requires that the strength of a structure or any part of it be adequate to withstand the kind of loads reasonably considered to be most critical as regards collapse.

In assessing the requirements for serviceability and safety just described, it is necessary to assess, for example, deflections and ultimate strengths which require assessments of Young's moduli and strengths for the concrete and reinforcement. These properties vary to some extent for any material used. For example, if one cast a large number of concrete cubes and endeavoured to make them identical so that they all had the same strength, on crushing these cubes one would obtain a result like the graph of *Figure 2.4*. One can hardly assume that this particular concrete can be assumed to have a strength equal to say its mean strength of $35\,\mathrm{N/mm^2}$ as shown on this graph because one or two cubes out of this very large number have failed at near to $15\,\mathrm{N/mm^2}$. Also it is not economic to try and assume this particular concrete to have the strength of the weakest cube tested. So a compromise based on experience, and involving a decision on chance with regard to safety, has to be made by any code committee. The tensile strength of specimens of steel reinforcement all thought to be the same, would give a graph similar to *Figure 2.4* except that the range and standard deviation of the histogram would be very much less.

Again, in assessing the previously described requirements for serviceability and safety, it is necessary to decide upon loads which may have to be carried during use and occasionally sustained to prevent collapse. It may well be impractical to consider the worst possible event which could ever occur, for example, a nuclear holocaust coinciding with an earthquake and a hurricane—the client has to be able to afford the building for his planned use. So a compromise based on experience, and probability with regard to serviceability and safety, has to be made by any code committee.

1.2 Elastic theory of design

This method (also called permissible stress method) of design is based on the assumptions described in Section 3.2.1.

The loading which has to be carried in use, or when working, is assessed and known as the 'working load'. Then using the elastic theory, sections of members are designed so that the maximum 'working stresses' in the concrete and reinforcement are not greater than certain 'permissible stresses' or 'allowable working stresses'. A permissible stress is restricted by a 'factor of safety' to be sufficiently below the ultimate stress of the material, to be well within the limit of proportionality of the steel reinforcement and sufficiently low to be within the initial fairly linear portion of the stress/strain curve for concrete (see *Figure 2.10*). The 'factor of safety' times the permissible stress is equal to either the yield or 0.2% proof stress for steel reinforcement or the cube strength for concrete. Codes used to make the factor of safety greater for concrete than steel because of the approximate linearity of the stress/strain curve for concrete not extending to much of a proportion of its ultimate stress. Subsequently with the arrival of recent codes of practice in the U.K. and U.S.A. the term 'factor of safety' almost requires definition each time it is used, so for any particular code the definition needs to be carefully studied. For example, the term 'factor of safety' as used in this section is not the same as the term 'partial safety factor' used in CP 110 (see later).

In the case of frames and continuous beams and slabs an elastic theory was used (sometimes modified slightly in later years) for evaluating bending moments and shear forces.

In the early days of (reasonable) structural concrete design, the elastic theory was well established and had proved reliable for designing steel structures. It therefore seemed to be the most reliable, sensible and indeed only theory to use for designing structural concrete since concrete appeared to have a fairly linear stress/strain relationship up to the stresses likely to be permissible. The permissible stress method was used in the U.K. and U.S.A., prior to 1957 and 1963, respectively. After these dates an alternative 'load factor' method (see later) was recommended by the respective British and A.C.I. codes. With regard to prestressed concrete the first national (previously private ones existed) code of practice CP 115[1] was published in 1959 and required both permissible stress and load factor designs to be made. The present British Code CP 110[2] does not use the permissible stress method for reinforced concrete design but uses it for the limit states of stress and deflection (see Section 8.4) for prestressed concrete. Yet the permissible stress method can still be used as CP 114[3] is still valid. The present A.C.I. code[4], like CP 110, is not based principally on the permissible stress method of design but yet mentions the latter as an acceptable alternative. The

British Code BS 5337 for designing water-retaining structures recommends permissible stress design and, as an alternative, a 'limit state design' (see later in this Chapter, Section 3.2.4 and Example 3.5).

Permissible stress design has certainly been very satisfactory for a long time.

1.3 Load factor method of design

When it was eventually considered that the ultimate moments of resistance of sections could be reasonably reliably assessed, the elastic theory for designing sections was thought to be basically uneconomic because of its inability to predict collapse or 'ultimate loads'. The theories for assessing ultimate bending moments made use of the plastic action of concrete, that is the behaviour at higher stresses when stress is not directly proportional to strain (see *Figure 2.10*) and peak stresses calculated by elastic theory are relieved by plastic action. Thus the load factor method is based on 'plastic theory' and is sometimes called 'plastic design' (see Section 3.7.2). The ratio of the ultimate load to the working load is called the 'load factor'.

In a structure, sections designed by elastic theory would have different load factors. It can be seen from *Figure 3.6* how the distribution of concrete stress in the upper part of a beam alters from that shown in *Figure 3.6(a)* for working stresses to that shown in *Figure 3.6(c)* just before failure. The reinforcement, if of mild steel, would have a stress/strain curve like curve 11 on *Figure 8.4*. The stress in it would therefore increase linearly with increase in bending moment from *Figure 3.6(a)* to *Figure 3.6(c)*, if the 'moment or lever arm' (see dimension z in *Figures 3.2(d)* and *3.7*), remained constant. From *Figures 3.2(d)*, *3.6* and *3.7* it can be seen that the moment arm reduces slightly towards failure. Thus if one designed a section of a beam by elastic theory, even if the same factors of safety for concrete and steel reinforcement were used, the load factor would not be the same as the factor of safety. This is made more so if the code used for elastic design uses different factors of safety for concrete and steel. As the elastic design requirements of CP 114[3] consider that the strength of concrete is less reliable, because of its method of manufacture, than the strength of steel, a greater factor of safety for concrete than steel is used. In other words, designing sections of different members such as beams, slabs and columns and various types of all these in a structure, by say using the elastic theory requirements of CP 114, results in these sections possessing differing load factors.

The advocates of load factor design considered a constant load factor desirable for economy and that this should take priority over permissible stress design. Now the latter did limit stresses and therefore strains and thus crack widths and deflections at working loads, whereas a load factor design did not. To endeavour to overcome this, and to not make radically different sized members from previously, the load factor design recommendations of CP 114 were more conservative. As the permissible stresses in CP 114: 1957 were increased from previously, greater deflections would occur so *Table 7.1* was introduced to endeavour to limit deflections (unfortunately it does not include loading which of course affects deflection).

In the early days of prestressed concrete design in the U.K., structural concrete members were being made considerably smaller than ordinary reinforced concrete members and contained thin wires instead of robust bars. Prior to code CP 115 they were designed by the permissible stress method, sometimes without checking the load factor. When CP 115 was introduced it required a load factor of 2 but this could be less if the member would fail at a load not less than the sum of 1.5 times the dead load plus 2.5 times the imposed, or live, load. This introduced the concept of what has subsequently been called 'partial safety factors' for loads in CP 110. The imposed load may increase by accident. For example, a flat roof may be designed for occasional access but while a procession was passing by it might become packed tight with spectators. The dead load cannot increase unless, for example, the finishes to a roof or floor are renewed or changed, in which case the client would usually seek or encounter some building advice. Thus the load factor used for the imposed load part of the loading must be greater than that used for the dead load part of the loading.

The illogicality that existed after the publication of CP 114 was that, for example, individual ordinary reinforced concrete sections of a frame, or continuous beam or slab, could be designed to have a constant load factor but the distribution of bending moments was obtained by elastic analysis. The ideas of plastic collapse mechanisms (see Chapter 6), first developed for steelwork structures, had not been established well enough for inclusion in CP 114 in any greater way than allowing bending moments obtained by elastic analysis at supports to be increased or decreased by up to 15% provided that these modified moments were used for the calculation of the corresponding moments in the spans.

Still most analyses used would give bending moments at sections which would not increase in direct proportion to the loading towards failure, so to design sections of indeterminate structures with a constant load factor seemed pointless. Also the load factor method, with a general conservatism incorporated, only indirectly controlled crack widths and deflections compared to the permissible stress design method. Historically, however, a start presumably had to be made somewhere and somehow with the introduction of methods endeavouring to gain extra economy by the use of load factor methods.

To summarise, when the load factor method of CP 114 was used for sections, crack size was limited by incorporating conservatism into the formulae (in effect limiting the tensile stress in the reinforcement) and deflection was limited by the use of *Table 7.1*. Of course in important cases the designer could use the elastic methods of CP 114 and calculate deflections.

The book by Evans and Wilby[5] gives considerable description and many examples on the elastic and plastic methods of CP 114 and the plastic method of the A.C.I.[6] code of practice.

1.4 CP 110 philosophy of design

The European Concrete Committee (abbreviated to C.E.B., the initials of the Committee in French) introduced the concept of probability and used statistics in connection with the strengths of materials, loadings and safety and produced recommendations[7] for a code of practice for reinforced concrete. The underlying philosophy involved has been used as a basis for the present British CP 110[2] and codes of practice in the U.S.A.[4]

With regard to concrete strength, the previous British practice was essentially to specify a minimum concrete strength below which no cubes should fail. This meant that the contractor needed to decide upon the quality of his control (see *Table 2.2*) to be able to calculate the average strength of the concrete he should endeavour to make. Then he designed his mix for this mean strength as in Section 2.3.10. When on the site, if any of the concrete cubes tested failed below the minimum strength then the concrete was either removed or cores of the concrete taken and tested or a load test was performed to see if the extra age had increased the strength and if the general monolithic construction (sometimes permitted to receive help from, for example, surrounding brickwork if any) was such that the construction could be considered to be safe. The CP 110 philosophy was to specify, not a minimum concrete strength as previously, but a strength which 5% of the cubes would not achieve, called the 'characteristic strength'. This involved the use of statistics and is explained in Section 2.3.9. The idea of accepting a strength below that at which some cubes would fail was hard for many British engineers to accept, because of their being brought up to think and desire that their designs should be very safe—failure was out of the question.

With regard to loading, the previous British practice was to assess the load which would be unlikely to be exceeded in use, and this would be called the 'working load'. Then if the CP 114 load factor method of design was used, sections would be designed to have a factor of safety of 1.8 against an ultimate load which would be taken as 1.8 times the working load. Now the CP 110 philosophy was not to assess the maximum load for the working load as previously but was to assess a load which, in effect, only 5% of occurrences of loading would exceed, called the characteristic load. This involved the use of statistics as is explained in Section 2.3.9. The idea of seemingly now accepting a working load which was planned to be sometimes exceeded was again hard for many British engineers to accept. Then, as if to make it more difficult for engineers to accept, CP 110 introduced the idea of probability of characteristic strengths and loads being variable.

British engineers had always prided themselves on designing structures which in their opinion could never fail. Well, of course, scientific reality cannot be ignored, materials do vary and probability does exist. Apart from negligence and natural catastrophes, the most likely cause of failure of a structure, or inadequacy at working loads (that is cracks or deflections being unacceptable), is the coincidental occurrence of both overload and excessive weakness at a critical section.

The probability of failure, for example, could involve the concept of an accident rate intuitively accepted for a given type of structure. For example, how often are crane gantries liable to fail by overload? The probability of failure could also involve economy, for example a reduced probability of failure will require a stronger structure at an increased cost.

Discussions of probability of failure become very emotive because of probable loss of life. A possible analogy is a motor coach full of passengers because if it crashes loss of life is also involved. There is a certain statistical