
REINFORCED AND PRESTRESSED CONCRETE

THIRD EDITION

The third edition of *Reinforced and Prestressed Concrete* continues to be the most comprehensive text for engineering students, instructors and practising engineers. Theoretical and practical aspects of analysis and design are presented in a clear, easy-to-follow manner and are complemented by numerous illustrative and design examples to aid students' comprehension of complex concepts. The text is divided into two parts: the first addresses the analysis and design of reinforced concrete structures and the second covers topics in prestressed concrete.

This edition has been fully updated to reflect recent amendments and addenda to the Australian Standard for Concrete Structures AS 3600–2009 and allied standards. Two new chapters, covering T-beams, irregular-shaped sections and continuous beams, and strut-and-tie modelling have been added as discrete modules to enhance the progression of topics. Additional information is provided on fire resistance, detailing including cover, long-term deflection and design for torsion. An expanded collection of end-of-chapter tutorial problems consolidate student learning and develop problem-solving skills.

With its thorough coverage of fundamental concepts and abundance of practical examples, *Reinforced and Prestressed Concrete* remains an indispensable resource for students and engineers continuing their professional development.

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THIRD EDITION

Yew-Chaye Loo AM
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In memory of our parents

Loo Khai Kee (1900–1989)
Lau Ching (1902–1961)
Shamsul Haque Chowdhury (1920–1999)
Syeda Nurun Nahar Chowdhury (1930–2007)

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PREFACE TO THE FIRST EDITION

Most of the contents of this book were originally developed in the late 1980s at the University of Wollongong, New South Wales. The contents were targeted towards third-year courses in reinforced and prestressed concrete structures. The book was believed useful for both students learning the subjects and practising engineers wishing to apply with confidence the then newly published Australian Standard AS 3600–1988. In 1995 and following the publication of AS 3600–1994, the contents were updated at Griffith University (Gold Coast campus) and used as the learning and teaching material for the third-year course, ‘Concrete structures’ (which also covers prestressed concrete). In 2002, further revisions were made to include the technical advances of AS 3600–2001. Some of the book’s more advanced topics were used for part of the Griffith University postgraduate course, ‘Advanced reinforced concrete’.

In anticipation of the publication of the current version of AS 3600, which was scheduled for 2007, a major rewrite began early that year to expand on the contents and present them in two parts. The effort continued into 2009, introducing in Part 1 ‘Reinforced concrete’, *inter alia*, the new chapters on walls, as well as on footings, pile caps and retaining walls, plus an appendix on strut-and-tie modelling. In addition, a new Part 2 had been written, which covered five new chapters on prestressed concrete. The entire manuscript was then thoroughly reviewed and revised as appropriate following the publication of AS 3600–2009 in late December 2009.

In line with the original aims, the book contains extensive fundamental materials for learning and teaching purposes. It is also useful for practising engineers, especially those wishing to have a full grasp of the new AS 3600–2009. This is important, as the 2009 contents have been updated and expanded significantly and, for the first time, provisions for concrete compressive strength up to 100 MPa are included. The increase in concrete strength has resulted in major changes to many of the analysis and design equations.

Part 1 contains 11 chapters. An introduction to the design requirements and load combinations is given in Chapter 1, and the properties of and specifications for concrete and reinforcing steel are discussed in Chapter 2. Chapter 3 presents, in detail, the bending analysis and design of rectangular beams, T-beams and other flanged sections. Some significant attention is given to doubly reinforced members. Deflection and crack control are considered in Chapter 4, which also features a section on the effects of repeated loading. Also presented is a unified crack-width formula for reinforced and prestressed beams.

Chapter 5 details transverse and longitudinal shear design, and Chapter 6 presents the design procedure for torsion. Bond and stress development are treated in Chapter 7, and Chapter 8 covers most of the practical aspects of slab analysis and design. It also includes a separate section describing a design exercise that features the complete (multiple-load case) analysis of a three-storey flat plate structure, as well as the detailed design of typical floor panels.

Chapter 9 deals with the analysis and design of columns, including the treatment of arbitrary cross-sections using numerical and semi-graphical methods. The new Chapter 10

examines the use of relevant strength design formulas for walls subjected to vertical axial loads, as well as under combined axial and horizontal in-plane shear forces. This is followed by the new Chapter 11, with an extensive and in-depth coverage of the design of wall and column footings, pile caps and retaining walls.

Part 2 contains five chapters. Prestressed concrete fundamentals, including pre- and post-tensioning processes, are introduced in Chapter 12. Chapters 13 and 14 cover the critical stress state approach to the analysis and design of fully prestressed concrete flexural members, which ensures a crack-free and overstress-free service life for those members. The ultimate strength analysis and design of fully and partially prestressed beams are dealt with in Chapter 15. The final chapter (Chapter 16) presents the design of end blocks for prestressing anchorages.

Appendices A and B present the formulas for computing the elastic neutral axes required in deflection analysis, and those for obtaining various critical punching shear perimeters used in flat plate design, respectively. The development of an integrated personal computer program package for the design of multistorey flat plate systems is described in Appendix C. This may be useful to the reader who has an interest in computer applications. Appendix D highlights the essence of the strut-and-tie modelling approach; it also reviews the advances made in this topic in recent years. Finally, the Australian Standard precast I-girders and super T-girders for prestressed concrete bridge construction are detailed in Appendix E.

In all of the chapters and appendixes, the major symbols used in AS 3600–2009 are adopted. Unless otherwise specified, the term ‘Standard’ refers to AS 3600–2009 and all the clause numbers referred to in the text are those from AS 3600–2009. For ease of reading, a full notation is provided as well as a subject index.

For the student learning the subject of reinforced and prestressed concrete, sufficient fundamentals and background information are provided in each of the chapters. Most of the analysis and design equations are derived and presented in an explicit form. The practitioner of concrete engineering should find these equations easy to apply in their work. Illustrative and design examples are given throughout to assist the reader with the learning process and with their interpretation of the provisions of the Standard. For the convenience of students and teachers alike, a collection of tutorial problems is included at the end of each relevant chapter. To assist teachers using the book for concrete engineering-related courses, an electronic solution manual is available and posted on a secure website (maintained and continuously updated by the authors).

The book is suitable for use in a university degree course that covers the analysis and design of reinforced and prestressed concrete structures. Selected topics may also be adopted in a postgraduate course in concrete engineering. The practising engineer wanting to apply the Australian Standard with confidence will also find the material helpful. In practice, the book can also serve as a reference manual for and user guide to AS 3600–2009.

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PREFACE TO THE SECOND EDITION

The second edition retains all of the features of the original book on the explicit and implicit advice of our peers via the mandatory Cambridge University Press review process. To limit the volume size, the old Appendix C, ‘Development of an integrated package for design of reinforced concrete flat plates on personal computer’, has been removed, being of diminishing practical importance. To enhance the contents, new and important materials are added, some of which were also on the advice of the reviewers:

- updated tables and figures to reflect the amendments and addenda to AS 3600–2009 promulgated by Standards Australia International since its first publication
- additional information on fire design, detailing and cover, long-term deflection, as well as aspects of partially prestressed concrete design; and
- an expanded Appendix on strut-and-tie modelling, encompassing the latest publications on the topic plus a numerical example.

Just as significant, another 37 tutorial problems have been added to the various chapters of the book. This makes a total of 108.

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PREFACE TO THE THIRD EDITION

This latest edition of the book is written in response to the domestic and international market needs as well as on the request of the publisher, Cambridge University Press. It retains the features of the original book but to enhance readability, every chapter now begins with an introduction and concludes with a summary, followed if applicable by an enlarged set of tutorial problems. In all 20 new problems are added making a grand total of 128.

The original Chapter 3 on bending analysis and design was judged by some peer-reviewers as being unduly lengthy. It is now split into two consecutive chapters. Based on a previous appendix, a new Chapter 13 on strut-and-tie modelling is added incorporating the latest material on the subject. Since the last edition, many significant amendments have been made and addenda added to the Australian Standard AS 3600–2009. These are incorporated in the current edition in the form of new and updated tables and figures. Also included are the latest information and recommendations on fire resistance, detailing including cover, long-term deflection, as well as torsion design.

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The contents of the Australian Standard AS 3600–2009 and allied Standards are extensively quoted in this book. The authors are grateful to SAI Global for the permission to reproduce some of the updated design data in tabulated form and in figures.

NOTATION

A	gross cross-sectional area of a member
A_b	cross-sectional area of a reinforcing bar
A_c	cross-sectional area of concrete only in a reinforced concrete section
A_{cc}	area of additional reinforcement provided for crack control at side faces of beams with $D > 750$ mm
A_g	gross cross-sectional area of a member
A_m	an area enclosed by the median lines of the walls of a single cell
A_p	cross-sectional area of prestressing steel
A_{pt}	cross-sectional area of the tendons in that zone, which will be tensile under ultimate load conditions
$A_{pt,ef}$	effective cross-sectional area of tendons
A_s	cross-sectional area of reinforcement
A_{sc}	cross-sectional area of compression reinforcement
A_{sf}	area of fully anchored shear reinforcement crossing the interface (shear plane)
A_{st}	cross-sectional area of tension reinforcement; the cross-sectional area of reinforcement in the zone that would be in tension under the design loads other than prestressing or axial loads
$A_{st,min}$	minimum cross-sectional area of reinforcement permitted in a beam in tension, or in a critical tensile zone of a beam or slab in flexure
A_{sv}	cross-sectional area of shear reinforcement
$A_{sv,min}$	cross-sectional area of minimum shear reinforcement
A_{sw}	cross-sectional area of the bar forming a closed tie
A_t	area of a polygon with vertices at the centre of longitudinal bars at the corners of the cross-section
A_{tr}	cross-sectional area of a transverse bar along the development length

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$A_{tr,min}$	cross-sectional area of the minimum transverse reinforcement along the development length
A_1	a bearing area
A_2	largest area of the supporting surface that is geometrically similar to and concentric with A_1
a	distance; or the maximum nominal size of the aggregate; or depth of equivalent concrete stress block from the extreme compression fibre; or dimension of the critical shear perimeter measured parallel to the direction of M_v^*
a_s	length of a span support
a_v	distance from the section at which shear is being considered to the face of the nearest support
b	width of a cross-section
b^*	overall width of the column head or drop panel, as applicable
b_c	width of the compression strut; or the smaller cross-sectional dimension of a rectangular column
b_{ef}	effective width of a compression face or flange of a member
b_f	width of the shear interface; or width of a footing
b_w	width of the web; or the minimum thickness of the wall of a hollow section
C	force resulting from compressive stresses
c	cover to reinforcing steel or tendons; or the permissible compressive stress
c_d	the smaller of the concrete covers to the deformed bar or half the clear distance to the next parallel
c_t	permissible tensile stress
D	overall depth of a cross-section in the plane of bending
D^*	overall depth of the column head or drop panel, as applicable
D_b	overall depth of a spandrel beam
D_c	diameter of circular column or the smaller dimension of rectangular column
D_f	greater dimension or length of a footing

D_s	overall depth of a slab or drop panel
d	effective depth of a cross-section
d_b	nominal diameter of a bar, wire or tendon
d_c	depth of a compression strut; or the distance from the extreme compressive fibre of the concrete to the centroid of compressive reinforcement
d_o	distance from the extreme compression fibre of the concrete to the centroid of the outermost layer of tensile reinforcement or tendons but for prestressed concrete members not less than $0.8D$
d_{om}	mean value of the shear effective depth (d_o) averaged around the critical shear perimeter
d_p	distance from the extreme compressive fibre of the concrete to the centroid of the tendons in that zone, which will be tensile under ultimate strength conditions
d_{pc}	distance of the plastic centre of a column from the extreme compressive fibre
E_c	mean value of the modulus of elasticity of concrete at 28 days
E_d	design action effect
E_p	modulus of elasticity of tendons
E_s	modulus of elasticity of reinforcement
E_u	action effect due to ultimate earthquake load
e	eccentricity of axial force from a centroidal axis; or the base of Napierian logarithms
e_B	eccentricity of prestressing tendons or cables
e_a	additional eccentricity
F_{BF}	horizontal pressure resultant for a retaining wall due to backfills
F_{SL}	horizontal pressure resultant for a retaining wall due to surcharge load
F_c^*	absolute value of the design force in the compressive zone due to flexure
F_d	uniformly distributed design load, factored for strength or serviceability as appropriate

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F_{def}	effective design service load per unit length or area, used in serviceability design
F_r	friction between retaining wall or footing base and soil
f	bending stress
f_b	bearing stress
f_c	concrete strength under working stress condition
f_{cB}	extreme bottom fibre stress
$f_{c,\text{cal}}$	calculated compressive strength of concrete in a compression strut
f_{cm}	mean value of cylinder strength
f_{cmi}	mean value of the in situ compressive strength of concrete at the relevant age
f_{cp}	compressive strength of concrete at transfer
f_{cs}	maximum shrinkage-induced tensile stress on the uncracked section at the extreme fibre at which cracking occurs
f_{cT}	extreme top fibre stress
f_{cv}	concrete shear strength
f_{heel}	subsoil pressure at the heel of a retaining wall
f_p	tensile strength of tendons
f_{py}	yield strength of tendons
f_s	maximum tensile stress permitted in the reinforcement immediately after the formation of a crack
f_{sc}	stress in the compression steel
f_{si}	serviceability limit stress in reinforcement
f_{sy}	yield strength of reinforcing steel
$f_{sy.f}$	yield strength of reinforcement used as fitments
f_{toe}	subsoil pressure at the toe of a retaining wall
f'_c	characteristic compressive (cylinder) strength of concrete at 28 days
f'_{cp}	minimum compressive strength of concrete at transfer
f'_{ct}	characteristic principal tensile strength of concrete

$f'_{ct.f}$	characteristic flexural tensile strength of concrete
G	action effect due to dead load
g	dead load, usually per unit length or area
g_p	permanent distributed load normal to the shear interface per unit length (N/mm)
H	height of a retaining wall; or the prestressing force
H_w	overall height of a wall
H_{we}	effective height of a wall
H_{wu}	unsupported height of a wall
I	second moment of area of the uncracked concrete cross-section about the centroidal axis
I_b	second moment of area of a beam
I_c	second moment of area of a column
I_{cr}	second moment of area of a cracked section with the reinforcement transformed to an equivalent area of concrete
I_{ef}	effective second moment of area
$I_{ef,max}$	maximum effective second moment of area
I_f	second moment of area of a flexural member
I_g	second moment of area, of the gross concrete cross-section about the centroidal axis
I_{rep}	equivalent moment of inertia at the T th loading cycle
J_t	torsional modulus
K	factor that accounts for the position of the bars being anchored with respect to the transverse reinforcement
K_a	active earth pressure coefficient
K_p	passive earth pressure coefficient
k	coefficient, ratio or factor used with and without numerical subscripts
k_A, k_B, k_C	factors for calculating ϕ for backfill materials which are functions of the angularity, grading and density of the backfill particles