Reinforced and Prestressed Concrete

Analysis and design with emphasis on the application of AS 3600-2009

Reinforced and Prestressed Concrete is the most comprehensive, up-to-the-minute text for students and instructors in civil and structural engineering, and for practising engineers requiring a full grasp of the latest Australian Concrete Structures Standard, AS 3600-2009.

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In Memory of Our Parents
Loo Khai Kee (1900–1989)
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Yew-Chaye Loo and Sanaul Huq Chowdhury
Frontmatter
More information

Contents

Preface

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 which produced in Part I 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 II has been written, which covers 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 I 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 II 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 the 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.

Appendixes 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 the 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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The peer-review process was patiently and professionally handled by Ms Debbie Lee, Publishing Manager at Cambridge University Press, Australia. Debbie also provided valuable editorial advice along the way. Under the direction of Ms Jodie Howell, Managing Editor, Academic & Professional, Cambridge University Press, the final editing work was done by Dr Eve Merton and Ms Carrie DeHaan from Biotext (Melbourne). The authors are grateful for their kind efforts, without which the book would have taken much longer to appear. To the six unnamed reviewers from academia and the profession, the authors wish to extend their sincere thanks and appreciation for their support and constructive suggestions, which have helped enrich the contents of the book. The contents of the Australian standard AS 3600-2009 and allied Standards are extensively quoted in this book. The authors are especially grateful to SAI Global for the permission to reproduce some of the recommended design data in tabulated form and in figures.

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Yew-Chaye Loo and Sanaul Huq Chowdhury
Frontmatter
More information

Notation

A_b	cross-sectional area of a reinforcing bar
A_{ct}	cross-sectional area of concrete in the tensile zone assuming the section is uncracked
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_s	cross-sectional area of reinforcement
A_{sc}	cross-sectional area of compression reinforcement
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
$A_{tr.min}$	cross-sectional area of the minimum transverse reinforcement along the development length
A_1	bearing area
A_2	supplementary area
A_1/A_2	ratio of areas
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_c	width of the compression strut; or the smaller cross-sectional dimension of a rectangular column

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Frontmatter
More information

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	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_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

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Frontmatter
More information

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
F_{def}	effective design service load per unit length or area, used in serviceability design
f	bending stress
$f_{c.cal}$	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_{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_{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_{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_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_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 function of the angularity, grading and density of the backfill particles
k_R	amplification factor
k_{co}	cohesion coefficient
k_{cs}	factor used in serviceability design to take account of the long-term effects of creep and shrinkage
k_r	ratio
k_u	neutral axis parameter, being the ratio, at ultimate strength and under any combination of bending and compression, of the depth to the neutral axis from the extreme compressive fibre, to d
k_{uB}	ratio, at ultimate strength, of the depth to the neutral axis from the extreme compressive fibre, to d, at balanced failure condition
k_{uo}	the ratio, at ultimate strength, of the depth to the neutral axis from the extreme compressive fibre, to d_o
L	centre-to-centre distance between the supports of a flexural member
L_e	effective length of a column
L_{ef}	effective span of a member, taken as the lesser of $(L_n + D)$ and L for a beam or slab; or $= (L_n + D/2)$ for a cantilever
L_l	distance between centres of lateral restraints
L_n	length of clear span in the direction in which moments are being determined, measured face-to-face of supporting beams, columns or walls, or for a cantilever, the clear projection
L_o	distance between the points of zero bending moment in a span
L'_o	length of a span
L_p	development length for pretensioned tendons
L_{pt}	transmission length for pretensioned tendons
L_{st}	development length of a bar for a tensile stress less than the yield stress
$L_{sy.c}$ ($L_{sy.t}$)	development length for compression (tension), being the length of embedment required to develop the yield strength of a bar in compression (tension)

$L_{sy.cb}$ ($L_{sy.tb}$)	basic design development length for compression (tension)
$L_{sy.t.lap}$	tensile lap length for either contact or non-contact splices
L_t	width of a design strip
L_u	unsupported length of a column, taken as the clear distance between the faces of members capable of providing lateral support to the column, where column capitals or haunches are present, L_u is measured to the lowest extremity of the capital or haunch
L_w	overall length of a wall
L_x	shorter effective span of a slab supported on four sides
L_y	longer effective span of a slab supported on four sides
l_b	basic development length
M'	effective or reliable moment capacity of a section (i.e. $= \phi M_u$)
M^*	bending moment at a cross-section calculated using the design load (i.e. the design bending moment)
M^*_v	design bending moment to be transferred from a slab to a support
M^*_x, M^*_y	design bending moment in a column about the major and minor axes respectively; or the positive design bending moment, at midspan in a slab, in the x and y direction respectively
M^*_1, M^*_2	smaller and larger design bending moment respectively at the ends of a column
M_{cr}	bending moment causing cracking of the section with due consideration to prestress, restrained shrinkage and temperature stresses
M_g	moment due to sustained or dead load
M_o	total static moment in a span; or the decompression moment
M_q	live load moment
M_s	moment due to service load
M^*_s	design bending moment at the serviceability limit state
$M^*_{s.1}$	design bending moment at the serviceability limit state, calculated with $\psi_s = 1.0$
M_u	ultimate strength in bending at a cross-section of an eccentrically loaded compression member
M_{uB}	particular ultimate strength in bending when $k_{uo} = 0.003/(0.003 + f_{sy}/E_s)$
M_{ud}	reduced ultimate strength in bending without axial force, at a cross-section
M_{uo}	ultimate strength in bending without axial force, at a cross-section
M_{ux}, M_{uy}	ultimate strength in bending about the major and minor axes respectively of a column under the design axial force N^*
M_y	yield moment
N^*	axial compressive or tensile force on a cross-section calculated using the design load (i.e. the design axial force)
N_c	buckling load used in column design

N_u	ultimate strength in compression, or tension, at a cross-section of an eccentrically loaded compression or tension member respectively
N_{uB}	particular ultimate strength in compression of a cross-section when $k_{uo} = 0.003/(0.003 + f_{sy}/E_s)$
N_{uo}	ultimate strength in compression without bending, of an axially loaded cross-section
n	number of bars uniformly spaced around a helix; or the modular ratio ($= E_s/E_c$)
P	force in the tendons; or the maximum force in the anchorage
P_p	axial load applied to a pile
P_v	vertical component of the prestressing force
p	reinforcement ratio
p_B	balanced steel ratio
p_{all}	maximum allowable steel ratio for beam without special consideration
p_c	compression steel ratio
p_t	tensile steel ratio
$p_{t.min}$	minimum steel ratio required for a section
p_w	reinforcement ratio in a wall
Q	action effect due to live load (including impact, if any)
q	live load usually per unit length or area
q_f	allowable soil bearing capacity
R_d	design capacity of a member or structure (equal to ϕR_u)
R_u	ultimate resistance strength
r	radius of gyration of a cross-section
S_u	action effect due to snow load or liquid pressure or earth and/or ground water pressure
S^*	design action effect (E_d)
s	centre-to-centre spacing of shear or torsional reinforcement, measured parallel to the longitudinal axis of a member; or the standard deviation; or the maximum spacing of transverse reinforcement within $L_{sy.c}$; or spacing of stirrups or ties; or spacing of successive turns of a helix – all measured centre to centre, in millimetres
s_b	clear distance between bars of the non-contact lapped splice
T	a temperature; or the force resultant of tensile stresses
T^*	torsional moment at a cross-section calculated using the design load (i.e. the design torsional moment)
T_u	ultimate torsional strength
T_{uc}	ultimate torsional strength of a beam without torsional reinforcement and in the presence of shear

T_{us}	ultimate torsional strength of a beam with torsional reinforcement
$T_{u.max}$	ultimate torsional strength of a beam limited by web crushing failure
t	thickness of the flange of a flanged section
t_w	thickness of a wall
u	length of the critical shear perimeter for two-way action
u_t	perimeter of the polygon defined for A_t
V_a	inclined shear stress resultant
V_c	concrete shear stress resultant
V_d	dowel force provided by the tension reinforcement
V_u	ultimate shear strength
$V_{u.max}$	ultimate shear strength limited by web crushing failure
$V_{u.min}$	ultimate shear strength of a beam provided with minimum shear reinforcement
V_{uc}	ultimate shear strength excluding shear reinforcement
V_{uf}	ultimate longitudinal shear strength at an interface
$V_{uf.c}$	ultimate longitudinal shear strength of a beam without shear reinforcement
V_{uo}	ultimate shear strength of a slab with no moment transfer
V_{us}	contribution by shear reinforcement to the ultimate shear strength of a beam or wall
V^*	shear force at a section, calculated using the design load (i.e. the design shear force)
v	percent by volume of the steel reinforcement in a reinforced or prestressed concrete section; or the shear stress
W_{BF}	weight of the backfill materials over the heel of a retaining wall
W_{FS}	weight of front surcharge materials over the toe of a retaining wall
W_{SL}	weight due to surcharge load over the heel of a retaining wall
W_u	action effect due to ultimate wind load
w_{cr}	average crack width
w_{max}	maximum crack width
X	dimension
x	shorter overall dimension of a rectangular part of a cross-section; or the smaller dimension of a component rectangle of a T, L or I-section
Y	dimension
y	longer overall dimension of a rectangular part of a cross-section; or the larger dimension of a component rectangle of a T, L or I-section
y_1	larger dimension of a closed rectangular tie
y_t	distance between the neutral axis and the extreme fibres in tension of the uncracked section

Z	section modulus of an uncracked cross-section
α	coefficient; or the inclination of the initial tangent to the concrete stress-strain curve; or a factor defining the geometry of the actual concrete stress block
α_M	coefficient for the calculation of deflection due to applied moment
α_n	coefficient
α_P	coefficient for the calculation of deflection due to concentrated load
α_v	angle between the inclined shear reinforcement and the longitudinal tensile reinforcement
α_w	coefficient for the calculation of deflection due to uniformly distributed load
α_2	factor defining the equivalent rectangular concrete stress block
β	coefficient with or without numerical subscripts; or a fixity factor; or a factor defining the geometry of the actual concrete stress block; or slope angle of the backfill for retaining walls
β_{BF}, β_{FS}, β_{SL}, β_W	load combination factors for calculating different component forces for a retaining wall
β_x, β_y	short and long span bending moment coefficients respectively, for slabs supported on four sides
γ	ratio, under design bending or combined bending and compression, of the depth of the assumed rectangular compressive stress block to k_{ud}
γ_1, γ_2	column end restraint coefficients
Δ	deflection
$\Delta_{A.g}$	accumulated sustained or dead load deflection caused by the dead load and the effects of all the previous live load repetitions
Δ_I	immediate deflection due to total service load
$\Delta_{I.g}$	immediate deflection caused by the sustained load or in most cases, the dead load
Δ_L	long-term deflection
Δ_T	total deflection
Δ_q	immediate live load deflection at the T^{th} cycle
δ, δ_b, δ_s	moment magnifiers for slenderness effects
ε	strain
ε_{cu}	ultimate strain of concrete
ε_s	strain in the tensile reinforcement
ε_{sc}	strain in compression steel
ε_{sy}	yield strain in reinforcing steel
η	factor accounting for the difference between the crushing strength of concrete cylinders and the concrete in the beam; or effective prestress coefficient

ν	Poisson ratio for concrete
θ_v, θ_t	angle between the concrete compression strut and the longitudinal axis of the member
ρ	density of concrete, in kilograms per cubic metre (kg/m^3)
ρ_w	unit weight of reinforced or prestressed concrete
σ_{ci}	sustained concrete stress
σ_{cp}	average intensity of effective prestress in concrete
$\sigma_{cp.f}$	compressive stress at the extreme fibre
$\sigma_{p.ef}$	effective stress in the tendon
σ_{pi}	stress in the tendon immediately after transfer
σ_{pu}	maximum stress which would be reached in a tendon at ultimate strength of a flexural member
σ_{scr}	tensile stress in reinforcement at a cracked section, due to the short-term load combination for the serviceability limit states when direct loads are applied
$\sigma_{scr.1}$	tensile stress in reinforcement at a cracked section, due to the short-term load combination for the serviceability limit states, calculated with $\psi_s = 1.0$, when direct loads are applied
σ_{st}	calculated tensile stress in reinforcement
τ^*	design shear stress acting on the interface
τ_u	unit shear strength
ϕ	capacity reduction factor; or angle of internal friction for soil
ψ_c	combination live load factor used in assessing the design load for strength
ψ_s	short-term live load factor used in assessing the design load for serviceability
ψ_l	long-term live load factor used in assessing the design load for serviceability

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Page 91: Tables 4.7(1) and 4.7(2)
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Page 155: Figure 8.2(4)
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Page 171: Table 8.3(3)
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Page 409: Figure D.6(1)
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Acronyms and abbreviations

AS	Australian Standard
Cg	centre of gravity
℄	centre line
CSS	critical stress state
ESO	evolutionary structural optimisation
LC	loading case
LDS	linearly distributed stress
NA	neutral axis
PC	plastic centre
SP	shear plane
the Standard	AS 3600-2009 *Concrete Structures*
STM	strut-and-tie model