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# REINFORCED AND PRESTRESSED CONCRETE

SECOND EDITION

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

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*Reinforced and Prestressed Concrete* remains the most comprehensive text for engineering students and instructors as well as practising engineers. This second edition has been updated and revised to reflect recent amendments and addenda to the Australian Standard for Concrete Structures AS 3600-2009 and other allied standards.

The content is presented in a clear, easy-to-follow manner, and this edition features even more illustrative and design examples to aid comprehension of complex concepts.

- Part 1 addresses the analysis and design of reinforced concrete structures encompassing bending, deflection and cracking, shear, torsion, bond, beams, slabs, columns and walls.
- Part 2 covers topics on prestressed concrete, including critical stress state analysis and design of beams, ultimate strength analysis of beams, and end blocks for prestressing anchorages.
- Additional technical and practical information is set out in four appendices.
- Tables and figures are updated to reflect the amendments and addenda to the Standard. Additional information is provided on fire design, detailing and cover, long-term deflection, and partially prestressed design aspects. The Appendix on strut-and-tie modelling is expanded to include the latest publications on the topic as well as a numerical example.

Each chapter includes a set of problems that helps consolidate what students have learnt. Worked solutions to the problems are available to instructors on the companion website at [www.cambridge.edu.au/academic/concrete](http://www.cambridge.edu.au/academic/concrete).

Thorough in its treatment, with many practical formulas, diagrams and tables, this new edition of *Reinforced and Prestressed Concrete* is an indispensable resource for students and engineers in their continuing learning and professional education.

**Yew-Chaye Loo**, PhD, FIEAust, FICE, FISStruct E, CPEng, NPER, CEng is Foundation Professor of Civil Engineering at Griffith University in Queensland. He is a former Dean of Engineering and Information Technology and is now Director, Internationalisation and Professional Liaison for the Science, Environment, Engineering and Technology Group.

**Sanaul Huq Chowdhury**, PhD, MIEAust, MACI, CPEng, NPER is a senior lecturer in Structural Engineering and Mechanics at Griffith School of Engineering, Griffith University.

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

**Yew-Chaye Loo**  
**Sanaul Huq Chowdhury**



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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

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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 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 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.

Yew-Chaye Loo  
Sanaul Huq Chowdhury

## PREFACE TO THE SECOND EDITION

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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 AS3600-2009 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.

YCL  
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## NOTATION

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$A_b$	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
$b_{ef}$	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
$D_b$	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

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$d_o$	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
$F_{def}$	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

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$H_{wu}$	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 $\phi$ for backfill materials which are functions 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

$k_{uo}$	ratio, at ultimate strength, without axial force 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 as $(L_n + D/2)$ 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

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$L_y$	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
$M^*_{s1}$	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 $\phi R_u$ )

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$R_u$	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 noncontact 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)
$v$	percentage 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

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$y_t$	distance between the neutral axis and the extreme fibres in tension of the uncracked section
$y_T, y_B$	distance between the neutral axis and the top and bottom extreme fibres of a beam, respectively
$Z$	section modulus of an uncracked cross-section
$\alpha$	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
$\alpha_M$	coefficient for the calculation of deflection due to applied moment
$\alpha_n$	coefficient
$\alpha_P$	coefficient for the calculation of deflection due to concentrated load
$\alpha_v$	angle between the inclined shear reinforcement and the longitudinal tensile reinforcement
$\alpha_w$	coefficient for the calculation of deflection due to uniformly distributed load
$\alpha_1, \alpha_2$	factors defining the equivalent rectangular stress blocks of concrete under uniform compression and flexure, respectively; or permissible compressive and tensile stress coefficients respectively, at transfer of prestress
$\beta_1, \beta_2$	permissible compressive and tensile stress coefficients respectively, after loss of prestress
$\beta$	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
$\beta_{BF}, \beta_{FS}, \beta_{SL}, \beta_W$	load combination factors for calculating different component forces for a retaining wall
$\beta_x, \beta_y$	short and long span bending moment coefficients respectively, for slabs supported on four sides
$\gamma$	ratio, under design bending or combined bending and compression, of the depth of the assumed rectangular compressive stress block to $k_{ud}$
$\gamma_1, \gamma_2$	column end restraint coefficients
$\Delta$	deflection