Structural Concrete

Theory and Design

Second Edition

M. Nadim Hassoun

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Second Edition

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PREFACE TO THE FIRST EDITION

The main objective of a course on reinforced concrete design is to develop, in the engineering student, the ability to analyze and design a reinforced concrete member subjected to different types of forces in a simple and logical manner using the basic principles of statics and some empirical formulas based on experimental results. Once the analysis and design procedure is fully understood, its application to different types of structures becomes simple and direct, provided that the student has a good background in structural analysis.

The material presented in this book is based on the requirements of the American Concrete Institute (ACI) Building Code (318-95). Also, information has been presented on material properties, including volume changes of concrete, stress-strain behavior, creep, and elastic and nonlinear behavior of reinforced concrete.

Concrete structures are widely used in the United States and almost all over the world. The progress in the design concept has increased in the last few decades, emphasizing safety, serviceability, and economy. To achieve economical design of a reinforced concrete member, specific restrictions, rules, and formulas are presented in the codes to ensure both safety and reliability of the structure. Engineering firms expect civil engineering graduates to understand the code rules and, consequently, to be able to design a concrete structure effectively and economically with minimum training period or overhead costs. Taking this into consideration, this book is written to achieve the following objectives:

1. To present the material for the design of reinforced concrete members in a simple and logical approach.
2. To arrange the sequence of chapters in a way compatible with the design procedure of actual structures.
3. To provide a large number of examples in each chapter in clear steps to explain the analysis and design of each type of structural member.
4. To provide an adequate number of practical problems at the end of each chapter to achieve a high level of comprehension.
5. To explain the failure mechanism of a reinforced concrete beam due to flexure and to develop the necessary relationships and formulas for design.
6. To explain *why* the code used specific equations and specific restrictions on the design approach based either on a mathematical model or experimental results. This approach will improve the design ability of the student.

7. To provide adequate number of design aids to help the student in reducing the repetitive computations of specific commonly used values.
8. To enhance the student's ability to use a total quality and economical approach in the design of concrete structures and to help the student to design reinforced concrete members with confidence.
9. To explain the nonlinear behavior and the development of plastic hinges and plastic rotations in continuous reinforced concrete structures.
10. To provide flowcharts to aid the students in writing their own programs, because computers are needed in the design of concrete structures. Flowcharts and computer programs are discussed in Chapter 21.
11. To provide a summary at the end of each chapter to help the student to review the materials of each chapter separately.
12. To provide new information on the design of some members, such as beams with variable depth (Chapter 8), stairs (Chapter 18); and curved beams (Chapter 19), that are not covered in other books on concrete.
13. To present information on the design of reinforced concrete frames, principles of limit design, and moment redistribution in continuous reinforced concrete structures.
14. To provide examples in SI units in all chapters of the book. Equivalent conversion factors from customary units to SI units are also presented. Design tables in SI units are given in Appendix B.
15. References are presented at the end of most chapters.

The book is an outgrowth of the author's lecture notes, which represent his teaching and industrial experience over the past 30 years. The industrial experience of the author includes the design and construction supervision and management of many reinforced, prestressed, and precast concrete structures. This is in addition to the consulting work he performed to international design and construction firms, professional registration in U.K. and other countries, and a comprehensive knowledge of other European codes on the design of concrete structures.

The book is written to cover two courses in reinforced concrete design. Depending on the proficiency required, the first course may cover Chapters 1 through 11 and part of Chapter 13, whereas the second course may cover the remaining chapters. Parts of the late chapters may also be taught in the first course as needed. A number of optional sections have been included in various chapters. These sections are indicated by an asterisk (*) in the Table of Contents, and may easily be distinguished from those which form the basic requirements of the first course. The optional sections may be covered in the second course or relagated to a reading assignment. Brief descriptions of the chapters are given below.

The first chapter of the book presents information on the historical development of concrete, codes of practice, loads and safety provisions, and design philosophy and concepts. The second chapter deals with the properties of concrete as well as steel reinforcement used in the design of reinforced concrete structures, including stress–strain relationships, modulus of elasticity and shear modulus of concrete, shrinkage, creep, fire resistance, high-performance concrete, and fibrous concrete. Because the current ACI Code gives emphasis to the strength design method, this approach has been adopted throughout the text, except in Chapter 5, where the analysis of reinforced concrete sections by the working stress design is explained in order to enable the student and designer to check the deflection of flexural members under service loads. Chapters 3 and 4 cover the analysis and design of reinforced concrete sections based on strength design concept. The behavior of reinforced concrete beams loaded to failure, the types of flexural failure, and failure mechanisms are explained in a way that differs from other textbooks. It is essential for the student to understand the failure concept and the inherent reserve strength before using the necessary design formulas.

Chapters 5 and 6 deal with the elastic behavior and serviceability of concrete beams, including deflection and control of cracking. Chapters 7 and 8 cover the bond, development length, shear, and diagonal tension. In Chapter 8, expressions are presented for designing members of variable depth in addition to prismatic sections. It is quite common to design members of variable depth in actual structures. Chapter 9 covers the design of one-way slabs, including joist-floor systems. Distribution of loads from slabs to beams and columns are also presented in this chapter to enhance the student's understanding of the design loads on each structural component. Chapters 10, 11, and 12 cover the design of axially loaded, eccentrically loaded, and long columns, respectively. Chapter 10 allows the student to understand the behavior of columns, failure conditions, ties and spirals, and other code limitations. Absorbing basic information, the student is introduced in Chapter 11 to the design of columns subjected to compression and bending. New mathematical models are introduced to analyze column sections controlled by compression or tension stresses. Biaxial bending for rectangular and circular columns are introduced using Bresler, PCA, and Hsu methods. Design of long columns is presented in Chapter 12 using the ACI moment magnifier method.

Chapters 13 and 14 cover the design of footings and retaining walls, whereas Chapter 15 covers the design of reinforced concrete sections for shear and torsion. Torsional theories as well as ACI Code design procedure are explained. Chapter 16 deals with continuous beams and frames. A unique feature of this chapter is the introduction of the design of frames, frame hinges, limit state design collapse mechanism, rotation and plastic hinges, and moment redistribution. Adequate examples are presented to explain these concepts.

Design of two-way slabs is introduced in Chapter 17. All types of two-way slabs, including waffle slabs, are presented with adequate examples. Summary of the design procedure is introduced with tables and diagrams. Chapter 18 covers the design of reinforced concrete stairs. Slab-type as well as stepped-type stairs are explained. The second type, although quite common, has not been covered in any text. Chapter 19 deals with the design of curved beams. In actual structures, curved beams are used frequently. These beams are subjected to flexure, shear, and torsion. Design coefficients are presented in this chapter. Chapter 20 covers an introduction to prestressed concrete. Methods of prestressing, fully and partially prestressed concrete design, losses, and shear design are presented with examples. Chapter 21 introduces computer programs as well as flowcharts.

The unified design method (UDM) for the design of reinforced and prestressed concrete flexural and compression members is presented in Chapter 22. This new approach introduces some basic changes in the design limits. Provisions for this method are introduced in the ACI Code, Appendix B. The author suggests that the concept of UDM be explained to the students with Chapters 3, 4, and 11. Examples of Chapter 22 can be presented with these chapter.

In the Appendix of this book, design tables using customary units and SI units are presented.

All the photos shown in this book were taken by the author.

My sincere thanks to the reviewers of the manuscript for their constructive comments and valuable suggestions:

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PREFACE TO THE SECOND EDITION

The second edition of this book revises the previous text to conform to the latest American Concrete Institute (ACI) Code 318-99. It also includes additional sections, revisions, and editing of various chapters of the book. In Chapter 1, Section 1.11 has been added to help the student understand the accuracy of calculations in engineering design. Additional examples are introduced in Chapters 3 and 4 to elaborate on the behavior of reinforced concrete beams at failure and to combine structural analysis with concrete design. In Chapter 6, the section on crack control has been revised to conform to the ACI Code limits on distribution of flexural reinforcement. The code also made some changes in the shear for circular sections and spiral lap splices and introduced a limit on column slenderness ratio. These changes are covered in Chapters 8, 10 and 12, respectively. An additional section on Coulomb theory for soil pressure has been introduced in Chapter 13. Revisions are also made in the design for torsion (Chapter 15) and in bars layout and extensions in two-way slabs without beams (Chapter 17). A new section on partially prestressed concrete has been added to Chapter 20. Structural aid tables are added as Appendix C to help the student and reader to determine the moment, shear, and deflection for simple and continuous beams. The book also contains numerous examples in International System (SI) units, summaries at the end of each chapter, and flow charts (in Chapter 21).

I would like to extend my sincere thanks to the reviewers for their constructive comments to revise the book in this final second edition.

Finally, the book is written to provide basic and reference materials on the analysis and design of reinforced concrete members in a simple, practical, and logical approach. Because this is a required course for seniors in civil engineering, I believe it will be accepted by reinforced concrete instructors at different universities as well as designers who can make use of the information in this book in their practical design of reinforced concrete structures. A solutions manual is provided. Software for the design of different reinforced concrete members is also available on a ftp site maintained by the publisher. Instructors should have received login instructions for themselves and their students from their Prentice Hall Engineering sales representative. All other users of the text should e-mail publisher at Prentice Hall at **www.prenhall.com/hassoun** to request login information.

M. Nadim Hassoun

NOTATION

a	Depth of the equivalent rectangular concrete stress block
a_b	Value of a for a balanced condition
A	Effective tension area of concrete surrounding one bar (This value is used for control of cracking.)
A_b	Area of individual bar
A_c	Area of core of spirally reinforced column
A_{cp}	Gross area enclosed by outside perimeter of cross section
ACI	American Concrete Institute
A_g	Gross (total) area of cross section
A_ℓ	Total area of longitudinal torsion steel
A_o	Gross area enclosed by shear flow $0.85A_{oh}$
A_{oh}	$x_1 y_1$
A_{ps}	Area of prestressed reinforcement in the tension zone
A_s	Area of flexural tension steel
A'_s	Area of compression steel
A_{sb}	Area of balanced steel
A_{st}	Total steel area in the section (column)
A_{sf}	Area of reinforcement to develop compressive strength of overhanging flanges in T- or L-sections
A_t	Area of one leg of closed stirrups used to resist torsion
A_{tc}	Transformed concrete area
A_v	Total area of shear reinforcement within a spacing S
A_1	Loaded area
A_2	Maximum area of supporting surface geometrically similar and concentric with the loaded area
b	Width of compression zone at extreme fiber
b_e	Effective width of flange
b_o	Perimeter of critical section for punching shear
b_w	Width of beam web
c	Distance from extreme compression fiber to neutral axis
c_b	c for a balanced section
c_1	Side of a rectangular column measured in the direction of span

c_2	Side of rectangular column measured transverse to the span
C	Cross-sectional constant = $\Sigma(1 - 0.63x/y)x^3y/3$; compression force
C_c	Compression force in a concrete section with a depth equal to a
C_m	Correction factor applied to the maximum end moment in columns
C_r	Creep coefficient = creep strain per unit stress per unit length
C_s	Force in compression steel
C_t	Factor relating shear and torsional stress properties = $b_w d/\Sigma x^2 y$
C_w	Compression force in web
C_1	Force in the compression steel
d	Distance from extreme compression fiber to centroid of tension steel
d'	Distance from extreme compression fiber to centroid of compression steel
d_b	Nominal diameter of reinforcing bar
d_c	Distance from tension extreme fiber to center of bar closest to that fiber, used for crack control
D	Dead load, diameter of a circular section
e	Eccentricity of load
e'	Eccentricity of load with respect to centroid of tension steel
E	Modulus of elasticity, force created by earthquake
E_c	Modulus of elasticity of concrete = $33W^{1.5}\sqrt{f'_c}$
E_{cb}	Modulus of elasticity of beam concrete
E_{cc}	Modulus of elasticity of column concrete
E_{cs}	Modulus of elasticity of slab concrete
EI	Flexural stiffness of compression member
E_s	Modulus of elasticity of steel = 29×10^6 psi = 2×10^5 MPa
f	Flexural stress
f_c	Maximum flexural compressive stress in concrete due to service loads
f_{ca}	Allowable compressive stress in concrete (alternate design method)
f'_c	28-day compressive strength of concrete (standard cylinder strength)
f_{ci}	Compressive strength of concrete at transfer (initial prestress)
f_{pc}	Compressive stress in concrete due to prestress after all losses
f_{pe}	Compressive stress in concrete at extreme fiber due to the effective prestressing force after all losses
f_{ps}	Stress in prestress steel at nominal strength
f_{pu}	Tensile strength of prestressing tendons
f_{py}	Yield strength of prestressing tendons
f_r	Modulus of rupture of concrete = $7.5\sqrt{f'_c}$ psi
f_s	Stress in tension steel due to service load
f'_s	Stress in the compression steel due to service load
f_{se}	Effective stress in prestressing steel after all losses
f_t	Tensile stress in concrete
f_y	Yield strength of steel reinforcement
F	Lateral pressure of liquids
G	Shear modulus of concrete (in torsion) = $0.45E_c$
h	Total depth of beam or slab or column
h_f	Depth of flange in flanged sections
h_v	Total depth of shearhead cross section
H	Lateral earth pressure
I	Moment of inertia
I_b	Moment of inertia of gross section of beam about its centroidal axis
I_c	Moment of inertia of gross section of column
I_{cr}	Moment of inertia of cracked transformed section

I_e	Effective moment of inertia, used in deflection
I_g	Moment of inertia of gross section neglecting steel
I_s	Moment of inertia of gross section of slab
I_{se}	Moment of inertia of steel reinforcement about centroidal axis of section
j	A factor relating internal couple arm to d in working stress analysis
J	Polar moment of inertia
k	A factor relating the position of the neutral axis with respect to d in working stress analysis, a constant
K	Kip = 1000 lb, a factor used to calculate effective column length
K_b	Flexural stiffness of beam
K_c	Flexural stiffness of column
K_{ec}	Flexural stiffness of equivalent column
K_s	Flexural stiffness of slab
K_t	Torsional stiffness of torsional member
KN	Kilonewton
Ksi	Kip per square inch
ℓ_n	Clear span
ℓ_u	Unsupported length of column
L	Live load, span length
l_d	Development length
l_{dh}	l_{hb} times the applicable modification factor
l_{hb}	Basic development length of a standard hook
l_n	Clear span
l_u	Unsupported length of compression member
l_v	Length of shearhead arm
l_1	Span length in the direction of moment
l_2	Span length in direction transverse to span l_1
M	Bending moment
M_1	Smaller end moment at end of column
M_2	Larger end moment at end of column
M_a	Maximum service load moment
M_b	Balanced moment in columns, used with P_b
M_{cr}	Cracking moment
M_m	Modified moment
M_n	Nominal ultimate moment $= M_u/\phi$
M'_n	Nominal ultimate moment using an eccentricity e'
M_o	Total factored moment
M_p	Plastic moment
M_u	Ultimate moment, moment due to factored loads
M_{u1}	Part of M_u when calculated as singly reinforced
M_{u2}	Part of M_u due to compression reinforcement or overhanging flanges in T- or L-sections
M'_u	Ultimate moment using an eccentricity e'
M_v	Shearhead moment resistance
n	Modular ratio $= E_s/E_c$
N	Normal force
N_u	Factored normal load
N_1	Normal force in bearing at base of column
NA	Neutral axis
psi	Pounds per square inch
P_{cp}	Outside perimeter of gross area $= 2(x_0 + y_0)$

P_o	Perimeter of shear flow in area A_0
P	Unfactored concentrated load
P_b	Balanced load in column (at failure)
P_c	Euler buckling load
P_n	Nominal axial strength of column for a given e
P_o	Axial strength of a concentrically loaded column
P_s	Prestressing force in the tendon at the jacking end
P_u	Factored load $= \phi P_n$
P_x	Prestressing force in the tendon at any point x
q	Soil-bearing capacity
q_a	Allowable bearing capacity of soil
q_u	Ultimate bearing capacity of soil using factored loads
r	Radius of gyration, radius of a circle
R	Resultant of force system, reduction factor for long columns, or $R = R_u/\phi$
R_u	A factor $= M_u/bd^2$
s	Spacing between bars, stirrups, or ties
SI	International system of units
t	Thickness of a slab
T	Torque, tension force
T_c	Nominal torsional strength provided by concrete
T_{cr}	Cracking torsional moment
T_n	Nominal torsional strength provided by concrete and steel
T_s	Nominal torsional strength provided by reinforcement
T_u	Torque provided by factored load $= \phi T_n$
u	Bond stress
U	Design strength required to resist factored loads
V	Shear stress produced by working loads
v_c	Shear stress of concrete
v_{cr}	Shear stress at which diagonal cracks develop
v_h	Horizontal shear stress
v_t	Shear stress produced by a torque
v_u	Shear stress produced by factored loads
V	Unfactored shear force
V_c	Shear strength of concrete
V_{ci}	Nominal shear strength of concrete when diagonal cracking results from combined shear and moment
V_{cw}	Nominal shear strength of concrete when diagonal cracking results from excessive principal tensile stress in web
V_d	Shear force at section due to unfactored dead load (d = distance from the face of support)
V_n	Nominal shear strength $= V_c + V_s$
V_p	Vertical component of effective prestress force at section
V_s	Shear strength carried by reinforcement
V_u	Shear force due to factored loads
w	Width of crack at the extreme tension fiber, unit weight of concrete
w_u	Factored load per unit length of beam or per unit area of slab
W	Wind load or total load
x_o	Length of the short side of a rectangular section
x_1	Length of the short side of a rectangular closed stirrup
y_b	Same as y_t, except to extreme bottom fibers
y_o	Length of the long side of a rectangular section

y_t	Distance from centroidal axis of gross section, neglecting reinforcement, to extreme top fiber
y_1	Length of the long side of a rectangular closed stirrup
z	Factor related to width of crack $= f_s\sqrt[3]{Ad_c}$
α	Angle of inclined stirrups with respect to longitudinal axis of beam, ratio of stiffness of beam to that of slab at a joint
α_c	Ratio of flexural stiffness of columns to combined flexural stiffness of the slabs and beams at a joint; $(\Sigma K_c)/\Sigma(K_s + K_b)$
α_{ec}	Ratio of flexural stiffness of equivalent column to combined flexural stiffness of the slabs and beams at a joint: $(K_{ec})/\Sigma(K_s + K_b)$
α_m	Average value of a for all beams on edges of a panel
α_v	Ratio of stiffness of shearhead arm to surrounding composite slab section
β	Ratio of long to short side of rectangular footing, measure of curvature in biaxial bending
β_1	Ratio of a/c, where $a =$ depth of stress block and $c =$ distance between neutral axis and extreme compression fibers (This factor is 0.85 for $f'_c \leq 4000$ psi and decreases by 0.05 for each 1000 psi in excess of 4000 psi but is at least 0.65.)
β_a	Ratio of unfactored dead load to unfactored live load per unit area
β_c	Ratio of long to short sides of column or loaded area
β_d	Ratio of maximum factored dead load moment to maximum factored total moment
β_t	Ratio of torsional stiffness of edge beam section to flexural stiffness of slab: $E_{cb}C/2E_{cs}I_s$
γ	Distance between rows of reinforcement on opposite sides of columns to total depth of column h
γ_f	Fraction of unbalanced moment transferred by flexure at slab-column connections
γ_p	Factor for type of prestressing tendon (0.4 or 0.28)
γ_v	Fraction of unbalanced moment transferred by eccentricity of shear at slab-column connections
δ	Magnification factor
δ_{ns}	Moment magnification factor for frames braced against sidesway
δ_s	Moment magnification factor for frames not braced against sidesway
Δ	Deflection
ε	Strain
ε_c	Strain in concrete
ε_s	Strain in steel
ε'_s	Strain in compression steel
ε_y	Yield strain $= f_y/E_s$
θ	Slope angle
λ	Multiplier for additional long-time deflection
μ	Poisson's ratio; coefficient of friction
ζ	Parameter for evaluating capacity of standard hook
π	A constant equal to approximately 3.1416
ρ	Ratio of the tension steel area to the effective concrete area $= A_s/bd$
ρ'	Ratio of compression steel area to effective concrete area $= A'_s/bd$
ρ_1	$(\rho - \rho')$
ρ_b	Balanced steel ratio
ρ_g	Ratio of total steel area to total concrete area
ρ_p	Ratio of prestressed reinforcement A_{ps}/bd
ρ_s	Ratio of volume of spiral steel to volume of core

ρ_w	$A_s/b_w d$
ϕ	Strength-reduction factor
ω	$\rho f_y/f'c$
ω'	$\rho' f_y/f'_c$
ω_p	$\rho_p f_{ps}/f'_c$
$\omega_{w'}$	Reinforcement indices for flanged sections comuputed as for ω, ω_p, and ω'
$\omega_{pw'}$	except that b shall be the web width, and reinforcement area shall be that
ω'_w	required to develop compressive strength of web only

CONVERSION FACTORS

To Convert	To	Multiply By
1. Length		
Inch	Millimeter	25.4
Foot	Millimeter	304.8
Yard	Meter	0.9144
Meter	Foot	3.281
Meter	Inch	39.37
2. Area		
Square inch	Square millimeter	645
Square foot	Square meter	0.0929
Square yard	Square meter	0.836
Square meter	Square foot	10.76
3. Volume		
Cubic inch	Cubic millimeter	16390
Cubic foot	Cubic meter	0.02832
Cubic yard	Cubic meter	0.765
Cubic foot	Liter	28.3
Cubic meter	Cubic foot	35.31
Cubic meter	Cubic yard	1.308
4. Mass		
Ounce	Gram	28.35
Pound (lb)	Kilogram	0.454
Pound	Gallon	0.12
Short ton (2000 lb)	Kilogram	907
Long ton (2240 lb)	Kilogram	1016
Kilogram	Pound (lb)	2.205
Slug	Kilogram	14.59
5. Density		
Pound/cubic foot	Kilogram/cubic meter	16.02
Kilogram/cubic meter	Pound/cubic foot	0.06243

To Convert	To	Multiply By
6. Force		
Pound (Ib)	Newton (N)	4.448
Kip (1000 lb)	Kilonewton (kN)	4.448
Newton (N)	Pound	0.2248
Kilonewton (kN)	Kip (K)	0.225
7. Force/length		
Kip/foot	Kilonewton/meter	14.59
Kilonewton/meter	Pound/foot	68.52
Kilonewton/meter	Kip/foot	0.06852
8. Force/area (stress)		
Pound/square inch (psi)	Newton/square centimeter	0.6895
Pound/square inch (psi)	Newton/square millimeter (MPa)	0.0069
Kip/square inch (Ksi)	Meganewton/square meter	6.895
Kip/square inch (Ksi)	Newton/square millimeter	6.895
Pounds/square foot	Kilonewton/square meter	0.04788
Pound/square foot	Newton/square meter	47.88
Kip/square foot	Kilonewton/square meter	47.88
Newton/square millimeter	Kip/square inch (Ksi)	0.145
Kilonewton/square meter	Kip/square foot	0.0208
Kilonewton/square meter	Pound,/square foot	20.8
9. Moments		
Foot · Kip	Kilonewton · meter	1.356
Inch · Kip	Kilonewton · meter	0.113
Inch · Kip	Kilogram force · meter	11.52
Kilonewton · meter	Foot · Kip	0.7375

Structural Concrete

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Second Edition

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