STRUCTURAL CONCRETE

THEORY AND DESIGN

SIXTH EDITION

M. NADIM HASSOUN, AKTHEM AL-MANASEER

WILEY

Structural Concrete

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PREFACE

The main objective of a course on structural 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 statistics 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 Standard 318-14, International Building Code IBC-2012, American society of Civil Engineers Load Standards ASCE 7-10, and AASHTO LRFD Bridge Design Specifications. Also, information has been presented on material properties, including volume changes of concrete, stress–strain behavior, creep, and elastic and nonlinear behavior or 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 most chapters 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 on either 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 review problems for concrete building component design in Chapter 23.
11. To provide a summary at the end of most chapters to help the student to review the materials of each chapter separately. Also to design and analysis flowcharts in Chapter 24.
12. To provide new information on the design of special members, such as beams with variable depth (Chapter 5), deep beams using ACI and AASHTO design methods (Chapter 8), stairs design (Chapter 18), seismic design utilizing IBC 2012 and ASCE 7-10 (Chapter 20), beams curved in plan (Chapter 21), and bridge design according to AASHTO (Chapter 22).
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 present examples on prediction of creep and shrinkage of concrete using the ACI and AASHTO codes.
15. 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.
16. References are presented at the end of most chapters.

The book is an outgrowth of the authors' lecture notes, which represent their teaching and industrial experience over the past 35 years. The industrial experience of the authors includes the design and construction supervision and management of many reinforced, prestressed, and precast concrete structures. This is in addition to the consulting work they performed for international design and construction firms, professional registration in the United Kingdom, Canada, 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 7, 9, 10, 11, 13, 23, and 24, 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 Contents and may easily be distinguished from those that form the basic requirements of the first course. The optional sections may be covered in the second course or relegated 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 emphasizes the strength approach based on strain limits, this approach has been adopted throughout the text. Chapters 3 and 4 cover the analysis and design of reinforced concrete sections based on strain limits. The behavior of reinforced concrete beams loaded to failure, the types of flexural failure, and failure mechanism are explained very clearly. It is essential for the student to understand the failure concept and the inherent reserve strength and ductility before using the necessary design formulas.

Chapter 5 covers shear design, including members with variable depth in actual structure.

Chapter 6 deals with the serviceability of reinforced concrete beams, including deflection and control of cracking. Chapter 7 covers bond and development length. Chapter 8 covers the design of deep beams utilizing the ACI and AASHTO strut-and-tie approach.

Chapter 9 covers the design of one-way slabs, including joist-floor systems. Distributions 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, tie and spiral design, and other code limitations. After absorbing the 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 is presented. The design of long columns is discussed in Chapter 12 using the ACI moment-magnifier method.

Chapters 13 and 14 cover the design of footings and retaining walls, then Chapter 15 covers the design of reinforced concrete sections for shear and torsion. Torsional theories and 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, the limit state design collapse mechanism, rotation and plastic hinges, and moment redistribution. Adequate examples are presented to explain these concepts.

The design of two-way slabs is introduced in Chapter 17. All types of two-way slabs, including waffle slabs, are presented with adequate examples. A summary of the design procedure is provided with tables and diagrams. Chapter 18 covers the design of reinforced concrete stairs. Slab-type and stepped-type stairs are explained. The second type, although quite common, has not been covered in any text. Chapter 19 covers an introduction to prestressed concrete. Methods of prestressing, fully and partially prestressed concrete design, losses, and shear design are presented with examples. Chapter 20 presents the seismic design and analysis of members utilizing the IBC 2012, ASCE 7-10, and the ACI Code. Chapter 21 deals with the design of curved beams. In actual structures curved beams are used frequently. These beams are subjected to flexure, shear, and torsion. Chapter 22 covers prestressed concrete bridge design based on the AASHTO LRFD bridge design specifications with design examples. Chapter 23 deals with sample problems review for concrete building component design. Chapter 24 provides flow charts to help the students and engineers to better understand the design and analysis of concrete structure.

In Appendixes A and B, design tables using customary units and SI units are presented.

Finally, the book is written to provide basic reference materials on the analysis and design of structural concrete members in a simple, practical, and logical approach. Because this is a required course for seniors in civil engineering, we believe this book will be accepted by reinforced concrete instructors at different universities as well as designers who can make use of the information in their practical design of reinforced concrete structures.

A companion Web site for the book is available at www.wiley.com/college/hassoun. This Web site contains MSExcel spreadsheets that enable students to evaluate different design aspects of concrete members in an interactive environment and a solutions manual for instructors.

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Most of the photos shown in this book were taken by the authors. We wish to express appreciation to John Gardner and Murat Saatcioglu from the University of Ottawa, Canada, for the photos provided in the seismic chapter.

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_{ch}	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 0.85 A_{oh}
A_{oh}	Area enclosed by centerline of the outmost closed transverse torsional reinforcement
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 close 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_2	Side of rectangular column measured transverse to the span
C	Cross-sectional constant $\sum (1 - 0.63x/y)x^3y/3$; 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 $= b_w d/\sum x^2 y$
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_t	Distance from extreme compression fibers to extreme tension steel
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 $= 29 \times 10^6$ psi $= 2 \times 10^5$ 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 $= 7.5\lambda\sqrt{f'_c}$ 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	Specified yield strength of steel reinforcement
f_{yt}	Specified yield strength of transverse reinforcement
F	Loads due to weight and pressure of fluids
F_n	Nominal strength of a strut, tie, or nodal zone
F_{ns}	Nominal strength of a strut
F_{nt}	Nominal strength of a tie
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_p	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 Polar moment of inertia
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_c Length of compression member in a frame
ℓ_n Clear span
ℓ_u Unsupported length of column
L Live load, span length
L_r Roof live load
l_d Development length
L_{dc} Development length in compression
l_{dh} Development length in tension of a standard hook
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_l
M Bending moment
M_1 Smaller factored end moment at end of column
M_2 Larger factored end moment at end of column
M_a Maximum service load moment
M_b Balanced moment in columns, used with P_b
M_c Factored moment amplified for long columns
M_{cr} Cracking moment
M_{cre} Moment causing flexural cracking at a section
M_m Factored modified moment
M_n Nominal moment strength = M_u/ϕ
M'_n Nominal moment strength using an eccentricity e′
M_0 Total factored moment
M_p Plastic moment
M_u Moment strength 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 Moment strength using an eccentricity e'
M_v Shearhead moment resistance
M_{1ns} Factored end moment in nonsway frame at which M_1 acts

M_{1s}	Factored end moment in sway frame at which M_1 acts
$M_{2,\min}$	Minimum value of M_2 in columns
M_{2ns}	Factored end moment in nonsway frame at which M_2 acts
M_{2s}	Factored end moment in sway frame at which M_2 acts
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	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_0	Perimeter of shear flow in area A_0
P_0	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
Q	Stability index for a story
r	Radius of gyration, radius of a circle
R	Resultant of force system, reduction factor for long columns, or $R = R_u/\phi$, also rain load
R_u	A factor $= M_u/bd^2$
S	Snow loads
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_0 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_0 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_l Length of the long side of a rectangular closed stirrup
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_f $(E_{cb}I_b/E_{cs}I_s)$
α_{f1} α_f in direction ℓ_1
α_{f2} α_f in direction ℓ_2
α_m Average value of α 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_{ds} Ratio used to account for reduction of stiffness of columns due to sustained lateral load
β_{dns} 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 factor for reduced mechanical properties of lightweight concrete
λ_Δ Multiplier for additional long-time deflection
μ Poisson's ratio; coefficient of friction

ζ	Parameter for evaluating capacity of standard hook
π	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
ψ_e	Factor used to modify development length based on reinforcement coating
ψ_s	Factor used to modify development length based on reinforcing size
ψ_t	Factor used to modify development length based on reinforcement location
ω	Tension reinforcing index = $\rho f_y/f' c$
ω'	Compression reinforcing index = $\rho' f_y/f'_c$
ω_p	Prestressed steel index = $\rho_p f_{ps}/f'_c$
ω_{pw}	Prestressed steel index for flanged sections
ω_w	Tension reinforcing index for flanged sections
ω'_w	Compression reinforcing index for flanged sections computed as for ω, ω_p, and ω'

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

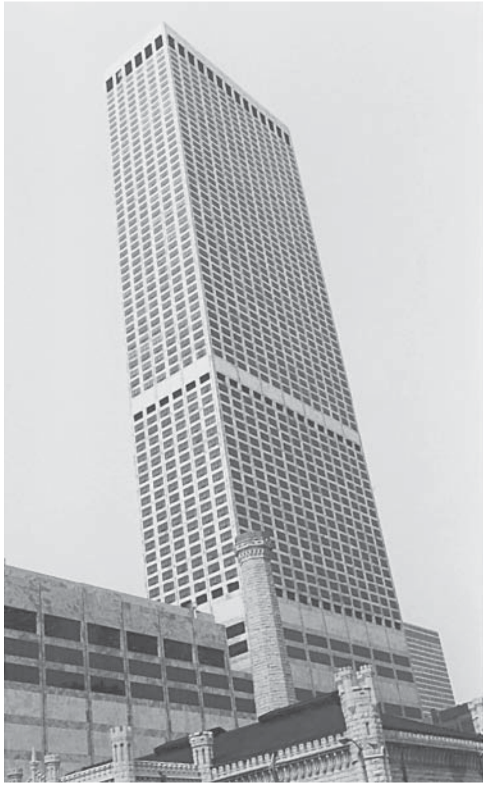
(*continued*)

To Convert	to	Multiply By
5. *Density*		
Pound/cubic foot	Kilogram/cubic meter	16.02
Kilogram/cubic meter	Pound/cubic foot	0.06243
6. Force		
Pound (lb)	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
Pound/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

CHAPTER 1

INTRODUCTION



Water Tower Place, Chicago, 74 stories, tallest concrete building in the United States.

1.1 STRUCTURAL CONCRETE

The design of different structures is achieved by performing, in general, two main steps: (1) determining the different forces acting on the structure using proper methods of structural analysis and (2) proportioning all structural members economically, considering the safety, stability, serviceability, and functionality of the structure. Structural concrete is one of the materials commonly used to design all types of buildings. Its two component materials, concrete and steel, work together to form structural members that can resist many types of loadings. The key to its performance lies in strengths that are complementary: Concrete resists compression and steel reinforcement resists tension forces.

The term *structural concrete* indicates all types of concrete used in structural applications. Structural concrete may be plain, reinforced, prestressed, or partially prestressed concrete; in addition, concrete is used in composite design. Composite design is used for any structural member, such as beams or columns, when the member contains a combination of concrete and steel shapes.

1.2 HISTORICAL BACKGROUND

The first modern record of concrete is as early as 1760, when John Smeaton used it in Britain in the first lock on the river Calder [1]. The walls of the lock were made of stones filled in with concrete. In 1796, J. Parker discovered Roman natural cement, and 15 years later Vicat burned a mixture of clay and lime to produce cement. In 1824, Joseph Aspdin manufactured portland cement in Wakefield, Britain. It was called portland cement because when it hardened it resembled stone from the quarries of the Isle of Portland.

In France, François Marte Le Brun built a concrete house in 1832 in Moissac in which he used concrete arches of 18-ft span. He used concrete to build a school in St. Aignan in 1834 and a church in Corbarièce in 1835. Joseph Louis Lambot [2] exhibited a small rowboat made of reinforced concrete at the Paris Exposition in 1854. In the same year, W. B. Wilkinson of England obtained a patent for a concrete floor reinforced by twisted cables. The Frenchman François Cignet obtained his first patent in 1855 for his system of iron bars, which were embedded in concrete floors and extended to the supports. One year later, he added nuts at the screw ends of the bars, and in 1869, he published a book describing the applications of reinforced concrete.

Joseph Monier, who obtained his patent in Paris on July 16, 1867, was given credit for the invention of reinforced concrete [3]. He made garden tubs and pots of concrete reinforced with iron mesh, which he exhibited in Paris in 1867. In 1873, he registered a patent to use reinforced concrete in tanks and bridges, and four years later, he registered another patent to use it in beams and columns [1].

In the United States, Thaddeus Hyatt conducted flexural tests on 50 beams that contained iron bars as tension reinforcement and published the results in 1877. He found that both concrete and steel can be assumed to behave in a homogeneous manner for all practical purposes. This assumption was important for the design of reinforced concrete members using elastic theory. He used prefabricated slabs in his experiments and considered prefabricated units to be best cast in T-sections and placed side by side to form a floor slab. Hyatt is generally credited with developing the principles upon which the analysis and design of reinforced concrete are now based.

A reinforced concrete house was built by W. E. Ward near Port Chester, New York, in 1875. It used reinforced concrete for walls, beams, slabs, and staircases. P. B. Write wrote in the *American Architect and Building News* in 1877 describing the applications of reinforced concrete in Ward's house as a new method in building construction.

E. L. Ransome, head of the Concrete Steel Company in San Francisco, used reinforced concrete in 1879 and deformed bars for the first time in 1884. During 1889 to 1891, he built the two-story Leland Stanford Museum in San Francisco using reinforced concrete. He also built a reinforced concrete bridge in San Francisco. In 1900, after Ransome introduced the reinforced concrete skeleton, the thick wall system started to disappear in construction. He registered the skeleton type of structure in 1902 using spiral reinforcement in the columns, as was suggested by Armand Considére of France. A. N. Talbot, of the University of Illinois, and F. E. Turneaure and M. O. Withney, of the University of Wisconsin, conducted extensive tests on concrete to determine its behavior, compressive strength, and modulus of elasticity.

In Germany, G. A. Wayass bought the French Monier patent in 1879 and published his book on Monier methods of construction in 1887. Rudolph Schuster bought the patent rights in Austria, and the name of Monier spread throughout Europe, which is the main reason for crediting Monier as the inventor of reinforced concrete.

In 1900, the Ministry of Public Works in France called for a committee headed by Armand Considére, chief engineer of roads and bridges, to establish specifications for reinforced concrete, which were published in 1906.

Reinforced concrete was further refined by introducing some precompression in the tension zone to decrease the excessive cracks. This refinement was the preliminary introduction of partial and full prestressing. In 1928, Eugene Freyssinet established the practical technique of using prestressed concrete [4].

The Barkwick House, a three-story concrete building built in 1905, Montreal, Canada.

From 1915 to 1935, research was conducted on axially loaded columns and creep effects on concrete; in 1940, eccentrically loaded columns were investigated. Ultimate-strength design started to receive special attention, in addition to diagonal tension and prestressed concrete. The American Concrete Institute Code (ACI Code) specified the use of ultimate-strength design in 1963 and included this method in all later codes. The method is called in the current ACI code the strength design method. Building codes and specifications for the design of reinforced concrete structures are established in most countries, and research continues on developing new applications and more economical designs.

1.3 ADVANTAGES AND DISADVANTAGES OF REINFORCED CONCRETE

Reinforced concrete, as a structural material, is widely used in many types of structures. It is competitive with steel if economically designed and executed.

The advantages of reinforced concrete can be summarized as follows:

1. It has a relatively high compressive strength.
2. It has better resistance to fire than steel.
3. It has a long service life with low maintenance cost.
4. In some types of structures, such as dams, piers, and footings, it is the most economical structural material.
5. It can be cast to take the shape required, making it widely used in precast structural components. It yields rigid members with minimum apparent deflection.

The disadvantages of reinforced concrete can be summarized as follows:

1. It has a low tensile strength of about one-tenth of its compressive strength.
2. It needs mixing, casting, and curing, all of which affect the final strength of concrete.
3. The cost of the forms used to cast concrete is relatively high. The cost of form material and artisanry may equal the cost of concrete placed in the forms.
4. It has a low compressive strength as compared to steel (the ratio is about 1:10, depending on materials), which leads to large sections in columns of multistory buildings.
5. Cracks develop in concrete due to shrinkage and the application of live loads.

1.4 CODES OF PRACTICE

The design engineer is usually guided by specifications called the codes of practice. Engineering specifications are set up by various organizations to represent the minimum requirements necessary for the safety of the public, although they are not necessarily for the purpose of restricting engineers.

Most codes specify design loads, allowable stresses, material quality, construction types, and other requirements for building construction. The most significant standard for structural concrete design in the United States is the Building Code Requirements for Structural Concrete, ACI 318, or the ACI Code. Most of the design examples of this book are based on this standard. Other codes of practice and material specifications in the United States include the International building Code (IBC), The American Society of Civil Engineers standard ASCE 7, The American Association of State Highway and Transportation Officials (AASHTO) specifications, and specifications issued by the American Society for Testing and Materials (ASTM), the American Railway Engineering Association (AREA), and the Bureau of Reclamation, Department of the Interior.

1.5 DESIGN PHILOSOPHY AND CONCEPTS

The design of a structure may be regarded as the process of selecting the proper materials and proportioning the different elements of the structure according to state-of-the-art engineering science and technology. In order to fulfill its purpose, the structure must meet the conditions of safety, serviceability, economy, and functionality. This can be achieved using design approach-based strain limits in concrete and steel reinforcement.

The unified design method (UDM) is based on the strength of structural members assuming a failure condition, whether due to the crushing of the concrete or to the yield of the reinforcing steel bars. Although there is some additional strength in the bars after yielding (due to strain hardening), this additional strength is not considered in the analysis of reinforced concrete members. In this approach, the actual loads, or working loads, are multiplied by load factors to obtain the factored design loads. The load factors represent a high percentage of the factor for safety required in the design. Details of this method are presented in Chapters 3, 4, and 11. The ACI Code emphasizes this method of design, and its provisions are presented in the body of the Code. The reason for introducing this approach by the ACI Code relates to the fact that different design methods were developed for reinforced and prestressed concrete beams and columns. Also, design procedures for prestressed concrete were different from reinforced concrete. The purpose of the Code approach is to simplify and unify the design requirements for reinforced and prestressed flexural members and compression members.

A second approach for the design of concrete members is called the strut-and-tie method (STM). The provisions of this method are introduced in the ACI Code, Chapter 23. It applies effectively in regions of discontinuity such as support and load applications on beams. Consequently, the structural element is divided into segments and then analyzed using the truss analogy approach, where the concrete resists compression forces as a strut, while the steel reinforcement resists tensile forces as a tie.

A basic method that is not commonly used is called the working stress design or the elastic design method. The design concept is based on the elastic theory assuming a straight-line stress distribution along the depth of the concrete section under service loads. The members are proportioned on the basis of certain allowable stresses in concrete and steel. The allowable stresses are fractions of the crushing strength of concrete and yield strength of steel. This method has been deleted from the ACI Code. The application of this approach is still used in the design of prestressed concrete members under service load conditions, as shown in Chapter 19.

Limit state design is a further step in the strength design method. It indicates the state of the member in which it ceases to meet the service requirements such as losing its ability to withstand external loads or suffering excessive deformation, cracking, or local damage. According to the limit state design, reinforced concrete members have to be analyzed with regard to three limiting states:

1. Load-carrying capacity (safety, stability, and durability)
2. Deformation (deflections, vibrations, and impact)
3. Formation of cracks

The aim of this analysis is to ensure that no limiting state will appear in the structural member during its service life.

1.6 UNITS OF MEASUREMENT

Two units of measurement are commonly used in the design of structural concrete. The first is the U.S. customary system (lying mostly in its human scale and its ingenious use of simple numerical proportions), and the second is the SI (Système International d'Unités), or metric, system.

The metric system is expected to be in universal use within the coming few years. The United States is committed to changing to SI units. Great Britain, Canada, Australia, and other countries have been using SI units for many years.

The base units in the SI system are the units of length, mass, and time, which are the meter (m), the kilogram (kg), and the second (s), respectively. The unit of force, a derived unit called the newton (N), is defined as the force that gives the acceleration of one meter per second ($1\ \text{m/s}^2$) to a mass of one kilogram, or $1\ \text{N} = 1\ \text{kg} \times \text{m/s}^2$.

The weight of a body, W, which is equal to the mass, m, multiplied by the local gravitational acceleration, g ($9.81\ \text{m/s}^2$), is expressed in newtons (N). The weight of a body of 1 kg mass is $W = mg = 1\ \text{kg} \times 9.81\ \text{m/s}^2 = 9.81\ \text{N}$.

Multiples and submultiples of the base SI units can be expressed through the use of prefixes. The prefixes most frequently used in structural calculations are the kilo (k), mega (M), milli (m), and micro (μ). For example,

$$1\ \text{km} = 1000\ \text{m} \qquad 1\ \text{mm} = 0.001\ \text{m} \qquad 1\ \mu\text{m} = 10^{-6}\ \text{m}$$

$$1\ \text{kN} = 1000\ \text{N} \qquad 1\ \text{Mg} = 1000\ \text{kg} = 10^{6}\ \text{g}$$

1.7 LOADS

Structural members must be designed to support specific loads.

Loads are those forces for which a given structure should be proportioned. In general, loads may be classified as dead or live.

Dead loads include the weight of the structure (its self-weight) and any permanent material placed on the structure, such as tiles, roofing materials, and walls. Dead loads can be determined with a high degree of accuracy from the dimensions of the elements and the unit weight of materials.

Live loads are all other loads that are not dead loads. They may be steady or unsteady or movable or moving; they may be applied slowly, suddenly, vertically, or laterally, and their magnitudes may fluctuate with time. In general, live loads include the following:

- Occupancy loads caused by the weight of the people, furniture, and goods
- Forces resulting from wind action and temperature changes
- The weight of snow if accumulation is probable
- The pressure of liquids or earth on retaining structures
- The weight of traffic on a bridge
- Dynamic forces resulting from moving loads (impact), earthquakes, or blast loading

The ACI Code does not specify loads on structures; however, occupancy loads on different types of buildings are prescribed by IBC-2012 and the American National Standards Institute (ANSI) [5]. Some typical values are shown in Table 1.1. Table 1.2 shows the weights and specific gravity of various materials.

Table 1.1 Typical Uniformly Distributed Design Loads

		Design Live Load	
Occupancy	**Contents**	**lb/ft^2**	**kN/m^2**
Assembly hall	Fixed seats	60	2.9
	Movable seats	100	4.8
Hospital	Operating rooms	60	2.9
	Private rooms	40	1.9
Hotel	Guest rooms	40	1.9
	Public rooms	100	4.8
	Balconies	100	4.8
Housing	Private houses and apartments	40	1.9
	Public rooms	100	4.8
Institution	Classrooms	40	1.9
	Corridors	100	4.8
Library	Reading rooms	60	2.9
	Stack rooms	150	7.2
Office building	Offices	50	2.4
	Lobbies	100	4.8
Stairs (or balconies)		100	4.8
Storage warehouses	Light	100	4.8
	Heavy	250	12.0
Yards and terraces		100	4.8

Table 1.2 Density and Specific Gravity of Various Materials

Material	**Density**		**Specific Gravity**
	lb/ft³	**kg/m³**	
Building materials			
Bricks	120	1924	1.8–2.0
Cement, portland, loose	90	1443	—
Cement, portland, set	183	2933	2.7–3.2
Earth, dry, packed	95	1523	—
Sand or gravel, dry, packed	100–120	1600–1924	—
Sand or gravel, wet	118–120	1892–1924	—
Liquids			
Oils	58	930	0.9–0.94
Water (at 4°C)	62.4	1000	1.0
Ice	56	898	0.88–0.92
Metals and minerals			
Aluminum	165	2645	2.55–2.75
Copper	556	8913	9.0
Iron	450	7214	7.2
Lead	710	11, 380	11.38
Steel, rolled	490	7855	7.85
Limestone or marble	165	2645	2.5–2.8
Sandstone	147	2356	2.2–2.5
Shale or slate	175	2805	2.7–2.9
Normal-weight concrete			
Plain	145	2324	2.2–2.4
Reinforced or prestressed	150	2405	2.3–2.5

AASHTO and AREA specifications prescribe vehicle loadings on highway and railway bridges, respectively. These loads are given in References 6 and 7.

Snow loads on structures may vary between 10 and 40 lb/ft^2 (0.5 and 2 kN/m^2), depending on the local climate.

Wind loads may vary between 15 and 30 lb/ft^2, depending on the velocity of wind. The wind pressure of a structure, F, can be estimated from the equation

$$F = 0.00256 C_s V^2 \tag{1.1}$$

where

V = velocity of air (mi/h)
C_s = shape factor of structure
F = dynamic wind pressure (lb/ft^2)

As an example, for a wind of 100 mi/h with $C_s = 1$, the wind pressure is equal to 25.6 lb/ft^2. It is sometimes necessary to consider the effect of gusts in computing the wind pressure by multiplying the wind velocity in Eq. 1.1 by a gust factor, which generally varies between 1.1 and 1.3.

The shape factor, C_s, varies with the horizontal angle of incidence of the wind. On vertical surfaces of rectangular buildings, C_s may vary between 1.2 and 1.3. Detailed information on wind loads can be found in Reference 5.

1.8 SAFETY PROVISIONS

Structural members must always be proportioned to resist loads greater than the service or actual load in order to provide proper safety against failure. In the strength design method, the member is designed to resist factored loads, which are obtained by multiplying the service loads by load factors. Different factors are used for different loadings. Because dead loads can be estimated quite accurately, their load factors are smaller than those of live loads, which have a high degree of uncertainty. Several load combinations must be considered in the design to compute the maximum and minimum design forces. Reduction factors are used for some combinations of loads to reflect the low probability of their simultaneous occurrences. The ACI Code presents specific values of load factors to be used in the design of concrete structures (see Chapter 3, Section 3.5).

In addition to load factors, the ACI Code specifies another factor to allow an additional reserve in the capacity of the structural member. The nominal strength is generally calculated using an accepted analytical procedure based on statistics and equilibrium; however, in order to account for the degree of accuracy within which the nominal strength can be calculated, and for adverse variations in materials and dimensions, a strength reduction factor, ϕ, should be used in the strength design method. Values of the strength reduction factors are given in Chapter 3, Section 3.6.

To summarize the above discussion, the ACI Code has separated the safety provision into an overload or load factor and to an undercapacity (or strength reduction) factor, ϕ. A safe design is achieved when the structure's strength, obtained by multiplying the nominal strength by the reduction factor, ϕ, exceeds or equals the strength needed to withstand the factored loadings (service loads times their load factors). For example,

$$M_u \le \phi M_n \qquad \text{and} \qquad V_u \le \phi V_n \tag{1.2}$$

where

M_u, V_u = external factored moment and shear forces, respectively
M_n, V_n = nominal flexural strength and shear strength of member, respectively

Given a load factor of 1.2 for dead load and a load factor of 1.6 for live load, the overall safety factor for a structure loaded by a dead load, D, and a live load, L, is

$$\text{Factor of safety} = \frac{1.2D + 1.6L}{D + L}\left(\frac{1}{\phi}\right) = \frac{1.2 + 1.6(L/D)}{1 + (L/D)}\left(\frac{1}{\phi}\right) \tag{1.3}$$

The factors of safety for the various values of ϕ and L/D ratios are as follows:

ϕ	**0.9**				**0.8**				**0.75**			
L/D	0	1	2	3	0	1	2	3	0	1	2	3
Factor of safety	1.33	1.56	1.63	1.67	1.50	1.74	1.83	1.88	1.6	1.87	1.96	2

For members subjected to flexure (beams), with tension-controlled sections, $\varphi = 0.9$, and the factor of safety ranges between 1.33 for $L/D = 0$ and 1.67 for $L/D = 3$. These values are less than those specified by the ACI Code 318 Appendix C of 1.56 for $L/D = 0$ and 1.81 for $L/D = 3.0$ based on load factors of 1.4 for dead load and 1.7 for live load. This reduction ranges between 17 and 8%, respectively.

For members subjected to axial forces (spiral columns), $\phi = 0.75$, and the factor of safety ranges between 1.60 for $L/D = 0$ and 2 for $L/D = 3$. The increase in the factor of safety in columns reflects the greater overall safety requirements of these critical building elements.

A general format of Eq. 1.2 may be written as [8]

$$\phi R \geq \upsilon_0 \sum (\upsilon_i Q_i) \tag{1.4}$$

where

R_n = nominal strength of structural number
ϕ = undercapacity factor (Reduction factor <1.0)
$\sum Q_i$ = sum of load effects
υ_i = overload factor
υ_0 = analysis factor (>1.0)

The subscript i indicates the load type, such as dead load, live load, and wind load. The analysis factor, υ_0, is greater than 1.0 and is introduced to account for uncertainties in structural analysis. The overload factor, υ_i, is introduced to account for several factors such as an increase in live load due to a change in the use of the structure and variations in erection procedures. The design concept is referred to as load and resistance factor design (LRFD).

1.9 STRUCTURAL CONCRETE ELEMENTS

Structural concrete can be used for almost all buildings, whether single story or multistory. The concrete building may contain some or all of the following main structural elements, which are explained in detail in other chapters of the book:

- *Slabs* are horizontal plate elements in building floors and roofs. They may carry gravity loads as well as lateral loads. The depth of the slab is usually very small relative to its length or width (Chapters 9 and 17).
- *Beams* are long, horizontal, or inclined members with limited width and depth. Their main function is to support loads from slabs (Chapters 3, 4, and 8).
- *Columns* are critical members that support loads from beams or slabs. They may be subjected to axial loads or axial loads and moments (Chapters 10, 11, and 12).
- *Frames* are structural members that consist of a combination of beams and columns or slabs, beams, and columns. They may be statically determinate or statically indeterminate frames (Chapter 16).
- *Footings* are pads or strips that support columns and spread their loads directly to the soil (Chapter 13).
- *Walls* are vertical plate elements resisting gravity as well as lateral loads as in the case of basement walls (Chapter 14).
- *Stairs* are provided in all buildings either low or high rise (Chapter 18).

1.10 STRUCTURAL CONCRETE DESIGN

The first step in the design of a building is the general planning carried out by the architect to determine the layout of each floor of the building to meet the owner's requirements. Once the