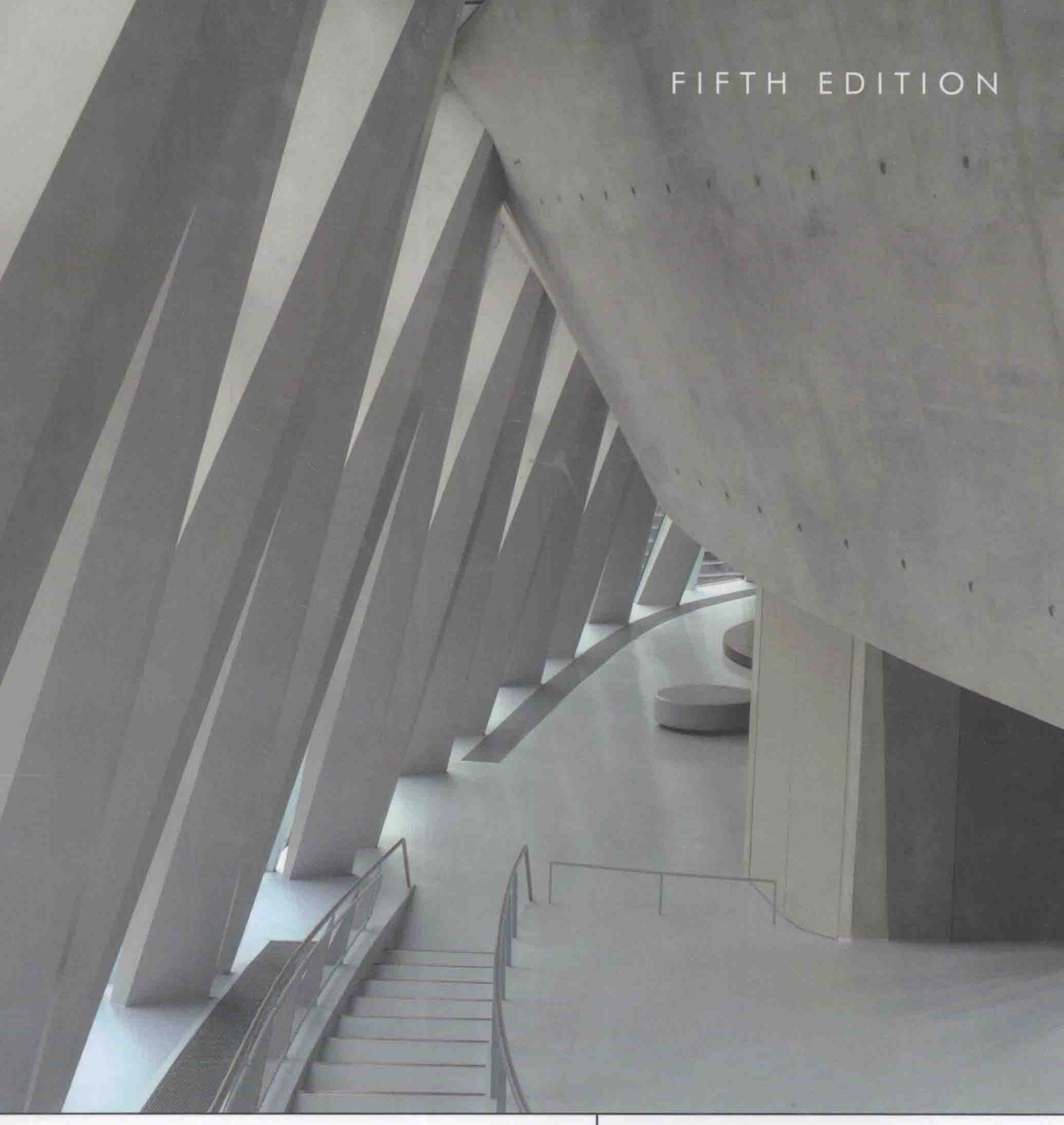

FIFTH EDITION

# STRUCTURAL CONCRETE

## THEORY & DESIGN

M. Nadim Hassoun
Akthem Al-Manaseer

# Structural Concrete

## Theory and Design

*Fifth Edition*

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# Structural Concrete

# 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 318-11, 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 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 a summary at the end of most chapters to help the student to review the materials of each chapter separately. Also to provide design and analysis flow charts in Chapter 23.
11. 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).
12. To present information on the design of reinforced concrete frames, principles of limit design, and moment redistribution in continuous reinforced concrete structures.
13. To present examples on prediction of creep and shrinkage of concrete using the ACI and AASHTO codes.
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 authors' lecture notes, which represent their teaching and industrial experience over the past 32 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, and 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 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. 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 is presented. 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, 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 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 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.

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.

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# 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 $= b_w d/\sum x^2y$ |
| $C_w$ | 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 |
| $\ell_c$ | Length of compression member in a frame |
| $\ell_n$ | Clear span |
| $\ell_u$ | 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 $l_1$ |
| $M$ | 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 = $M_u/\phi$ |
| $M'_n$ | 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 |
| $y_1$ | Length of the long side of a rectangular closed stirrup |
| $\alpha$ | Angle of inclined stirrups with respect to longitudinal axis of beam, ratio of stiffness of beam to that of slab at a joint . |
| $\alpha_c$ | Ratio of flexural stiffness of columns to combined flexural stiffness of the slabs and beams at a joint; $(\Sigma K_c)/\Sigma(K_s + K_b)$ |
| $\alpha_{ec}$ | Ratio of flexural stiffness of equivalent column to combined flexural stiffness of the slabs and beams at a joint: $(K_{ec})/\Sigma(K_s + K_b)$ |
| $\alpha_f$ | $(E_{cb}I_b/E_{cs}I_s)$ |
| $\alpha_{f1}$ | $\alpha_f$ in direction $\ell_1$ |
| $\alpha_{f2}$ | $\alpha_f$ in direction $\ell_2$ |
| $\alpha_m$ | Average value of $\alpha$ for all beams on edges of a panel |
| $\alpha_v$ | Ratio of stiffness of shearhead arm to surrounding composite slab section |
| $\beta$ | Ratio of long to short side of rectangular footing, measure of curvature in biaxial bending |
| $\beta_1$ | 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.) |
| $\beta_a$ | Ratio of unfactored dead-load to unfactored live load per unit area |
| $\beta_c$ | Ratio of long to short sides of column or loaded area |
| $\beta_{ds}$ | Ratio used to account for reduction of stiffness of columns due to sustained lateral load |
| $\beta_{dns}$ | Ratio of maximum factored dead-load moment to maximum factored total moment |
| $\beta_t$ | Ratio of torsional stiffness of edge beam section to flexural stiffness of slab: $E_{cb}C/2E_{cs}I_s$ |
| $\gamma$ | Distance between rows of reinforcement on opposite sides of columns to total depth of column $h$ |
| $\gamma_f$ | Fraction of unbalanced moment transferred by flexure at slab–column connections |
| $\gamma_p$ | Factor for type of prestressing tendon (0.4 or 0.28) |
| $\gamma_v$ | Fraction of unbalanced moment transferred by eccentricity of shear at slab-column connections |
| $\delta$ | Magnification factor |
| $\delta_{ns}$ | Moment magnification factor for frames braced against sidesway |
| $\delta_s$ | Moment magnification factor for frames not braced against sidesway |
| $\Delta$ | Deflection |
| $\varepsilon$ | Strain |
| $\varepsilon_c$ | Strain in concrete |
| $\varepsilon_s$ | Strain in steel |
| $\varepsilon'_s$ | Strain in compression steel |
| $\varepsilon_y$ | Yield strain $= f_y/E_s$ |
| $\theta$ | Slope angle |
| $\lambda$ | Multiplier factor for reduced mechanical properties of lightweight concrete |
| $\lambda_\Delta$ | Multiplier for additional long-time deflection |
| $\mu$ | Poisson's ratio; coefficient of friction |
| $\zeta$ | Parameter for evaluating capacity of standard hook |

| | |
|---|---|
| $\pi$ | Constant equal to approximately 3.1416 |
| $\rho$ | Ratio of the tension steel area to the effective concrete area $= A_s/bd$ |
| $\rho'$ | Ratio of compression steel area to effective concrete area $= A'_s/bd$ |
| $\rho_1$ | $\rho - \rho'$ |
| $\rho_b$ | Balanced steel ratio |
| $\rho_g$ | Ratio of total steel area to total concrete area |
| $\rho_p$ | Ratio of prestressed reinforcement $A_{ps}/bd$ |
| $\rho_s$ | Ratio of volume of spiral steel to volume of core |
| $\rho_w$ | $A_s/b_w d$ |
| $\phi$ | Strength reduction factor |
| $\psi_e$ | Factor used to modify development length based on reinforcement coating |
| $\psi_s$ | Factor used to modify development length based on reinforcing size |
| $\psi_t$ | Factor used to modify development length based on reinforcement location |
| $\omega$ | Tension reinforcing index $= \rho f_y/f'c$ |
| $\omega'$ | Compression reinforcing index $= \rho' f_y/f'_c$ |
| $\omega_p$ | Prestressed steel index $= \rho_p f_{ps}/f'_c$ |
| $\omega_{pw}$ | Prestressed steel index for flanged sections |
| $\omega_w$ | Tension reinforcing index for flanged sections |
| $\omega'_w$ | Compression reinforcing index for flanged sections computed as for $\omega$, $\omega_p$, and $\omega'$ |

# 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 |

| To Convert | to | Multiply By |
|---|---|---|
| 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 |
| *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 |

# CONTENTS