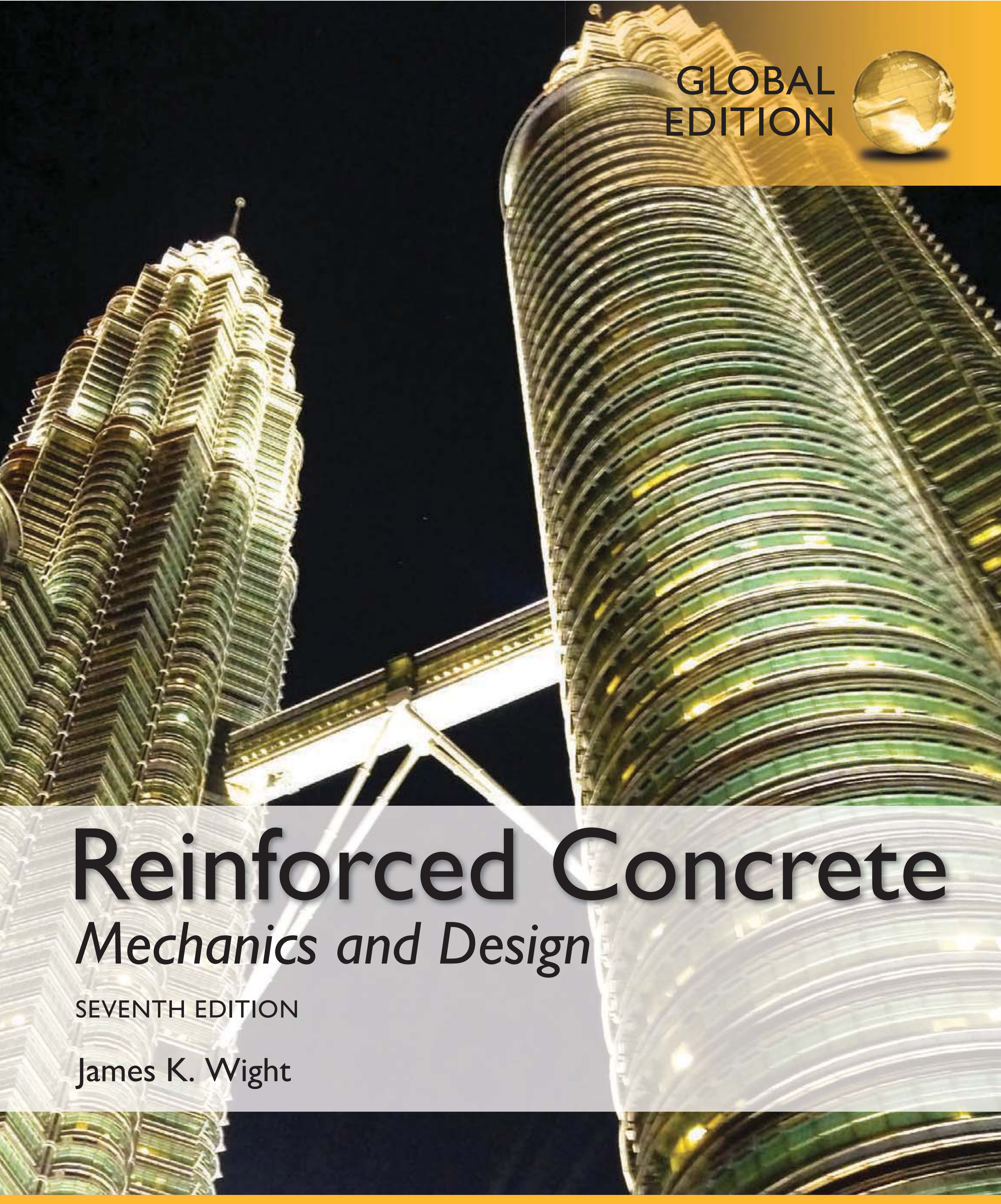

GLOBAL EDITION

# Reinforced Concrete

## *Mechanics and Design*

SEVENTH EDITION

James K. Wight

ALWAYS LEARNING

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# REINFORCED CONCRETE
# Mechanics and Design

## Global Edition

# About the Cover

Standing at 452 m, the KLCC Petronas Twin Towers are the tallest twin towers in the world. Constructed largely of reinforced concrete with a compressive strength of up to 80 MPa, the towers have 88 floors and six basement levels. They are supported by 23-by-23 metre concrete cores and an outer ring of super columns. The towers are connected by a sky bridge at levels 41 and 42. Tower One is occupied by Petronas. Tower Two's office spaces are mostly leased out to other companies. The lower levels are occupied by the Petronas Art Gallery, Kuala Lumpur Convention Centre, and the Dewan Filharmonik Petronas concert hall among others.

# REINFORCED CONCRETE
# Mechanics and Design

## SEVENTH EDITION
### GLOBAL EDITION

JAMES K. WIGHT

*F. E. Richart, Jr. Collegiate Professor*
*Department of Civil & Environmental Engineering*
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# Contents

# Preface

Reinforced concrete design encompasses both the art and science of engineering. This book presents the theory of reinforced concrete design as a direct application of the laws of statics and mechanics of materials. It emphasizes that a successful design not only satisfies design rules, but is capable of being built in a timely fashion for a reasonable cost and should provide a long service life.

## Philosophy of Reinforced Concrete: Mechanics and Design

A multitiered approach makes *Reinforced Concrete: Mechanics and Design* an outstanding textbook for a variety of university courses on reinforced concrete design. Topics are normally introduced at a fundamental level, and then move to higher levels where prior educational experience and the development of *engineering judgment* will be required. The analysis of the flexural strength of beam sections is presented in Chapter 4. Because this is the first significant design-related topic, it is presented at a level appropriate for new students. Closely related material on the analysis of column sections for combined axial load and bending is presented in Chapter 11 at a somewhat higher level, but still at a level suitable for a first course on reinforced concrete design. Advanced subjects are also presented in the same chapters at levels suitable for advanced undergraduate or graduate students. These topics include, for example, the complete moment versus curvature behavior of a beam section with various tension reinforcement percentages and the use of strain-compatibility to analyze either over-reinforced beam sections, or column sections with multiple layers of reinforcement. More advanced topics are covered in the later chapters, making this textbook valuable for both undergraduate and graduate courses, as well as serving as a key reference in design offices. Other features include the following:

**1.** Extensive figures are used to illustrate aspects of reinforced concrete member behavior and the design process.

**2.** Emphasis is placed on logical order and completeness for the many design examples presented in the book.

**3.** Guidance is given in the text and in examples to help students develop the engineering judgment required to become a successful designer of reinforced concrete structures.

**4.** Chapters 2 and 3 present general information on various topics related to structural design and construction, and concrete material properties. Frequent references are made back to these topics throughout the text.

## Overview—Reorganization of the ACI Building Code

The ACI 318-14 Building Code for Structural Concrete addresses design and detailing requirements for concrete members. The 2014 Code has been reorganized to make technical material more accessible by presenting it in a member-based design format. Each member chapter presents the required technical information for design of a specific member in a logical and repeatable format that should be more intuitive for younger and less-experienced engineers. Each member chapter is organized such that when a structural designer has completed the chapter, all of the design requirements for that member will have been satisfied. Also, the sequencing of the member-based design chapters were arranged to parallel a typical design process that follows the flow of forces from slabs, to beams, to columns, and finally to the foundation.

To avoid duplication from chapter to chapter, the code committee came up with the concept of "toolbox" chapters where key sets of equations and tabulated limits are located. For example, the design for shear strength in a beam, one-way slab or column may all use the same set of equations that are contained in a toolbox chapter. So, when designing a beam for shear, the structural engineering will be directed to the toolbox chapter to select the applicable shear strength equations. After completing the shear design, the engineer will return to the Beam Chapter and continue to the next design step.

A key change was to make more extensive use of tables to replace design requirements that were previously presented in a paragraph format. The code committee believed tables permitted the presentation of design requirements in a form that engineers understand, thus leading to less confusion or potential misinterpretations. Another change was to subdivide lengthy and difficult-to-interpret provisions into shorter statements that address a single design or detailing requirement.

The reorganization process identified overlapping provisions, which were consolidated into a single location, and technical gaps, which were filled with either new sections or chapters, for example chapters on Structural System Requirements and design and detailing for structural Diaphragms. During the reorganization effort, only a limited number of technical changes were made to existing design provisions. Thus, the knowledge base contained in prior editions of the ACI Code has been retained and enhanced.

## Changes and Features for the Seventh Edition

All chapters of the text have been reviewed and updated to be in compliance with the 2014 edition of the ACI Building Code. New problems were developed for several chapters and all of the examples given in the book were either reworked or checked for accuracy. Other changes and some continuing features include the following.

**1.** The presentation of technical information in Chapters 6, 7, and 17 was rearranged to provide a better flow from discussions of member behavior to development of design code requirements. In Chapter 7 additional information was given for the equivalent tube analogies used to define member strength and behavior before and after torsional cracking.

**2.** Changes were made in the earthquake-resistant design requirements in Chapter 19 to be in compliance with updates to seismic provisions in the ACI Building Code. A key change is the requirement for more transverse reinforcement in columns subjected to a high level of axial load.

**3.** Flexural design procedures for the full spectrum of beam sections are developed in Chapter 5. Although these design procedures are developed for beam sections, they are easily applied to the flexural design of one-way and two-way slab sections.

**4.** The design of coupled shear walls and coupling beams in seismic regions is given in Chapter 19, including a discussion of coupling beams with moderate span-to-depth ratios, a topic not well-covered in the ACI Building Code.

**5.** Chapter 2 contains a discussion of sustainability for design and construction of concrete structures. The use of concrete in building construction for reduced $CO_2$ emissions and life-cycle costs, as well as improved thermal properties and building aesthetics are discussed.

**6.** Information is provided for structural analysis of both one-way (Chapter 5) and two-way (Chapter 13) continuous floor systems. Typical modeling assumptions for both types of systems and the interplay between analysis and design are discussed.

**7.** Axial load vs. moment interaction diagrams are given for a variety of column sections in Appendix A. These diagrams include the required strength-reduction factor, and thus, are very useful for section design either in a classroom or a design office.

Video Solution

**8.** Video solutions are given for a variety of problems assigned in various chapters. These videos, which were developed by the author, provide step-by-step procedures for solving analysis or design problems. Icons in the margin identify problems for which video solutions are provided. Video Solutions are provided on the Companion Website at www.pearsonglobaleditions.com/wight.

## Use of Textbook in Undergraduate and Graduate Courses

The following paragraphs give a suggested set of topics and chapters to be covered in the first and second reinforced concrete design courses, normally given at the undergraduate and graduate levels, respectively. It is assumed that these are semester courses.

### *First Design Course*

**Chapters 1 through 3** should be assigned, but the detailed information on loading in Chapter 2 can be covered in a second course. The information on concrete material properties in Chapter 3 could be covered with more depth in a separate undergraduate materials course. **Chapters 4 and 5** are extremely important for all students and should form the foundation of the first undergraduate course. The information in Chapter 4 on moment vs. curvature behavior of beam sections is important for all designers, but this topic could be significantly expanded in a graduate course. Chapter 5 presents a variety of design procedures for developing efficient flexural designs of either singly-reinforced or doubly-reinforced sections. The discussion of structural analysis for continuous floor systems in Section 5-2 could be skipped if either time is limited or students are not yet prepared to handle this topic. The first undergraduate course should cover **Chapter 6** information on member behavior in shear and the shear design requirements given in the ACI Code. Discussions of other methods for determining the shear strength of concrete members can be saved for a second design course. Design for torsion, as covered in **Chapter 7**, could be covered in a first design course, but more often is left for a second design course. The reinforcement anchorage provisions of **Chapter 8** are important material for the first undergraduate design course. Students should develop a basic understanding of development length requirements for straight and hooked bars, as well as the procedure to determine bar cutoff points and reinforcement details required at those cutoff points. The serviceability requirements in **Chapter 9** for control of deflections and cracking are also important topics for the first undergraduate course. In particular, the ability to do an elastic section analysis and find moments of inertia for cracked and uncracked sections is an important skill for designers of concrete structures. **Chapter 10** serves to tie together all of the requirements for continuous floor systems introduced in Chapters 5 through 9. The examples include details for flexural and shear design, as well as full-span detailing of longitudinal and transverse reinforcement. This chapter could either be skipped for the first undergraduate course or be used as a source for a more extensive class design project. **Chapter 11** concentrates on the analysis and design of columns sections and should be included in the first undergraduate course. The portion of Chapter 11 that covers column sections subjected to biaxial bending may either be included in a first undergraduate course or saved for a graduate course. **Chapter 12** considers slenderness effects in columns, and the more detailed analysis required for this topic is commonly presented in a graduate course. If time permits, the basic information in **Chapter 15** on the design of typical concrete footings may be included in a first undergraduate course. This material may also be covered in a foundation design course taught at either the undergraduate or graduate level.

### *Second Design Course*

Clearly, the instructor in a graduate design course has many options for topics, depending on his/her interests and the preparation of the students. **Chapter 13** is a lengthy chapter and is intended to be a significant part of a graduate course. The chapter gives extensive coverage of flexural analysis and design of two-way floor systems that builds on the analysis and design of one-way floor systems covered in Chapter 5. The direct design method and the classic equivalent frame method are discussed, along with more modern analysis and modeling techniques. Problems related to punching shear and the combined transfer of shear and moment at slab-to-column connections are covered in detail. The design of slab shear reinforcement, including the use of shear studs, is also presented. Finally, procedures for calculating deflections in two-way floor systems are given. Design for torsion, as given in **Chapter 7**, should be covered in conjunction with the design and analysis of two-way floor systems in Chapter 13. The design procedure for compatibility torsion at the edges of a floor system has a direct impact on the design of adjacent floor members. The presentation of the yield-line method in **Chapter 14** gives students an alternative analysis and design method for two-way slab systems. This topic could also tie in with plastic analysis methods taught in graduate level analysis courses. The analysis and design of slender columns, as presented in **Chapter 12**, should also be part of a graduate design course. The students should be prepared to apply the frame analysis and member modeling techniques required to either directly determine secondary moments or calculate the required moment-magnification factors. Also, if the topic of biaxial bending in Chapter 11 was not covered in the first design course, it could be included at this point. **Chapter 18** covers bending and shear design of structural walls that resist lateral loads due to either wind or seismic effects. A capacity-design approach is introduced for the shear design of walls that resist earthquake-induced lateral forces. **Chapter 17** covers the concept of *disturbed* regions (D-regions) and the use of the strut-and-tie models to analyze the flow of forces through D-regions and to select appropriate reinforcement details. The chapter contains detailed examples to help students learn the concepts and code requirements for strut-and-tie models. If time permits, instructors could cover the design of combined footings in **Chapter 15**, shear-friction design concepts in **Chapter 16**, and design to resist earthquake-induced forces in **Chapter 19**.

## Instructor Materials

An Instructor's Solutions Manual and PowerPoints to accompany this text are available for download to instructors only at www.pearsonglobaleditions.com/wight.


## Acknowledgment

I would like to take this opportunity to acknowledge the pioneering work done for this textbook by my former co-author, Professor James G. MacGregor. Professor MacGregor was the sole author of this textbook through its first three editions. He initiated the layout of the chapters and the presentation style of first developing an understanding of member and structural behavior, followed by derivation of specific design requirements. I used Professor MacGregor's textbook in my reinforced concrete design classes and I was very happy to join him as a co-author for the Fourth Edition. I became the primary author for the Fifth and Sixth Editions, and I owe a great deal of gratitude to Professor MacGregor for creating an outstanding textbook that I have had the privilege of modifying and enhancing. I wish to express sincere thanks to my recently departed colleague, James G. MacGregor, and best wishes to his devoted wife, Barb.

Pearson would like to thank and acknowledge Wen-Cheng Liao, National Taiwan University, for contributing to the Global Edition, and Hany Maximos, Pharos University of Alexandria, and Kaustubh Dasgupta, Indian Institute of Technology Guwahati, for reviewing the Global Edition.


## Dedication

This book is dedicated to all of my colleagues and students who have either interacted with me or taken my classes over the years. My knowledge of the behavior of reinforced concrete members and my development of various design procedures for concrete members and structures was significantly enhanced by my numerous interactions with all of you. I also wish to dedicate this book to my wife, Linda, for her support and encouragement through many long evenings and lost weekends.

The manuscript for the fifth edition book was reviewed by Guillermo Ramirez of the University of Texas at Arlington; Devin Harris of Michigan Technological University; Sami Rizkalla of North Carolina State University; Aly Marei Said of the University of Nevada, Las Vegas; and Roberto Leon of Georgia Institute of Technology. Suggested changes for the sixth edition were submitted by Christopher Higgins and Thomas Schumacher of Oregon State University, Dionisio Bernal of Northeastern University, R. Paneer Selvam of the University of Arkansas, Aly Said of the University of Nevada and Chien-Chung Chen of Pennsylvania State University. The book was reviewed for accuracy by Robert W. Barnes and Anton K. Schindler of Auburn University. This book was greatly improved by all of their suggestions.


James K. Wight<br>
*F. E. Richart, Jr. Collegiate Professor*<br>
*University of Michigan*

# About the Author

**James K. Wight** received his B.S. and M.S. degrees in civil engineering from Michigan State University in 1969 and 1970, respectively, and his Ph.D. from the University of Illinois in 1973. He has been a professor of structural engineering in the Civil and Environmental Engineering Department at the University of Michigan since 1973. He teaches undergraduate and graduate classes on analysis and design of reinforced concrete structures. He is well known for his work in earthquake-resistant design of concrete structures and spent a one-year sabbatical leave in Japan where he was involved in the construction and simulated earthquake testing of a full-scale reinforced concrete building. Professor Wight has been an active member of the American Concrete Institute (ACI) since 1973 and was named a Fellow of the Institute in 1984. He is a Past-President of ACI and a past Chair of the ACI Building Code Committee 318. He is also past Chair of the ACI Technical Activities Committee and Committee 352 on Joints and Connections in Concrete Structures. He has received several awards from the American Concrete Institute including the Delmar Bloem Distinguished Service Award (1991), the Joe Kelly Award (1999), the Boise Award (2002), the C.P. Siess Structural Research Award (2003 and 2009), the Alfred Lindau Award (2008), the Wason Medal (2012), and the Charles S. Whitney Medal (2015). Professor Wight has received numerous awards for his teaching and service at the University of Michigan, including the ASCE Student Chapter Teacher of the Year Award, the College of Engineering Distinguished Service Award, the College of Engineering Teaching Excellence Award, the Chi Epsilon-Great Lakes District Excellence in Teaching Award, and the Rackham Distinguished Graduate Mentoring Award. He has also received Distinguished Alumnus Awards from the Civil and Environmental Engineering Departments of the University of Illinois (2008) and Michigan State University (2009).

# 1

# Introduction

## 1-1 REINFORCED CONCRETE STRUCTURES

Concrete and reinforced concrete are used as building construction materials in every country. In many, including the United States and Canada, reinforced concrete is a dominant structural material in engineered construction. The universal nature of reinforced concrete construction stems from the wide availability of reinforcing bars and of the constituents of concrete (gravel or crushed rock, sand, water, and cement), from the relatively simple skills required in concrete construction, and from the economy of reinforced concrete compared with other forms of construction. Plain concrete and reinforced concrete are used in buildings of all sorts (Fig. 1-1), underground structures, water tanks, wind turbine foundations (Fig. 1-2) and towers, offshore oil exploration and production structures, dams, bridges (Fig. 1-3), and even ships.

## 1-2 MECHANICS OF REINFORCED CONCRETE

Concrete is strong in compression, but weak in tension. As a result, cracks develop whenever loads, restrained shrinkage, or temperature changes give rise to tensile stresses in excess of the tensile strength of the concrete. In the plain concrete beam shown in Fig. 1-4b, the moments about point *O* due to applied loads are resisted by an internal tension–compression couple involving tension in the concrete. An unreinforced beam fails very suddenly and completely when the first crack forms. In a *reinforced concrete* beam (Fig. 1-4c), reinforcing bars are embedded in the concrete in such a way that the tension forces needed for moment equilibrium after the concrete cracks can be developed in the bars.

Alternatively, the reinforcement could be placed in a longitudinal duct near the bottom of the beam, as shown in Fig. 1-5, and stretched or *prestressed*, reacting on the concrete in the beam. This would put the reinforcement into tension and the concrete into compression. This compression would delay cracking of the beam. Such a member is said to be a *prestressed concrete* beam. The reinforcement in such a beam is referred to as *prestressing tendons* and must be fabricated from high-strength steel.

The construction of a reinforced concrete member involves building a form or mould in the shape of the member being built. The form must be strong enough to support the weight and hydrostatic pressure of the wet concrete, plus any forces applied to it by workers,

Fig. 1-1
Trump Tower of Chicago. (Photograph courtesy of Larry Novak, Portland Cement Association.)

*Completed in 2009, the 92-story Trump International Hotel and Tower is an icon of the Chicago skyline. With a height of 1170 ft (1389 ft to the top of the spire), the Trump Tower is the tallest building built in North America since the completion of Sears Tower in 1974. The all reinforced concrete residential/hotel tower was designed by Skidmore, Owings & Merrill LLP (SOM). The tower's 2.6 million $ft^2$ of floor space is clad in stainless steel and glass, providing panoramic views of the City and Lake Michigan. The project utilized high-performance concrete mixes specified by SOM and designed by Prairie Materials Sales. The project includes self-consolidating concrete with strengths as high as 16,000 psi. The Trump Tower is not only an extremely tall structure; it is also very slender with an aspect ratio exceeding 8 to 1 (height divided by structural base dimension). Slender buildings can be susceptible to dynamic motions under wind loads. To provide the required stiffness, damping, and mass to assist in minimizing the dynamic movements, high-performance reinforced concrete was selected as the primary structural material for the tower. Lateral wind loads are resisted by a core and outrigger system. Additional torsional stiffness and structural robustness is provided by perimeter belt walls at the roof and three mechanical levels. The typical residential floor system consists of 9-in. thick flat plates with spans up to 30 ft.*

concrete casting equipment, wind, and so on. The reinforcement is placed in the form and held in place during the concreting operation. After the concrete has reached sufficient strength, the forms can be removed.

## 1-3 REINFORCED CONCRETE MEMBERS

Reinforced concrete structures consist of a monolithic series of "members" that interact to support the loads placed on the structure. The second floor of the building in Fig. 1-6 is built of concrete joist–slab construction. Here, a series of parallel ribs or *joists* support the load from the top slab. The reactions supporting the joists apply loads to the beams, which in turn are supported by columns. In such a floor, the top slab has two functions: (1) it transfers load laterally to the joists, and (2) it serves as the top flange of the joists, which act as T-shaped beams that transmit the load to the beams running at right angles to the joists.

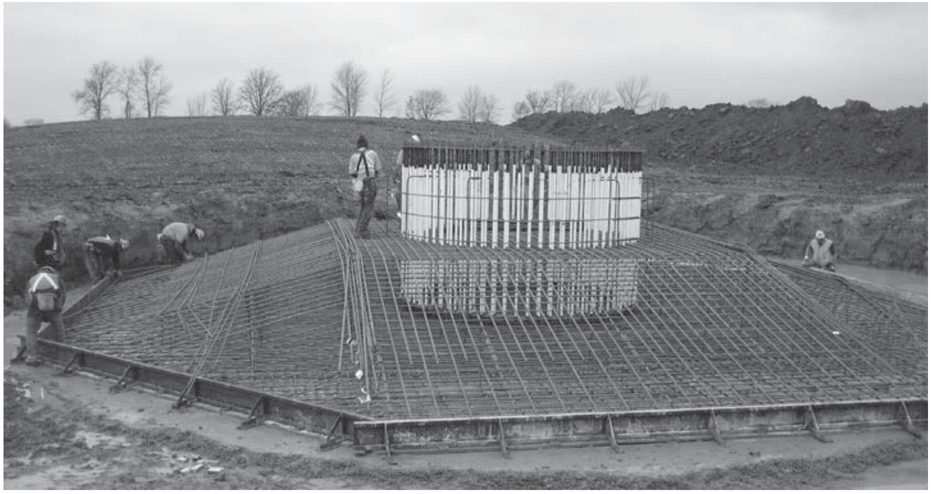

Fig. 1-2
Wind turbine foundation.
(Photograph courtesy of
Invenergy.)

*This wind turbine foundation was installed at Invenergy's Raleigh Wind Energy Center in Ontario, Canada, to support a 1.5 MW turbine with an 80 meter hub height. It consists of 313 cubic yards of 4350 psi concrete, 38,000 lbs of reinforcing steel and is designed to withstand an overturning moment of 29,000 kip-ft. Each of the 140 anchor bolts shown in the photo is post-tensioned to 72 kips.*

Fig. 1-3
St. Anthony Falls Bridge.
(Photograph courtesy of
FIGG Bridge Engineers, Inc.)

*The new I-35W Bridge (St. Anthony Falls Bridge) in Minneapolis, Minnesota, features a 504 ft main span over the Mississippi River. The concrete piers and superstructure were shaped to echo the arched bridges and natural features in the vicinity. The bridge was designed by FIGG Bridge Engineers, Inc. and constructed by Flatiron-Manson Joint Venture in less than 14 months after the tragic collapse of the former bridge at this site. Segmentally constructed post-tensioned box girders with a specified concrete strength of 6500 psi were used for the bridge superstructure. The tapered piers were cast-in-place and used a specified concrete strength of 4000 psi. Also, a new self-cleaning pollution-eating concrete was used to construct two 30-ft gateway sculptures located at each end of the bridge. A total of approximately 50,000 cubic yards of concrete and 7000 tons of reinforcing bars and post-tensioning steel were used in the project.*

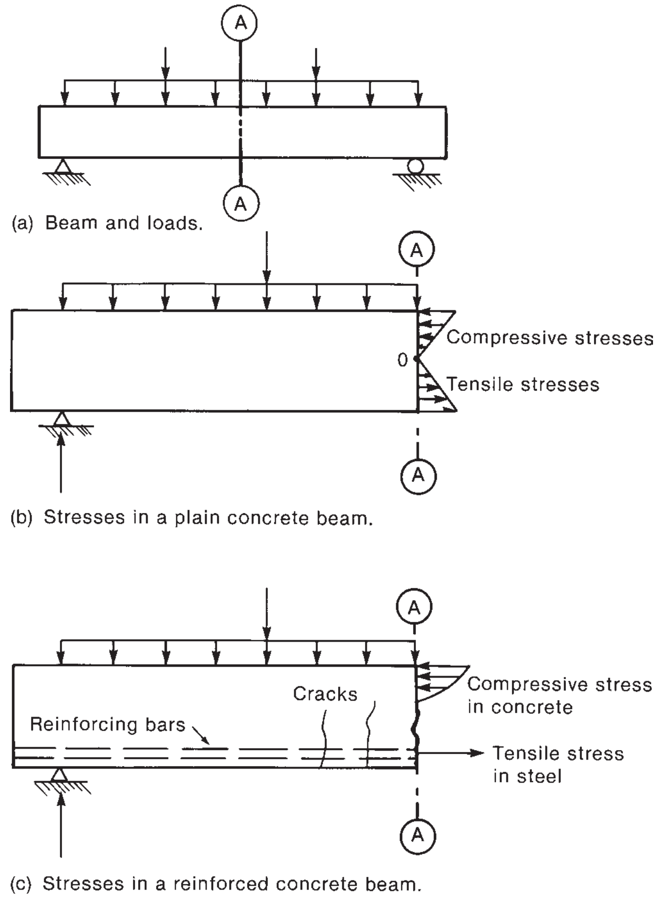


Fig. 1-4
Plain and reinforced concrete beams.

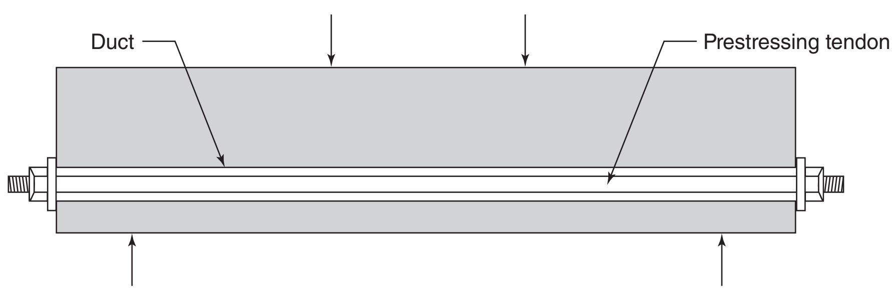


Fig. 1-5
Prestressed concrete beam.

The first floor of the building in Fig. 1-6 has a slab-and-beam design in which the slab spans between beams, which in turn apply loads to the columns. The column loads are applied to *spread footings*, which distribute the load over an area of soil sufficient to prevent overloading of the soil. Some soil conditions require the use of pile foundations or other deep foundations. At the perimeter of the building, the floor loads are supported either directly on the walls, as shown in Fig. 1-6, or on exterior columns, as shown in Fig. 1-7. The walls or columns, in turn, are supported by a basement wall and wall footings.

The first and second floor slabs in Fig. 1-6 are assumed to carry the loads in a north–south direction (see direction arrow) to the joists or beams, which carry the loads in an east–west

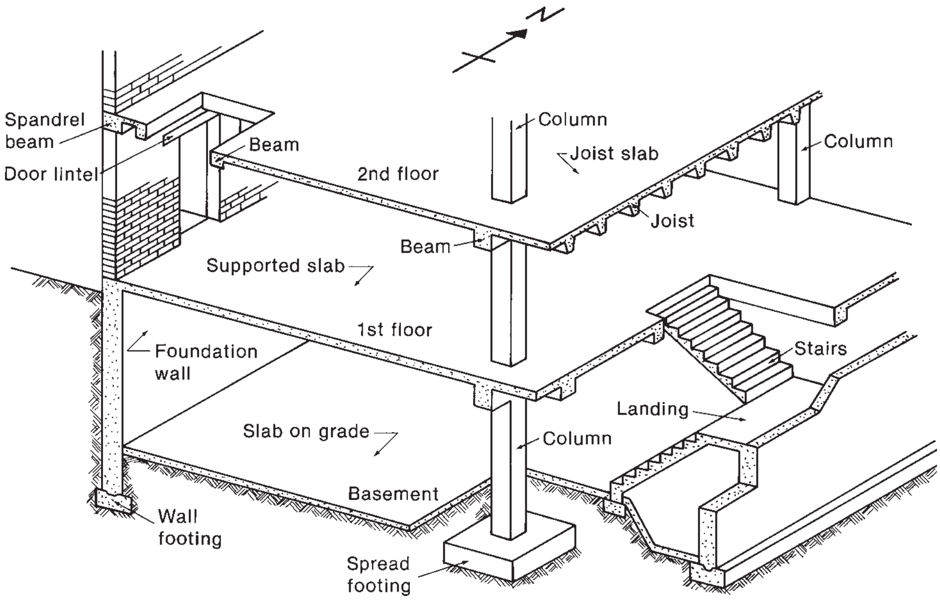


Fig. 1-6
Reinforced concrete building elements. (Adapted from [1-1].)

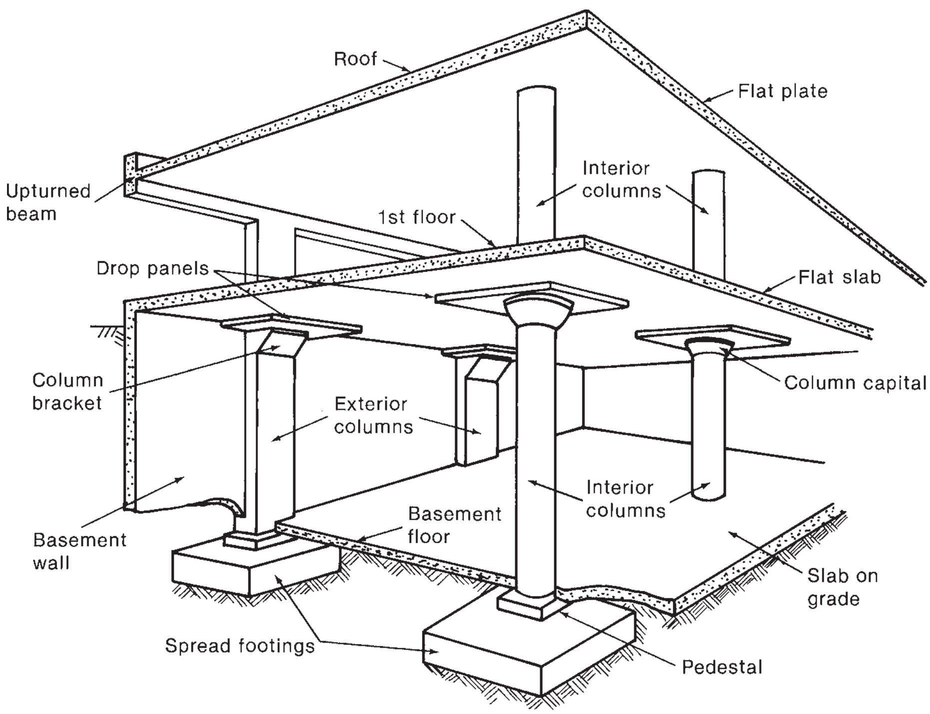


Fig. 1-7
Reinforced concrete building elements. (Adapted from [1-1].)

direction to other beams, girders, columns, or walls. This is referred to as *one-way slab* action and is analogous to a wooden floor in a house, in which the floor decking transmits loads to perpendicular floor joists, which carry the loads to supporting beams, and so on.

The ability to form and construct concrete slabs makes possible the slab or plate type of structure shown in Fig. 1-7. Here, the loads applied to the roof and the floor are transmitted in two directions to the columns by plate action. Such slabs are referred to as *two-way slabs*.

The first floor in Fig. 1-7 is a *flat slab* with thickened areas called *drop panels* at the columns. In addition, the tops of the columns are enlarged in the form of *capitals* or *brackets*. The thickening provides extra depth for moment and shear resistance adjacent to the columns. It also tends to reduce the slab deflections.

The roof of the building shown in Fig. 1-7 is of uniform thickness throughout, without drop panels or column capitals. Such a floor is a special type of *flat slab* referred to as a *flat plate*. Flat-plate floors are widely used in apartments because the underside of the slab is flat and hence, can be used as the ceiling of the room below. Of equal importance, the forming for a flat plate is generally cheaper than that for flat slabs with drop panels or for one-way slab-and-beam floors.

## 1-4 FACTORS AFFECTING CHOICE OF REINFORCED CONCRETE FOR A STRUCTURE

The choice of whether a structure should be built of reinforced concrete, steel, masonry, or timber depends on the availability of materials and on a number of value decisions.

**1. Economy.** Frequently, the foremost consideration is the overall cost of the structure. This is, of course, a function of the costs of the materials and of the labor and time necessary to erect the structure. Concrete floor systems tend to be thinner than structural steel systems because the girders and beams or joists all fit within the same depth, as shown in the second floor in Fig. 1-6, or the floors are flat plates or flat slabs, as shown in Fig. 1-7. This produces an overall reduction in the height of a building compared to a steel building, which leads to (a) lower wind loads because there is less area exposed to wind and (b) savings in cladding and mechanical and electrical risers.

Frequently, however, the overall cost is affected as much or more by the overall construction time, because the contractor and the owner must allocate money to carry out the construction and will not receive a return on their investment until the building is ready for occupancy. As a result, financial savings due to rapid construction may more than offset increased material and forming costs. The materials for reinforced concrete structures are widely available and can be produced as they are needed in the construction, whereas structural steel must be ordered and partially paid for in advance to schedule the job in a steel-fabricating yard.

Any measures the designer can take to standardize the design and forming will generally pay off in reduced overall costs. For example, column sizes may be kept the same for several floors to save money in form costs, while changing the concrete strength or the percentage of reinforcement allows for changes in column loads.

**2. Suitability of material for architectural and structural function.** A reinforced concrete system frequently allows the designer to combine the architectural and structural functions. Concrete has the advantage that it is placed in a plastic condition and is given the desired shape and texture by means of the forms and the finishing techniques. This allows such elements as flat plates or other types of slabs to serve as load-bearing elements while providing the finished floor and ceiling surfaces. Similarly, reinforced concrete walls can provide architecturally attractive surfaces in addition to having the ability to resist gravity, wind, or seismic loads. Finally, the choice of size or shape is governed by the designer and not by the availability of standard manufactured members.

**3. Fire resistance.** The structure in a building must withstand the effects of a fire and remain standing while the building is being evacuated and the fire extinguished. A concrete building inherently has a 1- to 3-hour fire rating without special fireproofing or other details. Structural steel or timber buildings must be fireproofed to attain similar fire ratings.

**4. Rigidity.** The occupants of a building may be disturbed if their building oscillates in the wind or if the floors vibrate as people walk by. Due to the greater stiffness and mass of a concrete structure, vibrations are seldom a problem.

**5. Low maintenance.** Concrete members inherently require less maintenance than do structural steel or timber members. This is particularly true if dense, air-entrained concrete has been used for surfaces exposed to the atmosphere and if care has been taken in the design to provide adequate drainage from the structure.

**6. Availability of materials.** Sand, gravel or crushed rock, water, cement, and concrete mixing facilities are very widely available, and reinforcing steel can be transported to most construction sites more easily than can structural steel. As a result, reinforced concrete is frequently the preferred construction material in remote areas.

On the other hand, there are a number of factors that may cause one to select a material other than reinforced concrete. These include:

**1. Low tensile strength.** As stated earlier, the tensile strength of concrete is much lower than its compressive strength (about $\frac{1}{10}$); hence, concrete is subject to cracking when subjected to tensile stresses. In structural uses, the cracking is restrained by using reinforcement, as shown in Fig. 1-4c, to carry tensile forces and limit crack widths to within acceptable values. Unless care is taken in design and construction, however, these cracks may be unsightly or may allow penetration of water and other potentially harmful contaminants.

**2. Forms and shoring.** The construction of a cast-in-place structure involves three steps not encountered in the construction of steel or timber structures. These are: (a) the construction of the forms, (b) the removal of these forms, and (c) the propping or shoring of the new concrete to support its weight until its strength is adequate. Each of these steps involves labor and/or materials that are not necessary with other forms of construction.

**3. Relatively low strength per unit of weight or volume.** The compressive strength of concrete is roughly 10 percent that of steel, while its unit density is roughly 30 percent that of steel. As a result, a concrete structure requires a larger volume and a greater weight of material than does a comparable steel structure. As a result, steel is often selected for long-span structures.

**4. Time-dependent volume changes.** Both concrete and steel undergo approximately the same amount of thermal expansion and contraction. Because there is less mass of steel to be heated or cooled, and because steel is a better conductor than concrete, a steel structure is generally affected by temperature changes to a greater extent than is a concrete structure. On the other hand, concrete undergoes drying shrinkage, which, if restrained, may cause deflections or cracking. Furthermore, deflections in a concrete floor will tend to increase with time, possibly doubling, due to creep of the concrete under sustained compression stress.

## 1-5 HISTORICAL DEVELOPMENT OF CONCRETE AND REINFORCED CONCRETE AS STRUCTURAL MATERIALS

### Cement and Concrete

Lime mortar was first used in structures in the Minoan civilization in Crete about 2000 B.C. and is still used in some areas. This type of mortar had the disadvantage of gradually dissolving when immersed in water and hence could not be used for exposed or underwater joints. About the third century B.C., the Romans discovered a fine sandy volcanic ash that, when mixed with lime mortar, gave a much stronger mortar, which could be used under water.

One of the most remarkable concrete structures built by the Romans was the dome of the Pantheon in Rome, completed in A.D. 126. This dome has a span of 144 ft, a span not exceeded until the nineteenth century. The lowest part of the dome was concrete with aggregate consisting of broken bricks. As the builders approached the top of the dome they used lighter and lighter aggregates, using pumice at the top to reduce the dead-load moments. Although the outside of the dome was, and still is, covered with decorations, the marks of the forms are still visible on the inside [1-2], [1-3].

While designing the Eddystone Lighthouse off the south coast of England just before A.D. 1800, the English engineer John Smeaton discovered that a mixture of burned limestone and clay could be used to make a cement that would set under water and be water resistant. Owing to the exposed nature of this lighthouse, however, Smeaton reverted to the tried-and-true Roman cement and mortised stonework.

In the ensuing years a number of people used Smeaton's material, but the difficulty of finding limestone and clay in the same quarry greatly restricted its use. In 1824, Joseph Aspdin mixed ground limestone and clay from different quarries and heated them in a kiln to make cement. Aspdin named his product Portland cement because concrete made from it resembled Portland stone, a high-grade limestone from the Isle of Portland in the south of England. This cement was used by Brunel in 1828 for the mortar in the masonry liner of a tunnel under the Thames River and in 1835 for mass concrete piers for a bridge. Occasionally in the production of cement, the mixture would be overheated, forming a hard clinker, which was considered to be spoiled and was discarded. In 1845, I. C. Johnson found that the best cement resulted from grinding this clinker. This is the material now known as Portland cement. Portland cement was produced in Pennsylvania in 1871 by D. O. Saylor and about the same time in Indiana by T. Millen of South Bend, but it was not until the early 1880s that significant amounts were produced in the United States.

## Reinforced Concrete

W. B. Wilkinson of Newcastle-upon-Tyne obtained a patent in 1854 for a reinforced concrete floor system that used hollow plaster domes as forms. The ribs between the forms were filled with concrete and were reinforced with discarded steel mine-hoist ropes in the center of the ribs. In France, Lambot built a rowboat of concrete reinforced with wire in 1848 and patented it in 1855. His patent included drawings of a reinforced concrete beam and a column reinforced with four round iron bars. In 1861, another Frenchman, Coignet, published a book illustrating uses of reinforced concrete.

The American lawyer and engineer Thaddeus Hyatt experimented with reinforced concrete beams in the 1850s. His beams had longitudinal bars in the tension zone and vertical stirrups for shear. Unfortunately, Hyatt's work was not known until he privately published a book describing his tests and building system in 1877.

Perhaps the greatest incentive to the early development of the scientific knowledge of reinforced concrete came from the work of Joseph Monier, owner of a French nursery garden. Monier began experimenting in about 1850 with concrete tubs reinforced with iron for planting trees. He patented his idea in 1867. This patent was rapidly followed by patents for reinforced pipes and tanks (1868), flat plates (1869), bridges (1873), and stairs (1875). In 1880 and 1881, Monier received German patents for many of the same applications. These were licensed to the construction firm Wayss and Freitag, which commissioned Professors Mörsch and Bach of the University of Stuttgart to test the strength of reinforced concrete and commissioned Mr. Koenen, chief building inspector for Prussia, to develop a method for computing the strength of reinforced concrete. Koenen's book, published in 1886, presented an analysis that assumed the neutral axis was at the midheight of the member.

The first reinforced concrete building in the United States was a house built on Long Island in 1875 by W. E. Ward, a mechanical engineer. E. L. Ransome of California experimented with reinforced concrete in the 1870s and patented a twisted steel reinforcing bar in 1884. In the same year, Ransome independently developed his own set of design procedures. In 1888, he constructed a building having cast-iron columns and a reinforced concrete floor system consisting of beams and a slab made from flat metal arches covered with concrete. In 1890, Ransome built the Leland Stanford, Jr. Museum in San Francisco. This two-story building used discarded cable-car rope as beam reinforcement. In 1903 in Pennsylvania, he built the first building in the United States completely framed with reinforced concrete.

In the period from 1875 to 1900, the science of reinforced concrete developed through a series of patents. An English textbook published in 1904 listed 43 patented systems, 15 in France, 14 in Germany or Austria–Hungary, 8 in the United States, 3 in the United Kingdom, and 3 elsewhere. Most of these differed in the shape of the bars and the manner in which the bars were bent.

From 1890 to 1920, practicing engineers gradually gained a knowledge of the mechanics of reinforced concrete, as books, technical articles, and codes presented the theories. In an 1894 paper to the French Society of Civil Engineers, Coignet (son of the earlier Coignet) and de Tedeskko extended Koenen's theories to develop the working-stress design method for flexure, which was used universally from 1900 to 1950. During the past seven decades, extensive research has been carried out on various aspects of reinforced concrete behavior, resulting in the current design procedures.

Prestressed concrete was pioneered by E. Freyssinet, who in 1928 concluded that it was necessary to use high-strength steel wire for prestressing because the creep of concrete dissipated most of the prestress force if normal reinforcing bars were used to develop the prestressing force. Freyssinet developed anchorages for the tendons and designed and built a number of pioneering bridges and structures.

## Design Specifications for Reinforced Concrete

The first set of building regulations for reinforced concrete were drafted under the leadership of Professor Mörsch of the University of Stuttgart and were issued in Prussia in 1904. Design regulations were issued in Britain, France, Austria, and Switzerland between 1907 and 1909.

The American Railway Engineering Association appointed a Committee on Masonry in 1890. In 1903 this committee presented specifications for portland cement concrete. Between 1908 and 1910, a series of committee reports led to the *Standard Building Regulations for the Use of Reinforced Concrete*, published in 1910 [1-4] by the National Association of Cement Users, which subsequently became the American Concrete Institute.

A Joint Committee on Concrete and Reinforced Concrete was established in 1904 by the American Society of Civil Engineers, the American Society for Testing and Materials, the American Railway Engineering Association, and the Association of American Portland Cement Manufacturers. This group was later joined by the American Concrete Institute. Between 1904 and 1910, the Joint Committee carried out research. A preliminary report issued in 1913 [1-5] lists the more important papers and books on reinforced concrete published between 1898 and 1911. The final report of this committee was published in 1916 [1-6]. The history of reinforced concrete building codes in the United States was reviewed in 1954 by Kerekes and Reid [1-7].

## 1-6 BUILDING CODES AND THE ACI CODE

The design and construction of buildings is regulated by municipal bylaws called *building codes*. These exist to protect the public's health and safety. Each city and town is free to write or adopt its own building code, and in that city or town, only that particular code has legal status. Because of the complexity of writing building codes, cities in the United States generally base their building codes on model codes. Prior to the year 2000, there were three model codes: the *Uniform Building Code* [1-8], the *Standard Building Code* [1-9], and the *Basic Building Code* [1-10]. These codes covered such topics as use and occupancy requirements, fire requirements, heating and ventilating requirements, and structural design. In 2000, these three codes were replaced by the *International Building Code* (*IBC*) [1-11], which is normally updated every three years.

The definitive design specification for reinforced concrete buildings in North America is the *Building Code Requirements for Structural Concrete* (ACI 318-14) and *Commentary* (ACI 318R-14) [1-12]. The code and the commentary are bound together in one volume.

This code, generally referred to as the *ACI Code*, has been incorporated by reference in the *International Building Code* and serves as the basis for comparable codes in Canada, New Zealand, Australia, most of Latin America, and some countries in Asia and the Middle East. The ACI Code has legal status only if adopted in a local building code.

In recent years, the ACI Code has undergone a major revision every three years. Current plans are to publish major revisions on a six-year cycle with interim revisions half-way through the cycle. This book refers extensively to the 2014 ACI Code. It is recommended that the reader have a copy available.

The term *structural concrete* is used to refer to the entire range of concrete structures: from *plain concrete* without any reinforcement; through *ordinary reinforced concrete*, reinforced with normal reinforcing bars; through *partially prestressed concrete*, generally containing both reinforcing bars and prestressing tendons; to *fully prestressed concrete*, with enough prestress to prevent cracking in everyday service. In 1995, the title of the ACI Code was changed from *Building Code Requirements for Reinforced Concrete* to *Building Code Requirements for Structural Concrete* to emphasize that the code deals with the entire spectrum of structural concrete.

The rules for the design of concrete highway bridges are specified in the *AASHTO LRFD Bridge Design Specifications*, American Association of State Highway and Transportation Officials, Washington, D.C. [1-13].

Each nation or group of nations in Europe has its own building code for reinforced concrete. The *fib Model Code for Concrete Structures* 2010 [1-14], published in 2013 by the International Federation for Structural Concrete (fib), Lausanne, Switzerland, is intended to serve as the basis for future attempts to unify European codes.

Another document that will be used extensively in Chapters 2 and 19 is the ASCE standard *ASCE/SEI 7-10*, entitled *Minimum Design Loads for Buildings and Other Structures* [1-16], published in 2010.

## REFERENCES

1-1 *Reinforcing Bar Detailing Manual*, Fourth Edition, Concrete Reinforcing Steel Institute, Chicago, IL, 290 pp.

1-2 Robert Mark, "Light, Wind and Structure: The Mystery of the Master Builders," *MIT Press*, Boston, 1990, pp. 52–67.

1-3 Michael P. Collins, "In Search of Elegance: The Evolution of the Art of Structural Engineering in the Western World," *Concrete International*, Vol. 23, No. 7, July 2001, pp. 57–72.