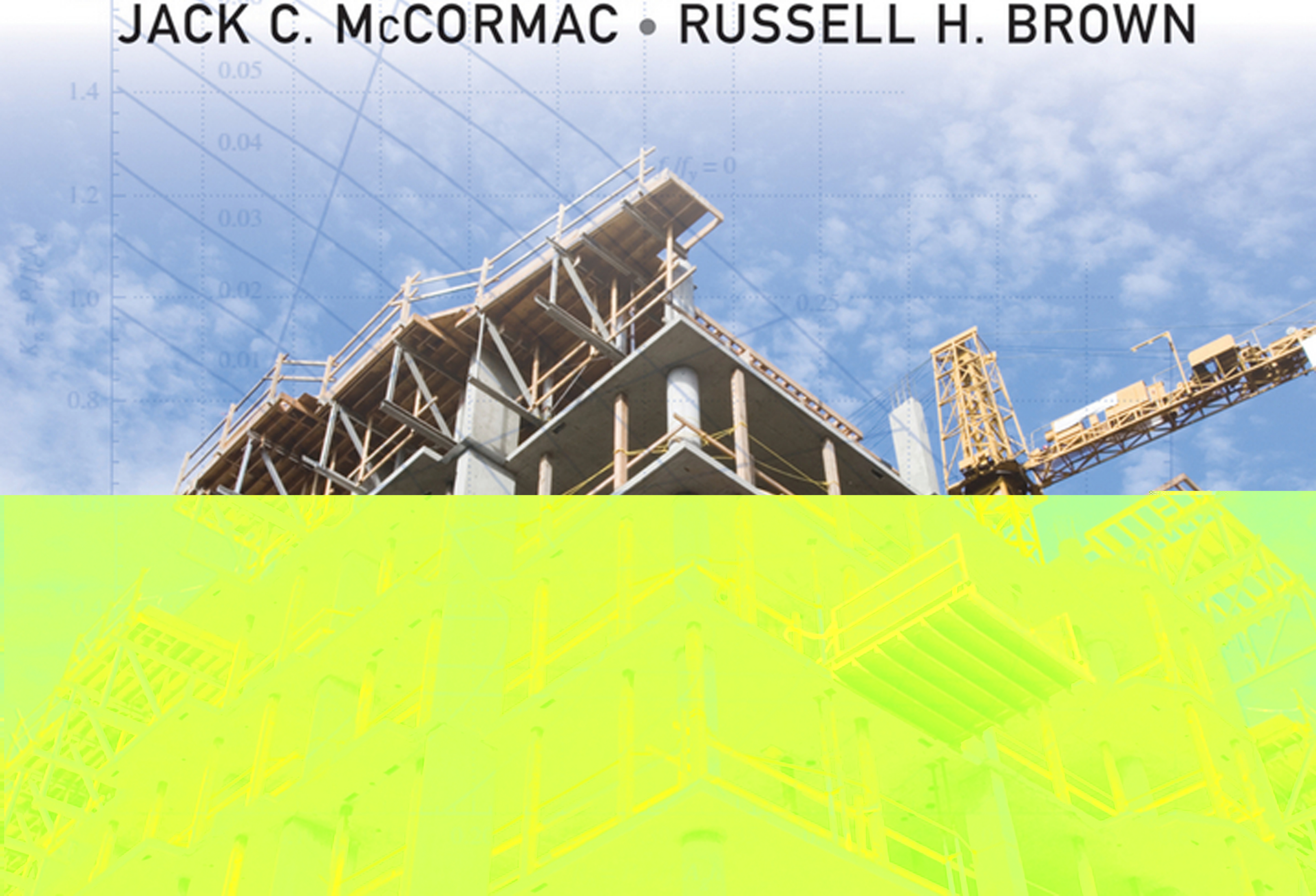
DESIGN OF REINFORCED CONCRETE

NINTH EDITION

JACK C. McCORMAC • RUSSELL H. BROWN



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ACI 318-11 Code Edition

Jack C. McCormac
Clemson University

Russell H. Brown
Clemson University

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Brief Contents

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Preface

Audience

This textbook presents an introduction to reinforced concrete design. We authors hope the material is written in such a manner as to interest students in the subject and to encourage them to continue its study in the years to come. The text was prepared with an introductory three-credit course in mind, but sufficient material is included for an additional three-credit course.

New to This Edition

Updated Code

With the ninth edition of this text, the contents have been updated to conform to the *2011 Building Code of the American Concrete Institute* (ACI 318-11). Changes to this edition of the code include:

- Factored load combinations are now based on ASCE/SEI 7-10, which now treats wind as a strength level load.
- Minor revisions to development length to headed bars.
- Addition of minimum reinforcement provisions to deep beams.
- Introduction of Grade 80 deformed bars in accordance with ASTM 615 and ASTM 706.
- Zinc and epoxy dual-coated reinforcing bars are now permitted in accordance with ASTM A1055.

New Chapter on Concrete Masonry

A new chapter on strength design of reinforced concrete masonry has been added to replace the previous Chapter 20 on formwork. Surveys revealed that the forms chapter was not being used and that a chapter on masonry would be more valuable. Because strength design of reinforced concrete masonry is so similar to that of reinforced concrete, the authors felt that this would be a logical extension to the application of the theories developed earlier in the text. The design of masonry lintels, walls loaded out-of-plane, and shear walls are included. The subject of this chapter could easily occupy an entire textbook, so this chapter is limited in scope to only the basics. An example of the design of each type of masonry element is also included to show the student some typical applications.

Units Added to Example Problems

The example problems now have units associated with the input values. This will assist the student in determining the source of each input value as well as help in the use of dimensional analysis in determining the correct answers and the units of the answers. Often the student can catch errors in calculations simply by checking the dimensions of the calculated answer against what the units are known to be.

Organization

The text is written in the order that the authors feel would follow the normal sequence of presentation for an introductory course in reinforced concrete design. In this way, it is hoped that skipping back and forth from chapter to chapter will be minimized. The material on columns is included in three chapters (Chapters 9, 10, and 11). Some instructors do not have time to cover the material on slender columns, so it was put in a separate chapter (Chapter 11). The remaining material on columns was separated into two chapters in order to emphasize the difference between columns that are primarily axially loaded (Chapter 9) and those with significant bending moment combined with axial load (Chapter 10). The material formerly in Chapter 21, "Seismic Design of Concrete Structures," has been updated and moved to a new appendix (Appendix D).

Instructor and Student Resources

The website for the book is located at www.wiley.com/college/mccormac and contains the following resources.

For Instructors

Solutions Manual A password-protected Solutions Manual, which contains complete solutions for all homework problems in the text, is available for download. Most are handwritten, but some are carried out using spreadsheets or Mathcad.

Figures in PPT Format Also available are the figures from the text in PowerPoint format, for easy creation of lecture slides.

Lecture Presentation Slides in PPT Format Presentation slides developed by Dr. Terry Weigel of the University of Louisville are available for instructors who prefer to use PowerPoint for their lectures. The PowerPoint files are posted rather than files in PDF format to permit the instructor to modify them as appropriate for his or her class.

Sample Exams Examples of sample exams are included for most topics in the text. Problems in the back of each chapter are also suitable for exam questions.

Course Syllabus A course syllabus along with a typical daily schedule are included in editable format.

Visit the Instructor Companion Site portion of the book website at www.wiley.com/college/mccormac to register for a password. These resources are available for instructors who have adopted the book for their course. The website may be updated periodically with additional material.

For Students and Instructors

Excel Spreadsheets Excel spreadsheets were created to provide the student and the instructor with tools to analyze and design reinforced concrete elements quickly to compare alternative solutions. Spreadsheets are provided for most chapters of the text, and their use is self-explanatory. Many of the cells contain comments to assist the new user. The spreadsheets can be modified by the student or instructor to suit their more specific needs. In most cases, calculations contained within the spreadsheets mirror those shown in the example problems in the text. The many uses of these spreadsheets are illustrated throughout the text. At the end of most chapters are example problems demonstrating the use of the spreadsheet for that particular chapter. Space does not permit examples for all of the spreadsheet capabilities. The examples chosen were thought by the authors to be the most relevant.

Visit the Student Companion Site portion of the book website at www.wiley.com/college/mccormac to download this software.

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Finally, we are also grateful to the reviewers and users of the previous editions of this book for their suggestions, corrections, and criticisms. We are always grateful to anyone who takes the time to contact us concerning any part of the book.

JACK C. MCCORMAC
RUSSELL H. BROWN

Introduction

CHAPTER 1

1.1 Concrete and Reinforced Concrete

Concrete is a mixture of sand, gravel, crushed rock, or other aggregates held together in a rocklike mass with a paste of cement and water. Sometimes one or more admixtures are added to change certain characteristics of the concrete such as its workability, durability, and time of hardening.

As with most rocklike substances, concrete has a high compressive strength and a very low tensile strength. *Reinforced concrete* is a combination of concrete and steel wherein the steel reinforcement provides the tensile strength lacking in the concrete. Steel reinforcing is also capable of resisting compression forces and is used in columns as well as in other situations, which are described later.

1.2 Advantages of Reinforced Concrete as a Structural Material

Reinforced concrete may be the most important material available for construction. It is used in one form or another for almost all structures, great or small—buildings, bridges, pavements, dams, retaining walls, tunnels, drainage and irrigation facilities, tanks, and so on.

The tremendous success of this universal construction material can be understood quite easily if its numerous advantages are considered. These include the following:

1. It has considerable compressive strength per unit cost compared with most other materials.
2. Reinforced concrete has great resistance to the actions of fire and water and, in fact, is the best structural material available for situations where water is present. During fires of average intensity, members with a satisfactory cover of concrete over the reinforcing bars suffer only surface damage without failure.
3. Reinforced concrete structures are very rigid.
4. It is a low-maintenance material.
5. As compared with other materials, it has a very long service life. Under proper conditions, reinforced concrete structures can be used indefinitely without reduction of their load-carrying abilities. This can be explained by the fact that the strength of concrete does not decrease with time but actually increases over a very long period, measured in years, because of the lengthy process of the solidification of the cement paste.
6. It is usually the only economical material available for footings, floor slabs, basement walls, piers, and similar applications.
7. A special feature of concrete is its ability to be cast into an extraordinary variety of shapes from simple slabs, beams, and columns to great arches and shells.

Courtesy of Portland Cement Association.

NCNB Tower in Charlotte, North Carolina, completed 1991.

8. In most areas, concrete takes advantage of inexpensive local materials (sand, gravel, and water) and requires relatively small amounts of cement and reinforcing steel, which may have to be shipped from other parts of the country.
9. A lower grade of skilled labor is required for erection as compared with other materials such as structural steel.

1.3 Disadvantages of Reinforced Concrete as a Structural Material

To use concrete successfully, the designer must be completely familiar with its weak points as well as its strong ones. Among its disadvantages are the following:

1. Concrete has a very low tensile strength, requiring the use of tensile reinforcing.
2. Forms are required to hold the concrete in place until it hardens sufficiently. In addition, falsework or shoring may be necessary to keep the forms in place for roofs, walls, floors, and similar structures until the concrete members gain sufficient strength to support themselves. Formwork is very expensive. In the United States, its costs run from one-third to two-thirds of the total cost of a reinforced concrete structure, with average

Courtesy of EFCO Corp.

The 320-ft-high Pyramid Sports Arena, Memphis, Tennessee.

values of about 50%. *It should be obvious that when efforts are made to improve the economy of reinforced concrete structures, the major emphasis is on reducing formwork costs.*

3. The low strength per unit of weight of concrete leads to heavy members. This becomes an increasingly important matter for long-span structures, where concrete's large dead weight has a great effect on bending moments. Lightweight aggregates can be used to reduce concrete weight, but the cost of the concrete is increased.

4. Similarly, the low strength per unit of volume of concrete means members will be relatively large, an important consideration for tall buildings and long-span structures.

5. The properties of concrete vary widely because of variations in its proportioning and mixing. Furthermore, the placing and curing of concrete is not as carefully controlled as is the production of other materials, such as structural steel and laminated wood.

Two other characteristics that can cause problems are concrete's shrinkage and creep. These characteristics are discussed in Section 1.11 of this chapter.

1.4 Historical Background

Most people believe that concrete has been in common use for many centuries, but this is not the case. The Romans did make use of a cement called *pozzolana* before the birth of Christ. They found large deposits of a sandy volcanic ash near Mt. Vesuvius and in other places in Italy. When they mixed this material with quicklime and water as well as sand and gravel, it hardened into a rocklike substance and was used as a building material. One might expect that a relatively poor grade of concrete would result, as compared with today's standards, but some Roman concrete structures are still in existence today. One example is the Pantheon (a building dedicated to all gods), which is located in Rome and was completed in A.D. 126.

The art of making pozzolanic concrete was lost during the Dark Ages and was not revived until the eighteenth and nineteenth centuries. A deposit of natural cement rock was discovered in England in 1796 and was sold as "Roman cement." Various other deposits of natural cement were discovered in both Europe and America and were used for several decades.

The real breakthrough for concrete occurred in 1824, when an English bricklayer named Joseph Aspdin, after long and laborious experiments, obtained a patent for a cement that he called portland cement because its color was quite similar to that of the stone quarried on the Isle of Portland off the English coast. He made his cement by taking certain quantities of clay and limestone, pulverizing them, burning them in his kitchen stove, and grinding the resulting clinker into a fine powder. During the early years after its development, his cement was used primarily in stuccos.[1] This wonderful product was adopted very slowly by the building industry and was not even introduced in the United States until 1868; the first portland cement was not manufactured in the United States until the 1870s.

The first uses of concrete are not very well known. Much of the early work was done by the Frenchmen François Le Brun, Joseph Lambot, and Joseph Monier. In 1832, Le Brun built a concrete house and followed it with the construction of a school and a church with the same material. In about 1850, Lambot built a concrete boat reinforced with a network of parallel wires or bars. Credit is usually given to Monier, however, for the invention of reinforced concrete. In 1867, he received a patent for the construction of concrete basins or tubs and reservoirs reinforced with a mesh of iron wire. His stated goal in working with this material was to obtain lightness without sacrificing strength.[2]

From 1867 to 1881, Monier received patents for reinforced concrete railroad ties, floor slabs, arches, footbridges, buildings, and other items in both France and Germany. Another Frenchman, François Coignet, built simple reinforced concrete structures and developed basic methods of design. In 1861, he published a book in which he presented quite a few applications. He was the first person to realize that the addition of too much water to the mix greatly reduced concrete's strength. Other Europeans who were early experimenters with reinforced concrete included the Englishmen William Fairbairn and William B. Wilkinson, the German G. A. Wayss, and another Frenchman, François Hennebique.[3,4]

William E. Ward built the first reinforced concrete building in the United States in Port Chester, New York, in 1875. In 1883, he presented a paper before the American Society of Mechanical Engineers in which he claimed that he got the idea of reinforced concrete by watching English laborers in 1867 trying to remove hardened cement from their iron tools.[5]

Thaddeus Hyatt, an American, was probably the first person to correctly analyze the stresses in a reinforced concrete beam, and in 1877, he published a 28-page book on the subject, entitled *An Account of Some Experiments with Portland Cement Concrete, Combined with Iron as a Building Material*. In this book he praised the use of reinforced concrete and said that "rolled beams (steel) have to be taken largely on faith." Hyatt put a great deal of emphasis on the high fire resistance of concrete.[6]

E. L. Ransome of San Francisco reportedly used reinforced concrete in the early 1870s and was the originator of deformed (or twisted) bars, for which he received a patent in 1884. These bars, which were square in cross section, were cold-twisted with one complete turn in a length of not more than 12 times the bar diameter.[7] (The purpose of the twisting was to provide better bonding or adhesion of the concrete and the steel.) In 1890 in San Francisco, Ransome built the Leland Stanford Jr. Museum. It is a reinforced concrete building 312 ft long and 2 stories high in which discarded wire rope from a cable-car system was used as tensile reinforcing. This building experienced little damage in the 1906 earthquake and the fire

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[1] Kirby, R. S. and Laurson, P. G., 1932, *The Early Years of Modern Civil Engineering* (New Haven: Yale University Press), p. 266.
[2] Ibid., pp. 273–275.
[3] Straub, H., 1964, *A History of Civil Engineering* (Cambridge: MIT Press), pp. 205–215. Translated from the German *Die Geschichte der Bauingenieurkunst* (Basel: Verlag Birkhauser), 1949.
[4] Kirby and Laurson, *The Early Years of Modern Civil Engineering*, pp. 273–275.
[5] Ward, W. E., 1883, "Béton in Combination with Iron as a Building Material," *Transactions ASME*, 4, pp. 388–403.
[6] Kirby and Laurson, *The Early Years of Modern Civil Engineering*, p. 275.
[7] American Society for Testing Materials, 1911, *Proceedings*, 11, pp. 66–68.

Installation of the concrete gravity base substructure (CGBS) for the LUNA oil-and-gas platform in the Sea of Okhotsk, Sakhalin region, Russia.

that ensued. The limited damage to this building and other concrete structures that withstood the great 1906 fire led to the widespread acceptance of this form of construction on the West Coast. Since the early 1900s, the development and use of reinforced concrete in the United States has been very rapid.[8,9]

1.5 Comparison of Reinforced Concrete and Structural Steel for Buildings and Bridges

When a particular type of structure is being considered, the student may be puzzled by the question, “Should reinforced concrete or structural steel be used?” There is much joking on this point, with the proponents of reinforced concrete referring to steel as that material that rusts and those favoring structural steel referring to concrete as the material that, when overstressed, tends to return to its natural state—that is, sand and gravel.

There is no simple answer to this question, inasmuch as both of these materials have many excellent characteristics that can be utilized successfully for so many types of structures. In fact, they are often used together in the same structures with wonderful results.

The selection of the structural material to be used for a particular building depends on the height and span of the structure, the material market, foundation conditions, local building codes, and architectural considerations. For buildings of less than 4 stories, reinforced concrete, structural steel, and wall-bearing construction are competitive. From 4 to about 20 stories, reinforced concrete and structural steel are economically competitive, with steel having been used in most of the jobs above 20 stories in the past. Today, however, reinforced concrete is becoming increasingly competitive above 20 stories, and there are a number of reinforced concrete buildings of greater height around the world. The 74-story, 859-ft-high Water Tower Place in Chicago is the tallest reinforced concrete building in the world. The 1465-ft CN tower (not a building) in Toronto, Canada, is the tallest reinforced concrete structure in the world.

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[8] Wang, C. K. and Salmon, C. G., 1998, *Reinforced Concrete Design*, 6th ed. (New York: HarperCollins), pp. 3–5.
[9] “The Story of Cement, Concrete and Reinforced Concrete,” *Civil Engineering*, November 1977, pp. 63–65.

Although we would all like to be involved in the design of tall, prestigious reinforced concrete buildings, there are just not enough of them to go around. As a result, nearly all of our work involves much smaller structures. Perhaps 9 out of 10 buildings in the United States are 3 stories or fewer in height, and more than two-thirds of them contain 15,000 sq ft or less of floor space.

Foundation conditions can often affect the selection of the material to be used for the structural frame. If foundation conditions are poor, using a lighter structural steel frame may be desirable. The building code in a particular city may favor one material over the other. For instance, many cities have fire zones in which only fireproof structures can be erected—a very favorable situation for reinforced concrete. Finally, the time element favors structural steel frames, as they can be erected more quickly than reinforced concrete ones. The time advantage, however, is not as great as it might seem at first because, if the structure is to have any type of fire rating, the builder will have to cover the steel with some kind of fireproofing material after it is erected.

Making decisions about using concrete or steel for a bridge involves several factors, such as span, foundation conditions, loads, architectural considerations, and others. In general, concrete is an excellent compression material and normally will be favored for short-span bridges and for cases where rigidity is required (as, perhaps, for railway bridges).

1.6 Compatibility of Concrete and Steel

Concrete and steel reinforcing work together beautifully in reinforced concrete structures. The advantages of each material seem to compensate for the disadvantages of the other. For instance, the great shortcoming of concrete is its lack of tensile strength, but tensile strength is one of the great advantages of steel. Reinforcing bars have tensile strengths equal to approximately 100 times that of the usual concretes used.

The two materials bond together very well so there is little chance of slippage between the two; thus, they will act together as a unit in resisting forces. The excellent bond obtained is the result of the chemical adhesion between the two materials, the natural roughness of the bars, and the closely spaced rib-shaped deformations rolled onto the bars' surfaces.

Reinforcing bars are subject to corrosion, but the concrete surrounding them provides them with excellent protection. The strength of exposed steel subjected to the temperatures reached in fires of ordinary intensity is nil, but enclosing the reinforcing steel in concrete produces very satisfactory fire ratings. Finally, concrete and steel work well together in relation to temperature changes because their coefficients of thermal expansion are quite close. For steel, the coefficient is 0.0000065 per unit length per degree Fahrenheit, while it varies for concrete from about 0.000004 to 0.000007 (average value: 0.0000055).

1.7 Design Codes

The most important code in the United States for reinforced concrete design is the American Concrete Institute's *Building Code Requirements for Structural Concrete* (ACI 318-11).[10] This code, which is used primarily for the design of buildings, is followed for the majority of the numerical examples given in this text. Frequent references are made to this document, and section numbers are provided. Design requirements for various types of reinforced concrete members are presented in the code along with a "commentary" on those requirements. The commentary provides explanations, suggestions, and additional information concerning the design requirements. As a result, users will obtain a better background and understanding of the code.

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[10] American Concrete Institute, 2011, *Building Code Requirements for Structural Concrete* (ACI 318-11), Farmington Hills, Michigan.

The ACI Code is not in itself a legally enforceable document. It is merely a statement of current good practice in reinforced concrete design. It is, however, written in the form of a code or law so that various public bodies, such as city councils, can easily vote it into their local building codes, and then it becomes legally enforceable in that area. In this manner, the ACI Code has been incorporated into law by countless government organizations throughout the United States. The International Building Code (IBC), which was first published in 2000 by the International Code Council, has consolidated the three regional building codes (Building Officials and Code Administrators, International Conference of Building Officials, and Southern Building Code Congress International) into one national document. The IBC Code is updated every three years and refers to the most recent edition of ACI 318 for most of its provisions related to reinforced concrete design, with only a few modifications. It is expected that IBC 2012 will refer to ACI 318-11 for most of its reinforced concrete provisions. The ACI 318 Code is also widely accepted in Canada and Mexico and has had tremendous influence on the concrete codes of all countries throughout the world.

As more knowledge is obtained pertaining to the behavior of reinforced concrete, the ACI revises its code. The present objective is to make yearly changes in the code in the form of supplements and to provide major revisions of the entire code every three years.

Other well-known reinforced concrete specifications are those of the American Association of State Highway and Transportation Officials (AASHTO) and the American Railway Engineering Association (AREA).

1.8 SI Units and Shaded Areas

Most of this book is devoted to the design of reinforced concrete structures using U.S. customary units. The authors, however, feel that it is absolutely necessary for today's engineer to be able to design in either customary or SI units. Thus, SI equations, where different from those in customary units, are presented herein, along with quite a few numerical examples using SI units. The equations are taken from the American Concrete Institute's metric version of *Building Code Requirements for Structural Concrete* (ACI 318M-11).[11]

For many people it is rather distracting to read a book in which numbers, equations, and so on are presented in two sets of units. To try to reduce this annoyance, the authors have placed a shaded area around any items pertaining to SI units throughout the text.

If readers are working at a particular time with customary units, they can completely ignore the shaded areas. It is hoped, however, that the same shaded areas will enable a person working with SI units to easily find appropriate equations, examples, and so on.

1.9 Types of Portland Cement

Concretes made with normal portland cement require about 2 weeks to achieve a sufficient strength to permit the removal of forms and the application of moderate loads. Such concretes reach their design strengths after about 28 days and continue to gain strength at a slower rate thereafter.

[11] Ibid.


Courtesy of Portland Cement Association.

One Peachtree Center in Atlanta, Georgia, is 854 ft high; built for the 1996 Olympics.

On many occasions it is desirable to speed up construction by using *high-early-strength cements*, which, although more expensive, enable us to obtain desired strengths in 3 to 7 days rather than the normal 28 days. These cements are particularly useful for the fabrication of precast members, in which the concrete is placed in forms where it quickly gains desired strengths and is then removed from the forms and the forms are used to produce more members. Obviously, the quicker the desired strength is obtained, the more efficient the operation. A similar case can be made for the forming of concrete buildings floor by floor. High-early-strength cements can also be used advantageously for emergency repairs of concrete and for *shotcreting* (where a mortar or concrete is blown through a hose at a high velocity onto a prepared surface).

There are other special types of portland cements available. The chemical process that occurs during the setting or hardening of concrete produces heat. For very massive concrete structures such as dams, mat foundations, and piers, the heat will dissipate very slowly and can cause serious problems. It will cause the concrete to expand during hydration. When cooling, the concrete will shrink and severe cracking will often occur.

Concrete may be used where it is exposed to various chlorides and/or sulfates. Such situations occur in seawater construction and for structures exposed to various types of soil.

Some portland cements are manufactured that have lower heat of hydration, and others are manufactured with greater resistance to attack by chlorides and sulfates.

In the United States, the American Society for Testing and Materials (ASTM) recognizes five types of portland cement. These different cements are manufactured from just about the same raw materials, but their properties are changed by using various blends of those materials. Type I cement is the normal cement used for most construction, but four other types are useful for special situations in which high early strength or low heat or sulfate resistance is needed:

Type I—The common, all-purpose cement used for general construction work.

Type II—A modified cement that has a lower heat of hydration than does Type I cement and that can withstand some exposure to sulfate attack.

Type III—A high-early-strength cement that will produce in the first 24 hours a concrete with a strength about twice that of Type I cement. This cement does have a much higher heat of hydration.

Type IV—A low-heat cement that produces a concrete which generates heat very slowly. It is used for very large concrete structures.

Type V—A cement used for concretes that are to be exposed to high concentrations of sulfate.

Should the desired type of cement not be available, various admixtures may be purchased with which the properties of Type I cement can be modified to produce the desired effect.

1.10 Admixtures

Materials added to concrete during or before mixing are referred to as admixtures. They are used to improve the performance of concrete in certain situations as well as to lower its cost. There is a rather well-known saying regarding admixtures, to the effect that they are to concrete as beauty aids are to the populace. Several of the most common types of admixtures are listed and briefly described here.

- *Air-entraining admixtures*, conforming to the requirements of ASTM C260 and C618, are used primarily to increase concrete's resistance to freezing and thawing and provide better resistance to the deteriorating action of deicing salts. The air-entraining agents cause the mixing water to foam, with the result that billions of closely spaced air bubbles are incorporated into the concrete. When concrete freezes, water moves into the air bubbles, relieving the pressure in the concrete. When the concrete thaws, the water can move out of the bubbles, with the result that there is less cracking than if air entrainment had not been used.

- The addition of *accelerating admixtures*, such as calcium chloride, to concrete will accelerate its early strength development. The results of such additions (particularly useful in cold climates) are reduced times required for curing and protection of the concrete and the earlier removal of forms. (Section 3.6.3 of the ACI Code states that because of corrosion problems, calcium chloride may not be added to concretes with embedded aluminum, concretes cast against stay-in-place galvanized steel forms, or prestressed concretes.) Other accelerating admixtures that may be used include various soluble salts as well as some other organic compounds.

- *Retarding admixtures* are used to slow the setting of the concrete and to retard temperature increases. They consist of various acids or sugars or sugar derivatives. Some concrete truck drivers keep sacks of sugar on hand to throw into the concrete in case they get caught in traffic jams or are otherwise delayed. Retarding admixtures are particularly useful for large pours where significant temperature increases may occur. They also prolong the plasticity of the concrete, enabling better blending or bonding of successive pours. Retarders can also slow the hydration of cement on exposed concrete surfaces or formed surfaces to produce attractive exposed aggregate finishes.

- *Superplasticizers* are admixtures made from organic sulfonates. Their use enables engineers to reduce the water content in concretes substantially while at the same time increasing their slumps. Although superplasticizers can also be used to keep water–cement ratios constant while using less cement, they are more commonly used to produce workable concretes with considerably higher strengths while using the same amount of cement. (See Section 1.13.) A relatively new product, self-consolidating concrete, uses superplasticizers and modifications in mix designs to produce an extremely workable mix that requires no vibration, even for the most congested placement situations.
- *Waterproofing materials* usually are applied to hardened concrete surfaces, but they may be added to concrete mixes. These admixtures generally consist of some type of soap or petroleum products, as perhaps asphalt emulsions. They may help retard the penetration of water into porous concretes but probably don't help dense, well-cured concretes very much.

1.11 Properties of Concrete

A thorough knowledge of the properties of concrete is necessary for the student before he or she begins to design reinforced concrete structures. An introduction to several of these properties is presented in this section.

Compressive Strength

The compressive strength of concrete, f_c', is determined by testing to failure 28-day-old 6-in. diameter by 12-in. concrete cylinders at a specified rate of loading (4-in. diameter by 8-in. cylinders were first permitted in the 2008 code in lieu of the larger cylinders). For the 28-day period, the cylinders are usually kept under water or in a room with constant temperature and 100% humidity. Although concretes are available with 28-day ultimate strengths from 2500 psi up to as high as 10,000 psi to 20,000 psi, most of the concretes used fall into the 3000-psi to 7000-psi range. For ordinary applications, 3000-psi and 4000-psi concretes are used, whereas for prestressed construction, 5000-psi and 6000-psi strengths are common. For some applications, such as for the columns of the lower stories of high-rise buildings, concretes with strengths up to 9000 psi or 10,000 psi have been used and can be furnished by ready-mix companies. As a result, the use of such high-strength concretes is becoming increasingly common. At Two Union Square in Seattle, concrete with strengths up to 19,000 psi was used.

The values obtained for the compressive strength of concretes, as determined by testing, are to a considerable degree dependent on the sizes and shapes of the test units and the manner in which they are loaded. In many countries, the test specimens are cubes, 200 mm (7.87 in.) on each side. For the same batches of concrete, the testing of 6-in. by 12-in. cylinders provides compressive strengths only equal to about 80% of the values in psi determined with the cubes.

It is quite feasible to move from 3000-psi concrete to 5000-psi concrete without requiring excessive amounts of labor or cement. The approximate increase in material cost for such a strength increase is 15% to 20%. To move above 5000-psi or 6000-psi concrete, however, requires very careful mix designs and considerable attention to such details as mixing, placing, and curing. These requirements cause relatively larger increases in cost.

Several comments are made throughout the text regarding the relative economy of using different strength concretes for different applications, such as those for beams, columns, footings, and prestressed members.

To ensure that the compressive strength of concrete in the structure is at least as strong as the specified value, f'_c, the design of the concrete mix must target a higher value, f'_{cr}. Section 5.3 of the ACI Code requires that the concrete compressive strengths used as a basis for selecting the concrete proportions exceed the specified 28-day strengths by fairly large values. For concrete production facilities that have sufficient field strength test records not older than 24 months to enable them to calculate satisfactory standard deviations (as described in ACI Section 5.3.1.1), a set of required average compressive strengths (f'_{cr}) to be used as the basis for selecting concrete properties is specified in ACI Table 5.3.2.1. For facilities that do not have sufficient records to calculate satisfactory standard deviations, ACI Table 5.3.2.2 provides increases in required average design compressive strength (f'_{cr}) of 1000 psi for specified concrete strength (f'_c) of less than 3000 psi and appreciably higher increases for higher f'_c concretes.

The stress–strain curves of Figure 1.1 represent the results obtained from compression tests of sets of 28-day-old standard cylinders of varying strengths. You should carefully study these curves because they bring out several significant points:

(a) The curves are roughly straight while the load is increased from zero to about one-third to one-half the concrete's ultimate strength.

(b) Beyond this range the behavior of concrete is nonlinear. This lack of linearity of concrete stress–strain curves at higher stresses causes some problems in the structural analysis of concrete structures because their behavior is also nonlinear at higher stresses.

(c) Of particular importance is the fact that regardless of strengths, all the concretes reach their ultimate strengths at strains of about 0.002.

(d) Concrete does not have a definite yield strength; rather, the curves run smoothly on to the point of rupture at strains of from 0.003 to 0.004. It will be assumed for the purpose of future calculations in this text that concrete fails at 0.003 (ACI 10.2.3). *The*

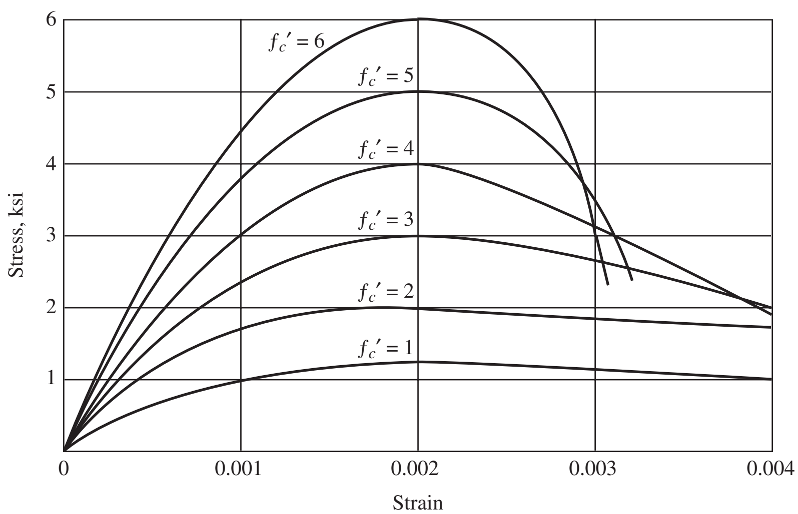

FIGURE 1.1 Typical concrete stress–strain curve, with short-term loading.

reader should note that this value, which is conservative for normal-strength concretes, may not be conservative for higher-strength concretes in the 8000-psi-and-above range. The European code uses a different value for ultimate compressive strain for columns (0.002) than for beams and eccentrically loaded columns (0.0035).[12]

(e) Many tests have clearly shown that stress–strain curves of concrete cylinders are almost identical to those for the compression sides of beams.

(f) It should be further noticed that the weaker grades of concrete are less brittle than the stronger ones—that is, they will take larger strains before breaking.

Static Modulus of Elasticity

Concrete has no clear-cut modulus of elasticity. Its value varies with different concrete strengths, concrete age, type of loading, and the characteristics and proportions of the cement and aggregates. Furthermore, there are several different definitions of the modulus:

(a) The *initial modulus* is the slope of the stress–strain diagram at the origin of the curve.

(b) The *tangent modulus* is the slope of a tangent to the curve at some point along the curve—for instance, at 50% of the ultimate strength of the concrete.

(c) The slope of a line drawn from the origin to a point on the curve somewhere between 25% and 50% of its ultimate compressive strength is referred to as a *secant modulus*.

(d) Another modulus, called the *apparent modulus* or the *long-term modulus*, is determined by using the stresses and strains obtained after the load has been applied for a certain length of time.

Section 8.5.1 of the ACI Code states that the following expression can be used for calculating the modulus of elasticity of concretes weighing from 90 lb/ft^3 to 155 lb/ft^3:

$$E_c = w_c^{1.5} 33 \sqrt{f_c'}$$

In this expression, E_c is the modulus of elasticity in psi, w_c is the weight of the concrete in pounds per cubic foot, and f_c' is its specified 28-day compressive strength in psi. This is actually a secant modulus with the line (whose slope equals the modulus) drawn from the origin to a point on the stress–strain curve corresponding approximately to the stress ($0.45f_c'$) that would occur under the estimated dead and live loads the structure must support.

For normal-weight concrete weighing approximately 145 lb/ft^3, the ACI Code states that the following simplified version of the previous expression may be used to determine the modulus:

$$E_c = 57{,}000\sqrt{f_c'}$$

Table A.1 (see Appendix A at the end of the book) shows values of E_c for different strength concretes having normal-weight aggregate. These values were calculated with the first of the preceding formulas assuming 145 lb/ft^3 concrete.

[12] MacGregor, J. G. and Wight, J. K., 2005, *Reinforced Concrete Mechanics and Design*, 4th ed. (Upper Saddle River, NJ: Pearson Prentice Hall), p. 111.

In SI units, $E_c = w_c^{1.5}(0.043)\sqrt{f'_c}$ with w_c varying from 1500 to 2500 kg/m^3 and with f'_c in N/mm^2 or MPa (megapascals). Should normal crushed stone or gravel concrete (with a mass of approximately 2320 kg/m^3) be used, $E_c = 4700\sqrt{f'_c}$. Table B.1 of Appendix B of this text provides moduli values for several different strength concretes.

The term *unit weight* is constantly used by structural engineers working with U.S. customary units. When using the SI system, however, this term should be replaced by the term *mass density* A kilogram is not a force unit and only indicates the amount of matter in an object. The mass of a particular object is the same anywhere on Earth, whereas the weight of an object in our customary units varies depending on altitude because of the change in gravitational acceleration.

Concretes with strength above 6000 psi are referred to as high-strength concretes. Tests have indicated that the usual ACI equations for E_c when applied to high-strength concretes result in values that are too large. Based on studies at Cornell University, the expression to follow has been recommended for normal-weight concretes with f'_c values greater than 6000 psi and up to 12,000 psi and for lightweight concretes with f'_c greater than 6000 psi and up to 9000 psi.[13,14]

$$E_c(\text{psi}) = \left[40{,}000\sqrt{f'_c} + 10^6\right]\left(\frac{w_c}{145}\right)^{1.5}$$

In SI units with f'_c in MPa and w_c in kg/m^3, the expression is

$$E_c(\text{MPa}) = \left[3.32\sqrt{f'_c} + 6895\right]\left(\frac{w_c}{2320}\right)^{1.5}$$

Dynamic Modulus of Elasticity

The dynamic modulus of elasticity, which corresponds to very small instantaneous strains, is usually obtained by sonic tests. It is generally 20% to 40% higher than the static modulus and is approximately equal to the initial modulus. When structures are being analyzed for seismic or impact loads, the use of the dynamic modulus seems appropriate.

Poisson's Ratio

As a concrete cylinder is subjected to compressive loads, it not only shortens in length but also expands laterally. The ratio of this lateral expansion to the longitudinal shortening is referred to as *Poisson's ratio*. Its value varies from about 0.11 for the higher-strength concretes to as high as 0.21 for the weaker-grade concretes, with average values of about 0.16. There does not seem to be any direct relationship between the value of the ratio and the values of items such as the water–cement ratio, amount of curing, aggregate size, and so on.

[13] Nawy, E. G., 2006, *Prestressed Concrete: A Fundamental Approach*, 5th ed. (Upper Saddle River, NJ: Prentice-Hall), p. 38.
[14] Carrasquillol, R., Nilson, A., and Slate, F., 1981, "Properties of High-Strength Concrete Subject to Short-Term Loads." *Journal of ACI Proceedings*, 78(3), May–June.

Concert at Naumburg bandshell in Central Park, New York, New York.

For most reinforced concrete designs, no consideration is given to the so-called Poisson effect. It may very well have to be considered, however, in the analysis and design of arch dams, tunnels, and some other statically indeterminate structures. Spiral reinforcing in columns takes advantage of Poisson's ratio and will be discussed in Chapter 9.

Shrinkage

When the materials for concrete are mixed, the paste consisting of cement and water fills the voids between the aggregate and bonds the aggregate together. This mixture needs to be sufficiently workable or fluid so that it can be made to flow in between the reinforcing bars and all through the forms. To achieve this desired workability, considerably more water (perhaps twice as much) is used than is necessary for the cement and water to react (called *hydration*).

After the concrete has been cured and begins to dry, the extra mixing water that was used begins to work its way out of the concrete to the surface, where it evaporates. As a result, the concrete shrinks and cracks. The resulting cracks may reduce the shear strength of the members and be detrimental to the appearance of the structure. In addition, the cracks may permit the reinforcing to be exposed to the atmosphere or chemicals, such as deicers, thereby increasing the possibility of corrosion. Shrinkage continues for many years, but under ordinary conditions probably about 90% of it occurs during the first year. The amount of moisture that is lost varies with the distance from the surface. Furthermore, the larger the surface area of a member in proportion to its volume, the larger the rate of shrinkage; that is, members with small cross sections shrink more proportionately than do those with large cross sections.

The amount of shrinkage is heavily dependent on the type of exposure. For instance, if concrete is subjected to a considerable amount of wind during curing, its shrinkage will be greater. In a related fashion, a humid atmosphere means less shrinkage, whereas a dry one means more.

It should also be realized that it is desirable to use low-absorptive aggregates such as those from granite and many limestones. When certain absorptive slates and sandstone aggregates are used, the result may be one and a half or even two times the shrinkage with other aggregates.

To minimize shrinkage it is desirable to: (1) keep the amount of mixing water to a minimum; (2) cure the concrete well; (3) place the concrete for walls, floors, and other large items in small sections (thus allowing some of the shrinkage to take place before the next section is placed); (4) use construction joints to control the position of cracks; (5) use shrinkage reinforcement; and (6) use appropriate dense and nonporous aggregates.[15]

Creep

Under sustained compressive loads, concrete will continue to deform for long periods of time. After the initial deformation occurs, the additional deformation is called *creep,* or *plastic flow*. If a compressive load is applied to a concrete member, an immediate or instantaneous elastic shortening occurs. If the load is left in place for a long time, the member will continue to shorten over a period of several years, and the final deformation will usually be two to three times the initial deformation. You will find in Chapter 6 that this means that long-term deflections may also be as much as two or three times initial deflections. Perhaps 75% of the total creep will occur during the first year.

Should the long-term load be removed, the member will recover most of its elastic strain and a little of its creep strain. If the load is replaced, both the elastic and creep strains will again develop.

The amount of creep is largely dependent on the amount of stress. It is almost directly proportional to stress as long as the sustained stress is not greater than about one-half of f_c'. Beyond this level, creep will increase rapidly.

Long-term loads not only cause creep but also can adversely affect the strength of the concrete. For loads maintained on concentrically loaded specimens for a year or longer, there may be a strength reduction of perhaps 15% to 25%. *Thus a member loaded with a sustained load of, say, 85% of its ultimate compression strength,* f_c', *may very well be satisfactory for a while but may fail later.*[16]

Several other items affecting the amount of creep are:

- The longer the concrete cures before loads are applied, the smaller will be the creep. Steam curing, which causes quicker strengthening, will also reduce creep.
- Higher-strength concretes have less creep than do lower-strength concretes stressed at the same values. However, applied stresses for higher-strength concretes are, in all probability, higher than those for lower-strength concretes, and this fact tends to cause increasing creep.
- Creep increases with higher temperatures. It is highest when the concrete is at about 150°F to 160°F.
- The higher the humidity, the smaller will be the free pore water that can escape from the concrete. Creep is almost twice as large at 50% humidity than at 100% humidity. It is obviously quite difficult to distinguish between shrinkage and creep.
- Concretes with the highest percentage of cement–water paste have the highest creep because the paste, not the aggregate, does the creeping. This is particularly true if a limestone aggregate is used.
- Obviously, the addition of reinforcing to the compression areas of concrete will greatly reduce creep because steel exhibits very little creep at ordinary stresses. As creep tends

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[15] Leet, K., 1991, *Reinforced Concrete Design*, 2nd ed. (New York: McGraw-Hill), p. 35.
[16] Rüsch, H., 1960, "Researches Toward a General Flexure Theory for Structural Concrete," *Journal ACI*, 57(1), pp. 1–28.

to occur in the concrete, the reinforcing will block it and pick up more and more of the load.

- Large concrete members (i.e., those with large volume-to-surface area ratios) will creep proportionately less than smaller thin members where the free water has smaller distances to travel to escape.

Tensile Strength

The tensile strength of concrete varies from about 8% to 15% of its compressive strength. A major reason for this small strength is the fact that concrete is filled with fine cracks. The cracks have little effect when concrete is subjected to compression loads because the loads cause the cracks to close and permit compression transfer. Obviously, this is not the case for tensile loads.

Although tensile strength is normally neglected in design calculations, it is nevertheless an important property that affects the sizes and extent of the cracks that occur. Furthermore, the tensile strength of concrete members has a definite reduction effect on their deflections. (Because of the small tensile strength of concrete, little effort has been made to determine its tensile modulus of elasticity. Based on this limited information, however, it seems that its value is equal to its compression modulus.)

You might wonder why concrete is not assumed to resist a portion of the tension in a flexural member and the steel the remainder. The reason is that concrete cracks at such small tensile strains that the low stresses in the steel up to that time would make its use uneconomical. Once tensile cracking has occurred, concrete has no more tensile strength.

The tensile strength of concrete doesn't vary in direct proportion to its ultimate compression strength, f'_c. It does, however, vary approximately in proportion to the square root of f'_c. This strength is quite difficult to measure with direct axial tension loads because of problems in gripping test specimens so as to avoid stress concentrations and because of difficulties in aligning the loads. As a result of these problems, two indirect tests have been developed to measure concrete's tensile strength. These are the *modulus of rupture* and the *split-cylinder tests*.

The tensile strength of concrete in flexure is quite important when considering beam cracks and deflections. For these considerations, the tensile strengths obtained with the modulus of rupture test have long been used. The modulus of rupture (which is defined as the flexural tensile strength of concrete) is usually measured by loading a 6-in. × 6-in. × 30-in. plain (i.e., unreinforced) rectangular beam (with simple supports placed 24 in. on center) to failure with equal concentrated loads at its one-third points as per ASTM C78-2002.[17] The load is increased until failure occurs by cracking on the tensile face of the beam. The modulus of rupture, f_r, is then determined from the flexure formula. In the following expressions, b is the beam width, h is its depth, and M is $PL/6$, which is the maximum computed moment:

$$f_r = \frac{Mc}{I} = \frac{M\ (h/2)}{\frac{1}{12}bh^3}$$

$$f_r = \text{modulus of rupture} = \frac{6M}{bh^2} = \frac{\text{PL}}{bh^2}$$

[17] American Society for Testing and Materials, 2002, *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)* (ASTM C78-2002), West Conshohocken, Pennsylvania.

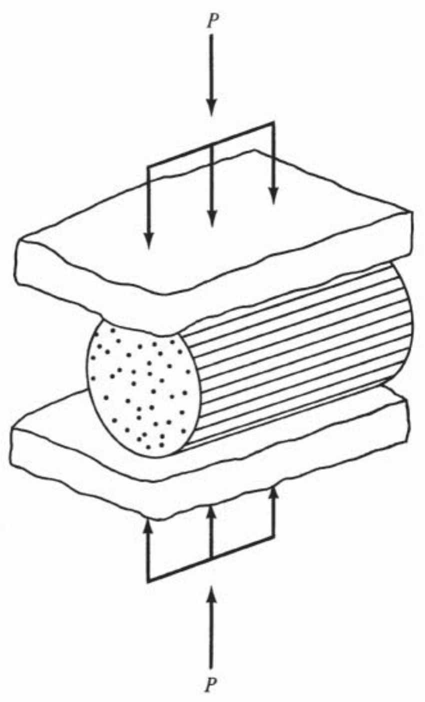

FIGURE 1.2 Split-cylinder test.

The stress determined in this manner is not very accurate because, in using the flexure formula, we are assuming the concrete stresses vary in direct proportion to distances from the neutral axis. This assumption is not very good.

Based on hundreds of tests, the code (Section 9.5.2.3) provides a modulus of rupture f_r equal to $7.5\lambda\sqrt{f_c'}$, where f_r and f_c' are in units of psi.[18] The λ term reduces the modulus of rupture when lightweight aggregates are used (see Section 1.12).

The tensile strength of concrete may also be measured with the split-cylinder test.[19] A cylinder is placed on its side in the testing machine, and a compressive load is applied uniformly along the length of the cylinder, with support supplied along the bottom for the cylinder's full length (see Figure 1.2). The cylinder will split in half from end to end when its tensile strength is reached. The tensile strength at which splitting occurs is referred to as the *split-cylinder strength* and can be calculated with the following expression, in which P is the maximum compressive force, L is the length, and D is the diameter of the cylinder:

$$f_t = \frac{2P}{\pi LD}$$

Even though pads are used under the loads, some local stress concentrations occur during the tests. In addition, some stresses develop at right angles to the tension stresses. As a result, the tensile strengths obtained are not very accurate.

Shear Strength

It is extremely difficult in laboratory testing to obtain pure shear failures unaffected by other stresses. As a result, the tests of concrete shearing strengths through the years have yielded

[18] In SI units, $f_r = 0.7\sqrt{f_c}$ MPa.
[19] American Society for Testing and Materials, *Standard Test Method.*

values all the way from one-third to four-fifths of the ultimate compressive strengths. You will learn in Chapter 8 that you do not have to worry about these inconsistent shear strength tests because design approaches are based on very conservative assumptions of that strength.

1.12 Aggregates

The aggregates used in concrete occupy about three-fourths of the concrete volume. Since they are less expensive than the cement, it is desirable to use as much of them as possible. Both fine aggregates (usually sand) and coarse aggregates (usually gravel or crushed stone) are used. Any aggregate that passes a No. 4 sieve (which has wires spaced $\frac{1}{4}$ in. on centers in each direction) is said to be fine aggregate. Material of a larger size is coarse aggregate.

The maximum-size aggregates that can be used in reinforced concrete are specified in Section 3.3.2 of the ACI Code. *These limiting values are as follows: one-fifth of the narrowest dimensions between the sides of the forms, one-third of the depth of slabs, or three-quarters of the minimum clear spacing between reinforcing*. Larger sizes may be used if, in the judgment of the engineer, the workability of the concrete and its method of consolidation are such that the aggregate used will not cause the development of honeycomb or voids.

Aggregates must be strong, durable, and clean. Should dust or other particles be present, they may interfere with the bond between the cement paste and the aggregate. The strength of the aggregate has an important effect on the strength of the concrete, and the aggregate properties greatly affect the concrete's durability.

Concretes that have 28-day strengths equal to or greater than 2500 psi and air-dry weights equal to or less than 115 lb/ft^3 are said to be *structural lightweight* concretes. The aggregates used for these concretes are made from expanded shales of volcanic origin, fired clays, or slag. When lightweight aggregates are used for both fine and coarse aggregate, the result is called *all-lightweight* concrete. If sand is used for fine aggregate and if the coarse aggregate is replaced with lightweight aggregate, the result is referred to as *sand-lightweight* concrete. Concretes made with lightweight aggregates may not be as durable or tough as those made with normal-weight aggregates.

Some of the structural properties of concrete are affected by the use of lightweight aggregates. ACI 318-11 Section 8.4 requires that the modulus of rupture be reduced by the introduction of the term λ in the equation

$$f_r = 7.5\lambda\sqrt{f'_c} \qquad \text{(ACI Equation 9-10)}$$

$$\text{or, in SI units with } f'_c \text{ in N/mm}^2,\ f_r = 0.7\lambda\sqrt{f'_c}$$

The value of λ depends on the aggregate that is replaced with lightweight material. If only the coarse aggregate is replaced (sand-lightweight concrete), λ is 0.85. If the sand is also replaced with lightweight material (all-lightweight concrete), λ is 0.75. Linear interpolation is permitted between the values of 0.85 and 1.0 as well as from 0.75 to 0.85 when partial replacement with lightweight material is used. Alternatively, if the average splitting tensile strength of lightweight concrete, f_{ct}, is specified, ACI 318-11 Section 8.6.1 defines λ as

$$\lambda = \frac{f_{ct}}{6.7\sqrt{f'_c}} \leq 1.0$$

For normal-weight concrete and for concrete having normal-weight fine aggregate and a blend of lightweight and normal-weight coarse aggregate, $\lambda = 1.0$. Use of lightweight aggregate concrete can affect beam deflections, shear strength, coefficient of friction, development lengths of reinforcing bars and hooked bars, and prestressed concrete design.

1.13 High-Strength Concretes

Concretes with compression strengths exceeding 6000 psi are referred to as *high-strength concretes*. Another name sometimes given to them is *high-performance concretes* because they have other excellent characteristics besides just high strengths. For instance, the low permeability of such concretes causes them to be quite durable as regards the various physical and chemical agents acting on them that may cause the material to deteriorate.

Up until a few decades ago, structural designers felt that ready-mix companies could not deliver concretes with compressive strengths much higher than 4000 psi or 5000 psi. This situation, however, is no longer the case as these same companies can today deliver concretes with compressive strengths up to at least 9000 psi. Even stronger concretes than these have been used. At Two Union Square in Seattle, 19,000-psi concrete was obtained using ready-mix concrete delivered to the site. Furthermore, concretes have been produced in laboratories with strengths higher than 20,000 psi. Perhaps these latter concretes should be called *super-high-strength concretes* or *super-high-performance concretes*.

If we are going to use a very high-strength cement paste, we must not forget to use a coarse aggregate that is equally as strong. If the planned concrete strength is, say, 15,000 psi to 20,000 psi, equally strong aggregate must be used, and such aggregate may very well not be available within reasonable distances. In addition to the strengths needed for the coarse aggregate, their sizes should be well graded, and their surfaces should be rough so that better bonding to the cement paste will be obtained. The rough surfaces of aggregates, however, may decrease the concrete's workability.

From an economical standpoint, you should realize that though concretes with 12,000-psi to 15,000-psi strengths cost approximately three times as much to produce as do 3000-psi concretes, their compressive strengths are four to five times as large.

High-strength concretes are sometimes used for both precast and prestressed members. They are particularly useful in the precast industry where their strength enables us to produce smaller and lighter members, with consequent savings in storage, handling, shipping, and erection costs. In addition, they have sometimes been used for offshore structures, but their common use has been for columns of tall reinforced concrete buildings, probably over 25 to 30 stories in height where the column loads are very large, say, 1000 kips or more. Actually, for such buildings, the columns for the upper floors, where the loads are relatively small, are probably constructed with conventional 4000-psi or 5000-psi concretes, while high-strength concretes are used for the lower heavily loaded columns. If conventional concretes were used for these lower columns, the columns could very well become so large that they would occupy excessive amounts of rentable floor space. High-strength concretes are also of advantage in constructing shear walls. (Shear walls are discussed in Chapter 18.)

To produce concretes with strengths above 6000 psi, it is first necessary to use more stringent quality control of the work and to exercise special care in the selection of the materials to be used. Strength increases can be made by using lower water–cement ratios, adding admixtures, and selecting good clean and solid aggregates. The actual concrete strengths used by the designer for a particular job will depend on the size of the loads and the quality of the aggregate available.

In recent years, appreciable improvements have been made in the placing, vibrating, and finishing of concrete. These improvements have resulted in lower water–cement ratios and, thus, higher strengths. The most important factor affecting the strength of concrete is its porosity, which is controlled primarily by the water–cement ratio. This ratio should be kept as small as possible as long as adequate workability is maintained. In this regard, there are various water-reducing admixtures with which the ratios can be appreciably reduced, while at the same time maintaining suitable workability.

Concretes with strengths from 6000 psi to 10,000 psi or 12,000 psi can easily be obtained if admixtures such as silica fume and superplasticizers are used. Silica fume, which is more than 90% silicon dioxide, is an extraordinarily fine powder that varies in color from light to dark gray and can even be blue-green-gray. It is obtained from electric arc furnaces as a by-product during the production of metallic silicon and various other silicon alloys. It is available in both powder and liquid form. The amount of silica fume used in a mix varies from 5% to 30% of the weight of the cement.

Silica fume particles have diameters approximately 100 times smaller than the average cement particle, and their surface areas per unit of weight are roughly 40 to 60 times those of portland cement. As a result, they hold more water. (By the way, this increase of surface area causes the generation of more heat of hydration.) The water–cement ratios are smaller, and strengths are higher. Silica fume is a *pozzolan*: a siliceous material that by itself has no cementing quality, but when used in concrete mixes its extraordinarily fine particles react with the calcium hydroxide in the cement to produce a cementious compound. Quite a few pozzolans are available that can be used satisfactorily in concrete. Two of the most common ones are fly ash and silica fume. Here, only silica fume is discussed.

When silica fume is used, it causes increases in the density and strength of the concrete. These improvements are due to the fact that the ultrafine silica fume particles are dispersed between the cement particles. Unfortunately, this causes a reduction in the workability of the concrete, and it is necessary to add *superplasticizers* to the mix. Superplasticizers, also called *high-range water reducers*, are added to concretes to increase their workability. They are made by treating formaldehyde or napthaline with sulfuric acid. Such materials used as admixtures lower the viscosity or resistance to flow of the concrete. As a result, less water can be used, thus yielding lower water–cement ratios and higher strengths.

Organic polymers can be used to replace a part of the cement as the binder. An organic polymer is composed of molecules that have been formed by the union of thousands of molecules. The most commonly used polymers in concrete are latexes. Such additives improve concrete's strength, durability, and adhesion. In addition, the resulting concretes have excellent resistance to abrasion, freezing, thawing, and impact.

Another procedure that can increase the strength of concrete is *consolidation*. When precast concrete products are consolidated, excess water and air are squeezed out, thus producing concretes with optimum air contents. In a similar manner, the centrifugal forces caused by the spinning of concrete pipes during their manufacture consolidate the concrete and reduce the water and air contents. Not much work has been done in the consolidation area for cast-in-place concrete because of the difficulty of applying the squeezing forces. To squeeze such concretes, it is necessary to apply pressure to the forms. One major difficulty in doing this is that very special care must be used to prevent distortion of the wet concrete members.

1.14 Fiber-Reinforced Concretes

In recent years, a great deal of interest has been shown in fiber-reinforced concrete, and today there is much ongoing research on the subject. The fibers used are made from steel, plastics, glass, and other materials. Various experiments have shown that the addition of such fibers in convenient quantities (normally up to about 1% or 2% by volume) to conventional concretes can appreciably improve their characteristics.

The compressive strengths of fiber-reinforced concretes are not significantly greater than they would be if the same mixes were used without the fibers. The resulting concretes, however, are substantially tougher and have greater resistance to cracking and higher impact resistance. The use of fibers has increased the versatility of concrete by reducing its brittleness. The reader should note that a reinforcing bar provides reinforcing only in the direction of the bar, while randomly distributed fibers provide additional strength in all directions.

Steel is the most commonly used material for the fibers. The resulting concretes seem to be quite durable, at least as long as the fibers are covered and protected by the cement mortar. Concretes reinforced with steel fibers are most often used in pavements, thin shells, and precast products as well as in various patches and overlays. Glass fibers are more often used for spray-on applications as in shotcrete. It is necessary to realize that ordinary glass will deteriorate when in contact with cement paste. As a result, using alkali-resistant glass fibers is necessary.

The fibers used vary in length from about 0.25 in. up to about 3 in. while their diameters run from approximately 0.01 in. to 0.03 in. For improving the bond with the cement paste, the fibers can be hooked or crimped. In addition, the surface characteristics of the fibers can be chemically modified in order to increase bonding.

The improvement obtained in the toughness of the concrete (the total energy absorbed in breaking a member in flexure) by adding fibers is dependent on the fibers' *aspect ratio* (length/diameter). Typically, the aspect ratios used vary from about 25 up to as much as 150, with 100 being about an average value. Other factors affecting toughness are the shape and texture of the fibers. ASTM C1018[20] is the test method for determining the toughness of fiber-reinforced concrete using the third-point beam-loading method described earlier.

When a crack opens up in a fiber-reinforced concrete member, the few fibers bridging the crack do not appreciably increase the strength of the concrete. They will, however, provide resistance to the opening up of the crack because of the considerable work that would be necessary to pull them out. As a result, the ductility and toughness of the concrete is increased. The use of fibers has been shown to increase the fatigue life of beams and lessen the widths of cracks when members are subject to fatigue loadings.

The use of fibers does significantly increase costs. It is probably for this reason that fiber-reinforced concretes have been used for overlays for highway pavements and airport runways rather than for whole concrete projects. Actually in the long run, if the increased service lives of fiber-reinforced concretes are considered, they may very well prove to be quite cost-effective. For instance, many residential contractors use fiber-reinforced concrete to construct driveways instead of regular reinforced concrete.

Some people have the feeling that the addition of fibers to concrete reduces its slump and workability as well as its strength. Apparently, they feel this way because the concrete looks stiffer to them. Actually, the fibers do not reduce the slump unless the quantity is too great—that is, much above about one pound per cubic yard. The fibers only appear to cause a reduction in workability, but as a result concrete finishers will often add more water so that water-cement ratios are increased and strengths decreased. ASTM C1018 uses the third-point beam-loading method described earlier to measure the toughness and first-crack strength of fiber-reinforced concrete.

1.15 Concrete Durability

The compressive strength of concrete may be dictated by exposure to freeze-thaw conditions or chemicals such as deicers or sulfates. These conditions may require a greater compressive strength or lower water–cement ratio than those required to carry the calculated loads. Chapter 4 of the 2008 code imposes limits on water–cement ratio, f_c', and entrained air for elements exposed to freeze-thaw cycles. For concrete exposed to deicing chemicals, the amount of fly ash or other pozzolans is limited in this chapter. Finally, the water–cement ratio is limited by exposure to sulfates as well. The designer is required to determine whether structural load-carrying requirements or durability requirements are more stringent and to specify the more restrictive requirements for f_c', water–cement ratio, and air content.

[20] American Society for Testing and Materials, 1997, *Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Simple Beam with Third-Point Loading)* (ASTM C1018-1997), West Conshohocken, Pennsylvania.

1.16 Reinforcing Steel

The reinforcing used for concrete structures may be in the form of bars or welded wire fabric. Reinforcing bars are referred to as *plain* or *deformed*. The deformed bars, which have ribbed projections rolled onto their surfaces (patterns differing with different manufacturers) to provide better bonding between the concrete and the steel, are used for almost all applications. Instead of rolled-on deformations, deformed wire has indentations pressed into it. Plain bars are not used very often except for wrapping around longitudinal bars, primarily in columns.

Plain round bars are indicated by their diameters in fractions of an inch as $\frac{3\text{ in.}}{8}\phi$, $\frac{1\text{ in.}}{2}\phi$, and $\frac{5\text{ in.}}{8}\phi$. Deformed bars are round and vary in sizes from #3 to #11, with two very large sizes, #14 and #18, also available. For bars up to and including #8, the number of the bar coincides with the bar diameter in eighths of an inch. For example, a #7 bar has a diameter of $\frac{7}{8}$ in. and a cross-sectional area of 0.60 in.^{2} (which is the area of a circle with a $\frac{7}{8}$-in. diameter). Bars were formerly manufactured in both round and square cross sections, but today all bars are round.

The #9, #10, and #11 bars have diameters that provide areas equal to the areas of the old 1-in. $\times$ 1-in. square bars, $1\frac{1}{8}$-in. $\times$ $1\frac{1}{8}$-in. square bars, and $1\frac{1}{4}$-in. $\times$ $1\frac{1}{4}$-in. square bars, respectively. Similarly, the #14 and #18 bars correspond to the old $1\frac{1}{2}$-in. $\times$ $1\frac{1}{2}$-in. square bars and 2-in. $\times$ 2-in. square bars, respectively. Table A.2 (see Appendix A) provides details as

Courtesy of EFCO Corp.

Round forms for grandstand support columns at the Texas Motor Speedway, Fort Worth, Texas.

to areas, diameters, and weights of reinforcing bars. Although #14 and #18 bars are shown in this table, the designer should check his or her suppliers to see if they have these very large sizes in stock. Reinforcing bars may be purchased in lengths up to 60 ft. Longer bars have to be specially ordered. In general, longer bars are too flexible and difficult to handle.

Welded wire fabric is also frequently used for reinforcing slabs, pavements, and shells, and places where there is normally not sufficient room for providing the necessary concrete cover required for regular reinforcing bars. The mesh is made of cold-drawn wires running in both directions and welded together at the points of intersection. The sizes and spacings of the wire may be the same in both directions or may be different, depending on design requirements. Wire mesh is easily placed and has excellent bond with the concrete, and the spacing of the wires is well controlled.

Table A.3(A) in Appendix A provides information concerning certain styles of welded wire fabric that have been recommended by the Wire Reinforcement Institute as common stock styles (normally carried in stock at the mills or at warehousing points and, thus, usually immediately available). Table A.3(B) provides detailed information about diameters, areas, weights, and spacings of quite a few wire sizes normally used to manufacture welded wire fabric. Smooth and deformed wire fabric is made from wires whose diameters range from 0.134 in. to 0.628 in. for plain wire and from 0.225 in. to 0.628 in. for deformed wires.

Smooth wire is denoted by the letter W followed by a number that equals the cross-sectional area of the wire in hundredths of a square inch. Deformed wire is denoted by the letter D followed by a number giving the area. For instance, a D4 wire is a deformed wire with a cross-sectional area equal to 0.04 in.^{2} Smooth wire fabric is actually included within the ACI Code's definition of deformed reinforcement because of its mechanical bonding to the concrete caused by the wire intersections. Wire fabric that actually has deformations on the wire surfaces bonds even more to the concrete because of the deformations as well as the wire intersections. According to the code, deformed wire is not permitted to be larger than D31 or smaller than D4.

Headed Steel Bars for Concrete Reinforcement (ASTM A970/970M) were added to the ACI 318 Code in 2008. Headed bars can be used instead of straight or hooked bars, with considerably less congestion in crowded areas such as beam–column intersections. The specification covers plain and deformed bars cut to lengths and having heads either forged or welded to one or both ends. Alternatively, heads may be connected to the bars by internal threads in the head mating to threads on the bar end or by a separate threaded nut to secure the head to the bar. Heads are forge formed, machined from bar stock, or cut from plate. Figure 1.3 illustrates a headed bar detail. The International Code Council has published acceptance criteria for headed ends of concrete reinforcement (ACC 347).

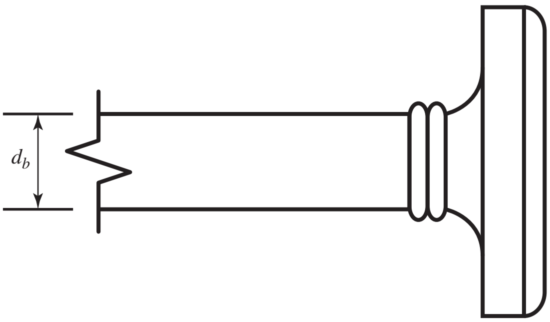

FIGURE 1.3 Headed deformed reinforcing bar.

1.17 Grades of Reinforcing Steel

Reinforcing bars may be rolled from billet steel, axle steel, or rail steel. Only occasionally, however, are they rolled from old train rails or locomotive axles. These latter steels have been cold-worked for many years and are not as ductile as the billet steels.

There are several types of reinforcing bars, designated by the ASTM, which are listed after this paragraph. These steels are available in different grades as Grade 50, Grade 60, and so on, where Grade 50 means the steel has a specified yield point of 50,000 psi, Grade 60 means 60,000 psi, and so on.

- ASTM A615: Deformed and plain billet steel bars. These bars, which must be marked with the letter S (for type of steel), are the most widely used reinforcing bars in the United States. Bars are of four minimum yield strength levels: 40,000 psi (280 MPa); 60,000 psi (420 MPa); 75,000 psi (520 MPa); and 80,000 psi (550 MPa).
- ASTM A706: Low-alloy deformed and plain bars. These bars, which must be marked with the letter W (for type of steel), are to be used where controlled tensile properties and/or specially controlled chemical composition is required for welding purposes. They are available in two grades: 60,000 psi (420 MPa) and 80,000 psi (550 MPa), designated as Grade 60 (420) and Grade 80 (550), respectively.
- ASTM A996: Deformed rail steel or axle steel bars. They must be marked with the letter R (for type of steel).
- When deformed bars are produced to meet both the A615 and A706 specifications, they must be marked with both the letters S and W.

Designers in almost all parts of the United States will probably never encounter rail or axle steel bars (A996) because they are available in such limited areas of the country. Of the 23 U.S. manufacturers of reinforcing bars listed by the Concrete Reinforcing Steel Institute,[21] only five manufacture rail steel bars and not one manufactures axle bars.

Almost all reinforcing bars conform to the A615 specification, and a large proportion of the material used to make them is not new steel but is melted reclaimed steel, such as that from old car bodies. Bars conforming to the A706 specification are intended for certain uses when welding and/or bending are of particular importance. Bars conforming to this specification may not always be available from local suppliers.

There is only a small difference between the prices of reinforcing steel with yield strengths of 40 ksi and 60 ksi. As a result, the 60-ksi bars are the most commonly used in reinforced concrete design.

When bars are made from steels with f_y of 60 ksi or more, the ACI (Section 3.5.3.2) states that the specified yield strength must be the stress corresponding to a strain of 0.35%. For bars with f_y less than 60 ksi, the yield strength shall be taken as the stress corresponding to a strain of 0.5%. The ACI (Section 9.4) has established an upper limit of 80 ksi on yield strengths permitted for design calculations for reinforced concrete. If the ACI were to permit the use of steels with yield strengths greater than 80 ksi, it would have to provide other design restrictions, since the yield strain of 80 ksi steel is almost equal to the ultimate concrete strain in compression. (This last sentence will make sense after the reader has studied Chapter 2.)

There has been gradually increasing demand through the years for Grade 75 and Grade 80 steel, particularly for use in high-rise buildings, where it is used in combination with high-strength concretes. The results are smaller columns, more rentable floor space, and smaller foundations for the resulting lighter buildings.

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[21] Concrete Reinforcing Steel Institute, 2001, *Manual of Standard Practice*, 27th ed., Chicago. Appendix A, pp. A-1 to A-5.

Grade 75 and Grade 80 steel are appreciably higher in cost, and the #14 and #18 bars are often unavailable from stock and will probably have to be specially ordered from the steel mills. This means that there may have to be a special rolling to supply the steel. As a result, its use may not be economically justified unless at least 50 or 60 tons are ordered.

Yield stresses above 60 ksi are also available in welded wire fabric, but the specified stresses must correspond to strains of 0.35%. Smooth fabric must conform to ASTM A185, whereas deformed fabric cannot be smaller than size D4 and must conform to ASTM A496.

The modulus of elasticity for nonprestressed steels is considered to be equal to 29×10^6 psi. For prestressed steels, it varies somewhat from manufacturer to manufacturer, with a value of 27×10^6 psi being fairly common.

Stainless steel reinforcing (ASTM A955) was introduced in the 2008 code. It is highly resistant to corrosion, especially pitting and crevice corrosion from exposure to chloride-containing solutions such as deicing salts. While it is more expensive than normal carbon steel reinforcement, its life-cycle cost may be less when the costs of maintenance and repairs are considered.

1.18 SI Bar Sizes and Material Strengths

The metric version of the ACI Code 318M-11 makes use of the same reinforcing bars used for designs using U.S. customary units. The metric bar dimensions are merely soft conversions (i.e., almost equivalent) of the customary sizes. The SI concrete strengths (f_c') and the minimum steel yield strengths (f_y) are converted from the customary values into metric units and rounded off a bit. A brief summary of metric bar sizes and material strengths is presented in the following paragraphs. These values are used for the SI examples and homework problems throughout the text.

1. The bar sizes used in the metric version of the code correspond to U.S. sizes #3 through #18 bars. They are numbered 10, 13, 16, 19, 22, 25, 29, 32, 36, 43, and 57. These numbers represent the U.S. customary bar diameters rounded to the nearest millimeter (mm). For instance, the metric #10 bar has a diameter equal to 9.5 mm, the metric #13 bar has a diameter equal to 12.7 mm, and so on. Detailed information concerning metric reinforcing bar diameters, cross-sectional areas, masses, and ASTM classifications is provided in Appendix B, Tables B.2 and B.3.

2. The steel reinforcing grades, or minimum steel yield strengths, referred to in the code are 300, 350, 420, and 520 MPa. These correspond, respectively, to 43,511, 50,763, 60,916, and 75,420 psi and, thus, correspond approximately to Grade 40, 50, 60, and 75 bars. Appendix B, Table B.3 provides ASTM numbers, steel grades, and bar sizes available in each grade.

3. The concrete strengths in metric units referred to in the code are 17, 21, 24, 28, 35, and 42 MPa. These correspond respectively to 2466, 3046, 3481, 4061, 5076, and 6092 psi, that is, to 2500-, 3000-, 3500-, 4000-, 5000-, and 6000-psi concretes.

In 1997, the producers of steel reinforcing bars in the United States began to produce soft metric bars. These are the same bars we have long called standard inch-pound bars, but they are marked with metric units. Today, the large proportion of metric bars manufactured in the United States are soft metric. By producing the exact same bars, the industry does not have to keep two different inventories (one set of inch-pound bar sizes and another set of different bar sizes in metric units). Table 1.1 shows the bar sizes given in both sets of units.

TABLE 1.1 Reinforcement Bar Sizes and Areas

Standard Inch-Pound Bars			Soft Metric Bars		
Bar No.	Diameter (in.)	Area (in.^{2})	Bar No.	Diameter (mm)	Area (mm^2)
3	0.375	0.11	10	9.5	71
4	0.500	0.20	13	12.7	129
5	0.625	0.31	16	15.9	199
6	0.750	0.44	19	19.1	284
7	0.875	0.60	22	22.2	387
8	1.000	0.79	25	25.4	510
9	1.128	1.00	29	28.7	645
10	1.270	1.27	32	32.3	819
11	1.410	1.56	36	35.8	1006
14	1.693	2.25	43	43.0	1452
18	2.257	4.00	57	57.3	2581

1.19 Corrosive Environments

When reinforced concrete is subjected to deicing salts, seawater, or spray from these substances, it is necessary to provide special corrosion protection for the reinforcing. The structures usually involved are bridge decks, parking garages, wastewater treatment plants, and various coastal structures. We must also consider structures subjected to occasional chemical spills that involve chlorides.

Should the reinforcement be insufficiently protected, it will corrode; as it corrodes, the resulting oxides occupy a volume far greater than that of the original metal. The results are large outward pressures that can lead to severe cracking and spalling of the concrete. This reduces the concrete protection, or *cover*, for the steel, and corrosion accelerates. Also, the *bond*, or sticking of the concrete to the steel, is reduced. The result of all of these factors is a decided reduction in the life of the structure.

Section 7.7.6 of the code requires that for corrosive environments, more concrete cover must be provided for the reinforcing; it also requires that special concrete proportions or mixes be used.

The lives of such structures can be greatly increased if *epoxy-coated reinforcing* bars are used. Such bars need to be handled very carefully so as not to break off any of the coating. Furthermore, they do not bond as well to the concrete, and their embedment lengths will have to be increased somewhat for that reason, as you will learn in Chapter 7. A new type of bar coating, a dual coating of a zinc alloy and an epoxy coating, was introduced in the 2011 ACI 318 Code: ASTM A1055. Use of stainless steel reinforcing, as described in Section 1.14, can also significantly increase the service life of structures exposed to corrosive environments.

1.20 Identifying Marks on Reinforcing Bars

It is essential for people in the shop and the field to be able to identify at a glance the sizes and grades of reinforcing bars. If they are not able to do this, smaller and lower-grade bars other than those intended by the designer may be used. To prevent such mistakes, deformed bars have rolled-in identification markings on their surfaces. These markings are described in the following list and are illustrated in Figure 1.4.

1. The producing company is identified with a letter.
2. The bar size number (3 to 18) is given next.

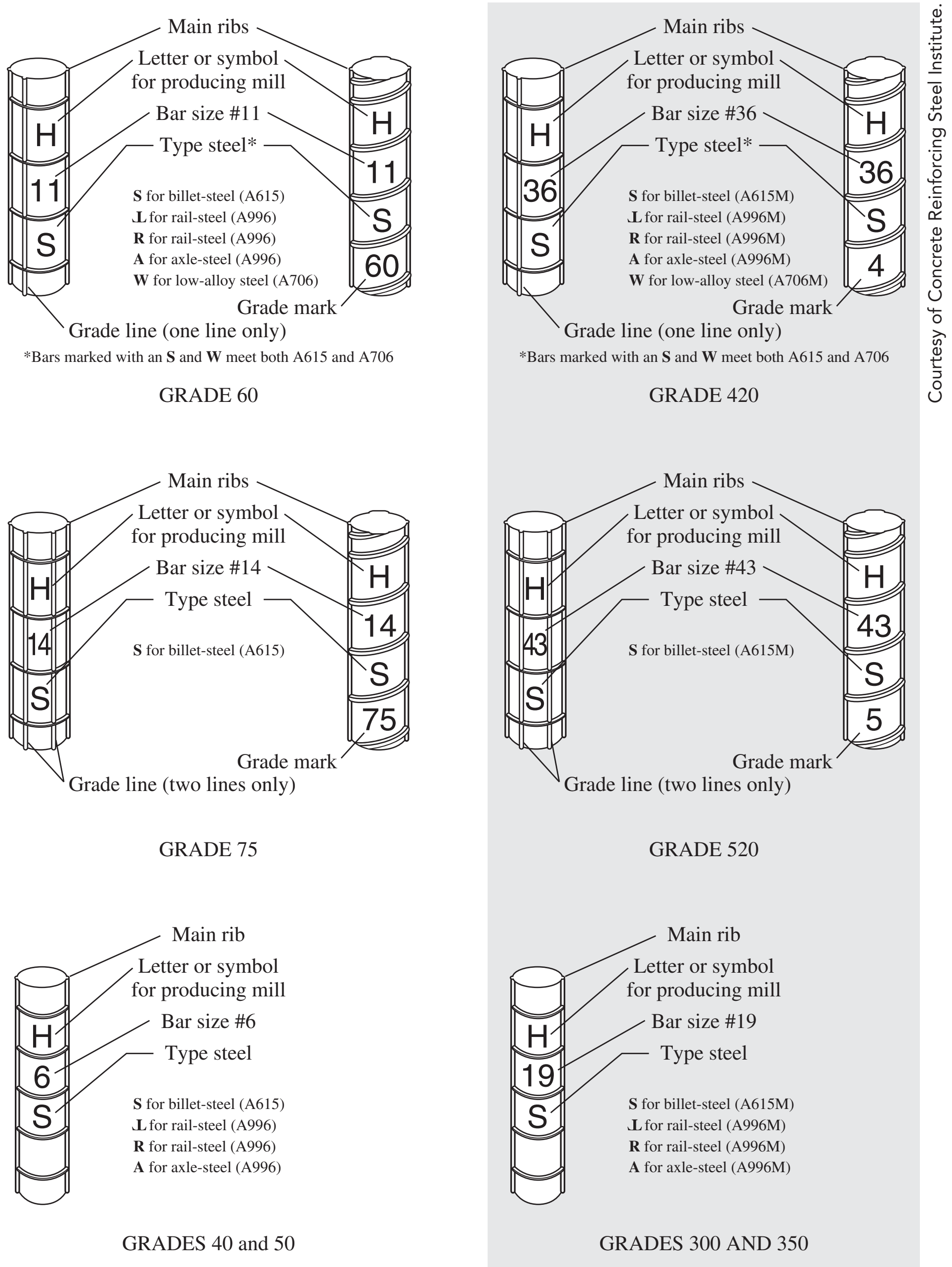


FIGURE 1.4 Identification marks for ASTM standard bars.

3. Another letter is shown to identify the type of steel (S for billet, R in addition to a rail sign for rail steel, A for axle, and W for low alloy).
4. Finally, the grade of the bars is shown either with numbers or with continuous lines. A Grade 60 bar has either the number 60 on it or a continuous longitudinal line in addition to its main ribs. A Grade 75 bar will have the number 75 on it or two continuous lines in addition to the main ribs.

1.21 Introduction to Loads

Perhaps the most important and most difficult task faced by the structural designer is the accurate estimation of the loads that may be applied to a structure during its life. No loads that may reasonably be expected to occur may be overlooked. After loads are estimated, the next problem is to decide the worst possible combinations of these loads that might occur at one time. For instance, would a highway bridge completely covered with ice and snow be simultaneously subjected to fast-moving lines of heavily loaded trailer trucks in every lane and to a 90-mile lateral wind, or is some lesser combination of these loads more reasonable?

The next few sections of this chapter provide a brief introduction to the types of loads with which the structural designer must be familiar. The purpose of these sections is not to discuss loads in great detail but rather to give the reader a feel for the subject. As will be seen, loads are classed as being dead, live, or environmental.

1.22 Dead Loads

Dead loads are loads of constant magnitude that remain in one position. They include the weight of the structure under consideration as well as any fixtures that are permanently attached to it. For a reinforced concrete building, some dead loads are the frames, walls, floors, ceilings, stairways, roofs, and plumbing.

To design a structure, it is necessary for the weights or dead loads of the various parts to be estimated for use in the analysis. The exact sizes and weights of the parts are not known until the structural analysis is made and the members of the structure are selected. The weights, as determined from the actual design, must be compared with the estimated weights. If large discrepancies are present, it will be necessary to repeat the analysis and design using better estimated weights.

Reasonable estimates of structure weights may be obtained by referring to similar structures or to various formulas and tables available in most civil engineering handbooks. An experienced designer can estimate very closely the weights of most structures and will spend little time repeating designs because of poor estimates.

The approximate weights of some common materials used for floors, walls, roofs, and the like are given in Table 1.2.

TABLE 1.2 Weights of Some Common Building Materials

Reinforced concrete (12 in.)	150 psf	2×12 @ 16-in. double wood floor	7 psf
Acoustical ceiling tile	1 psf	Linoleum or asphalt tile	1 psf
Suspended ceiling	2 psf	Hardwood flooring ($\frac{7}{8}$ in.)	4 psf
Plaster on concrete	5 psf	1-in. cement on stone-concrete fill	32 psf
Asphalt shingles	2 psf	Movable steel partitions	4 psf
3-ply ready roofing	1 psf	Wood studs with $\frac{1}{2}$-in. gypsum	8 psf
Mechanical duct allowance	4 psf	Clay brick wythes (4 in.)	39 psf

1.23 Live Loads

Live loads are loads that can change in magnitude and position. They include occupancy loads, warehouse materials, construction loads, overhead service cranes, equipment operating loads, and many others. In general, they are induced by gravity.

Some typical floor live loads that act on building structures are presented in Table 1.3. These loads, which are taken from Table 4-1 in ASCE 7-10,[22] act downward and are distributed uniformly over an entire floor. By contrast, roof live loads are 20 psf (pounds per square feet) maximum distributed uniformly over the entire roof.

Among the many other types of live loads are:

Traffic loads for bridges—Bridges are subjected to series of concentrated loads of varying magnitude caused by groups of truck or train wheels.

Impact loads—Impact loads are caused by the vibration of moving or movable loads. It is obvious that a crate dropped on the floor of a warehouse or a truck bouncing on uneven pavement of a bridge causes greater forces than would occur if the loads were applied gently and gradually. Impact loads are equal to the difference between the magnitude of the loads actually caused and the magnitude of the loads had they been dead loads.

Longitudinal loads—Longitudinal loads also need to be considered in designing some structures. Stopping a train on a railroad bridge or a truck on a highway bridge causes longitudinal forces to be applied. It is not difficult to imagine the tremendous longitudinal force developed when the driver of a 40-ton trailer truck traveling at 60 mph suddenly has to apply the brakes while crossing a highway bridge. There are other longitudinal load situations, such as ships running into docks and the movement of traveling cranes that are supported by building frames.

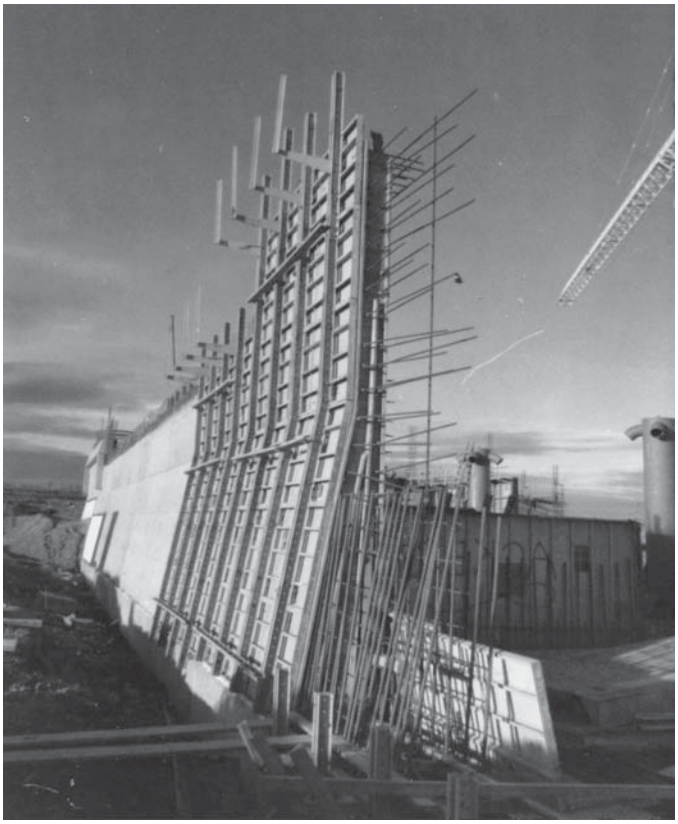
Miscellaneous loads—Among the other types of live loads with which the structural designer will have to contend are *soil pressures* (such as the exertion of lateral earth pressures on walls or upward pressures on foundations), *hydrostatic pressures* (such as water pressure on dams, inertia forces of large bodies of water during earthquakes, and uplift pressures on tanks and basement structures), *blast loads* (caused by explosions, sonic booms, and military weapons), and *centrifugal forces* (such as those caused on curved bridges by trucks and trains or similar effects on roller coasters).

TABLE 1.3 Some Typical Uniformly Distributed Live Loads

Lobbies of assembly areas	100 psf	Classrooms in schools	40 psf
Dance hall and ballrooms	100 psf	Upper-floor corridors in schools	80 psf
Library reading rooms	60 psf	Stairs and exitways	100 psf
Library stack rooms	150 psf	Heavy storage warehouse	250 psf
Light manufacturing	125 psf	Retail stores—first floor	100 psf
Offices in office buildings	50 psf	Retail stores—upper floors	75 psf
Residential dwelling areas	40 psf	Walkways and elevated platforms	60 psf

psf = pounds per square foot

[22] American Society of Civil Engineers, 2010, *Minimum Design Loads for Buildings and Other Structures*, ASCE 7-10 (Reston, VA: American Society of Civil Engineers), pp. 17–19.



Courtesy of The Burke Company.

Sewage treatment plant, Redwood City, California.

Live load reductions are permitted, according to Section 4.8 of ASCE 7, because is it unlikely that the entire structure will be subjected to its full design live load over its entire floor area all at one time. This reduction can significantly reduce the total design live load on a structure, resulting in much lower column loads at lower floors and footing loads.

1.24 Environmental Loads

Environmental loads are loads caused by the environment in which the structure is located. For buildings, they are caused by rain, snow, wind, temperature change, and earthquake. Strictly speaking, these are also live loads, but they are the result of the environment in which the structure is located. Although they do vary with time, they are not all caused by gravity or operating conditions, as is typical with other live loads. In the next few paragraphs, a few comments are made about the various kinds of environmental loads.

1. *Snow and ice.* In the colder states, snow and ice loads are often quite important. One inch of snow is equivalent to approximately 0.5 psf, but it may be higher at lower elevations where snow is denser. For roof designs, snow loads of from 10 psf to 40 psf are used, the magnitude depending primarily on the slope of the roof and to a lesser degree on the character of the roof surface. The larger values are used for flat roofs, the smaller ones for sloped roofs. Snow tends to slide off sloped roofs, particularly those with metal or slate surfaces. A load of approximately 10 psf might be used for 45° slopes, and a 40-psf load might be used for flat