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STRUCTURAL USE OF CONCRETE

This chapter presents some of the considerations for the use of concrete for structural purposes in building construction.

1.1 CONCRETE AS A STRUCTURAL MATERIAL

Concrete consists of a mixture that contains a mass of loose, inert particles of graded size (commonly sand and gravel) held together in solid form by a binding agent. That general description covers a wide range of end products. The loose particles may consist of wood chips, industrial wastes, mineral fibers, and various synthetic materials. The binding agent may be coal tar, gypsum, portland cement, or various synthetic compounds. The end products range from asphalt pavement, insulating fill, shingles, wall panels, and masonry units to the familiar sidewalks, roadways, foundations, and building frameworks.

This book deals primarily with concrete formed with the common binding agent of *portland cement*, and a loose mass consisting of sand

and gravel. This is what most of us mean when we use the term *concrete*. With minor variations, this is the material used mostly for structural concrete—to produce building structures, pavements, and foundations.

Concrete made from natural materials was used by ancient builders thousands of years ago. Modern concrete, made with industrially produced cement, was first produced in the early part of the nineteenth century when the process for producing portland cement was developed. Because of its lack of tensile strength, however, concrete was used principally for crude, massive structures—foundations, bridge piers, and heavy walls.

In the late nineteenth century, several builders experimented with the technique of inserting iron or steel rods into relatively thin structures of concrete to enhance their ability to resist tensile forces. This was the beginning of what we now know as *reinforced concrete*. Many of the basic forms of construction developed by these early experimenters have endured to become part of our common technical inventory for building structures.

Over the years, from ancient times until now, there has been a steady accumulation of experience derived from experiments, research, and, most recently, intense development of commercial products. As a result, there is currently available to the building designer an immense variety of products under the general classification of concrete. This range is somewhat smaller if major structural usage is required, but the potential variety is still significant.

1.2 COMMON FORMS OF CONCRETE STRUCTURES

For building structures, concrete is mostly used with one of three basic construction methods. The first is called *sitecast concrete*, in which the wet concrete mix is deposited in forms at the location where it is to be used. This method is also described as *cast-in-place* or *in situ* construction.

A second method consists of casting portions of the structure at a location away from the desired location of the construction. These elements—described as *precast concrete*—are then moved into position, much as blocks of stone or parts of steel frames are.

Finally, concrete may be used for masonry construction—in one of two ways. Precast units of concrete called concrete masonry units (CMUs), may be used in a manner similar to bricks or stones. Alternately, concrete fill may be used to produce solid masonry by being poured into cavities in masonry produced with bricks, stone, or CMUs. The latter technique, combined with the insertion of steel reinforcement into the cavities, is

widely used for masonry structures today. The use of concrete-filled masonry, however, is one of the oldest forms of concrete construction—used extensively by the Romans and the builders of early Christian churches.

Concrete is produced in great volume for various forms of construction. Building frames, walls, and other structural systems represent a minor usage of the total concrete produced. Pavements for sidewalks, parking lots, streets, and ground-level floor slabs in buildings use more concrete than all the building frameworks. Add the usage for the interstate highway system, water control, marine structures, and large bridges and tunnels, and building structural usage shrinks considerably in significance. One needs to understand this when considering the economics and operations of the concrete industry.

Other than pavements, the widest general use of concrete for building construction is foundations. Almost every building has a concrete foundation, whether the major above ground construction is concrete, masonry, wood, steel, aluminum, or fabric. For small buildings with shallow footings and no basement, the total foundation system may be modest, but for large buildings and those with many belowground levels, there may well be a gigantic underground concrete structure.

For above ground building construction, concrete is generally used in situations that fully realize the various advantages of the basic material and the common systems that derive from it. For structural applications, this means using the major compressive resistance of the material and in some situations its relatively high stiffness and inertial resistance (major dead weight). However, in many applications, the nonrotting, vermin- and insect-resistant, and fire-resistant properties may be of major significance. And for many uses, its relatively low bulk-volume cost is important.

Elements of Concrete Structures

Formation of a concrete structural system for a building usually consists of the assemblage of individual structural elements. Most commonly used structural systems are combinations of a few basic elements; these are:

- Structural walls
- Structural columns, piers, or other single supports
- Horizontal-spanning beams
- Horizontal-spanning decks

The actions of these individual elements and their various interactions for structural functions must be considered when designing building

structures. Concrete is also widely used for foundations, and the common elements utilized for this purpose are:

- Foundation walls
- Wall and single-column-bearing footings
- Pile caps for clusters of piles
- Piers, cast as columns in excavated holes

Consideration is given to each of these individual elements in this book. Some of the possibilities for their use in whole, assembled structures are illustrated in the building case study examples in Chapter 16.

Many special elements are also typically required for the completion of any building structure, such as pilasters, brackets, keys, pedestals, column caps, and so on. These are necessary, but essentially secondary, elements of the basic systems. Various situations for their use are illustrated in this book.

Many structures of more exotic forms can be realized with concrete beyond the simple systems treated in this book. Arches, domes, thin shells, folded plates, and other imaginative systems have been developed by designers who push the limits of the material's potentialities. We hope that readers may have the opportunity to work on such exciting structures at some time. Here, we start with the simplest, and most commonly used, structures.

1.3 PRIMARY SITUATIONS FOR INVESTIGATION AND DESIGN

A critical step in the visualization of structural behaviors is the consideration of the basic internal structural actions that occur in structural members. The five primary actions of internal structural resistance are tension, compression, shear, bending, and torsion. The structural functions of all the basic elements described previously can be developed with combinations of these basic internal actions.

There is another level down, of course, consisting of the basic stress actions that are a material's direct response to structural forces. Thus all the internal force actions can be produced from the basic stresses of tension, compression, and shear. For some materials the character of the stress is a critical concern since the material responds differently to the different stresses. Such is indeed the case with concrete, for which development of tension stress is a problem; this is the starting point for the design of reinforcement.

For our purposes here, it is useful to start with a basic element: the beam. This immediately presents all three basic stresses in the development of bending and shear for the basic beam action. And it makes a case for reinforcement, to develop significant internal tension for bending resistance, as well as an enhanced resistance to shear. The spanning slab represents essentially a variation on the basic beam function.

The second basic element to be considered is the column; that is the element whose basic task is resistance to compression. Variations here consist of the pier or pedestal (a very short column) and the bearing wall.

Finally, for the assembled system, a significant consideration is the interaction of elements in various framed configurations. This introduces the problem of joints or connections between elements, with the various force transfers necessary through the joints. It also involves consideration of the effects of one element on others to which it is connected; for example, the actions of adjacent beams on each other when continuity between spans occurs, and the interactions of beams and columns in a planar frame with continuous elements.

1.4 MATERIALS AND NATURE OF STRUCTURAL CONCRETE

This section presents discussions of the various ingredients of structural concrete and factors that influence the physical properties of the finished concrete. Other elements used to produce concrete structures are also discussed.

Common Forms of Structural Concrete

For serious structural usage, concrete must attain significant strength and stiffness, reasonable surface hardness, and other desired properties. While the mixture used to obtain concrete can be almost endlessly varied, the controlled mixes used for structural applications are developed within a quite limited set of variables. The most commonly used mix contains ordinary portland cement, clean water, medium-to-coarse sand, and a considerable volume of some fairly large pieces of rock. This common form of concrete will be used as a basis for comparison of mixes for special purposes.

Figure 1.1 shows the composition of ordinary concrete. The binder consists of the water and cement, whose chemical reaction results in the

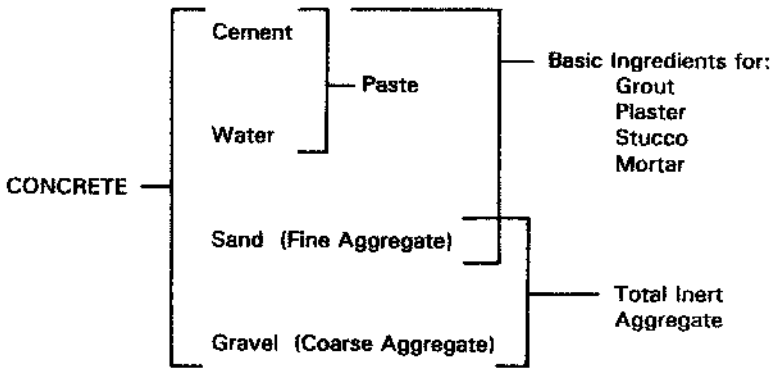


Figure 1.1 Composition of ordinary concrete.

hardening of the mass. The binder is mixed with some aggregate (loose, inert particles) so that the binder coats the surfaces and fills the voids between the particles of the aggregate. For materials such as grout, plaster, and stucco, the aggregate consists of sand of reasonably fine grain size. For concrete the grain size is extended into the category of gravel, with the maximum particle size limited only by the size of the structure. The end product—the hardened concrete—is highly variable, due to the choices for the individual basic ingredients; modifications in the mixing, handling, and curing processes; and possible addition of special ingredients.

Cement

The cement used most extensively in building construction is portland cement. Of the five standard types of portland cement generally available in the United States and for which the American Society for Testing and Materials has established specifications, two types account for most of the cement used in buildings. These are a general-purpose cement for use in concrete designed to reach its required strength in about 28 days, and a high-early-strength cement for use in concrete that attains its design strength in a period of a week or less.

All portland cements set and harden by reacting with water, and this hydration process is accompanied by generation of heat. In massive concrete structures such as dams, the resulting temperature rise of the materials becomes a critical factor in both design and construction, but the

problem is usually not significant in building construction. A low-heat cement is designed for use where the heat rise during hydration is a critical factor. It is, of course, essential that the cement actually used in construction correspond to that employed in designing the mix, to produce the specified compressive strength of the concrete.

Mixing Water

Water must be reasonably clean, free of oil, organic matter, and any substances that may affect the actions of hardening, curing, or general finish quality of the concrete. In general, drinking-quality (potable) water is usually adequate. Salt-bearing seawater may be used for plain concrete (without reinforcing) but may cause the corrosion of steel bars in reinforced concrete.

A critical concern for the production of good concrete is the *amount* of water used. In this regard there are three principal concerns, as follows:

1. Having enough water to react chemically with the cement so that the hardening and strength gain of the concrete proceeds over time until the desired quality of material is attained.
2. Having enough water to facilitate good mixing of the ingredients and allow for handling in casting and finishing of the concrete.
3. Having the amount of water low enough so that the combination of water and cement (the paste) is not too low in cement to perform its bonding action. This is a major factor in producing high-grade concrete for structural applications.

Stone Aggregate

The most common aggregates are sand, crushed stone, and pebbles. Particles smaller than $\frac{3}{16}$ in. in diameter constitute the *fine aggregate*. There should be only a very small amount of very fine materials, to allow for the free flow of the water-cement mixture between the aggregate particles. Material larger than $\frac{3}{16}$ in. is called the *coarse aggregate*. The maximum size of the aggregate particle is limited by specification, based on the thickness of the cast elements, spacing and cover of the reinforcing, and some consideration of finishing methods.

In general, the aggregate should be well graded, with some portion of large to small particles over a range to permit the smaller particles to fill the spaces between the larger ones. The volume of the concrete is, thus,

mostly composed of the total aggregate, the water and cement going into the spaces remaining between the smallest aggregate particles. The weight of the concrete is determined largely by the weight of the coarse aggregate. Strength is also dependent, to some degree, on the structural integrity of the large aggregate particles.

Special Aggregates

While stone is the most common coarse aggregate, for various reasons other materials may be used. One reason for this may be the absence of available stone of adequate quality, but more often there is some desire to impart particular modified properties to the concrete. Some of these desired properties and the types of aggregates used to achieve them are discussed in this section.

Weight Reduction. For structural concrete, a common desire is for some reduction of the dead load of the structure. This is most often desired for concrete elements of spanning structures. Since the coarse aggregate typically constitutes at least two-thirds of the total mass of the concrete, any significant reduction in unit density of the coarse aggregate will result in a significant weight reduction of the finished concrete. If a relatively high strength is also desired, there is a limit to how much reduction can be achieved. Various natural and synthetic materials may be used as substitutes for the ordinary stone, but if reasonable strength and stiffness is critical, the maximum reduction is usually around 25 to 30%; that is, a reduction from a typical density of 145 to 150 pounds per cubic foot (pcf) to something just over 100 pcf. Lower finished densities may be achieved, but usually with significant loss of both strength and stiffness.

Weight Increase. In some circumstances an increase of weight may be desired. This is usually achieved with selected stone of high density, typically one containing metal ores. Alternately, in some cases, it can be accomplished by using scrap iron as part of the aggregate. This seldom involves structures that are exposed to air or to view.

Better Resistance to Fire. Individual types of stone have different actions when exposed to the extreme heat of fires. This action may be critical for the concrete structure itself or for its utilization in providing fireproofing for a steel structure. A specific material may be selected for this property and may be either a natural stone or a synthetic product.

Fiber Aggregate. Fibrous materials may be added to the concrete in significant amounts, usually for the increased tension resistance they provide for the concrete. However, these are not used in amounts that significantly reduce the total mass of coarse aggregate. Thus, the development of a fibrous concrete still involves the selection of some material for the coarse aggregate.

For some uses of concrete, it may be possible to utilize some available material for part of the coarse aggregate to reduce cost or to achieve some goal for utilization of the material. In some coastal areas clam shells have been used as part of the coarse aggregate, usually because of the limited availability of good stone. Crushed, recycled glass has been used in limited amounts for some pavements and foundations. However, when the best structural concrete possible is desired, the choice is still most often for some good type of stone that is locally available in sufficient quantity.

Additions to the Basic Concrete Mix

Substances added to concrete to improve its workability, accelerate its set, harden its surface, and increase its waterproof qualities are known as *admixtures*. The term embraces all materials other than the cement, water, and aggregates that are added just before or during mixing. Many proprietary compounds contain hydrated lime, calcium chloride, and kaolin. Calcium chloride is the most commonly used admixture for accelerating the set of concrete, but corrosion of steel reinforcement may be the consequence of its excessive use.

Air-entrained concrete is produced by using an air-entraining portland cement or by introducing an air-entraining admixture as the concrete is mixed. Air-entraining agents produce billions of microscopic air cells per cubic foot; they are distributed uniformly throughout the mass. These minute voids prevent the accumulation of water, which, on freezing, would expand and result in spalling of the exposed surface under frost action. In addition to improving workability, entrained air permits lower water-cement ratios and significantly improves the durability of hardened concrete.

1.5 SIGNIFICANT PROPERTIES OF CONCRETE

In the production of elements of concrete structures, some particular properties of concrete emerge as most significant. This section discusses these major properties.

Strength

The primary index of strength of concrete is the *specified compressive strength*, designated f'_c . This is the unit compressive stress used for structural design and for a target for the mix design. It is usually given in units of psi, and it is a common practice to refer to the structural quality of the concrete simply by calling it by this number: 3000-lb concrete, for example. For strength design, this value is used to represent the ultimate compressive strength of the concrete. For working stress design, allowable maximum stresses are based on this limit, specified as some fraction of f'_c .

Hardness

The hardness of concrete refers essentially to its surface density. This is dependent primarily on the basic strength, as indicated by the value for compressive stress. However, surfaces may be somewhat softer than the central mass of concrete, owing to early drying at the surface. Some techniques are used to deliberately harden surfaces, especially those of the tops of slabs. Fine troweling will tend to draw a very cement-rich material to the surface, resulting in an enhanced density. Chemical hardeners can also be used, as well as sealing compounds that trap surface water and enhance the natural hardening process of the surface.

Stiffness

Stiffness of structural materials is a measure of resistance to deformation under stress. For compression and tension stress resistance, stiffness is measured by the *modulus of elasticity*, designated E . This modulus is established by tests and is the ratio of unit stress to unit strain. Since unit strain has no unit designation (measured as inch/inch, etc.), the unit for E , thus, becomes the unit for stress, usually lb/in.² [MPa].

The magnitude of elasticity for concrete, E_c , depends on the weight of the concrete and its strength. For values of unit (w) weight between 90 and 155 lb/ft³ or pcf, the value of E_c is

$$E_c = w^{1.5} 33 \sqrt{f'_c}$$

The unit weight for ordinary stone-aggregate concrete is usually assumed to be an average of 145 pcf. Substituting this value for w in the equation, we obtain a simpler form for the concrete modulus of

$$E_c = 57,000 \sqrt{f'_c}$$

For metric units, with stress measured in MPa, the expression becomes

$$E_c = 4730\sqrt{f'_c}$$

Distribution of stresses and strains in reinforced concrete is dependent on the concrete modulus, the steel modulus being a constant. This is discussed in Chapter 7. In the design of reinforced concrete members we employ the term n . This is the ratio of the modulus of elasticity of steel to that of concrete, or $n = E_s/E_c$. E_s is taken as 29,000 ksi [200,000 MPa], a constant. The value for concrete, however, is variable, as we have seen. Values for n are usually given in tables of properties, although they are typically rounded off.

When subjected to long-duration stress at a high level, concrete has a tendency to *creep*, a phenomenon in which strain increases over time under constant stress. This has effects on deflections and on the distributions of stresses between the concrete and reinforcing. Some of the implications of this for design are discussed in the chapters that deal with beams and columns.

As discussed in other sections, there are various controls that can be exercised to ensure a desired type of material in the form of the hardened concrete. The three properties of greatest concern are the water content of the wet mix and the density and compressive strength of the hardened concrete. Design of the mix, handling of the wet mix, and curing of the concrete after casting are the general means of controlling the end product.

In addition to the basic structural properties, there are various properties of concrete that bear on its use as a construction material and in some cases on its structural integrity.

Workability

This term generally refers to the ability of the wet mixed concrete to be handled, placed in the forms, and finished while still fluid. A certain degree of workability is essential to the proper forming and finishing of the material. However, the fluid nature of the mix is largely determined by the amount of water present, and the easiest way to make it more workable is to add water. Up to a point, this may be acceptable, but the extra water usually means less strength, greater porosity, and more shrinkage—all generally undesirable properties. Use is made of vibration, admixtures, and other techniques to facilitate handling without increasing the water content.

Watertightness

It is usually desirable to have a generally nonporous concrete. This may be quite essential for walls or for floors consisting of paving slabs, but is good in general for protection of reinforcing from corrosion. Watertightness is obtained by having a well-mixed, high-quality concrete (low water content, etc.) that is worked well into the forms and has dense surfaces with little cracking or voids. Concrete is absorptive, however, and when subjected to the continuous presence of water will become saturated. Moisture or waterproof barriers must be used where water penetration must be prevented.

Density

Concrete unit weight is essentially determined by the density of the coarse aggregate (ordinarily two-thirds or more of the total volume) and the amount of air in the mass of the finished concrete. With ordinary gravel aggregate and air limited to not more than 4% of the total volume, air dry concrete weighs around 145 lb/ft³. Use of strong but lightweight aggregates can result in weight reduction to close to 100 lb/ft³ with strengths generally competitive with that obtained with gravel. Lower densities are achieved by entraining air up to 20% of the volume and using very light aggregates, but strength and other properties are quickly reduced.

Fire Resistance

Concrete is noncombustible and its insulative, fire protection character is used to protect the steel reinforcing. However, under long exposure to fire, popping and cracking of the material will occur, resulting in actual structural collapse or a diminished capacity that requires replacement or repair after a fire. Design for fire resistance involves the following basic concerns:

- *Thickness of Parts.* Thin walls or slabs may crack quickly, permitting penetration of fire and gases.
- *Cover of Reinforcement.* More insulating protection is required for higher fire rating of the construction.
- *Character of the Aggregate.* Some are more vulnerable to high temperatures.

Design specifications and building code regulations deal with these issues, some of which are discussed in the development of the building design illustrations in Chapter 16.

Shrinkage

Water-mixed materials, such as plaster, mortar, and concrete, tend to shrink during the hardening process. For ordinary concrete, the shrinkage averages about 2% of the volume. Dimensional change of structural members is usually less, due to the presence of the steel bars; however, some consideration must be given to the shrinkage effects. Stresses caused by shrinkage are in some ways similar to those caused by thermal change, the combination resulting in specifications for minimum two-way reinforcing in walls and slabs. For the structure in general, shrinkage is usually dealt with by limiting the size of individual pours of concrete because the major shrinkage ordinarily occurs quite rapidly in the fresh concrete. For special situations, it is possible to modify the concrete with admixtures or special cements that cause a slight expansion to compensate for the normal shrinkage.

1.6 REINFORCEMENT

For most structural applications of concrete, it is necessary to compensate for the weakness of the material in resisting tension. The primary means of accomplishing this is to use steel reinforcing bars. A more recent development is to add fibrous materials to the concrete mix to alter the properties of the basic material.

Steel Reinforcement

The steel used in reinforced concrete consists of round bars, mostly of the deformed type, with lugs or projections on their surfaces. The surface deformations help to develop a greater bond between the steel rods and the enclosing concrete mass. The essential purpose of steel reinforcement is to reduce the cracking of the concrete due to tensile stresses. Structural actions are investigated for the development of tension in the structural members, and steel reinforcement in the proper amount is placed within the concrete mass to resist the tension. In some situations steel reinforcement may also be used to increase compressive resistance since the ratio of magnitudes of strength of the two materials is quite high; thus, the steel displaces a much weaker material and the member gains significant strength.

Tension can also be induced by shrinkage of the concrete during its drying out from the initial wet mix. Temperature variations may also induce tension in many situations. To address these latter occurrences, a minimum amount of reinforcing is used in surface-type members, such as walls and paving slabs, even when no structural action is anticipated.

The most common grades of steel used for ordinary reinforcing bars are Grade 40 and Grade 60, having yield strengths of 40 ksi [276 MPa] and 60 ksi [414 MPa], respectively. The yield strength of the steel is of primary interest for two reasons. Plastic yielding of the steel generally represents the limit of its practical utilization for reinforcing of the concrete because the extensive deformation of the steel in its plastic range results in major cracking of the concrete. Thus, for service load conditions, it is desirable to keep the stress in the steel within its elastic range of behavior where deformation is minimal. (See Figure 1.2.)

The second reason for the importance of the yield character of the reinforcing is its ability to impart a generally yielding nature (plastic deformation character) to the otherwise typically very brittle concrete structure. This is of particular importance for dynamic loading and is a major consideration in design for earthquake forces. Also of importance is the residual strength of the steel beyond its yield stress limit. As shown in

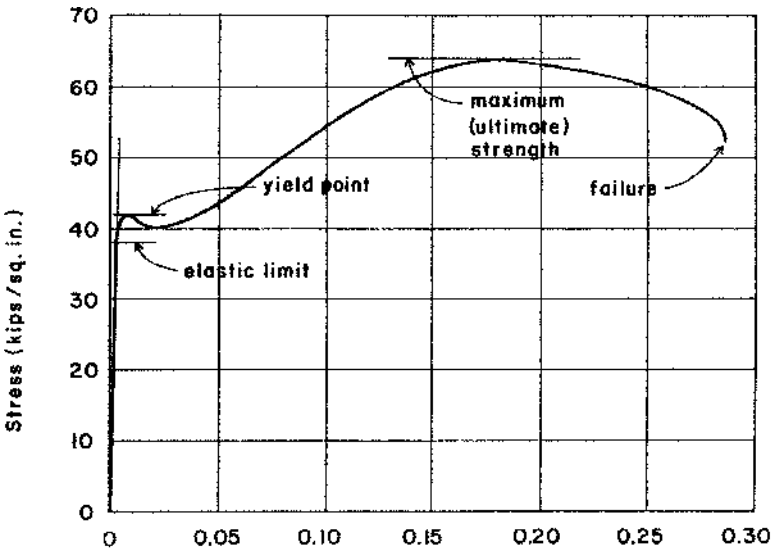


Figure 1.2 Stress/strain graph for ductile steel with yield strength of 40 ksi.

the graph in Figure 1.2, the steel continues to resist stress in its plastic range and then gains a second, higher, strength before failure. Thus, the failure induced by yielding is only a first stage response and a second level of resistance is reserved.

Ample concrete protection, called *cover*, must be provided for the steel reinforcement. This is important to protect the steel from rusting and to be sure that it is well engaged by the mass of concrete. Cover is measured as the distance from the outside face of the concrete to the edge of the reinforcing bar.

Code minimum requirements for cover are $\frac{3}{4}$ in. for walls and slabs and 1.5 in. for beams and columns. Additional distance of cover is required for extra fire protection or for special conditions where the concrete surface is exposed to weather or is in contact with the ground.

Where multiple bars are used in concrete members (which is the common situation), there are both upper and lower limits for the spacing of the bars. Lower limits are intended to facilitate the flow of wet concrete during casting and to permit adequate development of the concrete-to-steel stress transfers for individual bars. Maximum spacing is generally intended to ensure that there is some steel that relates to a concrete mass of limited size; that is, there is not too extensive a mass of concrete with no reinforcement. For relatively thin walls and slabs, there is also a concern with the scale of spacing related to the thickness of the concrete. Specific code requirements for bar spacing are discussed in Section 2.6.

For structural members, the amount of reinforcement is determined from structural computations as that required for the tension force in the member. This amount (in total cross-sectional area of the steel) is provided by some combination of bars. In various situations, however, there is a minimum amount of reinforcement that is desirable, which may on occasion exceed the amount determined by computation.

Minimum reinforcement may be specified as a minimum number of bars or as a minimum amount, the latter usually based on the cross-sectional area of the concrete member. These requirements are discussed in the sections that deal with the design of the various types of structural members.

In early concrete work, reinforcing bars took various shapes. A problem that emerged was how to properly bond the steel bars within the concrete mass, due to the tendency of the bars to slip or pull out of the concrete. This issue is still a critical one and is discussed in Chapter 8.

In order to anchor the bars in the concrete, various methods were used to produce something other than the usual smooth surfaces on bars. After

TABLE 1.1 Properties of Deformed Reinforcing Bars

Bar Size Designation	Nominal Dimensions					
	Nominal Weight		Diameter		Cross Sectional Area	
	lb/ft	kg/m	in.	mm	in. ²	mm ²
No. 3	0.376	0.560	0.375	9.5	0.11	71
No. 4	0.668	0.994	0.500	12.7	0.20	129
No. 5	1.043	1.552	0.625	15.9	0.31	200
No. 6	1.502	2.235	0.750	19.1	0.44	284
No. 7	2.044	3.042	0.875	22.2	0.60	387
No. 8	2.670	3.974	1.000	25.4	0.79	510
No. 9	3.400	5.060	1.128	28.7	1.00	645
No. 10	4.303	6.404	1.270	32.3	1.27	819
No. 11	5.313	7.907	1.410	35.8	1.56	1006
No. 14	7.650	11.390	1.693	43.0	2.25	1452
No. 18	13.600	20.240	2.257	57.3	4.00	2581

much experimentation and testing, a single set of bars was developed with surface deformations consisting of ridges. These deformed bars were produced in graduated sizes with bars identified by a single number (see Table 1.1).

For bars numbered 2 through 8, the cross-sectional area is equivalent to a round bar having a diameter of as many eighths of an inch as the bar number. Thus, a No. 4 bar is equivalent to a round bar of $\frac{4}{8}$ or 0.5 in. diameter. Bars numbered from 9 up lose this identity and are essentially identified by the tabulated properties in a reference document.

The bars in Table 1.1 are developed in U.S. units but can, of course, be used with their properties converted to metric units. However, a new set of bars has recently been developed, deriving their properties more logically from metric units. The properties of these bars are given in Table 1.2. The general range of sizes is similar for both sets of bars, and design work can readily be performed with either set. Metric-based bars are obviously more popular outside the United States, but for domestic use (nongovernment) in the United States, the old bars are still in wide use. This is part of a wider conflict over units, which is still going on.

The work in this book uses the old inch-based bars, simply because the computational examples are done in U.S. units. In addition, most of the references still in wide use have data presented basically with U.S. units and the old bar sizes.

TABLE 1.2 Properties of Deformed Reinforcing Bars (Metric Series)

Bar Size Designation	Nominal Mass (kg/m)	Nominal Dimensions		Comparison of Area with in. - lb. Bars
		Diameter (mm)	Cross Sectional Area (mm ²)	
10M	0.785	11.3	100	22% < No. 4
15M	1.570	16.0	200	Same as No. 5
20M	2.355	19.5	300	6% > No. 6
25M	3.925	25.2	500	2% < No. 8
30M	5.495	29.9	700	9% > No. 9
35M	7.850	35.7	1000	1% < No. 11
45M	11.775	43.7	1500	3% > No. 14
55M	19.625	56.4	2500	3% < No. 18

Fiber Reinforcement

Experiments have been conducted over many years on including fibrous elements in the concrete mix with the intention of giving an enhanced tension resistance to the basic hardened concrete. Steel needles, glass, and various mineral fibers have been used. The resulting tensile-enhanced material tends to resist cracking; permit very thin, flexible elements; resist freezing; and permit some applications without steel reinforcing rods. Only minor structural applications have been attempted, but the material is now commonly used for pavements and for thin roof tiles and cladding panels.

1.7 PRESTRESSED CONCRETE

Prestressing consists of the deliberate inducing of some internal stress condition in a structure prior to its sustaining of service loads. The purpose is to compensate in advance for the anticipated service load stress, which for concrete means some high level of tension stress. The “pre-” or “before” stress is, therefore, usually a compressive or reversal bending stress. This section discusses some uses of prestressing and some of the problems encountered in utilizing it for building structures.

Use of Prestressing

Prestressing is principally used for spanning elements, in which the major stress conditions to be counteracted are tension from bending and diagonal tension from shear. A principal advantage of prestressing is that, when

properly achieved, it does not result in the natural tension cracking associated with ordinary reinforced concrete. Since flexural cracking is proportionate to the depth of the member, which in turn is proportionate to the span, the use of prestressing frees spanning concrete members from the span limits associated with ordinary reinforcing. Thus, gigantic beam cross sections and phenomenal spans are possible—and indeed have been achieved, although mostly in bridge construction.

The cracking problem also limits the effective use of very high strengths of concrete with ordinary reinforcing. Free of this limit, the prestressed structure can utilize effectively the highest strengths of concrete achievable, and, thus, weight saving is possible, resulting in span-to-weight ratios that partly overcome the usual massiveness of spanning concrete structures.

The advantages just described have their greatest benefit in the development of long, flat-spanning roof structures. Thus, a major use of prestressing has been in the development of precast, prestressed units for roof structures. The hollow-cored slab, single-tee, and double-tee sections shown in Figure 1.3 are the most common forms of such units—now a standard part of our structural inventory. These units can also be used for floor structures, with a major advantage when span requirements are at the upper limits of feasibility for ordinary reinforced construction.

- *For Columns.* Concrete shafts may be prestressed for use as building columns, precast piles, or posts for street lights or signs. In this case the prestressing compensates for bending, shear, and torsion associated with service use and handling during production, transportation, and installation. The ability to use exceptionally high strength concrete is often quite significant in these applications.
- *For Two-Way Spanning Slabs.* Two-way, continuous prestressing can be used to provide for the complex deformations and stress conditions in concrete slabs with two-way spanning actions. A special usage is that for a paving slab designed as a spanning structure where ground settlement is anticipated. Crack reduction may be a significant advantage in these applications.
- *Tiedown Anchors.* When exceptionally high anchorage forces must be developed, and development of ordinary tension reinforcing may be difficult or impossible, it is sometimes possible to use the tension strands employed for prestressing. Large abutments, counterforts for large retaining walls, and other elements requiring considerable tension anchorage are sometimes built as prestressed elements.

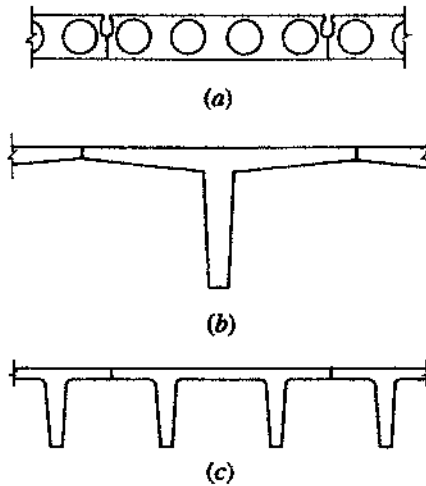


Figure 1.3 Forms of typical products of precast concrete used for horizontal-spanning structures.

- *Horizontal Ties.* Single-span arches and rigid frames that develop outward thrusts on their supports are sometimes tied with prestressing strands.

For any structure it is necessary to consider various loading conditions that occur during construction and over a lifetime of use. For the prestressed structure, this is a quite complex issue, and design must incorporate many different events over the life of the structure. For common usages, experience has produced various empirical adjustments (educated fudge factors) that account for the usual occurrences. For unique applications, there must be some reasonable tolerance for errors in assumptions or some provision for tuning up the finished structure. The prestressed structure is a complex object, and the design of other than very routine elements should be done by persons with considerable training and experience.

Pretensioned Structures

Prestressing is generally achieved by stretching high-strength steel strands (bunched wires) inside the concrete element. The stretching force is eventually transferred to the concrete, producing the desired compression in the

concrete. There are two common procedures for achieving the stretching of the strands: pretensioning and post-tensioning.

Pretensioning consists of stretching the strands prior to pouring the concrete. The strands are left exposed in the forms, the concrete is cast around them, and as the concrete hardens, it bonds to the strands. When the concrete is sufficiently hardened, the external stretching force is released, and the strand tension is transferred to the concrete through the bond action on the strand surfaces. This procedure requires some substantial element to develop the necessary resistance to the jacking force used to stretch the strands before the concrete is poured. Pretensioning is used mostly for factory precast units, for which the element resisting the stretching force is the casting form, sturdily built of steel and designed for repeated use.

Pretensioning is done primarily for cost-saving reasons. There is one particular disadvantage to pretensioning: it does not allow for any adjustment, and the precise stress and deformation conditions of the finished product are only approximately predictable. The exact amount of the strand bonding and the exact properties of the finished concrete are somewhat variable. Good quality control in production can keep the range of variability within some bounds, but the lack of precision must be allowed for in the design and construction. A particular problem is the control of deflection of adjacent units in systems consisting of side-by-side units.

Post-Tensioned Structures

In post-tensioned structures, the prestressing strands are installed in a slack condition, typically wrapped with a loose sleeve or conduit. The concrete is poured and allowed to harden around the sleeves and the end anchorage devices for the strand. When the concrete has attained sufficient strength, the strand is anchored at one end and stretched at the other end by jacking against the concrete. When the calibrated jacking force is observed to be sufficient, the jacked end of the strand is locked into the anchorage device, pressurized grout is injected to bond the strand inside the sleeve, and the jack is released.

Post-tensioning is generally used for elements that are cast in place because the forms need not resist the jacking forces. However, it may also be used for precast elements when jacking forces are considerable and/or a higher control of the net existing force is desired.

Until the strands are grouted inside the sleeves, they may be rejaacked to a higher stretching force condition repeatedly. In some situations this

is done as the construction proceeds, permitting the structure to be adjusted to changing load conditions.

Post-tensioning is usually more difficult and more costly, but there are some situations in which it is the only alternative for achieving the pre-stressed structure.

1.8 DESIGN OF CONCRETE MIXES

From a structural design point of view, mix design basically means dealing with the considerations involved in achieving a particular design strength, as measured by the value of the fundamental property: f'_c . For this, the principal factors are:

Cement Content

The amount of cement per unit volume is a major factor determining the richness of the cement-water paste and its ability to fully coat all of the aggregate particles and to fill the voids between them. Cement content is normally measured in terms of the number of sacks of cement (1 cubic foot each) per cubic yard of concrete mixed. The average for structural concrete is about 5 sacks per yard. If tests show that the mix exceeds or falls short of the desired results, the cement content is decreased or increased, respectively. The cement is by far the costliest ingredient, so its volume is critical in cost control.

Water-Cement Ratio

This is expressed in terms of gallons of water per sack of cement or gallons of water per yard of mixed concrete. The latter is usually held very close to an average of about 35 gallons per yard; less, and workability is questionable; more, and strength becomes difficult to obtain. Attaining very strong concrete usually means employing various means to reduce water content and to improve the ratio of cement to water without losing workability.

Fineness Modulus of the Sand

If the sand is too coarse, the wet mix will be grainy, and surfaces will be difficult to finish smoothly. If the sand is too fine, an excess of water will be required, resulting in high shrinkage and loss of strength due to thin-

ning out of the water/cement mixture. Grain size and size range are controlled by specification.

Character of the Coarse Aggregate

Shape, size limits, and type of material must be considered. Because this represents the major portion of the concrete volume, its properties are quite important to strength, weight, fire performance, and so on.

Development of the Mix Design

Concrete is obtained primarily from industrial plants that mix the materials and deliver them in mixer trucks. The mix design is developed cooperatively with the structural designer and the management of the mixing plant. Local materials must be used, and experience with them is an important consideration.

1.9 SPECIAL CONCRETES

Within the range of the general material discussed here, there are many special forms of concrete used for special situations and applications. Some of the principal ones are:

Lightweight Structural Concrete

This is concrete that achieves a significant reduction in weight, while retaining sufficient levels of structural properties to remain feasible for major structural usages. Maximum weight reduction is usually in the range of 30%. Strength levels may be kept reasonably high, but some loss in stiffness (modulus of elasticity) is inevitable, so deflections become more critical. The principal means for achieving weight reduction is using materials other than stone for the coarse aggregate. Some natural materials may be used for this, but for more typical applications synthetic materials are used. One major use is the concrete fill applied on top of formed sheet steel decking in steel-framed structures.

Super Heavyweight Concrete

For some purposes, it may be desirable to achieve an increase in the concrete density (unit weight). A simple means of achieving this is to use a particularly heavy material for the coarse aggregate. Some of the heavi-

est natural materials are metal ores, but careful analysis must be made of their potential chemical reactions with the concrete.

Insulating Concrete

Use of superlightweight aggregates, usually natural or “popped” mineral materials, together with deliberately entrapped air (foaming), can produce concrete with densities below 30 lb/ft³. Compressive strength drops to a few hundred psi, so major structural usage is out of the question, but the material is used for the fill on top of roof decks and, in some situations, to insulate steel framing from fire.

Superstrength Concrete

Through the use of specially selected materials, the addition of water-reducing and density-enhancing admixtures, and very special mixing, handling, and curing, concrete strengths in the range of 20,000 psi can now be achieved. The major use to date has been for the lower structures of very tall concrete buildings. This requires a major effort and considerable expertise and is very expensive but is now sometimes accomplished where it offers significant value. The nature of this material is out of the range of traditional procedures and specifications, so its design control is still being developed.

As materials research intensifies—both commercially and with some nonprofit sponsorship—new materials that provide new potential uses are sure to increase in number. Still, traditional sand-and-gravel concrete remains in wide use for common applications.