Concrete posts and beams would offer the best protection if the rebar is adequately covered. Heavy timber is large enough to burn and char, forming a protective "crust" on the outside of the wood. This leaves the interior fibers of the wood protected from the fire and able to remain intact, but would ultimately burn. Options C and D would more likely fail in the continued high heat of a building fire.

Solution

~~Heavy timber is large enough to burn and char, fo~~
~~wood. This leaves the interior fibers of the wood pr~~
~~other options would more likely fail in the continued~~

The answer is ~~(B)~~. A

STRUCTURAL SYSTEM SELECTION CRITERIA

The selection of an optimum structural system for a building can be a complex task. In addition to the wide variety of structural systems available and their many variations and combinations, there are dozens of other considerations that must be factored into making the final selection. The architect's job is to determine the full scope of the problem and find the best balance among often conflicting requirements. This section briefly outlines some of the major selection criteria to be familiar with when analyzing possible systems.

Resistance to Loads

Of course, the primary consideration is the ability of the structural system to resist the anticipated and unanticipated loads that will be placed on it. These include the weight of the structure itself (*dead load*); loads caused by external factors such as wind, snow, and earthquakes; loads caused by building use, such as people, furniture, and equipment (*live loads*), as well as others.

The anticipated loads can be calculated directly from known weights of materials and equipment and from requirements of building codes that set down what is statistically probable in a given situation—the load caused by people in a church, for example. Unanticipated loads are difficult to plan for but include such things as changes in the use of a building, overloading caused by extra people or equipment, unusual snow loads, ponding of water on a roof, and degradation of the structure itself.

When deciding on what material or system to use, there is always the consideration of what is reasonable for the particular circumstance. For example, wood can be made to support very heavy loads with long spans, but only at a very high cost with complex systems. A wood system does not make sense if other materials and systems, such as steel and concrete, are available.

Often, very unusual loads will be the primary determinant of the structural system and its effect on the appearance of the building. Extremely tall high-rise buildings like the Sears Tower or the John Hancock Building in Chicago, with its exterior diagonal framing, are examples of load-driven structural solutions.

Building Use and Function

The type of occupancy is one of the primary determinants of a structural system. A parking garage needs spans long enough to allow the easy movement and storage of automobiles. An office building works well with spans in the 30 ft to 40 ft range.

Sports arenas need quite large open areas. Some buildings have a fixed use over their lifespan and may work with fixed bearing walls, while others must remain flexible and require small, widely spaced columns.

These are all examples of somewhat obvious determinates of building systems. There are, however, many other needs that are not so apparent. For example, in a location where building height is limited, a client may want to squeeze as many floors into a multistory building as possible. This may require the use of concrete flat-plate construction with closely spaced columns even though another system would be more economical.

In another instance, a laboratory building may need large spaces between usable floors in which to run mechanical services. This may suggest the use of deep-span, open-web trusses. If the same laboratory were to house delicate, motion-sensitive equipment, then the use of a rigid, massive concrete structure might be warranted.

carried away through breeching into the flue or chimney. If the primary fuel source is electricity or steam, there is no need for an exhaust flue.

Principles of Refrigeration

There are two types of refrigeration processes that can produce chilled air or water.

- compressive refrigeration
- absorption

A third type, evaporative cooling, can be used in some climates to produce cool air.

Compressive Refrigeration

Compressive refrigeration is based on the transfer of heat during the liquefaction and evaporation of a refrigerant. As a refrigerant in a gaseous form is compressed, it liquefies and releases latent heat as it changes state. As the same liquid expands and vaporizes back to a gas, it absorbs latent heat from the surroundings into the gas. These principles are used in the basic refrigeration cycle shown in Fig. 17.1.

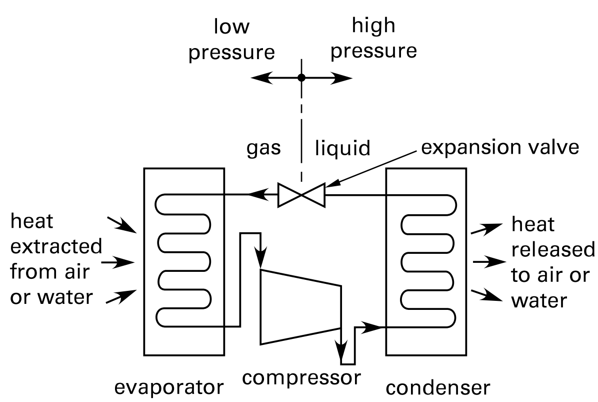


Figure 17.1 Compressive Refrigeration

In the past, refrigerants such as Freon were used in compressive refrigeration. However, these compounds contain chlorofluorocarbons (CFCs) that contribute to the depletion of the earth's ozone layer when leaked into the atmosphere; as a result, their use is prohibited. Newer refrigerants such as hydrofluorocarbons (HFCs) have replaced CFCs. However, although HFCs do not harm the ozone layer, they pose a threat to the atmosphere because of their global warming potential, which is much higher than that of carbon dioxide, and because of their increased use. Other common refrigerants such as ammonia, sulfur dioxide, and propane are friendlier to the environment if accidentally released, but raise concerns of their own about toxicity and flammability.

There are three fundamental components of a compressive refrigeration system: the *compressor*, the *condenser*, and the *evaporator*. The compressor receives the refrigerant as a gas and compresses it, turning it into a liquid. The liquid refrigerant leaves the compressor and flows into the condenser, where its latent heat is released. The condenser is usually located on the outside of the building, and the heat is released to the outside air or to water. The refrigerant then leaves the condenser and enters the evaporator, where it draws heat from its surroundings (either air or water) and expands, becoming a gas again. The gaseous refrigerant leaves the ~~condenser~~ evaporator and enters the compressor, and the process repeats.

For many small cooling units, air is forced over the evaporator coils by a fan, and it is this cooled air that is then circulated through the room or space. However, water is a much more efficient medium than air for carrying heat. In larger units designed for large buildings, water is pumped over the evaporator coils, and this chilled water is then pumped to remote cooling units where air is circulated over the chilled water pipes. On the condenser side, water draws the heat from the condenser pipes and then flows to remote cooling towers where it releases the heat to the air.

Absorption

Refrigeration by *absorption* also produces chilled water through the loss of heat when water evaporates, as shown in Fig. 17.2. This evaporation is produced in a closed system; a salt solution draws water vapor from the evaporator.

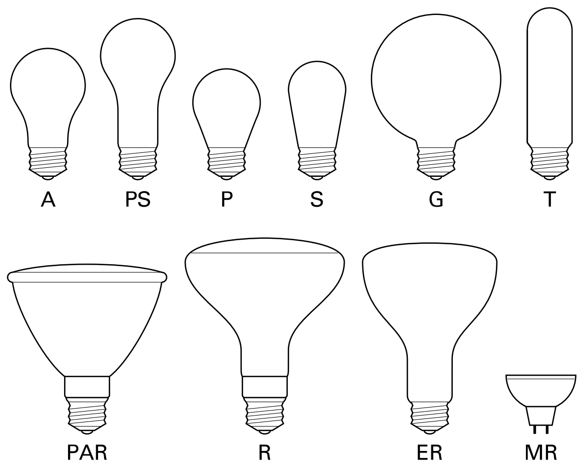
Table 19.1
Characteristics of Common Light Sources

lamp description	efficacy (lm/W)	color temperature (K)	CRI	approx. lamp life (h)
incandescent	5–20	2700–2800	100	750–4000
tungsten-halogen	18–22	~~300~~–3100	100	1000–4000
fluorescent (T12 and T8)	65–105	2700–7500	55–98	6000–24,000
fluorescent (T5)	95–105	3000–4100	75–95	6000–16,000
compact fluorescent	25–48	2700–4100	82	10,000
mercury-vapor	20–60	5500–5900	15–52	14,000–25,000
metal-halide	35–95	3200–4300	65–85	5000–20,000
ceramic metal-halide	80–100	3000–4100	80–90	15,000
high-pressure sodium	80–140	1800–2800	22–70	10,000–24,000
GU-24	40–70	varies	84	10,000–30,000
LED	80–150+*	varies	varies	10,000–50,000

Note: The values listed in the table are approximate and representative only. Individual manufacturers and lamps may provide different values.

*Values for the efficacy of LEDs are difficult to compare with other sources because as yet there are no industry standard test procedures for rating the luminous flux of LED devices and arrays. Values are also expected to increase rapidly as improvements in LEDs take place.

Figure 19.5
Incandescent Lamp Shapes



A arbitrary (standard shape)
PS pear shape, straight neck
P pear shape
S straight
G globe
T tubular
PAR parabolic aluminized reflector
R reflector
ER elliptical reflector
MR miniature reflector

The Energy Policy Act (EPAct) of 1992 set minimum energy efficiency standards for incandescent and fluorescent light sources. As a result, some types of incandescent and fluorescent lamps that have traditionally been used in architectural applications are no longer manufactured in or imported into the United States; the rest must satisfy EPAct requirements for minimum lumens per watt.

Incandescent Lamps

An *incandescent lamp* consists of a tungsten filament placed within a sealed glass bulb containing an inert gas. When electricity passes through the lamp, the filament glows, producing light. Incandescent lamps are produced in a wide variety of shapes, sizes, and wattages for different applications. Some of the more common shapes are shown in Fig. 19.5.

A typical designation of an incandescent lamp is a letter followed by a number; the letter indicates the shape or type, and the number indicates the size of the bulb at its widest point, in eighths of an inch. For example, an A-21 bulb has the standard arbitrary shape and the diameter of the bulb at its widest point is $^{21}/_{8}$ in ($2^{5}/_{8}$ in).

Incandescent lamps are inexpensive, compact, easy to dim, can be repeatedly started without a decrease in lamp life, and have a warm color rendition. In addition, their light output can be easily controlled with reflectors and lenses. Their disadvantages include low efficacy, short lamp life, and high heat output. The combination of low efficacy and heat production makes incandescent lamps undesirable for large, energy-efficient installations. For example, a standard 150 W lamp produces less than 20 lumens per watt, whereas a 40 W cool white fluorescent lamp has an efficacy of about 80 lm/W with much less heat output.

Another type of incandescent lamp is the *tungsten halogen lamp*. Light is produced by the incandescence of the filament, but there is a small amount of a halogen, such as iodine or bromine, in the bulb with the

Project Planning

Guidelines for Sound Absorption

There are several guidelines related to sound absorption that are useful to remember.

- The average absorption coefficient of a room should be at least 0.20. Indoor-outdoor carpet has an absorption coefficient of about 0.20, while heavy carpet on a concrete floor has an absorption coefficient of about 0.30. An average absorption coefficient above 0.50 is usually not desirable, nor is it economically justified. Materials with lower values are suitable for large rooms, while materials with higher values are suitable for small or noisy rooms.
- Each doubling of the amount of absorption in a room results in a noise reduction of only 3 dB.
- If additional absorptive material is being added to a room, the total absorption should be increased at least three times (amounting to a change of about 5 dB, which is clearly noticeable). The increase may need to be more or less than three times to bring absorption to between 0.20 and 0.50.
- When adding extra absorption, an increase of 10 times (a reverberant noise reduction of 10 dB) is the approximate practical limit. Beyond this, more absorption results in a decreasing amount of noise reduction as the practical limit of 0.50 total average absorption coefficient is approached.
- Each doubling of the absorption in a room reduces reverberation time by one-half.
- Although absorptive materials can be placed anywhere, ceiling treatment for sound absorption is more effective in large rooms, whereas wall treatment is more effective in small rooms.
- Generally, absorption increases with an increase in thickness of a porous absorber. However, excessive low-frequency noise may require special design treatment.
- The amount of absorption of a porous type of sound absorber such as fiberglass or mineral wool is dependent on (1) the material's thickness, (2) the material's density, (3) the material's porosity, and (4) the orientation of the fibers in the material. A porous sound absorber should be composed of open, interconnected voids.

Reverberation

Reverberation is an important quality of the acoustical environment of a space. It affects both the intelligibility of speech and the quality of conditions for music of all types. *Reverberation time* is the time it takes the sound level to decrease 60 dB after the source has stopped producing the sound. The reverberation time in seconds, T, is calculated using Eq. 19.12.

$$T = 0.05\left(\frac{V}{A}\right) = 0.05\left(\frac{V}{aS}\right) \qquad 19.12$$

V is the volume of the room in cubic feet. (If cubic meters are used, the factor is 0.16 instead of 0.05.)

Each type of use has its own preferred range of reverberation time, shorter times being best for smaller spaces and longer times working best for larger spaces. (See Table 19.7.)

Table 19.7
Recommended Reverberation Times

space	reverberation time (sec)
auditoriums (speech and music)	1.5–1.8
broadcast studios (speech only)	0.4–0.6
churches	1.4–3.4
elementary classrooms	0.6–0.8
lecture/conference rooms	0.9–~~1.0~~ 1.1
movie theaters	0.8–1.2
offices, small rooms for speech	0.3–0.6
opera halls	1.5–1.8
symphony concert halls	1.6–2.1
theaters (small dramatic)	0.9–1.4

There are two broad categories of wood use in construction: rough carpentry and finish carpentry. *Rough carpentry* includes the structural framing, sheathing, blocking, and miscellaneous pieces necessary to prepare the building for finish work. Most rough carpentry is hidden once construction is complete, but exposed lumber such as heavy timber beams, glued-laminated members, and outdoor deck frames is considered rough carpentry.

As the name implies, *finish carpentry* includes the exposed, finished pieces of lumber necessary to complete a job, including such things as window and door trim, base, wood paneling, cabinets, and shelving. Finish carpentry work is normally done on the job site, but it also includes architectural woodwork, which is the fabrication of wood items in a manufacturing plant. Finish carpentry and architectural woodwork are reviewed in ~~Chap. 40.~~ Chap 26.

This chapter includes a general review of wood as a structural material. However, methods for calculating sizes of members and fasteners are not included.

When discussing wood as a construction material, several terms are often used interchangeably, but there are distinctions. *Wood* is the fibrous substance forming the trunk, stems, and branches of the tree. *Lumber* is the product of sawing, planing, and otherwise preparing wood to be used as construction members. *Timber* is lumber with a 5 in minimum sectional dimension.

CHARACTERISTICS OF LUMBER

Lumber is a very versatile building material and has many advantages—it is plentiful, relatively low in cost, easy to shape and assemble, has good thermal insulating qualities, and is aesthetically pleasing. As a natural material, however, it lacks the uniform appearance and strength that manufactured materials have. Also, because of its cellular structure, it is susceptible to dimensional changes when its moisture content changes.

These disadvantages can be overcome with some of the manufactured wood products available. A few examples of these products are plywood, glued-laminated timber, and plywood web joists.

Types and Species

There are two general classifications of wood: softwood and hardwood. These terms have nothing to do with the actual hardness of the wood, but refer to whether the wood comes from a coniferous tree or a deciduous tree. *Conifers* (softwood) are cone-bearing, needle-leaved trees that hold their foliage in the winter, such as fir, spruce, and pine. Deciduous (hardwood) trees are broad-leaved trees that lose their leaves in the winter, such as oak, walnut, and maple. Softwoods are used for structural and rough carpentry because of their greater availability and lower cost. Finish carpentry and architectural woodwork utilize both hardwoods and softwoods.

There are literally hundreds of species of softwood and hardwood available throughout the world. However, only a few are used in the United States for rough carpentry, primarily due to local availability and cost. For example, southern pine is used in the southeastern portion of the United States, whereas Douglas fir or Douglas fir-larch is used in the western region. Other commonly used species for rough carpentry include hem-fir, eastern white pine, and hemlock. Redwood and cedar are commonly used for exterior applications where resistance to moisture is required.

Strength

The strength of lumber is dependent on the direction of the load relative to the direction of the wood's grain. Lumber is strongest when the load is parallel to the direction of the grain, such as with a compressive load on a wood column. Wood can resist slightly less tensile stress parallel to the grain and even less when compressive forces are perpendicular to the grain.

Wood is weakest when horizontal shear force is induced, which occurs when bending forces are applied to a beam and the fibers tend to slip apart parallel to the grain. Allowable forces used in structural calculations are lowest for horizontal shear, and this quite often governs the design of bending members.

In the worst case, temperature-induced loads can so overload a structural member that failure may occur. Most often, however, failing to account for temperature-induced loads causes other types of failures such as tight-fitting glass breaking when a metal frame contracts, or masonry walls cracking when expansion joints are not provided. In nearly all cases, the solution is fairly simple: the material or assembly of materials must be allowed to expand and contract for the expected distance. This is fairly easy to calculate, and detailed methods are described in Chap. 34.

Soil Loads

Retaining walls are required to resist the lateral pressure of the retained material in accordance with accepted engineering practice. Table 33.4 gives the minimum lateral pressures to be used in the design of retaining walls, as specified by the IBC. This is in addition to any surcharge such as vertical loads near the top of the wall or other lateral loads. In addition, retaining walls must be designed to resist sliding by at least 1.5 times the lateral force and resist overturning by at least 1.5 times the overturning moment.

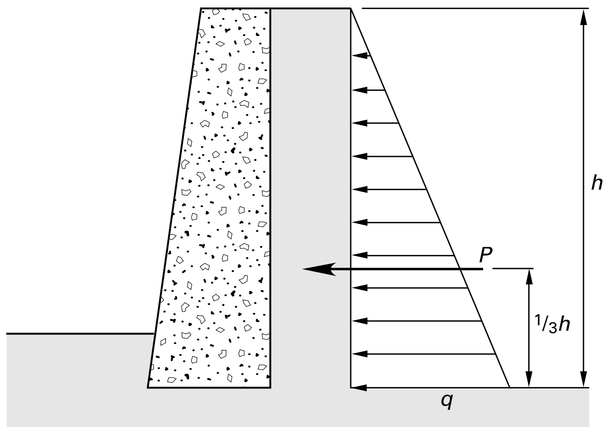


Figure 33.2
Load from Soil on Retaining Wall

To calculate the pressure at the bottom of the wall, p, simply multiply the design lateral soil pressure, q, by the depth of the wall, h, to get pounds per square foot. The active pressure specified in the table is used for free-draining backfill, while the passive pressure is used for other cases. Since the pressure varies uniformly from zero at the very top of the wall, where no earth is retained, to a maximum at the bottom, the total horizontal load per linear foot acting on the wall is found by calculating the area of the triangular distribution or the maximum earth pressure at the bottom times the height divided by two (see Fig. 33.2).

$$P = P_{\text{max}}\left(\frac{h}{2}\right) \qquad 33.8$$

Example 33.4

A retaining wall 8 ft high is retaining free-draining silty sand. From Table 33.4, an active pressure of 45 psf/ft may be used for the silty sand. What is the total horizontal load exerted on the wall?

(A) 650 plf

(B) 850 plf

(C) 1110 plf

(D) 1440 plf

Solution

The pressure at the bottom is (8 ft)(45 psf/ft), or 360 psf. The total horizontal load is (360 psf/2)(8 ft), or 1440 lbm/ft.

It will be shown that this total load acts at the centroid of a triangle, or one-third the distance from the base. Retaining wall design is discussed in more detail in ~~Chap. 21~~ Chap 37.

The answer is (D).

In order to find the moment of inertia for composite areas, transfer the moment of inertia of each section about its centroid to a new axis, typically the centroid of the composite section. The general formula for doing this, as illustrated in Fig. 34.8, is

$$I_n = I_X + Ax^2 \qquad 34.10$$

$$I_n = I_X + Ad^2 \qquad 34.11$$

The transferred moments of inertia of the various sections are then added to get the moment of inertia for the entire section.

The moment of inertia is dependent on the area of a section and the distance of the area from the neutral axis, but from that statement the moment of inertia is the summation of the areas times the square of the distances of those areas from the neutral axis. From Eq. 34.8 and Eq. 34.9, it is evident that a beam's depth has a greater bearing on the beam's resistance to bending than its width or total area. This explains why a board placed on edge between two supports is much stronger than the same board placed on its side.

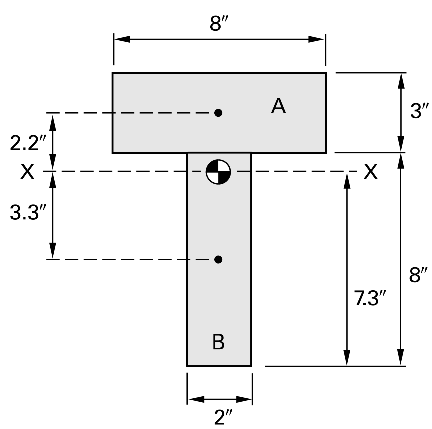
There are two other important properties of sections: the *section modulus* and the *radius of gyration*. However, these are more appropriately discussed in ~~Chap. 13.~~ Chap. 35 Section modulus will be explained in the sections on beams and the theory of bending, while radius of gyration will be discussed in the section on columns.

Example 34.6

Using the same composite section as shown in Ex. 34.4, calculate the moment of inertia.

Solution

The first step is to locate the centroid of the object. This was done in the previous example problem and was found to be 7.3 in above the base.



The next task is to transfer the individual moments of inertia about this centroidal axis and add them. To do this, it is helpful to set up a table so all the figures and calculations can be seen easily. This is an especially useful technique when dealing with several individual areas.

The moments of inertia of areas A and B are found with Eq. 34.8, and are denoted I_o to express the fact that these are the moments of inertia about an axis passing through the centroid of the elementary figure. y is the distance from the centroidal axis to the axes of areas A and B.

Project Development

simply supported beam, the maximum moment occurs at the center of the span and the beam is subjected to its highest bending stresses at the extreme top and bottom fibers. (*Fibers* is the general term, regardless of the beam's material.)

Therefore, in order for a beam to support loads, the material, size, and shape of the beam must be selected to sustain the resisting moments at the point on the beam where the moment is greatest. There must be some way to relate the bending moments to the actual properties of a real beam. Although the derivation will not be given, the final formula is simple.

$$\frac{M}{f_b} = \frac{I}{c} \qquad 35.3$$

Theoretically, Eq. 35.3 can be used to design a beam to resist bending forces, but it gets a little cumbersome with steel sections and unusual shapes. There is another property of every structural section that simplifies the formula even further. This is the *section modulus*, which is the ratio of the beam's moment of inertia to the distance from the neutral axis to the outermost part of the section (extreme fiber).

$$S = \frac{I}{c} \qquad 35.4$$

Substituting the value of S with Eq. 35.3 gives

$$S = \frac{M}{f_b} \qquad 35.5$$

Knowing only the maximum moment on a beam caused by a particular loading condition and the maximum allowable fiber stress (given in tables and building codes), the required section modulus can be calculated. The minimum required section to support the bending loads can be found from reference tables or manufacturers' tables. For example, the *Steel Construction Manual* published by the American Institute of Steel Construction (AISC) gives the section modulus for all beam sections. How this formula is used will be illustrated in the sample question.

Another fundamental type of stress in beams is *shear*. This is the tendency of two adjacent portions of the beam to slide past each other in a vertical direction. See Fig. 35.2(a).

There is also *horizontal shear*, which is the tendency of two adjacent portions of a beam to slide past each other in the direction parallel to the length of the beam. This tendency can readily be seen by considering that the top portions of a beam tend to compress and the bottom portions tend to stretch. See Fig. 35.2(b).

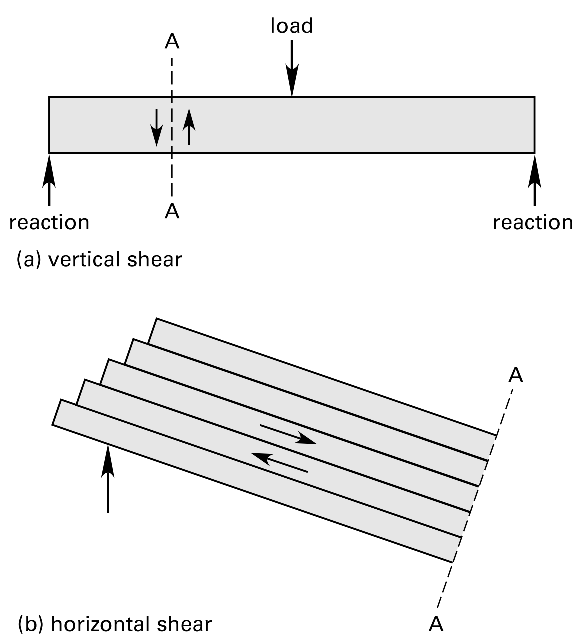


Figure 35.2 Shear Forces in Beams

The general equation for finding horizontal shear stress is

$$v_h = \frac{VQ}{Ib} \qquad 35.6$$

Q is the statical moment discussed in ~~Chap. 12~~ Chap. 34.

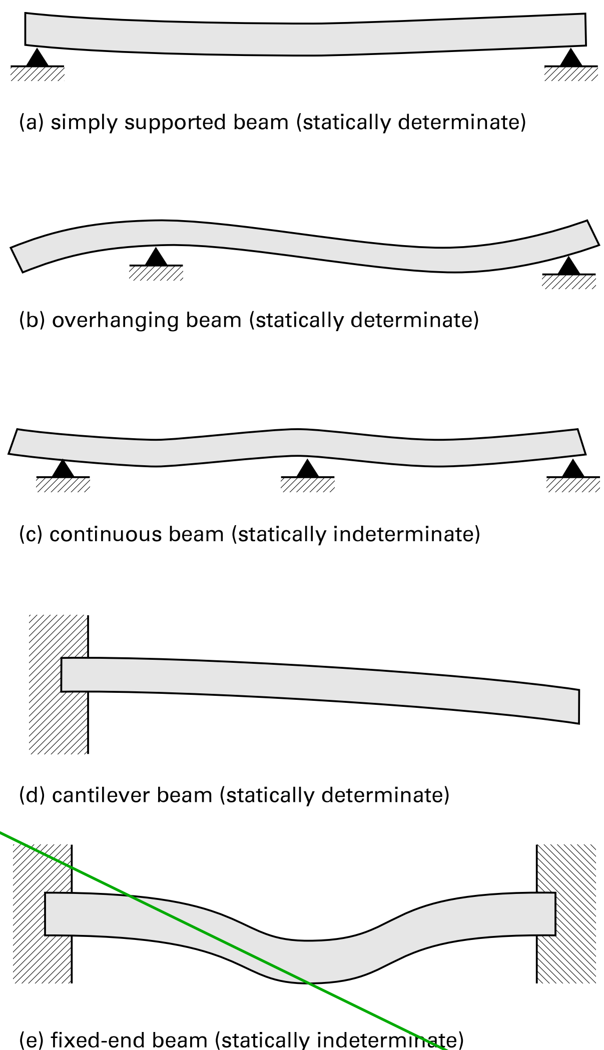
For rectangular sections, the horizontal shear stress at middepth of the beam, where the stress is a maximum, is given by

$$v_h = \frac{3V}{2bd} \quad \text{[at neutral axis of beam]} \qquad 35.7$$

This formula is obtained by substituting applicable terms in Eq. 35.6 for the specific case of a rectangular beam. Usually, horizontal shear is not a problem except in wood beams where the horizontal fibers of the wood make an ideal place for the beam to split and shear in this direction.

Another important aspect of the behavior of beams is their tendency to deflect under the action of external loads. Although beam deflection usually does not control the selection of beam size (as does bending or horizontal shear stress), it is an important factor that must be calculated. In some cases, it can be the controlling factor in determining beam size. Even though a large deflection will usually not lead to a structural collapse, excessive deflection can cause finish materials to crack, pull partitions away from the floor or ceiling, crush full-height walls, and result in a bouncy floor structure.

Figure 35.3
Types of Beams



Types of Beams

There are several basic types of beams. These are shown in Fig. 35.3, with their typical deflections under load shown exaggerated.

The simply supported, overhanging, and continuous beam all have ends that are free to rotate as the load is applied. The cantilever and fixed-end beams have one or both sides restrained against rotation. A continuous beam is one that is held up by more than two supports. Of course, there are many variations of these types, such as an overhanging beam with one end fixed, but these are the most typical situations.

There are also two typical kinds of loads on building structures: *concentrated load* and *uniformly distributed load*. Graphic representations of these loads are shown in Fig. 35.4. A concentrated load is shown with an arrow and designated *P*, and a uniformly distributed load is shown as *w* pounds per linear foot or *W* for the total load. Loads may either be expressed in pounds or kips (1 kip is 1000 pounds). The resultant of uniformly distributed loads is at the center of the loads. This principle is particularly useful when summing moments of partial uniform loads.

It is worth noting that simply supported, overhanging, and cantilever beams are *statically determinate*. This means that the reactions can be found using the equations of equilibrium. That is, the summation of horizontal, vertical, and moment forces equals zero as described in ~~Chap. 12~~ Chap. 34. Continuous and fixed-end beams are statically indeterminate, and other, more complex calculation methods are required to find reactions in these types of beams. The ARE will deal primarily with determinate beams, so only these types will be described in this section.

One of the basic requirements for the structural design of a beam is to determine the stresses due to bending moment and vertical shear caused by the particular loading conditions. Before these are determined, however, the reactions of the supports must be calculated. The method of doing this for statically determinate beams was introduced in ~~Chap. 12~~ Chap. 34 but will be briefly reviewed.

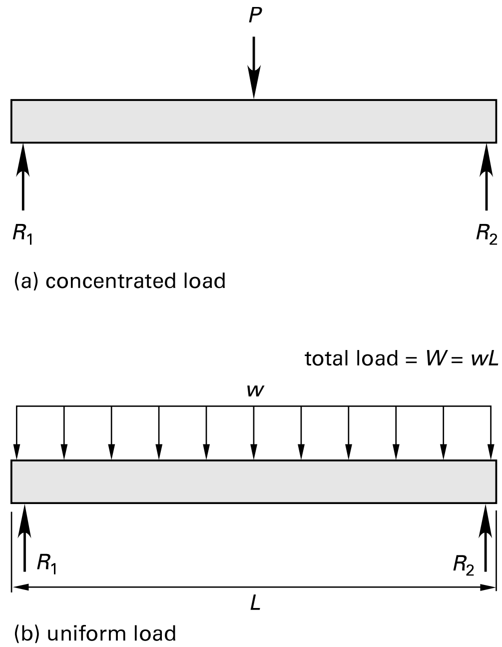


Figure 35.4
Types of Loads

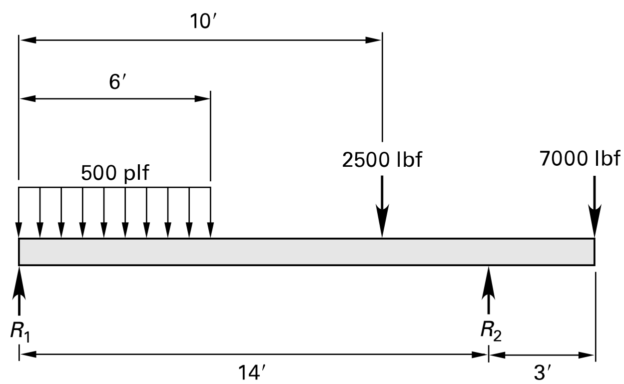
Remember the three basic principles of equilibrium.

- The sum of all vertical forces acting on a body equals zero.
- The sum of all horizontal forces acting on a body equals zero.
- The sum of all moments acting on a body or the moment of all forces about a point on the body equals zero.

Additionally, as a matter of convention, if a force tends to cause a clockwise rotation, the resulting moment is said to be positive; if it tends to cause a counterclockwise rotation, it is said to be negative.

Example 35.1

Find the approximate reactions of the beam shown.



(A) R_1 = 8000 lbf, R_2 = 2000 lbf

(B) R_1 = 9000 lbf, R_2 = 3600 lbf

(C) R_1 = 9500 lbf, R_2 = 500 lbf

(D) R_1 = 11,000 lbf, R_2 = 1600 lbf

Solution

Sum the moments about R_1 to eliminate one of the unknowns. Each of the three loads tends to cause a clockwise rotation about point R_1, so these will be positive numbers; the resisting reaction, R_2, will tend to cause a counterclockwise rotation, so this will be negative. The moment sum of the loads and the

Nomenclature

F_c	unit stress in compression perpendicular to the grain	lbf/in²
F_g	design value for end grain in bearing parallel to grain	lbf/in²
F_n	compressive normal stress at inclination θ with the direction of grain	lbf/in²
F_p	allowable bearing stress	lbf/in²
F_t	allowable tensile stress	lbf/in²
F_u	minimum tensile strength of steel or fastener	lbf/in²
F_v	allowable shear stress	lbf/in²
F_y	specified minimum yield stress of steel	lbf/in²
G	specific gravity	–
P	tensile load	lbf
t	thickness	in
Z	nominal lateral design value for single fastener connection	lbf
θ	angle between the direction of grain and direction of load normal to face considered	deg

The majority of structural failures occur in the connections of members, not in the members themselves. Either the incorrect types of connectors are used, or the connectors are undersized, too few in number, or improperly installed. It is therefore important for ARE candidates to have a good understanding of the various types of connectors and how they are used.

WOOD CONNECTIONS

There are several variables that affect the design of wood connections. The first, of course, is the load-carrying capacity of the connector itself. Nails and screws, for example, carry relatively light loads, while timber connectors can carry large loads. Other variables that apply to all connections include the species of wood, the type of load, the condition of the wood, the service conditions, whether or not the wood is fire-retardant-treated, and the angle of the load to the grain. Additional design considerations are the critical net section, the type of shear the joint is subjected to, the spacing of the connectors, and the end and edge distances to connectors.

Timber connectors

Species of Wood

The species and density of wood affect the holding power of connectors. ~~Species~~ are classified into four groups. There is one grouping for timber connectors, such as split ring connectors and shear plates, and another grouping for lag screws, nails, spikes, wood screws and metal plate connector loads. The four groups for timber connectors are designated Groups A, B, C, and D, while the grouping for other connectors are designated Groups I, II, III, and IV. Tables that give the allowable loads for connectors have separate columns for each group. Design values for connectors in a particular species apply to all grades of that species unless otherwise noted in the tables.

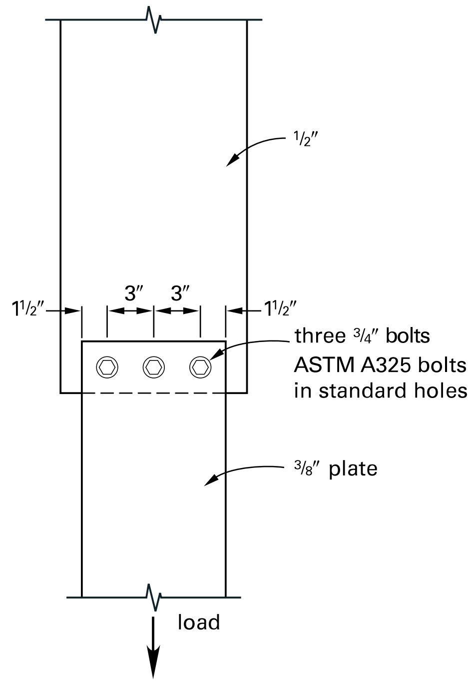
Type of Load

The design values for connectors can be adjusted for the duration of loading just as wood members can be (see Chap. 40). This is because wood can carry greater maximum loads for short durations than for long durations. The tables of allowable connector loads are for a normal duration of 10 years. For other conditions, the allowable values can be multiplied by the following factors.

- 0.90 for permanent loading over 10 years
- 1.15 for two months' duration (snow loading, for example)
- 1.25 for seven days' duration
- 1.60 for wind or earthquake loads
- 2.00 for impact loads

Example 38.3

A 3/8 in A36 steel plate is suspended from a 1/2 in plate with three 3/4 in A325 bolts in standard holes spaced as shown. The threads are excluded from the shear plane, and the connection is bearing type. Assuming full bearing capacity, what is the maximum load-carrying capacity of the 3/8 in plate?



Solution

First, check the shear capacity of the bolts. From Table 38.3, one bolt can carry a load of ~~13.3~~ 15.0 kips, or three bolts can carry (3)(~~13.3~~ 15.0 kips), or ~~39.9 kips.~~ 45 kips

Next, check bearing capacity. The thinner material governs, which is 3/8 in. In Table 38.4, read from the STD and $s \geq s_{\text{full}}$ row under the 3/4 in diameter column (with $F_u = 58$ and ASD). The available strength is 52.2 kips/in thickness. Multiply this value by the 3/8 in thickness to get 19.6 kips. Three bolts will then carry (3)(19.6 kips) = 58 kips.

Finally, determine the maximum stress on the net section through the holes. Once again, the thinner material is the most critical component. The allowable unit stress is

$$F_t = 0.50F_u = (0.50)(58\text{ kips}) = 29\text{ ksi}$$

The diameter of each hole is 1/8 in larger than the bolt for net sections, 1/8 or 7/8 in, which is 0.875 in. The net width of the 3/8 in plate is

$$9\text{ in} - (3)(0.875\text{ in}) = 6.375\text{ in}$$

The allowable load on the net section is

$$P = (6.375\text{ in})(0.375\text{ in})\left(29\ \frac{\text{kips}}{\text{in}^2}\right) = 69.33\text{ kips}$$

The allowable stress on the gross section is

$$P = (0.6)\left(36\ \frac{\text{kips}}{\text{in}^2}\right)(9\text{ in})(0.375\text{ in}) = 72.9\text{ kips}$$

From these four loads, the minimum governs, which is the shear capacity of the bolts, or ~~39.9~~ 45.0 kips.

There are many kinds of framed connections depending on the type of connector being used, the size and shape of the connected members, and the magnitude of the loads that must be transferred. Figure 38.8 illustrates some of the more typical kinds of steel connections. In most cases, the angle used to connect one piece with another is welded to one member in the shop and bolted to the other member during field erection. Slotted holes are sometimes used to allow for minor field adjustments.

If the top flange of one beam needs to be flush with another, the web is coped as shown in Fig. 38.8(b).

Simple beam-to-column connections are often made as illustrated in Fig. 38.8(c). The seat angle carries most of the gravity load, and the clip angle is used to provide stability from rotation. If a moment connection is required, a detail similar to Fig. 38.8(d) is used, although welding is more suitable for moment connections. For tubes and round columns, a single plate can be welded to the column and connected with beams as shown in Fig. 38.8(f). When the loads are heavy, some engineers prefer to slot the column and run the shear plate through, welding it at the front and back of the column.

Since connecting beams to columns and other beams with angles and bolts is such a common method of steel framing, the *AISC Manual* gives tables of allowable loads for various types and diameters of bolts and lengths and thicknesses of angles.

One of the important considerations in bolted steel connections, just as in wood connections, is the spacing of bolts and the edge distance from the last bolt to the edge of the member. The *AISC Manual* specifies minimum dimensions. The absolute minimum spacing is $2\frac{2}{3}$ times the diameter of the bolt being used, with 3 times the diameter being the preferred dimension. Many times, a dimension of 3 in is used for all sizes of bolts up to 1 in diameter.

The required edge distance varies with the diameter of the bolt being used: at the edges of plates, shapes, or bars, the dimension is 1 in for a $\frac{3}{4}$ in bolt and 1.25 in for a 1 in bolt. To simplify detailing and tabulated values, a dimension of 1.25 in is often used for all bolts having a diameter up to 1 in.

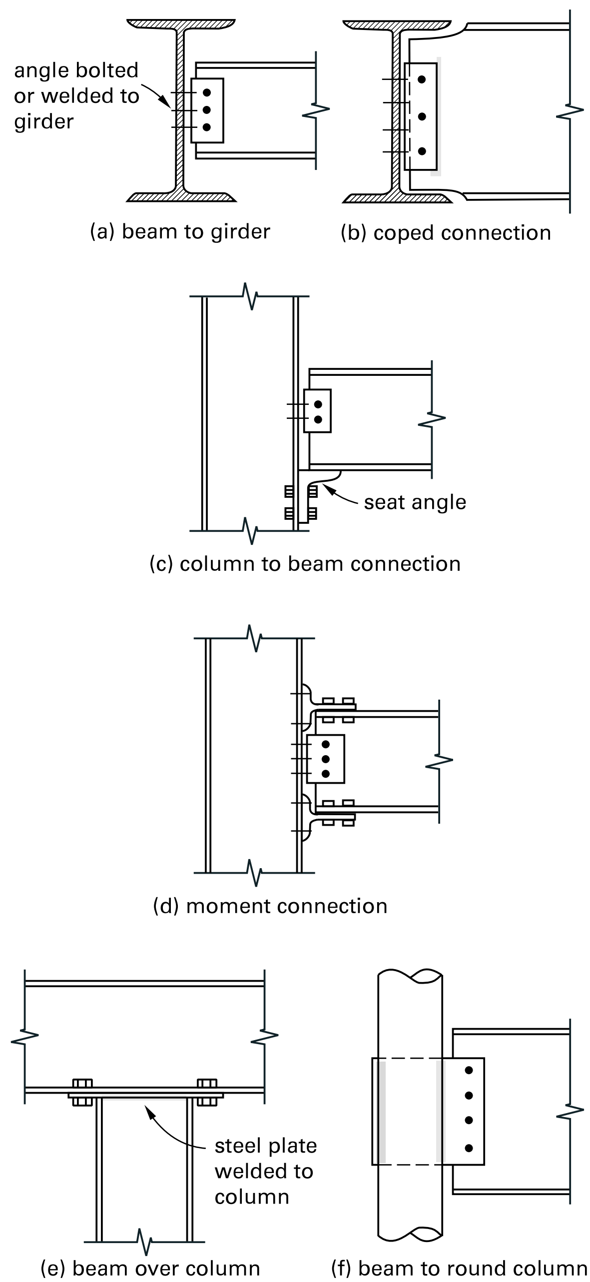


Figure 38.8 Typical Steel Framing Connections

Nomenclature

C_F	size factor	–
d	depth of beam	in
D	dead load	lbf/ft²
E	earthquake or seismic load	lbf/ft²
f_1	floor live load occupancy combination factor	–
f_2	snow load roof shape combination factor	–
f'_c	compressive strength	lbf/in²
F_b	allowable bending stress	lbf/in²
F_t	allowable axial tensile stress	lbf/in²
F_v	allowable shear stress	lbf/in²
F_y	specified minimum yield stress of the type of steel being used	lbf/in²
L	live load	lbf/ft²
L_r	roof live load	–
R	rain load	lbf/ft²
S	snow load	lbf/ft²
W	wind load	lbf/ft²
ω	wind load coefficient	–
Ω	safety factor (ASD)	–

Building code provisions related to structural design deal with how loads must be determined, what stresses are allowed in structural members, formulas for designing members of various materials, and miscellaneous requirements for construction. This chapter provides an overview of the requirements with which the candidate should be familiar. Specific provisions and calculation methods are presented in other chapters. Loads on buildings are covered in Chap. 33, wind loading and calculation methods in Chap. 44, and seismic design methods are reviewed in Chap. 45. The code provisions outlined are based on the *International Building Code* (IBC).

ALLOWABLE STRESSES

The IBC establishes basic allowable stresses for various types of construction materials. The design of any structural member must be such that these stresses are not exceeded. Although some provisions of the code are extremely complex (such as with concrete), this section outlines some of the more important provisions to be familiar with.

Wood

Tables 4A, 4B, 4C, 4D, 4E, 5A, 5B, and 5C of the *National Design Specification for Wood Construction* (NDS) give allowable unit stresses in structural lumber and glued-laminated timber. Examples of these tables are shown in ~~Chap. 18~~ Chap. 40. These include allowable stresses for extreme fiber in bending, tension parallel to the grain, horizontal shear, and compression perpendicular and parallel to the grain. The stresses given are for normal loading and must be adjusted according to various conditions of use as follows.

Repetitive use: A factor (C_r) equal to 1.15 is used when several beam members, such as joists or rafters, are used together. In order to use the repetitive factor C_r, the members cannot be over 4 in thick (nominal), cannot be spaced more than 24 in on center, and must be joined by transverse load-distributing elements (such as bridging or decking), and there must be at least three members in a group.

Duration of load: The amount of stress a wood member can withstand is dependent on the time during which the load producing the stress acts. This relation of strength to duration of load is shown graphically in Fig. 39.1. Allowable design loads are based on what is called *normal duration of load*, which is assumed to be 10 years. For duration of loads shorter than this, the allowable stress may be increased according to the following percentages.

- 15% for two months' duration, as for snow
- 25% for seven days' duration, as for roof loads
- 60% for wind or earthquake loads
- 100% for impact loads

In this case, it is important to keep units consistent in order for the answer to be in inches. Remember that in Eq. 40.7, w is the load per unit length and L is the length. If L is in inches, the load must be in pounds per inch, not feet. For calculating the total dead and live load, 350 plf is 350/12, or 29.167 lbf/in. The beam length of 12 ft must be converted to inches and then raised to the fourth power.

$$\begin{aligned}\Delta &= \frac{(5)\left(29.167\ \frac{\text{lbf}}{\text{ft}}\right)\left((12\ \text{ft})\left(12\ \frac{\text{in}}{\text{ft}}\right)\right)^4}{(384)\left(1{,}600{,}000\ \frac{\text{lbf}}{\text{in}^2}\right)(415.283\ \text{in}^4)} \\ &= 0.25\ \text{in}\end{aligned}$$

Another way to arrive at the same answer is to remember that Eq. 40.7 can also take the form

$$\Delta = \frac{5WL^3}{384EI} \qquad 40.8$$

W is the total uniformly distributed load on the beam. The length still needs to be converted to inches and then raised to the third power, so the calculation is

$$\begin{aligned}\Delta &= \frac{5WL^3}{384EI} = \frac{(5)\left(\left(350\ \frac{\text{lbf}}{\text{ft}}\right)(12\ \text{ft})\right)\left((12\ \text{ft})\left(12\ \frac{\text{in}}{\text{ft}}\right)\right)^3}{(384)\left(1{,}600{,}000\ \frac{\text{lbf}}{\text{in}^2}\right)(415.283\ \text{in}^4)} \\ &= 0.25\ \text{in for dead and live loads}\end{aligned}$$

For deflection due to the live load only,

$$\begin{aligned}\Delta &= \frac{5WL^3}{384EI} = \frac{(5)\left(\left(200\ \frac{\text{lbf}}{\text{ft}}\right)(12\ \text{ft})\right)\left((12\ \text{ft})\left(12\ \frac{\text{in}}{\text{ft}}\right)\right)^3}{(384)\left(1{,}600{,}000\ \frac{\text{lbf}}{\text{in}^2}\right)(415.283\ \text{in}^4)} \\ &= 0.14\ \text{in}\end{aligned}$$

Next, determine the allowable deflection limits. For the live load only,

$$\frac{L}{360} = \frac{(12\ \text{ft})\left(12\ \frac{\text{in}}{\text{ft}}\right)}{360} = 0.40\ \text{in}$$

This is more than the actual deflection under the live load only of 0.14 in, so this is acceptable. For the total load,

$$\frac{L}{240} = \frac{(12\ \text{ft})\left(12\ \frac{\text{in}}{\text{ft}}\right)}{240} = 0.60\ \text{in}$$

This is also more than the actual deflection under the total load of 0.25 in, so the 4 × 12 beam is acceptable for deflection requirements.

Reinforcing Steel

Because concrete's tensile strength is low, concrete is often reinforced with steel to increase its resistance to ~~bedding~~ bending and other tensile stresses. Concrete also has low ductility (that is, it is brittle), so that when a concrete beam or slab fails, it can shatter suddenly and with little or no warning.

For this reason, it is desirable that the amount of steel reinforcement be kept low enough that the steel will yield before the concrete fails. When this is the case, the concrete is said to be *under-reinforced*. An under-reinforced concrete beam will bend before the concrete fails, giving a visible warning of possible danger.

The cross-sectional areas and other dimensional properties of the standard reinforcing bars are given in Table 42.1, along with the amount of reinforcement given by various combinations of bars and spacings.

Table 42.1 Properties of Reinforcing Bars

dimensional properties of individual bars

bar no.	diameter	area (in^2)	perimeter (in)	weight (lbm/ft)
3	0.375	0.11	1.18	0.376
4	0.500	0.20	1.57	0.668
5	0.625	0.31	1.96	1.043
6	0.750	0.44	2.36	1.502
7	0.875	0.60	2.75	2.044
8	1.000	0.79	3.14	2.670
9	1.128	1.00	3.54	3.400
10	1.270	1.27	3.99	4.303
11	1.410	1.56	4.43	5.313
14	1.693	2.25	5.32	7.650
18	2.257	4.00	7.09	13.600

areas of bars in reinforced concrete (in^2/ft)

spacing (in)	bar size 3	4	5	6	7	8	9	10	11
3	0.44	0.80	1.24	1.76	2.40	3.16	4.00	5.08	6.25
3 1/2	0.38	0.69	1.06	1.51	2.06	2.71	3.43	4.35	5.35
4	0.33	0.60	0.93	1.32	1.80	2.37	3.00	3.81	4.68
4 1/2	0.29	0.53	0.83	1.17	1.60	2.11	2.67	3.39	4.16
5	0.26	0.48	0.74	1.06	1.44	1.90	2.40	3.05	3.74
5 1/2	0.24	0.44	0.68	0.96	1.31	1.72	2.18	2.77	3.40
6	0.22	0.40	0.62	0.88	1.20	1.58	2.00	2.54	3.12
6 1/2	0.20	0.37	0.57	0.81	1.11	1.46	1.85	2.34	2.88
7	0.19	0.34	0.53	0.75	1.03	1.35	1.71	2.18	2.67
7 1/2	0.18	0.32	0.50	0.70	0.96	1.26	1.60	2.03	2.50
8	0.17	0.30	0.46	0.66	0.90	1.18	1.50	1.90	2.34
9	0.15	0.27	0.41	0.59	0.80	1.05	1.33	1.69	2.08
10	0.13	0.24	0.37	0.53	0.72	0.94	1.20	1.52	1.87
12	0.11	0.20	0.31	0.44	0.60	0.79	1.00	1.27	1.56

Placing and Curing

Two important parts of the entire process of concrete design and construction are getting the concrete to the forms and ensuring that it is allowed to cure properly. Transporting the material from the truck or