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BUILDING ENGINEERING

Buildings include a wide range of construction intended for human occupancy or for sheltering machines or stored goods. Civil engineers play an important role in the design and construction of such structures. But sometimes, the civil engineer is only one of many design professionals participating in the planning and design of a building. Therefore, it is necessary that the engineer's design decisions take into consideration the objectives and needs of the other professionals. For this purpose, civil engineers must be well-informed on such subjects as architecture, building layout, lighting, electrical systems, elevators, plumbing, heating, and air conditioning, as well as structural design. To serve this need, this section summarizes briefly the design principles of those fields and lists references for more detailed study.

15.1 Influence of Zoning on Building Design

Localities use zoning to regulate use of land, control types of occupancies and size of buildings, and in various other ways safeguard the public health, safety, and welfare. Zoning regulations supplement building code requirements.

When selecting land for a building, the local zoning code should be checked to see if the type of occupancy planned—residential, commercial, industrial, school, church—is permitted. If it is not, the possibility of a variance or a code change should be investigated.

For some types of construction—housing, for example—lack of a zoning code may discourage selection of a parcel of land. Uncontrolled land use may permit undesirable neighbors—junkyards or odorous factories—with a resulting deflation in property values. When a zoning code exists, its control over land adjoining the parcels being considered should be examined, to determine whether neighboring occupancies will be desirable. See also Art. 14.22.

To ensure light and air to adjacent property, zoning codes restrict the height and bulk of buildings. Some codes limit the number of stories; some place a maximum on the height above the street. In some cases, codes permit unlimited height but require the buildings to be set back from the base after certain heights are reached, depending on the width of the street, measured between building lines. This type of requirement led in the past to "wedding cake" architecture, buildings that were made narrower and narrower in steps as they rose because of frequent setbacks. As an alternative, in which internal space is sacrificed in the interests of esthetics, a building may satisfy that type of regulation yet not have setbacks if it is erected as a sheer tower occupying only part of its site.

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* Revised and updated from Sec. 15 "Building Engineering," Frederick S. Merritt "Standard Handbook for Civil Engineers," 4th ed., McGraw-Hill Book Company.

Some codes control height and bulk by establishing a ratio between total floor area permitted and the area of the site. Extra floor area sometimes is allowed if part of the site at or near street level is devoted to a plaza. Thus, designers may shape the building any way they please within the building lines; they may make it tall and thin or short and broad, so long as the total floor area does not exceed that permitted. Codes, however, sometimes also require buildings to be set back at the base minimum distances from lot lines; these regulations should be determined and observed in locating a building on its site.

In addition to being restricted by zoning, building height may be limited by Federal aviation authorities, especially in the vicinity of airports. These regulations should be considered before land is selected for a project and especially before building height is decided on in the early design stages.

15.2 Building Codes

Localities, and sometimes the states, exercise the police power to safeguard public health, safety, and welfare by controlling building design and construction through building codes. The control generally extends over all phases, including specification of permissible design and construction methods, as well as field inspection to ensure compliance.

Codes may be classified as specification or performance-standards type. Specification-type codes are characterized by requirements that list acceptable materials and their minimum sizes for specific applications. Performance-standards codes specify the end result to be obtained in terms of such characteristics as strength, stability, permeability, hardness, and fire resistance. In practice, this type of code generally is supplemented by a catalog of acceptable materials and constructions after tests show they meet code requirements.

Since most communities have their own codes, which may differ from those of adjoining localities, building designers should become familiar with the local building codes for the areas in which their projects will be erected. Even where state codes exist, communities may have the power to set more stringent requirements than the state.

For projects in areas not under the jurisdiction of a state or local building code, building designers should adopt the code of a nearby large city or a model code applicable to the region. Nationally recognized model codes include: National Building Code—National Conference of States on Building Codes and Standards; Uniform Building Code—International Conference of Building Officials; Standard Building Code—Southern Building Code Congress International, Inc.; Basic Building Code—Building Officials and Code Administrators International, Inc., and International Building Code—International Code Council.

There are also Federal regulations that must be complied with by building owners, designers, and contractors. For example, the Occupational Safety and Health Administration (OSHA) sets standards, regulations, and procedures for building construction and conditions in buildings after construction. In general, OSHA requires that contractors and subcontractors not permit personnel to work in surroundings or under working conditions that are unsanitary, hazardous, or dangerous to health and safety. Employers are responsible for initiating and maintaining accident prevention programs. Detailed requirements are given in “Construction Industry: OSHA Safety and Health Standards (29 CFR 1926/1910),” Superintendent of Documents, Government Printing Office, Washington, DC 20402. (http://bookstore.gpo.gov)

Another example of Federal rules that must be considered is the Americans with Disabilities Acts (ADA). This federal law requires that buildings be accessible to individuals with disabilities. A copy of the guidelines for conformance with this Federal law can be obtained from the Access Board, 1331 F Street, NW, Suite 1000 Washington, DC 20004-1111. (www.access-board.gov)

15.3 Fire Protection for Buildings

An important consideration in the design of nearly all buildings is the fire resistance required by building codes and insurance companies. This resistance may require use of incombustible materials, fire-protective coverings, and sprinkler systems, which generally cost more than constructions of lower fire resistance. Also, codes may prohibit use of hazardous materials, for example, materials that may explode or emit excessive smoke or poisonous gases.

Sometimes, the lowest long-run costs for a building are obtained with a higher fire resistance than required by the local building code because of reductions in fire insurance premiums.

Fire-resistant construction aims at withstanding a fire locally for a specific period of time and preventing it from spreading—throughout the level at which it starts, or from story to story, or to adjacent buildings. The objective of sprinkler systems is to extinguish the fire quickly.

Fire ratings are assigned to building components in accordance with their performance in standard fire tests (ASTM E119, "Standard Methods of Fire Tests of Building Construction and Material"). If a component meets requirements after 1 h exposure in a standard furnace test, it is given a 1-h rating; if it withstands the test for 2 h, it gets a 2-h rating; and so on.

Fire protection for a building and its occupants involves prevention, detection and warning, containment, and extinguishment of fires, and provision for life safety.

Prevention ▪ Buildings should be designed to minimize the possibility of fire other than in such authorized places as furnaces and fireplaces. Where possible, construction materials—roofing, flooring, ceilings, and sash, for example—and coatings, paints, and curtains should be incombustible. Also, the fuel load from furnishings should be kept small.

Detection and Warning ▪ Buildings should be equipped in every story with devices that can detect fire or smoke and sound an alarm. Such devices can also automatically instigate extinguishment procedures. There are five general types of detectors; each employs a different physical means of operation.

Fixed-temperature detectors indicate the presence of fire when the device reaches a predetermined temperature.

Rate-of-rise detectors function when there is a rapid increase in temperature.

Photoelectric detectors are sensitive to smoke.

Combustion-products detectors recognize combustion products and are designed for very early warning.

Flame detectors respond to light, infrared or ultraviolet, produced by combustion reactions.

Detection should immediately signal a warning so that building occupants who may be endangered, life-safety supervisory personnel, and firefighters may be alerted.

Large buildings, especially those with many occupants, should have an emergency control center, or fire command station, on the ground floor to which detection signals are communicated. The center should have and control two-way communication with every floor and be able to direct rescuers and firefighters and transmit instructions to occupants to guide them to safety. The center should also be able to control all electromechanical systems, such as elevators, air conditioning, and fans. To assist firefighters, controls should be capable of venting, pressurizing, or sealing any zone in a building.

Containment ▪ Buildings should be so designed that, if fire or smoke should occur, it would be extinguished almost immediately, but in any event, it could not spread much beyond the place of occurrence. Spread of fire or smoke can be prevented by fire barriers, venting of heat and gases, and dampers.

Barriers. Large floor areas should be partitioned by fire walls into smaller areas. Fire doors protecting wall openings should be kept closed. Plenums, such as the spaces between floor and ceiling or roof and ceiling, should be isolated at frequent intervals by fire stops. Spandrels should have a high fire rating and should be sufficiently deep at each floor level to prevent flames extending out the windows in one story from igniting materials in the story above. (The National Building Code recommends a minimum depth of 3 ft.)

Venting systems should be provided to cool fires and keep heat and smoke from escape routes and refuge areas. Areas adjacent to a fire should be pressurized to keep out smoke. To clear smoke, windows should be openable or have smoke ventilation panels. Alternatively or in addition, an automatically vented smoke shaft should be provided. Also, the tops of fire towers enclosing elevators or stairs should permit venting of hot gases and smoke. Emergency ventilation of stairwells and elevator shafts may be assisted by fans. Fresh makeup air should be provided to keep safe areas habitable.

Automatic fire dampers should be installed in ducts, along with fire or smoke detectors that sample all air passing through. The dampers should be controlled to seal control zones, prevent smoke from spreading to escape routes and refuge areas, and guide ventilation area air to points where it is needed.

Extinguishment ▪ Means of fire suppression range from hand-held extinguishers to high-pressure water flows from hoses and sprays from installed sprinkler systems (Art. 15.33). (For some types of fires, carbon dioxide or chemicals may be necessary instead of water.) In addition, firefighters have various types of equipment for firefighting. Regardless of the means used, life safety and property damage depend primarily on early detection of fire and smoke and rapid application of the appropriate extinguishment method.

To assist firefighters, water must be supplied to them in adequate quantities and at sufficient pressures for firefighting. If necessary, storage or pumping facilities must be provided. An elevated water tank may be used for this purpose (National Fire Protection Association standard 22). The supply may be augmented by a fire pump (NFPA standard 20). Pressure should be at least 15 psi at the highest level of sprinklers, while flow at the base of the risers is at least 250 gal/min for light-hazard occupancies and 500 gal/min for ordinary-hazard occupancies. (Local building codes usually specify minimum pressures.)

The usual means of manually applying water to interior building fires is with hoses receiving water from standpipes. These generally are required in buildings more than about 50 ft high and should be so located that any part of a floor is not more than 130 ft from a standpipe outlet valve. Risers up to 75 ft high may be 4 in in diameter, but for greater heights, 6 in. Hose valves usually are $2\frac{1}{2}$ in in diameter.

Life Safety ▪ Buildings should provide for safe, easy escape in emergencies, preferably but not necessarily to outdoors at ground level. In some cases, it may be advisable to instruct occupants to stay in place or to provide refuge areas within the buildings to which occupants may proceed when alerted. Doors, hallways, and stairs should be adequate in number, size, and location to accommodate the number of occupants that may have to be evacuated in emergencies. (Requirements are specified in local building codes and in "Life Safety Code," NFPA101, National Fire Protection Association.) In addition, firefighters should be provided with safe access to fires.

In buildings with elevators, the cars should be equipped with controls for emergency use by firefighters and move automatically to the lobby floor to be available to them if needed. Control wiring should be protected against accidental operation by high temperatures.

Elevators and stairs should be enclosed in fire towers with walls having a 4-h rating (*fire walls*) and fire-resistant doors that are kept closed. Building entrances and exits should be especially protected. (See also Art. 15.18.)

(F. S. Merritt, "Building Design and Construction Handbook," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); F. S. Merritt, "Building Engineering and Systems Design," 2nd ed., Van Nostrand Reinhold Company, New York; "The SFPE Handbook of Fire Protection Engineering," "Automatic Sprinkler Systems Handbook," "Fire Protection Handbook," 17th ed., "Life Safety Code Handbook," and "National Fire Codes," National Fire Protection Association, Quincy, Mass (www.nfpa.org).)

15.4 Service Loads for Buildings

Service loads used in the design of a building should be the maximum probable loads to which the structure may be subjected. They should not be less, however, than the loads specified by the local building code. In the absence of a local code, the loads given in this article may be used, or the loads in a model building code, or the loads in "Building Code Requirements for Minimum Design Loads in Buildings and Other Structures," ASCE 7-02, American Society of Civil Engineers, New York (www.asce.org). See also Art. 15.5.

All structural components of a building must be designed for the full dead load as a minimum. When the dead load is not certain, for example, when the location of partitions is not known when the design is made, an allowance should be made. Some building codes require a uniformly distributed load of 20 psf to be added to the known dead load to allow for partitions not definitely located. Tables 15.1 and 15.2*c* list minimum design dead

Table 15.1 Minimum Design Dead Loads

	lb/ft²
Walls	
Clay brick	
High-absorption, per 4-in wythe	34
Medium-absorption, per 4-in wythe	39
Low-absorption, per 4-in wythe	46
Sand-lime brick, per 4-in wythe	38
Concrete brick	
4-in, with heavy aggregate	46
4-in, with light aggregate	33
Concrete block, hollow	
8-in, with heavy aggregate	55
8-in, with light aggregate	35
12-in, with heavy aggregate	85
12-in, with light aggregate	55
Clay tile, load-bearing	
4-in	24
8-in	42
12-in	58
Clay tile, non-load-bearing	
2-in	11
4-in	18
8-in	34
Furring tile	
1½-in	8
2-in	10
Glass block, 4-in	18
Gypsum block, hollow	
2-in	9.5
4-in	12.5
6-in	18.5
Partitions	
Plaster on masonry	
Gypsum, with sand, per in thick	8.5
Gypsum, light aggregate, per in	4
Cement, with sand, per in thick	10
Cement, light aggregate, per in	5
Plaster, 2-in solid	20
Metal studs	
Plastered two sides	18
Gypsumboard each side	6
Wood studs, 2 × 4-in	
Unplastered	3
Plastered one side	11
Plastered two sides	19
Gypsumboard each side	7
Concrete Slabs	
Stone aggregate, reinforced, per in	12.5
Slag, reinforced, per in thick	11.5
Light aggregate, reinforced, per in	6–10

	lb/ft²
Insulation	
Cork, per in thick	1.0
Foamed glass, per in thick	0.8
Glass-fiber bats, per in thick	0.06
Polystyrene, per in thick	0.21
Urethane, per in thick	0.17
Vermiculite, loose fill, per in thick	0.05

Wood joists, double wood floor, joist size	lb/ft² 12-in spacing	lb/ft² 16-in spacing
2 × 6	6	5
2 × 8	6	6
2 × 10	7	6
2 × 12	8	7
3 × 6	7	6
3 × 8	8	7
3 × 10	9	8
3 × 12	11	9
3 × 14	12	10

Floor Finishes	lb/ft²
Asphalt block, 2-in	24
Cement, 1-in	12
Ceramic or quarry tile, 1-in	12
Hardwood flooring, ⅞-in	4
Plywood subflooring, ½-in	1.5
Resilient flooring, such as asphalt tile	2
Slate, 1-in	15
Softwood subflooring per in thick	3
Terrazzo, 1-in	13
Wood block, 3-in	4
Floor Fill	
Cinders, no cement, per in thick	5
Cinders, with cement, per in thick	9
Sand, per in thick	8
Waterproofing	
Five-ply membrane	5
Glass	
Single-strength	1.2
Double-strength	1.6
Plate, ⅛-in	1.6
Ceilings	
Plaster (on tile or concrete)	5
Suspended metal lath, gypsum plaster	10
Suspended metal lath, cement plaster	15

(*Table continued*)

Table 15.1 (*Continued*)

	lb/ft^2		lb/ft^3
Roof and Wall Coverings		Masonry	
Clay tile	9–14	Cast-stone masonry	144
Asphalt shingles	2	Concrete, stone aggregate, reinforced	150
Composition:		Ashlar:	
3-ply ready roofing	1	Granite	165
4-ply felt and gravel	5.5	Limestone, crystalline	165
5-ply felt and gravel	6	Limestone, oölitic	135
Copper or tin	1	Marble	173
Corrugated steel	2	Sandstone	144
Sheathing (gypsum), ¼in	2		
Sheathing (wood), per in thickness	3		
Slate, ¼in	10		
Wood shingles	2		

loads for various materials. In computing dead load, the weight of the member being designed should be included, as well as the weight of the rest of the structure that it has to support.

Live loads for buildings generally are assumed uniformly distributed, except, of course, that the live load transmitted from a beam to a girder is a concentrated load on the girder. Some codes also require an additional concentrated load, applied at any point in a bay, for garages, machine rooms, and offices. But such loads as those from a moving crane on crane girders and columns should be treated as moving concentrated loads. Table 15.2 lists minimum design live loads for various occupancies.

Live loads should be placed on a structure to produce maximum stress and deformation in components being designed. For example, in design of a continuous beam for maximum positive moment at midspan, only alternate spans, including the one being designed, should carry full live load. Machine weight should be increased 25% and elevator loads 100% for impact.

When a very large area contributes live load to a member, most codes permit a reduction from that required for a member supporting a small loaded area. For floors, for example, some codes permit a reduction for members supporting 150 ft^2 or more of 0.08% per ft^2. But the reduction cannot exceed 60% or $23.1(1 + D/L)\%$, where D is the dead load per square foot of area supported and L the live load per square foot. And the reduction does not apply to one-way slabs, places of public assembly, or garages for trucks and buses. Where live loads exceed 100 lb/ft^2 and for passenger-car garages, live loads on columns supporting more than one floor may be reduced 20%.

Snow loads on roofs should be treated as live load and placed to produce maximum stress and deformation. Ordinary roofs should be designed for a live load of at least 20 lb/ft^2 of horizontal projection to provide for sleet and minor snow loads and loads incidental to construction and repair. Where snow loads may exceed 20 lb/ft^2, the roof should be designed for the maximum anticipated or that required by the local building code or the loads given in ASCE 7-02. Roofs used for incidental promenade purpose should be designed for a minimum live load of 60 lb/ft^2. When used for roof gardens or assembly purposes, they should be designed for 100 lb/ft^2.

Wind loads vary with location and height of building. Buildings should be designed for wind coming from any direction. Wind loads and live loads may act simultaneously, but wind loads need not be combined with seismic loads.

Horizontal pressures produced by wind are assumed for design purposes to act normal to the faces of buildings and may be directed toward the interior of the buildings or outward. These forces are called velocity pressures because they are primarily a function of the velocity of the wind striking the buildings. Building codes usually permit wind pressures to be either calculated or determined by tests on models of buildings and terrain.

The basic wind speed used in design is the fastest-mile wind speed recorded at a height of 10 m (32.8 ft) above open, level terrain with a

Table 15.2 Minimum Design Live Loads

a. Uniformly distributed live loads, lb/ft^2, impact included*

Occupancy or use	Load
Assembly spaces:	
Auditoriums[†] with fixed seats	60
Auditoriums[†] with movable seats	100
Ballrooms and dance halls	100
Bowling alleys, poolrooms, similar recreational areas	75
Conference and card rooms	50
Dining rooms, restaurants	100
Drill rooms	150
Grandstand and receiving-stand	100
seating areas	100
Gymnasiums	100
Lobbies, first-floor	100
Roof gardens, terraces	100
Skating rinks	100
Bakeries	150
Balconies (exterior)	100
Up to 100 ft^2 on one- and two-family houses	60
Bowling alleys, alleys only	40
Broadcasting studios	100
Catwalks	30
Corridors:	
Areas of public assembly, first-floor lobbies	100
Other floors same as occupancy served, except as indicated elsewhere in this table	
Fire escapes:	
Multifamily housing	40
Others	100
Garages:	
Passenger cars	50
Trucks and buses	‡
Hospitals:	
Operating rooms, laboratories, service areas	60
Patients' rooms, wards, personnel areas	40
Kitchens other than domestic	150
Laboratories, scientific	100
Libraries:	
Corridors above first floor	80
Reading rooms	60
Stack rooms, books and shelving at 65 lb/ft^3 but at least	150
Manufacturing and repair areas:	
Heavy	250
Light	125
Marquees	75
Morgue	125
Office buildings:	
Corridors above first floor	80
Files	125
Offices	50
Penal institutions:	
Cell blocks	40
Corridors	
Residential:	100
Dormitories:	
Nonpartitioned	60
Partitioned	40
Dwellings, multifamily:	
Apartments	40
Corridors	80
Hotels:	
Guest rooms, private corridors	40
Public corridors	80
Housing, one- and two-family:	
First floor	40
Storage attics	80
Uninhabitable attics	20
Upper floors, habitable attics	30
Schools:	
Classrooms	40
Corridors	80
Shops with light equipment	60
Stairs and exitways	100
Handrails, vertical and horizontal thrust, lb/lin ft	50
Storage warehouses:	
Heavy	250
Light	125
Stores:	
Retail:	
Basement and first floor	100
Upper floors	75
Wholesale:	100
Telephone equipment rooms	80
Theaters:	
Aisles, corridors, lobbies	100
Dressing rooms	40
Projection rooms	100
Stage floors	150
Toilet areas	40

(*Table continued*)

Table 15.2 (*Continued*)

b. Concentrated live loads[§]

Location	Load, lb
Elevator machine room grating (on 4-in^2 area)	300
Finish, light floor-plate construction (on 1-in^2 area)	200
Garages:	
Passenger cars:	
Manual parking (on 20-in^2 area)	2,000
Mechanical parking (no slab), per wheel	1,500
Trucks, buses (on 20-in^2 area), per wheel	16,000
Office floors (on area 2.5 ft square)	2,000
Roof-truss panel point over garage, manufacturing, or storage floors	2,000
Scuttles, skylight ribs, and accessible ceilings (on area 2.5 ft square)	200
Sidewalks (on area 2.5 ft square)	8,000
Stair treads (on 4-in^2 area at center of tread)	300

c. Minimum design loads for materials

Material	Load, lb/ft^3	Material	Load, lb/ft^3
Aluminum, cast	165	Gypsum, loose	70
Bituminous products:		Ice	57.2
Asphalt	81	Iron, cast	450
Petroleum, gasoline	42	Lead	710
Pitch	69	Lime, hydrated, loose	32
Tar	75	Lime, hydrated, compacted	45
Brass, cast	534	Magnesium alloys	112
Bronze, 8 to 14% tin	509	Mortar, hardened:	
Cement, portland, loose	90	Cement	130
Cement, portland, set	183	Lime	110
Charcoal	12	Riprap (not submerged):	
Coal, anthracite, piled	52	Limestone	83
Coal, bituminous or lignite, piled	47	Sandstone	90
Coal, peat, dry, piled	23	Sand, clean and dry	90
Copper	556	Sand, river; dry	106
Cork, compressed	14.4	Silver	656
Earth (not submerged):		Steel	490
Clay, dry	63	Stone, quarried, piled:	
Clay, damp	110	Basalt, granite, gneiss	96
Clay and gravel, dry	100	Limestone, marble, quartz	95
Sand and gravel, dry loose	100	Sandstone	82
Sand and gravel, dry, packed	110	Shale, slate	92
Sand and gravel, wet	120	Tin, cast	459
Silt, moist, loose	78	Water, fresh	62.4
Silt, moist, packed	96	Water, sea	64
Gold, solid	1,205	Zinc	450
Gravel, dry	104		

[*] See local building code for reductions permitted for members subjected to live loads from large loaded areas.

[†] Including churches, schools, theatres, courthouses, and lecture halls.

[‡] Use American Association of State Highway and Transportation Officials highway lane loadings.

[§] Use instead of uniformily distributed live load, except for roof trusses, if concentrated loads produce greater stresses or deflections. Add impact factor for machinery and moving loads: 100% for elevators, 20% for light machines, 50% for reciprocating machines, 33% for floor or balcony hangers. For craneways, add a vertical force equal to 25% of maximum wheel load; a lateral force equal to 10% of the weight of trolley and lifted load, at the top of each rail and a longitudinal force equal to 10% of maximum wheel loads, acting at top of rail.

50-year mean recurrence interval. In the absence of code specifications and reliable data, the basic wind speed may be approximated for preliminary design from the following:

Coastal areas, northwestern and southwestern United States and mountainous areas	110 mi/h
Northern and central United States	90 mi/h
Other parts of the contiguous states	80 mi/h

For design purposes, wind pressures should be determined in accordance with the degree to which terrain surrounding the proposed building exposes it to the wind. Exposures may be classified as follows:

Exposure A applies to centers of large cities, where for at least ½ mi upwind from the building the majority of structures are over 70 ft high and lower buildings extend at least one more mile upwind.

Exposure B applies to wooded or suburban terrain or to urban areas with closely spaced buildings mostly less than 70 ft high, where such conditions prevail upwind for a distance from the building of at least 1500 ft or 10 times the building height.

Exposure C exists for flat, open country or exposed terrain with obstructions less than 30 ft high.

Exposure D applies to flat, unobstructed areas exposed to wind blowing over a large expanse of water with a shoreline at a distance from the building of not more than 1500 ft or 10 times the building height.

For ordinary buildings not subject to hurricanes, the velocity pressure q_z, psf, at height z, ft, above grade may be calculated from

$$q_z = KV^2 \geq 10\,\text{psf} \tag{15.1}$$

where V = basic wind speed, mi/h, but not less than 70 mi/h

K = pressure coefficient from Table 15.3

For important buildings, such as hospitals and communications buildings, for tall, slender structures, and for high-occupancy buildings, such as auditoriums, q_z computed from Eq. (15.1) should be increased 15%. To allow for hurricanes, q_z should be increased 5% for ordinary buildings and 20% for important, wind-sensitive, or high-risk buildings along hurricane coastlines, such as those along the Atlantic Ocean and Gulf of Mexico. These increases, however, may be assumed to reduce uniformly with distance from the shore to zero for ordinary buildings and 15% for the more important or sensitive structures at points 100 mi inland.

For design of the main wind-force resisting system of ordinary, rectangular, multistory buildings, wind pressures at any height z may be computed from

$$p_{zw} = G_o C_{pw} q_z \tag{15.2}$$

where p_{zw} = design wind pressure, psf, on windward wall

G_o = gust response factor

C_{pw} = external pressure coefficient

For windward walls, C_{pw} may be taken as 0.8. For sidewalls, C_{pw} may be assumed as -0.7 (suction). For roofs and leeward walls, substitute in Eq. (15.2) an external pressure coefficient C_p for C_{pw}. Leeward walls are subject to suction and C_p depends on ratio of depth d to width b of the building. For d/b of 1 or less, $C_p = -0.5$; for $d/b = 2$, $C_p = -0.3$; and for d/b of 4 or more, $C_p = -0.2$. For roofs, q_z should be computed for z equal to the mean roof height. For flat roofs, C_p may be taken as -0.7. For sloping roofs, C_p depends on wind direction and roof slope

Table 15.3 Pressure Coefficients, K, for Computation of Wind Pressure

	$K \times 10^6$			
	Exposure A	Exposure B	Exposure C	Exposure D
Height z up to 15 ft	307	940	2046	3052
Height z over 15 ft	$50.45q_z^{2/3}$	$282q_z^{4/9}$	$943q_z^{2/7}$	$1776q_z^{1/5}$

(see "Minimum Design Loads for Buildings and Other Structures," ASCE 7-02, American Society of Civil Engineers, New York). The gust response factor may be taken approximately as

$$G_o = 0.65 + \frac{8.58D}{(h/30)^n} \geq 1 \qquad (15.3)$$

where $D = 0.16$ for Exposure A, 0.10 for Exposure B, 0.07 for Exposure C, and 0.05 for Exposure D

$n = \frac{1}{3}$ for Exposure A, $\frac{2}{9}$ for Exposure B, $\frac{1}{7}$ for Exposure C, and 0.1 for Exposure D

$h =$ mean roof height, ft

For design of the main wind-force resisting system of rectangular, one-story buildings, wind pressures vary with relative areas of openings of windward and leeward walls. For windward walls, pressures computed from Eq. (15.2) should be increased by $C_{pl}q_z$, where $C_{pl} = 0.75$ if the percentage of openings in one wall exceeds that of other walls by 10% or more, and $C_{pl} = 0.25$ for all other cases. For roofs and leeward walls, $C_{p2}q_z$ should be subtracted from pressures computed from Eq. (15.2), where $C_{p2} = 0.75$ or -0.25 if the percentage of openings in one wall exceeds that of other walls by 10% or more, and $C_{p2} = \pm 0.25$ for all other cases.

For flexible buildings (those with a fundamental natural frequency less than 1 Hz or with a ratio of height to least horizontal dimension exceeding 5), see ASCE 7-02.

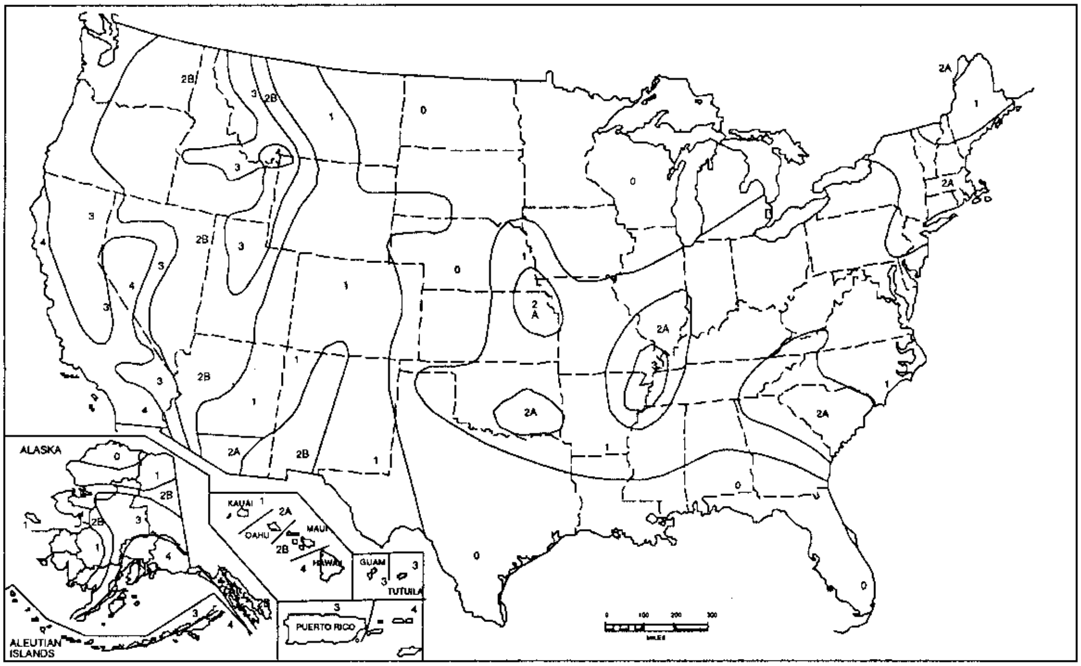
Design Seismic Forces ▪ The procedures and the limitations for determining seismic forces for the design of structures are dependent on site seismic hazard characteristics, site soil characteristics, site soil characteristics, occupancy, structure configuration, structural system and height. Current model building codes, such as, the 1999 National Building Code (NBC), the 1997 Uniform Building Code (UBC), the 2000 International Building Code (IBC), should be followed for determining seismic forces for the design and analysis of new structures and retrofit of existing structures. Building codes have been developed and updated based on better understanding of seismic risk and structural response through lessons learned from past earthquakes, and research in structural, geotechnical and earthquake engineering. The civil and structural engineers should follow the provisions of the model building codes in seismic design and analysis. There are far fewer structural failures when modern building codes are used.

Some key aspects of the seismic design provisions of the UBC will be used to discuss the determination of seismic forces and other design and analysis requirements. The engineers should refer to the UBC or other controlling building codes for complete and detailed seismic design criteria, procedures and limitations.

Seismic hazard characteristics for the site are based on seismic zones, proximity of the site to active seismic sources, and site soil profile characteristics. Each site is assigned a seismic zone. A seismic zone map of the United States is shown in Fig. 15.1. National maps of seismic hazards have been produced by the U.S. Geological Survey (USGS) since 1948. These maps are revised as new earthquake studies provide better understanding of the seismic hazard. The national maps of seismic hazards provide information essential to creating and updating the seismic design provisions building codes used in the United States. These maps may be obtained from USGS, Central Region, Geologic Hazards Team, Golden, Colorado or from the USGS web site: http://geohazards.cr.usgs.gov/eg.

A typical seismic hazard map may have the title, "Ground motions having 10 percent probability of being exceeded in 50 years." The 10 percent is an "exceedance probability" and the 50 years is an "exposure time." This means that the ground motions shown in this map has a 10 percent probability of being exceeded in 50 years. An event with this probability has a return period of about 475 years. This means the same as saying that these ground motions have an annual probability of occurrence of $\frac{1}{475}$ per year. This is commonly used in building and bridge codes as the design earthquake and the ground motions associated with the design earthquake are termed design ground motions. The ground motions are generally expressed as peak ground accelerations (PGA). A site-specific procedure must be used for determining the design ground motions if the site conditions are unusual, such as, high seismicity zones, soft soils, site is near to an active fault, or a very important structure.

However, building codes have been replacing maps having numbered zones with maps showing contours of design ground motion. At the present, the 1997 Uniform Building Code is the only



Seismic Zone	Seismic Zone Factor	Peak Ground Acceleration
1	0.075	0.075
2A	0.15	0.15
2B	0.20	0.20
3	0.30	0.30
4	0.40	0.40

Fig. 15.1 Seismic zone map of the United States [UBC].

building code that still uses seismic zones. It is anticipated that the new edition of the UBC will drop the zones and adopt the contours of design ground motion. The new format will avoid the need to revise zone boundaries by petition from various states.

Seismic Zones. Building codes traditionally divide a seismic hazard map into seismic zones in which a common level of seismic design is applied. For example, in the 1997 Uniform Building Code, the seismic hazard map of the United States is divided into six seismic zones of different levels of peak ground accelerations (PGA) as shown in Fig. 15.1.

For each structure, UBC assigns a seismic zone factor, Z, corresponding to the peak ground acceleration as shown in Fig. 15.1

Active Seismic Sources. Earthquakes occur on faults. A fault is a thin zone of crushed rock between two tectonic plates. It can also be a fracture within a tectonic plate or in the crust of the earth where rocks have moved relatively to one another. A fault can be of any length, from inches to thousands of miles. Active faults move at average of a fraction of an inch to about 4 inches per year. For example, the Juan de Fuca plate is known to be subducting beneath the North American plate along the cascadia subduction zone off the Pacific coast of Washington State at a rate of about 1.2 to 1.6 inches per year. When the rock on one side of a fault suddenly slips with respect to the other, energy is abruptly released, causing ground motions that rattle buildings. The larger slips correspond to larger energy release and larger ground motions. As expected, larger rupture length results in larger earthquake magnitude. The well known San Andreas Fault in California has a length of over 650 miles, extending to a depth of over 10 miles, and it has been the source of many

Table 15.4 Earthquake Magnitude vs Length of Slipped Fault

Magnitude	Length of slipped fault (miles)
8.0	190
7.0	25
6.0	5
5.0	2.1
4.0	0.83

large earthquakes, including the famous 1906 San Francisco Earthquake with magnitude 8.3. Table 15.4 gives an approximate relationship between earthquake magnitude and length of fault that has slipped.

The 1989 Loma Prieta Earthquake with magnitude 7.1 was reported to have a ruptured length of 25 to 30 miles.

Soil Characteristics. Each site is assigned a soil profile based on geotechnical data and the soil response to ground motions. For example, lessons from past earthquakes show that ground shaking is stronger in soft soil than in hard rock. There is amplification or deamplification in different soil types. Table 15.5 shows the 6 soil types used by UBC.

To account for the site effects of the soil profile types on structural response, seismic response coefficients are used by UBC to amplify the seismic zone factors Z for the seismic zones. The seismic response coefficients to be assigned to each structure are listed in Table 16-Q for C_a and Table 16-R for C_v of UBC. It may be noted that there is deamplification for Soil Profile Type S_A which is hard rock, and no amplification for Soil Profile Types S_B which is rock. There are significant amplifications for the other Soil Profile Types S_C, S_D, S_E and S_F.

Occupancy. The UBC design ground motion is based on a 10% probability of being exceeded in 50 years, which is an earthquake having a return period of 475 years. Buildings designed in accordance with UBC are expected to perform without major structural failures and loss of life under this design earthquake. However, for essential facilities, such as hospitals, fire and police stations, emergency response centers (ERC), structures housing equipment for ERC, etc. and hazardous facilities housing or supporting toxic or explosive chemicals or substances, the UBC assigns higher Seismic Importance Factors I and I_p to provide higher seismic resistance. UBC Table 16-K contains the definitions for the Occupancy Categories and the assignments of Seismic Importance Factors.

Structure Configuration. For seismic design purposes, structures are designed as being structurally regular or irregular. Regular structures have no significant physical discontinuities in plan or vertical configuration or in their lateral-force-resisting system. Irregular structures have significant physical discontinuities in configuration or in their lateral-force-resisting systems. Irregular features include torsional irregularity, re-entrant corners, diaphragm discontinuity, out-of-plane offsets, and buildings with nonparallel systems.

Structural Systems. Structural systems are covered in detail in Sec. 15.7 of this handbook. For the

Table 15.5 Shear Wave Velocity

Profile type	Soil type	Shear wave velocity, ft/sec
S_A	Hard rock	$>5{,}000$
S_B	Rock	2,500 to 5,000
S_C	Very dense soil and soft rock	1,200 to 2,500
S_D	Stiff soil profile	600 to 1,200
S_E	Soft soil profile	<600
S_F	Soil requiring site-specific evaluation*	

* Soil Profile Type S_F is defined as soils requiring site-specific evaluation as follows:

1. Soils vulnerable to potential failure or collapse under seismic loading, such as liquefiable soils, quick and highly sensitive clays, and collapsible weakly cemented soils.
2. Peats and/or highly organic clays, where the thickness of peat or highly organic clay exceeds 10 ft.
3. Very high plasticity clays with a plasticity index, PI > 75, where the depth of clay exceeds 25 ft.
4. Very thick soft/medium stiff clays, where the depth of clay exceeds 120 ft.

purpose of seismic design, they may be classified as follows: **Bearing wall system** is a structural system for supporting vertical loads, such as dead loads. There is no vertical load-carrying space frame. Shear walls or braced frames are needed to resist lateral earthquake forces. **Building frame system** is a structural system using vertical load-carrying space frame to support vertical or gravity loads. Shear walls or braced frames are needed to resistance lateral earthquake forces. **Moment-resisting frame system** is a structural system using space frame to support vertical or gravity loads and the moment-resisting frames to provide lateral resistance to earthquake forces. **Dual system** is a structural system vertical load-carrying space frame to support vertical or gravity loads, and shear wall, braced frame and/or moment-resisting frame to resist the lateral seismic forces. The total base shear in a dual system is resisted proportionately in accordance with the relative rigidities of the individual systems. **Cantilevered column system** is a structural system relying on the cantilevered column elements for lateral resistance. UBC Table 16-N shows a list of lateral-force-resisting systems.

Height. UBC imposes height limits for the various structural systems in Seismic Zones 3 and 4. The limitations are given in UBC Table 16-N.

Near-Source Factor. When a fault ruptures, seismic waves are generated along the entire length of the fault. The direction in which the rupture propagates is a significant factor for most large earthquakes. This directivity effect causes significant amplification of shaking and velocity impulse to structures situated in the near-source or near-fault region, which is generally considered as within 6 to 7 miles of the active fault. The directivity effect was observed in the 1989 Loma Prieta earthquake in California, and the 1995 Kobe earthquake in Japan. To account for the near-source effect, UBC defines three Seismic Source Types A, B, C and assigns Near-Source Factors N_a and N_v to each Seismic Source Type, depending on the distance to known seismic source. Subduction sources are not included in these definitions and should be evaluated on a site-specific basis. The Near-Source Factors are given in Tables 16-S and 16-T and the Seismic Source Types are defined in Table 16-U of the UBC.

Seismic Factors. The UBC uses the Seismic Force Overstrength Factor Ω_o, to assure that the structures are designed to have minimum design strength over and above the seismic force determined by analysis. This may be considered as a seismic force amplification factor to obtain structural overstrength against earthquake forces higher than those anticipated in the design. The UBC introduces the Response Modification Factor, R, to recognize the ductility of a structure. Ductility is the ability of a structure to undergo inelastic deformation without collapse. It is not economical to design a structure to resist large earthquakes elastically. The Response Modification Factor approach takes advantage of the inherent energy dissipation capacity of a structural system as it undergoes inelastic deformation in the components or connections. This approach demands stringent detailing requirements to assure ductile behavior of the structural system. The values of the Seismic Force Overstrength Factor, Ω_o, and the Response Modification Factor, R, are given in Table 16-N of the UBC.

Redundancy Factor. The UBC introduces a Redundancy Factor, ρ, to recognize the importance of providing redundancy or multiple load paths in a structural system. The engineering profession has considered it good design practice to build in as much redundancy in a structural system as feasible. The building code provisions have begun to address redundancy after the 1994 Northridge earthquake in California. More stringent design provisions are imposed on nonredundant structures than on redundant structures.

Design and Analysis. The UBC identifies the design requirements that must be followed to assure adequate strength to withstand the lateral displacements induced by the Design Basis Ground Motion, considering the inelastic response of the structure and the inherent redundancy, overstrength and ductility of the lateral-force-resisting system. The design and analysis procedures and methods are outlined in the UBC for the structural systems. Diligently following the provisions in UBC and updating with new research findings and experience the civil and structural engineers will achieve seismic resistant structures consistent with the level of performance desired.

Depending on the structure configuration and height, structural systems, occupancy, seismic zones, and soil profile types, the static and/or dynamic lateral-force procedures may be used for seismic design and analysis. The static procedure is generally used for structures, regular under 240 feet in height or irregular not more than five stories or 65 feet in height, in Seismic Zone 1 and in Occupancy Categories 4 and 5 in Seismic Zone 2. The dynamic procedure is used for other major and more complex structures, and structures located in Soil Profile Type S_F, and have a period greater than 0.7 second. For the dynamic procedure, the ground motion, as a minimum, shall be one having a 10-percent probability of being exceeded in 50 years, and it must not be reduced by the response modification factor, R. The ground motion may be represented by a site-specific elastic design response spectrum using a damping ratio of 0.05 or an elastic design response spectrum constructed in accordance with Fig. 15.2 (see Figure 16-3 of UBC), using C_a and C_v consistent with the specific site.

For a time-history dynamic analysis, the ground motion time histories may be developed for the specific using actual earthquake motions, individually or in combination. The response spectra from time histories must approximate the site spectrum, using a damping ratio of 0.05 and considering geologic, tectonic, seismologic and soil characteristics of the site.

Earthquake Load Combinations. Structures are designed for seismic forces acting in any horizontal direction. UBC provides the following load combinations for earthquake loads:

$$E = \rho E_h + E_v \tag{15.4a}$$

$$E_m = \Omega_o E_h \tag{15.4b}$$

Where E = combined earthquake load on an element of the structure

E_h = earthquake load due to base shear, V or lateral force F_p

E_m = estimated maximum earthquake force that can be developed in the structure

E_v = load effect from vertical component of ground motion

Ω_o = seismic force amplification factor for overstrength

ρ = reliability/redundancy factor given by

$$\rho = 2 - \frac{20}{r_{\max}\sqrt{A_B}} \geq 1.0 \tag{15.4c}$$

But need not be greater than 1.5

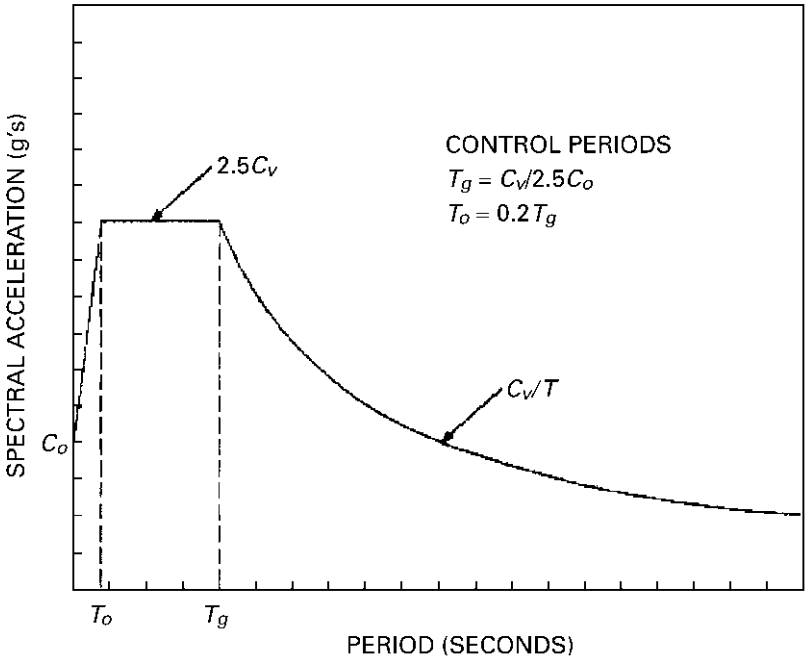


Fig. 15.2 Elastic design response spectrum (UBC).

where $r_{\max}$ = the maximum element-story shear ratio.

A_B = ground floor area of the structure in square feet.

Design Base Shear. The total design base shear in a given direction may be determined from the following formula based on the static force procedure:

$$V = \frac{C_v I}{RT} W \qquad (15.5)$$

The total design base shear need not exceed the following:

$$V = \frac{2.5 C_a I}{R} W \qquad (15.6)$$

The total design base shear shall not be less than the following:

$$V = 0.11 C_a I W \qquad (15.7)$$

where V = Total design base shear

C_a = Seismic coefficient, as given in UBC Table 16-Q

C_v = Seismic coefficient, as given in UBC Table 16-R

I = Importance factor, as given in UBC Table 16-K

R = Response modification factor, as given in UBC Table 16-N or 16-P

W = Total seismic dead load plus 25% of the floor live load for storage and warehouse, a minimum of 10 psf for a partition load, design snow load greater than 30 psf, and total weight of permanent equipment.

T = Fundamental period in seconds in the direction under consideration. T may be approximated from the following equation:

$$T = C_t (h_n)^{3/4} \qquad (15.8)$$

where C_t = 0.035 for steel moment-resisting frames

C_t = 0.030 for reinforced concrete moment-resisting frames and eccentrically braced frames.

C_t = 0.020 for all other buildings

h_n = height in feet above the base to the uppermost level.

The UBC requires that floor and roof diaphragms and horizontal bracing systems for seismic loads be designed to resist horizontal forces computed from

$$F_{px} = \frac{F_t + \sum_{i=x}^{n} F_i}{\sum_{i=x}^{n} w_i} w_{px} \le 1.0 C_a I w_x \qquad (15.9)$$

But not less than $0.5 C_a I w_{px}$

where F_{px} = Design seismic force on a diaphragm

F_t = that portion of the shear force, V, considered concentrated at the top of the structure in addition to F_n

F_i = Design seismic force applied to Level i

n = number of levels in the structure

w_i = that portion of dead load located at or assigned to Level i

w_{px} = the weight of the diaphragm and the element tributary thereto at Level x, including portions of other loads defined in Section 1630.1.1 of UBC

When the diaphragm is required to transfer design seismic forces from the vertical-resisting elements above the diaphragm to other vertical-resisting elements below the diaphragm due to offset in the placement of the elements or to changes in stiffness in the vertical elements, these forces shall be added to those determined from Equation 15.9.

Distribution of Seismic Loads ▪ Seismic forces are assumed to act at each floor level on vertical planar frames, or bents, or on shear walls extending in the direction of the loads. The seismic loads at each level should be distributed over the floor or roof area in accordance with the distribution of mass on that level.

The Uniform Building Code recommends that the seismic force F_x, to be assigned to any level at a height h_x, ft, above the ground be calculated from

$$F_x = (V - F_t) \frac{w_x h_x}{\sum_{i=1}^{n} w_i h_i} \qquad (15.10)$$

where w_x = portion of W located at or assigned to level x

h_x = height, ft, of level x above ground level

w_i = portion of W located at or assigned to level i

h_i = height, ft, of level i above ground level

n = number of levels in structure

V is the base shear computed from Eq. (15.4). F_t is an additional seismic force assigned to the top level of the structure and is calculated from

$$F_t = 0.07TV \qquad (15.11)$$

where T = fundamental natural period of vibration of the structure in the direction of the lateral force, s. F_t need not be more than 0.25 V and may be taken as zero when $T \leq 0.7$ s. Equation (15.12) recognizes the influence of higher modes of vibration as well as deviations from straight-line deflection patterns, particularly in tall buildings with relatively small dimensions in plan. Consequently, the design seismic shear at any level i is given by

$$V_i = F_t + \sum_{x=t}^{n} F_x \qquad (15.12)$$

This shear should be distributed to the bents or shear walls of the lateral-force system in proportion to their rigidities. The distribution-resisting should, however, take into account the rigidities of horizontal bracing and diaphragms (floors and roofs). In lightly loaded structures, for example, diaphragms may be sufficiently flexible to permit independent action of the lateral-force-resisting bents. A strong temblor could cause severe distress in frames and diaphragms if relative rigidities were not properly evaluated.

The design seismic force computed from Eq. (15.8) for an element of a structure or a nonstructural component supported by the structure should be distributed in proportion to the distribution of mass of the element or component.

Seismic force distribution for buildings or structural frames with irregular shapes should be determined by dynamic analysis.

Vertical Seismic Forces ▪ Provision should be made in aseismic design for the possibility of uplift due to seismic loads. When design of a structure is based on allowable unit stresses, only 85% of the dead load and no live loads should be considered available to counteract the uplift. Furthermore, the UBC requires for structures in Seismic Zones 3 and 4 that horizontal cantilever components be designed for a net uplift force of $F_{u'}$, where

$$F_{u'} = 0.7C_a I W_p \qquad (15.13)$$

In addition to all other applicable load combinations, horizontal prestressed components must be designed using not more than 50% of the dead load for the gravity load, alone or in combination with the lateral force effects.

Horizontal Shear and Torsion ▪ For calculating the effects of torsion due to seismic loads on a structure, the rigidity of diaphragms that distribute the seismic loads laterally to lateral-force-resisting framing should be considered. For the purpose, an inflexible diaphragm is defined as one for which the in-plane deflection of its midpoint due to the force F_{px}, computed from Eq. (15.8), is less than twice the average story drift of the stories above and below the diaphragm under the action of seismic forces V_i, calculated from Eq. (15.13). When diaphragms are inflexible, the Uniform Building Code requires that shears at any level i due to horizontal torsion be added to the direct horizontal shears. These are the shears at level i that result from the distribution of V_i, computed from Eq. (15.13), to the components of the vertical, lateral-force-resisting framing in proportion to their rigidities.

The design seismic torsion at any level i consists of two components: (1) The horizontal moment at level i due to eccentricities between the design seismic forces at upper levels and the vertical resisting components at level i. (2) An accidental torsion. This torsion is intended to account for uncertainties in location of seismic loads. For the purpose of computing eccentricities, the mass at each level is assumed to be displaced from the calculated center of mass a distance equal to 5% of the building dimension at that level and in the direction in which that dimension is measured. The displacements should be assumed to occur normal to the seismic load under consideration.

When a structure with inflexible diaphragms is torsionally irregular, the Uniform Building Code requires that the accidental torsion at each level i be multiplied by an amplification factor A_i. To determine whether a structure is torsionally irregular, locate the vertical, lateral-force-resisting bents (or shear walls) parallel to the design seismic loads and at or near the sides of the structure. Compute the maximum story drift due to the seismic shears, including accidental torsional shears, for each of those bents. (Story drift is the displacement of a level relative to the level above or below.) Let d_m be the larger of those drifts and d_a the average of the two. Then, if d_m exceeds $1.2d_a$, the structure is torsionally irregular. If it is, multiply the accidental torsion by A_i computed from

$$A_i = \left(\frac{d_m}{1.2d_a}\right)^2 < 3 \qquad (15.14)$$

Limitation on Story Drift ▪ To prevent damage to building components that could affect life safety, many building codes place limits on the amount of story drift permissible. For example, the UBC limits story drift to not more than 0.025 times the story height for structures having a fundamental period of less than 0.7 second, 0.02 times the story height for structures having a fundamental period of 0.7 second or greater.

Overturning ▪ The equivalent static lateral forces applied to a building at various levels induce overturning moments. At any level, the overturning moment equals the sum of the products of each force and its height above that level. The overturning moments acting on the base of the structure and in each story are resisted by axial forces in vertical elements and footings.

At any level, the increment in the design overturning moment should be distributed to the resisting elements in the same proportion as the distribution of shears to those elements. Where a vertical resisting element is discontinued, the overturning moment at that level should be carried down as loads to the foundation.

Importance of Proper Detailing. Proper detailing is of paramount importance in the design and construction of seismic-resistant structures. This fact is confirmed in every recent major earthquake. Experience in the 1994 Northridge Earthquake showed that new bridges designed and built to current design criteria and construction standards performed well. Existing bridges retrofitted to current retrofit standards also performed well.

With each major earthquake civil and structural engineers continue to learn and modify the seismic design criteria and construction practices to assure that new and retrofitted structures will perform well. Building and bridge codes have been undergoing progressive improvement based on research, experience and costly lessons from recent major earthquakes. Codes traditionally have been focusing on life safety. Modern codes, such as the UBC, are now paying attention to structural performance beyond the issues of life safety to more stringent performance based criteria. This shift is a direct reflection on the costly disruption of building use, commerce and communications. With the shift of emphasis to seismic performance criteria, the civil and structural engineers need to pay greater attention to proper detailing to assure adequate redundancy and ductility in the structures to meet the performance levels expected. For example, (1) for a low level earthquake there should be only minimal damage, and (2) for significant earthquake, collapse should be prevented but significant damage may occur. For critical structures, only repairable damage would be expected. The facility should be functional within a few days after the earthquake.

Proper detailing includes but not limited to the following:

1. Consider structural system reliability—a structure is a system of members, components and connections of the structure, including the foundation. Each structural element contributes to the integrity and safety of the bridge. Every member, component and connection must serve its function to resist and transmit seismic forces, and to accommodate displacements as expected in the design. Additionally, the structural elements should be designed to have reserved strength and ductility to absorb and dissipate energy of higher magnitude without fracture or collapse.
2. Provide at least one continuous viable load path to transmit inertial loads to the foundation—all members, components and connections along the load path must be capable of resisting the imposed load effects. Experience in past earthquake has shown that when one or more of the members, components or connections behaved in a ductile manner damage was much reduced.
3. Avoid irregularities in the structures as much as practicable—irregularities include geometric and stiffness irregularities, discontinuities in lateral force path, capacity and diaphragm, and large skews.
4. Consider commercially available and tested base isolation devices to limit the damaging seismic forces on the structure, and to maintain post-earthquake serviceability of critical existing and new structures.

5. Provide adequate anchorage between building and foundation—properly designed and detailed anchorage systems can have good ductility and absorb considerable energy without breaking.
6. Provide adequate reinforcing steel and confinement reinforcement in concrete and masonry members to assure ductile behavior under high seismic forces.
7. Design and detail steel members and connections to avoid local and global buckling, rupturing of welds and brittle fracture.

Good detailing practices are covered in the Building Codes, the provisions of Building Code requirements for Reinforced Concrete (ACI 318-95) and commentary, and the AISC LRFD Design Manual.

Risk Mitigation. Two most important lessons from recent major earthquakes in the United States and around the world are (1) thousands of nonductile buildings were damaged or collapsed, and (2) surface faulting ruptured lifelines, buildings, bridges and other critical facilities constructed over or across a fault. Nonductile structures, such as unreinforced masonry buildings, inadequately reinforced concrete buildings are prone to catastrophic failures. There is a large inventory of nonductile structures in the high seismicity regions in the United States. Surface faulting has caused some spectacular rupturing or fracturing of buildings, bridges and dams as evidenced in recent earthquakes in Turkey and Taiwan. The civil and structural engineers must work with governmental agencies to identify these failure-prone structures and take necessary actions to mitigate the risk.

In California the Alquist-Priolo Earthquake Fault Zoning Act was passed in 1972 to mitigate the hazard of surface faulting to structures for human occupancy. This state law was a direct result of the 1971 San Fernando Earthquake, which was associated with extensive surface fault ruptures that damaged numerous homes, commercial buildings, and other structures. The main purpose of the Act is to prevent the construction of structures used for human occupancy on the surface trace of active faults. Surface rupture is the most easily avoided seismic hazard for new construction. For existing structures, the only mitigation is to relocate the structures. In 1990, the California Legisture passed the Seismic Hazards Mapping Act to address non-surface fault rupture earthquake hazards, including liquefaction and seismically induced landslides.

Utah is situated on the 240 mile-long Wasatch Fault, which has the potential of producing large earthquakes above magnitude 7.5. The highly populated areas of Salt Lake City, Ogden, and Provo lie on soft lake sediments that will shake violently during large earthquakes. The Wasatch Fault has not caused a powerful earthquake for the past 150 years. However, the people of Utah are aware of the threat of a catastrophic earthquake. They bond with the communities and public agencies to plan and take action to reduce loss of life and property in future earthquakes. For example, the historic Salt Lake City and County Building has been made safer from earthquakes by installing base isolation devices beneath this 101-year old unreinforced masonry structure. Utah has made major improvement in the public infrastructure to reduce seismic risk. At least 10 fire stations in Salt Lake City and 4 major hospitals have been strengthened or replaced with new earthquake-resistant structures. Over 400 public and private school buildings in the region have been evaluated for seismic resistance. Three high schools and one grade school have been strengthened or replaced.

Utah and California set the examples on what can and should be done to mitigate earthquake risk.

(J. M. Biggs, "Introduction to Structural Dynamics," and R. Clough and J. Penzien, "Dynamics of Structures," McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); E. Rosenblueth, "Design of Earthquake-Resistant Structures," John Wiley & Sons, Inc., New York (www.wiley.com); N. M. Newmark and E. Rosenblueth, "Fundamentals of Earthquake Engineering," Prentice-Hall, Inc., Englewood Cliffs, N.J. (www.prenhall.com); S. Okamoto, "Introduction to Earthquake Engineering," John Wiley & Sons, Inc., New York (www.wiley.com).)

15.5 Factored Loads

Structural members must be designed with sufficient capacity to sustain without excessive deformation or failure those combinations of service loads that will produce the most unfavorable effects. Also, the effects of such conditions as ponding of water on roofs, saturation of soils, settlement, and dimensional changes must be included. In determination of the structural capacity of a member or structure, a safety margin must be provided and the possibility of variations of material properties from assumed design values and of inexactness of capacity calculations must be taken into account.

Building codes may permit either of two methods, allowable-stress design or load-and-resistance factor design (also known as ultimate-strength design), to be used for a structural member. In both methods, design loads, which determine the required structural capacity, are calculated by multiplying combinations of service loads by factors. Different factors are applied to the various possible load combinations in accordance with the probability of occurrence of the loads.

In allowable-stress design, required capacity is usually determined by the load combination that causes severe cracking or excessive deformation. For the purpose, dead, live, wind, seismic, snow, and other loads that may be imposed simultaneously are added together, then multiplied by a factor equal to or less than 1. Load combinations usually considered in allowable-stress design are:

$$(1)\ D\quad (2)\ D+G\quad (3)\ D+(W \text{ or } E)$$
$$(4)\ D+G+(W+E)$$

where D = dead load

$G = L + L$, or $L + S$ or $L + R$

L = live loads due to intended use of occupancy, including partitions

L_r = roof live loads

S = snow loads

R = rain loads

W = wind loads

E = effect of horizontal and vertical seismic loads = $\pm Q + 0.5ZD$

Q = effect of horizontal earthquake-induced forces

Z = seismic intensity coefficient defined for Eq. (15.4)

Building codes usually permit a smaller factor when the probability is small that combinations of extreme loads, such as dead load plus maximum live load plus maximum wind or seismic forces, will occur. Generally, for example, a factor of 0.75 is applied to load-combination sums (3) and (4) and 0.66 when dimensional changes are added to (4). Such factors are equivalent to permitting higher allowable unit stresses for the applicable loading conditions than for load combinations (1) and (2), for which the allowable stress is obtained by dividing by a safety factor more than unity the unit stress causing excessive deformation or failure.

In ultimate-strength design, the various types of loads are each multiplied by a load factor, the value of which is selected in accordance with the probability of occurrence of each type of load. The factored loads are then added to obtain the total load a member or system must sustain. A structural member is selected to provide a load-carrying capacity exceeding that sum. This capacity is determined by multiplying the ultimate-load capacity by a resistance factor, the value of which reflects the reliability of the estimate of capacity. Load combinations that may be used in the absence of local building code revisions are as follows:

1. $1.4D$
2. $1.2D + 1.6L + 0.5(L_r \text{ or } S \text{ or } R)$
3. $1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (0.5L \text{ or } 0.8W)$
4. $1.2D + 1.3W + 0.5G$
5. $1.2D + 1.0E + 0.5L + 0.2S$
6. $0.9D - (1.3W \text{ or } 1.0E')$

where E' = effect of horizontal and vertical seismic forces = $\pm Q - 0.5ZD$. For garages, places of public assembly, and areas for which live loads exceed 100 lb/ft^2, the load factor usually is taken as unity for L in combinations 3, 4, and 5. The load factor should be taken as 1.3 for liquid loads, 1.6 for loads from soils, and 1.2 for ponding loads, forces due to differential settlement, and restraining forces due to prevention of dimensional changes. The recommended load factors recognize the greater certainty of the magnitude of dead loads but provide a larger safety factor against overloads due to dead loads alone.

15.6 Modular Measure

This is a dimensioning system for building components and equipment to permit them to be field-assembled without cutting. The basic unit is a 4-in cube. Thus, buildings may be laid out around a continuous, three-dimensional rectangular grid with 4-in spacing (Fig. 15.3*a*).

Manufacturers make many building materials and some installed equipment to correspond to this module. The grid is a convenient tool for drawing assemblies of building products, be they modular or nonmodular.

Modular building products are assigned nominal dimensions corresponding to an even number of modules, although the actual dimensions may be slightly less to allow for joints. Nominal masonry dimensions, for example, equal the dimensions of a unit plus the thickness of one mortar joint. (Standard joint thickness is $\frac{3}{8}$ in for concrete block; $\frac{1}{2}$ in for clay backup and structural units; $\frac{3}{8}$ or $\frac{1}{2}$ in for brick; and $\frac{1}{4}$ in for salt-glazed, clear-glazed, and ceramic-glazed facing units.)

When preparing drawings, the designer can use the grid for both small-scale plans and large-scale details. At scales less than $\frac{3}{4}$ in = 1 ft, however, it is not practical to show grid lines at 4-in spacing. The designer should select a larger planning module that is a multiple of 4 in. For floor plans and elevations, for example, the module may be 2 ft 8 in, 4 ft, 5 ft, 6 ft 4 in, and so on. Materials should be shown actual size or to scale and located on or related to a grid line by a reference dimension. Dimensions on grid lines are shown by arrows; those not on grid lines, by dots (Fig. 15.3*b*).

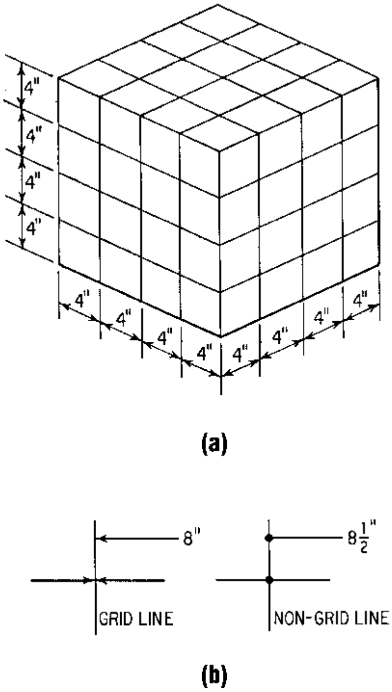


Fig. 15.3 Elements of modular measure.

15.7 Structural Systems

Foundations for buildings should be selected and designed in accordance with the principles given in Sec. 7. Basic principles for superstructure design are given in Secs. 6 and 8 to 11.

Buildings may have load-bearing-wall construction, skeleton framing, or a combination of the two. Generally, the engineer's responsibility is to select that type of construction that will serve the owner's total needs most economically. Thus, the most economical construction may not necessarily be the one that requires the least structural materials, or even the one that also has the lowest fabrication and erection costs. Architectural, mechanical, electrical, and other costs that may be affected by the structural system must be considered in any cost comparison.

Because of the large number of variables, which change with time and location, the superiority of one type of construction over the others is difficult to demonstrate, even for a specific building at a given location and time. Availability of materials and familiarity of contractors with required construction methods, or their willingness to take on a job, are important factors that complicate the selection of a structural system still more. Consequently, engineers should consider the specific conditions for each building in selecting the structural system.

Also, deciding on the spans to be used is no simple matter. Foundations, column or wall height, live load, bracing, and provisions for ducts and piping vary with each building and must be taken into account, along with the factors previously mentioned. It is possible, however, to standardize designs for simple buildings, such as one-story warehouses or factories, and determine the most economical arrangement and spans of structural components. But such designs should be reviewed and updated periodically because changing conditions, such as the introduction of new materials, new shapes, or new construction methods and price revisions, could change the economic balance.

Engineers also should bear in mind that the relative economics of a structural system can be improved if it can be made to serve more than just structural purposes. Money is saved if a facade also carries loads or if a structural slab is both floor and ceiling and also serves as air conditioning ducts.

Load-bearing wood walls frequently are used for one- and two-story houses. They usually consist of 2 × 4-in studs spaced 24 or 16 in c to c and set with wide faces perpendicular to the face of the wall. The walls have top and bottom plates, each consisting of two 2 × 4's. Unless supported laterally by adequate framing, maximum height of such a wall is 15 ft. Lumber or plywood sheathes the exterior; plaster or wallboard is placed on the interior. (N. L. Burbank and C. Phelps, "House Carpentry Simplified," McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com).)

Load-bearing masonry walls have been used for buildings 10 or more stories high. But unless design is based on rational engineering analysis instead of empirical requirements, thickness required at the base is very large. Some building codes require plain masonry bearing walls to have a minimum thickness of 12 in for the top 35 ft and to increase in thickness 4 in for each successive 35 ft down. Thus, walls for a 20-story building would have to be about 3 ft thick at the bottom.

Since thickness must be increased from the top down, a natural shape in vertical cross section for load-bearing masonry walls is trapezoidal. With the widest section at the bottom, such a shape is good for resisting overturning. In practice, however, the exterior wall face usually is kept plumb and the inside face is stepped where thickness must be increased.

In low buildings, minimum wall thickness may be governed by the ratio of unsupported wall height or length to thickness, whichever ratio is smaller. (For cavity walls, thickness is the sum of the nominal thickness of inner and outer wythes.) Usually, bearing-wall thickness must be at least 6 in; check the local building code. (See also Art. 15.2.)

Much thinner walls can be used with steel-reinforced masonry designed in accordance with Building Code Requirements for "Masonry Structure," Brick Industry Association, Reston, Va. ("Recommended Practice for Engineered Brick Masonry," Brick Industry Association, Reston, Va.; F. S. Merritt, "Building Design and Construction Handbook," 6th ed.; McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com).)

Load-bearing reinforced concrete walls may be much thinner than masonry for a given height. The American Concrete Institute Building Code Requirements for Reinforced Concrete (ACI 318-86) sets for superstructure walls a minimum thickness of at least $\frac{1}{25}$ the unsupported height or length, but not less than 4 in. Thickness of exterior basement walls and foundations, however, should be at least $7\frac{1}{2}$ in.

Load-bearing walls may be used for the exterior, partitions, wind bracing, and service-core enclosure. For these purposes, masonry has the disadvantage when used in combinations with skeleton framing of being erected more slowly. Thus, there may be delays in erection of the framing while masonry is being placed to support it.

When **load-bearing partitions** can be placed at relatively short intervals across the width of a building, curtain walls can be used on the exterior along the length of the building. Such partitions, together with flat-plate reinforced concrete floors (Fig. 15.4), make an efficient structural system for certain types of buildings, such as multistory apartment houses. In such buildings also, concrete walls around closets can double as columns.

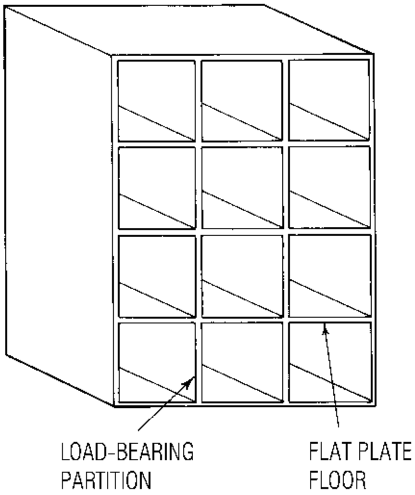


Fig. 15.4 Load-bearing partitions support flat-plate floors in an apartment building.

Load-bearing walls may serve as shear walls. (But unless they are relatively long, bending stresses due to lateral forces acting parallel to the walls may be large.) Thus, the walls, if properly arranged, will resist wind and earthquake forces in shear and bending. For example, in Fig. 15.5*a*, shear walls placed at the ends of the building may be designed to resist lateral forces in the narrow direction. In Fig. 15.5*b*, perpendicular shear walls can take lateral forces from all directions since the forces can be resolved into components parallel to the walls. In Fig. 15.5*c*, walls enclosing stairs, elevators, toilets, and service rooms (**service core**) may serve as shear walls in perpendicular directions. For earthquake forces, however, it is desirable to supplement the shear walls with a ductile, moment-resisting space frame, to prevent sudden collapse if a shear wall should fail.

Load-bearing service-core walls can be designed, however, to carry all the loads in a building. In that case, the roof and floors cantilever from the walls (Fig. 15.6*a*). When spans are large, cantilevers become uneconomical. Instead, columns may assist the service-core walls in carrying the vertical loads (Fig. 15.6*b*). As an alternative, the outer ends of the floors may be suspended from roof trusses, which are supported on but cantilever beyond the core walls (Fig. 15.6*c*). Other possibilities include service cores in pairs with floors supported between them, on girders, trusses, cables, or arches or combinations of these.

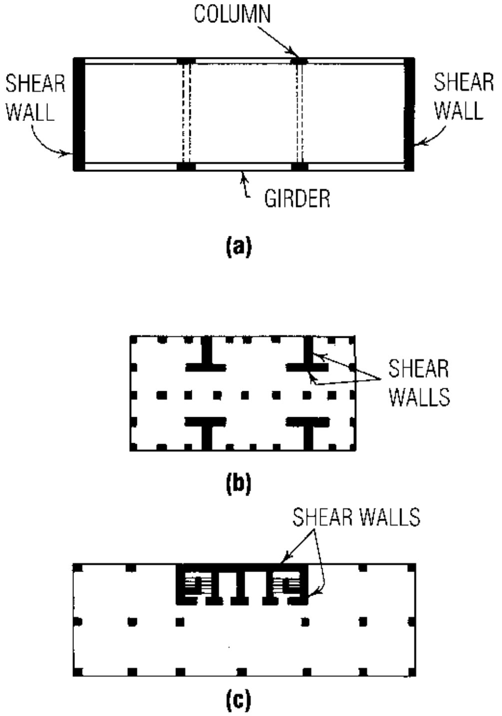


Fig. 15.5 Arrangements of shear walls for resisting lateral forces.

Architectural-structural walls represent a type of exterior construction somewhere between load-bearing walls and skeleton framing with curtain walls. The load-bearing elements in architectural-structural walls are linear, as in skeleton framing, rather than planar, as in load-bearing walls, and their function is clearly expressed architecturally. Spaces between the structural elements may be screens or curtains, or glass. The structural elements may lie on diagonal lines or verticals (Fig. 15.6*d*); they may be cross-shaped, combining columns and spandrels (Fig. 15.6*e*); they may be horizontal or vertical Vierendeel trusses (Fig. 15.6*f*); or they may be any other system that is structurally sound.

In **skeleton framing**, columns carry building loads to the foundations. Lateral forces are resisted by the columns and diagonal bracing or by rigid-frame action.

Floor and roof construction are much the same for skeleton and load-bearing construction. One principal component is a horizontal structural slab or deck. The deck underside may serve as or carry a ceiling. The upper surface may serve as or carry a wearing surface for traffic or weatherproofing. The deck may be solid, or it may be hollow to reduce weight, permit pipe and wiring to pass through, and serve as air ducts. When the deck does not transmit its loads directly to columns, as it does in flat-slab and flat-plate construction, other major components of floor and roof systems are trusses, beams, and girders (sometimes also called joists, purlins, or rafters, depending on arrangement and location). These support the deck and transmit the load to the columns.

Flat-plate construction employs a deck with constant thickness in each bay and transmits the load directly to columns. It generally is economical for residential and other lightly loaded structures, where spans are fairly short. It is used for *lift-slab construction*, in which the concrete slabs are cast on the ground, then raised to final position by jacks set on the columns. For longer spans, a waffle or two-way ribbed plate may be used.

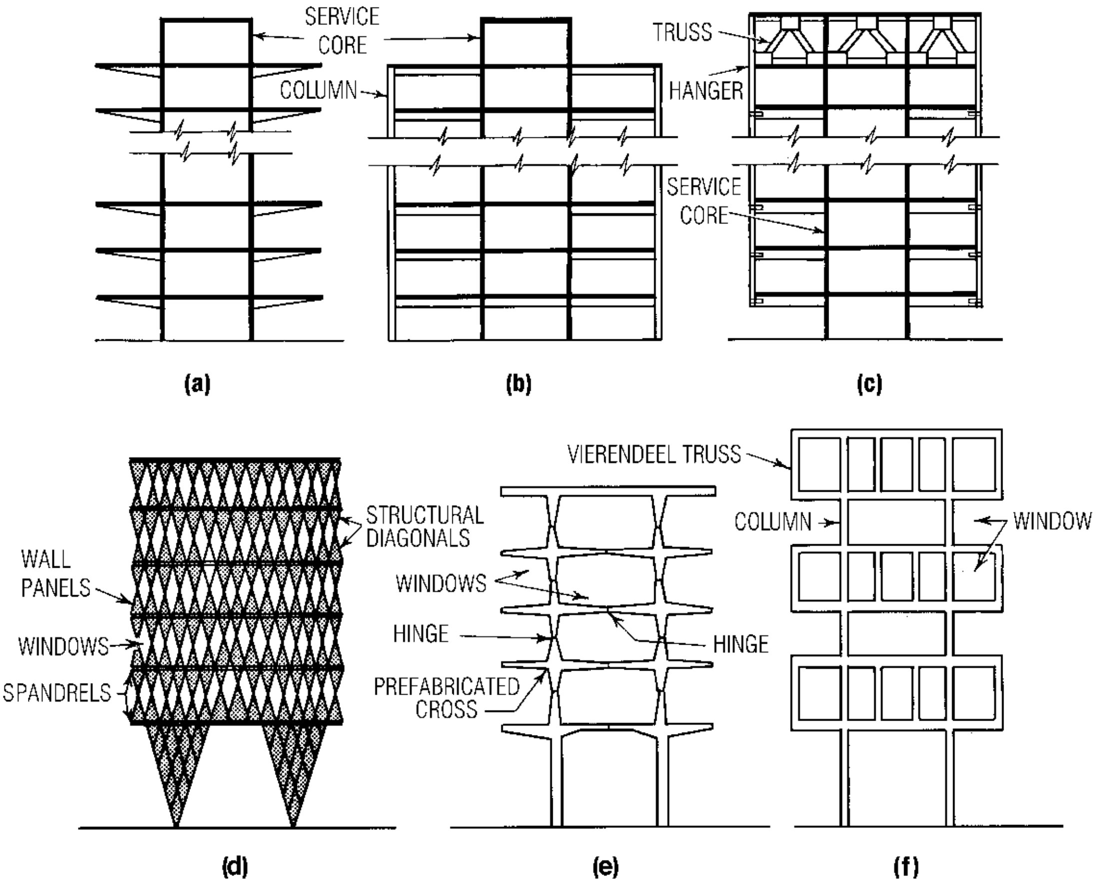


Fig. 15.6 (*a*), (*b*), (*c*)—Framing arranged to place all, or nearly all, loads on service-core walls; (*d*), (*e*), (*f*)—Examples of architectural-structural walls.

Flat-slab reinforced concrete construction may be more suitable for heavier loads. Also transmitting loads directly to columns, it differs from flat-plate in that the slab is thickened in the region around the columns (*drop panels*). Often too, the columns flare at the top (*capitals*). Waffle construction may be used for longer spans.

Slab-band construction is a variation of flat-plate and flat-slab in which wide, shallow beams are used to support the slab and transmit loads to the columns.

Two-way slabs are another variation; they are supported on girders spanning between columns along the border of each bay. Thus, longer spans and heavier loads can be supported more economically.

Beam-and-girder construction is economical for a wide range of conditions. In one- and two-story houses, wood joists or rafters spaced 16 or 24 in c to c generally are used on short spans in conjunction with lumber or plywood decking. For other lightly loaded structures, open-web steel joists, light, rolled-steel beams, or precast-concrete plank may be used, with wood or concrete floors. For heavier loads and longer spans, one-way ribbed-concrete slabs and girders (metal-pan construction); prestressed-concrete plank, tees, double tees, or girders; reinforced concrete beams and girders; laminated-wood girders; or structural-steel beams and girders, including steel-concrete composite construction, may be more suitable. For still longer spans, as usually is the case in industrial buildings, beams and trusses may be most economical.

Arches and catenary construction are appropriate for very long spans. Usually, they are used to support roofs of hangars, stadiums, auditoriums, railroad terminals, and exhibition halls. Their design must provide a means of resisting the horizontal thrust of their reactions.

Thin-shell construction is suitable for uniform loading where curved surfaces are permissible or desirable. It is economical for very long spans. **Folded-plate construction** often is an economic alternative.

(F. S. Merritt, "Building Design and Construction Handbook," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); F. S. Merritt and J. Ambrose, "Building Engineering and Systems Design," Van Nostrand Reinhold Company, New York.)

15.8 Lateral-Force Bracing

No structural system is complete unless it transmits all forces acting on it into adequate support in the ground. Hence, provision must be made in both low and tall buildings to carry into the foundations not only vertical loads but lateral forces, such as those from wind and earthquake. Also, the possibilities of blast loading and collision with vehicles must be considered. Without adequate provision for resisting lateral forces, buildings may be so unstable that they may collapse during or after construction under loads considerably less than the full design wind or seismic loads.

Low Wood Buildings ▪ In wood-frame houses one and two stories high, plywood or diagonal lumber sheathing may provide adequate resistance to lateral forces if it is properly nailed and glued. With diagonal lumber, each board should be nailed with two nails to every stud it crosses. Plywood $\frac{5}{8}$ in thick should be nailed with 8d common nails, 6 in c to c; $\frac{1}{4}$ in thick, with 6d nails, 3 in c to c. With other types of sheathing, it is advisable to brace the frame with diagonal studs, especially at end corners of the outside walls and important intermediate corners.

Rigid Frames ▪ Buildings of reinforced concrete beam-and-girder construction generally are designed as rigid frames, capable of taking lateral forces. Except possibly for tall structures subjected to severe earthquakes, rarely does additional provision have to be made for bracing against lateral forces. Tall flat-plate buildings also may be designed as rigid frames to resist wind. If the height-width ratio is large, wind resistance can be improved at relatively low cost by placing wings perpendicular or nearly so to the main portion, so that there are rigid frames with several bays parallel to the directions in which wind-force components may be resolved. Thus, the buildings may be made T-shaped, H-shaped, or cross-shaped in plan, or may have V-shaped wings at the ends. Alternatively, buildings may be curved in plan to improve wind resistance.

Shear Walls ▪ When it is impractical to rely on a moment-resisting space frame to take 100% of the lateral forces, shear walls can be used to take all or part of them. Made of structural-steel plates or reinforced brick or concrete, such walls should be long enough parallel to the wind that bending stresses are within the allowable for the concrete and steel. As shown in Fig. 15.5, shear walls may be placed parallel to the narrow width of the building and rigid frames used in the longitudinal direction, or perpendicular shear walls may take lateral forces from any direction, or service-core walls may double as shear walls (Art. 15.7). The floors should be designed to act as diaphragms or adequate horizontal bracing should be provided to ensure transfer of horizontal forces to the walls. For wind loads, provision must be made to brace exterior walls and transmit the loads from them to the floors. Walls should be adequately anchored to floors and roofs to prevent separation by wind suction or seismic forces.

In areas subjected to severe earthquakes, it is advisable that shear walls be supplemented by ductile, moment-resisting space frames, to prevent sudden collapse if the walls should fail.

Braced Frames ▪ Another method of resisting lateral forces is to use diagonal bracing. Frames that are X-braced generally are stiffer than similar frames relying solely on rigid-frame action.

Roof trusses should be braced against horizontal forces since the spans usually are long and roof decks are made of light material. Additional horizontal and vertical trusses may be used for the purpose. Also, the framework in the plane of the trusses may be stiffened by inserting knee braces between the columns supporting the trusses and the bottom chord. Purlins carrying the roof deck should be securely fastened to the top chords, which are in compression, to brace them laterally.

Trussed roof bracing may be placed in the plane of the top or bottom chords. Putting it in the plane of the top chords offers the advantages of simpler details, shorter unsupported length of diagonals, and less sagging of bracing because it can be connected to the purlins at all intersections. Bracing both top and bottom chords with separate truss systems seldom is necessary. But the bottom chord should be braced at frequent intervals, even though it is a tension member, to reduce its unsupported length.

Figure 15.7 illustrates typical bracing for a mill-building roof. Diagonal bracing is placed in the plane of the top chord in three bays, assuming that the purlins will be sufficiently well-connected to the trusses to transmit longitudinal forces from the unbraced trusses to the braced bays. Not more than five unbraced bays should be permitted between braced trusses. Struts are shown between lower chords at every panel point, but for a long truss, the struts may be placed at alternate panel points. At corresponding top-chord panel points, the purlins should be capable of carrying compressive forces in addition to vertical loading. The struts between the upper and lower chords should transmit longitudinal forces to the laterally braced bays, where cross frames are placed between the trusses in the plane of the struts, as indicated in Fig. 15.7, to prevent the trusses from tipping over.

Bracing the roof trusses, however, is not enough. The horizontal forces in the roof system must be brought to the ground. The designer must consider the building as a whole.

Figure 15.8 shows a simple bracing system to illustrate the principle. Wind forces on the windward long side of the building are transmitted to the leeward roof truss. This truss carries the loads to the ends of the building, where diagonals in the planes of the ends take the loads to the foundations. Wind on the ends is resisted by bracing in the side walls.

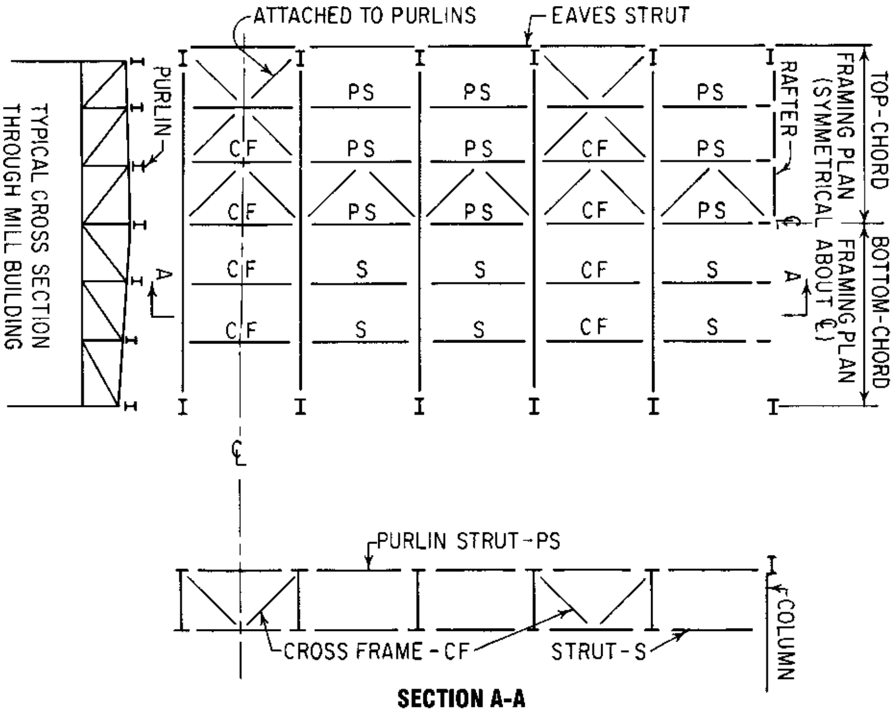


Fig. 15.7 Lateral bracing of roof trusses.

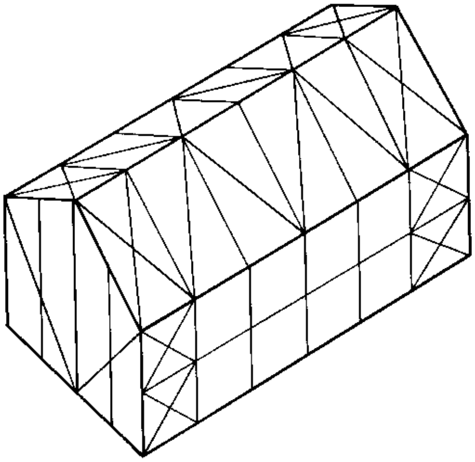


Fig. 15.8 X bracing carries lateral loads from roof to foundation.

Tall Buildings ▪ Similarly, when designing bracing for a tall building, the designer should consider the building as a whole. For example, lateral forces may be resisted by all the bents (Fig. 15.9*a*) or only the outer bents (Fig. 15.9*b*). In the latter case, the building may be designed as a hollow-tube cantilever for the horizontal forces. The floor and roof systems then must be capable of distributing the loads from the windward wall to the side and leeward walls.

For the bents individually, X bracing (Fig. 15.9*c*) is both efficient and economical. But it usually is impractical because it interferes with doors, windows, and clearance between floors and ceilings above. Generally, the only places X bracing can be installed in tall buildings are in walls without openings, such as elevator-shaft and fire-tower walls. When X bracing cannot be used, bracing that does not interfere with openings should be placed in each bent.

There are many alternatives to X bracing. One is knee bracing between girders and columns (Fig. 15.9*d*); but the braces may interfere with windows in exterior bents or may be objectionable in interior bents because they are unsightly or reduce floor-to-ceiling clearance. Portal framing of several types, including haunched, solid-web spandrels (Fig. 15.9*e*) or trusses, are other alternatives. At the columns, these members provide sufficient

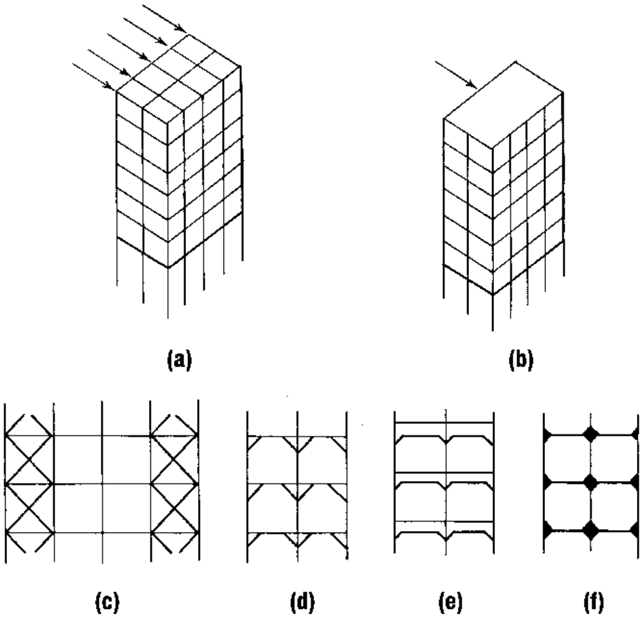


Fig. 15.9 Bracing for high-rise buildings: (*a*) All transverse bents resist lateral forces; (*b*) building acts as a vertical tube; (*c*) bent with X bracing; (*d*) knee bracing between columns and girders; (*e*) haunched spandrels; (*f*) moment-resisting connections between columns and girders.

depth for moment resistance, but at a short distance away from the columns, they become shallow enough to clear windows and doors. In exterior bents, the spandrels can extend from the window head in one story to the window sill in the story above. In interior bents, however, they may have the same disadvantages as knee braces.

Another alternative to diagonal bracing for tall buildings is moment-resisting or wind connections of the bracket type (Fig. 15.9*f*). Different types may be used, depending on size of members, magnitude of wind moment, and compactness needed to satisfy floor-to-ceiling clearance. In steel framing, the minimum type consists of angles attached to the columns and to top and bottom girder flanges. Plates welded to both girder flanges and butt-welded to the columns are an alternative. When greater moment resistance is needed, the angles may be replaced by tees (made by splitting a wide-flange beam at middepth). Also, the bottom flange may be seated on a beam-stub bracket.

The continuous rigid frames formed with these connections can be analyzed by the methods of Arts. 6.58 to 6.65. For preliminary design or to check computer programs, however, approximate methods may be used (Arts. 15.9 and 15.10).

It is noteworthy that for most buildings even the "exact" methods are not exact. First, the forces are not static loads but generally dynamic; they are uncertain in intensity, direction, and duration. Also, at the beginning of a design, the sizes of members are not known, so the exact resistance to lateral deformation cannot be calculated. Furthermore, floors, walls, and partitions help resist the lateral forces in a very uncertain way.

(F. S. Merritt, "Building Design and Construction Handbook," 6th ed., B. S. Taranath, "Structural Analysis and Design of Tall Buildings," McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com).)

15.9 Portal Method

Since, as pointed out in Art. 15.8, an exact analysis of stresses due to lateral forces on a tall building is impractical, most designers prefer a wind-analysis method based on reasonable assumptions and requiring a minimum of calculations. One such method is the so-called portal method, which is based on the assumptions that points of inflection occur at the midpoints of all members and that exterior columns take half as much shear as do interior columns. These assumptions enable all moments and shears to be computed by the laws of statics.

Consider, for example, the roof level (Fig. 15.10*a*) of a tall building. A wind load of 600 lb is assumed to act at the top line of girders. To apply the portal method, cut the building frame along a section through the inflection points of the top-story columns. These points of zero moment are assumed here to be at the column midpoints, 6 ft down from the top of the building. (Some designers prefer to take the top-story inflection points one-third the story height down from the roof girders because the sum of the stiffnesses of the members at each roof joint is likely to be much less than that at each joint in the story below. Similarly, they assume inflection points in the bottom story to be two-thirds the story height up from the base because the anchorage tends to fix the base.) Now, let us compute the stresses in the members above the section.

Since the exterior columns take only half as much shear as do the interior columns, 100 lb of the total 600-lb load is apportioned to each exterior column and 200 lb to each interior column. The moments at the top of the columns equal these shears times the distance from the top to the inflection point. The wall end of the end girders carries a moment equal to that in the exterior column. (At the floor below, as indicated in Fig. 15.10*b*, the end girder carries a moment equal to the sum of the column moments.) Since the inflection point in the girder is at the midpoint, the moment at the inner end of the girder must be the same as the outer end. The moment in the adjoining girder can be found by subtracting the end-girder moment from the column moment because the sum of the moments at the joint must be zero. (At the floor below, as shown in Fig. 15.10*b*, the moment in the interior girder is found by subtracting the moment in the end girder from the sum of the column moments.)

Girder shears then can be computed by dividing girder moments by the half span. When these shears have been found, column loads can be easily calculated from the fact that the sum of the vertical loads must be zero, by taking a section around each joint through column and girder inflection points. As a check, it should be noted that the column loads produce a moment that must be equal to the sum of the moments of the wind loads above the section for which the column loads were

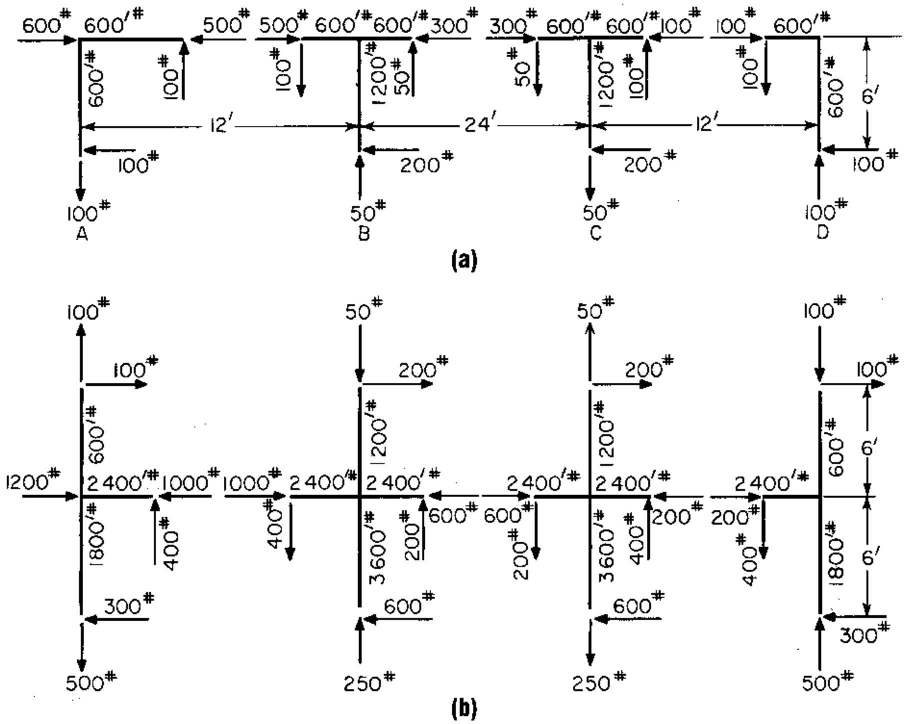


Fig. 15.10 Wind stresses in a tall building computed by the portal method.

computed. For the roof level section (Fig. 15.10*a*), for example, $-50 \times 24 + 100 \times 48 = 600 \times 6$.

See also Art. 15.10. (C. H. Norris et al., "Elementary Structural Analysis," 3rd ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com).)

15.10 Cantilever Method

This is an alternative to the portal method described in Art. 15.9 for determining stresses in tall buildings due to lateral forces. Basic assumptions are that inflection points are at the midpoints of all members and that direct stress in a column is proportional to its distance from the center of gravity of all the columns in the bent. The assumptions are sufficient to enable shears, axial forces in the columns, and moments in the frame to be determined from the laws of statics.

For multistory buildings with height-to-width ratio of 4 or more, the Spurr modification is recommended ("Welded Tier Buildings," U.S. Steel Corp.). In this method, the moments of inertia of the girders at each level are made proportional to the girder shears when the spans are equal; otherwise, the moments of inertia must also be proportional to the square of the spans.

The results obtained from the cantilever method generally will be different from those obtained from the portal method. In general, neither solution is correct, but the answers provide a reasonable estimate of the resistance to be provided against lateral forces. In buildings over about 25 stories high, the effects of changes in column lengths should be considered in the analysis. (See also *Transactions of the American Society of Civil Engineers*, vol. 105, pp. 1713–1739, 1940; vol. 126, pp. 1124–1198, 1961.)

15.11 Floor Coverings

When concrete is used as the structural deck in a building, it may be left exposed to serve as a wearing surface, depending on the quality of surface and the type of occupancy. This is generally done in warehouses and industrial buildings with heavy moving loads. Some engineers, however, prefer to place a higher-quality topping on the structural concrete slab. The topping may be applied before or after the base slab has hardened. Usually, integral toppings are ½ in thick, independent toppings about 1 in ("Finishing Concrete Slabs with Color and Texture," SS391, Portland Cement Association, Skokie, Ill (www.portcement.org). In office buildings where electricity and telephone wiring are distributed above the structural slab, a lightweight concrete fill covers the conduit and a floor covering protects the fill.

Wood floors may be made of the hardwoods—maple, beech, birch, oak, or pecan; or of the softwoods—yellow pine, Douglas fir, or western hemlock. The hardwoods are more resistant to wear and indentation. Solid-unit wood blocks are made from two or more units of strip-wood flooring fastened together with metal splines or other suitable devices. The tongued-and-grooved blocks are held in place with nails or an asphalt adhesive. Also, a laminated block is formed with plywood. Average moisture content of wood flooring at time of installation should be 6% in the dry southern states, 10% in damp southern coastal states, and 7% in the rest of the United States ("Moisture Content of Wood in Use," *U.S. Forest Products Laboratory Publication* 1655, Madison, Wis.). Leave at least 1 in of expansion space at walls and columns.

Asphalt tiles, composed of reinforcing fibers, mineral coloring pigments, and inert fillers with asphalt as the binder, are intended for use on rigid subfloors. They may be used on below-grade concrete subject to slight moisture from the ground.

Cork tile is made by baking cork granules with phenolic or other resin binders under pressure. It yields a surface suitable for areas where quiet and comfort are of utmost importance. It is intended for use on rigid subfloors above grade and free of moisture. Cork tile with natural finish should be sanded to level, sealed, and waxed immediately after installation. All cork floors must be maintained with sealers and protective coatings to prevent soiling.

Unbacked vinyl flooring, for use on rigid subfloors above grade, is made of polyvinyl chloride resin as a binder, plasticizers, stabilizers, extenders, inert fillers, and coloring pigments. Resilient under foot, it can withstand heavy loads without indentation but is easily scuffed and scratched unless protected with a floor polish. It is practically unaffected by grease, fat, oils, household cleaners, or solvents.

Vinyl also may be laminated to various backing materials.

Rubber flooring generally is intended for use on rigid subfloors above grade. It is resilient and has excellent resistance to permanent deformation under load.

Linoleum is made from drying oils, such as linseed, natural and synthetic resins, a filler, and pigments similar to those used in paints. Usually, it is backed with burlap or rag felt. Since the backing is susceptible to moisture and fungus attack, linoleum should not be used for floors where moisture can reach the backing. Properly maintained, it performs outstandingly on rigid subfloors above grade in residential and commercial buildings.

Since protection from moisture is a prime consideration for most thin floor coverings, moisture within a concrete slab must be brought to a low level before installation of the flooring begins. Moisture barriers should be placed under concrete slabs at or below grade, and a minimum of 30 days drying time should be allowed after concrete placement before installing the flooring. A longer drying time should be allowed for lightweight concrete.

Adhesives ▪ Concrete surfaces to receive adhesive-applied thin flooring should be smooth. A troweled-on underlayment of rubber latex composition or asphalt mastic should be used over rough floors. Usually, the adhesive for asphalt and vinyl-asbestos tiles is an emulsion or cutback asphalt; for rubber and vinyl above grade, latex; for linoleum, cork, and vinyl backed with felt, linoleum paste; for laminated or solid wood block, hot-melt or cutback asphalt; for vinyl backed with asbestos felt, latex on concrete and linoleum paste on plywood and hardboard. Laminated wood blocks also may be set with a rubber-base adhesive.

Ceramic Tiles ▪ These generally are bonded to the subfloor with portland cement mortar (see American National Standards Institute "Standard Specifications for the installation of Ceramic Tile," ANSI A108, A118, A136.1-19). For areas not subject to heavy traffic, concentrated loads, or excessive amounts of water, organic-adhesive thin setting beds may be used instead. Appearance and resistance to wear make ceramic tiles suitable for use in kitchens and bathrooms.

Ceramic mosaic tile is less than 6 in^2 in area. Paver tiles are larger, usually 3 × 3 to 6 × 6 in. Quarry tile is a denser product, highly resistant to freezing, abrasion, and moisture.

Terrazzo is a mosaic topping composed of 2 parts marble chips to 1 part portland cement, sometimes with color pigments, applied to concrete or steel decks. Rubber latex, epoxy, and polyesters are alternative matrix materials. The topping may be precast or cast in place. Sand cushion (floating) terrazzo, at least 3 in thick, is used where structural movement that might injure the topping is anticipated. When terrazzo is bonded to the under slab, the topping usually is at least 1¾ in thick; a monolithic topping may be ⅝ in thick.

(J. H. Callender, "Time-Saver Standards for Architectural Design Data," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com).)

15.12 Masonry Walls

Different design criteria are applied to masonry walls, depending on whether they are load-bearing or non-load-bearing. Minimum requirements for both types are given in "Building Code Requirements for Masonry," ACI 530-95/ASCE 5-95, and "Specifications for Masonry Structures," ACI 530.1-95/ASCE 6-95, American Concrete Institute and American Society of Civil Engineers.

Following are some terms most commonly encountered in masonry construction:

Architectural Terra Cotta ▪ (See Ceramic Veneer.)

Ashlar Masonry ▪ Masonry composed of rectangular units, usually larger in size than brick and properly bonded, having sawed, dressed, or squared beds. It is laid in mortar.

Bonder ▪ (See Header.)

Brick ▪ A rectangular masonry building unit, not less than 75% solid, made from burned clay, shale, or a mixture of these materials.

Buttress ▪ A bonded masonry column built as an integral part of a wall and decreasing in thickness from base to top, although never thinner than the wall. It is used to provide lateral stability to the wall.

Ceramic Veneer ▪ Hard-burned, non-load-bearing, clay building units, glazed or unglazed, plain or ornamental.

Chase ▪ A continuous recess in a wall to receive pipes, ducts, and conduits.

Collar Joint ▪ A vertical joint between wythes or a wythe and backup.

Column ▪ A compression member with width not exceeding four times the thickness, and with height more than three times the least lateral dimension.

Concrete Block ▪ A machine-formed masonry building unit composed of portland cement, aggregates, and water.

Coping ▪ A cap or finish on top of a wall, pier, chimney, or pilaster to prevent penetration of water to masonry below.

Corbel ▪ Successive courses of masonry projecting from the face of a wall to increase its thickness or to form a shelf or ledge.

Course ▪ A continuous horizontal layer of masonry units bonded together.

Cross-Sectional Area ▪ Net cross-sectional area of a masonry unit is the gross cross-sectional area minus the area of cores or cellular spaces. Gross cross-sectional area of scored units is determined to the outside of the scoring, but the cross-sectional area of the grooves is not deducted to obtain the net area.

Grout ▪ A mixture of cementitious material, fine aggregate, and sufficient water to produce pouring consistency without segregation of the constituents.

Grouted Masonry ▪ Masonry in which the interior joints are filled by pouring grout into them as the work progresses.

Header (Bonder) ▪ A brick or other masonry unit laid flat across a wall with end surface exposed, to bond two wythes.

Height of Wall ▪ Vertical distance from top of wall to foundation wall or other intermediate support.

Hollow Masonry Unit ▪ Masonry with net cross-sectional area in any plane parallel to the bearing surface less than 75% of its gross cross-sectional area measured in the same plane.

Masonry ▪ A built-up construction or combination of masonry units, such as clay brick, concrete block, or stone, bonded together with mortar or other cementitious material.

Mortar ▪ A plastic mixture of cementitious materials, fine aggregates, and water.

Partition ▪ An interior wall one story or less in height.

Pier ▪ An isolated column of masonry. A bearing wall not bonded at the sides into associated masonry is considered a pier when its horizontal dimension measured at right angles to the thickness does not exceed four times its thickness.

Pilaster ▪ A bonded or keyed column of masonry built as part of a wall and of uniform thickness throughout its height. It serves as a vertical beam, column, or both.

Rubble:

Coursed Rubble. Masonry composed of roughly shaped stones fitting approximately on level beds, well bonded and brought at vertical intervals to continuous level beds or courses.

Random Rubble. Masonry composed of roughly shaped stones, well bonded and brought at irregular intervals vertically to discontinuous but approximately level beds or courses.

Rough or Ordinary Rubble. Masonry composed of irregularly shaped stones laid without regularity of coursing, but well bonded.

Solid Masonry Unit ▪ A masonry unit with net cross-sectional area in every plane parallel to the bearing surface 75% or more of its gross cross-sectional area measured in the same plane.

Veneer ▪ A wythe securely attached to a wall but not considered as sharing load with or adding strength to it.

Wall ▪ Vertical or near-vertical construction for enclosing space or retaining earth or stored materials.

Bearing Wall. A wall that supports any vertical load in addition to its own weight.

Cavity Wall. (See Hollow Wall.)

Curtain Wall. A non-load-bearing exterior wall.

Faced Wall. A wall in which the masonry facing and backing are of different materials and so bonded as to exert a common reaction under load.

Hollow Wall. A wall of masonry so arranged as to provide an air space within the wall between the inner and outer wythes. A cavity wall is built of masonry units or plain concrete, or a combination of these materials, arranged to provide an air space within the wall, which may be filled with insulation, and in which inner and outer wythes are tied together with metal ties.

Nonbearing Wall. A wall that supports no vertical load other than its own weight.

Party Wall. A wall on an interior lot line used or adapted for joint service between two buildings.

Shear Wall. A wall that resists horizontal forces applied in the plane of the wall.

Spandrel Wall. An exterior curtain wall at the level of the outside floor beams in multistory buildings. It may extend from the head of the window below the floor to the sill of the window above.

Veneered Wall. A wall having a facing of masonry or other material securely attached to a backing, but not so bonded as to exert a common reaction under load.

Wythe ▪ Each continuous vertical section of a wall one masonry unit in thickness.

Materials used in masonry construction should be capable of meeting the requirements of the applicable standard of ASTM. For unit masonry, mortar should meet the requirements of ASTM Specifications C270 and C476. Mortars containing lime generally are preferred because of greater workability. Commonly used:

For concrete block, 1 part cement, 1 part lime putty, 5 to 6 parts sand

For rubble, 1 part cement, 1 to 2 parts lime hydrate or putty, 5 to 7 parts sand

For brick, 1 part cement, 1 part lime, 6 parts sand

For setting tile, 1 part cement, ½ part lime, 3 parts sand

Design of masonry structures should be based on elastic analysis, except that empirical design may be used for Seismic Zones 1 and 2 or where basic wind pressure is less than 25 psf, if no other lateral loads than wind or seismic loads are applied. Design should take into account the decrease in cross section and other weakening effects of embedding pipes and conduits in the masonry. Spacing should be at least three diameters center to center.

ACI 530-95/ASCE 5-95 sets the following requirements:

Masonry walls comprising two or more wythes, each wythe intended to resist individually the loads imposed on it (noncomposite action), should incorporate a cavity between the wythes, without headers, grout, or mortar. Width of the cavity should not exceed 4 in. The wythes should be connected by steel ties spaced not more than 16 in apart horizontally and vertically. Loads acting transversely to the plane of a wall should be distributed to each wythe in proportion to its relative stiffness.

Masonry walls designed for composite action of the wythes should have collar joints filled with mortar or grout or crossed by headers bonded to the wythes. For mortared collar joints, shear stresses between the wythes and collar joints or within headers should not exceed 5 psi; for grouted collar joints, these stresses should not exceed 10 psi. Headers should be embedded at least 3 in in each wythe and spaced uniformly over the wall. Total cross-sectional area of all the headers should be at least 4% of the wall surface area. Walls without headers should be bonded by steel ties, spaced not more than 36 in horizontally and 24 in vertically. At a minimum, one 9-gage tie should be used for every 2.67 ft^2 of wall surface, or one $\frac{3}{16}$-in-diameter tie for every 4.5 ft^2.

For resistance to wind and seismic loads, masonry walls should be anchored to floors and roofs that provide lateral support. Anchors should be embedded in reinforced bond beams or reinforced vertical cells and capable of resisting loads of at least 200 lb/lin ft of wall. Steel reinforcement should be incorporated both horizontally and vertically in the walls. Bearing walls should have a nominal thickness of at least 6 in.

Masonry columns should have a minimum nominal side dimension of at least 12 in for seismic resistance. The ratio of effective height to the smallest nominal side dimension should be 25 or less. Lateral ties at least ¼ in diameter should enclose longitudinal reinforcement bars in the columns. Spacing of the lateral ties should be less than 16 bar diameters, 48 tie diameters, and the smallest side dimension of the columns.

Empirical Design of Masonry Walls ▪ Where empirical design is permitted, bearing walls of one-story buildings may be only 6 in thick. Higher walls should be at least 8 in thick. Rubble stone walls, however, should be at least 16 in thick. Buildings using masonry walls to resist lateral loads should not be more than 35 ft high. If masonry shear walls are provided for lateral stability, they should be at least 8 in thick. Cumulative length of shear walls in any direction should be at least 40% of the long dimension of the building.

For lateral stability, solid or solid grouted, load-bearing masonry walls should have either a ratio of unsupported height to nominal thickness or a ratio of unsupported length to nominal thickness of 20 or less. For other types of load-bearing walls and exterior nonbearing walls, the ratio should not exceed 18. For interior nonbearing walls, the ratio should be 36 or less. Parapet walls should be at least 8 in thick. Their height should not exceed three times the thickness. Minimum thickness of foundation walls depends on the depth of unbalanced fill to be resisted. For example, walls 12 in thick are permitted a 6-ft depth for ungrouted hollow units, 7-ft depth for solid units, and 8-ft depth for fully grouted units.

Good Practice ▪ Backfill should not be placed against foundation walls until they have been braced to withstand horizontal pressure. Veneers should not be considered part of the wall when computing thickness for strength or stability.

When determining the unsupported length of walls, you may assume existing cross walls, piers, or buttresses as lateral supports if these members are well bonded or anchored to the walls and capable of transmitting the lateral forces to connected structural members or to the ground. When determining the unsupported height of walls, you may consider floors and roofs as lateral supports, if provision is made in the building to transmit the lateral forces to the ground. Ends of floor joists or beams bearing on masonry walls should be securely fastened to the walls. If lateral support of a partition depends on a ceiling, floor, or roof, the top of the partition should have adequate anchorage to transmit the forces. This anchorage may be accomplished with metal anchors or by keying the top of the partition to overhead work. Suspended ceilings may be considered as lateral support if ceilings and anchorages are capable of resisting a horizontal force of 200 lb/lin ft of wall.

Walls should not vary in thickness between lateral supports. When it is necessary to change thickness between floor levels to meet minimum thickness requirements, the greater thickness should be carried up to the next floor level. Where walls of hollow units or bonded hollow walls are decreased in thickness, a course of solid masonry should be interposed between the wall below and the thinner wall above, or else special units or construction should be used to transmit the loads between the walls of different thickness.

When two bearing walls intersect and the courses are built up together, the intersections should be bonded by laying in true bond at least half the units at the intersection. When the courses are carried up separately, the intersecting walls should be regularly toothed or blocked with 8-in maximum offsets. The joints should be provided with metal anchors having a minimum section of $\frac{1}{4} \times 1\frac{1}{2}$ in with ends bent up at least 2 in or with cross pins to form an anchorage. Such anchors should be at least 2 ft long and spaced not more than 4 ft apart.

(J. H. Matthys, "Masonry Designers' Guide," 3rd ed., The Masonry Society, 3970 Broadway, Ste 201D, Boulder, CO 80304-1135; F. S. Merritt, "Building Design and Construction Handbook," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); J. Ambrose, "Simplified Design of Masonry Structures," John Wiley & Sons, Inc., New York (www.wiley.com).)

15.13 Glass Block

Masonry walls of glass block may be used to control light that enters a building and to obtain better thermal and acoustic insulation than with ordinary glass panes. These units are hollow, $3\frac{7}{8}$ in thick by 6, 8, or 12 in square (actual length and height $\frac{1}{4}$ in less, for modular dimensioning). Faces of the units may be cut into prisms to direct light, or the block may be treated to diffuse light.

Glass block may serve as nonbearing walls or to fill openings in walls. Block so used should have a minimum thickness of $3\frac{1}{2}$ in at the joint. Also, surfaces of the block should be treated to permit satisfactory mortar bonding.

For exterior walls, glass-block panels should not have an unsupported area exceeding 144 ft^2. They should not be more than 25 ft long or more than 20 ft high between supports.

For interior walls, glass-block panels should not have an unsupported area of more than 250 ft^2. Neither length nor height should exceed 25 ft.

Exterior panels should be held in place in the wall opening to resist both internal and external wind pressures. The panels should be set in recesses at the jambs so as to provide a bearing surface at least 1 in wide along the edges. Panels more than 10 ft long also should be recessed at the head. (Some building codes, however, permit anchoring small panels in low buildings with noncorrodible perforated metal strips.) The sides and top, kept free of mortar and filled with resilient material, should permit expansion.

Mortar joints should be from $\frac{1}{4}$ to $\frac{3}{8}$ in thick. Steel reinforcement should be placed in the horizontal mortar joints at vertical intervals of 2 ft or less and should extend the full length of the joints. When splices are necessary, the reinforcement should be lapped at least 6 in. It should consist of two parallel longitudinal galvanized-steel wires. They should be No. 9 gage or larger, spaced 2 in apart, and having welded to them No. 14 or heavier gage cross wires at intervals of up to 8 in.

15.14 Curtain Walls

With skeleton-frame construction, exterior walls need carry no load other than their own weight. Their principal function is to keep wind and weather out of the building—hence the name curtain wall. Nonbearing walls may be supported on the structural frame of the building or projections from it, on supplementary framing (girts, for example) in turn supported on the structural frame, or on the floors.

Curtain walls need not be any thicker than required to serve their principal function. Many industrial buildings are enclosed only with light-gage metal. For structures with certain types of occupancies and for buildings close to others, however, fire resistance is an important characteristic; fire-resistance requirements in local building codes often govern when determining the thickness and type of material used for curtain walls.

In many types of buildings, it is desirable to have an exterior wall with good insulating properties. Sometimes, a dead air space is used for this purpose; sometimes, insulating material is incorporated into the wall or erected as a backup.

The exterior surface of a curtain wall should be made of a durable material, capable of lasting as long as the building. Maintenance should be a minimum; initial cost of the wall is not so important as the annual cost (amortized initial cost plus annual maintenance and repair costs).

Wood walls are used on one- and two-story buildings, generally with a wood frame. The frame may be sheathed on its outer sides with gypsum, lumber, or plywood and then a finish applied, or sheathing and siding can be combined in one unit. The exterior finish may be in the form of wood shingles, siding, half timbers, or plywood sheets.

Drop, or novelty, siding—tongued-and-grooved boards—is not considered a good finish for permanent structures. **Lap siding** or **clapboards** are better. These are beveled boards, thinner along one edge than the opposite edge, which are nailed over sheathing and building paper. Usually, narrow boards lap each other 1 in, wide boards more than 2 in. Normally, clapboards are installed with edges horizontal.

Half timbers may be used to form a structural frame of heavy horizontal, vertical, and diagonal members, the spaces between being filled with brick. This type of construction sometimes is imitated by nailing boards in a pattern similar to an ordinary sheathed frame and filling the spaces between boards with stucco.

Plywood for exterior use should be an exterior grade, with plies bonded with permanent waterproof glue. The curtain wall may consist of a single sheet of plywood or a sandwich of which plywood is a component. Also, plywood may be laminated to another material, such as a light-gage metal, to give it stiffness.

Stucco is an exterior wall finish applied like plaster and made of sand, portland cement, lime, and water. Two coats are applied to masonry, three coats on metal lath. The lath should be heavily galvanized. It should weigh 3.4 lb/yd^2 when supports are 16 in c to c and at least 2.5 lb with closely spaced furring. For the first coat, a common mix is 1 part portland cement, 1 part lime putty, and 5 or 6 parts sand. The second, or brown, coat may be based on lime or portland cement. With lime, the mix may be 1 part quicklime putty or hydrated lime putty and 3 parts sand by volume. With cement, the mix may be 1 part portland cement to 3 parts sand, plus lime putty in an amount equal to 15 to 25% of the volume of cement. The finish coat may have the same proportions as the brown coat. The brown coat may be applied as soon as the first, or scratch, coat has hardened, usually in 7 to 10 days. For the finish coat, it may be wise to wait several months, to let the building settle and the base coats shrink.

Metal siding may be used as curtain walls with or without insulating backup. Precautions should be taken to prevent water from penetrating between sheets. With corrugated sheeting, horizontal splices should lap about 4 in. Vertical splices should lap at least 1½ corrugations. Flat sheets may be installed in sash like window glass, or the splices may be covered with battens. Edges of metal sheets may be flanged to interlock and exclude wind and rain. Provision should be made in all cases for expansion and contraction with temperature changes.

In contrast to siding, in which a single material may form the complete wall, metal or glass sometimes is used as a facing and backed up with insulation, fire-resistant material, and an interior finish. The glass usually is tinted and held in a light frame in the same manner as window glass. Metal panels may be fastened similarly in a light frame, attached to mullions or other secondary framing members, anchored to brackets at each floor level, or connected to the structural frame of the building. The panels may be small and light enough for one person to carry or as high as one or two stories, prefabricated with windows. Provisions should be made for expansion and contraction and for prevention of moisture penetration at joints. Flashing and other details should be so arranged that should water penetrate the facing, it will drain to the outside.

Curtain walls also may be built of prefabricated panels consisting of an insulation core sandwiched between a thin, lightweight facing and backing. Such panels may be fastened in place in much the same manner as metal or glass facings. And the same precautions regarding expansion, contraction, and water penetration should be taken.

Metal curtain walls may be custom, commercial, or industrial. Custom-type walls are designed for a specific project, generally multistory buildings. Commercial-type walls are built up of parts standardized by manufacturers. Industrial-type walls comprise ribbed, fluted, or otherwise preformed metal sheets in stock sizes, standard metal sash, and insulation.

Metal curtain walls may be classified according to the methods used for field installation:

Stick Systems (Fig. 15.11*a*). Walls installed piece by piece. Each principal framing member, with windows and panels, is assembled in place separately (Fig. 15.11*b*). This type of system involves more parts and field joints than other types and is not so widely used.

Mullion-and-Panel Systems (Fig. 15.11*c*). Walls in which vertical supporting members (mullions) are erected first, and then wall units, usually incorporating windows (generally unglazed), are placed between them (Fig. 15-11*d*). Often, a cover strip is added to cap the vertical joint between units.

Panel Systems (Fig. 15-11*e*). Walls composed of factory-assembled units (generally unglazed) and

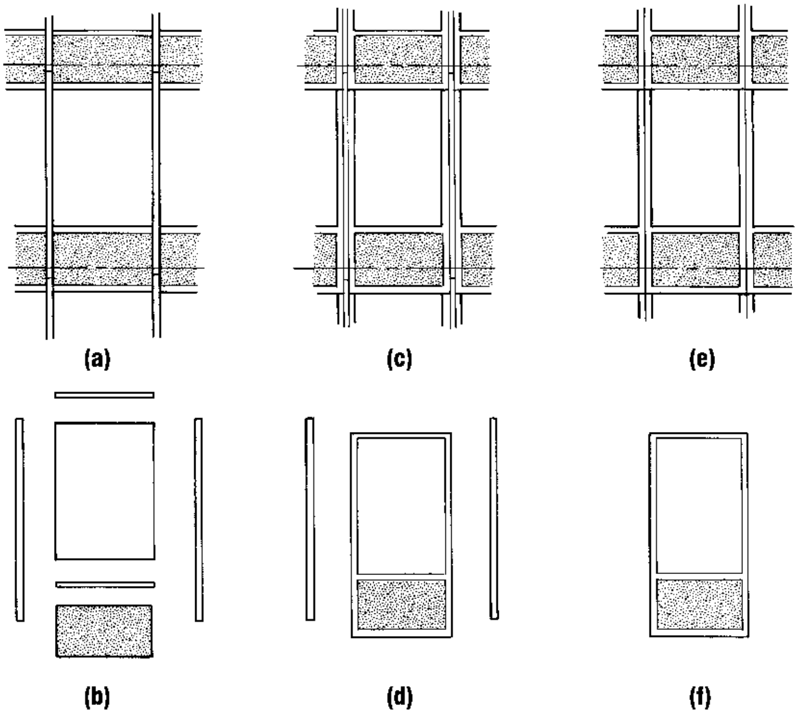


Fig. 15.11 Metal curtain walls: (*a*) Stick systems, which are installed piece by piece as shown in (*b*). Mullion-and-panel systems (*c*) have panels placed between verticals (*d*). Panel systems (*e*) come factory-assembled (*f*).

installed by connecting to anchors on the building frame and to each other (Fig. 15.11*f*). Units may be one or two stories high. This system requires fewer pieces and field joints than the other systems.

When mullions are used, it is customary to provide for horizontal movements of the wall at the mullions and, in multistory buildings, to accommodate vertical movement at each floor, or at alternate floors when two-story-high components are used. Common ways of providing for horizontal movements include use of split mullions, bellows mullions, batten mullions, and elastic structural gaskets. To permit vertical movement, mullions are spliced with a telescoping slip joint. When mullions are not used and wall panels are connected to each other along their vertical edges, the connection is generally made through deep flanges. With the bolts several inches from the face of the wall, movement is permitted by the flexibility of the flanges. Slotted holes are unreliable as a means of accommodating wall movement.

(W. F. Koppes, "Metal Curtain Wall Specifications Manual," National Association of Architectural Metal Manufacturers, 8 South Michigan A Suite 1000, Chicago, IL 60603 (www.naam.org); "Curtain Wall Handbook," U.S. Gypsum Co., Chicago, IL 60606; F. S. Merritt, "Building Design and Construction Handbook," 6th ed., and J. H. Callender, "Time-Saver Standards for Architectural Design Data," 6th ed., McGraw-Hill Publishing Company, New York (www.books.mcgraw-hill.com).

15.15 Partitions

Partitions are walls one story or less in height used to subdivide the interior space in buildings. They may be bearing or nonbearing walls.

Bearing partitions may be built of masonry or wood or light-gage steel studs. The masonry or studs may be faced with plaster, wallboard, plywood, wood boards, plastic, or other materials that meet functional and architectural requirements.

Nonbearing partitions may be permanently fixed in place, or temporary (movable) so that the walls can be easily shifted when desired. The temporary type includes folding partitions. Since the principal function is to separate space, construction and materials used vary widely. Partitions may be opaque or transparent, louvered or hollow or solid, extend from floor to ceiling or only partway, and may serve additionally as cabinets or closets or as a concealment for piping and electrical conduit. Fire resistance sometimes dictates the type of construction. Acoustic treatment may range from acoustic finishes on the surfaces to use of double walls separated completely by an air space or an insulating material.

Folding partitions, in a sense, are large doors. Depending on size and weight, they may be electrically or manually operated. They may be made of wood, light-gage metal, or synthetic fabric on a light collapsible frame. Provision should be made for framing and supporting them in a manner similar to that for large folding doors (Art. 15.18).

(F. S. Merritt, "Building Design and Construction Handbook," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com).)

15.16 Windows

Some building codes require that glass areas equal at least 10% of each room's floor area. But for many types of occupancy, it is good practice to provide glass areas in excess of 20%. Windows should be continuous and located as high as possible to lengthen the depth of light penetration. Continuous sash or one large window in a room gives better light distribution than separated narrow windows. Since windows also provide ventilation, the designer sometimes must compromise between locations, sizes, and arrangements of windows that give best lighting or best ventilation.

Window sash and frames generally are made of wood or metal. Fire-resistance requirements of building codes usually dictate use of metal.

White pine, sugar pine, ponderosa pine, fir, redwood, cedar, and cypress are used for exposed wood window parts because of their resistance to shrinkage and warping. A relatively hard wood should be used for the stiles against which a double-hung window slides. Inside parts of wood windows are usually made of the same material as trim.

Components of a typical window are shown in Fig. 15.12. Some commonly used terms are:

Sash ▪ A single assembly of stiles and rails made into a frame for holding glass, with or without dividing bars. It may be supplied glazed or unglazed.

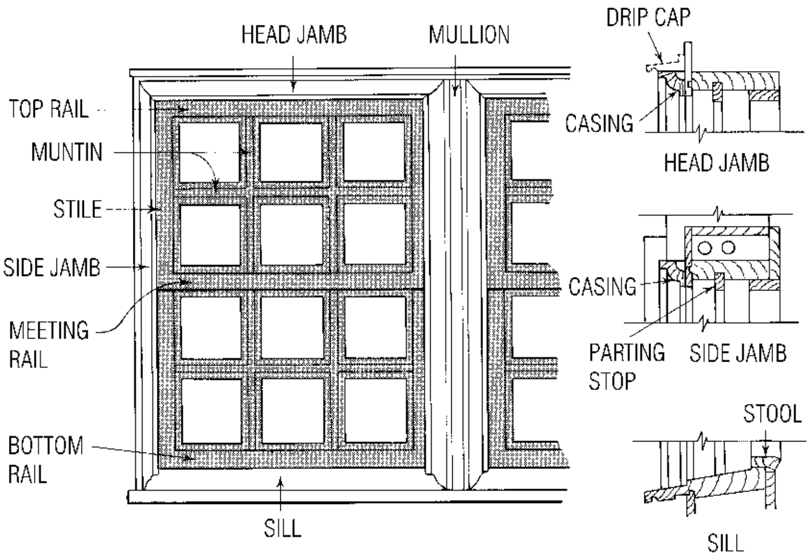


Fig. 15.12 Components of a window.

Window ▪ Sash and the glass that fill an opening.

Stiles ▪ Upright, or vertical, border pieces of a sash.

Rails ▪ Cross, or horizontal, members of a sash.

Check Rails ▪ Meeting rails sufficiently thicker than the window to fill the opening between the top and bottom sash made by the check strip or parting strip in the frame. They usually are beveled and rabbeted.

Bar ▪ Member that extends the height or width of the opening to be glazed.

Muntin ▪ A short, light bar.

Frame ▪ Wood parts machined and assembled to form an enclosure and support for a window.

Jamb ▪ Part of a frame that surrounds and contacts the window it supports. Side jambs form the vertical sides; head jamb, the top. A rabbeted jamb has a rectangular groove along its edges to receive a window.

Sill ▪ The horizontal bottom part of a frame.

Stool ▪ The part of the sill inside the building.

Pulley Stile ▪ A side jamb in which a pulley is installed and along which the sash slides.

Casing ▪ Molding of various widths and thicknesses used to trim window openings.

Drip Cap ▪ A molding placed on top of the head casing of a window frame to direct water away from it.

Blind Stop ▪ A thin strip of wood machined to fit the exterior vertical edge of the pulley stile or jamb and keep the sash in place.

Parting Stop ▪ A thin wood strip let into the jamb of a window frame to separate the sash.

Dado ▪ A rectangular groove cut across the grain of a frame member.

Jamb Liner ▪ A small strip of wood, either surfaced four sides or tongued on one edge, which,

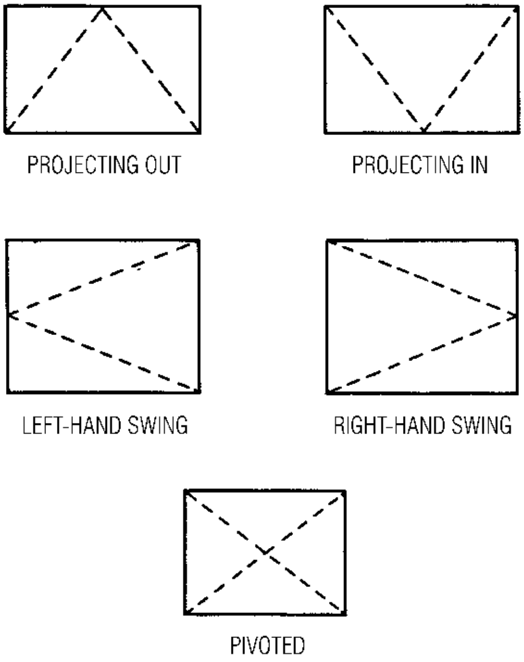


Fig. 15.13 Symbols for common types of windows (viewed from outside).

when applied to the inside edge of a jamb, increases its width for use in thicker walls.

Generally, steel windows are made from hot-rolled structural-grade new billet steel. Dimensions usually conform to the specifications of The Steel Window Institute. Similar types of windows also are available in aluminum but conforming to the specifications of the Aluminum Window Manufacturers Association.

Many types of windows are available (see symbols, Fig. 15.13). Among the more commonly used types are:

Pivoted windows (Fig. 15.14*a*), an industrial window used where very tight closure is not a necessity. Vents are pivoted about 2 in above the center. Top swings in. They may be mechanically operated in groups.

Projected windows (Fig. 15.14*b*), similar to pivoted windows except that the pivot is at the top or bottom. Commercial projected windows are used in commercial and industrial installations where initial cost is a prime consideration. Maximum opening is about 35°. Architectural projected windows are medium-quality, used for commercial, institutional, and industrial buildings. Intermediate projected windows are high-quality, used for schools, hospitals, commercial buildings, and many other structures. Basement and utility windows usually are projected, opening inward, generally with pivot at the bottom. Also, security windows, psychiatric projected, and detention windows generally are bottom-pivoted.

Double-hung windows (Fig. 15.14*c*), comprising a pair of vertically sliding sash. They are used for all types of buildings. Usually, the sash are balanced, to permit easy movement, by weights or other devices in the jambs. Horizontally sliding windows also are available.

Casement windows (Fig. 15.14*d*), consisting of a pair of vertically pivoted sash, generally opening

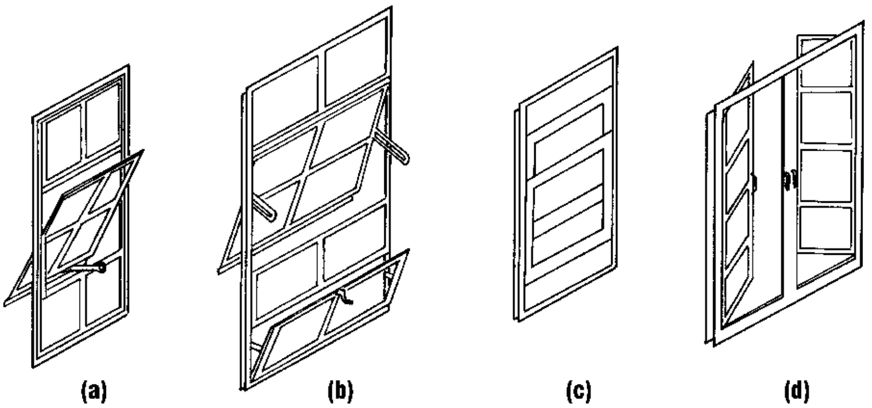


Fig. 15.14 Types of windows: (*a*) pivoted; (*b*) projected; (*c*) double-hung; (*d*) casement.

outward. Rotary or lever operators hold the vents at the desired position up to full opening. **Intermediate combination windows** come with casement windows above a vent that projects in.

Picture windows have fixed sash, and sometimes ventilating units.

Storm sash is another means of reducing heat loss. In effect, it is a second window installed outside the main window. The objective is to create a dead air space, which offers good thermal insulation, without decreasing visibility appreciably.

Windows may be supplied with or without screens. Storm sash and screens may be obtained as a single unit for some types of windows, for example, for double-hung and horizontally sliding windows.

Weather stripping is used on windows to reduce air leakage around joints. It is made of metal or a compressible resilient material.

(F. S. Merritt, "Building Design and Construction Handbook," 6th ed., and J. H. Callender, "Time-Saver Standards for Architectural Design Data," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com).)

15.17 Glazing

Window glass in common use includes:

Sheet Glass ▪ Used in all types of buildings. Classified by Federal standards according to defects. Grade A is used where appearance is important; Grade B for industrial buildings, low-cost housing, basements, garages, and so on. Sheet glass comes in single strength, $\frac{3}{32}$ in thick, up to 40 × 50 in; double strength, $\frac{1}{8}$ in thick, up to 60 × 80 in; and heavy sheet, $\frac{7}{32}$ in, up to 76 × 120 in. For appearance's sake, single and double strength should be limited in area to 7 ft^2.

Float Glass ▪ Used in store windows, picture windows, and better-grade buildings. Better appearance; no distortion of vision. Thickness ranges from $\frac{1}{8}$ to $\frac{7}{8}$ in.

Patterned (Figured or) Rolled Glass ▪ Types of obscure glass.

Obscure Wired Glass ▪ Used where resistance to fire or breakage is desired.

Polished Wired Glass ▪ More expensive than obscure wired glass. Used where clear vision is desired, such as in school or institutional doors.

There are also many special glasses for specific purposes:

Heat-absorbing glass reduces heat, glare, and a large percentage of ultraviolet rays, which bleach colored fabrics. It often is used for comfort and reduction of air conditioning loads where large areas of glass have a severe sun exposure. Because of differential temperature stresses and expansion induced by heat absorption under severe sun exposure, special attention must be given to edge conditions. Glass with clean-cut edges is particularly desirable because such cuts affect the edge strength, which in turn must resist the central-area expansion. A resilient glazing material should be used.

Corrugated glass, corrugated wire glass, and corrugated plastic panels are used for decorative treatments, diffusing light, or as translucent structural panels with color.

Laminated glass consists of two or more layers of glass laminated together by one or more coatings of a transparent plastic. This construction adds strength. Some types of laminated glass also provide a degree of security, sound isolation, heat absorption, and glare reduction. Where color and privacy are desired, fadeproof opaque colors can be included. When fractured, laminated glass tends to adhere to the inner layer of plastic and therefore shatters into small splinters, thus minimizing the hazard of flying glass.

Bullet-resisting glass is made of three or more layers of plate glass laminated under heat and pressure. Thicknesses of this glass vary from $\frac{3}{4}$ to 3 in. The more common thicknesses are $\frac{3}{16}$ in, to resist medium-powered small arms; $1\frac{1}{2}$ in, to resist high-powered small arms; and 2 in, to resist rifles and submachine guns. (Underwriters Laboratories lists materials having the required properties for various degrees of protection.) Greater thicknesses are used for protection against armor-piercing projectiles. Uses of bullet-resisting glass include cashier windows, bank teller cages, toll-bridge booths, peepholes, and many industrial and military applications. Transparent plastics also are used as bullet-resistant materials, and some of these materials have been tested by the Underwriters Laboratories. Thicknesses of $1\frac{1}{4}$ in or more have met UL standards for resisting medium-powered small arms.

Tempered glass is produced by a process of reheating and sudden cooling that greatly increases strength. All cutting and fabricating must be done before tempering. Doors of ½ and ¾-in-thick tempered glass are commonly used for commercial buildings. Other uses, with thicknesses from ⅛ to ⅞ in, include backboards for basketball, showcases, balustrades, sterilizing ovens, and windows, doors, and mirrors in institutions. Although tempered glass is 4½ to 5 times as strong as annealed glass of the same thickness, it is breakable, and when broken, disrupts into innumerable small fragments more or less cube shaped.

Tinted and coated glasses are available in several types and for varied uses. As well as decor, these uses can provide for light and heat reflection, lower light transmission, greater safety, sound reduction, reduced glare, and increased privacy.

Transparent mirror glass appears as a mirror when viewed from a brightly lighted side but is transparent to a viewer on the darker opposite side. This one-way-vision glass is available as a laminate, plate or float, tinted, and in tempered quality.

Plastic window glazing, made of such plastics as acrylic or polycarbonate, is used for urban school buildings and in areas where high vandalism might be anticipated. These plastics have substantially higher impact strength than glass or tempered glass. Allowance should be made in the framing and installation for expansion and contraction of plastics, which may be about eight times as much as that of glass. Note also that the modulus of elasticity (stiffness) of plastics is about one-twentieth that of glass. Standard sash, however, usually will accommodate the additional thickness of plastic and have sufficient rabbet depth.

Suspended glazing utilizes metal clamps bonded to tempered plate glass at the top edge, with vertical glass supports at right angles for resistance to wind pressure. These vertical supports, called stabilizers, have their exposed edges polished. The joints between the large plates and the stabilizers are sealed with a bonding cement. The bottom edge or sill is held in position by a metal channel and sealed with resilient waterproofing. Suspended glazing offers much greater latitude in use of glass and virtually eliminates visual barriers.

Factory-sealed double glazing is an insulating-glass unit composed of two panes of glass separated by a dehydrated air space. This type of sash is also manufactured with three panes of glass and two air spaces, providing additional insulation against heat flow or sound transmission. Heat loss and heat gain can be substantially reduced by this insulated glass, permitting larger window areas and added indoor comfort. Heat-absorbing glass often is used for the outside pane and a clear sheet or float glass for the inside.

Special Glazing ▪ American National Standards Institute's Specification Z-97, adopted by many states, requires entrance-way doors and appurtenances glazed with tempered, laminated, or plastic material.

Glass Thickness for Wind ▪ Figure 15.15 can be used to determine the nominal thickness of float or sheet glass for a given glass area, or the maximum area for a given thickness to withstand a specified wind pressure. Based on minimum thickness permitted by Federal Specification DD-G-451c, the wind-load chart provides a safety factor of 2.5. It is intended for rectangular lights with four edges glazed in a stiff, weathertight rabbet. Deflection of a glass support should not exceed $1/175$ of the span.

For example, determine the thickness of a 108 × 120 in (90-ft^2) light of polished plate glass to withstand a 20-lb/ft^2 wind load. Since the 20-lb/ft^2 and 90-ft^2 ordinates intersect at the ⅜-in glass thickness line, the thickness to use is ⅜ in.

The correction factors in Table 15.6 also allow Fig. 15.15 to be used to determine the thickness for certain types of fabricated glass products. However, the table makes no allowance for the weakening effect of such items as holes, notches, grooves, scratches, abrasion, and welding splatter.

The appropriate thickness for the fabricated glass product is obtained by multiplying the wind load, lb/ft^2, by the factor given in Table 15.6. The intersection of the vertical line drawn from the adjusted load and the horizontal line drawn from the glass area indicates the minimum recommended glass thickness.

Glazing Compounds ▪ Glass usually is held in place in sash by putty, glazing compound, rubber, plastic strips, metal clips (with metal sash), or glazing points (with wood sash). Commonly used glazing compounds include vegetable-oil

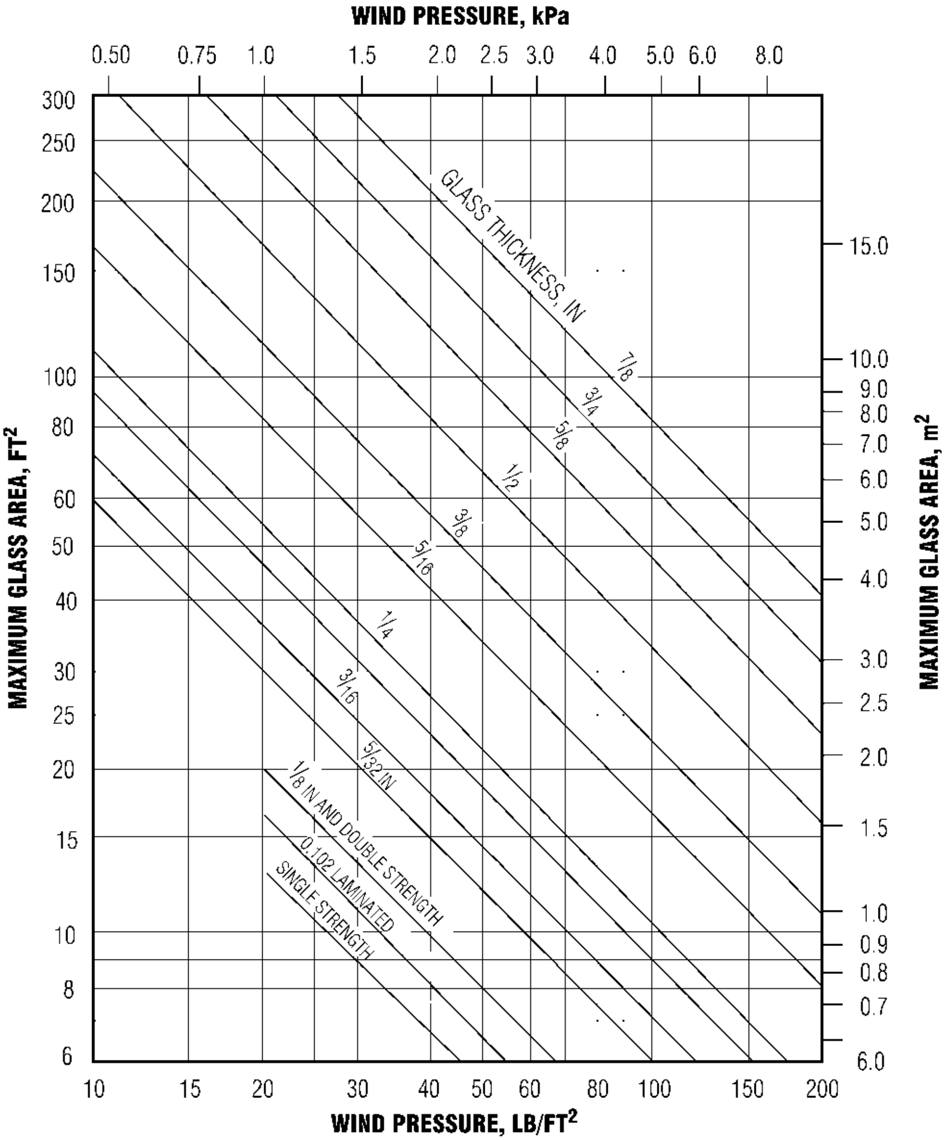


Fig. 15.15 Window chart indicates maximum glass area for various nominal thicknesses of sheet or float glass to withstand specified wind pressures, with design factor of 2.5. The chart is based on glazing firmly supported along all four edges and with length-to-width ratio not exceeding 5:1.

base (skin-forming type), vegetable-oil rubber or nondrying oil blends (polybutene), nondrying oil types—all of which may be applied by gun or knife—butyl rubber or polyisobutylene, applied as tacky tape; polysulfide rubber, applied by gun; Neoprene, applied by gun or as a preformed gasket; and vinyl chloride and copolymer, applied as preformed gaskets. Bedding of glass in glazing compound is desirable because it furnishes a smooth bearing surface for the glass, prevents rattling, and eliminates voids where moisture can collect. A thin layer of putty or bedding compound

Table 15.6 Relative Resistance of Glass to Wind Loads

Product	Factor*
Float sheet glass	1.0
Patterned glass	1.0
Sand blasted glass	2.5
Laminated glass†	1.33
Sealed double glazing‡	
2 panes	0.60
3 panes	0.40
Heat-strengthened glass	0.5
Fully tempered glass	0.25
Wired	2.0

* Enter Fig. 15.15 with the product of the wind load in lb/ft^2 multiplied by the factor.

† At 70°F or above, for two lights of equal thickness laminated to 0.015-in-thick vinyl. At 0°F, factor approaches 1.

‡ For thickness, use thinner of the two lights, not total thickness.

is first placed in the rabbet of the sash; the glass is then pressed into this bed, after which the sash is face-puttied and excess putty removed from the back.

Gaskets ▪ Preformed structural gaskets can be used as an alternative to sash. Gaskets are extruded from rubberlike materials or plastics in a single strip, molded into the shape of the window perimeter, and installed against the glass and window frame. The gasket may fit into a groove or, H-shaped in cross section, grip the glass and a continuous metal fin on the frame. A continuous locking strip of the same material as the gasket is forced into one side of the gasket to make it grip.

(F. S. Merritt, "Building Design and Construction Handbook," 6th ed., and J. H. Callender, "Time-Saver Standards for Architectural Design Data," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com).)

15.18 Doors

Selection of a door depends on more than just its function as a barrier to trespass, weather, drafts, noise, drafts, fire, and smoke. Cost, psychological effect, fire resistance, architectural harmony, and ornamental considerations are only a few of the other factors that must be taken into account.

Traffic Flow and Safety ▪ Openings in walls and partitions must be sized for their primary function of providing entry to or exit from a building or its interior spaces. Doors must be sized and capable of operating so as to prevent or permit such passage, as required by the occupants of the building. In addition, openings must be adequately sized to serve as an exit under emergency conditions. In all cases, traffic must be able to flow smoothly through the openings.

To serve these needs, doors must be properly selected for their intended use and properly arranged for maximum efficiency. In addition, they must be equipped with suitable hardware for the application.

Safety. Exit doors and doors leading to exit passageways should be so designed and arranged as to be clearly recognizable as such and to be readily accessible at all times. A door from a room to an exit or to an exit passageway should be the swinging type, installed to swing in the direction of travel to the exit.

Code Limitations on Door Sizes. To ensure smooth, safe traffic flow, building codes generally place maximum and minimum limits on door sizes. Typical restrictions are as follows:

No single leaf in an exit door should be less than 32 in wide (28 in in an existing building) or more than 48 in wide.

Minimum clear width of opening should be at least:

36 in for single corridor or exit doors

32 in for each of a pair of corridor or exit doors with central mullion

48 in for a pair of doors with no central mullion

32 in for doors to all occupiable and habitable rooms

44 in for doors to rooms used by bedridden patients and single doors used by patients in such buildings as hospitals, sanitariums, and nursing homes

32 in for toilet-room doors

Jambs, stops, and door thickness when the door is open should not restrict the required clear width of opening.

Nominal opening height for exit and corridor doors should be at least 6 ft 8 in. Jambs, stops, sills, and closures should not reduce the clear opening to less than 6 ft 6 in.

Opening Width Determined by Required Capacity. The width of an opening used as an exit is a measure of the traffic flow that the opening is permitted to accommodate. Capacities of exits and access facilities generally are measured in units of width of 22 in, and the number of persons per unit of width is determined by the type of occupancy. Thus, the number of units of exit width for a doorway is found by dividing by 22 the clear width of the doorway when the door is in the open position. Fractions of a unit of width less than 12 in should not be credited to door capacity. If, however, 12 in or more is added to a multiple of 22 in, one-half unit of width can be credited. Local building codes list capacities in persons per unit of width that may be assumed for various types of occupancy.

Every floor of a building should be provided exit facilities for its occupant load. The number of occupants for whom exit facilities must be provided is determined by the actual number of occupants for which the space is designed, or by dividing the net floor area by the net floor area per person specified in the local building code.

Fire and Smokestop Doors ▪ Building codes require fire-resistant doors in critical locations to prevent passage of fire. Such doors are required to have a specific minimum fire-resistance rating and are usually referred to as fire doors. The codes also may specify that doors in other critical locations be capable of preventing passage of smoke. Such doors, known as smokestop doors, need not be fire-rated.

Fire protection of an opening in a wall or partition depends on the door frame and hardware as well as on the door. All these components must be "labeled" or "listed" as suitable for the specific application. Bear in mind that fire doors are tested as an assembly of these components, and hence only approved assemblies should be specified.

All fire doors should be self-closing or close automatically when a fire occurs. In addition, they should be self-latching, so they remain closed. Push-pull hardware should not be used. Exit doors for places of assembly for more than 100 persons usually must be equipped with fire-exit (panic) hardware capable of releasing the door latch when pressure of 15 lb, or less, is applied to the device in the direction of exit. Combustible materials, such as flammable carpeting, should not be permitted to pass under a fire door.

Fire door assemblies are rated, in hours, according to their ability to withstand a standard fire test, such as that specified in ASTM E152. They may be identified as products qualified by tests by a UL label, provided by Underwriters Laboratories, Inc.; an FM symbol of approval, authorized by Factory Mutual Research Corp.; or a self-certified label, provided by the manufacturer (not accepted by some code officials).

Openings in walls and partitions that are required to have a minimum fire-resistance rating must have protection with a corresponding fire-resistance rating. Typical requirements are in Table 15.7.

This table also gives typical requirements for fire resistance of doors to stairs and exit passageways, corridor doors, and smokestop doors.

In addition, some building codes also limit the size of openings in fire barriers. Typical maximum areas, maximum dimensions, and maximum percent of wall length occupied by openings are in Table 15.8.

Smokestop doors should be of the construction indicated in Table 15.7, last footnote. They should close openings completely, with only the amount of clearance necessary for proper operation.

["Standard for Fire Doors and Windows," NFPA No. 80; Life Safety code, NFPA No. 101; "Fire Tests of Door Assemblies,"NFPA No. 252, National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02269 (www.nfpa.org).

"Fire Tests of Door Assemblies," Standard UL 10(b); "Fire Door Frames," Standard UL 63; "Building Materials List" (annual, with bimonthly supplements), Underwriters' Laboratories, Inc., 333 Pfingsten Road, Northbrook, IL 60062 (www.ul.com).

"Factory Mutual Approval Guide," Factory Mutual Research Corp., 1151 Boston-Providence Turnpike, Norwood, MA 02062.]

Ordinary Doors ▪ Swinging doors are hung on butts or hinges that permit rotation about a vertical axis at an edge. The door is hinged to and closes against a door frame. The frame consists of two verticals, or jambs, and a horizontal member, the header (Fig. 15.16). *Single-acting doors* can swing 90° or more in only one direction; *double-acting*

Table 15.7 Typical Fire Ratings Required for Doors

Door use	Rating, h*
Doors in 3- or 4-h fire barriers	3†
Doors in 2- or 1½-h fire barriers	1½
Doors in 1-h fire barriers	¾
Doors in exterior walls	
Subject to severe fire exposure from outside the building	¾
Subject to moderate or light fire exposure from outside the building	⅓
Doors to stairs and exit passageways	1½
Doors in 1-h corridors	⅓
Other corridor doors	0‡
Smokestop doors	⅓§

* Self-closing, swinging doors. Normally kept closed.

† A door should be installed on each side of the wall.

‡ Should be noncombustible or 1¾-in solid-core wood doors. Some codes do not require self-closing for doors in hospitals, sanitariums, nursing homes, and similar occupancies.

§ May be metal, metal-covered, or 1¾-in solid-core wood doors (1⅜-in in buildings less than three stories high), with 600-in^2 or larger, clear, wire-glass panels in each door.

doors can swing 90° or more in each of two directions.

To stop drafts and passage of light, the jamb about which the door swings has a rebate or projection, extending the full height, against which the door closes. The projection may be integral with the frame, or formed by attaching a stop on the surface of the frame, or inset slightly. With single-acting doors, the opposite jamb also is provided with a stop, against which the door closes.

Door frames for swinging doors generally are fastened to bucks, rough construction members. Joints between the frame and wall are covered with casings, or trim. With metal construction, the trim often is integral with the frame and designed to grip the bucks. The sill, at the bottom of the door, forms a division between the finished floor on one side and that on the other side.

Table 15.8 Maximum Sizes of Openings in Fire Barriers

Protection of adjoining areas	Max area, ft^2	Max dimension, ft
Unsprinklered	120*	12†
Sprinklers on both sides	150*	15*
Building fully sprinklered	Unlimited*	Unlimited*

* But not more than 25% of the wall length or 56 ft^2 per door if the fire barrier serves as a horizontal exit.

† But not more than 25% of the wall length.

Source: Based on New York City Building Code.

The sill for exterior doors generally serves also as a step since the door opening usually is raised above grade to prevent rain from entering. The top of the sill is sloped to drain water away from the interior. A raised section or separate threshold at the door is an additional barrier to water. A weather strip in the form of a hooked length of metal may be attached to the underside of the door. When the door is closed, the weather strip locks into the threshold to seal out water and reduce air leakage.

Selection of a swinging door involves consideration of the jamb to which the door is hinged and the direction in which it is to open. This relationship is called the *hand* of the door. Hand and hardware for swinging doors are discussed later.

Horizontally sliding doors roll on rails at top or bottom and slide in guides at the opposite edge. Some doors fold or collapse like an accordion, to occupy less space when open. A pocket should be provided in the walls on either or both sides to receive rigid doors; with folding or accordion types, a pocket is optional.

Vertically sliding doors may rise straight up, may rise up and swing in, or may pivot outward

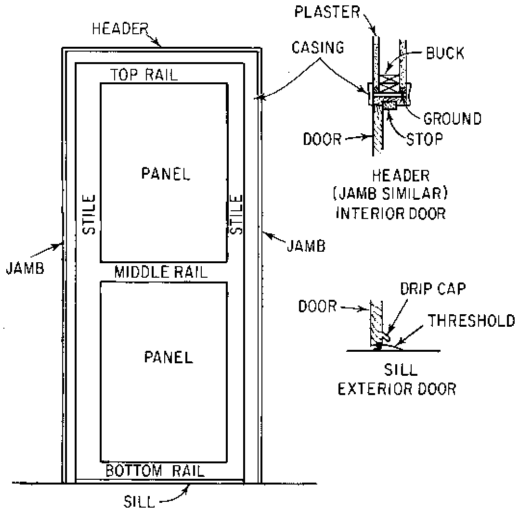


Fig. 15.16 Components of a door.

to form a canopy. Sometimes, the door may be in two sections, one rising up and the other dropping down. Generally, all types are counterweighted for ease of operation. To exclude weather, either the upper part is recessed into the wall above or the top part of the door extends slightly above the bottom of the wall on the inside. Similarly, door sides are recessed into the walls or lap them and are held firmly against the inside. Also, the finished floor is raised a little above outside grade.

Revolving doors are generally selected for entranceways carrying a continuous flow of traffic without a very high peak. They offer the advantage of keeping interchange of inside and outside air to a relatively small amount compared with other types of doors. Usually, they are used in combination with swinging doors because of the inability to handle large groups of people in a short time. Revolving doors consist of four leaves that rotate about a vertical axis inside a cylindrical enclosure with a 4- to 5-ft wide opening.

Special Doors ▪ Large-sized doors, such as those for hangars, garages, and craneway openings and for subdividing gymnasiums and auditoriums, often have to be designed individually, with special attention to their supports and controls. Manufacturers classify such special-purpose doors as horizontal-sliding, vertical-sliding, swing, and top- or horizontal-hinge.

Telescoping doors, a horizontal-sliding type, are used for airplane hangars. Normally composed of 6 to 20 leaves, they generally are center-parting. When opened, the doors are stacked in pockets at each end of the opening. Operation is by electric motor installed in the end pockets and driving an endless chain attached to the tops of the center leaves.

Folding doors are commonly used for subdividing gymnasiums, auditoriums, and cafeterias and for hangars with very wide openings. This type of door is made up of a series of leaves hinged together in pairs. The leaves fold outward, and when the door is shut, they are held by automatic folding stays. Motors that operate the doors usually are installed in mullions adjacent to the center of the opening. The mullions are connected by cables to the ends of the opening, and when the door is to be opened, the mullions are drawn toward the ends, sweeping the leaves along. The chief advantage over telescoping types is that only two guide channels are required.

Vertical-sliding doors are advantageous when space is available above and below an opening into which door leaves can be moved. Usually, the doors are counterweighted, even when motor-operated.

Large swing doors are used when there is insufficient space around openings for sliding doors. Common applications have been for fire-stations, where width-of-building clearance is essential, and railway entrances, where doors are interlocked with the signal system. Common variations include single-swing (solid leaf with vertical hinge on one jamb), double-swing (hinges on both jambs), two-fold (hinge on one jamb and another between folds and leaves), and four-fold (hinges on both jambs and between each pair of folds). The more folds, the less time required for opening and the smaller the radius needed for swing.

Horizontal-hinge doors are used in craneway entrances to buildings. Sometimes, horizontal-sliding doors are installed below the crane doors to increase the opening. If so, the top guides are contained in the bottom of the crane door; the sliding door must be opened before the swing door.

Radiation-shielding doors are used as a barrier against harmful radiation and atomic particles across openings for access to "hot" cells, and against similar radioactive-isotope handling arrangements and radiation chambers of high-energy x-ray machines or accelerators. Usually, the doors must protect not only personnel but instruments even more sensitive to radiation than people. Shielding doors usually are much thicker and heavier than ordinary doors because density is an important factor in barring radiation. These special-purpose doors are made of steel plates, steel-sheathed lead, or concrete. To reduce thickness, concrete doors may be of medium-heavy (240 lb/ft^3) or heavy (300 lb/ft^3) concrete, often made with iron-ore aggregate. They usually are operated hydraulically or by electric motor.

Common types of shielding doors include hinged, plug, and overlap. The hinged type is similar to a bank vault door. The plug type, flush with the walls when closed, may roll on floor-mounted tracks or hang from rails. Overlap doors, surface-mounted, also may roll or hang from rails. In addition, vertical-lift doors sometimes are used.

Door Materials ▪ Doors are made of a wide variety of materials. Wood is used in several forms. Better-grade doors are made with panels set in a frame or with flush construction. Paneled doors consist of solid wood or plywood panels held in place by stiles and rails (Fig. 15.16). The joints permit expansion and contraction of the wood with atmospheric changes. If the rails and stiles are made of a single piece of wood, the paneled door is called solid. When hardwood or better-quality woods are used, the doors generally are veneered; rails and stiles are made with cores of softwood sandwiched between the desired veneer. Tempered glass or plastic may be used instead of wood for panels. Flush doors also may be solid or veneered, or hollow-core.

Metal doors generally are constructed in one of three ways: cast as a single unit or separate frame and panel pieces; metal frame covered with sheet metal; and sheet metal over a wood or other type of insulating core. The heavier metal doors of the swinging type usually are pivoted at top and bottom. Metal-covered doors may be obtained with a wide variety of fire-resistant cores. A **Kalamein door** has a wood core (the wood will not burn as long as the sheet-metal cover prevents oxygen from reaching it).

Doors may be made wholly or partly transparent or translucent. Lights may be made of tempered glass or plastic. Doors made completely of glass are pivoted at top and bottom because the weight makes it difficult to support them with hinges or butts.

Sliding doors of the collapsible accordian type generally consist of wood slats or a light steel frame covered with textile. Plastic coverings frequently are used.

Hand of Doors ▪ Swinging doors are called left-hand doors if, when viewed from the outside, they are hinged to the left-hand jamb and open inward; they are left-hand reverse if they are hinged to the left-hand jamb and open outward. Similarly, they are right-hand and right-hand reverse, respectively, if they open inward and outward when hinged to the right-hand jamb. Since some butts and hinges are handed, the type of door may determine the type of hinge (Fig. 15.17).

Door Hardware ▪ The term **hinge** usually refers to the elongated strap type (Fig. 15.18*a* and *b*). It is suitable for mounting on the surface of a door. It consists of two leaves joined by a pin passing through knuckle joints where the leaves fit together.

When the device is to be mounted on the edge of a door, the length of the leaves must be shortened. The leaves thus retain only the portion near the pin,

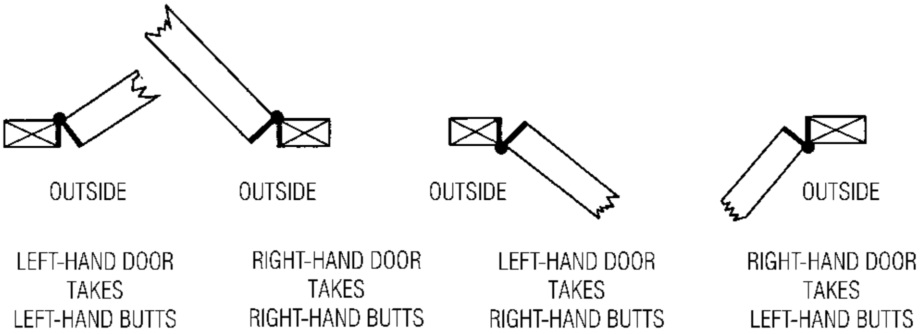


Fig. 15.17 Direction of opening classifies swinging doors.

or the butt end of the hinge (Fig. 15.18*c* to *g*). Thus, hinges applied to the edge of a door are referred to as **butts** or **butt hinges**.

Butts usually are mortised into the door edge. The number of butts required per door depends on the size and weight of the door and the conditions of use. In general, use two butts on doors up to 68 in high and three butts on doors 68 to 90 in high. The weight and usage of the door also determine whether the butts should be two- or four-bearing. When the butts are the type that may be mounted on both left- and right-hand doors, only half the bearing units available participate in carrying the vertical load. This should be considered when selecting butts.

The upper butt may be attached with its top about 5 in below the rabbet of the head jamb. The lowest butt may be set with its bottom 10 in from the finished floor. A third butt may be installed about midway between the other two.

Bearing butts (Fig. 15.18*e* and *f*) or butts with Oilite bearings are used for doors requiring silent operation, subject to heavy usage, or equipped with a door closer. Plain bearings (Fig. 15.18*g*) usually are used for residential doors.

Template hardware, manufactured to close tolerances, is attached to metal jambs and doors with machine screws. In butts, holes that are template-drilled usually form a crescent pattern (Fig. 15.18*c* and *e*). When the holes are staggered, the butts are nontemplate (Fig. 15.18*f* and *g*).

Butts and hinges come with loose or fast pins. Loose pins are used wherever practicable because they simplify door hanging. The fast (or tight) pin is permanently set in the butt at the time of manufacture; thus, a locked door cannot be opened by

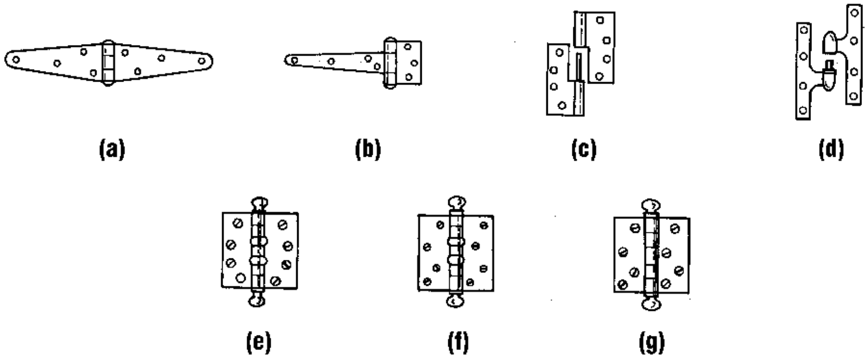


Fig. 15.18 Typical hinges and butts; (*a*) heavy strap hinge; (*b*) heavy T hinge; (*c*) loose-joint hinge; (*d*) olive knuckle hinge; (*e*) bearing template hinge; (*f*) bearing nontemplate hinge; (*g*) plain bearing nontemplate hinge.

removing the pins and separating the leaves of the butts. Also, nonremovable loose pins are available for the same purpose. Another type of loose pin is nonrising; it does not have the disadvantage of ordinary loose pins of working upward with repeated movements of the door.

Doors generally are equipped with locks or latches to hold them closed. **Rim locks or latches** are fastened on the surface of the door. Those mortised into the edge of the door are called **mortise locks or latches**. A latch has a beveled locking bolt, which slides into position automatically when the door is closed. Usually, it is operated by a knob or lever. When specifying a latch, the hand of the door should be given.

When the locking bolt is rectangular in shape and must be moved in and out by a thumb turn or key, the bolt is called a **dead bolt** and the lock a **dead lock**. A unit composed of latch bolts and dead bolts is known as a lock.

Unit locks are complete assemblies that can be installed in a standard notch. Bored-in locks similarly are complete assemblies, but installed in circular holes. Depending on the arrangement of holes, bored-in locks may be tubular or cylindrical lock sets.

Tubular locks have a horizontal tubular case perpendicular to the door edge. Another small hole is required normal to the first hole for the locking cylinder.

Cylinder locks need a relatively large hole perpendicular to the face of the door for the cylindrical case. Another small hole perpendicular to the door edge accommodates the bolt.

When selecting locks, choose a uniform size, if practicable, for the project. Then, standard-size cutouts or sinkages can be used throughout. This will reduce installation costs. In addition, if changes are made as the job progresses, hardware changes will be simple and special hardware avoided.

(F. S. Merritt, "Building Design and Construction Handbook," 6th ed., and J. H. Callender, "Time-Saver Standards for Architectural Design Data," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); "Life Safety Code Handbook," National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02269 (www.nfpa.org); "Specifiers Guide to Windows and Doors;" Window & Doors Manufacturers Association, 1400 East Touhy Ave. Ste. 470, Des Plaines, IL 60018, (www.wdma.com); "Recommended Standard Steel Doors, and Frame Details, Steel Door Institute, 712 Lakewood Center North, 30200 Detroit Ave., Cleveland, OH, 44145; "Entrance Manual," Door and Hardware Institute, 14150 Newbrook DR., Suite 200, Chantilly, VA 20151, (www.chi.org).)

15.19 Roof Coverings

Success of a roofing installation depends heavily on the roof deck. Roof framing should be sized and spaced to prevent significant deflection of the deck and consequent damage to the roofing. The deck itself should be smooth, dry, and clean. Many roof failures have resulted from application of roof coverings to damp decks. Pressures developed by the entrapped moisture caused blisters and rupture of the coverings.

Roofing may be single-unit or multiple-unit. The single-unit type, which includes built-up roofing of asphalt or coal-tar pitch, sprayed-on products, and flat-seam metal roofing, is suitable for flat roof decks, where water can collect before proceeding slowly to drainage outlets. Multiple-unit coverings, including shingles, tile, slate, and standing-seam metal panels, are used on steep roof decks, where water flows swiftly over each exposed unit to gutters and leaders.

A built-up roof consists of plies of felt mopped with asphalt or pitch. These form a seamless piece of flexible, waterproofed material, custom-built to conform to the roof deck and protect all angles formed by the roof deck and projecting surfaces.

Bitumen is a generic term used to indicate either asphalt or coal-tar pitch.

Asphalt is a by-product of the refining processes of petroleum oils.

Coal-tar pitch is a by-product of crude tars derived from the coking of coal. The crude tars are distilled to produce coal-tar pitch. It has a lower melting point than asphalt; hence pitch roofs must be protected by a covering of slag or gravel. Asphalt can be used on steeper slopes than pitch.

Felts, made of paper, wood pulp, rag, or glass fibers, aid the bitumens in water shedding and waterproofing. Felts are designated by a number that indicates their approximate weight in pounds per square (100 ft^2). The felts are saturated with bitumen and cemented to the deck and each other with bitumen. For roof decks that permit nailing, the first two plies of felt are nailed to the deck. For slopes steeper than 2 in on 12 in, where there is difficulty holding a slag or gravel covering, felt with minerals embedded in the surface may be used for the top, or cap, sheet. Minimum weight of the sheet should be 55 lb/square. For best results, the cap sheets should be applied over two 15 lb/square felts—the first one nailed, the second mopped.

Built-up roofing generally employs five plies of felt on a wood-sheathed or metal deck and four plies on a cast-in-place concrete deck. “Minimum” specifications require one or two fewer plies and layers of bitumen.

The bituminous roofing may be hot- or cold-process. For cold-process roofing, the bituminous materials, in some cases combined with chemicals, such as polyurethane, are thinned with solvents—for example, kerosene to cut back asphalt, toluene for tar—or emulsified with water. Felts and fabrics differ in the hot and cold processes. Since, in the cold process, cementing occurs on evaporation of solvents or emulsion water, the felts should be of a type that speeds the drying-out process, so an open weave is desirable. Cold-process materials are applied by brush or spray; hot bitumen is mopped in place.

Asphalt roofing materials may be used on slopes up to 4 in/ft:

1 in/ft	19-in selvage-edge roofing, built-up roofing
2 in/ft	Mineral-surfaced roll roofing, blind-nailed, square-butt strip shingles with two-ply felt underlay
3 in/ft	Mineral-surfaced roll roofing, exposed nailed
4 in/ft	Hexagonal, individual, three-tab square butt and lock-type shingles

Asphalt shingles are made of asphalt-saturated and coated felt in which is embedded a permanent mineral surfacing. Square-butt strip shingles are slotted at the butts to give the appearance of individual units. Other shapes, such as hexagonal, also are available. The shingles are installed over an underlayment of No. 15 asphalt felt fastened to the roof deck. A starter course at eaves should be cemented to the felt to prevent leakage through nail punctures. The starter strip may be a row of shingles turned upside down or, preferably, mineral-surfaced roll roofing, 18 in wide in normal-wind areas, 36 in wide in high-wind areas. The shingles should be nailed with nails at least 1¼ in long on new work and 1¾ in long on reroofing.

Wood shingles come in two varieties, machine-sawn and hand-split. Standard exposure is 5 in but may range from 3½ to 12 in. The shingles are laid in alternate courses, with joints broken relative to courses above and below, starting preferably with a triple layer at the eaves.

Concrete tile, cured under controlled temperature and humidity, may be colored throughout or have an exposed surface of a cementitious material colored with synthetic oxides. The tile may be classified as roll or flat. Roll tiles are available pan shape, with or without interlocking edges; cover, or barrel, semicircular shape; pan and cover shape; and S shape. Flat tile may be supplied as flat shingles or with flat ribs, with interlocking edges. For one-piece barrel and flat tiles, the roof slope should be at least 4 in/ft; for flat shingles, a minimum of 5 in/ft.

Slate roofs may employ standard commercial slating or textural (random) slating. For commercial slating, the material is graded at the quarry; for textural slating, the slates are delivered to the job in random sizes. Longer and heavier slates are placed at the eaves, medium-sized at the center, and the smallest at the ridge. Application starts with an undereaves course fastened over a batten, which slopes the first course. Slating nails should be driven level with the slate.

Clay roofing tile comes in two varieties: roll and flat. Roll tiles may be semicircular, reverse curve, pan and cover, or flat shingle. Application is much the same as for slate.

Metal Roofing ▪ Principal metals used in roofing are galvanized iron, terneplate, Monel metal, aluminum, and copper. Sometimes, zinc, lead, cast iron, or stainless steel is used. In all cases, care should be taken to prevent corrosion, especially from galvanic action. For example, a copper roof should not be applied directly over a wood deck; the copper must be insulated from attack by the steel nails in the deck. Fasteners used with metal roofing should preferably be of the same metal as the roofing. Also, provision should be made for expansion and contraction.

Common types of metal roof installation that allow for thermal movements include batten-seam, standing-seam, flat-seam, and corrugated-metal. Batten-seam and standing-seam coverings consist of narrow strips with loose-locked seams that permit lateral motion. Flat-seam construction consists of small sheets soldered on all edges. Movement is absorbed by buckling in the center of the small sheets.

Except for corrugated metal, large roof areas should be broken into small units, and no metal sheets should be fastened directly to the deck. Clips or battens should be used for fastening. With corrugated-metal roofing, the corrugations absorb thermal movements. Fasteners for corrugated metal include nails, clips, straps, clinch rivets, hook bolts, and welded studs. Where the sheets are fastened directly to roof framing, lead or Neoprene washers should be used with the fasteners.

Plastics Roofing ▪ This may be applied as a roof covering in liquid, sheet, or rigid form. Fluid-applied *elastomeric coatings*, such as Neoprene and Hypalon, conform to any shape of surface and expand and contract with it. Manufacturer's specifications should be followed carefully in all applications. *Plastic roofing sheets* may be made of Neoprene, polyvinyl fluoride, polyisobutylene, EPDM membrane, or other suitable materials, alone or in combination with other materials, for example, bonded to felt. They are applied in the same way as conventional roofing sheets. *Rigid polyvinyl chloride* is available as flat, corrugated, and ribbed panels. They can be cut on the job with portable power saws with abrasive cutting wheels.

("The NRCA Roofing and Waterproofing Manual," National Roofing Contractors Association, 10255 W. Higgins Road, Suite 600, Rosemont, IL 60018 (www.nrca.net); F. S. Merritt, "Building Design and Construction Handbook," 4th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com).)

15.20 Flashing

At all intersecting surfaces on a building exterior, flashing is necessary to prevent penetration of water through the joints or cracks that might form. Since thermal movements are likely to occur at the intersections, flashing should be elastic or shaped to permit motion.

Bituminous flashings have the ability to hug tight against building surfaces. Metal flashings require added protection, such as cap flashing, installed above and covering the top edge of the base flashing. Plastic flashing sheets have been particularly useful in sealing the junction of vents and pipes with roof decks.

At intersections of walls and flat roofs, at least 6 in of the base flashing should be fastened to the deck and 8 in to the wall. Counterflashing should overlap the base flashing from above at least 4 in and should penetrate at least $1\frac{1}{2}$ in into a raggle cut into the mortar line between the nearest row of bricks above the base flashing.

Step flashing should be used at intersections of walls and steep roofs. For this purpose, short pieces of metal are bent at right angles and one flange sandwiched between every roofing unit at the intersection and the other flange set in contact with the wall. Each flashing unit should lap the one below at least 2 in. Counterflashing also should be installed in steps.

Crickets or flashing saddles are needed between chimneys and sloping roofs to guide water away from the intersection. The saddle is a miniature roof, usually of metal, with a ridge and two valleys, secured to a base step flashing.

Flashing also is required at a number of places in exterior walls; for example, around spandrel beams, coping, sills, at grade, belt courses, water tables, cornices, roof valleys, gables, openings in roofs, and window and door heads.

("The NCRA Roofing and Waterproofing Manual," National Roofing Contractors Association 10255 W. Higgins Road, Suite 600, Rosemont, IL 60018 (www.nrca.net).)

15.21 Waterproofing

Properly built concrete and masonry walls, whether above or below grade, can keep water out of a building without protective coatings or integral waterproofing. Leakage through masonry walls usually occurs at the joints and results from failure to fill them with mortar and poor bond between masonry and mortar. Leakage through concrete walls usually occurs in porous material, or at wall ties or at intersections with other surfaces. Following are some terms most commonly encountered:

Permeability ▪ Quality or state of permitting passage of water and water vapor into, through, and from pores and interstices, without causing rupture or displacement.

Terms used in this section to describe the permeability of materials, coatings, structural elements, and structures follow in decreasing order of permeability:

Pervious or Leaky ▪ Cracks, crevices, leaks, or holes larger than capillary pores, which permit a flow or leakage of water, are present. The material may or may not contain capillary pores.

Water-Resistant ▪ Capillary pores exist that permit passage of water and water vapor, but there are few or no openings larger than capillaries that permit leakage of significant amounts of water.

Water-Repellent ▪ Not "wetted" by water; hence, not capable of transmitting water by capillary forces alone. However, the material may allow transmission of water under pressure and may be permeable to water vapor.

Waterproof ▪ No openings are present that permit leakage or passage of water and water vapor; the material is impervious to water and water vapor, whether or not under pressure.

These terms also describe the permeability of a surface coating or a treatment against water penetration, and they refer to the permeability of materials, structural members, and structures whether or not they have been coated or treated.

Permeability of Concrete and Masonry ▪ Concrete contains many interconnected voids and openings of various sizes and shapes, most of which are of capillary dimensions. If there are few larger voids and openings and they are not directly connected with each other, there will be little or no water penetration by leakage and the concrete may be considered water resistant.

Concrete in contact with water not under pressure ordinarily will absorb it. Resistance of concrete to penetration of water may be improved, however, by incorporating a water-repellent admixture into the mix during manufacture.

Water-repellent concrete is permeable to water vapor. The concrete is not made waterproof (in the full meaning of the term) by the use of an integral water repellent. Note also that water repellents may not make concrete impermeable to penetration of water under pressure.

Most masonry units also will absorb water. Some are highly pervious under pressure. The mortar commonly used in masonry will absorb water too but usually contains few openings permitting leakage.

Masonry walls may leak at the joints between the mortar and the units, however. Except in single-leaf walls of highly pervious units, leakage at the joints results from failure to fill them with mortar and poor bond between the masonry unit and mortar. As with concrete, rate of capillary penetration through masonry walls is small compared with the possible rate of leakage.

Capillary penetration of moisture through above-grade walls that resist leakage of wind-driven rain is usually of minor importance. Such penetration of moisture into well-ventilated subgrade structures may also be of minor importance if the moisture is readily evaporated. However, long-continued capillary penetration into some deep, confined subgrade interiors frequently results in an increase in relative humidity, a decrease in evaporation rate, and objectionable dampness.

Drainage for Subgrade Structures ▪ Subgrade structures located above groundwater level in drained soil may be in contact with water and wet soil for indefinite periods after long-continued rains and spring thaws. Drainage of surface and subsurface water, however, may greatly reduce the time during which the walls and floor of a structure are subjected to water, may prevent leakage through openings resulting from poor work, and reduce the capillary penetration of water into the structure. If subsurface water cannot be removed by drainage, the structure must be made waterproof or highly water-resistant.

Surface water may be diverted by grading the ground surface away from the walls and by carrying the runoff from roofs away from the building. The slope of the ground surface should be at least ¼ in/ft for a minimum distance of 10 ft from the walls. Runoff from high ground adjacent to the structure should also be diverted.

Proper subsurface drainage of groundwater away from basement walls and floors requires a drain of adequate size, sloped continuously, and, where necessary, carried around corners of the building without breaking continuity. The drain should lead to a storm sewer or to a lower elevation that will not be flooded and permit water to back up in the drain.

Drain tile should have a minimum diameter of 6 in and be laid in gravel or other kind of porous bed at least 6 in below the basement floor. The open joints between the tile should be covered with a wire screen or building paper to prevent clogging of the drain with fine material. Gravel should be laid above the tile, filling the excavation to an elevation well above the top of the footing. Where considerable water may be expected in heavy soil, the gravel fill should be carried up nearly to the ground surface and should extend from the wall a distance of at least 12 in (Fig. 15.19).

Concrete Floors on Ground ▪ These should preferably not be constructed in low-lying areas that are wet from groundwater or periodically flooded with surface water. The ground should slope away from the floor. The level of the finished floor should be at least 6 in above grade. Further protection against ground moisture and possible flooding of the slab from heavy surface runoffs may be obtained with subsurface drains located at the elevation of the wall footings.

All organic material and topsoil of poor bearing value should be removed in preparation of the subgrade, which should have a uniform bearing value to prevent unequal settlement of the floor slab. Backfill should be tamped and compacted in layers not exceeding 6 in in depth.

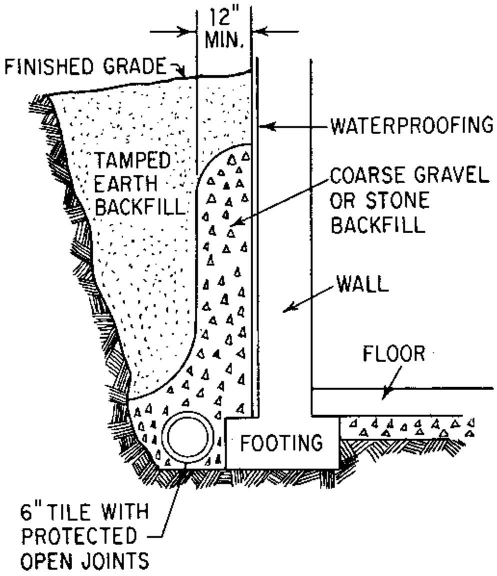


Fig. 15.19 Drainage of basement wall with drain tile along the footing and gravel fill.

Where the subgrade is well-drained, as where subsurface drains are used or are unnecessary, floor slabs of residences should be insulated either by placing a granular fill over the subgrade or by using a lightweight-aggregate concrete slab covered with a wearing surface of gravel or stone concrete. The granular fill, if used, should have a minimum thickness of 5 in and may consist of coarse slag, gravel, or crushed stone, preferably of 1-in minimum size. A layer of 3-, 4-, or 6-in-thick hollow masonry building units is preferred to gravel fill for insulation and provides a smooth, level bearing surface.

Where a complete barrier against the rise of moisture from the ground is desired, a two-ply bituminous membrane or other waterproofing material should be placed beneath the slab and over the insulating concrete or granular fill. The top of the lightweight-aggregate concrete, if used, should be troweled or brushed to a smooth level surface for the membrane. The top of the granular fill should be covered with a grout coating, similarly finished. Where there is no possible danger of water reaching the underside of the floor, a single layer of 55-lb smooth-surface asphalt roll roofing or an equivalent waterproofing membrane may be used under the floor. Joints between the sheets should be lapped and sealed with bituminous mastic. Great care should be taken to prevent puncturing the roofing layer during concreting operations.

(“A Guide to the Use of Waterproofing, Dampproofing, Protective and Decorative Barrier Systems for Concrete,” ACI 515.1R-79, American Concrete Institute (www.concrete.org).)

Basement Floors ▪ Where a basement is to be used in drained soils as living quarters or for the storage of items that may be damaged by moisture, the floor should be insulated and preferably contain the membrane waterproofing previously described. In general, the design and construction of such basement floors are similar to those of floors on ground.

If passage of moisture from the ground into the basement is unimportant or can be satisfactorily controlled by air conditioning or ventilation, the waterproof membrane need not be used. The concrete slab should have a minimum thickness of 4 in and need not be reinforced, but it should be laid on a granular fill or other insulation placed on a carefully prepared subgrade. The concrete in the slab should have a minimum compressive strength of 2000 psi and may contain an integral water repellent.

A basement floor below the water table will be subjected to hydrostatic upward pressures. The floor should be made heavy enough to counteract the uplift.

An appropriate sealant in the joint between the basement walls and a floor over drained soil will prevent leakage into the basement of any water that may occasionally accumulate under the slab. Space for the joint may be provided by use of beveled siding strips, which are removed after the concrete has hardened. After the slab is properly cured, it and the wall surface should be in as dry a condition as practicable before the joint is filled to ensure a good bond of the filler and to reduce the effects of slab shrinkage on the joint's permeability.

("Guide to Joint Sealants for Concrete Structures," ACI 504R, American Concrete Institute.)

Monolithic Concrete Basement Walls ▪ These should have a minimum thickness of 6 in. Where insulation is desirable, as where the basement is used for living quarters, lightweight aggregate, such as those prepared by calcining or sintering blast-furnace slag, clay, or shale that meet the requirements of ASTM Standard C330, may be used in the concrete. The concrete should have a minimum compressive strength of 2000 psi.

For the forms in which concrete for basement walls is cast, form ties of an internal-disconnecting type are preferable to twisted-wire ties. Entrance holes for the form ties should be sealed with mortar after the forms are removed. If twisted-wire ties are used, they should be cut a minimum distance of 1½ in inside the face of the wall and the holes filled with mortar.

The resistance of the wall to capillary penetration of water in temporary contact with the wall face may be increased by using a water-repellent admixture. The water repellent may also be used in the concrete at and just above grade to reduce the capillary rise of moisture from the ground into the superstructure walls.

Where it is desirable to make the wall resistant to passage of water vapor from the outside and to increase its resistance to capillary penetration of water, the exterior wall face may be treated with an impervious coating. The continuity and the resulting effectiveness in resisting moisture penetration of such a coating depend on the smoothness and regularity of the concrete surface and the skill and technique used in applying the coating to the dry concrete surface. Some bituminous coatings that can be used are listed in increasing order of their resistance to moisture penetration:

Spray- or brush-applied asphalt emulsions

Spray- or brush-applied bituminous cutbacks

Trowel coatings of bitumen with organic solvent, applied cold

Hot-applied asphalt or coal-tar pitch, preceded by application of a suitable primer

Cementitious brush-applied paints and grouts and trowel coatings of a mortar increase moisture resistance of monolithic concrete, especially if such coatings contain a water repellent. However, in properly drained soil, such coatings may not be justified unless needed to prevent leakage of water through openings in the concrete resulting from segregation of the aggregate and bad work in casting the walls. The trowel coatings may also be used to level irregular wall surfaces in preparation for the application of a bituminous coating. For information on other waterproofing materials, see "A Guide to the Use of Waterproofing, Dampproofing, Protective and Decorative Barrier Systems for Concrete," ACI 515.1R-79, American Concrete Institute.

Basement Walls of Masonry Units ▪ Water-resistant basement walls of masonry units should be carefully constructed of durable materials to prevent leakage and damage from frost and other weathering exposure. Frost action is most severe at the grade line and may cause structural damage and leakage of water.

The use of shotcrete or trowel-applied mortar coatings, ¾ in or more thick, to the outside faces of both monolithic concrete and unit-masonry walls greatly increases their resistance to penetration of moisture. Such plaster coatings cover and seal construction joints and other vulnerable joints in the walls against leakage. When applied in a thickness of 2 in or more, they may be reinforced with welded-wire fabric to reduce the incidence of large shrinkage cracks in the coating. However, the plaster does not protect the walls against leakage if the walls, and subsequently the coatings, are badly cracked as a result of unequal foundation settlement, excessive drying shrinkage, and thermal changes. ("Guide to Shotcrete," ACI 506, American Concrete Institute.)

Thin, impervious coatings may be applied to the plaster if resistance to penetration of water vapor is desired. (See ACI 515.1R.) The plaster should be dry and clean before the impervious coating is applied over the surface of the wall and the top of the footing.

Impervious Membranes ▪ These are waterproof barriers providing protection against penetration of water under hydrostatic pressure and water vapor. To resist hydrostatic pressure, the membrane should be made continuous in a basement's walls and floor. It also should be protected from damage during building operations and should be laid by experienced workers under competent supervision. It usually consists of three or more alternate layers of hot, mopped-on asphalt or coal-tar pitch and plies of treated glass fabric or bituminous saturated cotton or woven burlap fabric. The number of moppings exceeds the number of plies by one.

Materials used in the hot-applied system should meet the requirements of the following current ASTM Standards:

Creosote primer for coal-tar pitch—D43

Primer for asphalt—D41

Coal-tar pitch—D450, Type II

Asphalt—D449, Type A

Cotton fabric, bituminous saturated—D173

Woven burlap fabric, bituminous saturated—D1327

Treated glass fabric—D1668

Coal-tar saturated organic felt—D227

Asphalt saturated organic felt—D226

The number of plies of saturated felt or fabric should be increased with increase in the hydrostatic head to which the membrane is to be subjected. Five plies is the maximum commonly used in building construction, but 10 or more plies have been recommended for pressure heads of 35 ft or greater. The thickness of the membrane crossing the wall footings at the base of the wall should be no greater than necessary, to keep very small the possible settlement of the wall due to plastic flow in the membrane materials.

The membrane should be built up ply by ply, the strips of fabric or felt being laid immediately after each bed has been hot-mopped. The lap of succeeding plies or strips over each other depends on the width of the roll and number of plies. In any membrane there should be a lap of the top or final ply over the first, initial ply of at least 2 in. End laps should be staggered at least 24 in, and the laps between succeeding rolls should be at least 12 in.

At least one ply of a membrane should be fabric. The minimum weight of felt should be 13 lb/100 ft^2; of fabric, 10 oz/yd^2. About 1 gal of primer per 100 ft^2 of wall should be applied to the walls before the first mopping of bitumen. Immediately after a membrane has been completed, it should be protected by a l-in mortar coat or by other facings.

Alternatives to a hot-applied membrane system are cold-applied bituminous systems, liquid-applied membranes, and sheet-applied membranes, similar to those used for roofing. See also "The NRCA Waterproofing Manual," National Roofing Manufacturers Association," and ACI 515.1R-79.

Bellows-type water stops should be placed in expansion joints in basement walls. Made of 16-oz copper sheets, they should extend at least 6 in on each side of a joint. Metal-bellows water stops should be placed in both expansion and contraction joints if there is hydrostatic pressure. The protective facing of the membrane should be disconnected at expansion joints and the line of the facing filled.

Above-Grade Walls ▪ The rate of moisture penetration through capillaries in above-grade walls is low and usually of minor importance. However, such walls should not permit leakage of wind-driven rain through openings larger than those of capillary dimension.

Masonry walls above grade that leak may be made water-resistant with coatings of portland cement paints, grouts, stuccos, or pneumatically applied mortars. Pigmented organics, including conventional paints, if applied as a continuous coating without pinholes, also may be used. They are decorative but may not be so water-resistant, economical, or durable as cementitious coatings. Leakage through joints in masonry walls can be stopped by either repointing or grouting the joints. Repointing consists of cutting away and replacing the mortar from all joints to a depth of about $\frac{5}{8}$ in. Grouting consists of scrubbing a thin coating of grout over the joints. The grout may be composed of equal parts by volume of portland cement and sand passing a No. 30 sieve. Repointing is more effective but also more expensive.

(F. S. Merritt, "Building Design and Construction Handbook," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); "The NRCA Roofing and Waterproofing Manual," National Roofing Contractors Association, 10255 W. Higgins Road, Suite 600, Rosemont, IL 60018, (www.nrca.net).)

15.22 Stairs

Principal components of a stairway are described below and some are illustrated in Fig. 15.20.

Flight ▪ A series of steps extending from floor to floor, or from a floor to an intermediate landing or platform. Landings are used where turns are necessary or to break up long climbs.

Rise ▪ Distance from floor to floor.

Run ▪ Total length of stairs in a horizontal plane, including landings.

Riser ▪ Vertical face of a step. Its height generally is taken as the vertical distance between treads.

Tread ▪ Horizontal face of a step. Its width usually is taken as the horizontal distance between risers.

Nosing ▪ Projection of a tread beyond the riser below.

Carriage ▪ Rough timber supporting the steps of wood stairs.

Stringers ▪ Inclined members along the sides of a stairway. The stringer along a wall is called a wall stringer. Open stringers are those cut to follow the lines of risers and treads. Closed stringers have parallel top and bottom, and treads and risers are supported along their sides or mortised into them. In wood stairs, stringers are placed outside the carriage to provide a finish.

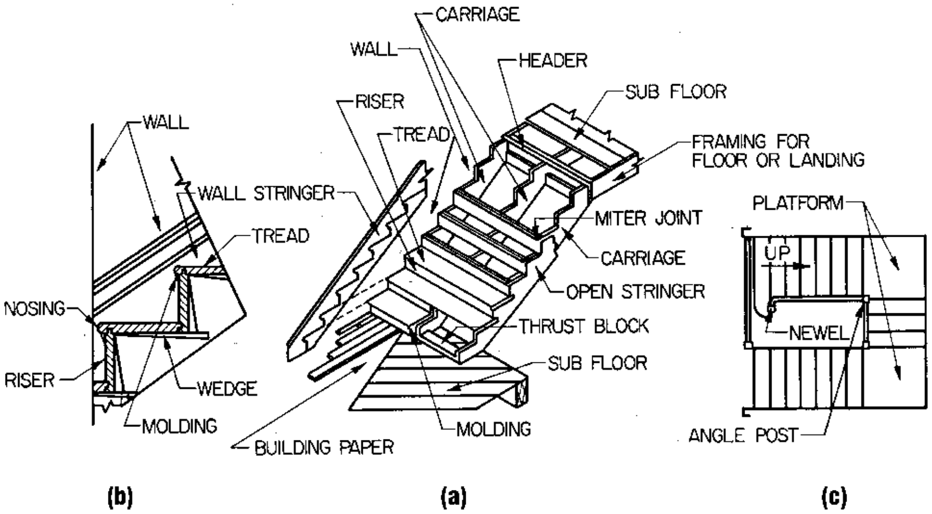


Fig. 15.20 Typical construction for wood stairs.

Railing ▪ Protective bar placed at a convenient distance above the stairs for a handhold.

Balustrade ▪ A railing composed of balusters capped by a handrail.

Handrail ▪ Protective bar placed at a convenient distance above the stairs for a handhold.

Baluster ▪ Vertical member supporting the railing.

Newel Post ▪ Post at which the railing terminates at each floor level.

Angel Post ▪ Railing support at landings or other breaks in the stairs. If an angle post projects beyond the bottom of the strings, the ornamental detail formed at the bottom of the post is called the **drop**.

Winders ▪ Steps with tapered treads in sharply curved stairs.

Headroom ▪ Minimum clear height from a tread to overhead construction, such as the ceiling of the next floor, ductwork, or piping.

Safety Rules ▪ Building codes restrict stair dimensions and also control the number of stairways. This control may be achieved by restricting the horizontal distance from any point on a floor to a stairway or the floor area contributory to a stairway. In addition, codes usually have special provisions for public buildings and the maximum capacity of a stairway.

Vertical Clearance. Minimum vertical distance from the nosing of a tread to overhead construction should never be less than 6 ft 8 in and preferably not less than 7 ft. But in general, a person of average height should be able to extend one hand forward and upward without touching an obstruction. Height between landings should not exceed 12 ft.

Stair Widths. Building codes usually specify minimum width of stairs for buildings of various types of occupancy; for example, 36 in for one- and two-family dwellings and 44 in for other types of occupancy. But the stairs should be wider than these minimums if necessary to accommodate the number of people who will use them in peak periods and emergencies. (See also "Life Safety Code," NFPA 101, National Fire Protection Association, Quincy, Mass.)

Step Sizes. The most comfortable height of risers is 7 to 7½ in. Risers less than 6 in and more than 8 in high should not be used. Treads should be 11 to 14 in wide, exclusive of nosing. Simple formulas sometimes used to proportion risers and treads include:

1. Product of riser and tread must be between 70 and 75.
2. Riser plus tread must equal 17 to 17.5.
3. Sum of the tread and twice the riser must lie between 24 and 25.5.

When designing stairs, account should be taken of the fact that there always is one less tread than riser per flight.

Guards. Barriers, called guards, at least 42 in high, should be placed along edges of stairs and landings, to prevent people from falling over the edges. The guards should be designed for a horizontal force of 50 lb/ft^2 applied 42 in above the floor or for the force transmitted by handrails on them.

Railings. Handrails, 1¼ to 2 in in diameter, should be set 2 ft 10 in to 3 ft 2 in above the intersections of tread and risers at the front of the steps on both sides of stairs. At turns of stairs, inside handrails at landings should be continuous between flights. Wide stairways should have intermediate handrails spaced not more than 60 in apart along the natural path of travel.

Emergency Use. In many types of buildings, exit stairs must be enclosed with walls having a high resistance to fire and self-closing fire-resistant doors, to prevent spread of smoke and flame (Arts. 15.3 and 15.18). In public buildings, there should be more than one fire tower, as far apart as possible.

Materials ▪ Stairs may be constructed of wood for wood-frame buildings, low nonfireproof buildings, and one- and two-story houses (Fig. 15.20). They may be built in place or shop-fabricated.

Cold-formed or plate steel stairs often are used in fire-resistant buildings. The sheets are formed into risers and subtreads or pans, into which one of several types of treads may be inserted. Treads may be made of stone, concrete, composition, or metal and usually have a nonslip surface. Stringers generally are channel-shaped.

Concrete stairs may be designed as cantilevered or inclined beams and slabs. The entire stairway may be cast in place as a single unit, or slabs or T beams formed first and the steps built up later. Concrete treads should have metal nosings to protect the edges.

(F. S. Merritt, "Building Design and Construction Handbook," 6th ed., and J. H. Callender, "Time-Saver Standards for Architectural Design Data," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); "Metal Stairs Manual," National Association of Architectural Metal Manufacturers," 8 S. Michigan Ave., Chicago, IL 60603 (www.arcat.com); "Life Safety Code Handbook," National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02269 (www.nfpa.org).)

15.23 Escalators

Providing continuous operation without operators, escalators, or powered stairs, are used when it is necessary to move large numbers of people from floor to floor. They have large capacity with low power consumption. Large department stores provide vertical-transportation facilities for one person per hour for every 20 to 25 ft^2 of sales area above the entrance floor, and powered stairs generally carry 75 to 90% of the traffic, elevators the rest.

In effect, an escalator is an inclined bridge spanning between floors, with an endless belt to transport passengers. Main components are a steel trussed framework, handrails, and an endless belt with steps. At the upper end is a matching pair of motor-driven sprocket wheels and a worm-gear driving machine. At the lower end is a matching pair of sprocket wheels. Two precision-made roller chains travel over the sprockets pulling the endless belt. The steps move on an accurately made set of tracks attached to the trusses. Each step is mounted on resilient rollers.

Normally, escalators move at 90 or 120 ft/min and are reversible in direction. Slope is standardized at 30°.

For a given speed, width of step determines the capacity of the powered stairs. Standard widths are 32 and 48 in between handrails, with corresponding capacities at 90 ft/min of 5000 and 8000 persons per hour. At 120 ft/min, a 48-in escalator can carry as many as 10,000 persons per hour.

Escalators usually are installed in pairs—one for carrying traffic up and the other for moving traffic down. The units may be placed parallel to each other in each story or crisscrossed; the latter placement generally is preferred for compactness. Fire-protection devices may be incorporated into the stairway installation.

A structural frame should be erected around the stairwell to carry the floor and wellway railing. The stairway should be independent of this frame.

("Life Safety Code Handbook," National Fire Protection Association, Quincy, Mass (www.nfpa.org); "Safety Code for Elevators, Dumbwaiters, Escalators, and Moving Walls," A 17.1, American National Standards Institute, New York (webstore.ansi.org); G. R. Strakosch, "Vertical Transportation: Elevators and Escalators," and B. Stein et al., "Mechanical and Electrical Equipment for Buildings," 7th ed., John Wiley & Sons, Inc., New York (www.wiley.com).)

15.24 Elevators

Electric traction elevators are used exclusively in tall buildings. Hydraulic elevators are usually used for low-rise freight, with lifts up to about 50 ft, but may be used for passenger service in buildings up to six stories high, where they cost less to operate.

Major components of an electric traction installation include the hoistway, car or cab, hoist wire ropes, driving machine, control equipment, counterweights, guide rails, safety devices, machine room, and pit (Fig. 15.21). The car is a cage of light metal supported on a structural frame, to the top of which the ropes are attached. The ropes raise and lower the car. They pass over a grooved motor-driven sheave and are fastened to the counterweights. The elevator machine that drives the sheave consists of an electric motor, brakes, and auxiliary equipment, which are mounted, with the sheave, on a heavy structural frame. The counterweights, consisting of blocks of cast iron in a frame, are needed to reduce power requirements.

The paths of the counterweights and the car are controlled by separate sets of T-shaped guide rails. The control and operating machinery may be placed in a penthouse above the shaft or in the basement. Safety springs or buffers are placed in

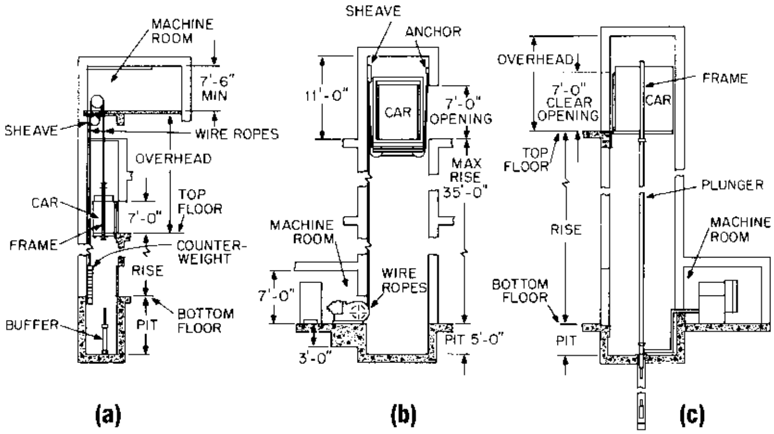


Fig. 15.21 Some lifting arrangements for elevators: (*a*) electric elevator with driving machine at the top of the hoistway; (*b*) electric elevator with driving machine in the basement; (*c*) hydraulic elevator moved by plunger.

the pit to bring the car and counterweights to a safe stop if either passes the bottom terminal at normal speed. Hoistways must be enclosed with noncombustible materials of high fire resistance (Art. 15.3).

Elevators and related equipment, such as machinery, signal systems, controls, ropes, and guide rails, are generally supplied and installed by the manufacturer. The general contractor has to guarantee the dimensions of the shaft and its freedom from encroachments. The owner's architect or engineer is responsible for the design and construction of components needed for supporting the plant, including buffer supports, machine-room floors, trolley beams, and guide-rail bracket supports. Magnitudes of loads generally are supplied by the manufacturer, with a 100% allowance for impact.

Driving machines may be winding-drum or traction type, depending on whether the ropes are wound on drums on the drive shaft or are powered by a drive sheave. The traction type is usually used; it may be double-wrap or single-wrap. For the double-wrap, to obtain sufficient traction between the ropes and the driving sheave, which has U-shaped or round-seat grooves, a secondary or idler sheave is used (Fig. 15.22*a*). In the single-wrap types, the ropes pass over the traction or driving sheave only once, so there is a single wrap, or less, of the ropes on the sheave (Fig. 15.22*d*). The traction sheave has wedge-shaped or undercut grooves for gripping the ropes. For the same weight of car and counterweight, the sheave has half the loading of the double-wrap machine.

In most buildings, driving machines are installed in a penthouse. When heavy loads are to be handled and speed is not important, a 2:1 roping may be used (Fig. 15.22*c*), in which case the car speed is only half that of the rope. Ends of the rope are anchored to the overhead beams, instead of being attached to the car and counterweights, as for 1:1 roping. With this arrangement, the anchorages carry half the weight of car and counterweights, so the loading on the traction and secondary sheaves is only about half that for the 1:1 machine. Therefore, a less costly motor can be used. When a machine must be installed in the basement (Fig. 15.22*b*), the load on the overhead supports is increased, cable length is tripled, and additional sheaves are needed, adding substantially to the cost.

Passenger Elevators ▪ The number of passenger elevators needed to serve a building adequately depends on their capacity, volume of traffic, and interval between cars. Platform sizes should conform to the standards of the National Elevator Industry, Inc.

Traffic is measured by the number of persons handled in 5-min periods. Dividing the peak 5-min traffic flow by the 5-min handling capacity of an

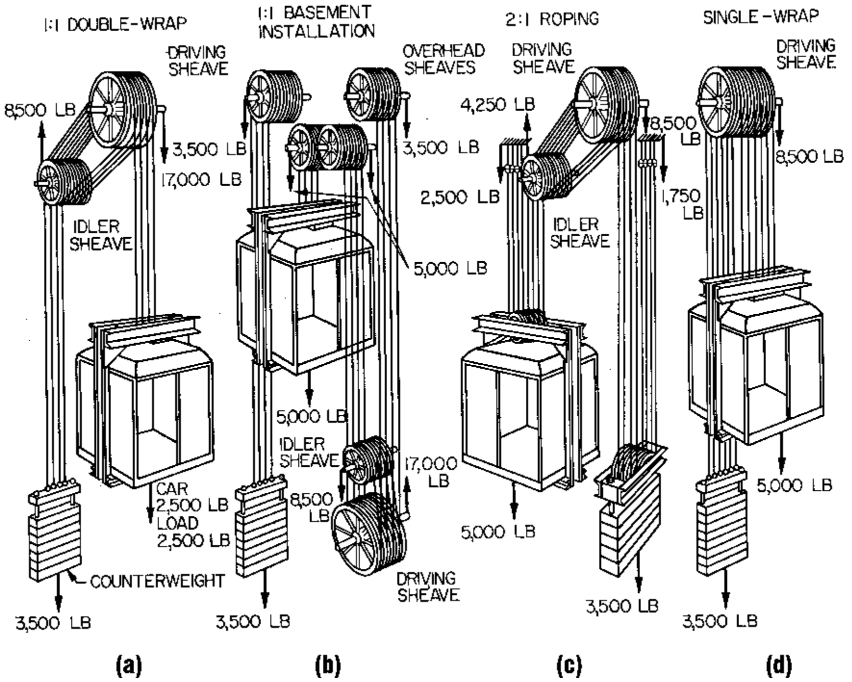


Fig. 15.22 Types of roping for elevators driven by electric traction machines.

elevator gives the minimum number of elevators required. The 5-min handling capacity of an elevator is determined from the round-trip time. Round-trip time is composed principally of the time for a full-speed round trip without stops, time for accelerating and decelerating per stop, time for leveling at each stop, time for opening or closing gates and doors, time for passengers to move in and out, reaction time of operator, lost time due to false stops, and standing time at top and bottom floors.

After the number of elevators has been computed on the basis of traffic flow, a check should be made on the **interval**, the average time between elevators leaving the ground floor. Interval is a significant measure of good service.

Fully automatic elevators are used in nearly all multistory buildings. These systems are capable of adjusting to varying traffic conditions. Since the elevators are operatorless, several safety devices are incorporated in addition to those commonly installed in manually operated systems—an automatic load weigher to prevent overcrowding, buttons in car and starter station to stop the doors from closing and hold them open, lights to indicate floor stops pressed, two-way loudspeaker system for communication with the starter station, and auxiliary power systems if the primary power and supervisory systems fail. Safety devices also prevent the doors from closing when a passenger is standing in the doorway. The elevators cannot move when the doors are open.

Department stores should be served by a coordinated system of moving stairs and elevators (see Art. 15.23). The required capacity of the vertical-transportation system should be based on the transportation or merchandising area and the maximum density to which it is expected to be occupied by shoppers. The transportation area is all the floor space above or below the first floor to which shoppers and employees must be moved. The transportation capacity is the number of persons per hour that the vertical-transportation system can distribute from the main floor to the other merchandising floors. The ratio of the peak transportation capacity to the transportation area is called the density ratio, which is about 1:20 for a busy department store. So the required hourly handling capacity of a combined moving stairs and elevator system equals 5% of the transportation area. The elevator system generally is designed to handle about 10% of the total.

Multivoltage controls normally are used for passenger elevators. Freight elevators may have variable voltage or ac rheostatic. With multivoltage, the hoisting motor is dc operated. A motor-generator set is provided for each elevator, and the speed and direction of motion of the car are controlled by varying the generator field. This type of elevator permits the most accurate stops, the most rapid acceleration and deceleration, and minimum power consumption for an active elevator. Automatic leveling to compensate for rope stretch or other variations from floor level is an inherent part of multivoltage equipment. The ac rheostatic type generally is chosen to keep initial cost down when the elevator is to be used infrequently (less than five trips per hour on a normal business day).

For low-rise elevators, hydraulic equipment may be used to lift the car. It sits atop a plunger, or ram, which operates in a pressure cylinder (Fig. 15.21*c*). Oil is the pressure fluid and is supplied through a motor-driven positive-displacement pump, actuated by an electric-hydraulic control system. To raise the car, the pump is started, discharging oil into the pressure cylinder and forcing the ram up. When the car reaches the desired level, the pump stops. To lower the car, oil is released from the pressure cylinder and returns to a storage tank.

Capacity of electrohydraulic passenger elevators ranges from 1000 to 4000 lb at speeds from 40 to 125 ft/min. With gravity lowering, down speed may be 1.5 to 2 times up speed. So the average speed for a round trip can be considerably higher than the up speed. Capacity of standard electrohydraulic freight elevators ranges from 2000 to 20,000 lb at 20 to 85 ft/min, but they can be designed for much greater loads.

(G. R. Strakosch, "Vertical Transportation: Elevators and Escalators," 3rd ed. and B. Stein et al., "Mechanical and Electrical Equipment for Buildings," 9th ed., John Wiley & Sons, Inc., New York (www.wiley.com); "Safety Code for Elevators, Dumbwaiters, Escalators, and Moving Walks," ANSI A17.1, American National Standards Institute, New York (webstore.ansi.org); F. S. Merritt, "Building Design and Construction Handbook," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com).)

15.25 Heat Flow and Thermal Insulation

Heat transfer into and out of a building or its parts may be substantially decreased by use of materials that resist heat flow or a type of construction that achieves the purpose. Some structural materials, such as wood and lightweight concrete, also have good insulating properties. But in general, certain nonstructural materials offer greater resistance to heat flow for a given thickness and therefore may be more economical in many applications.

Most insulating materials employ still air as the insulator. Some, such as cork, cellular glass, and foamed plastics, enclose small particles of air in cells. Granular materials, such as pumice, vermiculite, and perlite, trap air in relatively large enclosures. In fibrous materials, thin films of air cling persistently to all surfaces and serve as the heat barrier. In cavity-wall construction, a dead air space is formed between the wythes.

Reflective insulation involves a different principle. Metal foil is combined with an air gap to reduce heat flow. The shiny metal reflects heat, conducts it rapidly away from a heat source, and radiates heat slowly. An air gap of $\frac{3}{4}$ to 2 in on at least one side of the foil acts as a barrier to heat transfer by conduction. So if heat is radiated to a bright aluminum foil, 95% will be reflected back. If it receives heat by conduction, it will lose only 5% by radiation from the opposite face. To prevent condensation troubles, use at least two reflective surfaces separated by a dead air space. But do not place a foil on the cold side of a construction unless a better vapor barrier is provided close to the warm side.

Heat is transmitted by conduction, convection, and radiation. All materials conduct heat; some, such as metals, are excellent conductors, but others, such as cork, are poor conductors. Convection occurs when heat is transmitted by air flow; heat is transferred by conduction from a warm surface to cooler air in contact with it and from warm air to a cooler surface. Since warm air tends to rise and cool air to fall, the air flow may carry heat from a warm area to a cooler one. Heat transmitted by conduction or convection is proportional to temperature difference. Radiation, in contrast, is the flow of heat between a warm and cool surface with no material contact.

Heat usually is measured in **British thermal units (Btu)**. For practical purposes, 1 Btu is the amount of heat required to raise the temperature of 1 lb of water 1 degree Fahrenheit. Heat flow is measured by **thermal conductivity** *K*, which is defined as the number of Btu that will flow in 1 h through a material 1 ft square and 1 in thick because of a temperature difference of 1 °F. Similarly, **thermal conductance** *C* is defined as the heat flow through a given thickness of 1-ft-square material with a 1 °F temperature differential. Note that these basic units do not include the insulating values of air films at the surfaces of the material, only flow from surface to surface. **Resistance** *R* is the reciprocal of conductance.

Since building components are built up of several materials, including air spaces and surface films, the **overall conductance** *U* of a construction is needed in heat-transfer calculations. This factor is defined as the number of Btu that will flow in 1 h through 1 ft^2 of the structure from air to air with a temperature differential of 1 °F. Values of *K*, *C*, and *U* or *R* have been determined experimentally for many materials and types of construction ("Handbook of Fundamentals," American Society of Heating, Refrigerating and Air Conditioning Engineers, 1791 Tullie Circle, N.E., Atlanta, Ga (www.ashrae.org).).

The thermal conductance of an outside air film in a 15-mi/h wind is 6.00 Btu/h, of an inside air film (still air), 1.65 Btu/h; and of an air space ¾ in or more wide, 1.10 Btu/h.

When the overall conductance of a construction is not given in a table, it may be computed from tabulated values of conductance of each component and air films. For example, consider a wall composed of 4 in of brick ($K = 9.2$) and ½-in wallboard ($C = 1.00$) separated by an air space ($C = 1.10$). The calculations are shown in Table 15.9.

Suppose, now, 1 in of insulation ($K = 0.25$) were to be incorporated into this wall. The resistance *R* of the insulation ($1/K$) is 4. Thus, the resistance of the original wall is increased to $3.116 + 4$, or 7.116; the new overall conductance *U* becomes $1/7.116 = 0.14$.

15.26 Prevention of Condensation

Normally, air contains water vapor, which tends to move from a warm region to a cooler one. The lower the temperature, the less vapor the air can hold. If the air is saturated (100% relative humidity), a temperature drop will cause some of the vapor to condense. The temperature at which this occurs is called the **dew point**.

Since almost all building materials or the joints between them are porous, vapor will permeate them. If the dew point is reached between inner and outer surfaces, the vapor will condense, and the temperature differential will cause more vapor to penetrate, repeating the process. In cold weather, the dew point often occurs within insulation in walls and roofs. If vapor reaches it, the condensation may saturate the insulation, drastically reducing its insulating value. Furthermore, the moisture may rot or rust the structure or stain interior finishes. If temperatures are low, the water may freeze and in expanding, as ice always does, crack the structure.

A simple solution to condensation is to stop the flow of water vapor with a vapor barrier on the warm side. Since the dangers of condensation are greatest in the heating season, vapor barriers should be installed on the interior side of walls and roofs, next to the insulation.

Table 15.9 Calculation of Overall Conductance of a Wall

Item	*K*	Thickness, in	*C*	$R = 1/C$
Outside film			6	0.166
Brick	9.2	4	2.30	0.434
Air space			1.10	0.910
Wallboard		½	1.00	1.000
Inside film			1.65	0.606
Total resistance				3.116

Overall conductance $U = 1/3.116 = 0.32$.

Aluminum foil is a good, economical vapor barrier. Some insulations come equipped with it attached to one side. Other vapor barriers include aluminum paints, plastic paints and films, asphalt paints, rubber-base paints, asphalt, and foil-laminated papers.

The ability of a material to pass vapor is measured by the **perm**, defined as a vapor-transmission rate of 1 grain of water vapor through 1 ft^2 of material per hour when the vapor-pressure difference equals 1 in of mercury (7000 grains = 1 lb). A material with a vapor-transmission rate of 1 perm or less is considered a good vapor barrier. **Rep** is the reciprocal of perm; it measures resistance to vapor transmission.

Since vapor barriers are not likely to be perfect or installed perfectly, some vapor may penetrate to the insulation. Means should be provided to let this vapor escape. Hence, the exterior surface should be as porous as possible or vented and yet prevent rain from penetrating. Cold-side venting may be desirable, even though condensation does not occur in the insulation, because it may occur instead in back of the exterior facing. Whenever the dew point occurs within a material, condensation will not take place until the water vapor encounters the surface of another material with greater resistance to the vapor flow.

Vapor also tends to flow through insulated ceilings into attics and air spaces under a roof. If these spaces are not ventilated with air capable of removing the moisture, trouble can result. In general, vent area should total about $\frac{1}{300}$ of the horizontal projection of the roof area. If possible, both high and low vents should be installed to ensure air flow.

15.27 Heating

Required capacity of a heating plant is determined mainly by the total heat loss from a building through conduction, radiation, and infiltration. To allow for the temperature pickup usually required in the morning, however, the plant should have a capacity 20% larger than this heat loss. But do not choose too large a unit, because then operating efficiency suffers.

The heat loss depends on the design inside and outside temperatures. (See tables in the "ASHRAE Guide and Data Book," American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, Ga. The design outdoor temperatures are not the lowest ever attained in the region, but a slightly higher recommended value.) The difference between inside and outside temperatures is the temperature gradient. When multiplied by the exposed surface area of a material or construction and its overall thermal conductance *U* (Art. 15.25), the gradient determines the hourly heat flow in Btu. The sum of these products for all exposed surfaces—walls, windows, roofs,—yields the total heat loss through them.

Heat loss through basement floors and walls may be determined from groundwater temperature, which ranges from about 40 to 60 °F in the northern sections of the United States and from 60 to 76 °F in the southern sections (Table 15.10). (For specific areas, see the "ASHRAE Guide.")

Heat loss from a floor on grade without edge insulation is about 75 Btu/h per linear foot of exposed edge in the cold northern sections of the United States, 65 in the temperate zones, and 60 in the warm south. With 1 in of insulation, these rates drop to 60, 55, and 50; with 2 in, to 50, 45, and 40.

To obtain the heat loss through unheated attics, the equilibrium attic temperature must first be computed by equating heat gain to the attic via the ceiling to heat loss through the roof. The same procedure should be used to obtain the temperature of other unheated spaces, such as cellars and attached garages.

To the heat load for exposed surfaces must be added the load due to cold air infiltrating and warm air leaking out. The amount of leakage depends on crack area, wind velocity, and number of exposures, among other things. To account for leakage, the assumption is made that cold outside air will be heated and pumped into the building to create a static pressure large enough to prevent

Table 15.10 Heat Losses Below Grade

Groundwater temp, °F	Basement-floor loss,* Btu/h ft^2	Below-grade wall loss, Btu/h ft^2
40	3.0	6.0
50	2.0	4.0
60	1.0	2.0

* Based on basement temperature of 70°F.

cold air from infiltrating. The amount of heat q in Btu/h required to warm up this cold air is given by

$$q = 1.08QT \tag{15.15}$$

where $Q = \text{ft}^3/\text{min}$ of air to be warmed $= VN/60$
$T =$ temperature rise of air, °F
$V =$ volume of room, ft^3
$N =$ number of air changes per hour

If the heating plant also will be used to produce hot water, the added capacity for this purpose should be determined and added to the heat load.

A **warm-air heating system** supplies heat to a room by bringing in a quantity of air above room temperature. The amount of heat added by the air must be at least equal to that required to counteract heat losses. Equation (15.15) gives this heat if T is taken as the difference between the temperature of the air leaving the grille and the room temperature and Q as the ft^3/min of air supplied to the room. In good systems, the discharge temperatures range from 135 to 140 °F. Supply grilles should be arranged to blow a curtain of air across exposed walls and windows. The best location is near the floor. Return-air grilles should be installed in the interior, preferably at the ceiling.

Ducts for warm-air systems generally are designed by the equal-friction method. Sizes are calculated to accommodate the design air quantity of the heater with a predetermined friction factor. The pressure loss due to friction should not exceed 0.15 in of water per 100 ft of duct. Also, starting velocity of the air in main ducts should be kept below 900 ft/min in residences; 1300 ft/min in schools, theaters, and public buildings; and 1800 ft/min in industrial buildings. Velocity in branch ducts should be about two-thirds of these, and in branch risers, about one-half. But too low a velocity will require uneconomical, bulky ducts. (See the "ASHRAE Guide and Data Book.")

In a forced warm-air system, a thermostat calls for heat, starting a heat source. When the air chamber in the heater reaches about 120 °F, the fan starts. (If the discharge temperature exceeds 180 °F, a safety element in the air chamber shuts off the heat source.) The heat source stops when the indoor temperature reaches the value at which the thermostat is set. But the fan continues to operate until the air cools to below 120 °F.

In warm-air perimeter heating, often used with concrete floors on ground, the heater discharges warm air to two or more underfloor radial ducts feeding a perimeter duct. Floor grilles or baseboard grilles are located as in a conventional warm-air heating system, with collars connected to the perimeter duct.

A **hot-water heating system** consists of a heater or furnace, radiators, piping systems, and circulator. Normally, forced circulation systems are used because they can maintain higher water velocities and therefore require smaller pipes and provide more sensitive control.

Three types of piping systems are in general use. The one-pipe system (Fig. 15.23*a*) has many disadvantages and is not usually recommended. The two-pipe direct-return system (Fig. 15.23*b*) provides all radiators with the same supply-water temperature, but the last radiator has more pipe resistance than the first. This can be balanced out by installing orifices in the other radiators to add an equivalent resistance and by sizing the pump for the longest run. In the two-pipe reversed-return

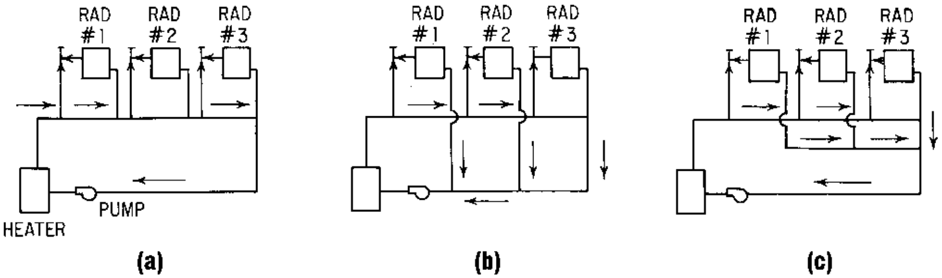


Fig. 15.23 Types of hot-water heating systems: (*a*) one pipe; (*b*) two-pipe direct-return; (*c*) two-pipe reversed-return.

system (Fig. 15.23*c*), the total pipe resistance is about the same for all radiators.

For a hot-water system, supply design temperatures usually are 180 °F, with a 20 °F drop assumed through the radiators. Thus, the temperature of the return riser would be 160 °F. The amount of heat required to offset the 20 °F drop, in Btu/h, is

$$q = 10{,}000Q \qquad (15.16)$$

where Q = flow of water, gal/min. Piping may be sized for the required water flow with the aid of friction flow charts and tables showing equivalent pipe lengths for fittings. (See, for example, the ASHRAE "Handbook of Fundamentals.") Water velocity should be limited to a maximum of 4 ft/s. Loss of pressure due to friction should be between 0.25 and 0.60 in of water per foot. The system must be provided with an expansion tank, located at least 3 ft above the highest radiator and in a location where the water will not freeze. The tank should be sized for 6% of the total volume of water in radiators, heaters, and piping. In very tall buildings, to avoid too high a static pressure on the boiler, heat exchangers should be provided in the upper levels.

In a hot-water system, an immersion thermostat in the heater controls the heat source to maintain design heater water temperature (usually about 180 °F). When the room thermostat calls for heat, the circulator starts. Thus, an immediate supply of hot water is available for the radiators. For 170 °F average water temperature, 1 ft^2 of radiation surface emits 150 Btu/h.

A **steam-heating system** consists of a boiler or steam generator and a piping system connecting to individual radiators or convectors. In a one-pipe system (Fig. 15.24*a*), the pipe supplying steam to the radiators also is used to return condensate to the boiler. On start-up, the steam must push air out of the pipe and radiators. For this purpose, the radiators are equipped with thermostatic air valves. Orifice size in the air vents must be varied to balance the system; otherwise, radiators at the far end of a pipe run may get steam much later than the near end. Valves in a one-pipe system must be fully open or closed. In a two-pipe system (Fig. 15.24*b*), steam is fed to the radiators through one pipe and the condensate returned through a second pipe. When condensate cools the radiator below 180 °F, a trap opens to allow the condensate to return to a collecting tank, from which it is pumped to the boiler. The wet-return system (Fig. 15.24*c*) usually has a smaller pressure head available for pipe loss. It is a self-adjusting system depending on the load. When the condensate collects sufficiently in the return main above boiler level, the pressure will force the condensate into the boiler.

In all cases, the steam-supply pipes must be pitched to remove condensate from the pipe. Where condensate flows against the steam, the pipe may have to be oversized. Pipe capacities for supply risers, runouts, and radiator connections are given in the ASHRAE "Handbook of Fundamentals." Capacities are expressed in square feet of equivalent direct radiation (EDR).

$$1\ \text{ft}^2\ \text{EDR} = 240\ \text{Btu/h} \qquad (15.17)$$

Where capacities are in pounds per hour, 1 lb/h = 970 Btu/h.

A **vacuum-heating system** is similar to a steam pressure system with a condensate return pump. The vacuum pump pulls noncondensables from the piping and radiators for discharge to the atmosphere, whereas in a steam pressure system thermostatic vents are opened for this purpose.

Unit heaters often are used for large open areas, such as garages, showrooms, stores, and workshops. The units usually consist of a heat source or heat exchanger and an electrically operated fan. Heat may be supplied by steam or electricity or by burning gas. When gas-fired unit heaters are used, however, an outside flue must be provided to dispose of the products of combustion. Sizes of gas piping and burning rates for gas can be obtained from the ASHRAE handbook. Efficiency of most gas-fired equipment is between 70 and 80%.

Radiant heating, or panel heating, consists of a warm pipe or electric cables embedded in the floor, ceiling, or walls. Joints in ferrous pipe should be welded, whereas those in nonferrous pipe should be soldered, and return bends should be made with a pipe bender instead of with fittings, to avoid joints. All piping should be subjected to a hydrostatic test of at least three times the working pressure, with a minimum of 150 psig. Repairs are costly after construction has been completed. Piping and circuiting are similar to those for a hot-water system with radiators and convectors, except that cooler water is used. But a 20 °F temperature drop usually is assumed. Therefore, charts used for the design of hot-water piping systems may be used for panel heating too. Floor

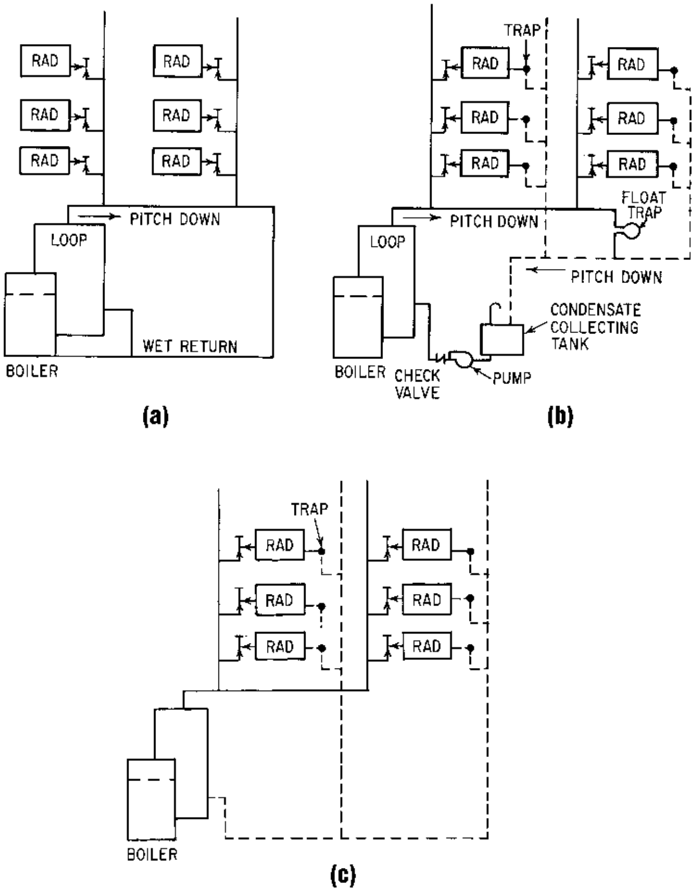


Fig. 15.24 Types of steam-heating systems: (*a*) one-pipe with condensate returning through the supply pipe; (*b*) two-pipe; (*c*) two-pipe wet-return.

panel temperatures generally are maintained about 85 °F or lower and ceiling panel temperatures at 100 °F or lower. It is possible with panel heating to maintain relatively low room air temperatures with comfort, but the system should be designed for standard room temperatures to prevent discomfort after the thermostat stops water circulation.

("ASHRAE Handbook of Fundamentals," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Ga (www.ashrae.org); B. Stein et al., "Mechanical and Electrical Equipment for Buildings," John Wiley & Sons, Inc., New York (www.wiley.com); F. S. Merritt, "Building Design and Construction Handbook," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com).)

15.28 Air Conditioning

Required capacity of a cooling plant is determined by the heat transmitted to the conditioned space through the walls, glass, ceiling, floor, and so on and all the heat generated in the space. The total cooling load consists of sensible and latent heat. Sensible heat is the part that shows up in the form of a dry-bulb temperature rise. It includes heat transmitted through the building enclosure; radiation from the sun; and heat from lights, people, electrical and gas appliances, and outside air brought into the air-conditioned space. Latent heat is that needed to remove moisture from the air. Usually, the moisture is condensed out on the cooling coils in the cooling unit; 1050 Btu is required per pound of condensation.

Design conditions for comfort cooling usually are 80 °F dry bulb and 50% relative humidity. Design outdoor temperatures are not the highest ever recorded in a region but a slightly lower recommended value. (See tables in the "ASHRAE Handbook of Fundamentals.") The difference between indoor and outdoor temperatures multiplied by the area of walls, roofs, windows, and so forth and the respective overall coefficients of conductance *U* (Art. 15.24) yields the heat gain through each.

Radiation from the sun through glass and roofs adds substantially to the heat load. (The sun effect on walls, however, generally can be neglected.) Sun through unshaded window glass can add about 200 $\text{Btu/h}\cdot\text{ft}^2$ through windows facing east and west; about three-fourths as much for windows facing northeast and northwest; and half as much for windows facing south. For most roofs, total equivalent temperature difference for calculating heat gain due to the sun is about 50 °F. Roof sprays sometimes are used to reduce this load. With a water spray, the equivalent temperature difference may be taken as 18 °F.

Heat from electric lights and other electrical appliances can be computed from

$$q = 3.42W \tag{15.18}$$

where q = Btu/h developed

W = watts of electricity used

For fluorescent lighting, add 25% of the lamp rating for the heat generated in the ballast.

Heat gain from people for various types of activities is given in tables in the ASHRAE handbook.

The sensible heat from outside air brought into a conditioned space can be computed from

$$q_s = 1.08Q(T_o - T_i) \tag{15.19}$$

where q_s = sensible load due to outside air, Btu/h

Q = ft^3/min of outside air brought into conditioned space

T_o = design dry-bulb temperature of outside air

T_i = design dry-bulb temperature of conditioned space

The latent load due to outside air in Btu/h is

$$q_l = 0.67Q(G_o - G_i) \tag{15.20}$$

where G_o = moisture content of outside air, grains/lb of air

G_i = moisture content of inside air, grains/lb of air

The moisture content of air at various conditions may be obtained from a psychrometric chart.

The total heat load for sizing a cooling plant also must include heat from fans in the air conditioning system, which usually ranges from 3½ to 5% of the sensible load, and heat loss from ducts. The load can be converted to tons of refrigeration by

$$\text{Load in tons} = \frac{\text{load in Btu/h}}{12{,}000} \tag{15.21}$$

A **ton of refrigeration** is the amount of cooling that can be done by a ton of ice melting in 24 h.

Basic Cycle ▪ Figure 15.25*a* shows the basic air conditioning cycle of the direct-expansion type. The compressor takes refrigerant gas at a relatively low pressure and compresses it to a higher pressure. The hot gas is passed to a condenser where heat is removed and the refrigerant liquefied. This liquid then is piped to the cooling coil of an air-handling unit and allowed to expand to a lower pressure (suction pressure). The liquid vaporizes or is boiled off by the relatively warm air passing over the coil. The compressor pulls away the vaporized refrigerant to maintain the required low coil pressure with its accompanying low temperature. A system in which the refrigerant chills water, which is circulated to air-handling units for cooling air, is shown in Fig. 15.25*b*.

Air Quantity ▪ The amount of air, ft^3/min, to be handled can be computed from

$$Q = \frac{q_s}{1.08(T_i - T_d)} \tag{15.22}$$

where q_s = total sensible heat load, Btu/h

T_i = indoor temperature (dry bulb)

T_d = dry-bulb temperature of air discharged from air-handling unit

T_d should be about 3 °F higher than the room dew point, to avoid sweating ducts.

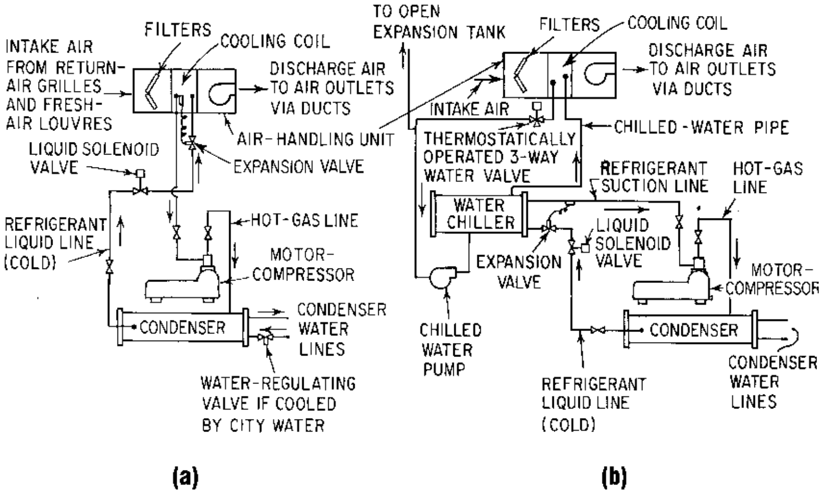


Fig. 15.25 Air conditioning cycles: (*a*) direct-expansion; (*b*) chilled water.

Condensers ▪ If a water-cooled condenser is used to remove heat from the refrigerant, it may be supplied with city water, and the warm water may be discharged to a sewer. Or a water tower may be used to cool condenser water, which then can be recirculated to the condenser. If the wet-bulb temperature is low enough, the condenser and water tower can be replaced by an evaporative condenser. The capacity of such water savers as towers and evaporative condensers decreases as the wet-bulb temperature increases. The amount of water in gallons per minute required for condensers is

$$Q = \frac{\text{tons of cooling} \times 30}{\text{water-temperature rise}} \tag{15.23}$$

Condensers for small cooling units can be cooled by a fan blowing air over the refrigerant coils.

Zoning ▪ Multizone air-handling units control the temperature of several zones in a building without a separate air-handling unit for each zone. When a zone thermostat calls for cooling, the damper motor for that zone opens the cold deck dampers and throttles the warm deck dampers. Thus, the same unit can provide cooling for one zone while it supplies heat for another zone.

Filters ▪ The area of the filters in the air-handling units should be large enough so that the air velocity does not exceed 350 ft/min for low-velocity filters and 550 ft/min for high-velocity filters. Minimum filter area in square feet equals air flow in ft^3/min divided by maximum air velocity across the filters, ft/min. Most filters are the throwaway or cleanable type. Electrostatic filters usually are used in industrial installations, where a higher percentage of dust removal must be obtained, in combination with regular throwaway or cleanable filters, which remove large particles.

Packaged Units ▪ For lower-cost air conditioning installations, "packaged" or preassembled units may be used. They generally operate on the complete cycle shown in Fig. 15.25*a*. For window units, the condenser, projecting outside the building, is air-cooled, and the same motor usually runs both the fan for the cooling coil and that for the condenser. Small floor-type units may be air-cooled; larger ones generally are water-cooled.

Built-Up Units ▪ These are air conditioning units assembled on the site. Usually limited to large units, with capacity of 50 tons or more, they provide cooling air in summer and heated air in winter. They are equipped with filters, return-air fan, compressor, condenser, dampers, and controls, as required. The units may be installed outdoors at grade or on roofs, or indoors as a central plant.

Absorption Chillers ▪ These use heat to regenerate the refrigerant. The compressor of the basic air conditioning cycle (Fig. 15.25*a*) is replaced by an absorber, pump, and generator. The refrigerant is regenerated by absorption in a weak solution of refrigerant and water, forming a strong solution, which is heated in the generator. The refrigerant vapor thus is driven out of the solution and brought to the condenser under pressure. When low-cost steam is available, absorption systems may be more economical to operate than the systems with compressors. In general, steam consumption is about 20 lb/h per ton of refrigeration.

Variable-Air-Volume (VAV) Systems ▪ In a VAV system, air is supplied at constant temperature, but the volume is varied to meet changing loads in interior spaces or zones (Fig. 15.26*a*). Zoning is important for good temperature control.

Any type of diffuser, or register, may be used with VAV control units. Generally, however, linear-slot-type diffusers (Fig. 15.26*b*) are preferred, because they discharge air into a room with a horizontal flow that hugs the ceiling and results in more uniform temperature within the room.

While variable air volume can be produced by modulating the supply-air fan, terminal control units usually give better results. Types of control units generally used include the following:

Shut-off control diffusers, which may provide shut-off operation, multiple slots, integral slot diffuser, and electric-pneumatic or system- powered controls.

Fan-powered control units, often used for perimeter and special areas, which may come with pressure-compensating controls with factory-installed hot-water or multistage electric coils that have pneumatic or electric controls.

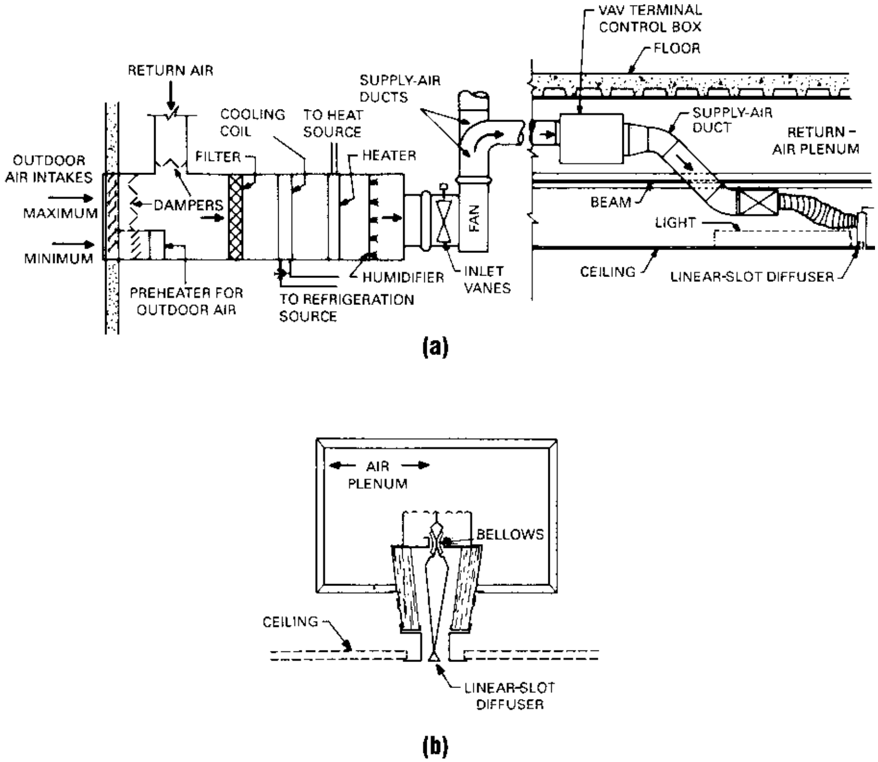


Fig. 15.26 Variable-air volume system. (*a*) Fan blows supply air at constant temperature but with variable flow through a terminal box to a diffuser. (*b*) Terminal box with linear-slot diffuser.

Dual-duct VAV control units, which are used for dual-duct systems that require VAV for perimeter areas. They feature pressured-compensated shutoff operation with pneumatic, electric, or system-powered controls, with a variable-volume cold deck and constant-volume or variable-volume hot deck.

Air-Water Systems ▪ An alternative to the all-air systems, air-water systems furnish chilled water from a remote chiller or central plant to the room terminal devices. These contain a cooling coil or a heating coil, or both. Room temperature is maintained by varying the flow of chilled water or heating fluid through the coils with valves that respond to the thermostat. Ventilation air is provided from a separate central plant directly to the room or the terminal device.

Two- or four-pipe systems are used for distribution of chilled water and hot water to the room terminals from a central plant. In a two-pipe system, the supply pipe may carry either chilled water or hot water and the second pipe is used as a return. The four-pipe system provides two pipes for chilled-water supply and return and two pipes for hot water supply and return. The installation cost of the two-pipe system is less than that of the four-pipe system, but the versatility is less. The major disadvantage of the two-pipe system is its inability to provide both heating and cooling with a common supply pipe on days for which both heating and cooling are desired. The four-pipe system has a major drawback in loss of temperature control whenever a changeover from cooling to heating is desired. To overcome this, thermostats are used that permit selection of either cooling or heating by a manual changeover at the thermostats.

Terminal devices for air-water systems are usually of the fan-coil or induction types.

A fan-coil terminal device consists of a fan or blower section, chilled-water coil, hot water heating coil or electric-resistance heating elements, filter, return-air connection, and a housing for these components with an opening for ventilation air. The electric-resistance heating coil is often used with two-pipe systems to provide the performance of a four-pipe system without the cost of the two extra pipes for hot water, insulation, pumps, and accessories. Fan-coil units may be floor-mounted, ceiling-mounted-exposed or ceiling-mounted-recessed, or ceiling-mounted-recessed with supply- and return-air ductwork. When furnished with heating coils, the units are usually mounted on the outside wall or under a window, to neutralize the effects of perimeter heat losses.

Built-in centrifugal fans recirculate room air through the cooling coil. Chilled water circulating through the coil absorbs the room heat load. Ventilation air that is conditioned by another remote central plant is ducted throughout the building and supplied directly to the room or room terminal devices, such as a fan-coil unit. A room thermostat varies the amount of cooling water passing through the cooling coil, thus varying the discharge temperature from the terminal unit and satisfying the room thermostat.

Induction terminal units, frequently used in large office buildings, are served by a remote air-handling unit that provides high-pressure conditioned air, which may be heated or cooled and is referred to as primary air. At the terminal induction unit, which is mounted on the outside walls of each room or zone, a flow of the high-pressure primary air through several nozzles induces a flow of room air through the heating or cooling coil in the unit, to provide a mixed-air temperature that satisfies the thermal requirements of the space. The induction system is a large energy consumer because of the extra power required to maintain high air-distribution pressure and to operate simultaneously with heating and cooling.

Air-water systems generally have substantially lower installation and operating costs than all-air systems. They do not, however, provide as good control over room temperature, humidity, air quality, air movement, and noise. The best control of an air-water system is achieved with a fan-coil unit with supplemental ventilation air from a central, primary-air system that provides ventilation air.

A **heat pump** comprises equipment for heating a building by using the heat removed by the condenser in a refrigeration cycle. The heat absorbed by the refrigerant evaporator is taken from some other heat source, often outdoor air, instead of from the building. When the heat is exhausted outside the building, the heat pump also can be used for cooling. In general, heat pumps are economical for regions where the cooling season is substantially longer than the heating season and winter temperatures are not extreme. The colder the outdoor temperature, the lower the heat-pump capacity becomes, unless a constant-temperature heat source, such as warm water from a deep well, is available.

(H. E. Bovay, Jr., "Handbook of Mechanical and Electrical Systems for Buildings"; N. R. Grimm and R. C. Rosaler, "Handbook of HVAC Design"; R. W. Haines, "HVAC Systems Design Handbook"; F. S. Merritt, "Building Design and Construction Handbook," 6th ed.; R. Shuttleworth, "Mechanical and Electrical Systems for Construction," McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); F. C. McQuiston and J. D. Parker, "Heating, Ventilation, and Air Conditioning," 3rd ed.; and B. Stein et al., "Mechanical and Electrical Equipment for Buildings," 9th ed., John Wiley & Sons, Inc., New York (www.wiley.com).)

15.29 Ventilation

Natural air movement or air replacement in a room depends on prevailing winds, temperature difference between interior and exterior, height of structure, window openings, etc. For controlled ventilation, a mechanical method of air change is desirable.

Where people are working, the amount of ventilation air required will vary from one air change per hour where no heat or offensive odors are generated to about 60 air changes per hour. Table 15.11 gives the minimum amount of air recommended for various activities.

The number of air changes per hour equals $60Q/V$, where Q is the air supplied, ft^3/min, and V is the volume of ventilated space, ft^3. If there is less than one air change per hour, the ventilation system will take too long to produce a noticeable effect when first put into operation. Five air changes per hour generally is considered a practical minimum. Air changes above 60 per hour usually will create some discomfort because air velocities will be too high. Toilet and locker-room ventilation generally are covered by local building codes; 50 ft^3/min per water closet and urinal is the usual minimum for toilets and six changes per hour minimum for both toilets and locker rooms.

Removal of heat by ventilation is best done by installing exhaust outlets close to the heat source. Where concentrated sources of heat are present, canopy hoods should be used. When heat is discharged into a room, the amount of ventilation air, ft^3/min, required to remove heat not lost by transmission through enclosures is

$$Q = \frac{q}{1.08(T_i - T_0)} \tag{15.24}$$

where q = heat, Btu/h, carried away by ventilation air

T_i = indoor temperature to be maintained

T_0 = temperature of fresh air (usually outdoor air)

If a gas or moisture in the air is to be diluted, the amount of ventilation air, ft^3/min, required is $Q = X/Y$, where the vapor or gas is formed at the rate of X lb/min and Y is the allowable concentration, lb/ft^3. See also Art. 15.28.

15.30 Electric Power for Buildings

Electrical design and construction for buildings are based usually on the National Electrical Code (National Fire Protection Association, 1 Battery--march Park, Quincy MA 02269). But local building codes may have some more restrictive require-

Table 15.11 Minimum Ventilation Air for Various Activities

Type of occupancy	Ventilation ft^3/min per person
Inactive, theaters	5
Light activity, offices	10
Light activity with some odor generation, restaurants	15
Light activity with moderate odor generation, bars	20
Active work, shipping rooms	30
Very active work, gymnasiums	50

ments and should be checked. These codes contain minimum safety standards. Use of these standards does not guarantee adequate performance of an electrical system.

A building's electrical systems operate on electric currents supplied at specified effective voltages. An electric current I, amperes (A), is the rate at which electric charges flow through a circuit. If the current always flows in the same direction, it is called a direct current (dc). The current is assumed to flow from a positive to a negative terminal. An alternating current (ac) reverses direction at regular intervals.

Electromotive force or potential difference E, volts, is the force that makes electrons move in the circuit. It is opposed by a resistance R. Ohm's law relates E, I, and R:

$$E = IR \tag{15.25}$$

Electric power watts (W), or kilowatts (1 kW = 1000 W), is the rate of doing electrical work: 746 W = 0.746 kW = 1 hp. Direct-current power, W, is given by

$$W = EI = I^2R \tag{15.26}$$

Phases ▪ In single-phase ac circuits, power is the product of voltage, current, and a power factor, which equals 100% only when current and voltage are in phase, that is, pass through zero, maximums, and minimums at the same time.

If current and voltage are represented by a sine curve, one may lead or lag the other by nearly 360°. If, for example, the maximum of a sinusoidal current occurs 60° before the maximum of the voltage, the current leads the voltage by 60° or lags by 300°. In a single-phase ac system, the power factor equals the cosine of the angle between the voltage and current phases. Hence, the closer the phase angle is to 90° or 270°, the smaller the power factor and the larger the equipment and conductors needed to deliver the required power. Low power factors often may be corrected by installing synchronous motors, or by connecting static condensers across the line.

Inductance L, henrys, makes current lag voltage. **Capacitance** C, farads, makes current lead voltage. Both inductive reactance X_L, ohms, and capacitive reactance X_c, ohms, impede the flow of current. **Impedance** Z, ohms, is the total opposition to the flow of current and equals the vector sum of resistance and reactance:

$$Z^2 = R^2 + (X_L - X_c)^2 \tag{15.27}$$

Maximum voltage drop across an impedance equals maximum current times impedance.

Types of Circuits ▪ Basic circuits are either series or parallel types. A series circuit has components connected in sequence. If there is a break in a series circuit, current will not flow; hence, if one lamp goes out, all go out. Parallel (multiple or shunt) circuits, in contrast, have components with common terminals. Voltage across the components is the same, and the current divides among them, in accordance with Ohm's law [Eq. (15.25)]. Parallel circuits generally are used for electrical distribution in buildings, whereas series circuits often are used for street lighting.

Service equipment consists of a circuit breaker or switch and fuses, and their accessories, located near the point of entrance of supply conductors to a building and intended to constitute the main control and means of cutoff of the supply. **Feeders** are the conductors between the service equipment, or the generator switchboard of an isolated plant, and branch-circuit over-current-protective devices. A **branch circuit** is the part of the system between the feeder and the load, or current-consuming equipment. Branch circuits deliver current to outlets, points where current is taken for equipment. A **receptacle**, or convenience outlet, permits the circuit to be tapped with a plug and flexible cord.

Electrical Loads ▪ All conductors should be sized for the sum of the loads, in kilowatts, for lighting, motors, and appliances. Since all lights may not be on at the same time, codes generally permit for feeders a reduction in the lighting load by application of a demand factor. Codes also specify that feeders and branch circuits be sized for a minimum load, in W/ft^2 of floor area, that depends on type of occupancy. But usually, the actual load will exceed these minimums.

Conductors should not be smaller than No. 12 in branch circuits.

Small installations, such as dwellings, usually are supplied with three-wire service. This consists of a neutral and two power wires with current differing 180° in phase. Tapping across the phase wires yields a single-phase two-wire 230-volt (V) supply. Either phase wire and the neutral yield a single-phase two-wire 115-V supply. In addition, for safety reasons, a separate ground wire should be provided since the neutral, though grounded, carries current.

For larger installations, a 120/208-V three-phase, four-wire system usually is used. This consists of a neutral and three power wires carrying current differing 120° in phase. Tapping across any two phase wires yields a single-phase two-wire 208-V supply. Any phase wire and the neutral provide a single-phase two-wire 120-V supply. Other combinations yield two- or three-phase 120/208-V supplies.

No current flows in the neutral when the loads on the system's circuits are balanced. Hence, the system should be so designed that, under full load, the load on each phase leg will be nearly equal.

Current in a conductor may be computed from the following formulas, in which

I = conductor current, A
W = power, W
f = power factor, as decimal
E_p = voltage between any two phase legs
E_g = voltage between phase leg and neutral, or ground

Single-phase two-wire circuits:

$$I = \frac{W}{E_p f} \quad \text{or} \quad I = \frac{W}{E_g f} \tag{15.28}$$

Single-phase three-wire (and balanced two-phase three-wire) circuits:

$$I = \frac{W}{2E_g f} \tag{15.29}$$

Three-phase three-wire (and balanced three-phase four-wire) circuits:

$$I = \frac{W}{3E_g f} \tag{15.30}$$

Voltage drop in a circuit may be computed from the following formulas, in which

V_d = voltage drop between any two phase legs, or between phase leg and neutral when only one phase wire is used in circuit
L = one-way run, ft
cmil = circular mils (1 cmil = area of a circle 0.001 in in diameter)

Single-phase two-wire (and balanced single-phase three-wire) circuits:

$$V_d = \frac{2RIL}{\text{cmil}} \tag{15.31}$$

Balanced two-phase three-wire, three-phase three-wire, and balanced three-phase four-wire circuits:

$$V_d = \frac{\sqrt{3}\,RIL}{\text{cmil}} \tag{15.32}$$

Equations (15.31) and (15.32) contain a factor R that represents the resistance to direct current, in ohms, of 1 mil-ft of wire. For wires smaller than No. 3, resistance is the same for alternating and direct currents. For wires larger than No. 3 carrying alternating current, a correction factor should be applied because of the higher resistance. The value for R may be taken as 10.7 for copper and 17.7 for aluminum.

Copper conductors may be more economical for small-diameter conductors, for which weight is not an important consideration. The smaller weight may be advantageous for large conductors. To avoid excessive heat and incendiary conditions at splices with aluminum, use conductors preferably No. 4 AWG or larger.

In design of feeders and branch conductors, voltage drops may range from 1 to 5%. Some codes limit the voltage drop to 2.5% for combined light and power circuits from the service equipment to branch panels. For economy, the greater part of the voltage drop, 1.5 to 2%, may be assigned to the smaller, more numerous feeders, and only 0.5 to 1% to the heavy main feeders. For motor loads only, the maximum voltage drop may be increased to 5%. Of this, 4% can be assigned to feeders.

The general procedure in sizing conductors is to start with the minimum-size wire permitted by code and test it for voltage drop. If this drop is excessive, test a larger size, and repeat until a wire is found for which the voltage drop is within the desired limit.

Fuses and circuit breakers should be incorporated into the circuits to protect motors from overcurrents of long duration yet permit high, short-duration starting currents to pass. The National Electrical Code allows such overcurrent protective devices to have a higher ampere rating than the allowable current-carrying capacity of the wire. In branch circuits with one motor, conductors should have an allowable current-carrying capacity of at least 125% of the motor full-load current. For feeders supplying several motors, the conductor capacity should be at least 125% of the full-load current of the largest motor plus the sum of the full-load currents of the other motors.

The part of the wiring system at service switches and main distribution panels connected near these switches consists of heavy cables or buses and large switches that have very low resistance. If a short circuit occurs, very high currents will flow, and ordinary fuses or circuit breakers will not be able to interrupt them before wiring or equipment is damaged. For this purpose, high-interrupting-capacity current-limiting fuses, such as Amp-Traps and Hi-Caps, are needed. Ask the utility company for the interrupting capacity required.

Codes generally require that incoming service in a multiple-occupancy building be controlled near the point of entry by not more than six switches or circuit breakers. Meters, furnished by the utility company, also must be installed near the point of entry. The service switch and metering equipment may be combined in one unit, or the switch may be connected by conduit to a separate meter trough.

(F. S. Merritt, “Building Design and Construction Handbook,” 6th ed., D. G. Fink and H. W. Beaty, “Standard Handbook for Electrical Engineers,” 14th ed., H. Richter and W. Schwan, “Practical Electrical Wiring,” 15th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); “National Electrical Code Handbook,” National Fire Protection Association, Quincy, MA 02269.)

15.31 Electric Lighting for Buildings

Artificial illumination is installed primarily for seeing, but it also may serve architectural purposes. With electric lighting, room illumination is not limited to window and skylight openings and by the vagaries of sunlight.

A basic lighting unit usually consists of a light source, or lamp, and a luminaire for housing the lamp, and accessory equipment, such as lenses and the ballasts required for fluorescent lighting. Either the lamp itself or, more commonly, both lamp and luminaire are designed to control brightness and light intensity in various directions. Generally, comfort in seeing is as important as ease in seeing.

Like design of other building systems, lighting design is significantly affected by building codes. These generally contain minimum requirements for illumination levels, for the safety and health of building occupants. In addition, electric-lighting equipment and electrical distribution must conform to safety requirements in building codes and the National Electrical Code, which is promulgated by the National Fire Protection Association, and to standards of the Underwriters Laboratories, Inc. Also, the Illuminating Engineering Society has developed standards and recommended practices to promote good lighting design.

In the interests of energy conservation, Federal and state government agencies have set limits on the amount of energy that may be expended (energy budget) for operation of buildings. These limits may establish maximum levels of illumination for specific purposes in buildings.

Illumination level at any point is inversely proportional to the square of distance from the point light source.

This is known as the inverse square law for radiation of light. For large light sources, the law holds approximately at large distances (at least five times the largest dimension of the sources) from the sources.

Light Source Power ▪ Analogous to a pump in a water system or a battery in an electrical system, a light source emits luminous power. The unit used to measure this power is **candlepower** (cp), or **candela** (cd) (metric unit). (At one time, 1 cp was assumed equivalent to the luminous intensity of a wax candle, but now a more precise definition based on radiation from a heated blackbody is used.) The unit used to measure luminous power at a distance from the light source is the lumen (lm).

A **lumen** is the luminous power on an area of 1 ft^2 at a distance of 1 ft from a 1-cp light source.

Luminous efficacy is the unit used to measure the effectiveness of light sources. It is calculated by dividing the total lumen output of a light source by the total input, W, and thus is measured in lm/W.

Level of Illumination ▪ A major objective of lighting design is to provide a specified **illuminance**, or level of illumination, on a task. For design purposes, the task often is taken as a flat surface, called a **work plane**. If the task is uniformly illuminated, the level of illumination equals the lumens striking the surface divided by the area. The unit used to measure illuminance is the **footcandle** (fc). In accordance with the inverse square law, the illuminance on a work plane normal to the direction to a point light source is given by

$$fc = \frac{cp}{D^2} \tag{15.33}$$

where D = distance, ft, from work plane to light source

cp = candlepower of light source

For a work plane at an angle θ to the direction of the light source,

$$fc = \frac{cp \sin \theta}{D^2} \tag{15.34}$$

A **luminaire** is a lighting device that consists of one or more lamps, or light sources, a fixture that positions and shields them, components that distribute the light, and elements that connect the lamps to the power supply. In general, luminaires do not radiate light of equal intensity in all directions because of the characteristics of the lamps or the geometry of the fixtures. The actual illuminance around a single luminaire is an important design consideration. This environment may be characterized by the candlepower distribution curve of the luminaire. The curve indicates the variation in illuminance with direction from the light source.

Brightness ▪ An observer sees an object because of light reflected from it. The observer interprets the intensity of the sensation experienced as brightness. The sensation of brightness usually is partly attributable to the general luminous environment, which affects the state of adaptation of the eye, and partly attributable to the intensity of light emanating from the object. The latter component is called luminance, or photometric brightness.

Luminance is the luminous power emitted, transmitted, or reflected by a surface in a given direction, per unit of area of the surface projected on a plane normal to that direction. The unit of measurement of luminance is the footlambert (fL).

A **footlambert** of luminance in a given direction is produced by one lumen per square foot emanating from a surface in that direction. Thus, a self-luminous surface emitting 10 lm/ft^2 has a luminance of 10 fL. For surfaces that reflect or transmit light, however, luminance depends on both the illuminance of light incident on the surface and characteristics of the surface.

For a reflecting surface, luminance is determined from

$$fL = fc \times \text{reflectance} \tag{15.35}$$

where fc = footcandles of incident light. A mirror (specular reflector) may give almost 100% reflection, whereas a black surface absorbs light and therefore has negligible reflectance. Most materials have an intermediate value of reflectance.

For a transmitting surface, luminance is determined from

$$fL = fc \times \text{transmittance} \tag{15.36}$$

Clear glass (transparent material) may have a transmittance of about 90%, whereas an opaque material has no transmittance. Transmittances of other transparent materials may be about the same as that for clear glass; transmittances of translucent materials may be 50% or less. Light incident on a surface and not reflected or transmitted is absorbed by it.

Generally, visibility improves with increase in brightness of a task. Because increase in brightness is usually accomplished at increase in operating cost caused by consumption of electric power, it is neither necessary nor desirable, however, to maintain levels of illumination higher than the minimum needed for satisfactory performance of the task. For example, tests show that speed of reading and comprehension are nearly independent of illuminance above a minimum level. This level depends on several factors, such as difficulty of the task, age of observers, duration of the task, and luminance relation between task and its surroundings. The more difficult the task, the older the occupants, and the longer the task, the higher the minimum level of illumination should be.

High brightness also is useful in attracting visual attention and accenting texture. For this reason, bright lights are played on merchandise and works of art.

Contrast ▪ This is created when the brightness of an object and its surroundings are different. The effects of contrast on visibility depend on several factors, especially the ratio of brightness of object to that of its background. Ideally, the brightness of a task should be the same as that of its background. A 3:1 brightness ratio, however, is not objectionable; it will be noticed but usually will not attract attention. A 10:1 brightness ratio will draw attention, and a brightness ratio of 50:1 or more will accent the object and detract attention from everything else in the field of vision.

High background brightness, or low brightness ratios, may have adverse or beneficial effects on visibility. Such high contrast is undesirable when it causes glare or draws attention from the task or creates discordant light and dark patterns (visual noise). On the other hand, high contrast is advantageous when it helps the observer detect task details, for example, read fine print. High contrast makes the object viewed appear dark so that its size and silhouette can be readily discerned. But under such circumstances, if surface detail on the object must be detected, object brightness must be increased at least to the level of that of the background.

Color Rendering ▪ A blackbody is colorless. When increasing heat is applied to such a body, it eventually develops a deep red glow, then cherry red, next orange, and finally blue-white. The color of the radiated light is thus related to the temperature of the heated body. This phenomenon is the basis for a temperature scale used for the comparison of the color of light from different sources. For example, the light from an incandescent lamp, which tends to be yellowish, may be designated in degrees as 2500 Kelvin (K), whereas a cool white fluorescent lamp may be designated 4500 K.

Light used for general illumination is mainly white, but white light is a combination of colors, and some colors are more predominant than others in light emitted from light sources commonly used. When light other than white is desired, it may be obtained by selection of a light source rich in the desired hue or through use of a filter that produces that hue by absorbing other colors.

Color rendering is the degree to which a light source affects the apparent color of objects. **Color rendering index** is a measure of this degree relative to the perceived color of the same objects when illuminated by a reference source for specified conditions. The index actually is a measure of how closely light approximates daylight of the same color temperature. The higher the index, the better the color rendering. The index for commonly used light sources ranges from about 20 to 99.

Quantity of Light ▪ Methods for selecting illuminance, or level of illumination, fc, have been developed by the Illuminating Engineering Society of North America (IES) and published in the "IES Lighting Handbook." These methods take into account

Luminance, or brightness, of the task

Luminance relation between task and surroundings

Color rendering of the light

Size of details to be detected

Contrast of the details with their background

Duration and frequency of occurrence of the task

Speed and accuracy required in performance of the task

Age of workers

Lighting Methods ▪ To meet specific lighting objectives, the following lighting methods may be used alone or in combination: general lighting, local or functional lighting, accent lighting, and decorative lighting.

Illumination may be classified as indirect, semiindirect, diffuse or direct-indirect, semidirect, or direct.

For indirect lighting, about 90 to 100% of the illumination provided in a space is directed at the ceiling and upper walls, and nearly all the light reaches the task by reflection from them. The resulting illumination is therefore diffuse and uniform, with little or no glare.

For semiindirect lighting, about 60 to 90% of the illumination is directed at the ceiling and upper walls, the remaining percentage in generally downward directions. When overhead luminaires are used, the downward components should be dispersed by passage through a diffusing or diffracting lens to reduce direct glare. The resulting illumination on a task is diffuse and nearly glarefree.

General diffuse or direct-indirect lighting is designed to provide nearly equal distribution of light upward and downward. General-diffuse luminaires enclose the light source in a translucent material to diffuse the light and produce light in all directions. Direct-indirect luminaires give little light near the horizontal. Quality of the resulting illumination from either type depends on the type of task and the layout of the luminaires.

For semidirect lighting, about 60 to 90% of the illumination is directed downward, the remaining percentage upward. Depending on the eye adaptation level, as determined by overall room luminance, the upward component may reduce glare. Diffuseness of the lighting depends on reflectance of room enclosures and furnishings.

For direct lighting, almost all the illumination is directed downward. If such luminaires are spread out, reflections from room enclosures and furnishings may diffuse the light sufficiently that it can be used for general lighting, for example, in large offices. A concentrated layout of these luminaires is suitable for accent, decorative, or local lighting. Because direct lighting provides little illumination on vertical surfaces, provision of supplementary perimeter lighting often is desirable.

Characteristics of Lamps ▪ Selection of the most suitable lamp consistent with design objectives is critical to performance and cost of a lighting system. This decision should be carefully made before selecting a fixture for the lamp. Luminaires are designed for specific lamps.

Lamps are constructed to operate at a specific voltage and wattage, or power consumption. Generally, the higher the wattage rating of a specific type of lamp, the greater its **efficacy**, or lumen output per watt.

Greatest economy will be secured for a lighting installation through use of a lamp with the highest lumen output per watt with good quality of illumination. In addition to lumen output, however, color rendering and other characteristics, such as lighting distribution, should also be considered in lamp selection. Information on these characteristics can be obtained from lamp manufacturers. Latest data should be requested because characteristics affecting lamp performance are changed periodically.

Lamps that are commonly used may be generally classified as incandescent, tungsten-halogen, fluorescent, or high-intensity-discharge (HID). HID lamps include mercury-vapor, metal-halide, low-pressure sodium, and high-pressure sodium lamps.

Consideration in Luminaire Selection ▪ Because luminaires are designed for specific types of lamps and for specific voltage and wattage ratings of the lamps, a prime consideration in choosing a luminaire is its compatibility with lamps to be used. Other factors to consider include:

Conformance with the chosen lighting method

Degree to which a luminaire helps meet objectives for quantity and quality of light through emission and distribution of light

Luminous efficiency of a luminaire, the ratio of lumens output by the luminaire to lumens produced by the lamps

Esthetics—in particular, coordination of size and shape of luminaires with room dimensions so that luminaires are not overly conspicuous

Durability

Ease of installation and maintenance

Light distribution from luminaires may be accomplished by means of transmission, reflection, refraction, absorption, and diffusion. Reflectors play an important role. Their reflectance, consequently, should be high—at least 85%. The shape of a reflector—spherical, parabolic, elliptical, hyperbolic—should be selected to meet design objectives; for example, to spot or spread light in a building space or to spread light over a luminaire lens that controls light distribution. (The need for a curved reflector, which affects the size of the luminaire, can be avoided by use of a Fresnel lens, which performs the same function as a reflector. With this type of lens, therefore, a smaller fixture is possible.) Light control also is affected by shielding, baffles, and louvers that are positioned on luminaires to prevent light from being emitted in undesirable directions.

A wide range of light control can be achieved with lenses. Flat or contoured lenses may be used to diffuse, diffract, polarize, or color light, as required. Lenses composed of prisms, cones, or spherical shapes may serve as refractors, producing uniform dispersion of light or concentration in specific directions.

Maintenance of Lamp Output ▪ The efficiency of a lighting system decreases with time because of dirt accumulation, decrease in lumen output as lamps age, lamp failures, and deteriorating luminaires. Depending on type of luminaires, cleanliness of the environment, and time between cleanings of lamps and luminaires, lumen losses due to dirt may range from 8 to 10% in a clean environment to more than 50% under severe conditions. Also, the longer lamps operate, the dimmer they become; for example, a fluorescent lamp at the end of its life will yield only 80 to 85% of its initial lumen output. And when one or more lamps fail and are not replaced, the space being illuminated may suffer a substantial loss in light. Furthermore, in the case of lights operating with ballasts, the lamps, before burning out, overload the ballast and may cause it to fail. Consequently, a poorly maintained lighting installation does not provide the illumination for which it was designed and wastes money on the power consumed.

("IES Lighting Handbook, 9th ed." Illuminating Engineering Society, 120 Wall Street, Floor 17, New York, NY 10017 (www.iesna.org); M. D. Egan, "Concepts in Lighting for Architecture," F. S. Merritt, "Building Design and Construction Handbook," 6th ed., and L. Watson, "Lighting Design Handbook," McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); B. Stein et al., "Mechanical and Electrical Equipment for Buildings," John Wiley & Sons, Inc., New York (www.wiley.com).)

15.32 Waste Piping

One function of a plumbing system in a building is to remove safely and quickly human, natural, and industrial wastes. The National Plumbing Code, ANSI Standard A40.8 (American Society of Mechanical Engineers, 345 E. 47th St., New York, NY 10017) (www.asme.org), contains minimum standards for the design of such systems. But local building codes may have more restrictive requirements and should be checked. Table 15.12, which lists the minimum number of fixtures required for various occupancies, indicates requirements of the New York City Building Code.

Associated with each fixture is a soil or waste stack, a vent or vent stack, and a trap. Soil stacks conduct wastes from one or more fixtures to a sloped house or building drain at the base of the building. Vents and vent stacks supply fresh air to the plumbing system to dilute gases and balance air pressure. Connected to each drainage pipe, vent stacks (vertical) must extend above the roof. They may have branch vents connected to them. Traps provide a water seal that prevents gases from discharging from the drainage pipes through the fixtures. The house or building drain, located below the lowest fixture, conducts the waste to the house or building sewer, which starts 4 or 5 ft outside the foundation walls. That sewer, in turn, carries the wastes to a public sewer or other main sewer. Generally, a cleanout is required at the upper end of the house drain.

The piping generally is made of cast iron lined internally with cement or coal-tar enamel, copper, galvanized steel or ductile iron, or plastics. Codes specify the type of joint to be used with each material.

For convenience, the discharges from fixtures are measured in terms of fixture units, which are used to determine pipe sizes. Tables 15.13 and 15.14 list the number of fixture units assigned to various types of fixtures in the National Standard Plumbing Code, as well as the minimum trap size recommended. Table 15.15 notes the maximum number of fixture units (equivalent to maximum permissible discharge) that may be connected to stacks and horizontal fixture branches of various diameters. Also, the table gives the maximum number of fixture units that may be connected to building drains and sewers of various diameters. And Table 15.16 gives the diameter of vent and maximum length permitted with various sizes of soil or waste stacks and various fixture units.

The plumbing system also may be required to dispose of rain on roofs, yards, areaways, and exposed floors. Normally, exterior sheet-metal leaders and gutters are not included in the plumbing contract, but interior leaders and storm-water drains are. Although storm drains may sometimes be permitted to discharge into sanitary drains, codes generally prohibit use of storm drains for disposing of sewage. Recommended sizes of vertical leaders and horizontal storm drains are listed in Table 15.17. Table 15.18 lists recommended sizes of semicircular gutters.

Indirect-waste piping usually is required for the discharge from commercial food-handling equipment and dishwashers, rinse sinks, laundry washers, steam tables, refrigerators, egg boilers, iceboxes, coffee urns, stills, and sterilizers and from units that must be fitted with drip or drainage connections but are not ordinarily regarded as plumbing fixtures. An indirect-waste pipe is not connected directly to the building drains but discharges wastes into a plumbing fixture or receptacle, from which they flow to the drains. An air gap should separate the indirect-waste pipe from the drains. The length of the gap should be at

Table 15.12 Minimum Number of Plumbing Fixtures for Various Occupancies[a]

Type of building or occupancy	Water closets		Urinals		Lavatories		Bathtubs or showers	Drinking fountains[c]
Dwellings or apartment buildings[d]	1 for each dwelling or apartment unit				1 for each unit		1 for each unit	
Public buildings, offices, business mercantile, storage; warehouses, factories, and institutional employees[e]	No. of persons of each sex	No. of fixtures	Urinals may be provided in men's toilet rooms in lieu of water closets but for not more than ½ of required water closets when more than 35 persons.		No. of persons	No. of fixtures	1 shower for each 15 persons exposed to excessive heat or skin contamination	1 for each 75 persons
	1–15	1			1–20	1		
	16–35	2			21–40	2		
	36–55	3			41–60	3		
	56–80	4			61–90	4		
	81–110	5			91–125	5		
	111–150	6			1 fixture for each additional 45 persons[g, h]			
	1 fixture for each additional 40 persons							
Schools:[f]	Males	Females					For gyms or pools, one for every 3 pupils of largest class using pool at one time	1/50 persons but at least 1 per floor
Elementary	1/90	1/35	1/30 males		1/50 pupils			
Secondary	1/90	1/35	1/30 males		1/50 pupils Over 300 pupils 1/100 pupils			
Assembly—Auditoriums, theaters, convention halls	No. of persons	No. of fixtures	No. of persons	No. of fixtures	No. of persons	No. of fixtures		1 for each 1000 persons except that there shall be at least 1 fixture each assembly floor
	1–100	1	1–200	1	1–200	1		
	101–200	2	201–400	2	201–400	2		
	201–400	3	401–600	3	401–750	3		
	Over 400, add 1 fixture for each additional 500 men and 1 for each 800 women		Over 600, add 1 fixture for each 300 men[e]		Over 750, add 1 fixture for each 500 persons			
Dormitories[i]	Men: 1 for each 10 persons Women: 1 for each 8 persons		1 for each 25 men. Over 150, add 1 fixture for each 50 men[e]		1 for each 12 persons		1/8 persons. For every 30 women, substitute 1 bathtub for 1 shower	1 for each 75 persons
Worker temporary facilities	1/30 workers		1/30 workers					At least 1 per floor equivalent for each 100 workers

[a] Figures shown are based on one fixture being the minimum required for the number of persons indicated or any fraction thereof. Population used in determining the number of fixtures required should be based on the number of persons to occupy the space but not less than 125 ft^2 of net floor area per person.

[b] Building categories not shown in this table will be considered separately by the administrative authority.

[c] Drinking fountains shall not be installed in toilet rooms.

[d] Laundry trays—one single compartment tray for each dwelling unit or 2 compartment trays for each 10 apartments. Kitchen sinks—1 for each dwelling or apartment unit.

[e] As required by the ANSI Standard Safety Code for Industrial Sanitation in Manufacturing Establishments (ANS Z4.1-1935).

[f] This schedule was adopted (1945) by the National Council on Schoolhouse Construction.

[g] Where there is exposure to skin contamination with poisonous, infectious, or irritating materials, provide 1 lavatory for each 5 persons.

[h] 24 lin in of wash sink or 18 in of a circular basin, when provided with water outlets for such space, shall be considered equivalent to 1 lavatory.

[i] Laundry trays, 1 for each 50 persons. Slop sinks, 1 for each 100 persons.

[j] Temporary work personnel facilities:
24-in urinal trough = 1 urinal. 48-in urinal trough = 2 urinals.
36-in urinal trough = 2 urinals. 60-in urinal trough = 3 urinals. 72-in urinal trough = 4 urinals.

General. In applying this schedule of facilities, consideration must be given to the fixtures. Conformity purely on a numerical basis may not result in an installation suited to the need of the individual establishment. For example, schools should be provided with toilet facilities on each floor having classrooms.

Table 15.13 Fixture Units per Fixture or Group

Fixture type	Fixture-unit value as load factors	Min size of trap, in
1 bathroom group consisting of water closet, lavatory, and bathtub or shower stall	Tank water closet, 6 Flush-valve water closet, 8	
Bathtub* (with or without overhead shower)	2	1½
Bidet	1	1¼
Clothes washer, domestic, automatic	3	2
Drinking fountain	½	1
Dishwasher, domestic	2	1½
Floor drains†	1	2
Kitchen sink, domestic	2	1½
Kitchen sink, domestic, with food-waste grinder and dishwasher	2	2
Lavatory‡	1	1½
Laundry tray (1 or 2 compartments)	2	1½
Shower stall, domestic	2	2
Showers (group) per head	3	2
Urinal, pedestal, siphon jet, blowout	6	Nominal 3
Urinal, wall lip	4	1½
Urinal stall, washout	4	2
Urinal trough (each 2-ft section)	2	1½
Water closet, tank operated	4	2
Water closet, valve-operated	6	3

Source: National Standard Plumbing Code.

* A shower head over a bathtub does not increase the fixture value.

† Size of floor drain shall be determined by the area of surface water to be drained.

‡ Lavatories with 1¼- or 1½-in trap have the same load value; larger P.O. (plumbing orifice) plugs have greater flow rate.

least twice the diameter of the drain served. This requirement is met by a pipe discharging into a vented or trapped floor drain, slop sink, or similar fixture not used for domestic or culinary purposes. The indirect-waste pipe should be terminated at least 2 in above the floor level of the fixture.

On completion of the plumbing, the system should be inspected or tested with either air or water. In a water test, all openings but the highest one are tightly sealed. The pipes then are filled with water, so that the minimum head is 10 ft, except for the top 10 ft of the system. In an air test, the system is sealed and subjected to 5-psi pressure. For a final test, either a strong-smelling smoke or peppermint is used. With smoke, a pressure of at least 1 in of water should be maintained on the sealed system

Table 15.14 Estimates of Other Fixture Units per Fixture or Group

Fixture drain or trap size, in	Fixture-unit value
1¼ in and smaller	1
1½	2
2	3
2½	4
3	5
4	6

Source: National Standard Plumbing Code.

Table 15.15 Maximum Permissible Loads, Fixture Units, for Sanitary Drainage Piping

Dia of pipe, in	Max number of fixture units that may be connected to: Any horizontal fixture branch*	One stack of 3 stories in height or 3 intervals	More than 3 stories in height: Total for stack	More than 3 stories in height: Total at one story or branch interval	Max number of fixture units that may be connected to any portion* of the building drain or the building sewer. Fall per ft: ¹⁄₁₆ in	⅛ in	¼ in	½ in
1¼	1	2	2	1				
1½	3	4	8	2				
2	6	10	24	6			21	26
2½	12	20	42	9			24	31
3	20†	30‡	60‡	16†		20‡	27†	36†
4	160	240	500	90		180	216	250
5	360	540	1,100	200		390	480	575
6	620	960	1,900	350		700	840	1,000
8	1,400	2,200	3,600	600	1,400	1,600	1,920	2,300
10	2,500	3,800	5,600	1,000	2,500	2,900	3,500	4,200
12	3,900	6,000	8,400	1,500	3,900	4,600	5,600	6,700
15	7,000				7,000	8,300	10,000	12,000

Source: National Standard Plumbing Code.
* Include branches of the building drain.
† Not over two water closets.
‡ Not over six water closets.

for 15 min before inspection begins. For the peppermint test, 2 oz of oil of peppermint is injected into each line or stack.

(H. E. Bovay, Jr., "Handbook of Mechanical and Electrical Design for Buildings," T. G. Hicks, "Plumbing Design and Installation Reference Guide," J. F. Mueller, "Plumbing Design and Installation Details," L. Nielsen, "Standard Plumbing Engineering Design," McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); B. Stein et al., "Mechanical and Electrical Equipment for Buildings," John Wiley & Sons, Inc., New York (www.wiley.com); "National Standard Plumbing Code," National Association of

Table 15.16 Size and Length of Vent Stacks and Branch Vents

Size, in, of soil or waste stack	Fixture units connected	Diameter of vent required, in: 1¼	1½	2	2½	3	4	5	6	8
		Maximum developed length of vent, ft								
1¼	2	30								
1½	8		150							
2	24		50	150						
2½	42			100	300					
3	72				80	400				
4	500					180	700			
5	1100						200	700		
6	1900							200	700	
8	3600									800
10	5600									250

Table 15.17 Maximum Drainage Areas for Vertical Leaders and Horizontal Storm Drains for Rainfall of 1 in/h*

Vertical Leaders		Horizontal Storm Drains			
Size of leader or conductor, † in	Maximum projected area, ft²	Dia of Drain, in	Maximum projected roof area, ft², for drains of various slopes, in/ft		
			1/8	1/4	1/2
2	2,880	3	3,288	4,640	6,576
2½	5,200	4	7,520	10,600	15,040
3	8,800	5	13,360	18,880	26,720
4	18,400	6	21,400	30,200	42,800
5	34,600	8	46,000	65,200	92,000
6	54,000	10	82,800	116,800	165,600
8	116,000	12	133,300	188,000	266,400
		15	238,000	336,000	476,000

* Divide tabulated roof areas by design rainfall rate, in/h, if it is larger than 1 in/h.

† The equivalent diameter of square or rectangular leader may be taken as the diameter of a circle inscribed in leader area.

Plumbing-Heating-Cooling Contractors, Falls Church, VA 22046 (www.phccweb.org); "Uniform Plumbing Code," International Association of Plumbing and Mechanical Officials, Ontario, CA. (www.iapmo.org); "ASPE Data Book," American Society of Plumbing Engineers, Chicago, IL (www.aspe.org).)

15.33 Fire-Sprinkler Systems

Consisting essentially of parallel horizontal pipes installed near ceilings, sprinklers have been very effective in preventing spread of fires in buildings. The extinguishing agent usually is water, although for some hazards carbon dioxide is used. The agent, kept under pressure, is discharged from the pipes through sprinklers preset to open when air temperature rises rapidly or reaches a specified level, usually 135 to 160 °F.

Common types of sprinkler systems include wet-pipe, dry-pipe, preaction, and deluge. Pipes in a wet-pipe system contain water at all times and discharge immediately when the sprinklers open. In a dry-pipe system, air under pressure in the pipes is discharged when the sprinklers open, thus

Table 15.18 Maximum Drainage Areas for Roof Gutters for Rainfall of 1 in/h*

Dia of gutters,† in.	Maximum projected roof area, ft², for gutters of various slopes, in/ft			
	1/16	1/8	1/4	1/2
3	680	960	1,360	1,920
4	1,440	2,040	2,880	4,080
5	2,500	3,520	5,000	7,080
6	3,840	5,440	7,680	11,080
7	5,520	7,800	11,040	15,600
8	7,960	11,200	15,920	22,400
10	14,400	20,400	28,800	40,000

* Divide tabulated roof areas by design rainfall rate, in/h, if it is larger than 1 in/h.

† Gutters other than semicircular may be used if they have an equivalent cross-sectional area.

allowing water pressure to open a valve to allow water to flow to the sprinklers. Such systems are suitable for unheated areas in cold climates. Preaction systems have pipes containing air, which may not be under pressure. Heat-responsive devices near sprinklers open water valves when a fire occurs. The deluge system has sprinklers attached to a piping system. Heat responsive devices in the same area as the sprinklers open a valve permitting water to discharge from all sprinklers when a fire occurs in the area served.

The sprinkler system should have a water supply of adequate capacity and pressure. For a secondary supply, a motor-driven automatically controlled fire pump supplied from a water main or pressure-storage system of sufficient capacity may be acceptable.

Local fire-prevention authorities and fire underwriters have specific requirements for type, material, size, and spacing of pipes and sprinklers. They should be consulted before a system is designed.

(C. M. Harris, "Handbook of Utilities and Services for Buildings," and F. S. Merritt, "Building Design and Construction Handbook," 6th ed., McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); R. E. Solomon, "Automatic Sprinklers Handbook," "Life Safety Code Handbook," and "The SFPE Handbook of Fire Protection Engineering," National Fire Protection Association, Quincy, MA 02269 (www.nfpa.org).)

15.34 Hot- and Cold-Water Piping for Buildings

Local building codes contain minimum standards for hot- and cold-water piping. For example, the New York City Building Code requires a pressure at a faucet or water outlet with the outlet wide open of at least 8 psi. Maximum pressure should not exceed 85 psi with no flow. In addition, units may be used for which manufacturers have higher requirements, for example, for pressure. Care should be exercised using previously recommended criteria for fixture and faucet pressures and flows, because of advances in design since establishment of those criteria. Check with the manufacturers of the individual units for latest recommendations.

Sufficient allowance should be made for pressure loss in pipe and fittings between the supply source and the fixtures, so that required pressures will be present at the fixtures. If necessary to maintain pressure, booster pumps and gravity and pressure tanks may have to be used. If there is danger of excessive pressure in some parts of the system causing water hammer, an air chamber or approved device must be installed to protect the pipes from pressure surges and to reduce noise.

Pipes and tubes for water distribution may be made of copper, brass, cast iron, wrought iron, steel, or plastic. The local building code should be checked for approved materials and types of joints for each. Use of solder containing lead or other health hazards should be avoided.

The system should be designed so that there is no possibility of backflow at any time. Codes generally require that an air gap—space between fixture outlet and flood-level rim of the receptacle—of specified size for each type of fixture be maintained.

Hot water may be supplied by upfeed or downfeed systems, with unused water returned to the heater. In an upfeed system, fixtures are supplied with hot water by a riser directly from the heater. In a downfeed system, hot water is brought to the highest floor in a supply riser and vented at the top through a vent valve, and the fixtures are supplied by the return riser.

Generally, hot water is delivered at 130 to 140 °F. (See Table 15.19.) For floor cleaning, slop sinks may be fed 150 °F water.

Heaters ▪ Domestic-water heaters may be direct-fired or unfired. Two types of unfired heaters are in general use: storage and instantaneous. Heat for storage heaters may be supplied by steam or hot water. The tank stores hot water for future use. For occupancies with uneven demand for hot water, such as industrial, office, and school buildings, a relatively large storage capacity is needed. But for occupancies with a nearly uniform demand, such as hotels, apartment buildings, and hospitals, storage capacity may be smaller, but capacity of the heating coil must be larger. With instantaneous heaters, however, water is heated as needed; there is no storage tank. These heaters have V-shaped or straight tubes through which the supply water passes to be heated.

Table 15.19 Hot-Water Demand per Fixture for Various Building Types (Based on average conditions for types of buildings listed, gallons of water per hour per fixture at 140°F)

Type of fixture	Apartment	Hospital	Hotel	Industrial Plant	Office Building
Basins, private lavatories	2	2	2	2	2
Basins, public lavatories	4	6	8	12	6
Bathtubs	20	20	20		
Showers	30	75	75	225	30
Slop sinks	20	20	30	20	15
Dishwashers		50–150	50–200	20–100	
Pantry sinks	5	10	10		
Demand factor	0.30	0.25	0.25	0.40	0.30
Storage factor	1.25	0.60	0.80	1.00	2.00

Cold Water ▪ Required flow at cold-water fixtures usually is measured in terms of fixture units. The load for each type of fixture is determined by multiplying the number of each to be installed on a branch or a riser or in the building by the demand weight in fixture units (Table 15.20). Figure 15.27 relates the fixture units to the probable demand in gallons of water per minute. Figure 15.28 is an enlargement of Fig. 15.27 in the range of 0 to 250 units. Hot-water demand per fixture in gallons per hour at 140°F for various building occupancies is given in Table 15.19.

Minimum sizes for hot- and cold-water fixture-supply pipes to keep flow velocity within code limits are listed in Table 15.21. For small buildings, the following diameters can be used for the mains supplying water to the fixture branches:

½ in for mains with up to three ⅜-in branches

¾ in for mains with up to three ½-in or five ⅜-in branches

1 in for mains with up to three ⅜-in or eight ½-in or fifteen ⅜-in branches

The minimum pipe sizes in Table 15.21 may be satisfactory for short branches to individual fixtures. But required flow and pressure may make larger sizes necessary. Sizes of risers may be computed from the required flow in gallons per minute and the pressure drop permitted between the supply main and the highest fixtures.

When the potable-water piping has been completed and before it is put into use, it should be disinfected with chlorine by a procedure approved by the local code.

Bibliography ▪ See Art. 15.32, p. 15.72.

15.35 Acoustics

As applied to buildings, acoustics involves the creation of conditions for comfortable listening and means for noise control. At present, acoustics is both an art and a science, for what is comfortable and what is noise depends on judgment and the function of the room to be treated. A sound one person finds too loud may not bother someone else, what is comfortable in a factory may not be acceptable in a school; the music enjoyed by a high-fidelity fan may be noise to a neighbor trying to sleep. Noise is unwanted sound.

Sounds are characterized by their pitch, or frequency; intensity, or loudness; and spectral distribution of energy, or sound quality. An average person can hear from 20 Hz (Hertz or cycles, or vibrations, per second) to 20 kHz. High-frequency, or high-pitched, sounds are more annoying to most people than low-pitched sounds of the same intensity. But high-pitched sounds attenuate faster in air than low-pitched.

Loudness is a subjective evaluation of sound pressure or intensity. But because human response to loudness varies with frequency, any measure of loudness must, in some way, include frequency as well as pressure or intensity to be of significance in building acoustics. In addition, changes in human response to loudness depend on the ratio of the

Table 15.20 Fixture Units for Estimating Water Flow at Fixtures*

Fixture or group	Occupancy	Type of supply control	Fixture units Hot	 Cold	 Total
Water closet	Public	Flush valve		10	10
Water closet	Public	Flush tank		5	5
Pedestal urinal	Public	Flush valve		10	10
Stall or wall urinal	Public	Flush valve		5	5
Stall or wall urinal	Public	Flush tank		3	3
Lavatory	Public	Faucet	1.5	1.5	2
Bathtub	Public	Faucet	3	3	4
Shower head	Public	Mixing valve	3	3	4
Service sink	Office, etc.	Faucet	2	2	4
Kitchen sink	Hotel or restaurant	Faucet	3	3	4
Drinking fountain	Various	$\frac{3}{8}$-in valve	0.25		0.25
Water closet	Private	Flush valve		6	6
Water closet	Private	Flush tank		3	3
Lavatory	Private	Faucet	0.75	0.75	1
Bathtub	Private	Faucet	1.5	1.5	2
Shower head	Private	Mixing valve	1.5	1.5	2
Bathroom group	Private	Flush valve W.C.	2.25	6	8
Bathroom group	Private	Flush tank W.C.	2.25	4.5	6
Separate shower	Private	Mixing valve	1.5	1.5	2
Kitchen sink	Private	Faucet	1.5	1.5	2
Laundry tray	Private	Faucet	2	2	3
Dishwasher	Private	Automatic		1	1

* For calculating maximum probable demand, add fixture units; then determine flow from Fig. 15.26 or 15.27, or similar charts or tables. For example, to determine the probable water flow from two branches, add the fixture units assigned to each branch and use the sum to determine the flow, gal/min.

intensities of the sound. In acoustics, the ratio 10:1 is called a bel. For practical reasons, the unit frequently used, however, is the decibel (dB), equal to 0.1 bel.

Intensity level *IL*, dB, used as a measure of loudness, is defined by

$$IL = 10 \log_{10} \frac{I}{I_o} \qquad (15.37)$$

where I = intensity, measured, W/cm^2

I_o = reference intensity = 10^{-16} W/cm^2

Equation (15.37) indicates that zero level corresponds with $I = I_o$, the reference intensity, which, in turn, corresponds with the average threshold of human hearing of sound at about 1 kHz.

Sound pressure level *SPL*, dB, since intensity varies as the square of pressure, is accordingly defined by

$$SPL = 20 \log_{10} \frac{p}{p_o} \qquad (15.38)$$

where p = pressure, measured, pascals (Pa)

p_o = reference pressure = 0.00002 Pa

A change in sound level of less than about 3 dB is not likely to be perceptible, but a change of 5 dB will be noticeable. An increase of 10 dB will appear to be twice as great as an increase of 5 dB, and an increase of 20 dB much greater than an increase of 10 dB—not quite proportionately.

Sound levels usually are measured with electronic instruments that respond to sound pressures. Readings on the A scale of such instruments are often used because this scale is adjusted for frequencies that correspond somewhat with the

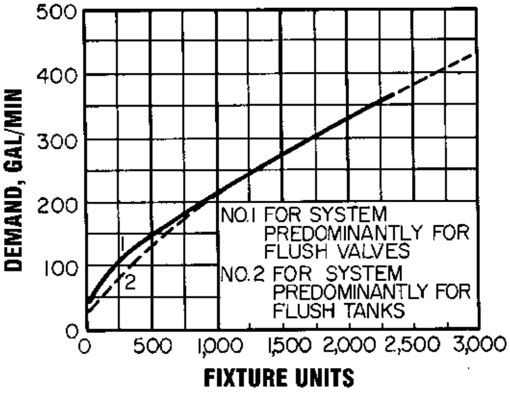


Fig. 15.27 Curves for estimating demand load for domestic water supply.

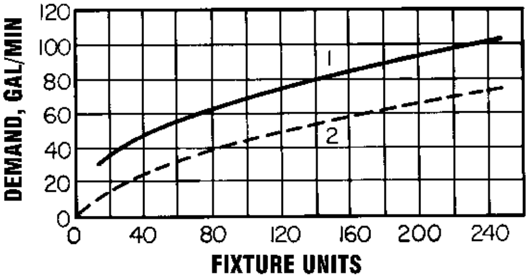


Fig. 15.28 Enlargement of the low-demand portion of Fig. 15.27.

Table 15.22 Comparison of Intensity, Sound Pressure Level, and Common Sounds

Relative intensity	SPL, dBA*	Loudness
100,000,000,000,000	140	Jet aircraft and artillery fire
10,000,000,000,000	130	Threshold of pain
1,000,000,000,000	120	Threshold of feeling
100,000,000,000	110	Chainsaw, weed wacker
10,000,000,000	100	Loud factory
1,000,000,000	90	Full symphony or band
100,000,000	80	Busy restaurant
10,000,000	70	Conversation, face-to-face
1,000,000	60	Busy store
100,000	50	Inside general office
10,000	40	Inside private office
1,000	30	Inside bedroom
100	20	Inside empty theater
10	10	Normal breathing
1	0	Threshold of hearing

* SPL as measured on A scale of standard sound level meter.

response of the human ear. In such cases, the unit is indicated by dBA.

Table 15.22 presents a comparison of intensity, *SPL*, and common sounds.

Acoustical analysis and design aim at both sound and vibration control. Sound control is accomplished with barriers and enclosures, acoustically absorbent materials, and other materials properly shaped and assembled. Vibration control is accomplished with energy-absorptive construction, usually with resilient materials, or by damping, involving use of viscoelastic materials.

Table 15.21 Minimum Sizes for Fixture-Supply Pipes*

Type of fixture or device	Pipe size, in	Type of Fixture or device	Pipe size, in
Bathtubs	½	Shower (single head)	½
Combination sink and tray	½	Sinks(service, slop)	½
Drinking fountain	⅜	Sinks, Rushing rim	¾
Dishwasher (domestic)	½	Urinal (flush tank)	½
Kitchen sink, residential	½	Urinal (direct flush valve)	¾
Kitchen sink, commercial	¾	Water closet (tank type)	⅜
Lavatory	⅜	Water closet (Rush valve type)	1
Laundry tray, 1, 2, or 3 compartments	½	Hose bibs	½
		Wall hydrant	½

* Objective is to restrict the velocity of flow to not more than 8 or 10 ft/s, depending on the local building-code requirements.

Effectiveness of a barrier in stopping sound is measured by **sound transmission loss**, the loss in energy level as sound passes through a barrier. The greater the mass of a barrier, the greater the sound transmission loss and the more effective the barrier. Mass and transmission loss, however, are not related linearly. At low frequencies losses tend to be larger, and at other frequencies, smaller, than required for a linear relationship. Table 15.23 lists the performance of various barriers and rating systems for their performance.

The purpose of a barrier with a high sound transmission loss, however, can be defeated if sound can bypass the barrier through openings or by transmission through adjoining construction. Ducts, pipes, and almost any continuous, rigid component of a building can carry sound past a barrier. Therefore, precautions should be taken to prevent such bypassing. Carpet over a resilient pad, for example, effectively helps absorb such sounds as footfalls, heel clicks, and impact of dropped light objects. Openings should be plugged. Vibrations from machines and other equipment can be absorbed by supporting them on springs, elastomeric pads, or other resilient mounts.

Vibration of barriers resulting from impact of sound or transmission of vibrations from machines can be damped out by proper assembly in any of several ways. One way is to attach to a barrier a material with high internal friction or poor connections between particles, or viscoelastic materials, such as asphaltic compounds that are neither completely elastic nor completely viscous. Also, components of the barrier may be connected with a viscoelastic adhesive.

Table 15.23 Sound Transmission Class (STC) of Various Constructions

Construction	STC
¼-in plate glass	26
Double glazing, ¼-in panes, 4-in air gap	48
1½-in hollow-core door	22
1¾-in solid-wood door	30
¾-in plywood	28
½-in gypsumboard, both sides of 2 × 4 studs	33
¼-in steel plate	36
6-in concrete block wall	42
8-in reinforced concrete wall	51
12-in concrete block wall	53
Cavity wall, 6-in concrete block, 2-in air space, 6-in concrete block	56

Sound Absorption ▪ Reflection of sound from a surface can be curtailed by covering the surface with an acoustical absorbent, usually lightweight, porous boards, blankets, or panels, which convert the mechanical energy of sound into heat. Exposed surfaces may be smooth or textured, fissured or perforated, or decorated or etched in many ways. Selection of an absorbent usually is based on its absorptive efficiency, appearance, fire resistance, moisture resistance, strength, and maintenance requirements. An absorbent, however, may have poor resistance to sound transmission and should not be used in an attempt to improve the airborne sound isolation of a barrier.

Sound absorption coefficients are used as an indication of the absorptive efficiency of building products. The sound absorption coefficient of a product is the ratio of the energy it will absorb from a sound wave to the total energy impinging. A perfect absorber would be assigned a coefficient of 1. Sound absorption, however, depends on the frequency of the sound (Table 15.24). Consequently, coefficients for a product are given for specific frequencies, or sometimes as a composite for a group of frequencies, such as the noise reduction coefficient *NRC* in (Table 15.24).

Generally, absorbents are used not only to reduce undesirable sound reflection, such as echoes and flutter, but also to secure desirable reverberations. *Echoes* are distinct reflections. *Flutter* is produced by rapid, repeated, partly distinguishable echoes, such as those that occur between parallel sidewalls of a corridor, *Reverberation* results from very rapid, repeated, jumbled echoes, which produce a continuing indistinct sound that persists after the sound producing the echoes has ceased.

Reverberation within a room can garble speech or distort music. But, properly controlled, reverberation can enhance the sound of music. Good reverberation can be achieved with proper proportioning and shaping of rooms, echo control, and absorption of noise. Generally, acoustical absorbents on room surfaces are desirable to absorb acoustical energy to prevent buildup of undesirable sounds.

Table 15.24 Noise Reduction and Sound Absorption Coefficients

Absorbent	Thickness, in	Density, lb per ft^3	Noise reduction coefficient
Mineral or glass fiber blankets	½–4	½–6	0.45–0.95
Molded or felted tiles, panels, and boards	½–1⅛	8–25	0.45–0.90
Plasters (porous)	⅜–¾	20–30	0.25–0.40
Sprayed-on fibers and binders	⅜–1⅛	15–30	0.25–0.75
Foamed, open-cell plastics, elastomers, etc.	½–2	1–3	0.35–0 .90
Carpets	Varies with weave, texture, backing pad, etc.		0.30–0.60
Draperies	Varies with weave, texture, weight, fullness		0.10–0.60

Absorbent	Absorption coefficient per ft^2 of floor area at frequencies, Hz					
	125	250	500	1000	2000	4000
Seated audience	0.60	0.75	0.85	0.95	0.95	0.85
Unoccupied upholstered (fabric) seats	0.50	0.65	0.80	0.90	0.80	0.70

Noise reduction *NR*, dB, achieved through addition of absorbents can be computed from

$$NR = 10\log_{10}\frac{A_o + A_a}{A_o} \qquad (15.39)$$

where A_o = original acoustical absorption present

A_a = added acoustical absorption

Acoustical absorption equals the sum of the products of the absorption coefficient of each material forming the enclosure surface and the corresponding surface area.

Sometimes materials are rated with a **noise reduction coefficient** *NRC*, the arithmetic average of the sound absorption coefficients of a material at 250, 500, 1000, and 2000 Hz (Table 15.24).

Reverberation Time ▪ This is the time, in seconds, that a sound pulse within a room takes to decay 60 dB, to one-millionth of its original level. Reverberation time T can be computed from the Sabine formula:

$$T = \frac{0.49V}{A} \qquad (15.40)$$

where V = volume of room, ft^3

A = total acoustical absorption in room

Reverberation times falling within the shaded area in Fig. 15.29 may be considered satisfactory under ordinary conditions. For critical spaces, such as concert halls, radio studios, and auditoriums,

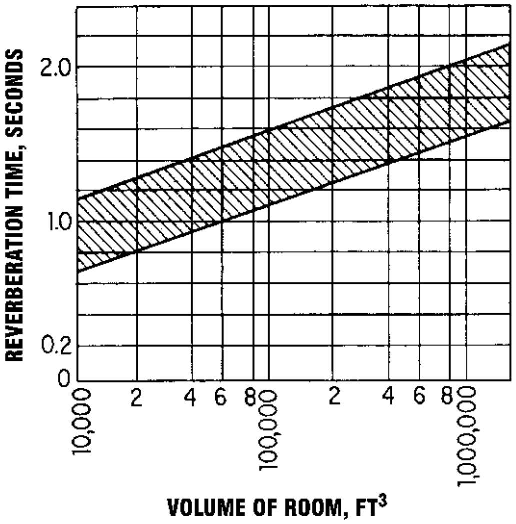


Fig. 15.29 Recommended reverberation time, indicated by shaded area, varies with size of room.

Table 15.25 Impact Insulation Class of Floor Constructions

Construction	*IIC*
Oak flooring on ½-in plywood subfloor, 2 × 10 joists, ½-in gypsumboard ceiling	23
With carpet and pad	48
8-in concrete slab	35
With carpet and pad	57
2½-in concrete on light metal forms, steel bar joists	27
With carpet and pad	50

advice of an acoustical consultant should be obtained.

Rating Systems ▪ ASTM has adopted rating systems for evaluating acoustical performance of materials, such as:

Sound transmission class STC for indicating the insulation against airborne sound of partitions, floor-ceiling assemblies, and other barriers (ASTM E90 and E413). Table 15.23 lists some typical ratings.

Impact insulation class IIC for indicating the impact insulation of floor-ceiling assemblies (ASTM RM 14-4). See Table 15.25.

Table 15.26 Guide Criteria for Acoustical Design

Isolation requirements between rooms					
For sound			For impact		
Between Room	and Adjacent area	Sound isolation requirement, *STC*	Between Room	and Room below	Impact isolation requirement, *IIC*
Hotel bedroom	Hotel bedroom	47	Hotel bedroom	Hotel bedroom	55
Hotel bedroom	Corridor	47	Public spaces	Hotel bedroom	60
Hotel bedroom	Exterior	42	Classroom	Classroom	47
Normal office	Normal office	33	Music room	Classroom	55
Executive office	Executive office	42	Music room	Theater	62
Bedroom	Mechanical room	52	Office	Office	47
Classroom	Classroom	37			
Classroom	Corridor	33			
Theater	Classroom	52			
Theater	Music rehearsal	57			

Typical Sound Pressures		Acceptable background levels	
Source of sound	Pressure level, dBA*	Space	Background level, dBA*
Washing machine	60	Recording studio	25
TV (at 10 ft)	67	Suburban bedroom	30
Telephone (at 5 to 15 ft), ringing	61	Theater	30
Water closet, tank type, refilling	55	Church	35
Conversational speech, normal	73	Classroom	35
Rock-and-roll music (amplified)	102	Private office	40
Trucks (at 20 ft)	75	General office	50
Classrooms	73	Dining room	55
Computer room	77	Computer room	70

* Average of sound pressure at 250, 500, 1000, 2000 Hz.

Impact noise rating INR, an alternative measure of impact insulation of floor-ceiling assemblies. *IIC* ratings can be converted to *INR* by deduction of 51 points.

Sound absorption coefficients for indicating the absorptive efficiency of acoustical absorbents (ASTM C423). See Table 15.24.

Noise reduction coefficients, an alternative measure of absorptive efficiency (Table 15.24).

Acoustical Criteria ▪ Although governmental agencies and others have adopted design criteria to achieve desired sound reduction and insulation, the criteria are based on subjective response to acoustical parameters. Accordingly, small deviations from such criteria may not necessarily result in unsatisfactory performance. Usually, a tolerance of ±2.5 points from a numerical value is acceptable in practice. Table 15.26 presents some acoustical criteria that may be used as a guide.

("McGraw-Hill's Acoustics Source Book," M. D. Egan, "Architectural Acoustics," C. M. Harris, "Handbook of Acoustical Measurements and Noise Control," McGraw-Hill Publishing Company, New York (books.mcgraw-hill.com); L. F. Yerges, "Sound, Noise and Vibration Control," Van Nostrand Reinhold Company, New York.)