

14

LATERAL FORCES—EARTHQUAKES

Nomenclature

C_a	numerical coefficient used in Equation 14.2, given in UBC Table 16-Q	
C_v	numerical coefficient used in Equation 14.1, given in UBC Table 16-R	
C_t	numerical coefficient for calculating the period of vibration	
F_p	lateral force on part of a structure	pounds or kips
F_t	the portion of V considered concentrated at the top of the structure in addition to F_x	pounds or kips
F_x	lateral force applied to level x	pounds or kips
h_n	total height of building	ft
h_x	height above base to level x	ft
I	occupancy importance factor	
I_p	importance factor for elements given in UBC Table 16-K	
R	numerical coefficient given in UBC Tables 16-N and 16-P	
S_A	soil profile types	
S_F	given in UBC Table 16-J	
T	fundamental period of vibration	sec
V	total design lateral force or base shear	pounds or kips
w_x	the portion of W that is located at level x	pounds or kips
W	weight	pounds or kips
W_p	weight of a portion of a structure	pounds or kips
Z	seismic zone factor given in UBC Table 16-I	

Although a great deal has been learned about earthquakes and their effects on buildings during the last 50 years, seismic design is still an inexact science. Because seismic design deals with dynamic forces rather than static forces, and because of the many variables involved, it is often difficult to precisely predict the performance of a building in an earthquake and provide the best possible design to resist the resulting lateral forces.

Another difficulty with seismic design is that the forces produced by an earthquake are so great that no building can economically and reasonably be designed to completely resist all loads in a major earthquake without damage. Building codes and analytical methods of design are, therefore, a compromise between what could resist all earthquakes and what is reasonable. Because of this, the current approach in designing earthquake-resistant structures is that they should first of all not collapse during major seismic activity. Additionally, the components of buildings should not cause other damage or personal injury even though they may be structurally damaged themselves. Finally, structures should be able to withstand minor earthquakes without significant damage.

The analytic methods of analysis and design of earthquake-resistant structures are complex, even with the simplified static analysis method allowed by the Uniform Building Code (UBC). However, a great deal of resistance is provided by the basic configuration and structural system of a building. The design of buildings for earthquake loads requires an early and close collaboration between the architect and engineer to arrive at the optimum structural design while still satisfying the functional and aesthetic needs of the client.

This chapter will discuss some of the basic principles of earthquakes and the primary design and planning guidelines with which you should be familiar. In addition, a basic review of the static analysis method will be

presented along with some simplified problems to help explain the design concepts.

1 BASIC PRINCIPLES

The UBC provides for two methods of design for seismic forces: the static lateral force procedure and the dynamic lateral force procedure. The static method treats the seismic loads as equivalent lateral loads acting on the various levels of the building. The total base shear is calculated and then distributed along the height of the building. The dynamic method uses a computer to mathematically model the building so the response of the structure can be studied at each moment in time using an actual or simulated earthquake accelerogram. The dynamic method is very complex and its details are not covered in the ARE. The static method is reviewed in Section 4.

The UBC is specific about which analysis method may or must be used. In general, any structure may be, and certain structures must be, designed using the dynamic lateral force procedures. The static method may be used for the following types of structures.

- all structures in seismic zone 1 and in zone 2 with occupancy category 4 or 5, whether they are regular or irregular
- regular structures using one of the lateral force resistance systems listed in Table 16-N if they are under 240 feet in height (see Table 14.1)
- irregular structures not more than 5 stories or 65 feet in height
- structures with a flexible upper portion supported on a rigid lower portion if all of the following conditions are met:
 - when both portions are considered separately, they can both be classified as regular
 - the average story stiffness of the lower portion is at least ten times the average story stiffness of the upper portion
 - the period of the whole structure is no more than 1.1 times the period of the upper portion considered as a separate structure fixed at the base

All other structures must be designed using the dynamic method.

A. Characteristics of Earthquakes

Earthquakes are caused by the slippage of adjacent plates of the earth's crust and the subsequent release

of energy in the form of ground waves. Seismology is based on the science of plate tectonics, which proposes that the earth is composed of several very large plates of hard crust many miles thick, riding on a layer of molten rock closer to the earth's core. These plates are slowly moving relative to one another, and over time tremendous stress is built up by friction. Occasionally the two plates slip, releasing the energy we know as earthquakes. One of the most well known boundaries between two plates occurs between the Pacific plate and the North American plate along the coast of California. Earthquakes also occur in midplates, but the exact mechanism, other than fault slippage, is not fully understood.

The plates slip where the stress is maximum, usually several miles below the surface of the earth. Where this occurs is called the *hypocenter* of the earthquake. The term heard more often is the *epicenter*, which is the point on the earth's surface directly above the hypocenter.

When an earthquake occurs, complex actions are set up. One result is the development of waves that ultimately produce the shaking experienced in a building. There are three types of waves: *P* or *pressure waves*, *S* or *shear waves*, and *surface waves*. Pressure waves cause a relatively small movement in the direction of wave travel. Shear waves produce a sideways or up-and-down motion that shakes the ground in three directions. These are the waves that cause the most damage to buildings. Surface waves travel at or near the surface and can cause both vertical and horizontal earth movement.

The ground movement can be measured in three ways: by acceleration, velocity, and displacement. All three occur over time, with most earthquakes lasting only a few seconds. It is the acceleration of the ground that induces forces on a structure.

The interaction of the various waves and ground movement is complex. Not only does the earth move in three directions, but each direction has a different, random acceleration and amplitude. In addition, the movement reverses, creating a vibrating action. Even though there is vertical movement, the UBC allows it to be neglected under certain types of seismic design. The weight of a structure is usually enough to resist vertical forces. It is the side-to-side movement that causes the most damage.

B. Measurement of Earthquakes

Earthquake strength is commonly measured in two ways: with the *Richter Scale* and with the *Modified Mercalli Intensity Scale*. The Richter Scale measures magnitude as an indirect measure of released energy based on instrument recordings according to certain

defined procedures. The scale runs from zero at the low end and is open at the upper end, although the largest earthquake ever recorded had a Richter magnitude of nine.

The scale is logarithmic, each whole number value on the scale represents a tenfold increase in amplitude. In terms of energy released, each scale number represents about 32 times the amount of energy below it.

The Modified Mercalli Intensity Scale is a measure of an earthquake's intensity. It is an entirely subjective rating based on the observed damage to structures and other physical effects. The scale ranges from I to XII, with the upper rating being the most severe. Each scale includes a verbal description of the effects and damage of an earthquake.

The Modified Mercalli Scale is imprecise because it depends on people's observations, but it does provide information on how an earthquake affects structures and how the same earthquake affects areas at different distances from the epicenter, both of which cannot be accounted for with the Richter Scale.

Unfortunately for building design, neither scale is useful. This is because neither provides any information on the acceleration or duration of an earthquake, both of which are critical in the analysis and design of structures. However, they are used for risk analysis and determination of seismic zones.

Objective, quantified data useful for building design is provided by the *strong motion accelerometer*. This machine measures the acceleration of the ground or a building. The UBC requires that in seismic zones 3 and 4 every building over 6 stories with an aggregate floor area of 60,000 square feet or more, and every building over 10 stories regardless of floor area, be provided with not less than three accelerographs. These must be placed in the basement, midportion, and near the top of the building. Some jurisdictions may have additional requirements.

The records obtained by these instruments provide valuable data for research and design of similar buildings in the same geographical area. The acceleration they measure is usually expressed as a fraction of the acceleration of gravity, g , which is 32 feet per second per second. Thus, an earthquake may be recorded as having an acceleration of $0.55g$.

C. Seismic Zones

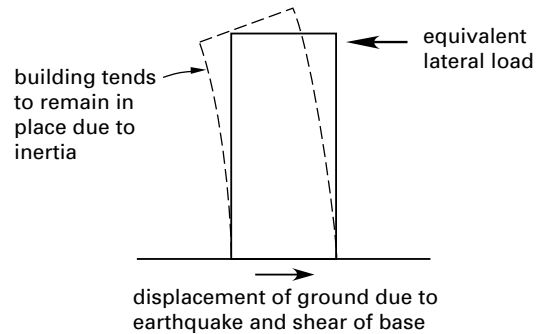
Based on seismic records, experience, and research, some areas of the United States are determined to have a greater probability of earthquakes than others, and some areas have more severe earthquakes (areas where two major plates abut, for example). This is taken into

account by dividing the country into different zones that represent estimates of future earthquake occurrence and strength.

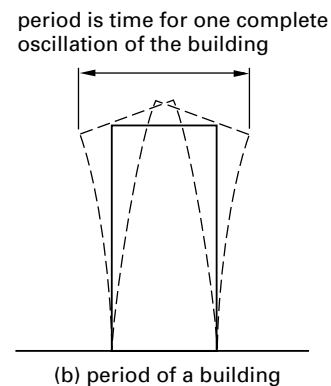
The map used by the UBC is shown in Figure 14.2. The procedure for incorporating the zones will be discussed in a later section.

D. The Effect of Earthquakes on Buildings

When an earthquake occurs, the first response of a building is not to move at all due to the inertia of the structure's mass. Almost instantaneously, however, the acceleration of the ground causes the building to move sideways at the base causing a lateral load on the building and a shear force at the base, as though forces were being applied in the opposite direction. See Figure 14.1(a). As the direction of the acceleration changes, the building begins to vibrate back and forth.



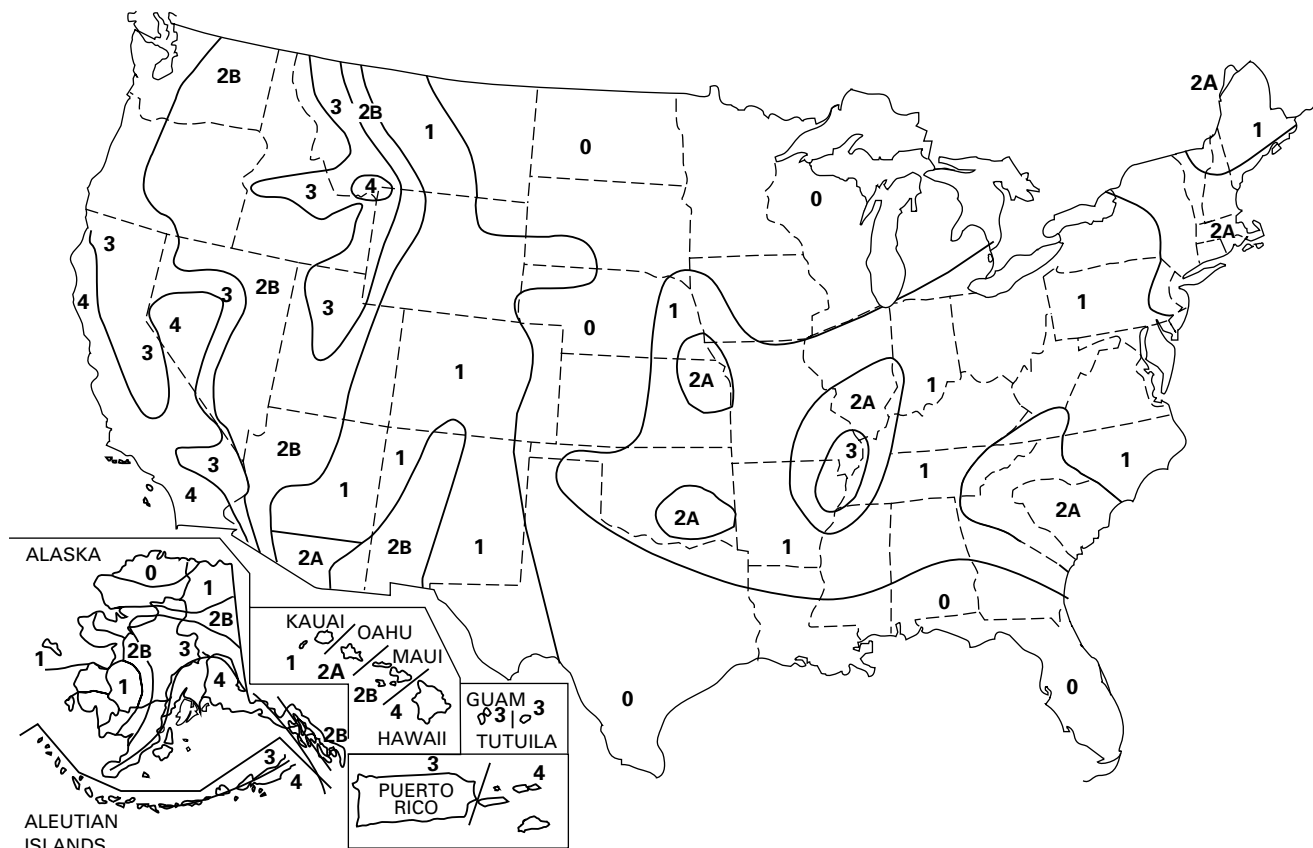
(a) response of a building to earthquake



(b) period of a building

Figure 14.1 Building Motion During an Earthquake

Theoretically, the force on the building can be found by using Newton's law, which states that force equals mass times acceleration. Since the acceleration is established by the given earthquake, the greater the mass of the building, the greater the force acting on it. However, the acceleration of the building depends on another property of the structure—its natural period.



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Figure 14.2 Seismic Risk Map of the United States

If a building is deflected by a lateral force such as the wind or an earthquake, it moves from side to side. The period is the time in seconds it takes for a building to complete one full side-to-side oscillation. See Figure 14.1(b). The period is dependent on the mass and the stiffness of the building.

In a theoretical, completely stiff building, there is no movement, and the natural period is zero. The acceleration of such an infinitely rigid building is the same as the ground. As the building becomes more flexible, its period increases and the corresponding acceleration decreases. As mentioned above, as the acceleration decreases, so does the force on the building. Therefore, flexible, long-period buildings have less lateral force induced, and stiff, short-period buildings have more lateral force induced.

As the building moves, the forces applied to it are either transmitted through the structure to the foundation, absorbed by the building components, or released in other ways such as collapse of structural elements.

The goal of seismic design is to build a structure that can safely transfer the loads to the foundation and back to the ground and absorb some of the energy present rather than suffering damage.

The ability of a structure to absorb some of the energy is known as *ductility*, which occurs when the building deflects in the inelastic range without failing or collapsing. The elastic limit, as discussed in Chapter 3, is the limit beyond which the structure sustains permanent deformation. The greater the ductility of a building, the greater is its capacity to absorb energy.

Ductility varies with the material. Steel is a very ductile material because of its ability to deform under a load above the elastic limit without collapsing. Concrete and masonry, on the other hand, are brittle materials. When they are stressed beyond the elastic limit, they break suddenly and without warning. Concrete can be made more ductile with reinforcement, but at a higher cost.

2 STRUCTURAL SYSTEMS TO RESIST LATERAL LOADS

The UBC specifies the types of structural systems used to resist seismic loads. The code requires that structural systems be classified as one of the types listed in Table 16-N. (See Table 14.1.) In addition to outlining the various types of structural systems, Table 16-N gives

the *R* factor used in calculations and the maximum height of each type of structural system. There are four broad categories of systems.

A. Bearing Wall System

A bearing wall system is a structural system without a complete vertical load-carrying space frame in which

Table 14.1
Structural Systems

BASIC STRUCTURAL SYSTEM ²	LATERAL-FORCE-RESISTING SYSTEM DESCRIPTION	<i>R</i>	Ω_o	HEIGHT LIMIT FOR SEISMIC ZONES 3 AND 4 (ft)
				× 304.8 for mm
1. Bearing wall system	1. Light-framed walls with shear panels	5.5	2.8	65
	a. Wood structural panel walls for structures three stories or less	4.5	2.8	65
	b. All other light-framed walls			
	2. Shear walls			
	a. Concrete	4.5	2.8	160
	b. Masonry	4.5	2.8	160
	3. Light steel-framed bearing walls with tension-only bracing	2.8	2.2	65
	4. Braced frames where bracing carries gravity load			
	a. Steel	4.4	2.2	160
	b. Concrete ³	2.8	2.2	—
c. Heavy timber	2.8	2.2	65	
2. Building frame system	1. Steel eccentrically braced frame (EBF)	7.0	2.8	240
	2. Light-framed walls with shear panels			
	a. Wood structural panel walls for structures three stories or less	6.5	2.8	65
	b. All other light-framed walls	5.0	2.8	65
	3. Shear walls			
	a. Concrete	5.5	2.8	240
	b. Masonry	5.5	2.8	160
	4. Ordinary braced frames			
	a. Steel	5.6	2.2	160
	b. Concrete ³	5.6	2.2	—
c. Heavy timber	5.6	2.2	65	
5. Special concentrically braced frames				
a. Steel	6.4	2.2	240	
3. Moment-resisting frame system	1. Special moment-resisting frame (SMRF)			
	a. Steel	8.5	2.8	N.L.
	b. Concrete ⁴	8.5	2.8	N.L.
	2. Masonry moment-resisting wall frame (MMRWF)	6.5	2.8	160
	3. Concrete intermediate moment-resisting frame (IMRF) ⁵	5.5	2.8	—
	4. Ordinary moment-resisting frame (OMRF)			
	a. Steel ⁶	4.5	2.8	160
b. Concrete ⁷	3.5	2.8	—	
5. Special truss moment frames of steel (STMF)	6.5	2.8	240	
4. Dual systems	1. Shear walls			
	a. Concrete with SMRF	8.5	2.8	N.L.
	b. Concrete with steel OMRF	4.2	2.8	160
	c. Concrete with concrete IMRF ⁵	6.5	2.8	160
	d. Masonry with SMRF	5.5	2.8	160
	e. Masonry with OMRF	4.2	2.8	160
	f. Masonry with IMRF ³	4.2	2.8	—
	g. Masonry with masonry MMRWF	6.0	2.8	160
	2. Steel EBF			
	a. With steel SMRF	8.5	2.8	N.L.
	b. With steel OMRF	4.2	2.8	160
	3. Ordinary braced frames			
	a. Steel with steel SMRF	6.5	2.8	N.L.
	b. Steel with steel OMRF	4.2	2.8	160
	c. Concrete with concrete SMRF ³	6.5	2.8	—
	d. Concrete with concrete IMRF ³	4.2	2.8	—
	4. Special concentrically braced frames			
a. Steel with steel SMRF	7.5	2.8	N.L.	
b. Steel with steel SMRF	4.2	2.8	160	
5. Cantilevered column building systems	1. Cantilevered column elements	2.2	2.0	35 ⁶
6. Shear wall-frame interaction systems	1. Concrete ⁸	5.5	2.8	160
7. Undefined systems	See Sections 1629.6.7 and 1629.9.2	—	—	—

N.L.—no limit

¹See Section 1630.4 for combination of structural systems.

²Basic structural systems are defined in Section 1629.6.

³Prohibited in Seismic Zones 3 and 4.

⁴Includes precast concrete conforming to Section 1921.2.7.

⁵Prohibited in Seismic Zones 3 and 4, except as permitted in Section 1634.2.

⁶Ordinary moment-resisting frames in Seismic Zone I meeting the requirements of Section 2211.6 may use an *R* value of 8.

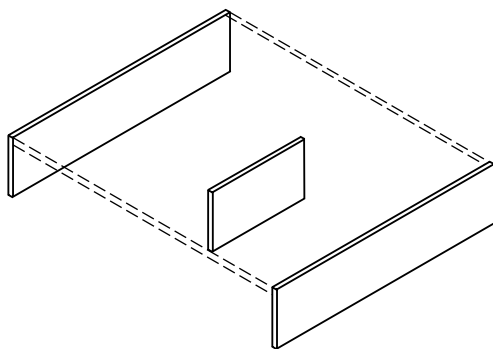
⁷Total height of the building including cantilevered columns.

⁸Prohibited in Seismic Zones 2A, 2B, 3 and 4. See Section 1633.2.7.

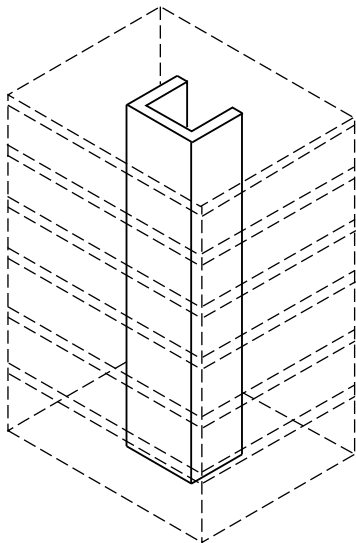
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the lateral loads are resisted by shear walls or braced frames. Bearing walls or bracing systems provide support for all or most gravity loads. Remember that a space frame is defined as a three-dimensional structural system, without bearing walls, that is comprised of members interconnected such that it functions as a complete, self-contained unit.

A *shear wall* is a vertical structural element that resists lateral forces in the plane of the wall through shear and bending. Such a wall acts as a beam cantilevered out of the ground or foundation, and, just as with a beam, part of its strength derives from its depth. Figure 14.3 shows two examples of a shear wall, one in a simple one-story building and another in a multistory building.



(a) end shear walls and interior shear wall



(b) interior shear walls for bracing in two directions

Figure 14.3 Shear Walls

In Figure 14.3(a), the shear walls are oriented in one direction, so only lateral forces in this direction can be resisted. The roof serves as the horizontal diaphragm and must also be designed to resist the lateral loads and transfer them to the shear walls.

Figure 14.3(a) also shows an important aspect of shear walls in particular and vertical elements in general. This is the aspect of symmetry that has a bearing on whether torsional effects will be produced. The shear walls in Figure 14.3(a) show the shear walls symmetrical in the plane of loading. Torsion will be discussed in a later section.

Figure 14.3(b) illustrates a common use of shear walls at the interior of a multistory building. Because walls enclosing stairways, elevator shafts, and mechanical chases are mostly solid and run the entire height of the building, they are often used for shear walls. Although not as efficient from a strictly structural point of view, interior shear walls do leave the exterior of the building open for windows.

Notice that in 14.3(b) there are shear walls in both directions, which is a more realistic situation because both wind and earthquake forces need to be resisted in both directions. In this diagram, the two shear walls are symmetrical in one direction, but the single shear wall produces a nonsymmetrical condition in the other since it is off center. Shear walls do not need to be symmetrical in a building, but symmetry is preferred to avoid torsional effects.

Shear walls can be constructed from a variety of materials, but the most common are plywood on wood framing for residential and small commercial buildings, and concrete for larger buildings. Reinforced masonry walls can also be used. Shear walls may have openings in them, but the calculations are more difficult and their ability to resist lateral loads is reduced depending on the percentage of open area.

B. Building Frame Systems

A building frame system is one with an essentially complete space frame that provides support for gravity loads in which the lateral loads are resisted by shear walls or braced frames. A braced frame is a truss system of the concentric or eccentric type in which the lateral forces are resisted through axial stresses in the members. Just as with a truss, the braced frame depends on diagonal members to provide a load path for lateral forces from each building element to the foundation. Figure 14.4(a) shows a simple one-story braced frame. At one end of the building two bays are braced, and at the other end only one bay is braced. As with Figure 14.3, this building is only braced in one direction and uses compression braces because the diagonal member may be either in tension or compression, depending on which way the force is applied.

Figure 14.4(b) shows two methods of bracing a multistory building. A single diagonal compression member in one bay can be used to brace against lateral loads

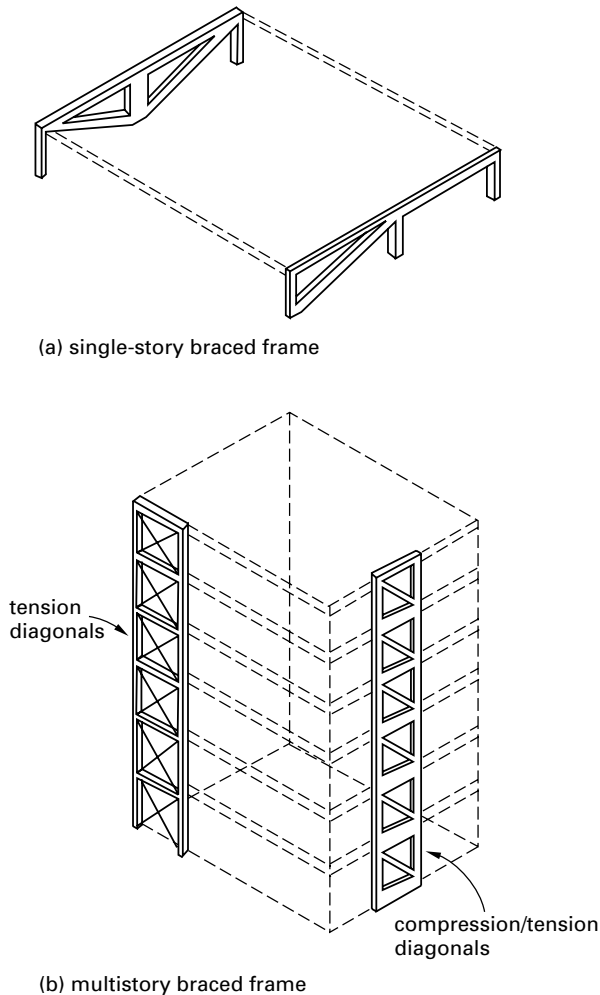


Figure 14.4 Braced Frames

coming from either direction. Alternately, tension diagonals can be used to accomplish the same result, but they must be run both ways to account for the load coming from either direction.

Braced framing can be placed on the exterior or interior of a building, and may be placed in one structural bay or several. In a trussed tube building, the diagonals span between several floors of the building. Obviously, a braced frame can present design problems for windows and doorways, but it is a very efficient and rigid lateral force resisting system.

C. Moment-Resisting Frame Systems

Moment-resisting frames carry lateral loads primarily by flexure in the members and joints. Joints are designed and constructed so they are theoretically completely rigid, and therefore any lateral deflection of the frame occurs from the bending of columns and beams. The UBC differentiates between three types of moment-resisting frames.

The first type is the special moment-resisting frame that must be specifically detailed to provide ductile behavior and comply with the provisions of Chapters 19 and 22 (Concrete and Steel) of the UBC.

The second type is the intermediate moment-resisting frame, which is a concrete frame with less restrictive requirements than special moment-resisting frames. However, intermediate frames cannot be used in seismic zones 3 or 4.

The third type is the ordinary moment-resisting frame. This is a steel or concrete moment-resisting frame that does not meet the special detailing requirements for ductile behavior. Ordinary steel frames may be used in any seismic zone while ordinary concrete frames cannot be used in zones 3 or 4.

Moment-resisting frames are more flexible than shear wall structures or braced frames; the horizontal deflection, or drift, is greater. Adjacent buildings cannot be located too close to each other, and special attention must be paid to the eccentricity developed in columns, which increases the column bending stresses.

Two types of moment-resisting frames are shown in Figure 14.5.

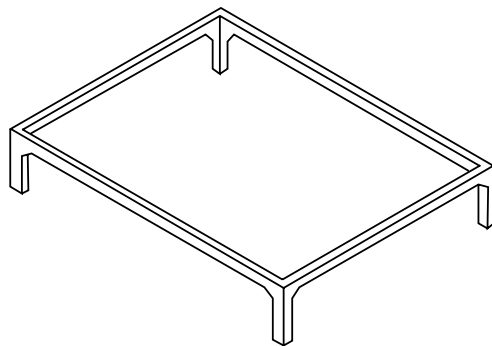
D. Dual Systems

A dual system is a structural system in which an essentially complete frame provides support for gravity loads, and resistance to lateral loads is provided by a specially detailed moment-resisting frame and shear walls or braced frames. The moment-resisting frame must be capable of resisting at least 25 percent of the base shear, and the two systems must be designed to resist the total lateral load in proportion to their relative rigidities. The moment-resisting frame may be either steel or concrete, but concrete intermediate frames cannot be used in seismic zones 3 or 4.

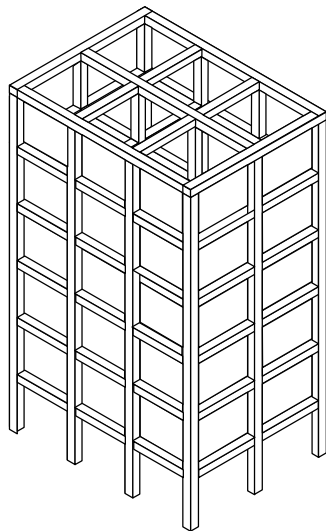
E. Horizontal Elements

In all lateral force-resisting systems, there must be a way to transmit lateral forces to the vertical resisting elements. This is done with several types of structures, but the most common way used is the *diaphragm*. As discussed in Chapter 13, a diaphragm acts as a horizontal beam resisting forces with shear and bending action. Refer to Figure 13.5.

Other types of horizontal elements include horizontal trussed frames and horizontal moment-resisting frames. There are two types of diaphragms: flexible and rigid. Although no horizontal element is completely flexible or rigid, distinction is made between the two types because the type affects the way in which lateral forces are distributed.



(a) single-story frame

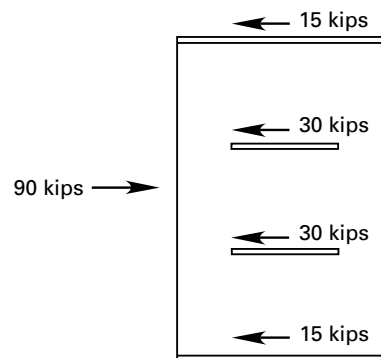


(b) multistory frame

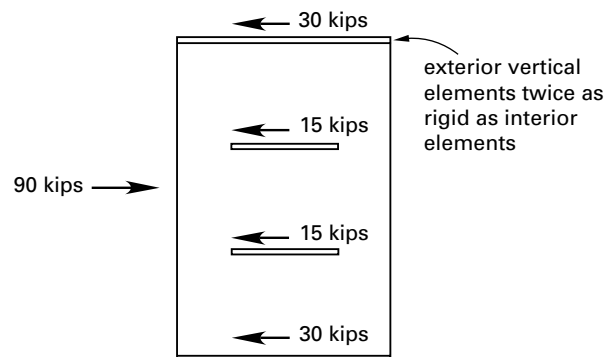
Figure 14.5 Moment-Resisting Frames

A flexible diaphragm is one that has a maximum lateral deformation more than two times the average story drift of that story. This deformation can be determined by comparing the midpoint in-plane deflection of the diaphragm with the story drift of the adjoining vertical resisting elements under equivalent tributary load. The lateral load is distributed according to tributary areas as shown in Figure 14.6(a).

With a *rigid diaphragm*, the shear forces transmitted from the diaphragm to the vertical elements will be in proportion to the relative stiffness of the vertical elements (assuming there is no torsion). See Figure 14.6(b). If the end walls in the diagram are twice as stiff as the interior walls, then one-third of the load is distributed to each end wall and one-third to the two interior walls which is equally divided between these two. The illustration shows symmetrically placed shear walls, so the distribution is equal. However, if the vertical resisting elements are asymmetric, the shearing forces are unequal.



(a) flexible diaphragm load distribution



(b) rigid diaphragm load distribution

Figure 14.6 Diaphragm Load Distribution

Concrete floors are considered rigid diaphragms, as are steel and concrete composite deck construction. Steel decks may be either flexible or rigid, depending on the details of their construction. Wood decks are considered flexible diaphragms.

3 BUILDING CONFIGURATION

In recent years, there has been increased emphasis on the importance of a building's configuration in resisting seismic forces. Early decisions concerning size, shape, arrangement, and location of major elements can have a significant influence on the performance of a structure. Since the design professional plays a large role in these early decisions, it is imperative that the architect thoroughly understand the concepts involved.

Building configuration refers to the overall building size and shape and the size and arrangement of the primary structural frame, as well as the size and location of the nonstructural components of the building that may affect its structural performance. Significant nonstructural components include such things as heavy nonbearing partitions, exterior cladding, and large weights like equipment or swimming pools.

In the current UBC, elements that constitute both horizontal and vertical irregularities are specifically defined,

so it is clear which structures must be designed with the dynamic method and which structures may be designed using the static analysis method.

The code states that all buildings must be classified as either regular or irregular. Whether a building is regular or not helps determine if the static method may be used. Irregular structures generally require design by the dynamic method (with exceptions mentioned in Section 1), and additional detailed design requirements are imposed depending on what type of irregularity exists.

Table 16-L (see Table 14.2) lists and defines five types of vertical structural irregularities along with references to the specific code sections that give specific design requirements. Table 16-M (see Table 14.3) lists and defines five types of plan structural irregularities along with their code references. Note that the definition of torsional irregularity (Plan Structural Irregularity Type 1 in Table 14.3) mentions diaphragms that are not flexible. Flexible diaphragms are defined in Section 2E.

Also note that the definition of nonparallel systems (Plan Structural Irregularity Type 5 in Table 14.3) includes buildings in which a column forms part of two or more intersecting lateral force-resisting systems, unless the axial load due to seismic forces acting in either direction is less than 20 percent of the column allowable axial load.

The following sections describe some of the important aspects of building configuration.

A. Torsion

Lateral forces on a portion of a building are assumed to be uniformly distributed and can be resolved into a single line of action acting on a building. In a similar way, the shear reaction forces produced by the vertical resisting elements can be resolved into a single line of action. For symmetric buildings with vertical resisting elements of equal rigidity, these lines of action pass through the same point as shown diagrammatically in Figure 14.7(a).

If the shear walls or other vertical elements are not symmetric or are of unequal rigidity, the resultant of their shear resisting forces, the center of rigidity, does not coincide with the applied lateral force. This is shown in Figure 14.7(b). Since the forces are acting in opposite directions with an eccentricity, torsion force is developed, which is in addition to the lateral load alone.

When the force on a vertical element caused by the eccentricity acts in the same direction as that caused by the lateral load directly, they must be added. However, when the torsional force acts in the opposite direction, one cannot be subtracted from the other.

Table 14.2
Vertical Structural Irregularities

IRREGULARITY TYPE AND DEFINITION	REFERENCE SECTION
1. Stiffness irregularity—soft story A soft story is one in which the lateral stiffness is less than 70 percent of that in the story above or less than 80 percent of the average stiffness of the three stories above.	1629.8.4, Item 2
2. Weight (mass) irregularity Mass irregularity shall be considered to exist where the effective mass of any story is more than 150 percent of the effective mass of an adjacent story. A roof that is lighter than the floor below need not be considered.	1629.8.4, Item 2
3. Vertical geometric irregularity Vertical geometric irregularity shall be considered to exist where the horizontal dimension of the lateral-force-resisting system in any story is more than 130 percent of that in an adjacent story. One-story penthouses need not be considered.	1629.8.4, Item 2
4. In-plane discontinuity in vertical lateral-force-resisting element An in-plane offset of the lateral-load-resisting elements greater than the length of those elements.	1630.8.2
5. Discontinuity in capacity—weak story A weak story is one in which the story strength is less than 80 percent of that in the story above. The story strength is the total strength of all seismic-resisting elements sharing the story shear for the direction under consideration.	1629.9.1

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Table 14.3
Plan Structural Irregularities

IRREGULARITY TYPE AND DEFINITION	REFERENCE SECTION
1. Torsional irregularity—to be considered when diaphragms are not flexible Torsional irregularity shall be considered to exist when the maximum story drift, computed including accidental torsion, at one end of the structure transverse to an axis is more than 1.2 times the average of the story drifts of the two ends of the structure.	1633.2.9, Item 6
2. Re-entrant corners Plan configurations of a structure and its lateral-force-resisting system contain re-entrant corners, where both projections of the structure beyond a re-entrant corner are greater than 15 percent of the plan dimension of the structure in the given direction.	1633.2.9, Items 6 and 7
3. Diaphragm discontinuity Diaphragms with abrupt discontinuities or variations in stiffness, including those having cutout or open areas greater than 50 percent of the gross enclosed area of the diaphragm, or changes in effective diaphragm stiffness of more than 50 percent from one try to the next.	1633.2.9, Item 6
4. Out-of-plane offsets Discontinuities in a lateral force path, such as out-of-plane offsets of the vertical elements.	1630.8.2; 1633.2.9, Item 6; 2213.8
5. Nonparallel systems The vertical lateral-load-resisting elements are not parallel or symmetric about the major orthogonal axes of the lateral-force-resisting system.	1633.1

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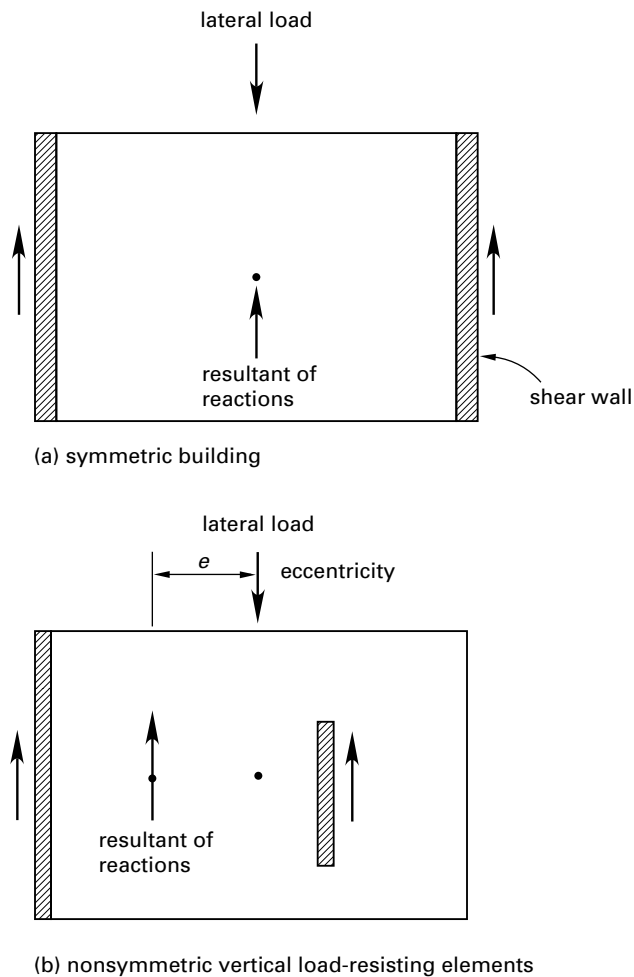


Figure 14.7 Development of Torsion

The UBC requires that even in symmetrical buildings a certain amount of accidental torsion be planned for. This accounts for the fact that the position of loads in an occupied building cannot be known for certain. The code requires that the mass at each level is assumed to be displaced from the calculated center of mass in each direction by a distance equal to 5 percent of the building dimension at that level perpendicular to the direction of the force under consideration. For example, for a building 50 feet wide and 100 feet long, the center of mass for forces acting perpendicular to the 100-foot dimension is offset 5 feet. For forces acting in the other direction, the center of mass is offset 2 1/2 feet.

The importance of understanding the concept of torsion will become apparent in the following sections.

B. Plan Shape

Irregularities in plan shape can create torsion and concentrations of stress, both of which should be avoided whenever possible. One of the most common and troublesome plan shapes is the re-entrant corner. Figure 14.8(a) shows some common varieties of this shape.

During an earthquake, the ground motion causes the structure to move in such a way that stress concentrations are developed at the inside corners. See Figure 14.8(b).

In addition, since the center of mass and the center of rigidity do not coincide, there is an eccentricity established that results in a twisting of the entire structure as discussed in the previous section and is shown in Figure 14.7(b).

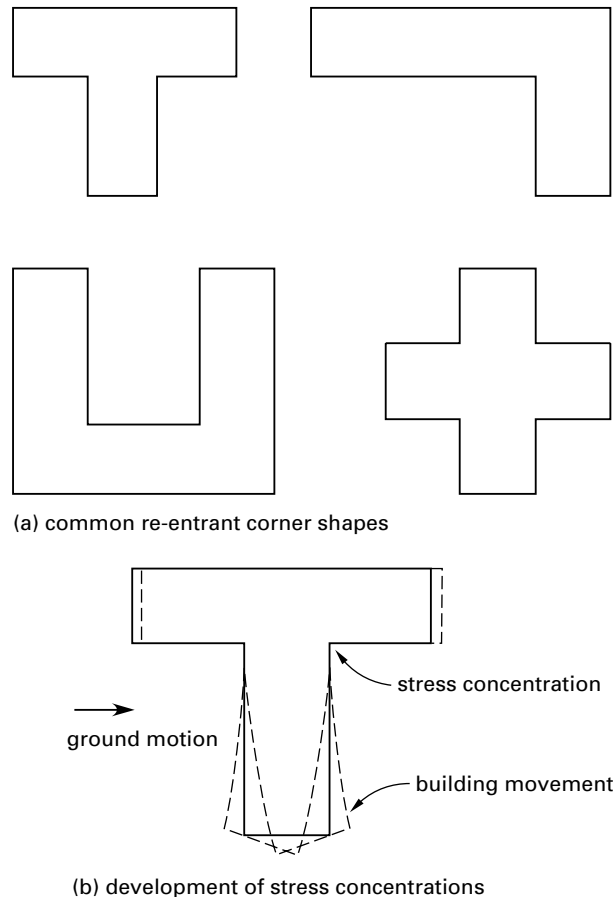
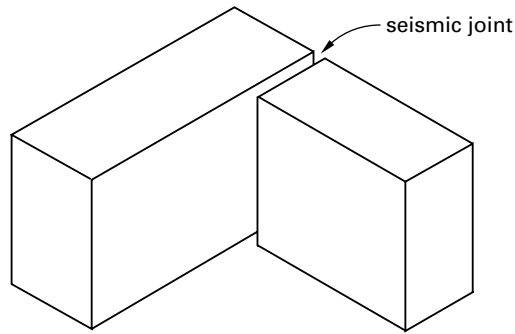


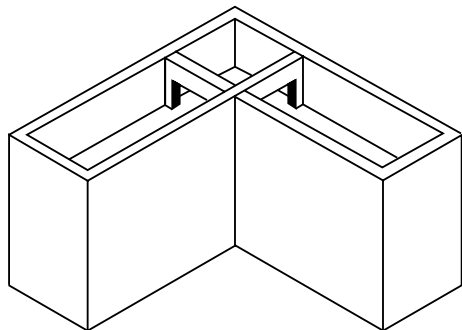
Figure 14.8 Problem Plan Shapes

Of course, building shape is often dictated by the site, the program, or other requirements beyond the control of the architect or engineer. In the cases where such shapes are unavoidable, there are ways to minimize the problem. The portions of the building can be separated with a seismic joint, they can be tied together across the connection, or the inside corner can be splayed. These design approaches are shown in Figure 14.9.

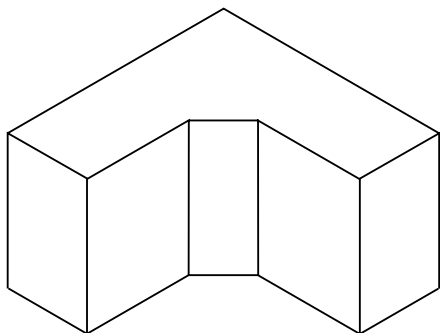
A second common problem that arises with building plans is a variation in the stiffness and strength of the perimeter. Even though a building may be symmetric, the distribution of mass and lateral resisting elements may place the centers of mass and rigidity in such a way that torsion is developed. One example of this is shown



(a) separate wings



(b) provide strong connection



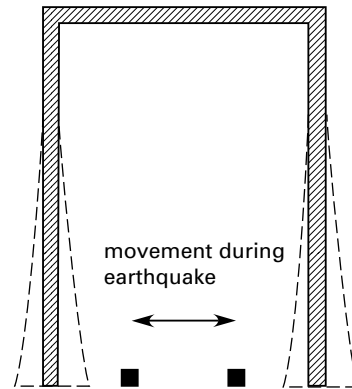
(c) splay corner

Figure 14.9 Solutions to Re-entrant Corners

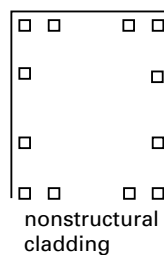
diagrammatically in Figure 14.10(a), where a building has rigid shear walls on three sides but is open in the front.

During an earthquake, the open end of the building acts as a cantilevered beam causing lateral displacement and torsion. There are four possible ways to alleviate the problem. These are shown in Figure 14.10.

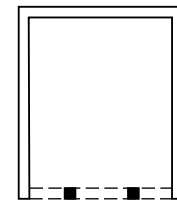
In the first instance, a rigid frame can be constructed with symmetric rigidity and then the cladding can be made nonstructural. Secondly, a strong, moment-resisting or braced frame can be added that has a stiffness similar to the other walls. Third, shear walls can



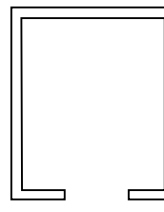
(a) variation in perimeter stiffness—plan



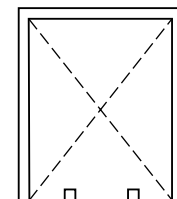
nonstructural cladding



design strong moment-resisting frame



add shear walls



design diaphragm and frame to resist torsion

Figure 14.10 Variation in Perimeter Stiffness

be added to the front if this does not compromise the function of the building. Finally, for small buildings, the structure can simply be designed to resist the expected torsion forces.

C. Elevation Design

The ideal elevation from a seismic design standpoint is one that is regular, symmetrical, continuous, and that matches the other elevations in configuration and seismic resistance. Setbacks and offsets should be avoided for the same reason as re-entrant corners in plan should be avoided; that is, to avoid areas of stress concentration. Of course, perfect symmetry is not always possible due to the functional and aesthetic requirements of the building, but there are two basic configurations that should (and can) be avoided by the architect early in the design process.

The first problem configuration is a discontinuous shear wall. This is a major mistake and should never happen. Discontinuities can occur when large openings are placed in shear walls, when they are stopped short of the foundation, or when they are altered in some other way. Since the entire purpose of a shear wall is to carry lateral loads to the foundation and act as a beam cantilevered out of the foundation, any interruption of this is counterproductive. Of course, small openings like doors and small windows can be placed in shear walls if proper reinforcement is provided.

Two common examples of discontinuous shear walls are shown in Figure 14.11. In the first, the shear wall is stopped at the second floor level and supported by columns. This is often done to open up the first floor, but it creates a situation where stress concentrations are so great that even extra reinforcing cannot always resist the build-up of stress.

The second example, shown in Figure 14.11(b), is also a common design feature where the second floor and floors above are cantilevered slightly from the first floor shear wall. Even though the shear wall continues, the offset also creates an undesirable situation because the direct load path for the lateral loads is interrupted, and the floor structure has to carry the transfer of forces from one shear wall to the next.

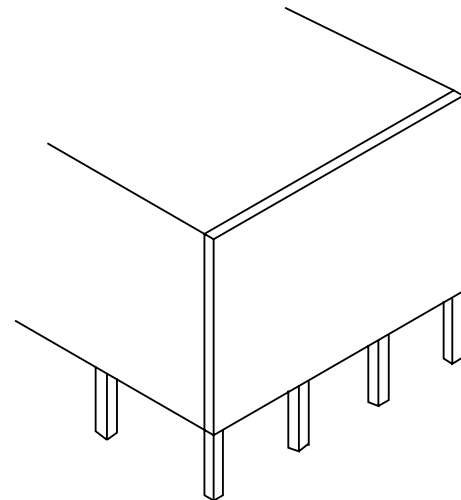
In all cases of discontinuous shear walls, the solution is simple: shear walls should run continuously to the foundation.

Another serious problem with building configuration is the soft story. This occurs when the ground floor is weaker than the floors above. Although a soft story can occur at any floor, it is most serious at grade level because this is where the lateral loads are the greatest. The discontinuous shear wall discussed in the previous section is a special case of the soft story. Others can occur when all columns do not extend to the ground or when the first story is high compared with the other floors of the structure. See Figure 14.12.

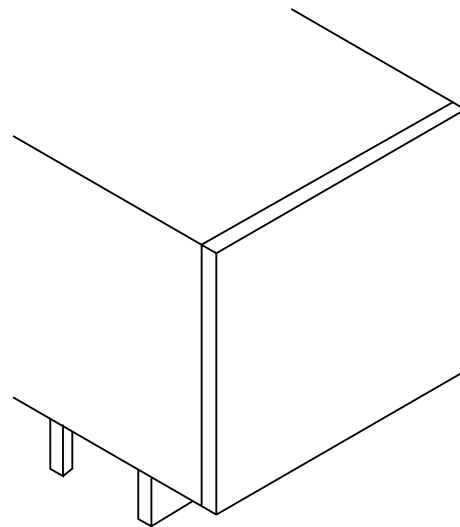
A soft story can also be created when there is heavy exterior cladding above the first story and the ground level is open. Of course, there are usually valid reasons for all of these situations to occur. For example, a hotel may need a high first story, but shorter floors above for the guest rooms.

When earthquake loads occur, the forces and deformations are concentrated at the weak floor instead of being uniformly distributed among all the floors and structural members.

There are several ways to solve the problem of a soft story. The first, of course, is to eliminate it and try



(a) shear wall to column transition



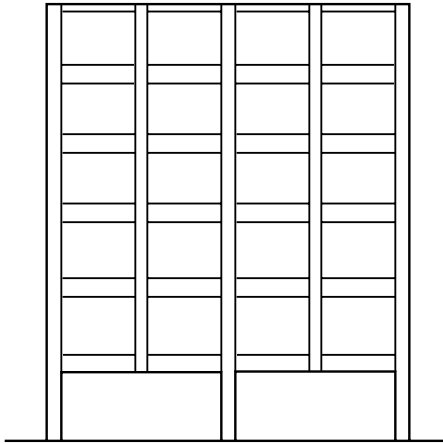
(b) offset shear walls

Figure 14.11 Discontinuous Shear Walls

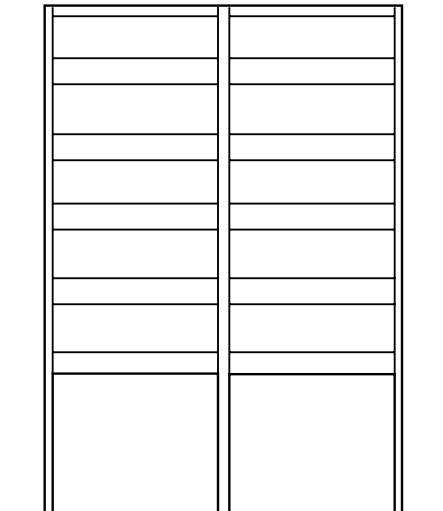
to work the architectural solution around the extra columns or lower height. If height is critical, extra columns can be added at the first floor. Another solution is to add extra horizontal and diagonal bracing. Finally, the framing of the upper stories can be made the same as the first story. The entire structure then has a uniform stiffness. Lighter, intermediate floors can be added above the first between the larger bays so they do not affect the behavior of the primary structural system.

4 ANALYSIS OF EARTHQUAKE LOADING

This section discusses the equivalent static load method for determining the base shear, or total lateral force, on a building. Except for structures required to be



(a) discontinuous columns



(b) high first story

Figure 14.12 Soft First Stories

designed according to dynamic analysis as previously mentioned, the UBC allows the total seismic force on the main structural frame to be calculated according to a simplified formula. When using this formula, the base shear in each of the main axes of the building must be determined and the structural system designed to resist the forces.

In addition, the code requires that forces on elements of structures and nonstructural components be calculated according to a different formula. This will be reviewed in a later section.

When a structure meets the requirements listed in Section 1, the static force procedure may be used. The formula for finding the total lateral force or shear at the base of a structure is

$$V = \left(\frac{C_v I}{RT} \right) W \tag{14.1}$$

The total base shear need not exceed the following:

$$V = \left(\frac{2.5C_a I}{R} \right) W \tag{14.2}$$

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

$$V = 0.11C_a I W \tag{14.3}$$

Once the total lateral force is determined, it is used to determine the forces on the various horizontal and vertical structural elements.

A. I Factor

The importance factor, *I*, is either 1.0 or 1.25, depending on the occupancy categories that are listed in UBC Table 16-K. (See Table 14.4.)

Table 14.4
Occupancy Categories and Requirements

OCCUPANCY CATEGORY	OCCUPANCY OR FUNCTIONS OF STRUCTURE	SEISMIC IMPORTANCE FACTOR, <i>I</i>	SEISMIC IMPORTANCE ¹ FACTOR, <i>I_p</i>	WIND IMPORTANCE FACTOR, <i>I_w</i>
1. Essential facilities ²	Group I, Division 1 Occupancies having surgery and emergency treatment areas Fire and police stations Garages and shelters for emergency vehicles and emergency aircraft Structures and shelters in emergency-preparedness centers Aviation control towers Structures and equipment in government communication centers and other facilities required for emergency response Standby power-generating equipment for Category 1 facilities Tanks or other structures containing housing or supporting water or other fire-suppression material or equipment required for the protection of Category 1, 2, or 3 structures	1.25	1.50	1.15
2. Hazardous facilities	Group H, Divisions 1, 2, 6 and 7 Occupancies and structures therein housing or supporting toxic or explosive chemicals or substances Nonbuilding structures housing, supporting or containing quantities of toxic or explosive substances that, if contained within a building, would cause that building to be classified as a Group H, Division 1, 2 or 7 Occupancy	1.25	1.50	1.15
3. Special occupancy structures ³	Group A, Divisions 1, 2 and 2.1 Occupancies Buildings housing Group E, Divisions 1 and 3 Occupancies with a capacity greater than 300 students Buildings housing Group B Occupancies used for college or adult education with a capacity greater than 500 students Group I, Divisions 1 and 2 Occupancies with 50 or more resident incapacitated patients, but not included in Category 1 Group I, Division 3 Occupancies All structures with an occupancy greater than 5000 persons Structures and equipment in power-generating stations, and other public utility facilities not included in Category 1 or Category 2 above, and required for continued operation	1.00	1.00	1.00
4. Standard occupancy structures ³	All structures housing occupancies or having functions not listed in Category 1, 2 or 3 and Group U Occupancy towers	1.00	1.00	1.00
5. Miscellaneous structures	Group U Occupancies except for towers	1.00	1.00	1.00

¹The limitation of *I_p* for panel connections in Section 1633.2.4 shall be 1.0 for the entire connector.

²Structural observation requirements are given in Section 1702.

³For anchorage of machinery and equipment required for life-safety systems, the value of *I_p* shall be taken as 1.5.

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B. C_v Factor/ C_a Factor

The C_v factor represents both the seismicity of a region and the characteristics of the soil. Table 16-R of the 1997 UBC gives the C_v factors used in Equation 14.1. (See Table 14.5.) UBC Table 16-Q (see Table 14.6) provides C_a factors used in Equations 14.2 and 14.3.

UBC Table 16-J (see Table 14.7) gives six soil profile types ($S_A, S_B, S_C, S_D, S_E,$ and S_F) to account for the effect of soil characteristics in determination of design base shear.

Table 14.5
Seismic Coefficient C_v

SOIL PROFILE TYPE	SEISMIC ZONE FACTOR, Z				
	$Z = 0.075$	$Z = 0.15$	$Z = 0.2$	$Z = 0.3$	$Z = 0.4$
S_A	0.06	0.12	0.16	0.24	$0.32N_v$
S_B	0.08	0.15	0.20	0.30	$0.40N_v$
S_C	0.13	0.25	0.32	0.45	$0.56N_v$
S_D	0.18	0.32	0.40	0.54	$0.64N_v$
S_E	0.26	0.50	0.64	0.84	$0.96N_v$
S_F	See Footnote 1				

¹Site-specific geotechnical investigation and dynamic site response analysis shall be performed to determine seismic coefficients for Soil Profile Type S_F .

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Table 14.6
Seismic Coefficient C_a

SOIL PROFILE TYPE	SEISMIC ZONE FACTOR, Z				
	$Z = 0.075$	$Z = 0.15$	$Z = 0.2$	$Z = 0.3$	$Z = 0.4$
S_A	0.06	0.12	0.16	0.24	$0.32N_a$
S_B	0.08	0.15	0.20	0.30	$0.40N_a$
S_C	0.09	0.18	0.24	0.33	$0.40N_a$
S_D	0.12	0.22	0.28	0.36	$0.44N_a$
S_E	0.19	0.30	0.34	0.36	$0.36N_a$
S_F	See Footnote 1				

¹Site-specific geotechnical investigation and dynamic site response analysis shall be performed to determine seismic coefficients for Soil Profile Type S_F .

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C. Z Factor

The amount of seismic risk present in any given geographical location is represented by the Z factor. The seismic zone map has six zones, with zone 0 being the

Table 14.7
Soil Profile Types

SOIL PROFILE TYPE	SOIL PROFILE NAME/GENERIC DESCRIPTION	AVERAGE SOIL PROPERTIES FOR TOP 100 FEET (30 480 mm) OF SOIL PROFILE		
		Shear Wave Velocity, V_s feet/second (m/s)	Standard Penetration Test, \bar{N} [or \bar{N}_{CH} for cohesionless soil layers] (blows/foot)	Undrained Shear Strength, \bar{s}_u psf (kPa)
S_A	Hard Rock	> 5,000 (1,500)	—	—
S_B	Rock	2,500 to 5,000 (760 to 1,500)	—	—
S_C	Very Dense Soil and Soft Rock	1,200 to 2,500 (360 to 760)	> 50	> 2,000 (100)
S_D	Stiff Soil Profile	600 to 1,200 (180 to 360)	15 to 50	1,000 to 2,000 (50 to 100)
S_E^1	Soft Soil Profile	< 600 (180)	< 15	< 1000 (50)
S_F	Soil Requiring Site-specific Evaluation. See Section 1629.3.1.			

¹Soil Profile Type S_E also includes any soil profile with more than 10 feet (3048 mm) of soft clay defined as a soil with a plasticity index, $PI > 20$, $w_{mc} \geq 40$ percent and $s_u < 500$ psf (24 kPa). The Plasticity Index, PI , and the moisture content, w_{mc} , shall be determined in accordance with approved national standards.

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one of least risk. (See Figure 14.2.) The following list gives the Z factors for each zone as stated in Table 16-I of the 1997 UBC.

Zone 1	$Z = 0.075$	Zone 2B	$Z = 0.20$
Zone 2A	$Z = 0.15$	Zone 3	$Z = 0.30$
		Zone 4	$Z = 0.40$

D. T Factor

The UBC gives two methods of determining T : an approximate method that can be used for all buildings, and a more complex method based on the deformational characteristics of the resisting elements in the building. The formula for approximating T is

$$T = C_t(h_n)^{\frac{3}{4}} \tag{14.4}$$

In Equation 14.4, $C_t = 0.035$ for steel moment-resisting frames, $C_t = 0.030$ for reinforced concrete moment-resisting frames and eccentric braced frames, and $C_t = 0.020$ for all other buildings.

The code also gives another formula for finding the value of C_t for structures with concrete or masonry shear walls. Refer to Sec. 1630.2.2 of the UBC for this formula.

E. R Factor

The R factor is based on the type of structural system used. These factors are given in Table 16-N (see Table 14.1) as previously discussed. For nonbuilding structures, the R factor is given in UBC Table 16-P.

The R factor reflects the energy-absorbing capabilities of various types of structural systems. Notice that systems with high ductility, such as steel special moment-resisting space frames, have a higher R value than systems with less ductility. Because the R value is now placed in the denominator of Equations 14.1 and 14.2, a higher value results in a lower value of V , the design seismic force.

F. W Factor

The W factor is the total dead load of the building. Other applicable loads listed here must also be added:

- In warehouses and storage occupancies, a minimum of 25 percent of the floor live load must be added.
- When partition loads are used in the design of the floor, not less than 10 pounds per square foot must be included.
- Where snow load exceeds 30 pounds per square foot, it must also be included except when a reduction of up to 75 percent is approved by the building official.
- The total weight of permanent equipment must be included.

Example 14.1

A small, three-story hospital is being planned for Denver, Colorado. The structure is to be 45 feet high, 80 feet wide, and 170 feet long. Preliminary soil reports indicate 50 feet of soft clay soil. Snow load is 30 psf. If a bearing wall system with concrete shear walls is planned and the estimated weight is 3500 kips, what is the base shear?

From Figure 14.2, Denver is in zone 1, so the Z factor is 0.075. From Table 14.7, the soil profile type is S_E .

Because this is a hospital, the importance factor, I , from Table 14.4, is 1.25.

Using Equation 14.4, the period is determined as

$$\begin{aligned} T &= C_t(h_n)^{\frac{3}{4}} = (0.020)(45)^{\frac{3}{4}} \\ &= 0.35 \text{ seconds} \end{aligned}$$

From Table 14.5, for $Z = 0.075$ and soil profile type S_E , the seismic coefficient, $C_v = 0.26$.

From Table 14.1, the R factor is 4.5.

Calculate the base shear, using Equation 14.1.

$$\begin{aligned} V &= \left(\frac{C_v I}{RT} \right) W = \left(\frac{(0.26)(1.25)}{(4.5)(0.35)} \right) (3500) \\ &= 722 \text{ kips} \end{aligned}$$

From Equation 14.2,

$$V_{\max} = \left(\frac{2.5C_a I}{R} \right) W$$

From Table 14.6, seismic coefficient $C_a = 0.19$.

Therefore,

$$\begin{aligned} V_{\max} &= \left(\frac{(2.5)(0.19)(1.25)}{4.5} \right) (3500) \\ &= 462 \text{ kips} \end{aligned}$$

Using Equation 14.3,

$$\begin{aligned} V_{\min} &= 0.11C_a I W = (0.11)(0.19)(1.25)(3500) \\ &= 91.4 \text{ kips} \end{aligned}$$

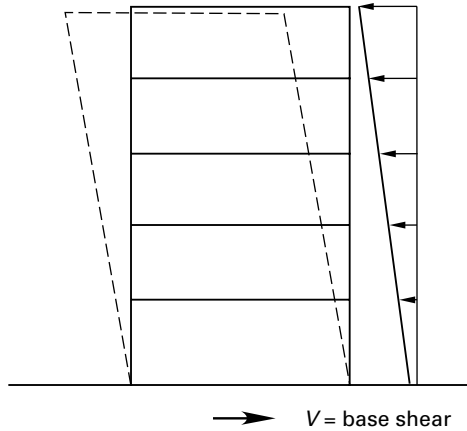
Therefore, $V = 462$ kips.

G. Distribution of Base Shear

Once the total base shear is known, it is used to determine the forces on the various building elements. For single-story buildings, this is fairly straightforward. For multistory buildings, the forces must be distributed according to the displacement that occurs during an earthquake. Although structural movement under seismic forces is complex, the static lateral force procedure uses the most pronounced displacement that takes place, which results in an inverted force triangle varying from zero at the base to the maximum at the top. See Figure 14.13(a).

With this simplified approach, it is assumed that there is uniform mass distribution and equal floor heights, but the code does provide for variations as will be shown in Equation 14.6. The sum of the loads at each level equals the total base shear. Also note that while the greatest force is at the top of the building, the shear increases from zero at the top to its maximum at the base. Each floor shear is successively added to the sum from above. This method for the distribution of loads is only for the design of vertical lateral load resisting elements. There is another formula for determining the force on the diaphragm at each level of a multistory building.

To account for tall buildings that do not have a uniform triangular distribution, the UBC requires that an additional force be applied at the top of the building, but



(a) distribution of forces using the equivalent static load method

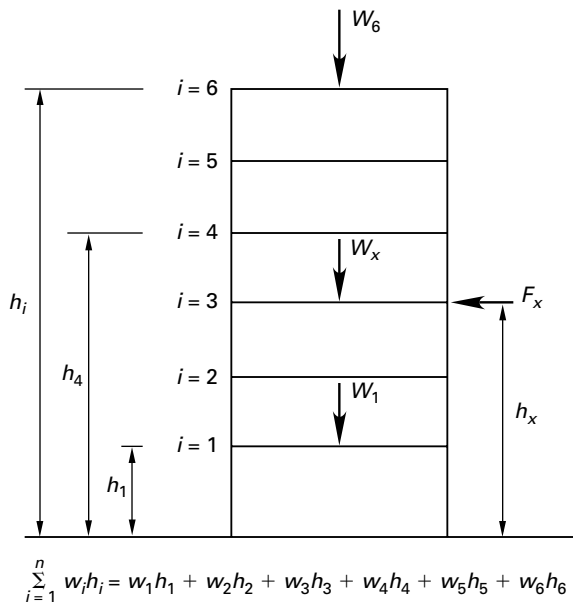


Figure 14.13 Distribution of Base Shear

only if the period, T , is greater than 0.7 seconds. This force is

$$F_t = 0.07TV \tag{14.5}$$

However, this force value does not have to be greater than $0.25V$. The remaining base shear, $V - F_t$, is then distributed to the roof and each floor according to the formula

$$F_x = \frac{(V - F_t)w_x h_x}{\sum_{i=1}^n w_i h_i} \tag{14.6}$$

The value of the denominator is the summation of all the floor weights times their heights at the floor under consideration. The formula can be solved easily using a tabular approach as shown in the next example. The

values included in Equation 14.6 are shown graphically in Figure 14.13.

Example 14.2

A three-story office building located in Gary, Indiana, is 40 feet wide and 80 feet long. Each floor is 12 feet high, and the building is wood frame construction with plywood shear walls at each end. Building weights are as follows.

roof	15 psf
floors	20 psf
exterior walls	18 psf
partitions	8 psf

Determine the distribution of shear in the transverse direction.

step 1. Determine the weight of each floor and the total weight. The roof weight is 74 kips, and the second and third floor weights are 142 kips each, for a total weight of 358 kips.

step 2. Determine the seismic factors and calculate the base shear. From Figure 14.2, Gary, Indiana, is in zone 1.

$$Z = 0.075$$

Using Table 14.4, an office building is a “standard occupancy structure,” so

$$I = 1.0$$

$$T = C_t(h_n)^{\frac{3}{4}} \quad \text{[from Equation 14.4]}$$

Using a value of 0.020 for C_t and a height of 36 feet,

$$T = 0.294 \text{ seconds}$$

Because no soil information is given, soil type S_E is assumed (conservative). From Table 14.5, $C_v = 0.26$.

From UBC Table 16-N (Table 14.1), $R = 5.5$ (structure type 1.1.a).

From step 1,

$$W = 358 \text{ kips}$$

The base shear is then calculated using Equation 14.1.

$$\begin{aligned} V &= \left(\frac{C_v I}{RT} \right) W = \left(\frac{(0.26)(1.0)}{(5.5)(0.294)} \right) (358) \\ &= 57.6 \text{ kips} \end{aligned}$$

From Equation 14.2,

$$V_{\max} = \left(\frac{2.5C_a I}{R} \right) W$$

From Table 14.6, $C_a = 0.19$.

Therefore,

$$\begin{aligned}
 V_{\max} &= \left(\frac{(2.5)(0.19)(1.0)}{5.5} \right) (358) = 30.9 \text{ kips} \\
 V_{\min} &= 0.11C_aIW && 14.3 \\
 &= (0.11)(0.19)(1.0)(358) = 7.5 \text{ kips}
 \end{aligned}$$

Therefore, $V = 30.9$ kips.

Because the period, T , is less than 0.7, $F_t = 0$ so the $V - F_t$ value is 30.9 kips.

step 3. Tabulate the values needed for solving Equation 14.6 and calculate the results.

1 level	2 w_x	3 h_x	4 $w_x h_x$	5	6 F_z
roof	74	36	2664	0.34	10.5
3	142	24	3408	0.44	13.6
2	142	12	1704	0.22	6.8
Σ			7776	1.00	30.9

The values in column 5 are calculated by taking the value in column 4 and dividing by the summation of column 4, which is 7776. The values in column 5 are then multiplied by the base shear, 30.9 kips, to arrive at the distributed force at each level in column six.

H. Parts of Buildings

The code requires that in addition to the primary structural frame, individual elements of structures, nonstructural components, and their connections be designed to withstand seismic forces. Of particular importance are connections of the floors and roof to the walls and columns, walls to the structural frame, partitions to floors and ceilings, ceilings to boundary walls, millwork to floors and walls, equipment and fixtures to floors, piping and ducts to the structure, and suspended lights to the ceilings.

The force these parts must withstand is determined by

$$F_p = 4.0C_aI_pW_p \quad 14.7$$

There are two types of elements: rigid and nonrigid. Rigid elements are defined as those having a fixed base period less than or equal to 0.06 second. Nonrigid elements or flexibly supported items have a fixed base period greater than 0.06 second.

Example 14.3

It is decided that the building in Example 14.2 is to have an 8-inch masonry exterior and a parapet 3 feet

high. Determine the load on the parapet if it weighs 55 psf.

From Example 14.2, $Z = 0.075$ and $I = 1.0$.

The force on each square foot of parapet is

$$\begin{aligned}
 F_p &= (4.0)(0.19)(1.0)(55) \\
 &= 41.8 \text{ psf}
 \end{aligned}$$

This value can be used to determine the moment on the parapet and the subsequent reinforcing required to resist the moment.

I. Load Combinations Required

As with wind loading, the UBC requires that various combinations of loads on a building be calculated and the most critical one be used to design the structure. For earthquake loading, the following combinations must be reviewed.

The basic load combinations in UBC Section 1612.3.1 are as follows.

- dead
- dead plus seismic/1.4
- 0.9 times dead plus or minus seismic/1.4
- dead plus 0.75 times (floor live plus roof live or snow plus seismic/1.4)

Alternate basic load combinations per Section 1612.3.2 are as follows.

- dead plus floor live plus seismic/1.4
- dead plus floor live plus snow plus seismic/1.4
- 0.9 times dead plus or minus seismic/1.4

Snow loads less than 30 pounds per square foot need not be combined with seismic, and snow loads over 30 pounds per square foot may be reduced 75 percent if approved by the building official.

5 ADDITIONAL CONSIDERATIONS

The complete and detailed design of earthquake-resistant structures is a complex procedure and beyond the scope of this book. However, this section outlines some additional concepts with which you should be familiar.

A. Overturning Moment

Because the inertial force created by an earthquake acts through the center of mass of a building, there is a tendency for the moment created by this force acting above the base to overturn the structure. This overturning

force must be counteracted in some way. Normally, the dead weight of the building, also acting through the center of mass, is sufficient to resist the overturning force, but it must always be checked. However, only 90 percent of the dead load may be used to resist uplift. Figure 14.14 shows these two forces and the resulting moments diagrammatically.

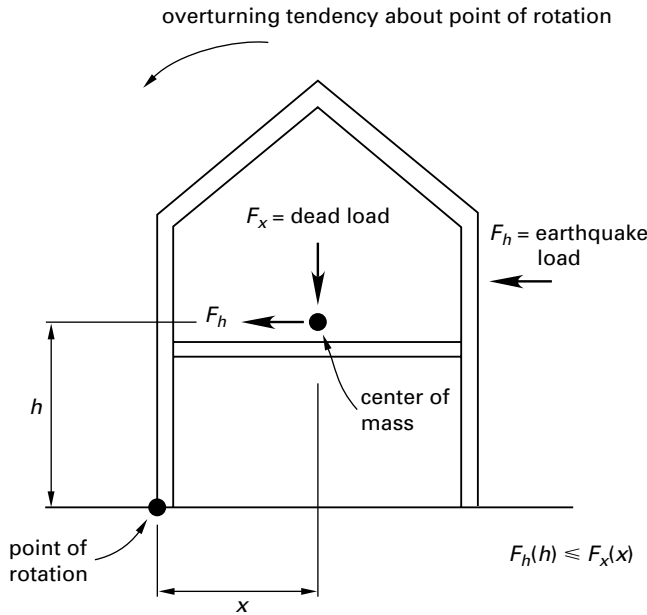


Figure 14.14 Overturning Moment

B. Drift

Drift is the lateral movement of a building under the influence of earthquake- or wind-induced vibrations. Story drift is the displacement of one level relative to the level above or below. The UBC gives stringent limitations on story drift. A static analysis shall be used to determine the design level response displacement, Δ_S . The maximum inelastic response displacement, Δ_M , shall be computed as follows.

$$\Delta_M = 0.7R\Delta_S \quad 14.8$$

The value of R is obtained from Table 14.1. The calculated story drift using Δ_M shall not exceed 0.025 times the story height for structures having a fundamental period of less than 0.7 second. For structures having a fundamental period of 0.7 second or greater, the calculated story drift shall not exceed 0.020 time the story height.

Drift as a limiting factor is important in order to ensure that exterior facades do not break off or crack excessively. When two buildings or portions of buildings are isolated by a seismic joint, they must be separated by at least the sum of the drifts to avoid pounding during an earthquake.

SAMPLE QUESTIONS

The answers to questions 1 through 3 can be found on the following key list. Select only one answer for each question.

- A0 accelerograph
- A1 bearing wall system
- A2 braced frame
- A3 building frame system
- A4 ductility
- A5 framed tube
- A6 irregular
- A7 modified Mercalli scale
- A8 moment-resisting space frame
- A9 natural period
- B0 re-entrant corner
- B1 regular
- B2 Richter scale
- B3 shear wall discontinuity
- B4 soft story
- B5 symmetric

1. A building is constructed of an ordinary moment-resisting frame and is raised on columns above an open plaza below. What is this an example of?
 - A. 257 kips
 - B. 1185 kips
 - C. 1300 kips
 - D. 1950 kips
2. What provides information most useful for seismic design?
 - A. 257 kips
 - B. 1185 kips
 - C. 1300 kips
 - D. 1950 kips
3. What describes a building whose lateral force-resisting system consists of members stressed in flexure.
 - A. 257 kips
 - B. 1185 kips
 - C. 1300 kips
 - D. 1950 kips
4. A store in Seattle, Washington will have a steel, ordinary moment-resisting frame. It will be 120 feet wide, 180 feet long, and 50 feet high, with two stories. Soil reports show stiff soil with an average standard penetration test value of 40 blows/foot over the top 100 feet. The structure has a dead load of 6500 kips and has no building irregularities in the longitudinal direction. What is the total base shear in the longitudinal direction?
 - A. 257 kips
 - B. 1185 kips
 - C. 1300 kips
 - D. 1950 kips
5. A dynamic analysis method would be required if which of the following conditions existed?
 - A. a 5-story, square hotel building with a skylight-topped atrium in the middle that comprises 55 percent of the building's area
 - B. a 40-story, rectangular office building in seismic zone 3 with an ordinary moment-resisting space frame
 - C. a 3-story, L-shaped department store
 - D. all of the above
6. Select the incorrect statement from the following.
 - A. Ductility is important above the elastic limit.
 - B. Flexible buildings are good at resisting earthquake and wind loads.
 - C. A penthouse swimming pool would not be a good idea in seismic zone 2B.
 - D. All other things being equal, reinforced concrete is a poorer choice than steel for a structural system in seismic zone 3.
7. Which of the following are true?
 - I. The epicenter is the location of fault slippage.
 - II. Vertical ground movement is usually critical when calculating its effect on a building
 - III. A building's fundamental period of vibration is dependent on its mass and stiffness.
 - IV. Buildings in seismic zone 1 require some earthquake-resistant design considerations.
 - V. Useful information in seismic zones 3 and 4 can be gathered from existing buildings.
 - A. I, II, and III
 - B. II, III, and IV
 - C. II, IV, and V
 - D. III, IV, and V
8. An 8-inch exterior concrete wall is used for a police station in Kansas City, Missouri. Soil reports show a soft soil profile. What seismic design pressure should be applied to the wall?
 - A. 100 psf
 - B. 120 psf
 - C. 180 psf
 - D. 270 psf

9. The distribution of base shear in a multistory building does not depend on which of the following?

- A. the height of the building
- B. the rigidity of the diaphragms
- C. the distribution of mass
- D. the height of the floors

10. Select the correct statements about shear walls.

- I. The width-to-height ratio should be made as large as possible.
 - II. The force normal to the shear wall is not critical compared to the shear force in the plane of the wall.
 - III. Shear walls are best located at the perimeter of the building.
 - IV. Shear walls should not be offset.
 - V. Shear walls can be used in a bearing wall system.
- A. I, III, and IV
 - B. I, II, and IV
 - C. I, III, IV, and V
 - D. all of the above