eave and ridge tiles, etc., in windstorms. Wind tunnel studies on scale models of buildings have confirmed that three distinct high-pressure and suction areas develop around buildings, as shown schematically in Figure 2.26:

1. Positive-pressure zone on the upstream face (Region 1)
2. Negative-pressure zones at the upstream corners (Regions 2)
3. Negative-pressure zone on the downstream face (Region 3)

The highest negative pressures are generated in the upstream corners designated as Regions 2 in Figure 2.26. Wind pressures on a building’s surface are not constant, but fluctuate continuously. The positive pressure on the upstream or the windward face fluctuates more than the negative pressure on the downstream or the leeward face. The negative-pressure region remains relatively steady as compared to the positive-pressure zone. The fluctuation of pressure is random and varies from point to point on the building surface. Therefore, the design of the cladding is strongly influenced by local pressures. As mentioned earlier, the design pressure can be thought of as a combination of the mean and the fluctuating velocity. As in the design of buildings, whether or not the pressure component arising from the fluctuating velocity of wind is treated as a dynamic or as a pseudostatic load is a function of the period of the cladding. The period of cladding on a building is usually on the order of 0.2–0.02 s, which is much shorter than the period it takes for wind to fluctuate from a gust velocity to a mean velocity. Therefore, it is sufficiently accurate to consider both the static and the gust components of winds as equivalent static loads in the design of cladding.

The strength of glass, and indeed of any other cladding material, is not known with the same certainty as the strength of other construction materials such as steel or concrete. For example, it is not possible to buy glass based on yield strength criteria as with steel. Therefore, the selection, testing, and acceptance criteria for glass are based on statistical probabilities rather than on absolute strength. The glass industry has addressed this problem and commonly uses 8 failures per 1000 lights (panes) of glass as an acceptable probability of failure.
Local Cladding Loads and Overall Design Loads

The design wind loads that we use in lateral analysis are an overall combination of positive and negative pressures occurring simultaneously around the building. The local wind loads that act on specific areas of the building are not required for overall building design but are vital for the design of exterior cladding elements and their connections to building. The methodology of determining these two types of loads (1) overall building design load and (2) local components and cladding design load, differ significantly. Important differences are the following:

1. Local winds are more influenced by the configuration of the building than the overall loading.
2. Local load is the maximum load that may occur at any location at any instant of time on any wall surface, whereas the overall load is the summation of positive and negative pressures occurring simultaneously over the entire building surface.
3. Intensity and character of local loading for any given wind direction and velocity differ substantially on various parts of the building surface, whereas the overall load is considered to have a specific intensity and direction.
4. Local loading is sensitive to the momentary nature of wind, but in determining critical overall loading, only gusts of about 2 s or more are significant.
5. Generally, maximum local negative pressures, also referred to as suction, are of greater intensity than overall load.
6. Internal pressures caused by leakage of air through cladding systems have a significant effect on local cladding loads but are of no consequence in determining overall load on typical fully enclosed buildings.

The relative importance of designing for these two types of wind loading is quite obvious. Although proper assessment of overall wind load is important, very few, if any, buildings have been toppled by winds. There are no classic examples of building failures comparable to the Tacoma bridge disaster. On the other hand, local failures of roofs, windows, and wall cladding are not uncommon.

The analytical determination of wind pressure or suction at a specific surface of a building under varying wind direction and velocity is a complex problem. Contributing to the complexity are the vagaries of wind action as influenced both by adjacent surroundings and the configuration of the wall surface itself. Much research is needed on the micro effects of common architectural features such as projecting mullions, column covers, and deep window reveals. In the meantime, model testing of building in wind tunnels is perhaps the only recourse.

Probably the most important fact established by tests is that the negative or outward-acting wind loads on wall surfaces are greater and more critical than had formerly been assumed. They may be as much as twice the magnitude of positive loading. In most instances of local cladding failures, glass panels have blown off of the building, not into it, and the majority of such failures have occurred in areas near building corners. Therefore, it is important to give careful attention to the design of both anchorage and glazing details to resist outward-acting forces.

Another feature that has come to light for quite some time from model testing is that wind loads on wall surfaces are greater and more critical than had formerly been assumed. They may be as much as twice the magnitude of positive loading. In most instances of local cladding failures, glass panels have blown off of the building, not into it, and the majority of such failures have occurred in areas near building corners. Therefore, it is important to give careful attention to the design of both anchorage and glazing details to resist outward-acting forces.

Another feature that has come to light for quite some time from model testing is that wind loads, both positive and negative, do not vary in proportion to height aboveground (see Figure 2.27). Typically, the positive-pressure contours follow a concentric pattern as illustrated in Figure 2.27b, with the highest pressure near the lower center of the facade, and pressures at the very top somewhat less than those a few stories below the roof. Figure 2.27e shows a pressure diagram for the design of cladding of a high-rise building measured in wind tunnel tests. The block pressure diagram shown in Figure 2.27f gives zones of design pressures based on the building grid system, to assist in the cladding design.
FIGURE 2.27 Pressure contours for cladding design: (a) peak negative pressures; (b) peak positive pressures; (c) peak positive pressures, building in open country; (d) peak positive pressures, building in city; (e) pressures measured in wind tunnel; and (f) simplified pressure diagram tied to building grid. *Note:* Pressures shown are in psf.
2.6.3 Comments on ASCE 7-10 Wind Provisions

It is perhaps evident from the brief discussion given earlier that the wind-load provisions of the ASCE 7-10 are quite tedious if not migranious. Could the provisions be simplified? Yes, certainly they can be but at a cost—the cost resulting from adding a level of conservatism that would cover all special conditions. However, the current trend, particularly with the availability of computers, is to perform rigorous calculations that result in the most economical and efficient use of our resources, so don’t expect the ASCE wind provisions to get easier any time soon (Figures 2.28 and 2.29).

**FIGURE 2.28** Maximum dynamic load factor for sinusoidal load, $F_1 \sin \Omega t$, damped systems.

**FIGURE 2.29** Vortex shedding: periodic shedding of vertices generates building vibrations in the transverse direction.
Earthquake Effects on Buildings

PREVIEW

Earthquakes have wreaked destruction since oldest antiquity, and it is only in the last 50 years that our knowledge of earthquakes and of their impact on buildings has resulted in the design of earthquake-resistant structures. These are built with particularly strong lateral bracing systems capable of resisting the jerking forces of an earthquake. Even so, the number of quake victims is still high all over the world. When 27,000 people died in the Guatemala earthquake of 1967, we thought we had seen the worst, but when 242,000 people died in an earthquake later in the same year in the region north of Peking. The Earth's crust floats over a core of molten rock and some of its parts have a tendency to move with respect to one another. This movement creates stresses in the crust, which may break out along fractures called faults. The break occurs through a sudden sliding motion in the direction of the fault and jerks the buildings in the area. Since the dynamic impact forces due to this jerky motion are mostly horizontal, they can be resisted by the same kind of bracing used against wind.

Earthquake strengths are evaluated on scales like the Richter scale, which measures the magnitude of the energy in the earthquake. For example, an earthquake measuring 4 or 5 on the Richter scale does little damage to well-built buildings, while one measuring 8 or above collapses buildings and may cause many deaths. Not all parts of the earth are subjected to earthquakes, but there are two wide zones on the Earth's surface where the worst earthquakes take place. One follows a line through the Mediterranean, Asia Minor, the Himalayas, and the East Indies, and the other the western, northern, and eastern shores of the Pacific.

Earthquakes are catastrophic events that occur mostly at the boundaries of portions of the Earth's crust called tectonic plates. When movement occurs in these regions, along faults, waves are generated at the Earth's surface that can produce very destructive effects.

Aftershocks are smaller quakes that occur after all large earthquakes. They are usually most intense in size and number within the first week of the original quake. They can cause very significant reshaking of damaged structures, which makes earthquake-induced disasters more hazardous. A number of moderate quakes (6+ magnitude) have had aftershocks that were very similar in size to the original quake. Aftershocks diminish in intensity and number with time. They generally follow a pattern of there being at least 1 large (within 1 Richter magnitude) aftershock, at least 10 lesser (within 2 Richter magnitude) aftershocks, 100 within 3, and so on. The Loma Prieta earthquake had many aftershocks, but the largest was only magnitude 5.0 with the original quake being magnitude 7.1.

Some of the most destructive effects caused by earthquake shaking are those that produce lateral loads in a structure. The input shaking causes the foundation of a building to oscillate back and forth in a more or less horizontal plane. The building mass has inertia and wants to remain where it is, and therefore, lateral forces are exerted on the mass in order to bring it along with the foundation. For analysis purposes, this dynamic action is simplified as a group of horizontal forces that are applied to the structure in proportion to its mass and to the height of the mass above the ground. In multi-story buildings with floors of equal weight, the loading is further simplified as a group of loads, each being applied at a floor line and each being greater than the one below in a triangular distribution (see Figure 3.1). Seismically resistant structures are designed to resist these lateral forces through...
Inelastic and primarily for economic reason and must, therefore, be detailed accordingly. These loads are often expressed in terms of a percent of gravity weight of the building and can vary from a few percent to near 50% of gravity weight. There are also vertical loads generated in a structure by earthquake shaking, but these forces rarely overload the vertical-load-resisting system. However, earthquake-induced vertical forces have caused damage to structures with high dead load compared to design live load. These vertical forces also increase the chance of collapse due to either increased or decreased compression forces in the columns. Increased compression overloads columns, while decreased compression reduces column bending strength.

In earthquake engineering, we deal with random variables, and therefore, the design must be treated differently from the orthodox design. The orthodox viewpoint maintains that the objective of design is to prevent failure; it idealizes variables as deterministic. This simple approach is still valid, applied to design under only mild uncertainty. But when confronted with the effects of earthquakes, this orthodox viewpoint seems so overtrustful as to be worthless. In dealing with earthquakes, we must contend with appreciable probabilities that failure will occur in the near future. Otherwise, all the wealth of this world would prove insufficient to fill our needs: the most modest structures would be fortresses. We must also face uncertainty on a large scale while designing engineering systems—whose pertinent properties are still debated to resist future earthquakes—about whose characteristics we know even less.

Although over the years, experience and research have diminished our uncertainties and concerns regarding the characteristics of earthquake motions and manifestations, it is unlikely, though, that there will be such a change in the nature of knowledge to relieve us of the necessity of dealing openly with random variables. In a way, earthquake engineering is a parody of other branches of engineering. Earthquake effects on structures systematically bring out the mistakes made in design and construction, even the minutest mistakes. Add to this the undeniable dynamic nature of disturbances, the importance of soil–structure interaction, and the extremely random nature of it all; in a manner of speaking, earthquake engineering is to the rest of the engineering disciplines what psychiatry is to other branches of medicine. This aspect of earthquake engineering makes it challenging and fascinating and gives it an educational value beyond its immediate objectives. If structural engineers are to acquire fruitful experience in a brief span of time, expose them to the concepts of earthquake engineering, even if their interest in earthquake-resistant design is indirect. Sooner or later, they will learn that the difficulties encountered in seismic design are technically intriguing and begin to exercise that nebulous trait called engineering judgment to make allowance for these unknown factors.

To understand the seismic behavior of buildings, it is helpful to study strong-motion seismograms (also called time histories). The familiar wiggly line graphic records shown in Figure 3.2 are not the actual motion of the ground but have been filtered in some way by both the recording instrument and by the agency providing the data. In most cases, however, for practical applications, the engineer need not be concerned about the difference.

Modern instruments capable of recording large motions strategically placed in structures provide information on the structural response. In this case, it is evident that there is amplification of both short-period and long-period motions in the upper floors. This effect is reflected in seismic design by applying larger loads up the building height.
Until the 1990s, seismic building codes used a single map of the United States that divided the country into numbered seismic zones (0, 1, 2, 3, 4) in which each zone was assigned a single acceleration value in %g, which was used to determine seismic loads on the structure.

Starting in the 1970s, new hazard maps began to be developed on a probabilistic basis. In the 1994 National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions, two maps of the United States were provided, showing effective peak acceleration coefficients and effective peak velocity–related coefficients by use of contour lines that designate regions of equal value. The ground motions were based on estimated probabilities of 10% of exceedance in various exposure times (50, 100, and 250 years).

The probabilistic analysis is typically represented in maps in the form of a percentage probability of exceedance in a specified number of years. For example, commonly used probabilities are a 10% probability of exceedance in 50 years (a return period of about 475 years) and 2% probability of exceedance in 50 years (a return period of about 2,500 years). These maps show ground motions that may be equaled but are not expected to be exceeded in the next 50 years: the odds that they will not be exceeded are 90% and 98%, respectively.

Seismic hazard probability maps are produced by the United States Geological Survey (USGS). The latest sets of USGS of maps provide a variety of maps for peak ground acceleration and spectral acceleration, with explanatory material, and are available on the USGS website.

The USGS map is a probabilistic representation of hazard for the contiguous United States. This shows the spectral acceleration in %g with a 2% probability of exceedance in 50 years: this degree of probability is the basis of the maps used in the building codes.

The return period of 1 in 2,500 years may seem very infrequent, but this is a statistical value, not a prediction, so some earthquakes will occur much sooner and some much later. The design dilemma is that if a more frequent earthquake—for example, the return period of 475 years—was used in the lower seismic regions, the difference between the high- and low-probability earthquakes is a ratio of between 2 and 5. Design for the high-probability earthquake would be largely ineffective when the low-probability event occurred.

In practical terms, the building designer must assume that the large earthquake may occur at any time. Thus, use of the 2,500 return period earthquakes in the lower seismic regions ensures protection against rare earthquakes, such as the recurrence of the 1811–1812 earthquake sequence in New Madrid, Missouri, or the 1898 Charleston, South Carolina, earthquake. The selection of 2% in 50-year likelihood as the maximum considered earthquake (MCE) ground motion is believed to result in acceptable levels of seismic safety for the nation.
The acceleration experienced by a building will vary depending on the period of the building, and in general, short-period buildings will experience more accelerations than long-period buildings. The USGS maps recognize this phenomenon by providing acceleration values for periods of 0.2 s (short) and 1.0 s (long). These are referred to as spectral acceleration, and the values are approximately what are experienced by a building (as distinct from the peak acceleration that is experienced at the ground). The spectral acceleration is usually considerably more than the peak ground accelerations.

The USGS maps are based on MCE ground motion—the most severe earthquake considered in the US seismic standards. They are based on a 2% probability of occurrence in 50 years.

These USGS probability maps provide the basis for the maps used in building codes that provide design values for spectral acceleration used by structural engineers to calculate the seismic forces on a structure. These design value maps differ by use of an MCE for the regions. For most regions of the country, the MCE is defined as ground motion with a uniform likelihood of exceedance of 2% in 50 years (a return period of about 2,500 years) and is identical to the USGS probability maps. However, in regions of high seismicity, such as coastal California, the seismic hazard is typically controlled by large-magnitude events occurring on a limited number of well-defined fault systems. For these regions, rather than using the 2% in 50-year likelihood, it is considered more appropriate to directly determine the MCE ground motions based on the characteristic earthquakes of those defined faults.

It is to be noted that the acceleration values shown on the maps are not used directly for design. Instead, they are reduced by two-thirds of this value to determine the design earthquake (DE) and are the values used by engineers for design. The reason for this is that it is believed by engineers that the design provisions contain at least a margin of 1.5 against structural failure. MCE is inferred to provide collapse prevention level, while the actual design is done using the DE, which is 2/3 MCE for code-level, life-safety protection level. This belief is the result of the study of the performance of many types of buildings in earthquakes, mostly in California.

The building response to earthquake shaking occurs over the time of a few seconds. During this time, several types of seismic waves are combining to shake the building in ways that are different in detail for each earthquake. In addition, as the result of variations in fault slippage, differing rock through which the waves pass, and the different geological nature of each site, the resultant shaking at each site is different. The characteristics of each building are different, whether in size, configuration, material, structural system, age, or quality of construction: each of these characteristics affects the building response.

In spite of the complexity of the interactions between the building and the ground during the few seconds of shaking, there is broad understanding of how different building types will perform under different shaking conditions. This understanding comes mainly from extensive observation of buildings in earthquakes all over the world and to a lesser extent from analytical and experimental research.

Understanding the ground and building characteristics discussed in this chapter is essential to give designers a feel for how their building will react to shaking, which is necessary to guide the conceptual design of their building.

In this chapter, we

- Provide an introduction to some of the key issues involved in seismic design, including a summary of the effect of earthquakes on building structures
- Outline the characteristics of earthquake that are important for building design
- Explain the basic ways in which earthquake-induced ground motion affects buildings
- Discuss how the building becomes more prone to failure and less predictable as the building becomes more complex in its configuration

### 3.1 Inertial Forces and Acceleration

The seismic waves create internal forces within the building. Inertial forces are generated when an outside force tries to make the building move if it is at rest or change its rate or direction of motion if it is moving.
Consider a freestanding water tower shown in Figure 3.3a subjected to earthquake ground motions. A simplified analytical model for the tower may be represented by a cantilever column with a concentrated mass $M$ at top, as shown in Figure 3.3b. When the base of the cantilever is subjected to sudden ground motion, the initial tendency for the water tower, that is, the mass $M$, is to stay put. The shifting of the ground is too rapid for the tower to keep up.

After a moment, the tower accelerates laterally to catch up with the movement of the ground. From Newton’s second law of motion, we can surmise that the equivalent lateral force (ELF) $F$ at the top is equal to the mass $M$ of the tower and the acceleration at the base. Thus,

$$ F = Ma $$

where

- $F$ is an inertial force
- $M$ is the mass (equal to building weight divided by acceleration due to gravity, $g$)
- $a$ is the acceleration

This part of Newton’s law explains why light buildings, such as wood-frame houses, tend to perform better in earthquakes than large heavy ones.

The acceleration, or the rate of change of the velocity of the seismic waves setting the building in motion, determines the percentage of the building mass or weight that must be dealt with as an equivalent horizontal force.

Acceleration is measured in terms of the acceleration due to gravity or $g$. One $g$ is the rate of change of velocity of a free-falling body in space. This is an additive velocity of 32 ft/s. Thus, at the end of the first second, the velocity is 32 ft/s; a second later, it is 64 ft/s, and so on. When parachutists or bungee jumpers are in the free fall, they are experiencing an acceleration of $1g$. While the roller-coaster riders reach as much as $4g$. The aerobatic pilots are undergoing about $9g$. The human body is very sensitive and can feel accelerations as small as $0.001g$, such as when you shake hands with another person. A building in an earthquake experiences for a fraction of a second very high forces in one direction before
they abruptly change direction. Poorly constructed buildings begin to suffer damage at about 10% g (or 0.1g). In a moderate earthquake, vibration may last for a few seconds, and accelerations may be approximately 0.2g. Short accelerations may, for a fraction of a second, exceed 1.0g. In the Northridge earthquake in 1994, a recording station in Tarzana, 5 miles from the epicenter, recorded 1.92g.

3.2 DURATION, VELOCITY, AND DISPLACEMENT

Acceleration is a key factor in determining the forces on a building, but a more significant measure is that of acceleration combined with duration, which takes into account the impact of earthquake forces over time. In general, a number of cycles of moderate acceleration, sustained over time, can be much more difficult for a building to withstand than a single much larger peak. Continued shaking weakens a building structure and reduces its resistance to earthquake damage.

The duration of strong motion, termed the *bracketed duration*, is measured above a certain threshold acceleration value, commonly taken as 0.05g, and is defined as the time between the first and last peaks of motion that exceeds this threshold value. In the San Fernando earthquake of 1971, the bracketed duration was only about 6 s. In both the Loma Prieta and the Northridge earthquakes, the strong motion lasted a little over 10 s yet caused much destruction. In the 1906 San Francisco earthquake, the severe shaking lasted 45 s, while in Alaska, in 1964, the severe motion lasted for over 3 min.

Two other measures of wave motion are directly related to acceleration and can be mathematically derived from it. Velocity, which is measured in inches or centimeters per second, refers to the rate of motion of the seismic waves as they travel through the earth. This is very fast. Typically the *P wave* travels at between 3 and 8 km/s or 7,000–18,000 mph. The *S wave* is slower, traveling at between 2 and 5 km/s or 4,000–11,000 mph.

Displacement refers to the distance that points on the ground are moved from their initial locations by the seismic waves. These distances, except immediately adjacent to or over the fault rupture, are quite small and are measured in inches or centimeters. For example, in the Northridge earthquake, parking structures at Burbank, about 18 miles (29 km) from the epicenter, recorded displacements at the roof of 1.6 in. (4.0 cm) at an acceleration of 0.47g. In the same earthquake, the Olive View hospital in Sylmar, about 7.5 miles (12 km) from the epicenter, recorded a roof displacement of 13.5 in. (34 cm) at an acceleration of 1.5g.

The velocity of motion on the ground caused by seismic waves is quite slow—huge quantities of earth and rock are being moved. The velocity varies from about 2 cm/s in a small earthquake to about 60 cm/s in a major shake. Thus, typical building motion is slow and the displacements are small, but because thousands of tons of steel and concrete are wrenched in all directions several times a second, building failure or severe damage is likely to occur.

In earthquakes, the values of ground displacement, velocity, and acceleration (DVA) vary a great deal in relation to the frequency of the wave motion. High-frequency waves (higher than 10 Hz) tend to have high amplitudes of acceleration but small amplitudes of displacement, compared to low-frequency waves, which have small accelerations and relatively large velocities and displacements.

3.3 ACCELERATION AMPLIFICATION DUE TO SOFT SOIL

Earthquake shaking is initiated by a fault slippage in the underlying rock. As the shaking propagates to the surface, it may be amplified, depending on the intensity of shaking, the nature of the rock, and the surface soil type and depth.

A layer of soft soil, measuring from a few feet to a hundred feet or so, may result in an amplification factor ranging from 1.5 to 6 over the rock shaking. This amplification is most pronounced at longer periods and may not be so significant at short periods. The amplification also tends to decrease as the level of shaking increases.

As a result, earthquake damage tends to be more severe in areas of soft ground. This characteristic became very clear when the effects of 1906 San Francisco earthquake were studied. Also,