Appendix F
Earthquakes and How Buildings Resist Them

F.1 The Nature of Earthquakes

In a global sense, earthquakes result from motion between plates comprising the earth's crust (see Figure F-1). These plates are driven by the convective motion of the material in the earth's mantle between the core and the crust, which in turn is driven by heat generated at the earth's core. Just as in a heated pot of water, heat from the earth's core causes material to rise to the earth's surface. Forces between the rising material and the earth's crustal plates cause the plates to move. The resulting relative motions of the plates are associated with the generation of earthquakes. Where the plates spread apart, molten material fills the void. An example is the ridge on the ocean floor, at the middle of the Atlantic Ocean. This material quickly cools and, over millions of years, is driven by newer, viscous, fluid material across the ocean floor.

These large pieces of the earth's surface, termed tectonic plates, move very slowly and irregularly. Forces build up for decades, centuries, or millennia at the interfaces (or faults) between plates, until a large releasing movement suddenly occurs. This sudden, violent motion produces the nearby shaking that is felt as an earthquake. Strong shaking produces strong horizontal forces on structures, which can cause direct damage to buildings, bridges, and other man-made structures as well as triggering fires, landslides, road damage, tidal waves (tsunamis) and other damaging phenomena.

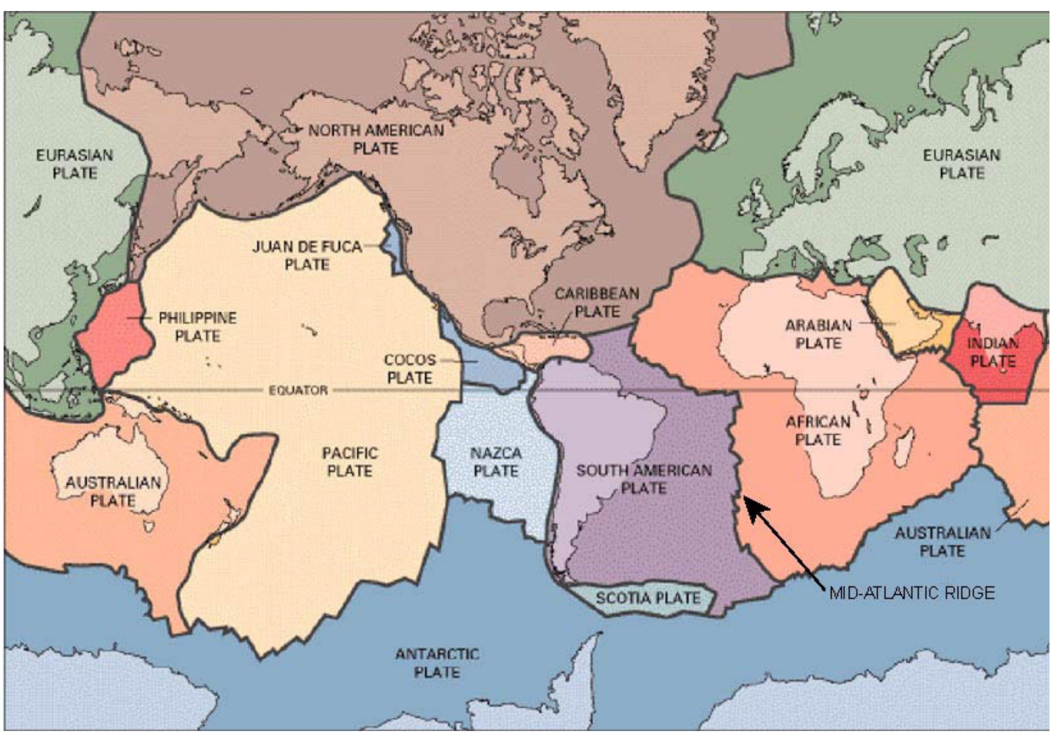

Figure F-1 The separate tectonic plates comprising the earth's crust superimposed on a map of the world.

A fault is like a "tear" in the earth's crust and its fault surface may be from one to over one hundred miles deep. In some cases, faults are the physical expression of the boundary between adjacent tectonic plates and thus are hundreds of miles long. In addition, there are shorter faults, parallel to, or branching out from, a main fault zone. Generally, the longer a fault, the larger magnitude earthquake it can generate. Beyond the main tectonic plates, there are many smaller sub-plates, "platelets" and simple blocks of crust which can move or shift due to the "jostling" of their neighbors and the major plates. The known existence of these many sub-plates implies that smaller but still damaging earthquakes are possible almost anywhere.

With the present understanding of the earthquake generating mechanism, the times, sizes and locations of earthquakes cannot be reliably predicted. Generally, earthquakes will be concentrated in the vicinity of faults, and certain faults are more likely than others to produce a large event, but the earthquake generating process is not understood well enough to predict the exact time of earthquake occurrence. Therefore, communities must be prepared for an earthquake to occur at any time.

Four major factors can affect the severity of ground shaking and thus potential damage at a site. These are the magnitude of the earthquake, the type of earthquake, the distance from the source of the earthquake to the site, and the hardness or softness of the rock or soil at the site. Larger earthquakes will shake longer and harder, and thus cause more damage. Experience has shown that the ground motion can be felt for several seconds to a minute or longer. In preparing for earthquakes, both horizontal (side to side) and vertical shaking must be considered.

There are many ways to describe the size and severity of an earthquake and associated ground shaking. Perhaps the most familiar are earthquake magnitude and Modified Mercalli Intensity (MMI, often simply termed "intensity"). Earthquake magnitude is technically known as the Richter magnitude, a numerical description of the maximum amplitude of ground movement measured by a seismograph (adjusted to a standard setting). On the Richter scale, the largest recorded earthquakes have had magnitudes of about 8.5. It is a logarithmic scale, and a unit increase in magnitude corresponds to a ten-fold increase in the adjusted ground displacement amplitude, and to approximately a thirty-fold increase in total potential strain energy released by the earthquake.

Modified Mercalli Intensity (MMI) is a subjective scale defining the level of shaking at specific sites on a scale of I to XII. (MMI is expressed in Roman numerals, to connote its approximate nature.) For example, slight shaking that causes few instances of fallen plaster or cracks in chimneys constitutes MMI VI. It is difficult to find a reliable precise relationship between magnitude, which is a description of the earthquake's total energy level, and intensity, which is a subjective description of the level of shaking of the earthquake at specific sites, because shaking intensity can vary with earthquake magnitude, soil type, and distance from the event.

The following analogy may be worth remembering: earthquake magnitude and intensity are similar to a light bulb and the light it emits. A particular light bulb has only one energy level, or wattage (e.g., 100 watts, analogous to an earthquake's magnitude). Near the light bulb, the light intensity is very bright (perhaps 100 foot-candles, analogous to MMI IX), while farther away the intensity decreases (e.g., 10 foot-candles, MMI V). A particular earthquake has only one magnitude value, whereas it has intensity values that differ throughout the surrounding land.

MMI is a subjective measure of seismic intensity at a site, and cannot be measured using a scientific instrument. Rather, MMI is estimated by scientists and engineers based on observations, such as the degree of disturbance to the ground, the degree of damage to typical buildings and the behavior of people. A more objective measure of seismic shaking at a site, which can be measured by instruments, is a simple structure's acceleration in response to the ground motion. In this *Handbook*, the level of ground shaking is described by the spectral response acceleration.

F.2 Seismicity of the United States

Maps showing the locations of earthquake epicenters over a specified time period are often used to characterize the seismicity of given regions. Figures F-2, F-3, and F-4 show the locations of earthquake epicenters[4] in the conterminous United States, Alaska, and Hawaii, respectively, recorded during the time period, 1977-1997. It is evident from Figures F-2 through F-4 that some parts of the country have experienced more earthquakes than others. The boundary between the North American and Pacific tectonic plates lies along the west coast of the United States and south of Alaska. The San Andreas fault in California and the Aleutian Trench off the coast of Alaska are part of this boundary. These active seismic zones have generated earthquakes with Richter

[4]An epicenter is defined as the point on the earth's surface beneath which the rupture process for a given earthquake commenced.

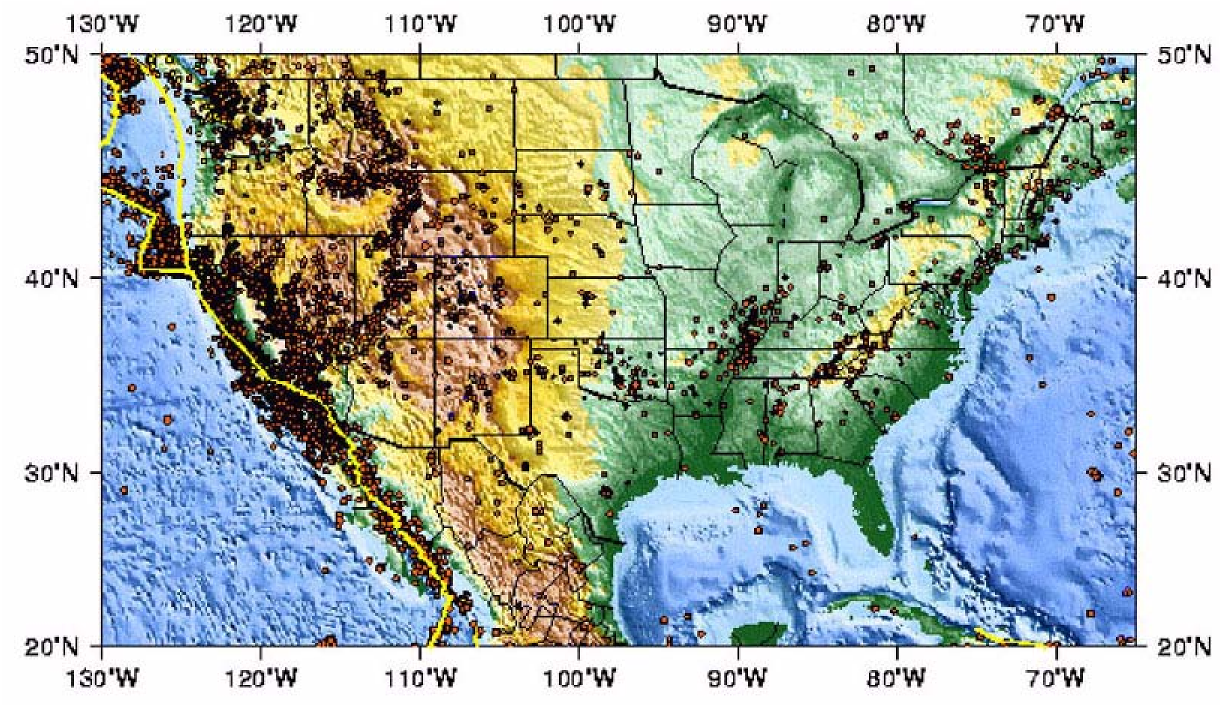

Figure F-2 Seismicity of the conterminous United States 1977 – 1997 (from the website at http://neic.usgs.gov/neis/general/seismicity/us.html). This reproduction shows earthquake locations without regard to magnitude or depth. The San Andreas fault and other plate boundaries are indicated with white lines.

magnitudes greater than 8. There are many other smaller fault zones throughout the western United States that are also participating intermittently in releasing the stresses and strains that are built up as the tectonic plates try to move past one another. Because earthquakes always occur along faults, the seismic hazard will be greater for those population centers close to active fault zones.

In California the earthquake hazard is so significant that special study zones have been created by the legislature, and named Alquist-Priola Special Study Zones. These zones cover the larger known faults and require special geotechnical studies to be performed in order to establish design parameters.

On the east coast of the United States, the sources of earthquakes are less understood. There is no plate boundary and few locations of faults are known. Therefore, it is difficult to make statements about where earthquakes are most likely to occur. Several significant historical earthquakes have occurred, such as in Charleston, South Carolina, in 1886 and New Madrid, Missouri, in 1811 and 1812, indicating that there is potential for large earthquakes. However, most earthquakes in the eastern United States are smaller magnitude events. Because of regional geologic differences, specifically, the hardness of the crustal rock, eastern and central U.S. earthquakes are felt at much greater distances from their sources than those in the western United States, sometimes at distances up to a thousand miles.

F.3 Earthquake Effects

Many different types of damage can occur in buildings. Damage can be divided into two categories: structural and nonstructural, both of which can be hazardous to building occupants. Structural damage means degradation of the building's structural support systems (i.e., vertical- and lateral-force-resisting systems), such as the building frames and walls. Nonstructural damage refers to any damage that does not affect the integrity of the structural support systems. Examples of nonstructural damage are chimneys collapsing, windows breaking, or ceilings falling. The type of damage to be expected is a complex issue that depends on the structural type and age of the building, its configuration, construction materials, the site conditions, the proximity of the building to neighboring buildings, and the type of nonstructural elements.

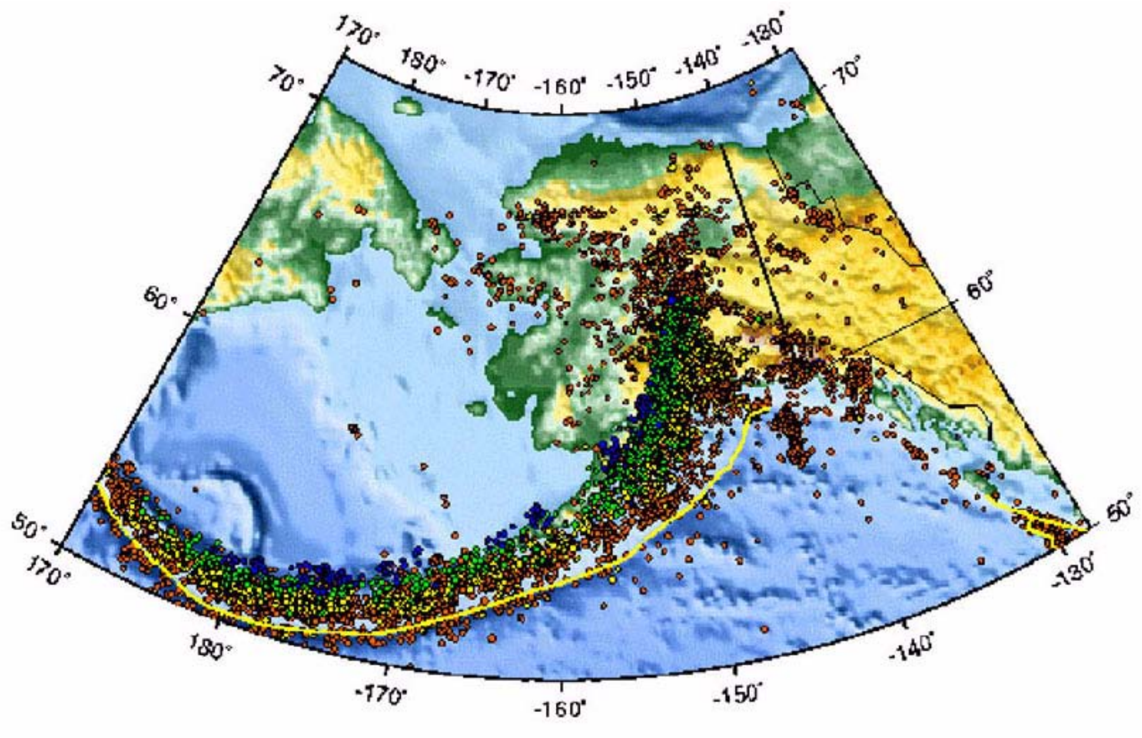

Figure F-3 Seismicity of Alaska 1977 – 1997. The white line close to most of the earthquakes is the plate boundary, on the ocean floor, between the Pacific and North America plates.

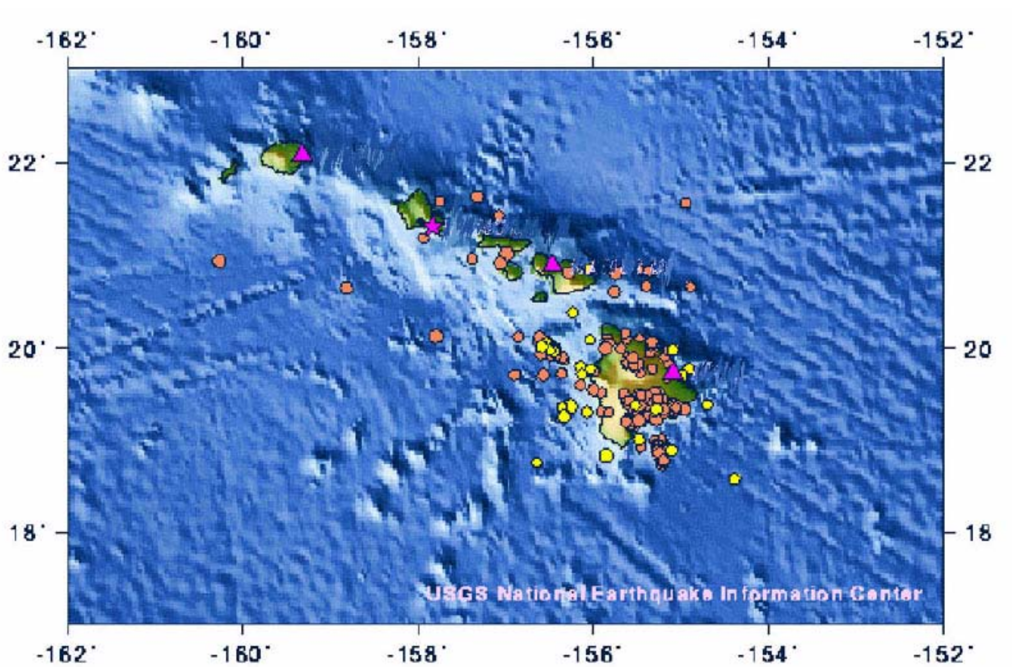

Figure F-4 Seismicity of Hawaii 1977 – 1997. See Figure F-2 caption.

When strong earthquake shaking occurs, a building is thrown mostly from side to side, and also up and down. That is, while the ground is violently moving from side to side, taking the building foundation with it, the building structure tends to stay at rest, similar to a passenger standing on a bus that accelerates quickly. Once the building starts moving, it tends to continue in the same direction, but the ground moves back in the opposite direction (as if the bus driver first accelerated quickly, then suddenly braked). Thus the building gets thrown back and forth by the motion of the ground, with some parts of the building lagging behind the foundation movement, and then moving in the opposite direction. The force F that an upper floor level or roof level of the building should successfully resist is related to its mass m and its acceleration a, according to Newton's law, $F = ma$. The heavier the building the more the force is exerted. Therefore, a tall, heavy, reinforced-concrete building will be subject to more force than a lightweight, one-story, wood-frame house, given the same acceleration.

Damage can be due either to structural members (beams and columns) being overloaded or differential movements between different parts of the structure. If the structure is sufficiently strong to resist these forces or differential movements, little damage will result. If the structure cannot resist these forces or differential movements, structural members will be damaged, and collapse may occur.

Building damage is related to the duration and the severity of the ground shaking. Larger earthquakes tend to shake longer and harder and therefore cause more damage to structures. Earthquakes with Richter magnitudes less than 5 rarely cause significant damage to buildings, since acceleration levels (except when the site is on the fault) and duration of shaking for these earthquakes are relatively small.

In addition to damage caused by ground shaking, damage can be caused by buildings pounding against one another, ground failure that causes the degradation of the building foundation, landslides, fires and tidal waves (tsunamis). Most of these "indirect" forms of damage are not addressed in this *Handbook*.

Generally, the farther from the source of an earthquake, the less severe the motion. The rate at which motion decreases with distance is a function of the regional geology, inherent characteristics and details of the earthquake, and its source location. The underlying geology of the site can also have a significant effect on the amplitude of the ground motion there. Soft, loose soils tend to amplify the ground motion and in many cases a resonance effect can make it last longer. In such circumstances, building damage can be accentuated. In the San Francisco earthquake of 1906, damage was greater in the areas where buildings were constructed on loose, man-made fill and less at the tops of the rocky hills. Even more dramatic was the 1985 Mexico City earthquake. This earthquake occurred 250 miles from the city, but very soft soils beneath the city amplified the ground shaking enough to cause weak mid-rise buildings to collapse (see Figure F-5). Resonance of the building frequency with the amplified ground shaking frequency played a significant role. Sites with rock close to or at the surface will be less likely to amplify motion. The type of motion felt also changes with distance from the earthquake. Close to the source the motion tends to be violent rapid shaking, whereas farther away the motion is normally more of a swaying nature. Buildings will respond differently to the rapid shaking than to the swaying motion.

Each building has its own vibrational characteristics that depend on building height and structural type. Similarly, each earthquake has its own vibrational characteristics that depend on the geology of the site, distance from the source, and the type and site of the earthquake source mechanism. Sometimes a natural resonant frequency of the building and a prominent frequency of the earthquake motion are similar and cause a sympathetic response, termed resonance. This causes an increase in the amplitude of the building's vibration and consequently increases the potential for damage.

Resonance was a major problem in the 1985 Mexico City earthquake, in which the total collapse of many mid-rise buildings (Figure F-5) caused many fatalities. Tall buildings at large distances from the earthquake source have a small, but finite, probability of being subjected to ground motions containing frequencies that can cause resonance.

Where taller, more flexible, buildings are susceptible to distant earthquakes (swaying motion) shorter

Figure F-5 Mid-rise building collapse, 1985 Mexico City earthquake.

Figure F-6 Near-field effects, 1992 Landers earthquake, showing house (white arrow) close to surface faulting (black arrow); the insert shows a house interior.

and stiffer buildings are more susceptible to nearby earthquakes (rapid shaking). Figure F-6 shows the effects on shorter, stiffer structures that are close to the source. The inset picture shows the interior of the house. Accompanying the near field effects is surface faulting also shown in Figure F-6.

The level of damage that results from a major earthquake depends on how well a building has been designed and constructed. The exact type of damage cannot be predicted because no two buildings undergo identical motion. However, there are some general trends that have been observed in many earthquakes.

- Newer buildings generally sustain less damage than older buildings designed to earlier codes.
- Common problems in wood-frame construction are the collapse of unreinforced chimneys (Figure F-7) houses sliding off their foundations (Figure F-8),collapse of cripple walls (Figure F-9), or collapse of post and pier foundations (Figure F-10). Although such damage may be costly to repair, it is not usually life threatening.
- The collapse of load bearing walls that support an entire structure is a common form of damage in unreinforced masonry structures (Figure F-11).

Figure F-7 Collapsed chimney with damaged roof, 1987 Whittier Narrows earthquake.

- Similar types of damage have occurred in many older tilt-up buildings (Figure F-12).

From a life-safety perspective, vulnerable buildings need to be clearly identified, and then strengthened or demolished.

F.4 How Buildings Resist Earthquakes

As described above, buildings experience horizontal distortion when subjected to earthquake motion. When these distortions get large, the damage can be catastrophic. Therefore, most buildings are designed

Figure F-8 House that slid off foundation, 1994 Northridge earthquake.

Figure F-9 Collapsed cripple stud walls dropped this house to the ground, 1992 Landers and Big Bear earthquakes.

Figure F-10 This house has settled to the ground due to collapse of its post and pier foundation.

Figure F-11 Collapse of unreinforced masonry bearing wall, 1933 Long Beach earthquake.

Figure F-12 Collapse of a tilt-up bearing wall.

with lateral-force-resisting systems (or seismic systems), to resist the effects of earthquake forces. In many cases seismic systems make a building stiffer against horizontal forces, and thus minimize the amount of relative lateral movement and consequently the damage. Seismic systems are usually designed to resist only forces that result from horizontal ground motion, as distinct from vertical ground motion.

The combined action of seismic systems along the width and length of a building can typically resist earthquake motion from any direction. Seismic systems differ from building to building because the type of system is controlled to some extent by the basic layout and structural elements of the building. Basically, seismic systems consist of axial-, shear- and bending-resistant elements.

In wood-frame, stud-wall buildings, plywood siding is typically used to prevent excessive lateral deflection in the plane of the wall. Without the extra strength provided by the plywood, walls would distort excessively or "rack," resulting in broken windows and stuck doors. In older wood frame houses, this resistance to lateral loads is provided by either wood or steel diagonal bracing.

The earthquake-resisting systems in modern steel buildings take many forms. In moment-resisting steel frames, the connections between the beams and the columns are designed to resist the rotation of the column relative to the beam. Thus, the beam and the column work together and resist lateral movement and lateral displacement by bending. Steel frames sometimes include diagonal bracing configurations, such as single diagonal braces, cross-bracing and "K-bracing." In braced frames, horizontal loads are resisted through tension and compression forces in the braces with resulting changed forces in the beams and columns. Steel buildings are sometimes constructed with moment-resistant frames in one direction and braced frames in the other.

In concrete structures, shear walls are sometimes used to provide lateral resistance in the plane of the wall, in addition to moment-resisting frames. Ideally, these shear walls are continuous reinforced-concrete walls extending from the foundation to the roof of the building. They can be exterior walls or interior walls. They are interconnected with the rest of the concrete frame, and thus resist the horizontal motion of one floor relative to another. Shear walls can also be constructed of reinforced masonry, using bricks or concrete blocks.

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