Making Schools Safe from Earthquakes

Course No: S05-012

Credit: 5 PDH

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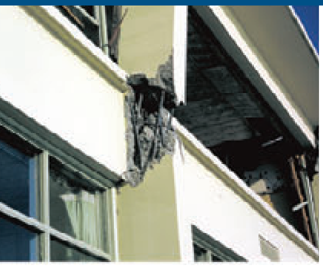
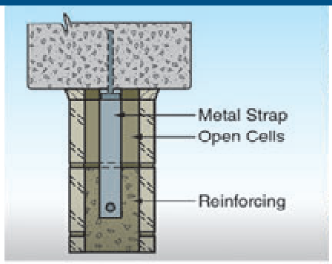
Introduction to the Study Guide

The Study Guide for the present course consists of Chapter 4, “Making Schools Safe From Earthquakes,” of the “Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds,” FEMA P-424 / December, 2010. This Chapter has been excerpted and begins on the next page.

The entire Design Guide can be downloaded by clicking on this link, but the present course is based solely on the material in Chapter 4.

RISK MANAGEMENT SERIES PUBLICATION



Design Guide

for Improving School Safety in Earthquakes, Floods, and High Winds

4 Making Schools Safe From Earthquakes

4.1 Introduction

This chapter outlines the earthquake risk to schools and the processes and methods that can be used to reduce it. An explanation of the nature and probability of earthquakes is provided, together with procedures for determining the earthquake threat to specific locations and for evaluating the vulnerability of a school building. An assessment of the scope and effectiveness of seismic building codes is followed by a description of current methods of designing for seismic resistance in new buildings and upgrading existing buildings. Lastly, this chapter presents guidance for school districts, facility planners, and designers on determining acceptable risk and the use of performance-based design.

4.2 The Nature and Probability of Earthquakes

Although earthquakes cannot be prevented, modern science and engineering provide tools that can be used to reduce their effects. Science can now identify, with considerable accuracy, where earthquakes are likely to occur and what forces they will generate. This information is readily available and can be obtained for local geographic regions (see Section 4.2.3).

4.2.1 Earthquakes and Other Geologic Hazards

Earthquakes have long been feared as one of nature's most terrifying phenomena. Early in human history, the sudden shaking of the earth and the death and destruction that resulted were seen as mysterious and uncontrollable. We now understand the origin of earthquakes and know that they must be accepted as a natural environmental process. Scientific explanations, however, have not lessened the terrifying nature of the earthquake experience. Other types of phenomena sometimes accompany seismic ground shaking and are generally identified as geologic hazards:

- **Liquefaction** occurs when loose granular soils and sand in the presence of water change temporarily from a solid to a liquid state when subjected to ground shaking. Soils that are loose, not well graded, and saturated with water are prone to liquefaction. These conditions often occur near waterways such as rivers, lakes, and bays, but not always. In addition to the soil type, the probability of liquefaction also depends on the depth from the surface to the vulnerable soil layer, and the intensity of ground motion. Further, the results of liquefaction can vary from a small, uniform ground settlement across a site, to loss of foundation bearing, resulting in extreme ground settlement and horizontal movement of tens of feet (called lateral spreading). Lastly, the risk of liquefaction is directly dependent on the earthquake risk. Due to this complex set of conditions, damage potential from liquefaction is difficult to map. For all but the smallest projects, many building jurisdictions in seismic areas require that the liquefaction potential be assessed in a site-specific geotechnical report, particularly in areas of known potential vulnerability. On sites where liquefaction is more than a remote possibility, the likely results of liquefaction at the ground surface or at the building foundations is also estimated. Small settlements may be tolerated without mitigation. Larger potential settlements can be prevented by site remediation measures, if economically justified. Building on sites with potential massive liquefaction and lateral spreading may not be cost effective. Officials in some regions of high seismicity have developed maps of local areas that are potentially susceptible to liquefaction and require site-specific investigation before building/permitting begins.

- **Landslides**, which involve the slipping of soil and rock on sloping ground, can be triggered by earthquake ground motion (see Figure 4-1). The shaking from earthquakes can cause landslides, depending on the slope, type, and configuration of soil stratum. Landslides can cause damage to improvements built within the slide area or near the top of the slide, ranging from complete destruction to distortion from relatively small vertical or lateral movements. Sites can also be threatened by landslides occurring uphill, sometimes completely offsite and quite a distance away.

  Similar to liquefaction, accurate probability of land sliding is difficult to map on a regional or national scale, and this threat is normally identified in site-specific geologic hazard studies. Also similar to liquefaction, the largest portion of the risk may be a triggering event. In some cases, stabilizing small areas at risk of potential landslides may be possible and cost effective. Stabilizing larger areas at risk of landslides may not be feasible. Some regions of high seismicity have developed maps of the areas susceptible to landslides based on average slopes, geologic soil types, and the past history of sliding. Building jurisdictions require site-specific investigations for sites within these susceptible zones.

Figure 4-1: School in Anchorage, AK, 1964, severely damaged by earthquake-induced landslide

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

- **Tsunamis** are seismic wave movements in the ocean that travel at high speed and may result in large coastal waves of 30 feet or more. They are sometimes, and incorrectly, called tidal waves. Researchers have studied tsunamis for many years. Sites near large bodies of water at elevations 50 feet or less above the water surface are susceptible. Although similar to storm surge, the height and the potential velocity of a tsunami wave represent a separate hazard and must be mapped separately. In addition to dependence on local conditions, quantification of the risk from tsunamis is difficult because not every earthquake generates such a wave. Studies considering the individual characteristics of the site and the facility are required to establish the risk and identify possible mitigating measures.

- **Seiches** are similar to tsunamis, but take the form of sloshing in closed lakes or bays; they have the potential to cause serious damage, although such occurrences have been very rare.

For all of the above geologic hazards, the only truly effective defense is the application of good land-use practices that limit development in hazard-prone locations. Seismic design and construction is aimed at reducing the consequences of seismic ground shaking, which is the primary cause of damage and casualties from an earthquake.

4.2.2 Earthquakes: A National Problem

The U.S. Congress recognized earthquakes as a national problem in 1977 when it passed legislation authorizing the National Earthquake Hazards Reduction Program (NEHRP) to reduce risks to life and property in the United States that result from earthquakes. NEHRP has supported considerable research and hazard mitigation efforts since that time.

Most people now know that, although most frequent in California and Alaska, earthquakes are not restricted to just a few areas In the United States. In fact, two of the greatest earthquakes in U.S. history occurred not in California, but near New Madrid, Missouri, in 1811 and 1812. In the International Building Code (IBC) (ICC, 2009), the most common model building code in use in the United States and its territories, buildings on sites with a low enough seismic risk that specific design for seismic forces is not required are classified as Seismic Design Category (SDC) A. As shown in Figure 4-2, 37 of 50 States have regions with sufficient seismic risk to require designs more stringent than SDC A. The likelihood of a damaging earthquake occurring west of the Rocky Mountains, and particularly in California, Oregon, Washington, Alaska, and Utah, is much greater than it is in the East, Midwest, or South. However, the New Madrid, MO, and Charleston, SC, regions are subject to potentially more severe earthquakes with a lesser probability. According to the IBC design maps, and the USGS hazard maps, on which they are based, other locations should also plan for intermediate ground motions.

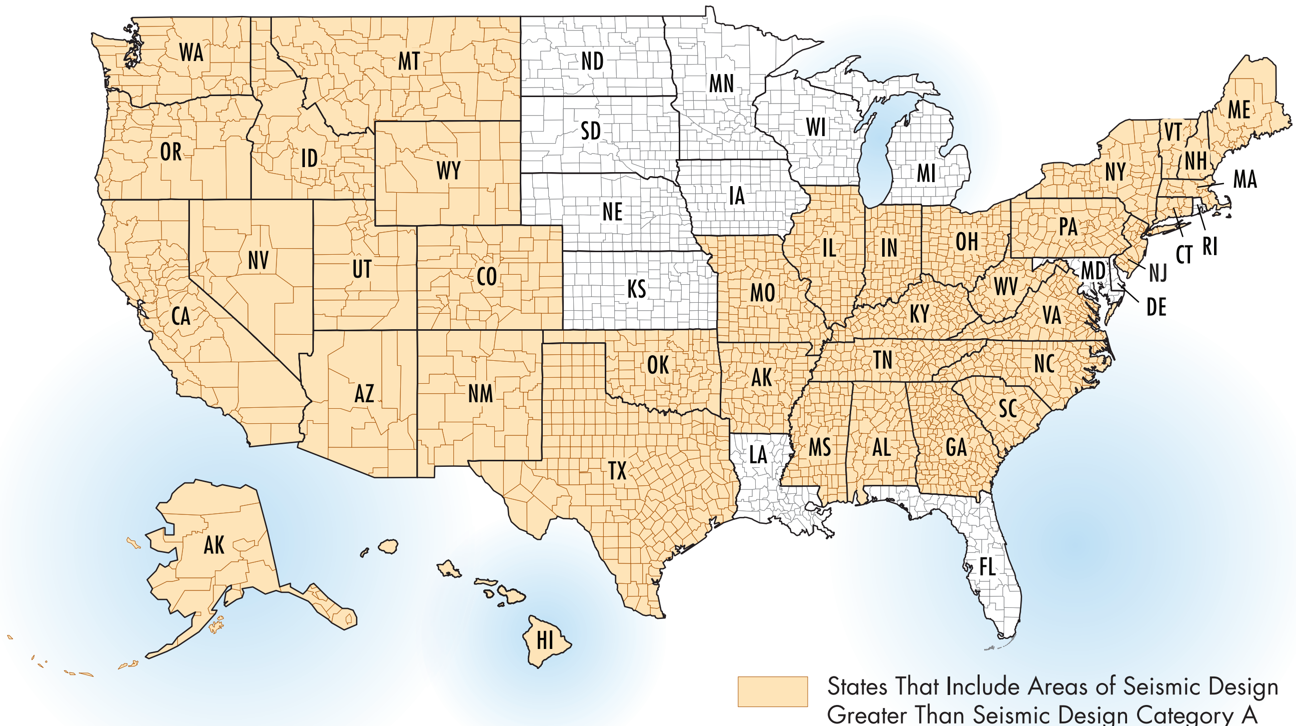


Figure 4-2: States with seismic risk

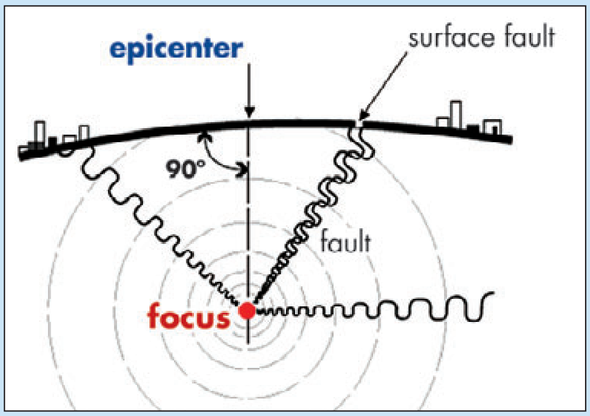
Records show that some seismic zones in the United States experience moderate to major earthquakes approximately every 50 to 70 years, while other areas have "recurrence intervals" for the same size earthquake of about 200 to 400 years. These frequencies of occurrence are simply statistical probabilities and one or several earthquakes could occur in a much shorter than average period. Based on current knowledge, schools to be located in earthquake-prone regions must be designed assuming that a large earthquake is likely to occur at any time.

Moderate and even very large earthquakes may occur in areas of normally low seismicity. Even buildings in these regions are vulnerable to seismic damages if not constructed in accordance with building code requirements for seismic resistance. In high seismic regions, however, the earthquake threat is quite familiar. Schools in many areas of California and Alaska will be shaken by an earthquake perhaps two or three times a year and, since the early 20th century, have been built to incorporate some level of earthquake-resistant design. While the areas where earthquakes are likely to occur and the potential size or magnitude of these earthquakes are well identified, predicting the near-term occurrence of a damaging earthquake is not yet possible. Lacking useful predictions, it makes sense in any seismic region to take at least the minimum affordable prudent actions to save lives. Because most lives are lost in earthquakes when buildings collapse, U.S. seismic building code provisions require the minimum measures necessary to prevent building collapse.

In California, schools are further protected by the Field Act of 1933, which mandated additional requirements relating to design qualifications, plan checking, and site inspection. The Field Act is discussed in more detail in Section 4.3.2.

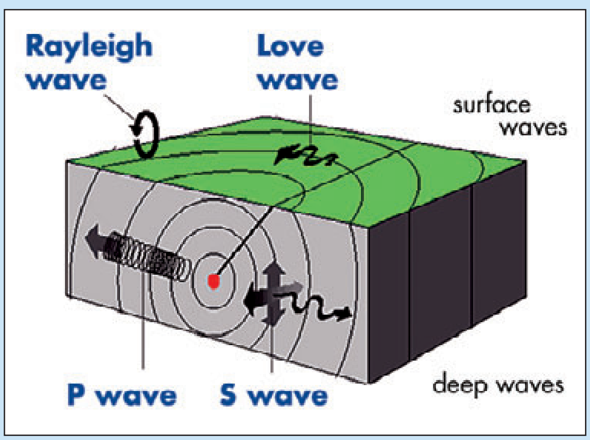
The following graphics explain some earthquake terminology and characteristics of ground motion.

What Earthquakes Do



The Origin of Earthquakes

This diagram explains some of the common terms used in talking about earthquakes. Waves of vibration radiate out from the fault break.



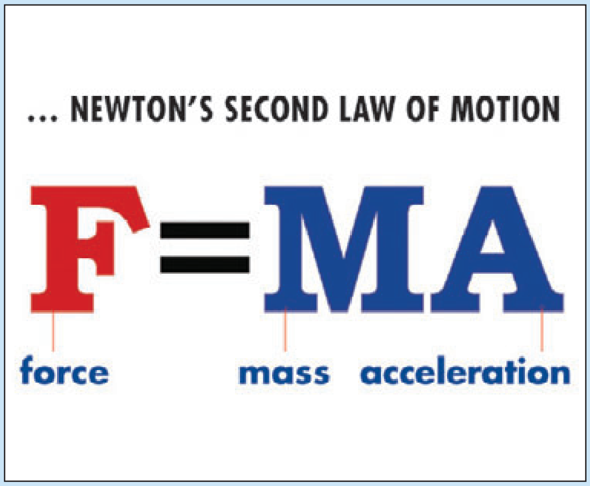
Types of Seismic Waves

Four main types of waves radiate from a fault break. The P or Primary wave, a back-and-forth motion, arrives first, followed by the S wave (secondary or shear) that is more of a rolling motion. These are deep waves that travel through the earth to the surface. The Love and Rayleigh waves, named after their discoverers, travel along the earth's surface.

Motion at Site

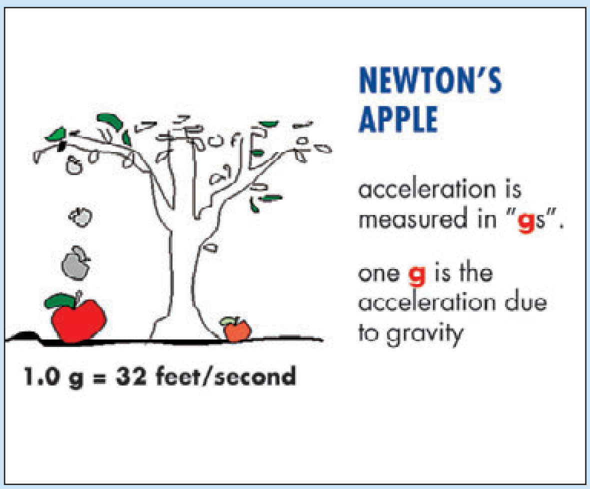
Scratch left on a floor by a kitchen range in the 1933 Long Beach earthquake that shows the random nature of earthquake motion.

Acceleration Forces



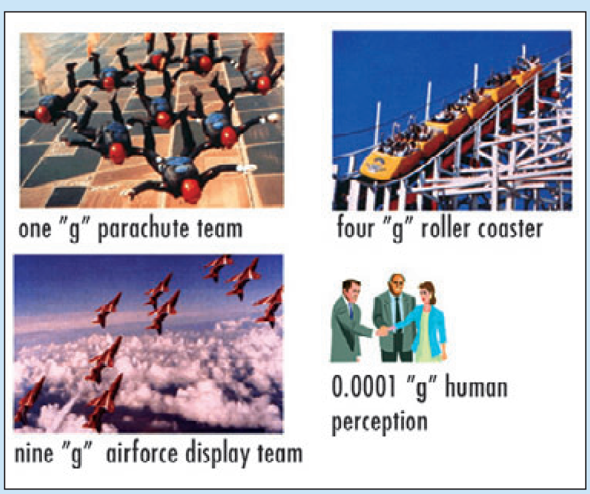
Forces and Gravity

Because ground motion waves produce inertial forces within structures, these forces obey Newton's Second Law of Motion. This fundamental equation establishes the forces for which buildings must be designed to resist earthquakes.



Acceleration

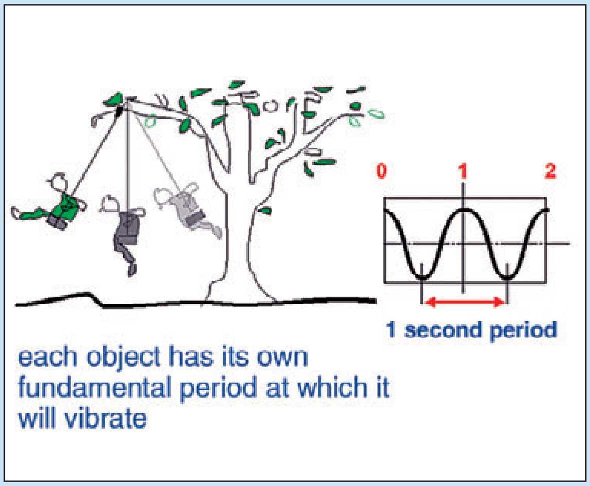
The acceleration, or the rate of change of the velocity of the waves that set the building in motion, is used in an equation, derived from Newton's Second Law of Motion to estimate the percentage of the building mass or weight that must be dealt with as a horizontal force.



Acceleration

Some common examples of acceleration. The skydivers are falling under the action of gravity, 1g.

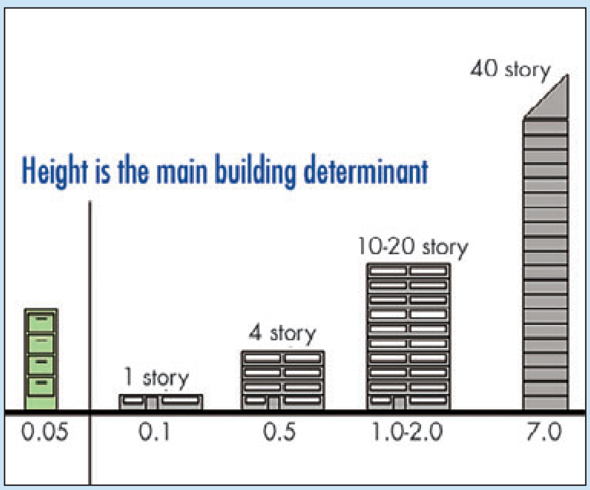
Period and Resonance



Fundamental Period and Resonance

Every object has a fundamental period at which it vibrates if it is set in motion. It cannot vibrate at another period unless it is dragged back and forth. The ground also has a fundamental period. If an object is set in motion by an external force such as ground shaking, which is at the fundamental period of the object, the result will be "resonance" and the motion of the object will tend to increase. When you push a child on a swing, you instinctively give it a push at its fundamental period, which results in an enjoyable increase in the motion with very little force applied.

Similarly, if the ground pushes a building with the same period as the motion, the accelerations in the building will increase, perhaps four or five times.



Fundamental Period in Seconds

This shows typical periods for structures. The main determinant of period is building height and proportion; thus, a tall slender object will have a long period and sway back and forth quite slowly while the 40-story building will sway gently back and forth once every 7 seconds.

SOURCE: ARNOLD AND ALEXANDER, 2001.

4.2.3 Common Measures of Earthquakes

Perhaps the most familiar measure of earthquakes is the Richter Magnitude, devised by Professor Charles Richter of the California Institute of Technology in 1935. Richter's scale is based on the maximum amplitude of certain seismic waves recorded on a standard seismograph at a distance of 100 kilometers (km) from the earthquake epicenter. Because the instruments are unlikely to be exactly 100 km from the source, Richter devised a method to allow for the diminishing of wave amplitude with increased distance. The Richter scale is logarithmic, and each unit of magnitude indicates a ten-fold increase in wave amplitude. The energy level is multiplied by approximately 31 times for a unit increase in Richter magnitude scale. The scale is open-ended, but a magnitude of about 9.5 represents the largest earthquake scientists now expect within the current understanding of movement in the earth's crust.

Magnitude is not a measure of damage, but a physical characteristic of an earthquake. An earthquake with magnitude 6.7 that occurs in a remote area may cause no damage to manmade structures, but one with the same magnitude can cause considerable damage if it occurs close to an urban area.

Among scientists, the Richter Magnitude has been replaced by the Moment Magnitude, a similar measure of energy that is based on the physical characteristics of the fault rupture, which is a more useful measure for large events. The Moment Magnitude scale produces values similar to the Richter scale, and for damaging earthquakes, values are normally in the 5.5 to 8.0 range, although magnitudes over 9.0 also occur.

The level of earthquake damage is often measured by intensity scales; one common scale used in the United States is the Modified Mercalli Intensity (MMI) scale, reported in Roman Numerals from I to XII. MMI is often incorrectly used to measure the size of an earthquake. In fact, the MMI is assigned to small areas, like zip codes, based on the local damage to structures or movements of soil. Many MMIs can be associated with a single earthquake because the shaking, and therefore the damage, diminishes as the distance to the epicenter increases. Although the MMI is useful for the purpose of comparing damage from one event to another (particularly events for which little or no instrumental measurements are available), it is very subjective, and scientists and engineers prefer instrumental measurements of the ground shaking to measure intensity.

Scientists and engineers need measures of the damaging characteristics of earthquakes to compare the inherent risk at different locations, and to develop design solutions to limit damage to acceptable levels. The universal characteristic of earthquakes, and the one that can be measured most precisely, is ground motion. Extensive networks of instruments are now employed on the ground and in buildings and other structures to record continuously the motions during an earthquake. The ever-growing database of earthquake recordings can be analyzed in various ways to develop appropriate measures of intensity that best predict potential damage to buildings and other structures, nonstructural systems, and the possibility of liquefaction and landslides.

Table 4-1 shows significant earthquakes (Magnitude VI or over) that occurred in 47 of the 50 U.S. States between 1568 and 1989.

Table 4-1: Known historic (1558–1989) earthquakes in 47 U.S. States

	Number of Quakes with Reported Maximum Modified Mercalli Intensity (MMI) of:		
State	VI[a]	VII[b]	VII+
Alabama	5	7	—
Alaska	41	21	13
Arizona	11	3	1
Arkansas	8	3	2
California	329	131	66
Colorado	19	1	—
Connecticut	2	1	—
Delaware	—	1	—
Florida	2	—	—
Georgia	5	—	—
Hawaii	30	13	10
Idaho	12	4	2
Illinois	18	12	—
Indiana	5	2	—
Kansas	4	2	—
Kentucky	8	1	—
Louisiana	1	—	—
Maine	7	2	—
Massachusetts	8	7	3
Michigan	1	1	1
Minnesota	3	—	—
Mississippi	2	—	—
Missouri	14	2	3
Montana	35	4	5
Nebraska	4	2	—
Nevada	28	10	8
New Hampshire	7	2	—
New Jersey	5	1	—
New Mexico	29	10	8
New York	16	6	2
North Carolina	5	2	—
North Dakota	1	—	—

Table 4-1: Known historic (1558–1989) earthquakes in 47 U.S. States

	Number of Quakes with Reported Maximum Modified Mercalli Intensity (MMI) of:		
State	VI[a]	VII[b]	VII+
Ohio	9	5	1
Oklahoma	9	2	—
Oregon	10	1	—
Pennsylvania	7	1	—
Rhode Island	1	—	—
South Carolina	17	2	1
South Dakota	6	—	—
Tennessee	12	2	—
Texas	7	1	—
Utah	31	8	5
Vermont	1	—	—
Virginia	12	1	1
Washington	37	6	3
West Virginia	1	—	—
Wyoming	8	1	—

Notes:

a. Felt by all. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.

b. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.

4.2.4 Determination of Local Earthquake Hazards

Earthquake hazard maps are available in model codes, such as the IBC, and standards such as ASCE 7. Values representing ground shaking hazard are mapped for building periods of 0.2 second and 1.0 second. Examples of these maps are shown in Figure 4-3. Building codes and standards allow engineers to calculate the appropriate spectral response value for other building periods, as shown in Figure 4-4. Mapped values are for a hypothetical earthquake with a 2-percent probability of exceedance in 50 years. Site class, which is a measure of soil conditions at the building site, is also described in building codes and standards and influences the determination of ground shaking hazard at the building site. Site Class A represents hard rock, and Site Class E represents a very soft site with potential soil failure.

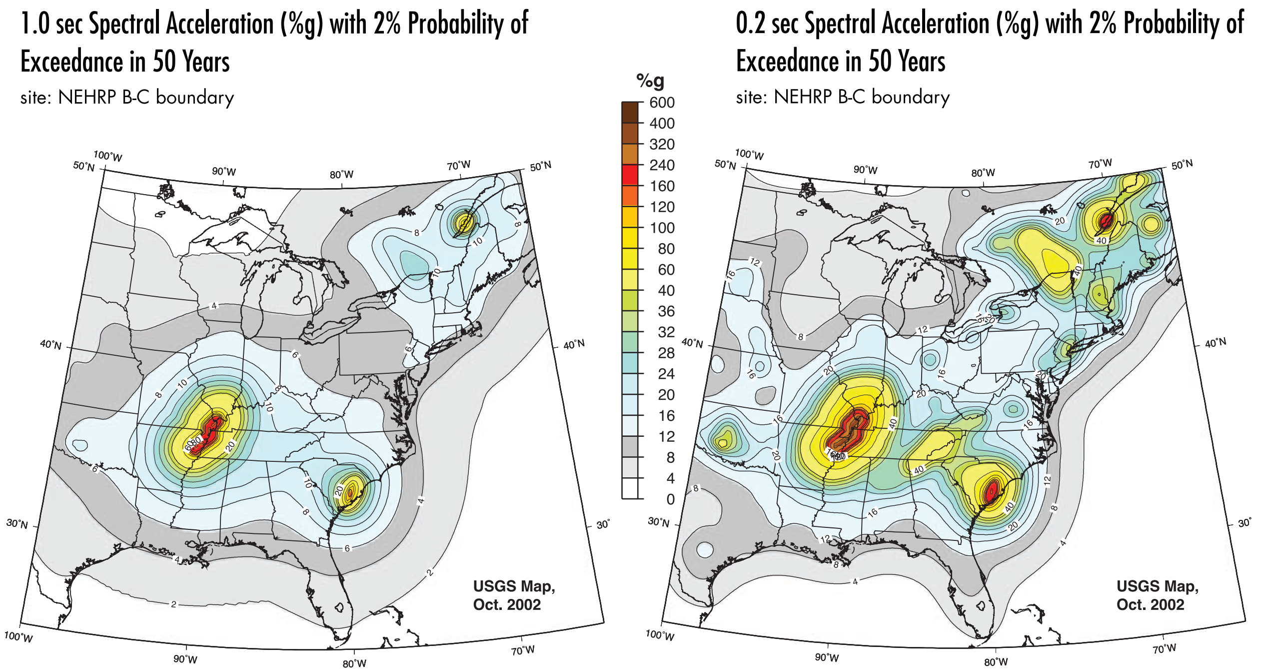
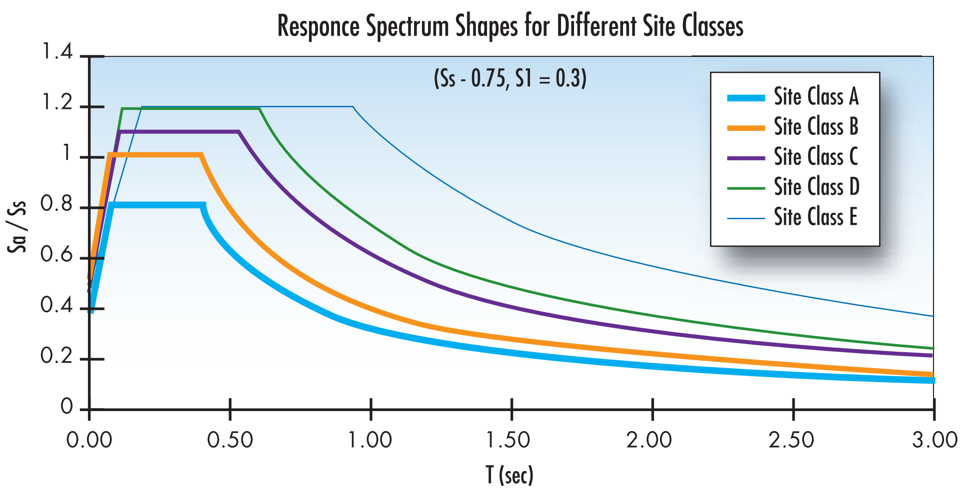


Figure 4-3: Examples of national seismic hazard maps

Figure 4-4: Representative shapes of building code (or design) response spectra for different soils



More detailed information on the seismic hazard than is shown on the code maps, such as those in the IBC or ASCE 7, can be obtained from the USGS Earthquake Hazards Program Web site at http://earthquake.usgs.gov/. The USGS provides more detailed earthquake hazard maps for general regions such as the western, central, and eastern United States. The USGS provides more localized seismicity information for any location in the United States on the basis of latitude and longitude or zip code. This information can be obtained by downloading the Ground Motion Parameter Calculator at http://earthquake.usgs.gov/hazards/designmaps/javacalc.php. The calculator provides the seismic design parameters generally needed to conform to current building codes.

4.3 Vulnerability: What Earthquakes Can Do to Schools

Much of the information developed on what earthquakes can do to schools comes from California because of the prevalence of earthquakes in that State. In general, the seismic performance of newer buildings has been good, although considerable costly and dangerous nonstructural damage still occurs. California public school design and construction has been subject to strict regulation since 1933, which undoubtedly contributes to good performance. Many of the damage examples shown in this section are of older school buildings, which reflects the continued use of long-lived school buildings constructed in the early 20th century.

4.3.1 Vulnerability of Schools

Older unreinforced masonry school buildings present a very high seismic risk, and have been prohibited by law in California since the mid-1930s following severe damage to schools of this type in the 1933 Long Beach earthquake. Mid-rise nonductile reinforced concrete frame structures pose an even greater risk. "Nonductile" refers to the frame's lack of ductility (flexibility), or ability to deform considerably before breaking (see Figure 4-5). Reinforced concrete frames are made ductile by introducing an appropriate, code-specified amount of specifically designed steel reinforcing. Unfortunately, the need for this ductility was not recognized in seismic codes until the mid-1970s, so a large inventory of nonductile structures is still in use (see Figure 4-6).

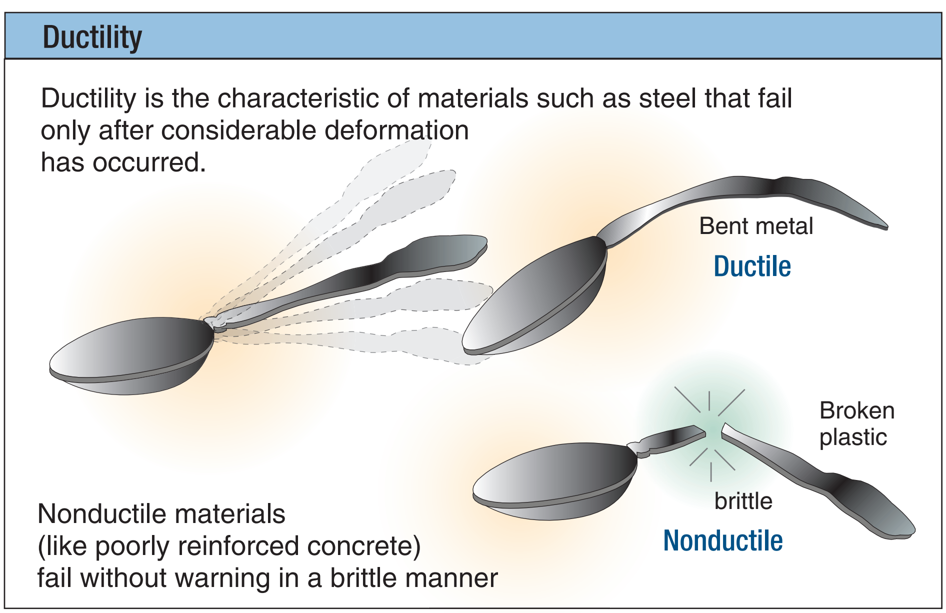


Figure 4-5: Ductility

SOURCE: ARNOLD AND ALEXANDER, 2001

Figure 4-6: Collapse of portion of nonductile concrete frame school structure, Helena, MT, 1935

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

Wood frame structures perform effectively, provided that they are well constructed with code-specified nailing of shear walls and properly detailed roof-to-wall connections. Good maintenance, ensuring continued protection against moisture and insects, is also critical to the performance of wood frame structures. Newer structures, employing frames and fewer walls, also perform effectively if well designed and constructed in accordance with building codes. Their response differs from that of shear wall structures, which are stiff and resistant to lateral forces. Frame structures can be more flexible than rigid shear wall structures because the forces on the structural members are reduced.

Modular structures, often used as temporary classrooms, are liable to topple off their foundations during an earthquake, unless securely attached and braced. This damage is not life-threatening, but makes the building unusable; fractured power, gas, and waste lines may be a hazard (see Figure 4-7).

Figure 4-7: Modular classrooms pushed off their foundations; note stairs at left, Northridge, CA, 1994

SOURCE: GARY MCGAVIN, REDLANDS, CA

If the structure type employs long-span roof and floor members, seismic forces may cause excessive drift, or sway, which can damage non-structural components, such as hung ceilings, light fixtures, light partitions, and contents. Storage units, filing cabinets, and library shelving in any type of structure can be hazardous if not properly braced (see Figure 4-8), as can heavy equipment (see Figure 4-9). Piping, ductwork, electrical conduits, and communication pathways (cable trays) may also be damaged. Broken pipes can create additional hazards in the form of flooding or loss of water for fire protection.

Figure 4-8:
Fallen filing cabinets and shelves, Northridge, CA, 1994

SOURCE: GARY MCGAVIN, REDLANDS, CA

School occupants are particularly vulnerable to nonstructural damage. Although students and staff may duck under desks and be safe from falling objects such as lighting fixtures and ceiling tiles, ceiling components that fall in hallways and stairs can make movement difficult, particularly if combined with power failure and loss of lighting. Wall-mounted televisions or ceiling-mounted liquid crystal display (LCD) projectors are common in schools and present additional falling hazards.

Pendant light fixtures may fall if they are not securely attached and not designed to swing freely (see Figure 4-10). Large glass walls and windows, not designed to accommodate inter-story drift due to seismic forces, present another hazard for

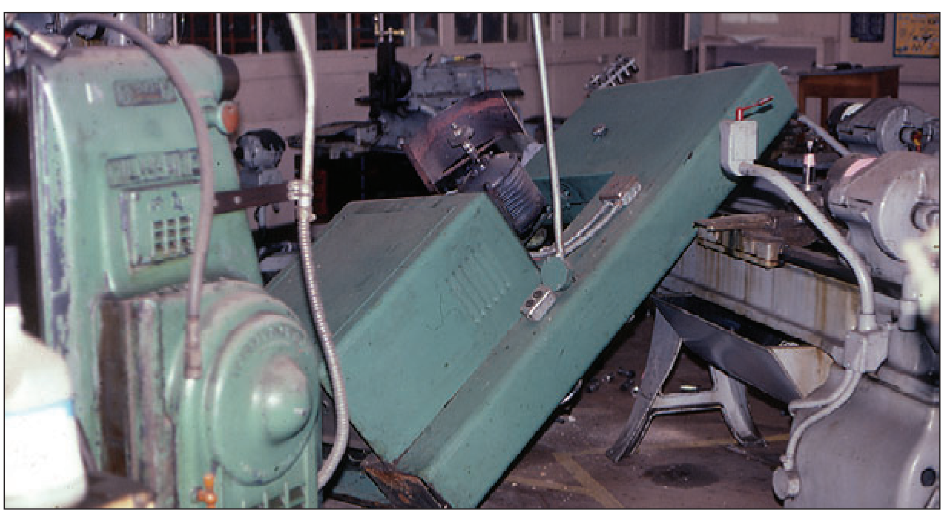


Figure 4-9:
Fallen shop equipment, Coalinga, CA, 1983

SOURCE: GARY MCGAVIN, REDLANDS, CA

Figure 4-10:
Fallen light fixtures, library, Coalinga, CA, 1983

SOURCE: GARY MCGAVIN, REDLANDS, CA

densely occupied classrooms as demonstrated in California schools that have suffered from recent earthquakes. Incorporating glazing designed to resist wind-borne debris and physical attack, as well as glazing support systems that can accommodate inter-story drift, can reduce the hazards caused by earthquake motion.

Heavy lath and plaster ceilings in older auditoriums (and assembly buildings) can also be dangerous depending on their attachment and materials (see Figure 4-11).

4.3.2 Earthquake Damage to Schools

Most available information on earthquake damage to schools comes from California. Its high incidence of earthquake activity has led to the adoption of sophisticated seismic building codes for all buildings, and special plan checking and inspection requirements, enforced by the State, for school buildings.

Considering the number of significant earthquakes in California since the early years of the 20th century, severe structural damage to schools and casualties has been relatively limited, except in the Long Beach earthquake of 1933. No student has been killed or seriously injured in a California school during an earthquake since 1933. In the Long Beach earthquake, which struck at 5:55 p.m. on March 10, 1933, damage to unreinforced masonry (URM)

Figure 4-11:
Fallen heavy lath and plaster ceiling across auditorium seating, Northridge, CA, 1994

SOURCE: GARY MCGAVIN, REDLANDS, CA

school buildings was so severe that there would have been many casualties had they been occupied (see Figures 4-12, 4-13, and 4-14). As a result, the State passed the Field Act within a month of the earthquake.

Figure 4-12: Damage to the John Muir School, Long Beach, CA, 1933

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

The Field Act required that all public school buildings be designed by a California-licensed architect or structural engineer, that plans be checked by the then Department of General Services, and that construction be continuously inspected by qualified independent inspectors retained by the local school board. The Department of General Services set up a special division, staffed by structural engineers, to administer the provisions of the Act. The Field Act, which is still enforced today, has greatly reduced structural damage to California schools.

The earthquake also resulted in the passage of the Riley Act, which governed the design of all buildings, with a few exceptions. The Riley Act required all buildings in the State be designed to a specified lateral force, and effectively outlawed unreinforced masonry construction.

Figure 4-13: Damage to shop building, Compton Junior High School, Long Beach, CA, 1933

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

Figure 4-14: A dangerous passageway between two buildings, Polytechnic High School, Long Beach, CA, 1933

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

In 1952, Kern County, in the Bakersfield region, some 70 miles north of Los Angeles, experienced a series of earthquakes. Two groups of earthquakes occurred; the first, in the last week of July, included one with a magnitude of 7.6 on the Richter scale. The second group occurred in late August, and one earthquake, near the city of Bakersfield, had a magnitude of 5.9 on the Richter scale. Ten deaths resulted from the July earthquake and two from the August earthquake.

The Bakersfield earthquakes are of particular interest because the incidence of school damage is comparable to that resulting from earthquakes striking today in regions where seismic codes have not been adopted and enforced due to the rarity of seismic events (see Figures 4-15, 4-16, and 4-17).

Figure 4-15: A heavy corridor lintel ready to fall, Emerson School, Bakersfield, Kern County, CA, 1952

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

Figure 4-16:
Overturned shop equipment and failed light fixtures, Kern County, CA, 1952

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

Figure 4-17:
Destroyed exit corridor, Bakersfield, Kern County, CA, 1952

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

There were no school-related casualties in 1952, as the earthquakes occurred outside school hours. At that time, the Field Act had been in force for nearly 20 years, and the newer schools had been constructed to conform to its requirements. Of the 58 masonry schools in the region, 18 had been constructed after the Field Act. Of these, one school constructed of grouted reinforced brick and incurred approximately 1 percent, or moderate, damage. Of the 40 non-Field Act schools, 1 collapsed, 15 suffered severe damage, and 14 suffered moderate damage. In the Bakersfield City School District, 175 classrooms and 6,500 students were displaced and only about 10 classrooms were quickly put back in service. Nonstructural damage to ceilings and light fixtures was considerable.

Other States have experienced similar damage to URM and early reinforced concrete structures. Schools in Helena, MT, suffered considerable damage in 1935 (see Figure 4-18). In 1949, several URM schools in Seattle were severely damaged, resulting in one fatality (see Figures 4-19 and 4-20). At Puyallup High School, three boys on a stage just managed to escape when the roof collapsed (see Figure 4-21). The furniture and contents also sustained widespread damage (see Figure 4-22).

Figure 4-18: Typical school damage, Helena, MT, 1935

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

Figure 4-19:
The student body president was killed here by falling brickwork, Seattle, WA, 1949

SOURCE: EARTHQUAKE ENGINEERING RESEARCH INSTITUTE, OAKLAND, CA. PHOTO FROM A.E. MILLER COLLECTION, UNIVERSITY OF WASHINGTON ARCHIVES

Figure 4-20:
Another dangerous entry collapse, Seattle, WA, 1949

SOURCE: EARTHQUAKE ENGINEERING RESEARCH INSTITUTE, OAKLAND, CA. PHOTO FROM SEATTLE SCHOOL ARCHIVES

Figure 4-21:
Collapse of roof over stage, Seattle, WA, 1949

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

Figure 4-22:
Damage to library shelving, Seattle, WA, 1949

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

4.3.3 Significant School Damage in U.S. Earthquakes

In the Anchorage, AK, earthquake of 1964, which registered 8.4 on the Richter scale, a number of public schools were damaged, but none collapsed. The earthquake occurred on Good Friday at 5:36 p.m. when the schools were unoccupied. The most seriously damaged school (shown in Figure 4-1) was subsequently demolished. At the West Anchorage High School (see Figures 4-23 and 4-24), a two-story nonductile concrete-frame and shear-wall classroom wing suffered severe structural damage and the near total failure of a number of columns. Structural distortion also created a number of severe glass breakages. The second floor was removed during reconstruction and the first floor was repaired and retained. In the San Fernando, CA, earthquake of 1971, there were no injuries and no schools collapsed; however, the earthquake caused $13.2 million in damages (in 1971 dollars), and 100 pre-Field Act schools were demolished within 1½ years after the earthquake.

Figure 4-23: Severe structural damage to the West Anchorage High School, Anchorage, AK, 1964

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

A survey of 1,544 public school buildings showed that only three schools sustained severe damage as a result of the magnitude 6.9 Loma Prieta (San Francisco Bay area) earthquake of 1989. A portable classroom near Santa Cruz was rocked off its unbraced and unanchored supports. An elementary school in Los Gatos was subjected to severe shaking, but damage was limited to nonstructural and contents shifting, except in one classroom wing, where ground heaving raised and cracked the floor slab, jamming a door and window shut.

Figure 4-24:
Brittle failure at nonductile concrete column, West Anchorage High School, 1964

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY

Tagging

A post-earthquake evaluation procedure has been developed in California that employs colored placards, or "tags," affixed to buildings, that show that the building has been inspected and indicate the level of safety. The colors of the tags and their safety level classification follow:

A red tag indicates **UNSAFE**: Extreme hazard, may collapse. Imminent danger of collapse from an aftershock. Unsafe for occupancy or entry, except by authorities.

A yellow tag indicates **LIMITED ENTRY**: Dangerous condition believed to be present. Entry by owner permitted only for emergency purposes and only at own risk. No usage on continuous basis. Entry by public not permitted. Possible major aftershock hazard.

A green tag indicates **INSPECTED**: No apparent hazard found, although repairs may be required. Original lateral load capacity not significantly decreased. No restriction on use or occupancy.

SOURCE: ATC, 1995

A San Francisco High School suffered severe structural cracking from the Loma Prieta earthquake. The school was constructed in 1920 as an automobile manufacturing building and was structurally upgraded in 1947. Restoration costs after the earthquake were estimated at $10 million.

Total restorations for the San Francisco school district were estimated to be $30 million; for Oakland, the district losses were $1.5 million. Though undamaged, an elementary school in San Francisco was closed because of the potential collapse of a nearby elevated freeway structure, which was considered a hazard to the building and its occupants. Hazards from unbraced and unanchored nonstructural items were evident in many buildings, including pendant-mounted light fixtures, suspended acoustical ceilings, and unanchored furniture and contents such as filing cabinets and shelving.

In the Northridge, CA, earthquake of 1994, 17 school buildings were red tagged and 89 buildings were yellow-tagged. All of the public schools in this area, except for one, were capable of receiving students after post-earthquake debris was cleared. In some schools, portions of the campus and certain structures needed to be closed to students until further evaluations could be performed, but the schools were able to open (McGavin 1994). Examples of nonstructural damage are provided in Figures 4-25, 4-26, and 4-27). If the schools had been in session, nonstructural damage could have caused injuries. In 1995, the California Seismic Safety Commission (CSSC) recommended that a percentage of future school bond proceeds be used to abate life-threatening nonstructural and building contents deficiencies in public schools (1995). In 1999, legislation was passed for public schools to address securing nonstructural elements, and in 2003 detailed guidelines were published to aid public schools in identifying and correcting nonstructural hazards (California Emergency Management Agency, 2003).

Figure 4-25: Ceiling damage, Northridge, CA, 1994

SOURCE: GARY MCGAVIN, REDLANDS, CA

Figure 4-26:
Damage to ceramic kiln, including fractured gas line, Northridge, CA, 1994

SOURCE: GARY MCGAVIN, REDLANDS, CA

Figure 4-27:
Line of suspended light fixtures fallen on teacher's station, Northridge, CA, 1994

SOURCE: EARTHQUAKE ENGINEERING RESEARCH INSTITUTE, OAKLAND, CA, AND GARY MCGAVIN, REDLANDS, CA

4.3.4 Consequences: Casualties, Financial Loss, and Operational Disruption

Casualties in California schools have been few, primarily due to regulation by the Field Act and by chance. Significant Alaskan and California earthquakes, from Santa Barbara (1925) to Northridge (1984) have all occurred outside of school hours. Consequently, the effects of a major earthquake when schools are fully occupied have not been experienced. In other regions, casualties have been few; in the Seattle earthquake of 1949, two school children died in Tacoma when bricks cascaded onto exit ways. The closure of other Seattle schools for spring vacation averted fatalities and serious injuries in similar building failures.

The impact of school closure as a result of damage is the loss of public service and severe disruption for students, faculty, and staff. Ultimately, the taxpayer bears the costs, but this is spread over the whole community, the State, and the Federal Government. Typically, schools are self-insured and do not purchase insurance on the private market. For a private school, closure means a serious loss of revenue; in addition to the costs of repair, the students may not return if the school is closed for a long time. Therefore, obtaining insurance may be a prudent measure.

As with any of the natural hazards reviewed in this manual, an earthquake can close a school, keeping the school district from doing its main job (i.e., teaching students). The length of the closure will depend on the severity and types of damage. It may also depend on whether the building was fully insured or whether disaster assistance will be available quickly enough to allow speedy repairs and reconstruction. Sometimes repairs are put on hold, pending a decision on whether the building should be repaired or condemned.

School closures from natural disasters also result in social and psychological difficulties for students, parents, faculty, staff, and the administration during the time the school is not usable, as illustrated by the quotations.

- *"From the standpoint of children and families, after an impact is a particularly bad time for schools to be closed. Damaged homes and neighborhoods are dangerous and depressing places. Children are often left with no safe place to play when yards, playgrounds, and recreational programs are lost, no one to play with when playmates and friends are forced to relocate and parents are too busy dealing with survival and rebuilding issues to have much time for them."*
- *"The closing of a local school is highly disruptive to social networks and, if it becomes permanent, can rob a neighborhood of its identity and cohesion. One of the most dramatic effects that can occur to a severely impacted community is when a school is closed for a long time, maybe even permanently, due to regional depopulation after homes are destroyed."*
- *"Getting schools reopened quickly has been found to be an important step toward rebuilding the community as a whole."*
- *"An understudied area is the long-term effect of major disasters on the education and development of children."*
- *"The shock of being uprooted and moved to a new school, even temporarily, can be very difficult for children. The effects can be particularly traumatic if they occur at a critical developmental time, such as the senior year with its preparation for college and graduation festivities."*

SOURCE: THE HEINZ CENTER, HUMAN LINKS TO COASTAL DISASTERS, H. JOHN HEINZ III CENTER FOR SCIENCE, ECONOMICS AND THE ENVIRONMENT, WASHINGTON, DC, 2002

4.4 Scope, Effectiveness, and Limitations of Codes

Seismic design is highly developed, complex, and strictly regulated by codes and standards. Seismic codes present criteria for the design and construction of new structures subject to earthquake ground motions in order to minimize the hazard to life and to improve the capability of essential facilities to function after an earthquake. To these ends, current building codes provide the minimum requirements necessary for reasonable and prudent life safety.

Seismic code requirements include:

- A methodology for establishing the design ground motion at any site based on seismicity and soil type
- Procedures for the seismic analysis of the building structure and key nonstructural components and systems
- Some detailed design requirements for materials, systems, and components
- Definitions of irregular building configurations and limitations on their use
- Building height limitations related to structural type and level of seismicity

Building codes and seismic design practices evolved rapidly as the result of intensive research and development in the United States and elsewhere during the second half of the 20th century.

Building codes for cities, States, or other jurisdictions throughout the United States are typically based on the adoption, sometimes with more restrictive local modification, of a model building code. Up until the mid-1990s, there were three primary model building code organizations: Building Officials and Code Administrators International, Inc. (BOCA), International Conference of Building Officials (ICBO), and Southern Building Code Congress International, Inc. (SBCCI). In 1994, these three organizations united to found the ICC, a nonprofit organization dedicated to developing a single set of comprehensive and coordinated national model construction codes. The first code published by ICC was the 2000 IBC, which reflected the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* (NEHRP Provisions) (2000a). Later editions of the IBC reference ASCE 7 for its seismic provisions. Some jurisdictions in the country may still be using the Uniform Building Code (UBC) seismic provisions (its final update was in 1997), though most have adopted or are preparing to adopt the IBC. Provisions of the IBC are predominantly used throughout the United States.

4.4.1 The Background of Seismic Provisions in Building Codes

Building code provisions for seismic design have been available in the United States since the initial regulations for the protection of buildings against earthquakes first appeared in the UBC in California in 1927. Beginning in the 1950s, the earthquake-resistant design provisions of the three model codes used as the basis for building regulation in the United States were based on recommendations developed by the seismology committee of the Structural Engineers Association of California and contained in their publication known as the "Blue Book."

In the early 1980s, FEMA—one of the lead agencies in NEHRP—issued a contract to the Building Seismic Safety Council for the update and continued development of a seminal document, *Tentative Provisions for the Development of Seismic Regulations for Buildings*, ATC-3-06, originally published in 1978 by the ATC, a non-profit research foundation set up after the San Fernando earthquake of 1978 to recommend improvements in the seismic building code. Provisions of ATC-3-06 subsequently provided the basis for the NEHRP Provisions (2000a), which was released in 1985 and continues to serve as the primary resource document for earthquake design requirements in ASCE 7.

Building codes such as the IBC currently address seismic design primarily through reference to ASCE 7.

4.4.2 Seismic Codes and Schools

Seismic codes are concerned primarily with types of structures and include few provisions that relate to specific occupancies. The IBC (2009) categorizes school buildings with occupant load greater than 250 as Type III: "…buildings and other structures that represent a substantial hazard to human life in the event of failure…." Type III buildings are assigned an Importance Factor of 1.25. This means that the seismic force calculated by use of the Equivalent Lateral Force (ELF) procedure would be multiplied by 1.25 so that schools are designed to a higher standard than ordinary buildings.

As previously mentioned, California K-12 schools are regulated by the Field Act, which singles out the design and construction of schools to resist earthquakes and is an important model for other States to consider. However, the Field Act is not a code; it requires that schools be designed by a licensed architect or structural engineer, that plans and specifications be checked by the Department of the State Architect, and that independent testing and inspection be conducted during construction.

Implementing the nonstructural provisions of the seismic code will significantly reduce damage to nonstructural components and reduce the potential for school closings because of ceiling and lighting damage, partition failures, and loss of essential utilities. In the case of nonstructural provisions, the code goes somewhat beyond the structural objective of only reducing the risk of casualties. However, recent experience with earthquakes has shown that nonstructural damage to schools can be dangerous to the occupants, costly to repair, and operationally disruptive. Guidance on design to reduce nonstructural damage is provided in FEMA 74, *Reducing the Risks of Nonstructural Earthquake Damage: A Practical Guide* (1994).

4.4.3 The Effectiveness of Seismic Codes

Building codes originated in the effort to reduce risk to health and safety, rather than reducing property loss, but as they evolved, they indirectly and directly assisted in reducing building damage. They establish the minimum standards for safety commensurate with affordability and other impacts such as measures that might create extreme inconvenience to occupants or seriously reduce the building's functional efficiency.

Engineers generally agree that, based on California's earthquake experience, regulation through a properly enforced seismic code has largely fulfilled the intent of ensuring an acceptable level of safety to avoid death and injury. The performance of school buildings in recent California earthquakes substantiates this; structural damage has been minimal in schools designed to the most recent seismic codes. Application of the Field Act ensures that schools are designed and constructed to more rigorous standards than most other buildings.

However, the effectiveness of seismic codes is subject to some qualifications:

- The standards of code enforcement vary considerably, and smaller jurisdictions may not have trained engineering staff to conduct effective plan checks and inspections.
- The nonstructural provisions of the seismic codes are often not adopted at the local level. Nonstructural components have not been regulated to the same level of care as structural components, and have been the cause of considerable economic loss and disruption of operation.
- The code can be misinterpreted and design errors made due to inexperience of both designers and building officials.

4.5 Evaluating Existing Schools for Seismic Risk and Specific Risk Reduction Methods

Several FEMA-sponsored publications are available to assist in the evaluation process. These guides, first developed in the 1980s, are used extensively. This section also provides a simple seismic evaluation checklist that focuses specifically on schools.

The procedures for seismic evaluation of schools are listed below in the order in which they would be used, starting with a simple screening process.

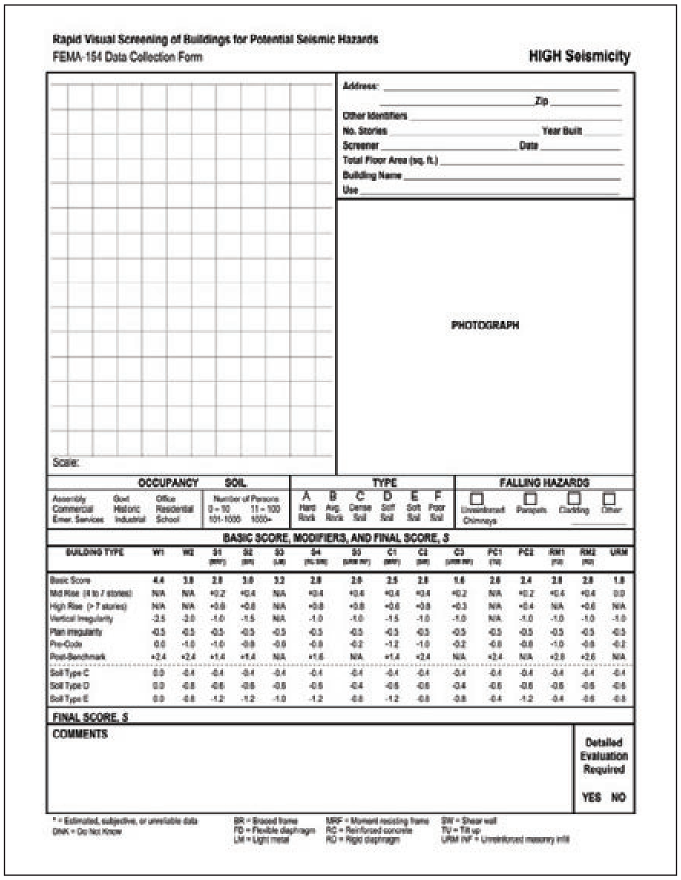
4.5.1 Rapid Visual Screening

The Rapid Screening Procedure (RSP) published in FEMA 154, *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook* (2002b), is intended as an initial step in identifying hazardous buildings and their deficiencies. Buildings identified by this procedure to be potentially hazardous must be examined in more detail by a professional engineer experienced in seismic design. Because this screening is aimed at providing a low-cost method of identifying large inventories of potentially hazardous buildings for public and private owners, and thus reducing the number of buildings that should be subject to a more detailed evaluation, it is designed to be performed from the street without benefit of entry into a building.

The screening procedures can be completed in 20 to 30 minutes for each building. In some cases, hazardous details may not be visible, and seismically hazardous structures will not be identified as such. Nonstructural interior components are not evaluated. Conversely, buildings identified as potentially hazardous may prove to be adequate.

The RSP is most useful for large school districts, municipalities, or even States that wish to get an economical preliminary evaluation of the seismic risks faced by their school inventory. The procedure is not intended to provide a definitive evaluation of the individual buildings.

The RSP is based on a visual survey of the building and a data collection form used to collect critical information. The collection form includes space for sketches and a photo of the building, as well as pertinent earthquake-safety related data. FEMA 154 provides the inspector with background information and data required to complete the form (see Figure 4-28). The procedure is designed to be performed by individuals with some knowledge of buildings who are not necessarily professional architects or engineers and are not familiar with seismic design. It has been successfully applied by



Rapid Visual Screening of Buildings for Potential Seismic Hazards
FEMA-154 Data Collection Form

HIGH Seismicity

Address: ______________________ Zip ______
Other Identifiers ______________________
No. Stories ______________ Year Built ______
Screener ______________ Date ______
Total Floor Area (sq. ft.) ______________________
Building Name ______________________
Use ______________________

Scale:

PHOTOGRAPH

OCCUPANCY: Assembly, Govt, Office, Commercial, Historic, Residential, Emer. Services, Industrial, School

SOIL: Number of Persons: 0 – 10, 11 – 100, 101-1000, 1000+

TYPE: A Hard Rock, B Avg. Rock, C Dense Soil, D Stiff Soil, E Soft Soil, F Poor Soil

FALLING HAZARDS: Unreinforced Chimneys, Parapets, Cladding, Other

BASIC SCORE, MODIFIERS, AND FINAL SCORE, S

BUILDING TYPE	W1	W2	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	S5 (URM INF)	C1 (MRF)	C2 (SW)	C3 (URM INF)	PC1 (TU)	PC2	RM1 (FD)	RM2 (RD)	URM
Basic Score	4.4	3.8	2.8	3.0	3.2	2.8	2.0	2.5	2.8	1.6	2.6	2.4	2.8	2.8	1.8
Mid Rise (4 to 7 stories)	N/A	N/A	+0.2	+0.4	N/A	+0.4	+0.4	+0.4	+0.4	+0.2	N/A	+0.2	+0.4	+0.4	0.0
High Rise (> 7 stories)	N/A	N/A	+0.6	+0.8	N/A	+0.8	+0.8	+0.6	+0.8	+0.3	N/A	+0.4	N/A	+0.6	N/A
Vertical Irregularity	-2.5	-2.0	-1.0	-1.5	N/A	-1.0	-1.0	-1.5	-1.0	-1.0	N/A	-1.0	-1.0	-1.0	-1.0
Plan irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Pre-Code	0.0	-1.0	-1.0	-0.8	-0.6	-0.8	-0.2	-1.2	-1.0	-0.2	-0.8	-0.8	-1.0	-0.8	-0.2
Post-Benchmark	+2.4	+2.4	+1.4	+1.4	N/A	+1.6	N/A	+1.4	+2.4	N/A	+2.4	N/A	+2.8	+2.6	N/A
Soil Type C	0.0	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
Soil Type D	0.0	-0.8	-0.6	-0.6	-0.6	-0.6	-0.4	-0.6	-0.6	-0.4	-0.6	-0.6	-0.6	-0.6	-0.6
Soil Type E	0.0	-0.8	-1.2	-1.2	-1.0	-1.2	-0.8	-1.2	-0.8	-0.8	-0.4	-1.2	-0.4	-0.6	-0.8

FINAL SCORE, S

COMMENTS

Detailed Evaluation Required: YES NO

* = Estimated, subjective, or unreliable data
DNK = Do Not Know
BR = Braced frame
FD = Flexible diaphragm
LM = Light metal
MRF = Moment resisting frame
RC = Reinforced concrete
RD = Rigid diaphragm
SW = Shear wall
TU = Tilt up
URM INF = Unreinforced masonry infill

Figure 4-28: Example of rapid visual screening information form

architectural and engineering students. The methodology enables the inspector to identify significant seismic-related defects and to arrive at a numerical score, with a hazard ranking of 1–6.

Surveyed buildings are divided into two categories: those that are expected to have acceptable seismic performance, and those that may be seismically hazardous and should be studied further. A score of 2 is suggested as a "cut-off" based on current seismic knowledge (i.e., if a building has a hazard ranking of 2 or less, it should be investigated by a structural engineer experienced in seismic design).

4.5.2 Systems Checklist for School Seismic Safety Evaluation

Table 4-2 represents a simplified version of ASCE 31, S*eismic Evaluation of Existing Buildings* (2003); also see Section 4.5.3. This simplified version focuses on structural and nonstructural systems and components found in schools. The evaluation questions are organized by system basis and are designed to establish whether the building is a potential seismic hazard and, if so, what its specific vulnerabilities are. Use of the checklist requires some seismic engineering knowledge, but the information can be obtained by visual inspection and no engineering calculations are necessary. The checklist can be used in conjunction with the RSP procedure, and augments the RSP analysis because it requires access to the building and review of design drawings, both of which are likely to be available to evaluate a public school building.

The checklist can also be useful in interdisciplinary discussions between consultants and school district personnel, and can assist consultants in fee negotiation with the client.

Table 4-2: School seismic safety evaluation checklist

System Identifier	Evaluation Question	Evaluation Y or N or comment	Guidance	Data References
1	Site			
	Is there is an active fault on or adjacent to the site?		If suspected, site-specific geologic investigations should be performed.	Local building department, State geologist, local university, or local geotechnical consultant
	Does the site consist of stiff or dense soil or rock?		If softer soils that can lead to force amplification are suspected, site-specific geologic investigations should be performed.	Local building department, State geologist, local university, or local geotechnical consultant
	Are post-earthquake site egress and access secured?		Alternative routes, unlikely to be blocked by falling buildings, power lines, etc., are desirable.	Inspection by district personnel/architect
	Are utility and communications lifelines vulnerable to disruption and failure?		Security of the entire utility and communications network is the issue: the school may be impacted by off-site failures.	Inspection on site by district personnel and Mechanical/Electrical/Plumbing (M/E/P) consultants; for off site, contact local power and communications providers
	Are there alternate or backup sources for vital utilities?		Alternate sources increase the probability of the school remaining functional after an event, particularly if the school is used for post-earthquake shelter.	Inspection personnel and district personnel, M/E/P consultants, and local utility suppliers
1	Site			
	Are building setbacks adequate to prevent battering from adjacent buildings?		Inadequate spaces between building walls are common in dense urban settings.	ASCE 31, Section 4.3.1.2
	Is there adequate space on the site for a safe and "defensible" area of refuge from hazards for building occupants?		Outside spaces can be used as safe post-earthquake assembly areas for school occupants and possibly the community.	Inspection personnel and district personnel/architect/local emergency staff
2	Architectural			
	Configuration			
	Is the architectural/structural configuration regular?		Irregular vertical and horizontal configurations, such as re-entrant corners and soft first stories, may lead to significant stress concentrations.	ASCE 31, Section 4.3.2

Table 4-2: School seismic safety evaluation checklist

System Identifier	Evaluation Question	Evaluation Y or N or comment	Guidance	Data References
2	Architectural			
	Planning and Function			
	Are exit routes, including stairs, protected from damage and clear from nonstructural elements or contents that might fall and block exit ways?		Schools sometimes have large unbraced lockers in hallways, or store other materials, such as tall filing cabinets or bookcases, that may fall and block exits.	Inspection by district personnel ASCE 31, Section 4.8.11.
	Ceilings			
	Are suspended ceilings braced and correctly attached at walls?		Suspended ceilings easily distort (particularly in light and flexible frame structures), thus causing ceiling panels to fall if not properly designed and constructed.	ASCE 31, Section 4.8.2.
	Are heavy plaster suspended ceilings securely supported and braced?		Heavy lath and plaster ceilings in older schools are very dangerous if poorly supported.	ASCE 31, Section 4.8.2.
	Partitions and Space Division			
	Are partitions that terminate at a hung ceiling braced to the structure above?		Partitions need support for out-of-plane forces. Attachment to a suspended ceiling is inadequate.	ASCE 31, Section 4.8.1.
	Are masonry or hollow tile partitions reinforced or braced, particularly those surrounding exit stairs?		Heavy partitions develop strong earthquake forces because of their stiffness and mass, and are prone to damage. They are particularly dangerous around stairs and exit ways and occupied classrooms.	ASCE 31, Section 4.8.1
	Other Elements			
	Are exterior entrance canopies and walkways engineered to ensure no collapse?		Post-earthquake safety of these structures is critical to ensure safe exit after an event.	ASCE 31, Section 4.8.8
	Are parapets, appendages, etc., securely attached and braced to the building structure?		Unreinforced masonry parapets are especially vulnerable, as are items such as cornices, signs, and large satellite communication dishes.	ASCE 31, Section 4.8.8
	Are heavy lockers, library shelves, and vertical filing cabinets that could fall on people braced to the structure?		These can topple and injure occupants, and also block exit ways.	ASCE 31, Section 4.8.11

Table 4-2: School seismic safety evaluation checklist

System Identifier	Evaluation Question	Evaluation Y or N or comment	Guidance	Data References
3	Structural System			
	Is there a continuous load path from the foundation to the roof?		This is an important characteristic to ensure good seismic performance. This also sometimes relates to irregularity in configuration.	Engineer to check design of school structure ASCE 31, Section 4.3.1.
	Does the structure provide adequate redundancy in the event of the loss of some structural supports?		Typical characteristics of redundancy include multiple lines of resistance and multiple bays within each line to distribute lateral forces.	ASCE 31, Section 4.4.1.1.1 and Section 4.4.2.1.1
	Is all load-bearing structural masonry reinforced according to code?		Unreinforced masonry has limited ductility and cannot withstand large earthquake-induced repetitive displacements.	Engineer to check against local code requirements
	Is the structure's reinforced concrete designed to seismic code later than 1976?		The reinforced concrete codes changed in 1976, and structures designed before these codes were adopted may be inadequate.	Check date of design, and edition of code used
	Is the structure's wood frame well maintained, with little or no deterioration?		Wood framing is subject to attack by termites and water damage, both of which can seriously weaken the structure.	School district personnel to inspect
	Are horizontal structural members securely connected to walls and columns?		Good connections between all structural members are very important for structural integrity.	Structural engineer to check ASCE 31, Section 4.6.1
	Are horizontal diaphragms correctly designed and constructed with necessary chords and collectors?		Large diaphragm openings and the edges of diaphragms must be designed to ensure forces are properly transmitted to walls and frames.	Structural engineer to check ASCE 31, Section 4.5.1
4	Building Envelope			
	Wall Cladding			
	Is the building cladding attached to structural frames so that it can accommodate drift?		Frames are flexible and cladding must be detailed to accommodate calculated drifts and deformations.	ASCE 31, Section 4.8.4
	Are heavy veneer facing materials such as brick or stone securely attached to the structural walls?		Shear wall structures are very stiff and carry large earthquake forces; heavy attachments must be securely attached.	Structural engineer to check design and field condition
	Are heavy roofing materials such as tile and slate securely attached to the structure?		Installation of these materials over points of egress may be dangerous, because they may fall off and hit someone exiting the building and may also litter the exit path with debris.	IBC Table 1507.3.7

Table 4-2: School seismic safety evaluation checklist

System Identifier	Evaluation Question	Evaluation Y or N or comment	Guidance	Data References
4	Building Envelope			
	Glazing			
	Are glazing and other panels attached so that they can accommodate drift?		Glazing must be installed with sufficient bite, and adequate space between glass and metal.	ASCE 31, Section 4.8.4
	Is the glazing material inserted into a surrounding structure that limits drift and racking?		Glazing is dependent on the surrounding structure to limit racking.	Structural engineer to inspect framing and structural conditions
5	Utilities			
	Are building utility distribution systems well supported and adequately braced?		Flexible connections may be necessary where utilities enter the building.	ASCE 31, Section 4.8.13.
6	Mechanical			
	Is heavy mechanical equipment adequately secured and are isolators provided with snubbers?		Spring-isolated equipment must be restrained from jumping off isolators.	ASCE 31, Section 4.8.12
	Is the heating piping properly braced and provided with expansion joints?		Bracing and expansion joints increase the likelihood of continued post-event function.	Inspection by school district personnel and M/E/P consultants
	Is ductwork properly supported and braced?		Proper support and bracing increase the likelihood of continued post-event function.	Inspection by school district personnel and M/E/P consultants
	Are water heaters and other tanks securely braced?		Gas heaters or tanks with flammable or hazardous materials must be secured against toppling.	ASCE 31, Section 4.8.12
7	Plumbing			
	Are plumbing lines adequately supported and braced?		Protection of joints is especially important.	ASCE 31, Section 4.8.13
	Is fire protection piping correctly installed and braced?		Correct installation and bracing increase the likelihood of continued post-event function.	Inspection by school district personnel and M/E/P consultants
	Are ducts and piping that pass through seismic joints minimized and provided with flexible connections?		Differential movement between sections of the building can cause breakage and leaks in pipes and ducts if no provision is made for movement. If walls at joint are firewalls, penetrations should be fireproofed.	ASCE 31, Section 4.8.13.2

Table 4-2: School seismic safety evaluation checklist

System Identifier	Evaluation Question	Evaluation Y or N or comment	Guidance	Data References
8	Electrical			
	Are suspended lighting fixtures securely attached, braced, or designed to sway safely?		Older suspended lighting fixtures have performed badly in earthquakes and are an injury hazard.	ASCE 31, Section 4.8.3
	Are light fixtures supported in a ceiling, braced, and provided with safety wires?		Light fixtures within a grid often fall when the grid is distorted, unless the fixtures are secured with safety wires.	ASCE 31, Section 4.8.3
	Is heavy electrical equipment adequately secured?		Switch gear and transformers are heavy and failure can shut down the electrical system.	ASCE 31, Section 4.8.12
9	Fire Alarm			
	Is the fire alarm system connected to a secondary power supply?		This is also necessary to support daily operational needs, including lighting, heating, communications, etc., and if the building is used as a post-earthquake shelter.	Inspection by district maintenance personnel and M/E/P consultants
	Is the fire alarm system provided with a battery backup system capable of operating the system for 24 hours after power loss?		Required by code even if the building will not be used after an event so that the school can be evacuated.	Inspection by district maintenance personnel and M/E/P consultants
10	Communications and IT Systems			
	Are communications components adequately braced and supported?		Post-event communications are vital for issuing instructions to school administrators, students, faculty, and staff. Some components, such as large satellite dish antennas, are easily damaged if not properly supported.	ASCE 31, Section 4.8.12
	Are building intercom systems connected to a standby generator or battery?		Necessary to enable continued communications, whether loss of power is caused by earthquake or not.	Inspection by maintenance personnel and M/E/P consultants
11	Equipment Operations and Maintenance			
12	Security Systems			
13	Security Master Plan			

4.5.3 Seismic Evaluation of Existing Buildings

For those buildings that, as the result of a preliminary screening, are candidates for a more detailed investigation, the Building Seismic Safety Council (BSSC) developed a procedure for the systematic evaluation of any type of building (FEMA 178, *The NEHRP Handbook for the Seismic Evaluation of Existing Buildings* (1992), later updated as FEMA 310, *Handbook for Seismic Evaluation of Buildings: A Prestandard* (1998). FEMA 310 was subsequently superseded by ASCE 31 (2003), a standard of the American Society of Civil Engineers approved by the American National Standards Institute.

ASCE 31 can be used to evaluate the structural and nonstructural systems and components for any type or size of individual school building. However, the procedure focuses on evaluating whether the building or building components pose a potential earthquake-related risk to human life. The procedure does not address code compliance, damage control, or other aspects of seismic performance not related to life safety.

The ASCE 31 methodology involves answering two sets of questions: one set addresses the characteristics of 15 common structural types and the other set deals with structural elements, foundations, geologic site hazards, and nonstructural components and systems. These questions are designed to uncover the flaws and weaknesses of a building, and are in the form of positive evaluation statements describing building characteristics that are essential if the failures observed in past earthquakes are to be avoided. The evaluating architect or engineer should address each statement on the checklist and determine whether an item is compliant or non-compliant. Compliant statements identify conditions that are acceptable and non-compliant statements identify conditions in need of further investigation. The handbook also details a process for dealing with statements on the checklist that are found to be non-compliant.

The evaluation requires some basic structural calculations and a site visit. Follow-up field work is also necessary. The primary product of the evaluation is the identification building vulnerabilities that could precipitate structural or component failure. Although the procedure provides guidance on structural deficiencies, it is not intended to identify appropriate seismic retrofit options. The design engineer must understand the overall deficiencies of the building before attempting to identify retrofit design approaches. The overall deficiencies may be due to a combination of component deficiencies, inherent adverse design, construction deficiencies, deterioration, or a serious weakness in the structural and nonstructural systems.

4.6 Earthquake Risk Reduction Methods

Although the general principles of design are similar for new or existing schools, differences in code requirements and overall project delivery processes reflect the design freedoms for new buildings and the constraints for existing ones.

Engineering of structural and nonstructural risk reduction methods is similar for new and existing schools. New school design offers the possibility of construction on a site subject to less ground motion because of better soil conditions or further proximity to a fault. New schools can be designed with the most appropriate structural system, using known and tested materials and a good building configuration. These possibilities are not available when retrofitting an existing school; the building may have been designed to an obsolete seismic code or no code at all, its materials may be questionable, and the building configuration and structural system may be inappropriate. Therefore, the protection of an existing school must start with a careful evaluation of its vulnerability. Seismic retrofitting is expensive and time consuming; however, an incremental retrofit procedure, as described in Section 4.6.2, can help to keep time and cost within reasonable limits by integrating retrofits into normal repairs and capital improvement projects.

4.6.1 Risk Reduction for New Schools

Methods of design for earthquake protection involve three main characteristics of the school: its site, its structure, and its nonstructural components.

In terms of risk reduction, the first priority is the implementation of measures that will reduce the risk of casualties to students, staff, and visitors. The second priority is the reduction of damage that leads to downtime and disruption. The third priority is the reduction of damage and repair costs.

Alternative measures to achieve these objectives are as follows, in ascending order of cost:

- New Schools Regulated by Seismic Codes
  - Provide personal protection training.
  - Evaluate code provisions against risk priorities. Evaluate whether design to current code will meet acceptable risk objectives for damage costs and reduction of downtime.
  - Consider adopting California's Field Act model for quality control of design and construction; it can be administered by a single district with specification provisions for inspection in contract documents.
  - Use performance-based design procedures if code-based design does not meet acceptable risk objectives.
- New Schools Not Regulated by Seismic Codes
  - Provide personal protection training.
  - Design to appropriate code standards on a voluntary basis.
  - Use performance-based design procedures to meet acceptable risk objectives.

- Consider adoption of seismic code; requires community-wide cooperation.

Damage reduction is common to all the objectives. The following sections give an overview of the design strategies that are used to achieve acceptable levels of protection in new schools.

School Sites. Protection of schools and their occupants from earthquakes depends on correct seismic design and construction to resist the estimated earthquake forces that the building could encounter at its specific site. Because ground motion from a single earthquake may vary considerably, depending on the nature of the soil and the distance of the building from known earthquake faults, careful site selection is a critical first step in reducing the forces on the building. School sites are generally selected based on factors such as availability, student population, cost, convenience of access for the school students and staff, and general demographic concerns rather than seismicity. However, a large district that is developing a multi-school plan of new facilities should include recognition of any natural hazard vulnerabilities as a factor in the evaluation of alternative sites. A school district can reduce its seismic vulnerability in several ways:

> In the late 1960s, the small school district of Portola Valley, CA, was faced with declining enrollment for its intermediate school, which was also outdated. In addition, the school was located very close to the San Andreas Fault. Concerned about seismic risk, the district deemed the site unsuitable for school purposes and sold the site to the city for $1. The city subsequently used the site for recreational purposes.

- **Locate the building in an area of lower seismicity, where earthquakes occur less frequently or with typically smaller intensities**. Although it would be very rare for a school district to make a site selection decision based solely on seismic risk, moving a school even a few miles in some cases can make a big difference to its seismic hazard.
- **Locate the building on a soil type that reduces the hazard.** Local soil profiles can be highly variable, especially near water, on sloped surfaces, or close to faults. In an extreme case, siting on poor soils can lead to damages caused by liquefaction, land sliding, or lateral spreading of the soil. Similar buildings located less than 1 mile apart have performed in dramatically different ways in earthquakes because of differing soil conditions. Even when soil-related geologic hazards are not present, earthquake motions that have to travel through softer soils will be amplified more than those traveling through firm soils or rock. If soil types at a site are a concern, the effects of soil hazard on risk should be determined by a geotechnical or engineer. A professional should assess the potential vulnerabilities associated with differing site conditions. These vulnerabilities should be weighed against the costs, both direct and indirect, of locating the facility on soils that will result in better performance.

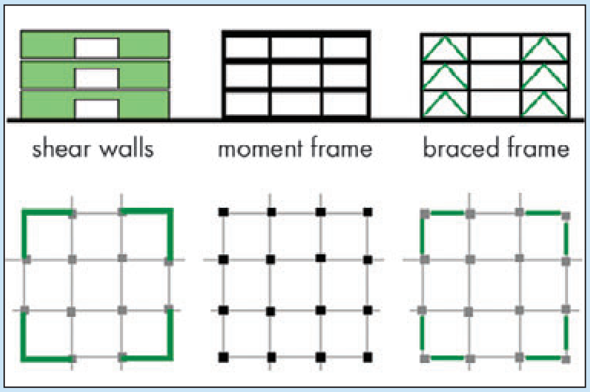
- **Engineer the building site to increase building performance and reduce vulnerability.** If building relocation to an area of lower seismicity or to an area with a better natural soil profile is not a cost-effective option, the soil at the designated site can sometimes be treated to reduce the hazard. For example, on a liquefiable site, the soil can be grouted or otherwise treated to reduce the likelihood of liquefaction. Soft soils can be excavated and replaced, or combined with foreign materials to make them stiffer. Alternatively, the building foundation itself can be modified to account for the potential effects of the soil, reducing the building's susceptibility to damage even if liquefaction or limited land sliding does occur. The school district should weigh the additional costs of modifying the soil characteristics or the building foundation with the expected reduction in damage and loss. However, because most schools are one or two stories in height, site area usage is considerable, and site treatment is likely to be costly.

The ELF equation in the IBC is $V=C_s W$, where V= the shear, or pushing, force at the base of the building, which represents the total earthquake force on the building, and C_s is a coefficient representing the estimated site acceleration (derived from maps provided in the code) and modified by factors related to the characteristics of the structure, the importance of the building, and the nature of the soil. W is the weight of the building.

In most cases, a designated school site will be accepted. Proposed construction directly over a fault is probably the only siting characteristic that would lead to rejection of an otherwise suitable location. The forces a school must be designed to withstand increase if it is near a fault, which increases the structural cost. Sites are assigned to one of six categories, from A, which represents hard rock, to F, which represents soils vulnerable to potential failure or collapse such as liquefiable soils, sensitive clays, and weak soils and clays. Variations in soil type are addressed in design by increasing or decreasing the design forces by application of a coefficient within the calculation of the ELF equation, which is used to establish the design lateral forces on the building.

Reducing Damage to School Structures. Minimum standards and criteria for structural design are defined in the building codes. The codes provide maps that show whether the location is subject to earthquakes and, if so, the probability of occurrence, expressed by varying levels of seismic forces for which a building must be designed. Seismic codes are adopted by State or local authorities, so a seismically-prone region could be exempt from seismic code regulations if the local community has chosen not to adopt a seismic building code. Although a seismic hazard exists, based on historic and scientific data, some communities choose to ignore the risk, because no one has experienced an earthquake in their lifetime. Such a policy should be of serious concern to school district officials, the local school board, and parents.

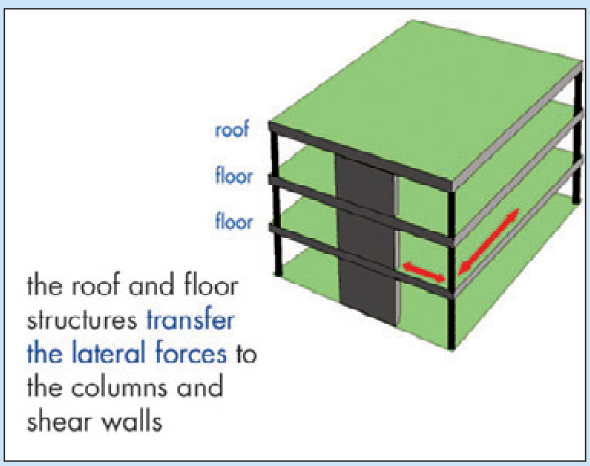
How Buildings Resist Earthquakes



Lateral Force Resisting Systems – Basic Types

This figure shows the basic types of lateral force resisting structural systems. They tend to be mutually exclusive (i.e., it is desirable not to mix the systems in a single building because of the different strength and stiffness characteristics of the systems). Shear walls are very stiff while moment-resistant frames are flexible. Braced systems are in between.

The systems have major architectural implications. Shear walls, which should run uninterrupted from foundation to roof, may impose major planning constraints on a building. Moment frames create unobstructed floors, but, because of their special connection requirements, are expensive. They are subject to more deformation that may result in costly damage to nonstructural components and systems. Braced frames are a common compromise.



Diaphragms

Together with the lateral force resisting system, diaphragms form a horizontal system that connects the vertical elements and carries their loads down to the foundation. Large openings in the diaphragm may limit its ability to be effective in transferring forces.

SOURCE: ARNOLD AND ALEXANDER, 2001

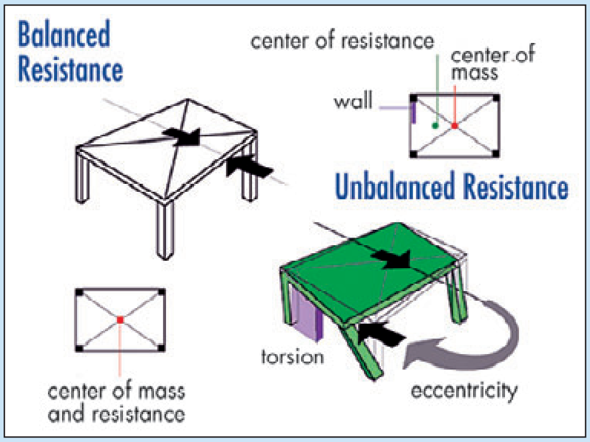
Although the risk may appear to be minimal, the effects of a significant event could be catastrophic. Communities with minimal risk may have no history of design for earthquakes, leaving the building stock especially vulnerable. School buildings are an important community resource (along with other essential buildings such as hospitals and fire and police stations) that should not be gambled on the avoidance of a rare event.

Reducing structural and nonstructural damage in earthquakes depends on:

- The correct application of code criteria and analytical methods. Seismic codes have become increasingly complex and a high standard of care and engineering judgment is necessary to ensure correct application.
- The appropriate selection and application of structural systems and materials. Different structural systems have varied characteristics that must be matched to the nature and purpose of the school. The following two graphics show the basic types of structural lateral force resisting systems.
- The correct design of critical elements such as frames, shear walls, and diaphragms and their connections to one another: earthquake forces expose the weak links between structural members. Serious damage and collapse is often initiated by connection failure. These critical elements provide seismic resistance and must be correctly sized, located, and detailed.
- Careful attention to key structural design principles such as provision of a direct load path and structural redundancy.
- The correct design of the connections between structural elements and nonstructural components.
- A simple and regular building configuration (its size and shape) as planning and aesthetic requirements permit. Experience has shown that certain building shapes and architectural design elements contribute to poor seismic performance and are expensive to design and build.
- A high level of quality assurance to ensure that the building is properly constructed. Careful seismic design is pointless if not properly executed.
- A high level of maintenance to ensure that the building retains its integrity over time. Corrosion of steel and termite infestation or dry rot in wood can seriously affect structural integrity.

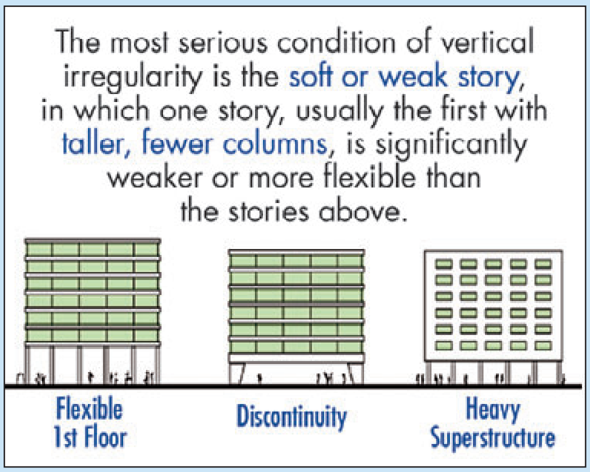
The following graphics show some problems caused by irregular building configurations.

Some Typical Design Problems



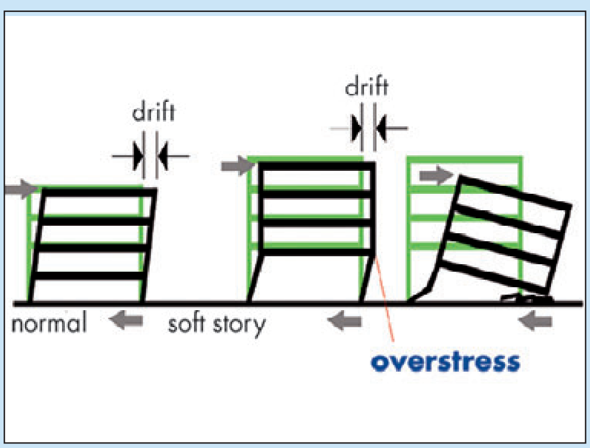
Torsional Forces

This figure shows how torsion occurs. If the center of mass and center of resistance do not coincide, the building tends to rotate around the center of resistance.



Stress Concentrations

Stress concentration is the excessive concentration of forces at one or a few points of the building, such as a particular set of beams, columns, or walls. These few members may fail and, by a chain reaction, bring down the whole building.



Soft Stories

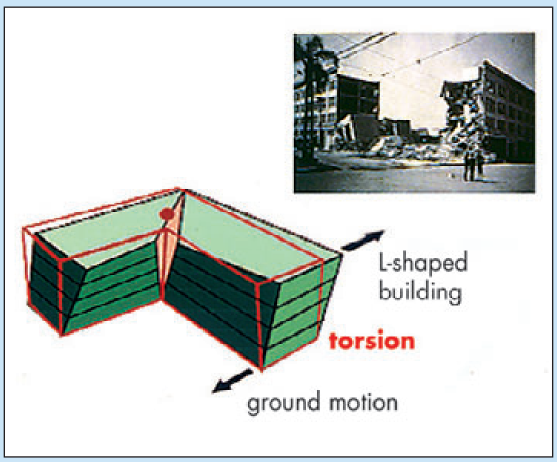
This figure shows the failure mechanism of a soft or weak story. A regular building with equal floor heights distributes its drift equally to each floor so that each is subjected to manageable drift. In the soft story building, the overall drift is the same, but the second floor connections are subject to all, or almost all, the drift, creating a failure mechanism.

SOURCE: ARNOLD AND ALEXANDER, 2001

Torsional Forces and Stress Concentration

Soft Stories

Typical examples of soft story-induced damage.



Re-entrant Corners

Buildings with re-entrant corners (L-shape, U-shape, etc.) are subject to torsion and stress concentrations. Special design measures are necessary to counteract these tendencies. Where buildings are structurally separated to remove stress concentrations at corners, adequate separation distance must be provided to prevent damages caused by pounding (e.g., the buildings deflecting toward each other and making contact.

SOURCE: ARNOLD AND ALEXANDER, 2001

Reducing Damage to Nonstructural Components and Systems. Nonstructural components and systems are defined as those elements that do not contribute to the seismic resistance of the building (see Figures 4-29a and b). They typically comprise from 75 to 80 percent of the total school building value, and they provide weather protection, heating, cooling, lighting, and acoustic control for the structure. Damage to these components can be costly and render the building functionally useless even if the building structure performs in accordance with the intent of the seismic code. Nonstructural components are generally broadly classified as:

- Architectural
  - Exterior envelope – opaque or glazed, roof and wall coverings
  - Veneers

    - Interior partitions
    - Ceilings
    - Parapets and appendages (e.g., signs and decorative elements)
    - Canopies and marquees
    - Chimneys and stacks
- Mechanical
    - Boilers and furnaces
    - HVAC source equipment and distribution components
- Electrical and Electronic
    - Source power equipment and distribution components
    - Source communications equipment and distribution components
    - Light fixtures
- Plumbing
    - Storage vessels and tanks
    - Piping systems
    - Hazardous materials (HazMat) distribution
- Furnishings and Interior Equipment
    - Bookcases, filing cabinets, and other storage
    - Shop and art equipment
    - HazMat storage

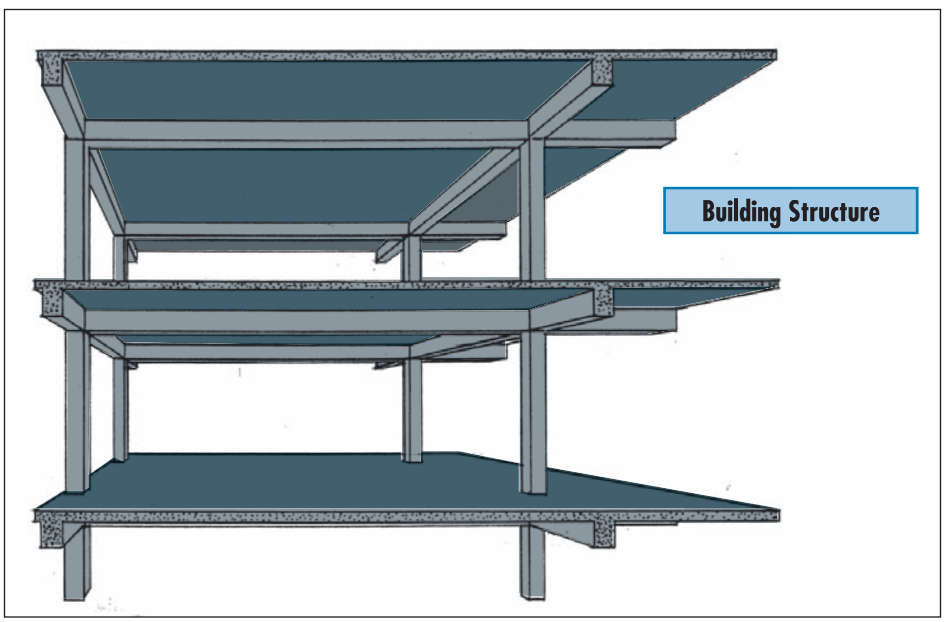


Figure 4-29a: Structural and nonstructural elements of a building

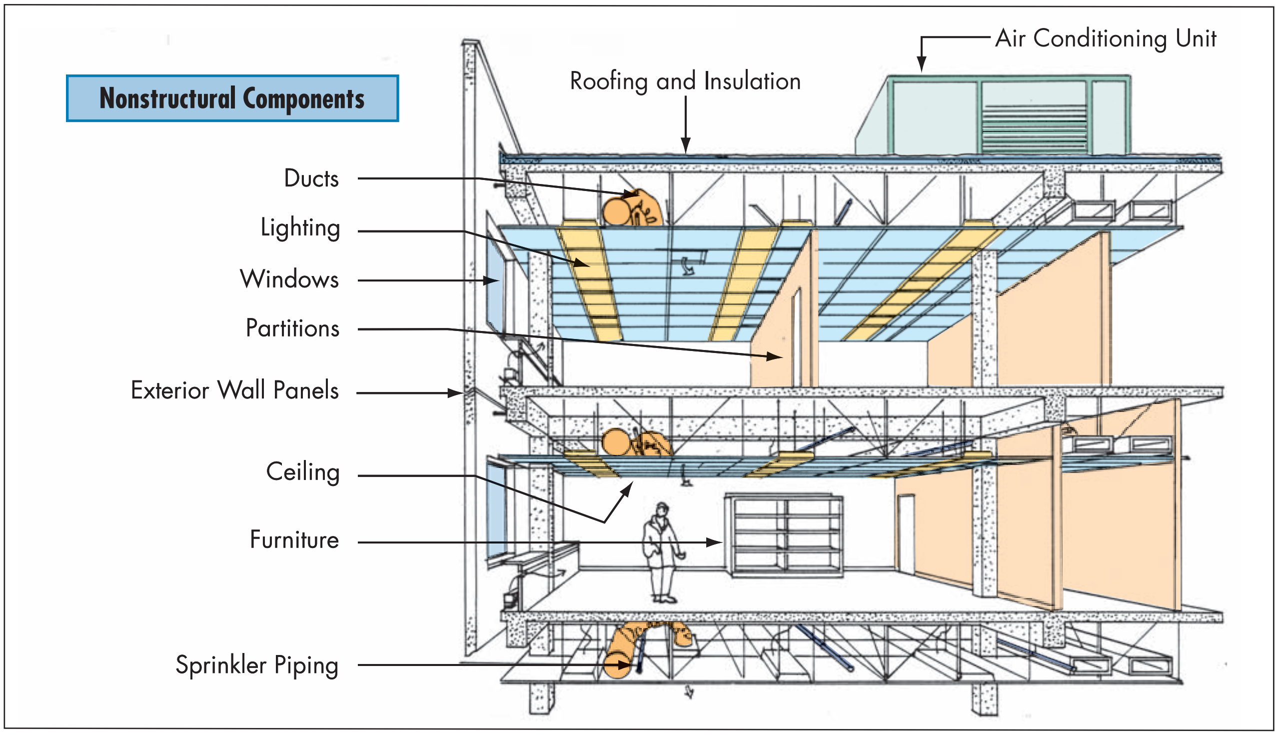


Figure 4-29b: Structural and nonstructural elements of a building

Reduction of damage to nonstructural components depends on using methods of support and bracing the components to avoid failure (see examples in Figures 4-30, 4-31, 4-32, and 4-33). Seismic codes provide the design force for which the nonstructural components must be designed, together with a number of specific design requirements that must be followed.

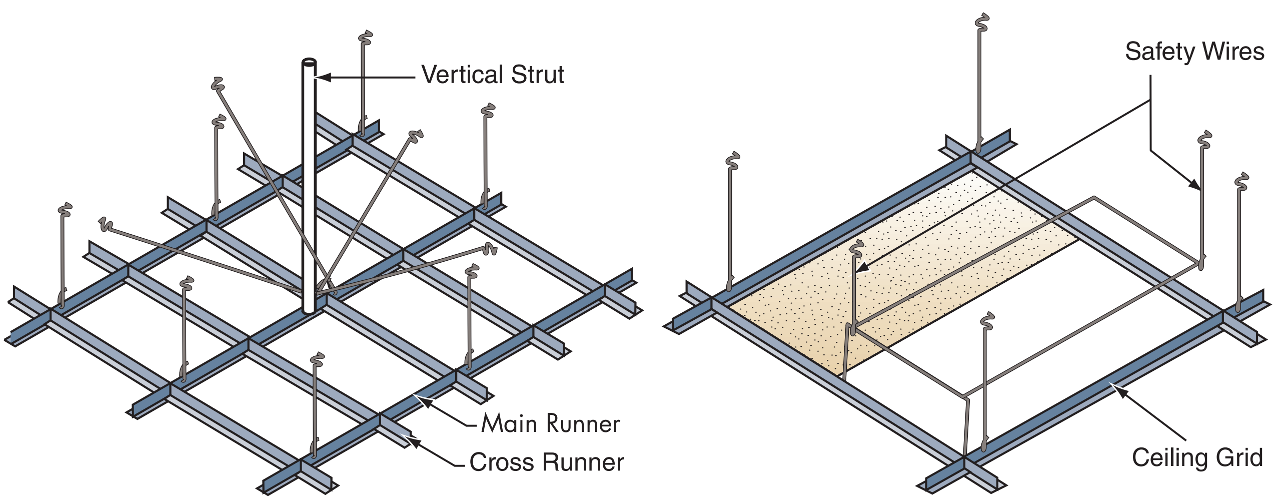


Figure 4-30: Suspended ceiling and light fixture bracing and support

Figure 4-31:
Bracing tall shelving to the structure

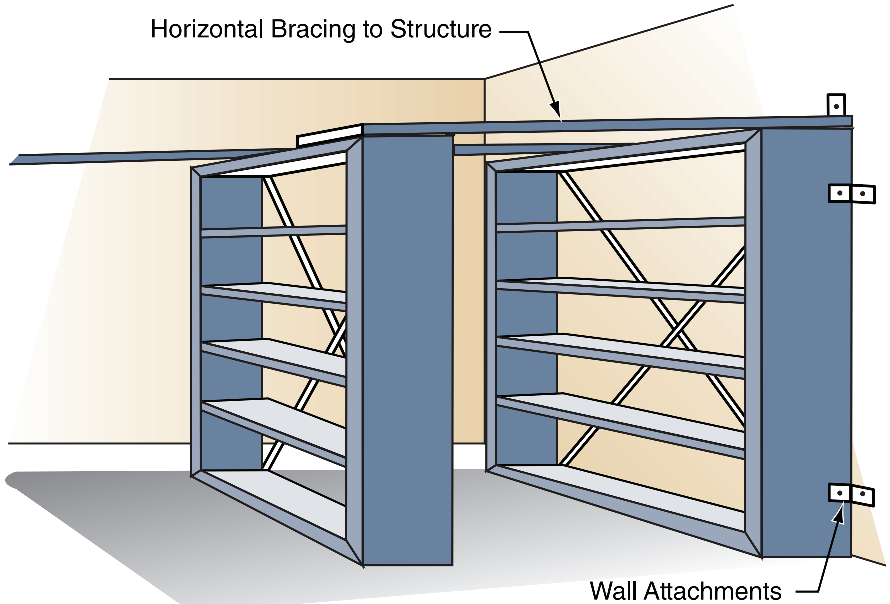


Figure 4-32:
Connection of nonstructural masonry wall to structure to permit independent movement

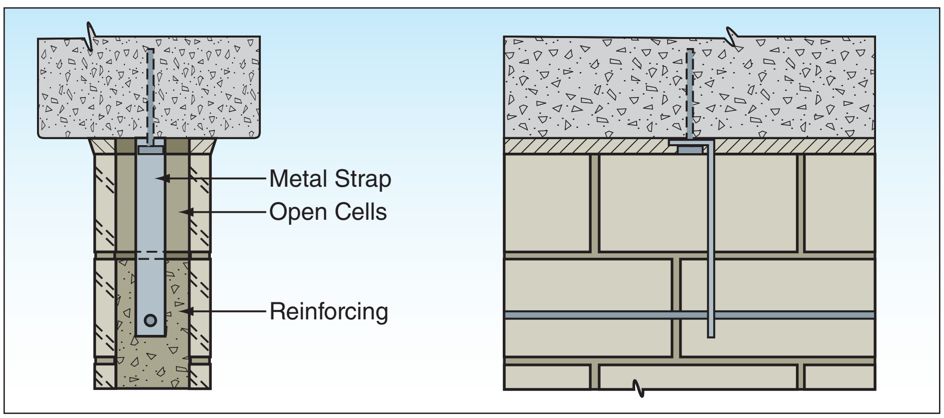
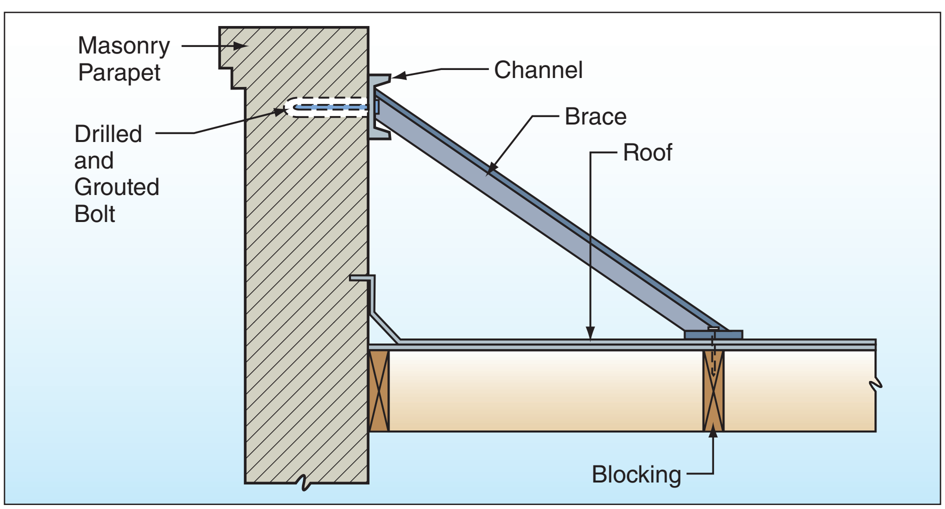


Figure 4-33:
Bracing for existing unreinforced masonry parapet wall



4.6.2 Risk Reduction for Existing Schools

Procedures and Design Strategies. Additions to an existing school must meet all of the code requirements for a new building. Currently, no seismic codes apply to the retrofit of existing schools. Typically, the standards to be applied are derived from the code for new buildings and negotiated with the applicable building department. Bringing an existing structure into full compliance with a current code is difficult and in some cases impossible, so some compromises have to be made; however, there is no general agreement on how to apply the code for new buildings to the retrofit design of existing ones.

Reducing the seismic risk for an existing building requires the same general design principles as those necessary for a new building, but the architect and engineer are faced with existing structural and nonstructural systems and materials that may be far from ideal.

The process should begin with an evaluation procedure such as those outlined in Section 4.5. If the evaluation results in a decision to retrofit an existing school, the school district can use ASCE 41 to select seismic protection criteria. ASCE 41 supersedes FEMA 356, *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (2000b), and FEMA 273, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (1997b) and FEMA 274, *NEHRP Commentary on the Guidelines for the Seismic Rehabilitation of Buildings* (1997a), and provides the latest generation of performance-based seismic rehabilitation methodology.

ASCE 41 provides methods and design criteria to achieve several different levels and ranges of seismic performance (unlike a conventional code that implies, but does not define, a single performance level). "Seismic performance" refers to the nature and extent of damage that the building exhibits as a result of an earthquake. ASCE 41 provides a thorough and systematic approach to performance-based seismic design to achieve an acceptable level of risk based on stakeholders needs.

The performance-based design approach outlined in ASCE 41 provides uniform protection criteria for the retrofit of existing buildings to attain a wide range of performance levels for earthquakes of varying severities and probabilities of occurrence. To start, school districts select specific performance goals as a basis for design, and then evaluate the design requirements, including complexity and cost, to meet those goals.

Typical design strategies for improving the protection of an existing school include (see Figure 4-34):

- Modifying and improving local components or materials, such as beam/column connections. This involves retrofitting connections and strengthening structural members by reinforcing or replacing them with new components.
- Removing or reducing configuration irregularities. This involves providing seismic separations in irregular configurations or adding shear walls or bracing to reduce torsional effects, thereby strengthening and/or stiffening the entire structural system. This is a major retrofit that involves adding bracing or shear walls, replacing many structural members.
- Reducing the mass of the building (to reduce forces). This involves changing the location of heavy items (e.g., bookcases) within the building, but would not apply to a one-story building, except where a tile or slate roof covering might be replaced with a lightweight material.

Retrofit Methods. Seismic (base) isolation (to reduce force on the building superstructure) is a technique that has been successfully used in the retrofit of large buildings, but it is not generally appropriate to the scale and nature of school buildings unless the school building is considered a historical building. A newer technique is passive energy dissipation, the insertion of supplemental energy devices (to reduce movement), which might be applicable to certain types of school structures (e.g., large gymnasiums, multiuse buildings, or auditoriums). Seismic retrofit at any large scale is expensive, both in design and construction, because of the more complex analyses that must be conducted and the construction constraints that must be overcome. In addition, closure of a school for an extended period (beyond that of the normal summer break) is usually unacceptable. Although rare, some major seismic retrofit projects have been completed, primarily with the goal of saving a building that is not only a place of learning, but a historic community resource. The retrofitting of the B.F. Day School in Seattle is one such project (see Figures 4-35 and 4-36).

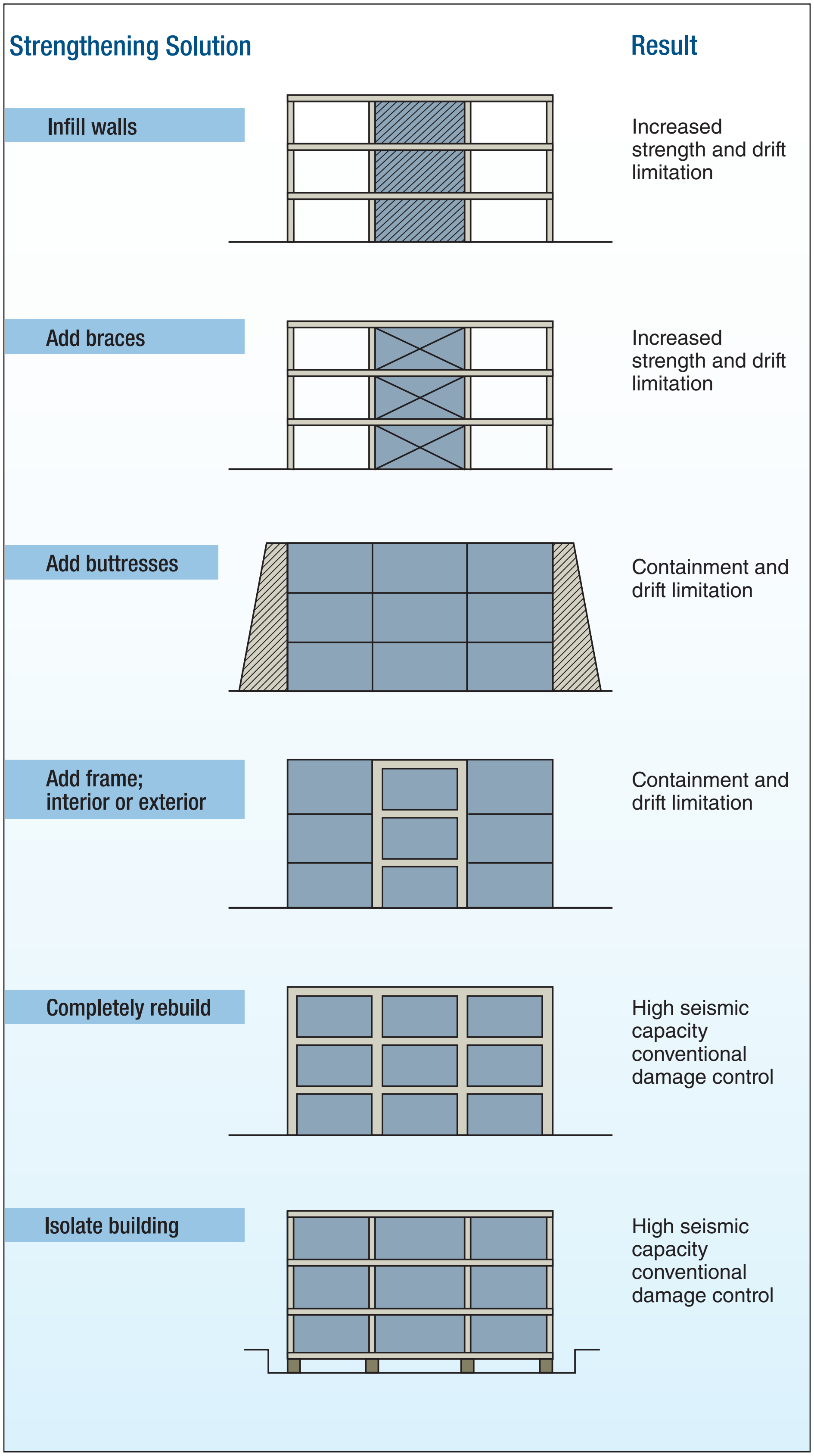


Figure 4-34: Design strategies for seismic retrofit of existing buildings

SOURCE: *BUILDINGS AT RISK: SEISMIC DESIGN BASICS FOR PRACTICING ARCHITECTS,* AIA/ACSA COUNCIL ON ARCHITECTURAL RESEARCH, WASHINGTON, DC, 1994, ERIC ELSESSER

Figure 4-35:

Retrofit of B.F. Day Elementary School, Seattle, WA

SOURCE: EARTHQUAKE ENGINEERING RESEARCH INSTITUTE, OAKLAND, CA; B.F. DAY ELEMENTARY SCHOOL , SEATTLE, TODD W. PERBIX AND LINDA L. NOSON, 1996

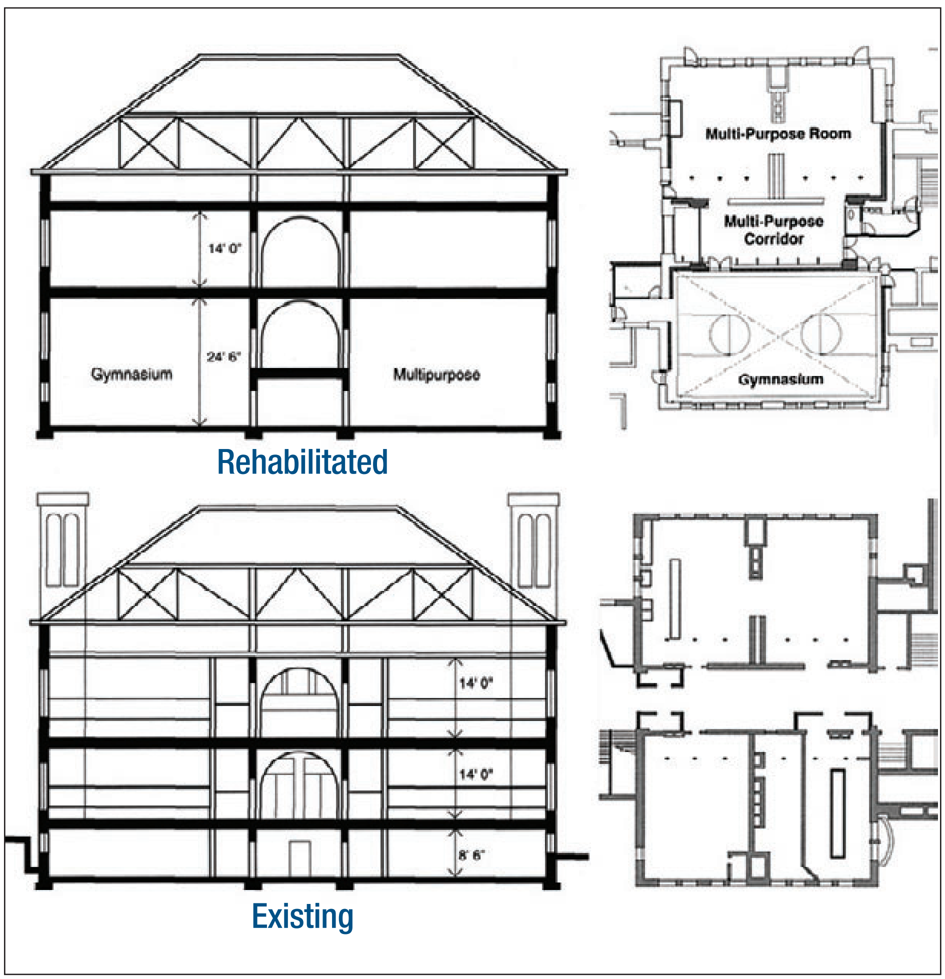


Figure 4-36: Sections and plans of the B.F. Day School: existing at bottom, retrofitted at top. Note that the retrofit has also opened up the basement and first floor to provide large spaces suitable for today's educational needs.

SOURCE: EARTHQUAKE ENGINEERING RESEARCH INSTITUTE, OAKLAND, CA; B.F. DAY ELEMENTARY SCHOOL , SEATTLE, TODD W. PERBIX AND LINDA L. NOSON, 1996

Incremental Seismic Rehabilitation. An approach that greatly improves the feasibility of retrofitting a school is "Incremental Seismic Rehabilitation." The principles of this process are described below. A full description is presented in FEMA 395, *Incremental Seismic Rehabilitation of School Buildings (K-12)* (2003c).

Whereas extensive single-stage seismic retrofitting of an existing school represents a significant cost, retrofit tasks can be divided into increments and integrated into normal repairs and capital improvement projects. Implementation of incremental seismic retrofit involves assessing the buildings, establishing retrofit priorities, and planning integration with other projects. Integration reduces the cost of the seismic work by sharing engineering design costs and some aspects of construction costs. An "integration opportunity" occurs when a seismic retrofit measure can be paired with other repair or replacement tasks or categories. Integration opportunities are a key consideration in determining the sequence of retrofit tasks.

School districts often categorize maintenance and capital improvement projects in the following eight categories:

- Reroofing
- Exterior wall and window replacement
- Fire and life safety improvements
- Modernization/remodeling/new technology accommodation
- Under floor and basement maintenance and repair
- Energy conservation/weatherizing/air-conditioning
- Hazardous materials abatement
- Accessibility improvements

FEMA 395 provides five matrices that show possible combinations of seismic improvement measures with typical work categories. Table 4-3 represents a typical matrix from FEMA 395 and shows possible seismic improvements relating to roof maintenance and repair.

Table 4-3: Roofing maintenance and repair/re-roofing

Rank*	Level of Seismicity			Building Structural Element	Structural Subsystem	Seismic Performance Improvement	Wood	Masonry[1]		Concrete		Steel	
	L	M	H					Unreinforced Masonry	Reinforced Masonry	Wood Diaphragm	Concrete Diaphragm	Wood Diaphragm	Concrete Diaphragm
Nonstructural													
1	✔	✔	✔	n/a	n/a	Bracing of Parapets, Gables, Ornamentation, and Appendages		■		■	■	■	■
2	✔	✔	✔	n/a	n/a	Anchorage of Canopies at Exits	■	■	■	■	■	■	■
3		✔	✔	n/a	n/a	Bracing or Removal of Chimneys	■	■	■	■	■	■	■
10		✔	✔	n/a	n/a	Anchorage and Detailing of Rooftop Equipment	■	■	■	■	■	■	■
Structural													
n/a		✔	✔	All Elements		Load Path and Collectors	❑	❑	❑	❑	❑	❑	❑
n/a		✔	✔	Horizontal Elements	Diaphragms	Attachment and Strengthening at Boundaries	■	■	■	■	❑	■	❑
n/a		✔	✔	Horizontal Elements	Diaphragms	Strength/Stiffness	■	■	■	■	❑	■	❑
n/a		✔	✔	Horizontal Elements	Diaphragms	Strengthening at Openings	❑	❑	❑	❑		❑	
n/a		✔	✔	Horizontal Elements	Diaphragms	Strengthening at Re-entrant Corners	❑	❑	❑	❑	❑	❑	❑
n/a		✔	✔	Horizontal Elements	Diaphragms	Topping Slab for Precast Concrete		❑	❑		❑		❑
n/a	✔	✔	✔	Vertical Elements	Load Path	Lateral Resisting System to Diaphragm Connection		■	■	■	❍	■	❍
n/a	✔	✔	✔	Vertical Elements		Out-of-Plane Anchorage of Concrete or Masonry Wall		■	■	■	❑	■	❑

* Nonstructural improvements are ranked on the basis of engineering judgment of their relative impact on improving life safety in schools.

Structural improvements are not ranked, but are organized by structural element and subsystem.

- ■ Work that may be included in the building rehabilitation/maintenance/repair project using little or no engineering.
- ❑ Work requiring detailed engineering design to be included in the project.
- ❍ Work requiring detailed engineering design and evaluation of sequencing requirements. Work could redistribute loads, overstressing some elements.

Note 1: Masonry buildings with a concrete roof deck should use the concrete building, concrete diaphragm for integration opportunities.

n/a = Not Applicable.

Incremental seismic retrofit is an effective, affordable, and non-disruptive strategy to mitigate seismic risk. At the lower levels of protection, some effective construction measures (e.g., bracing nonstructural bookcases and filing cabinets, and anchoring key desktop equipment such as computers) can be implemented by school district maintenance personnel. As a last resort in cases of extreme risk and badly antiquated school buildings, demolition is the only solution.

4.7 The School as a Post-Earthquake Shelter

In the aftermath of any damaging earthquake, there is an immediate need of shelter for people who have been displaced from their homes. In earthquake-prone regions, school sites are often used to provide immediate shelter (on the day or night of the earthquake). Schools are conveniently located in every community, with easy and known access to the local population that they serve. They also have suitable spaces (e.g., gymnasiums or multiuse rooms) in which large numbers of people can be accommodated for a few days. Food service is often available, as is ample space for assembly, processing, and delivery of goods and equipment. Because schools are public property, the costs using the facilities for a few weeks are minimal. Also, particularly in California, where schools are subject to the Field Act, schools are well constructed and among the most likely of all the community's buildings to survive intact and in a usable condition.

No specific design decisions are necessary for this use, nor is it necessary to stockpile emergency supplies. The exact circumstances of the event and the number and types of people to be accommodated will determine the supplies that are necessary. Experience has shown that local and even regional manufacturers and suppliers are very effective in providing services after an event. Following the 1983 Coalinga earthquake, temporary shelter was provided in the high school gymnasium. A regional beer canning plant substituted drinking water for beer for a few shifts and rapidly delivered the chilled cans to the site.

The school district and the local emergency services agency should plan for an earthquake event. This includes determining what spaces will be available and how many people can be accommodated, signing a pre-contract with a local engineer or architect for immediate post-earthquake inspection to determine safety, examining strategies for continued operation in the event some spaces are occupied by refugees, and determining a means for providing food and sanitary supplies.

Possible use of school buildings as a safe haven for the community in the event of chemical, biological, radiological, or explosive attack involves complex design and construction issues. This use of school property is discussed in FEMA 428, *Primer to Design Safe School Projects in Case of Terrorist Attacks,* Chapter 6 (2003b), and FEMA 453, *Design Guidance for Shelters and Safe Rooms (*2006).

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4.9 Glossary of Earthquake Terms

Acceleration. Rate of change of velocity with time.

Amplification. A relative increase in ground motion between one type of soil and another or an increase in building response as a result of resonance.

Amplitude. Maximum deviation from mean of the center line of a wave.

Architectural Components. Components such as exterior cladding, ceilings, partitions, and finishes.

Building. Any structure that could be used for the shelter of human occupants.

Component (also Element). Part of an architectural, structural, electrical, or mechanical system.

Configuration. The size, shape, and geometrical proportions of a building.

Connection. A means by which different materials or components are joined to each other.

Damage. Any physical destruction caused by earthquakes.

Deflection. The state of being turned aside from a straight line, generally used in the horizontal sense; see also "Drift."

Design Earthquake. In the International Building Code (IBC), the earthquake that produces ground motions at a site that are two/thirds those of the "Maximum Considered Earthquake."

Design Ground Motion. See "Design Earthquake."

Diaphragm. A horizontal or nearly horizontal structural element designed to transmit lateral forces to the vertical elements of the seismic force resisting system.

Drift. Vertical deflection of a building or structure caused by lateral forces; see also "Story Drift."

Ductility. Property of some materials, such as steel, to distort when subjected to forces while still retaining considerable strength.

Earthquake. A sudden motion or vibration in the earth caused by the abrupt release of energy in the earth's lithosphere.

Effective Peak Acceleration and Effective Peak Velocity Related Acceleration. Coefficients shown on maps in the IBC for determining prescribed seismic forces.

Elastic. Capable of recovering size and shape after deformation.

Epicenter. A point on the earth's surface that is directly above the focus of an earthquake.

Exceedance Probability. The probability that a specified level of ground motion or specified social or economic consequences of earthquakes will be exceeded at a site or in a region during a specified exposure time.

Exposure. The potential economic loss to all or certain subsets of the built environment as a result of one or more earthquakes in an area; this term usually refers to the insured value of structures carried by one or more insurers.

Fault. A fracture in the earth's crust accompanied by displacement of one side of the fracture with respect to the other in a direction parallel to the fracture.

Focus. The location of a fault break where an earthquake originates; also termed "Hypocenter."

Force. Agency or influence that tries to deform an object or overcome its resistance to motion.

Frame, Braced. Diagonal members connecting components of a structural frame to resist lateral forces.

Frame, Space. A structural system composed of interconnected members, other than bearing walls, that is capable of supporting vertical loads and that also may provide resistance to seismic forces.

Frame System, Building. A structural system with an essentially complete space frame providing support for vertical loads; seismic forces are resisted by shear walls or braced frames.

Frame System, Moment. A frame in which members and joints are capable of resisting lateral forces by flexure as well as along the axis of the members; varying levels of resistance are provided by ordinary, intermediate, and special moment frames as defined in the IBC with special frames providing the most resistance.

"g". The acceleration due to gravity or 32 feet per second.

Ground Failure. Physical changes to the ground surface produced by an earthquake, such as lateral spreading, landslides, or liquefaction.

Hypocenter. See "Focus."

Intensity. The apparent effect that an earthquake produces at a given location; in the United States, intensity generally is measured by the modified Mercalli intensity scale.

Irregular. Deviation of a building configuration from a simple symmetrical shape.

Joint. Location of connections between structural or nonstructural members and components.

Liquefaction. The conversion of a solid into a liquid by heat, pressure, or violent motion; sometimes occurs to the ground in earthquakes.

Loss. Any adverse economic or social consequences caused by earthquakes.

Mass. A constant quantity or aggregate of matter; the inertia or sluggishness that an object, when frictionlessly mounted, exhibits in response to any effort made to start it or stop it or to change in any way its state of motion.

Maximum Considered Earthquake Ground Motion. The most severe earthquake effects considered in the IBC. These are represented by the mapped spectral response accelerations at short and long periods, obtained from maps in the IBC, adjusted for Site Class effects using site coefficients.

Mercalli Scale (or Index). A measure of earthquake intensity named after Giuseppe Mercalli, an Italian priest and geologist.

Nonbuilding Structure. A structure, other than a building, designed and constructed in a manner similar to buildings and having a basic lateral and vertical seismic-force-resisting system conforming to a type included in Chapter 14 of the IBC.

Occupancy Importance Factor. A factor, between 1.0–1.5, assigned to each structure according to its Seismic Occupancy Category.

Partition. See "Wall, Nonbearing."

Period. The elapsed time (generally in seconds) of a single cycle of a vibratory motion or oscillation; the inverse of frequency.

P-Wave. The primary or fastest waves traveling away from a fault rupture through the earth's crust and consisting of a series of compressions and dilations of the ground material.

Quality Assurance Plan. A detailed written procedure that establishes the systems and components subject to special inspection and testing.

Recurrence Interval. See "Return Period."

Resonance. The amplification of a vibratory motion occurring when the period of an impulse or periodic stimulus coincides with the period of the oscillating body.

Return Period. The time period in years in which the probability is 63 percent that an earthquake of a certain magnitude will recur.

Richter Magnitude (or Scale). A logarithmic scale expressing the magnitude of a seismic (earthquake) disturbance in terms of the maximum amplitude of the seismic waves at a standard distance from their focus; named after its creator, the American seismologist Charles R. Richter.

Rigidity. Relative stiffness of a structure or element; in numerical terms, equal to the reciprocal of displacement caused by unit force.

Seismic. Of, subject to, or caused by an earthquake or an earth vibration.

Seismic Event. The abrupt release of energy in the earth's lithosphere causing an earth vibration; an earthquake.

Seismic Force Resisting System. The part of the structural system that is designed to provide required resistance to prescribed seismic forces.

Seismic Forces. The actual forces created by earthquake motion; assumed forces prescribed in the IBC that are used in the seismic design of a building and its components.

Seismic Hazard. Any physical phenomenon such as ground shaking or ground failure associated with an earthquake that may produce adverse effects on the built environment and human activities; also the probability of earthquakes of defined magnitude or intensity affecting a given location.

Seismic Occupancy Category. A classification assigned to a structure based on its occupancy and use as defined in the IBC.

Seismic Risk. The probability that the social or economic consequences of an earthquake will equal or exceed specified values at a site during a specified exposure time; in general, seismic risk is vulnerability multiplied by the seismic hazard.

Seismic Waves. See "Waves, Seismic."

Seismic Zone. Generally, areas defined on a map within which seismic design requirements are constant; in the IBC, seismic zones are defined both by contour lines and county boundaries.

Shear. A force that acts by attempting to cause the fibers or planes of an object to slide over one another.

Shear Wall. See "Wall, Shear."

Speed. Rate of change of distance traveled with time irrespective of direction.

Stiffness. Resistance to deflection or drift of a structural component or system.

Story Drift. Vertical deflection of a single story of a building caused by lateral forces.

Strain. Deformation of a material per unit of the original dimension.

Strength. The capability of a material or structural member to resist or withstand applied forces.

Stress. Applied load per unit area or internal resistance within a material that opposes a force's attempts to deform it.

S-Wave. Shear or secondary wave produced essentially by the shearing or tearing motions of earthquakes at right angles to the direction of wave propagation.

System. An assembly of components or elements, such as a structural system, designed to perform a specific function.

Torsion. The twisting of a structural member about its longitudinal axis.

Velocity. Rate of change of distance traveled with time in a given direction; in earthquakes, it usually refers to seismic waves and is expressed in inches or centimeters per second.

Vulnerability. The degree of loss to a given element at risk, or set of such elements, resulting from an earthquake of a given intensity or magnitude; expressed in a scale ranging from no damage to total loss; a measure of the probability of damage to a structure or a number of structures.

Wall, Bearing. An interior or exterior wall providing support for vertical loads.

Wall, Nonbearing. An interior or exterior wall that does not provide support for vertical loads other than its own weight as permitted by the building code; see also "Partition."

Wall, Shear. A wall, bearing or nonbearing, designed to resist lateral forces parallel to the plane of the wall.

Wall System, Bearing. A structural system with bearing walls providing support for all or major portions of the vertical loads; seismic resistance may be provided by shear walls or braced frames.

Waves, Seismic. Vibrations in the form of waves created in the earth by an earthquake.

Weight. Name given to the mutual gravitational force between the earth and an object under consideration; varies depending on location of the object at the surface of the earth.