2.1 INTRODUCTION

This chapter examines potential earthquake damage to hospitals and how these facilities can most efficiently improve their expected performance. An explanation of the nature and probability of earthquakes is provided, together with procedures for determining the approximate earthquake threat to specific locations. Typical seismic damages and the possible resulting effects on building function or risk to occupants are described and related to standard damage states currently used in performance-based earthquake engineering design.

The enhanced performance normally expected from hospitals is discussed, specifically as it relates to protection of inpatients and provision of care for the injured and other outpatients. Since many older buildings may not have been designed for seismic forces, particularly for enhanced performance, estimation of the actual expected performance is critical for adequate emergency planning.

The case studies in this chapter illustrate the performance of hospital buildings in earthquakes, and look at the enhancements made in the existing seismic protection of the structural and nonstructural systems to improve performance. The chapter ends with a review of best practices in seismic design and seismic retrofit of hospital facilities.

2.1.1 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.

Firstly, science can now identify where earthquakes are likely to occur, at what magnitude, and determine the relative likelihood of a range of ground shaking levels. This information is readily available to architects, engineers, code writers, planners, and to the general public. Secondly, seismic researchers and structural engineers with experience in seismic design have sufficient understanding of the effects of earthquake shaking on buildings to create designs that will be safe for various intensities of shaking. Modern building codes incorporate all of this information and require buildings to have seismic designs appropriate for each region.

However, earthquakes are complex phenomena, and the exact nature of ground shaking, and a building's response to that shaking, are still shrouded in considerable uncertainty. The primary intent of the seismic provisions of building codes is to provide buildings that will be safe in the expected earthquake. Current buildings designed to modern codes are extremely unlikely to sustain serious structural damage or partial collapse in a design earthquake. However, subtle changes in shaking from site to site, the wide range of building types and configurations, and the variation in skill and thoroughness with which any one building is designed and constructed can result in a wide range of damage levels in any given earthquake. Perhaps more importantly, many older hospital buildings were designed and built without seismic design features, or at best outdated ones. These buildings cannot be expected to perform well enough to serve their intended roles after an earthquake event. Lastly, it is now well known that the nonstructural systems of essential buildings are extremely important in maintaining post-earthquake functionality. Until very recently these systems, in general, have not been designed and installed with adequate seismic protection.

2.1.2 EARTHQUAKE EFFECTS

Fractures and movements within the earth's crust generate earthquake ground motion by sending waves through the rocks and soil outward from the source. Most commonly, these sources are known faults, defined as cracks or weakened planes in the earth's crust most likely to "break" as a result of global tectonic movements. The propagation of the waves through the crust produces movement of the earth's surface. Any one location on the surface will move in every direction simultaneously, back and forth, side to side, and up and down, creating the shaking effect that is both strange and frightening. The shaking effect, or *seismic ground motion,* is felt in all directions from the *epicenter*—the location where the fracture started—and diminishes with distance from the epicenter. Buildings, bridges, transmission towers, and other structures supported by, and attached to, the ground will also be shaken. If the intensity of shaking is high, most structures will sustain some damage. The criteria used to determine the capacity of the ground motion to inflict damage on the built environment are somewhat intuitive: large displacements of the ground (3 feet versus 3 inches), rapid changes in the movement (measured in units of *acceleration*), or the duration of shaking.

Although seismic ground motion is most often identified with earthquakes, it is not the only phenomenon that causes damage. Earthquakes involve movements of large portions of the earth's crust, and the resulting shaking can produce other geologic hazards:

Surface Fault Rupture affects a small strip at the ground when the movement on a fault deep within the earth breaks through to the surface. The relative displacement of the ground on each side of the rupture may be several feet or more, and structures straddling this zone are likely to be severely damaged.

Liquefaction occurs when the behavior of loose granular soils and sand in the presence of water changes temporarily from that of a solid to that of a liquid material when subjected to ground shaking. This condition occurs mainly at sites located near rivers, lakes, and bays.

Landslides occur when the top layers of soil and rock slip on sloping ground, triggered by earthquake ground motion.

Tsunamis are earthquake-caused 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.

Seiches are waves similar to tsunamis. They can be triggered by earthquakes and generated by sloshing in closed lakes or bays; they have the potential to cause serious damage, although such occurrences are very rare.

2.1.3 MEASURING EARTHQUAKE EFFECTS

Earthquakes vary in many respects, but the resulting shaking depends mainly on the magnitude of the earthquake and the distance from the epicenter. The potential risk to manmade structures is determined on the basis of frequency of occurrence of earthquakes at a given site, and measurements of a number of physical characteristics of ground shaking. The following section discusses the measurements used for this purpose, and their role as damage parameters.

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 approximately by 31 for a unit increase in Ritcher 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.

Among scientists, Richter Magnitude has been replaced by 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 has been set to produce 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 damage is often measured by intensity scales, and the most 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.

> It is important to understand that 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.

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 the ground motion. Extensive networks of instruments are now employed on the ground and in manmade 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, and the possibility of liquefaction and landslides. Tsunamis and seiches are normally not caused by the traveling seismic waves, but by large, single movements of land under water as part of the fault movement or resulting large landslides.

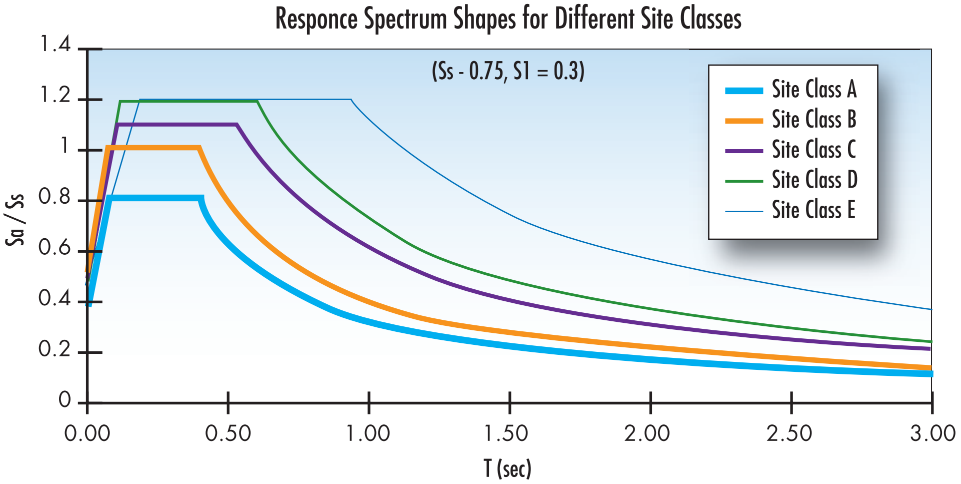
2.1.3.1 Measuring Seismic Ground Motion

Acceleration is a measure of velocity changes over time, and is commonly experienced when our heads snap back when a car starts off rapidly. Similarly, acceleration causes a building to "snap back" as a result of sudden large ground movement. This movement within the building or other structure, which becomes very complex when caused by 20 seconds or more of ongoing, rapidly changing accelerations, is what causes direct shaking damage. Consequently, it is common to describe earthquake motion using the largest acceleration that occurred during the event, or *peak ground acceleration* (PGA).

Although PGA is useful as a simple way to measure and compare ground motions, it is not the most comprehensive one. From studies of ground motions and structural responses to ground motions, engineers and researchers have developed parameters that consider the characteristics of the entire motion, rather than the one instant when the PGA occurs. This characterization of the ground motion is called a *response spectrum* and measures the extent of shaking different structures will experience, based on their natural period of vibration, when subjected to a given ground motion (see section 2.2.2.1). The maximum response to a specific ground motion of a structure with a given period is called the *spectral ordinate*. The full response spectrum simply represents the suite of spectral ordinates for a wide range of structures—from periods of about 0.2 seconds (short, very stiff buildings) to periods of about 4.0 seconds (tall, very flexible buildings).

Response spectra can be calculated for the entire database of recorded ground motions, and trends analyzed. For example, it has been determined that the response spectrum for most earthquake shaking has a similar shape, and that this shape has subtle changes based on the soil on which it was recorded. Figure 2-1 shows the typical shape of earthquake ground motion spectra and the variations that will be caused, on average, by different site soils. Like PGA, higher spectral ordinates typically mean more intense and potentially damaging motions. By studying the location of potential earthquake sources and the probability of them generating an earthquake in any given time period, scientists can develop a response spectrum for earthquake shaking likely to occur at that site. This has been done by the U.S. Geological Survey (USGS) for the entire United States, and is the basis for seismic design requirements in building codes. This information is presented on maps. For simplicity, only two spectral ordinates are mapped, for periods of 0.2 second and 1.0 second. Examples of these maps are shown in Figure 2-2. Rules in the building codes allow engineers to calculate the appropriate spectral ordinate for all periods, as shown in Figure 2-1, based on the mapped values. Site classes in the figure are also defined in the building codes, Class A being hard rock, and Class E being a very soft site with potential soil failure.

Figure 2-1: Representative shapes of building code (or design) response spectra for different soils



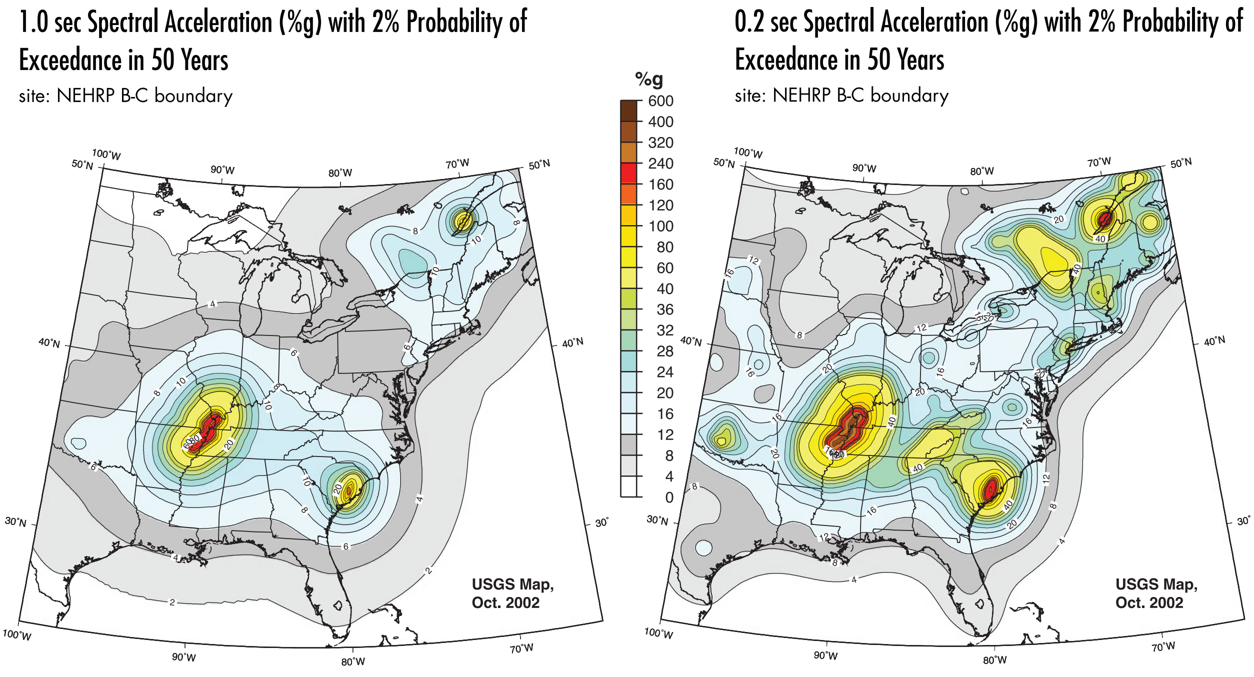


Figure 2-2: Example of national seismic hazard maps

2.1.3.2 Measuring Potential for Liquefaction

Soils that are loose, not well graded, and saturated with water are prone to liquefaction. These conditions often occur near waterways, but not always. In addition to the soil type, the probability of liquefaction also depends on the depth from the surface to the layer, and the intensity of ground motion. Further, the results of liquefaction can vary from a small, uniform settlement across a site, to loss of foundation bearing, resulting in extreme 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 identification of liquefaction potential in the 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 will also be estimated. Small settlements may be tolerated without mitigation. Larger potential settlements can be prevented by site remediation measures, if economically justified. In some cases of potential massive liquefaction and lateral spreading, using the site for structures 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.

2.1.3.3 Measuring Potential for Landslide

The shaking from earthquakes can also 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, it is possible and cost effective to stabilize small areas at risk of potential landslides. 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. Sites within these susceptible zones require site-specific investigation.

2.1.3.4 Measuring Potential for Tsunami and Seiche

Researchers have studied tsunamis and seiches for many years, but the tragic tsunami in the Indian Ocean in December 2004 highlighted the need for better measurement of the threat in terms of magnitude and location. Obviously, only sites near large bodies of water are susceptible, and normally at elevations 50 feet or less above the water surface, although bays and narrow canyons can amplify the wave height. Although similar to storm surge, the height and the potential velocity of a tsunami wave represent a separate risk and must be mapped separately. In addition to dependence on local conditions, quantification of the risk from tsunamis and seiches is made more difficult because not every earthquake generates such a wave. Studies are required that consider the individual characteristics of the site and the facility, to establish the risk and identify possible mitigating measures.

2.1.4 EARTHQUAKES: A NATIONAL PROBLEM

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, MO, in 1811 and 1812. In the International Building Code (IBC), 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 2-3, 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, Alaska, Oregon, Washington, and Utah—is much greater than it is in the East, Midwest, or South. However, the New Madrid and Charleston, SC, regions are subject to potentially more severe earthquakes, although with a lower probability, than most regions of the western United States. According to the IBC design maps and the USGS hazard maps upon which they are based, other locations should also plan for intermediate ground motions.

The U.S. Congress recognized earthquakes as a national problem by passing legislation authorizing the National Earthquake Hazards Reduction Program (NEHRP) in 1977. NEHRP has since supported numerous research and hazard mitigation efforts.

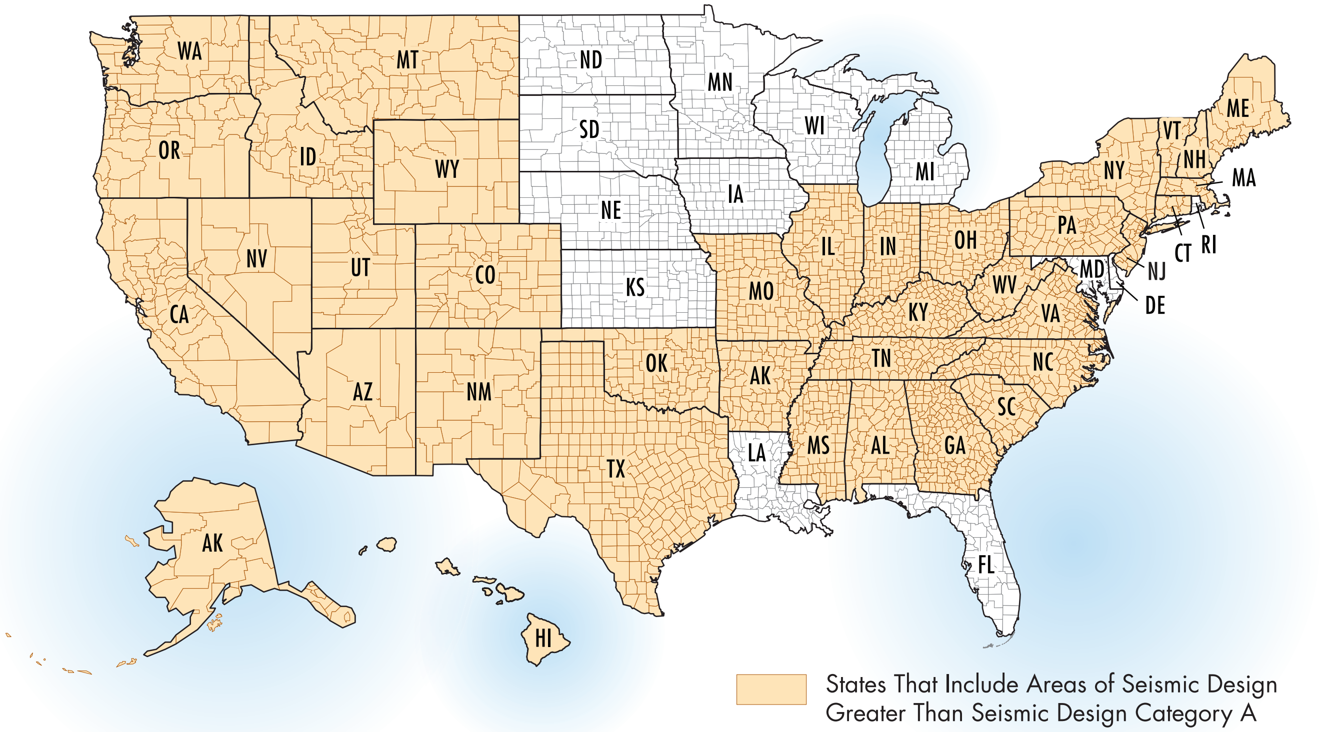


Figure 2-3: States with seismic risk

Records show that some seismic zones in the United States experience potentially damaging 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. With current knowledge, there is no practical alternative for those responsible for healthcare facilities located in earthquake-prone regions but to assume that the design earthquake, specified in the building code for the local area, could occur at any time, and that appropriate planning for that event should be undertaken.

Moderate and even very large earthquakes are inevitable, although very infrequent, in some areas of normally low seismicity. Consequently, in these regions, most buildings in the past were not designed to deal with an earthquake threat; they are extremely vulnerable. In other places, however, the earthquake threat is quite familiar. Medical facilities in many areas of California and Alaska will be shaken by an earthquake, perhaps two or three times a year, and some level of "earthquake-resistant" design has been accepted as a way of life since the early 20th century.

Nationally, the areas where earthquakes are likely to occur have been identified, and scientists have a broad statistical knowledge of the potential magnitude of these earthquakes and the likelihood of their occurrence. However, it is not yet possible to predict the near-term occurrence of a damaging earthquake. Therefore, it makes sense to take the minimum precautionary measures and conform to local seismic building code requirements for new buildings. U.S. seismic building code provisions focus on requiring the minimum measures necessary to prevent building collapse, because most lives are lost in earthquakes as a result of building collapse. The code provisions for essential buildings intended to remain functional after a major earthquake have not yet been thoroughly tested.

If a healthcare facility or community desires to obtain more detailed information on the seismic hazard than is shown on the code maps, or if the location does not enforce a seismic code but there is concern about seismicity, the USGS Web page at www.USGS.gov, Earthquake Hazards Program, is an excellent resource. The USGS provides more detailed earthquake hazard maps for general regions such as the Western, Central, and Eastern United States. Local building or planning departments, fire departments, or other local emergency management agencies should be consulted for the availability of mapping for liquefaction, landslide, tsunami, and seiche. For even more localized information, the USGS provides 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 referring to the Seismic Hazard listings on the USGS Web page, and opening “Hazards by Latitude and Longitude,” or “Hazards by Zip Code.” These listings show information on the expected maximum shaking that is estimated for the location. The information and terminology are quite technical, and may need to be interpreted by qualified staff at the responsible local code office, a structural engineer, or other knowledgeable seismic professional.

2.2 SEISMIC BUILDING DESIGN

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.

More basic information about seismic design of buildings can be found in FEMA 454, *Designing for Earthquakes* (FEMA, 2007)

Building design 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 International Code Council (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 International Building Code (IBC; ICC, 2000) and was based on the NERHP Provisions. The IBC now references ASCE 7, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2005) 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), while most have adopted or are preparing to adopt the IBC. In this document, code references are to the IBC Code and to its seismic standard, ASCE 7.

Seismic code requirements cover:

- 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

Current codes and seismic design practices have evolved rapidly as the result of intensive research and development in the United States and elsewhere during the second half of the twentieth century. The advances in the development of the code during this period are illustrated by the fact that the 1961 Earthquake Provisions of the Uniform Building Code took seven pages, eight equations, and one map of the United States. The current provisions in the IBC cover about 80 pages, 96 equations, and 22 maps of the United States.

2.2.1 THE EQUIVALENT LATERAL FORCE (ELF) ANALYSIS METHODOLOGY

Of the 96 equations in the IBC, the ***Equivalent Lateral Force*** (ELF) equation is the key element in the most-used code methodology for determining seismic forces. This force is termed the *equivalent* force because it represents, in greatly simplified and reduced form, the complex to-and-fro, multidirectional earthquake forces with a single static force applied at the base of the building. Once this force is determined, all the structural components of the building (walls, beams, columns, etc.) can be analyzed through other code-prescribed procedures to determine what proportion of this force must be assigned to each of them. This general methodology is characteristic of all seismic codes throughout the world.

The ELF equation is derived from Newton's Second Law of Motion, which defines inertial force as the product of mass and acceleration. The ELF equation replaces Newton's acceleration with an acceleration coefficient that incorporates some of the other factors necessary to represent more accurately the acceleration of the mass of the building, which is generally higher than the ground acceleration. To determine this coefficient, the code provides another equation and additional coefficients that encompass most of the characteristics that affect the building's seismic performance. The ELF procedure is used for the great majority of buildings. Buildings of unusual form, or with other special features or site conditions, may be required to use more complex analytical methods.

Hospitals are classified in the building code as Occupancy Category IV—"essential for post-earthquake response and recovery"—and therefore have special design requirements intended to improve performance. Designers should use 50 percent greater earthquake forces for design of Category IV buildings than for normal buildings, which will provide an additional safety factor and reduce potential structural damage. In addition, design rules for Category IV buildings allow less movement between floors during earthquake shaking, reducing nonstructural damage to windows, walls, stairways, and elevators. Lastly, these buildings are required to incorporate more complete and stronger anchorage and bracing of nonstructural components and systems than normal buildings.

2.2.1.1 Acceleration

The most common and widespread cause of earthquake damage is ground shaking caused by the seismic waves that radiate out from the focus of the earthquake. The waves begin like ripples in a still pond when a pebble is thrown into it, but rapidly become more complex. There are four main wave types, of which "body" waves, within the earth, are most important for seismic design purposes. First to arrive at a given site is the *P* or *Primary* wave: this wave successively pushes and pulls the ground along the wave front as it moves forward. The effect is felt as a sharp punch—it feels as if a truck has hit the building. The P wave is followed by *S*, the *secondary* or *shear* wave, which is a lateral motion, back and forth, but perpendicular to the wave front.

The nature of the waves and their interactions are such that actual movement of the ground will be random: predominantly horizontal, often with considerable directional emphasis and sometimes with a considerable vertical component. Because of the random nature of the shaking, structures must be designed on the assumption that earthquake forces will come from all directions in very rapid succession, often fractions of a second apart.

The *inertial* forces inside the building, generated by ground shaking, depend on the building's mass and acceleration.[1] The seismic code provides 22 maps that provide values for *spectral acceleration* (the acceleration to be experienced by structures of different periods). These values, with some

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[1] Acceleration is the change of velocity (or speed) in a certain direction over time, and is a function of the earthquake characteristics: acceleration is measured in "g," which is the acceleration of a falling body due to gravity.

additional operations, are inserted into the ELF equation and provide the acceleration value and eventually the base shear value for the structure.

Figure 2-4 shows an example of a portion of map from the IBC, showing contour lines of spectral acceleration. The numbers are the acceleration values to be used in the equation, based on the project location.

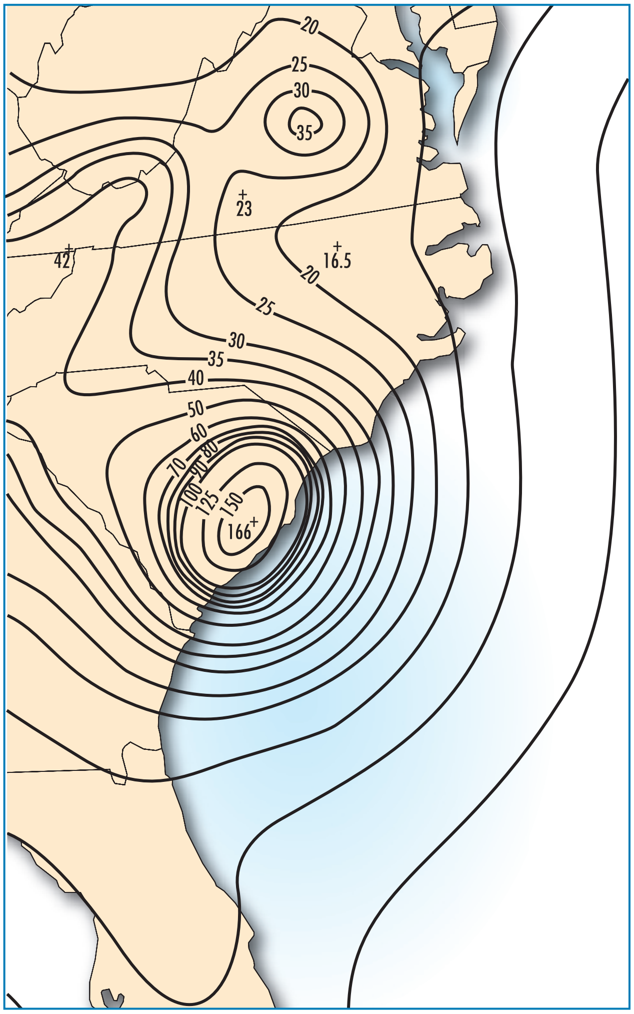


Figure 2-4:
Portion of an earthquake ground motion map used in the seismic code

2.2.1.2 Amplification and Soil Type

As seismic vibrations propagate towards the earth's surface, they may be amplified depending on the intensity of the shaking, the nature of the rock and, above all, by the surface soil type and depth. Earthquake shaking tends to be more severe on soft ground than in stiff soil or rock, which produces greater building damage in areas of soft soils. This amplification is most pronounced for shaking at longer periods and may not be significant at short periods. Studies after the 1989 Loma Prieta Earthquake showed that shaking in the soft ground was 2.5 to 3.5 times that of shaking in rock.

The ELF equation deals with soil amplification by introducing a soil type coefficient in the process of determining the acceleration coefficient. The code defines six soil types, ranging from hard rock to very soft soil, and provides varying coefficients that relate soil type to building period, because the amplification is also modified by building period.

2.2.1.3 Building Period

All objects have a natural or fundamental period. This is the rate at which they will vibrate if they are given a horizontal push. When a building begins to vibrate as a result of ground motion, it will tend to sway back and forth at its natural period (Figure 2-5).

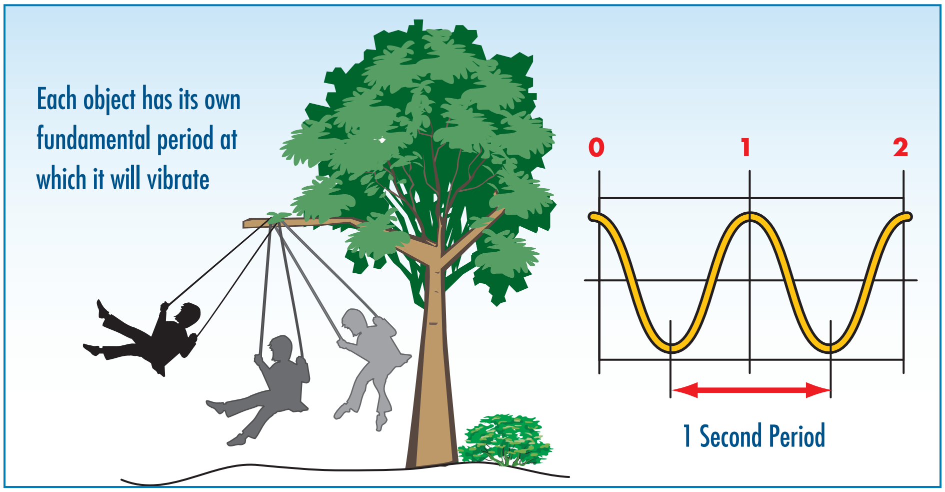
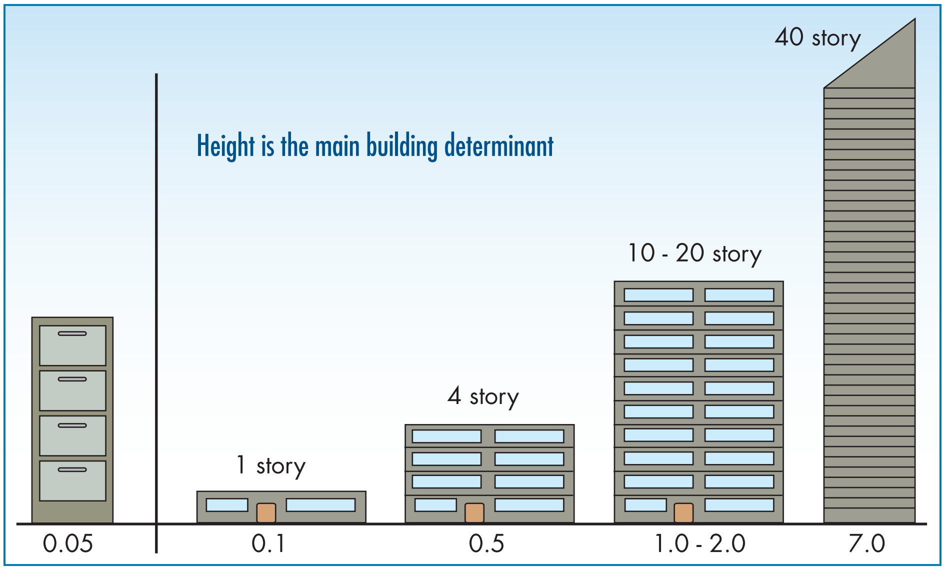


Figure 2-5: Natural period

More complex structures will oscillate at several different periods, the longest one (greatest amount of time to complete one cycle) often being called the fundamental period. The fundamental periods of structures vary from about 0.05 second for a piece of equipment anchored to the ground to about 0.10 second for a one-story building. Taller buildings between 10 to 20 stories will oscillate in the fundamental mode at periods of between 1 and 2 seconds. The building height is normally the main determinant of building period (Figure 2-6), although more technically, the period is based on the mass and stiffness characteristics of the structure.

Acceleration within the building is influenced by its period, and diminishes as the period increases (the motion changes from abrupt shocks to a gentler swaying) as explained in Section 2.1.3.1.

Figure 2-6:
Period (in seconds) and building height



2.2.2 CRITICAL BUILDING CHARACTERISTICS

2.2.2.1 Period and Resonance

As described in Section 2.1.3.1, the natural period of a building measures the time it takes to vibrate one full cycle. This basic characteristic of the structure will determine to a large degree how a building responds to earthquake ground shaking. Short, stiff buildings will have a short period and will shake with sharp, jerky movements (high accelerations), which will tend to cause contents such as equipment or furniture to slide around and possibly overturn. Taller, more flexible buildings will have longer periods and “shake” slower and smoother, but with larger “to and fro” movement than short buildings. The larger movements may create more relative displacement between floors and cause damage to walls, stairs, and elevators connected to multiple floors. In rare cases, buildings with periods over about 1.5 seconds on soft sites may match the vibration patterns of the site and resonate, causing large amplifications of the motions within the buildings.

2.2.2.2 Damping

A pendulum—or a child’s swing—is a very effective oscillator, and will continue to swing for many minutes after a push, although the extent of the swinging, or amplitude, will gradually diminish. Buildings and other objects do not oscillate as effectively because the vibration is damped, or reduced. The extent of damping in a building depends on the structural system, materials of construction; how the structural components are connected; and on the type and quantity of architectural elements such as partitions, ceilings, and exterior walls. A high level of damping, in which the vibration of the building will rapidly diminish, is a desirable feature.

2.2.2.3 Nonlinear Behavior

It is generally not cost-effective to design buildings to be completely undamaged in strong earthquake motion. Building codes require designers to base their designs on forces that are not as great as the shaking can generate, on the assumption that the building's structure will deform and absorb part of the energy, thus limiting the forces that can be generated. These severe deformations represent "nonlinear behavior" and structural damage, ranging from minor (that can be left alone) to more serious (that will require repair). The building code has been "tuned" over the last 5 or 6 decades by adjusting code requirements according to the results of detailed observations of the behavior of buildings. Nonlinear deformations are expected in hospitals and other critical buildings, but to a lesser extent than normal buildings. The intent is to minimize structural damage to enable the buildings to remain occupied after the shaking.

Some materials and structural systems can accept nonlinear behavior better than others and are thus considered superior seismic systems.

2.2.2.4 Ductility

Ductility is the characteristic of certain materials—steel in particular—that fail only after considerable distortion or deformation has occurred. This is why it is more difficult to break a metal spoon by bending it than one made of plastic. The metal object will remain whole, though distorted, while the plastic spoon will break suddenly without warning (Figure 2-7). This property of materials is used to ensure that a building may adequately resist more than its design ground motion.

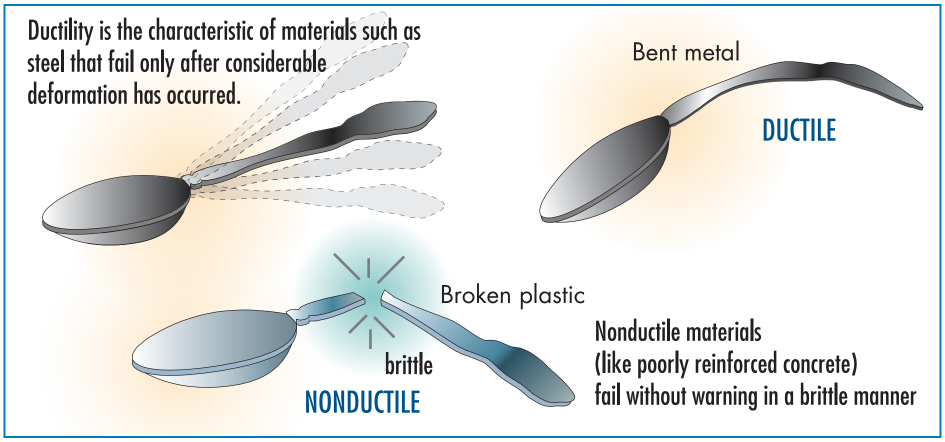


Figure 2-7: Ductility

The deformation of metal, even in the spoon, absorbs energy and defers absolute failure of the structure. Brittle materials, such as unreinforced masonry or ceramic tile, fail suddenly with a minimum of distortion. Ductility is an important characteristic of the structural system. Thus, buildings with appropriate seismic designs are either designed so that the materials and connections will distort but not break, in case they are subjected to forces higher than those required by the code, or they are designed for very large forces. Some structural materials, like masonry and concrete, are brittle on their own, but when properly combined with steel reinforcing bars, can exhibit high ductility. This characteristic of the structural system is also considered in the ELF methodology.

2.2.2.5 Strength and Stiffness

Strength and stiffness are the two of most important seismic characteristics of any structure. Two structural beams may be equally strong (or safe) in supporting a load, but may vary in their stiffness—the extent to which they bend or deflect in doing so. Stiffness is a material property but is also dependent on shape. For vertical forces this is usually the only aspect of stiffness that is of concern. When floor joists are designed for a house, for instance, their deflection rather than strength is what often dictates their size. Typically, an unacceptable amount of deflection will occur well before the members are stressed to the point at which they break.

In seismic design, there is another very important aspect to stiffness. The problem of determining the overall lateral force on the building by multiplying its weight by its acceleration has already been discussed. But how is this force distributed among the various structural members so that the engineer can design each one appropriately? Relative stiffness enters into this issue because the applied forces are “attracted to” and concentrated at the stiffer elements of the structure—in engineering terms, the forces are distributed in proportion to the *stiffness* of the *resisting elements*. Mathematically, the stiffness of a structural member varies approximately as the cube of its length: thus one column that is half the length of another will be eight times stiffer (2^3) and will be subject to eight times the horizontal load of the long column. This concept has serious implications for structures with lateral members of varying lengths, and in designing such a structure the engineer tries to equalize the stiffness of the resisting elements so that no one member or small group of members takes a disproportionate amount of the overall load (Figure 2-8).

Short columns represent a problem that emphasizes the need for good structural seismic design. Columns in this category may not even be part of the lateral force resisting system. Nevertheless, if the structural and nonstructural components create such a condition, these columns are likely to be severely damaged during strong ground shaking.

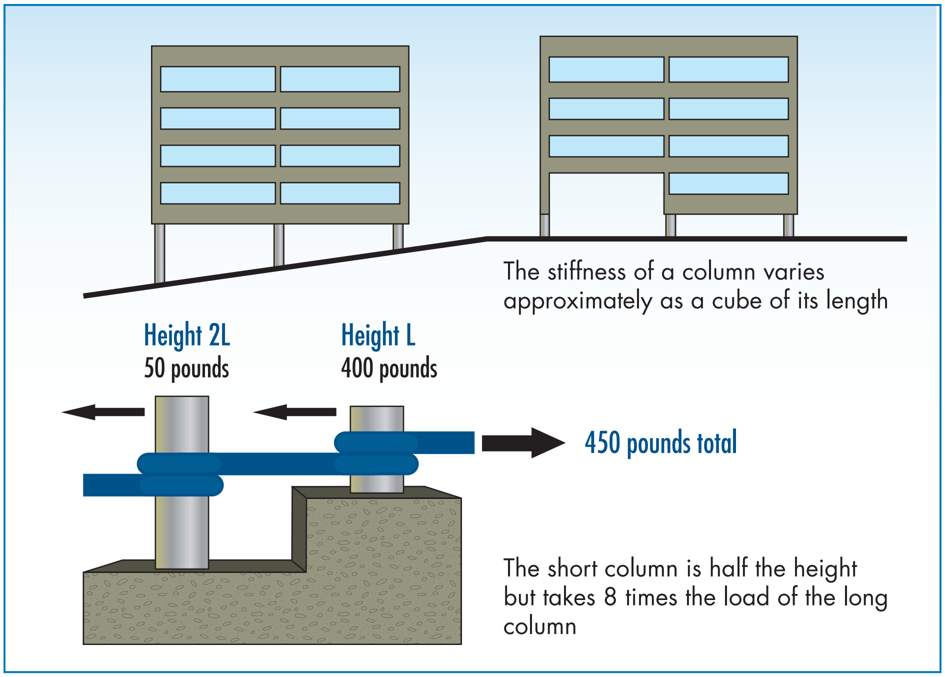
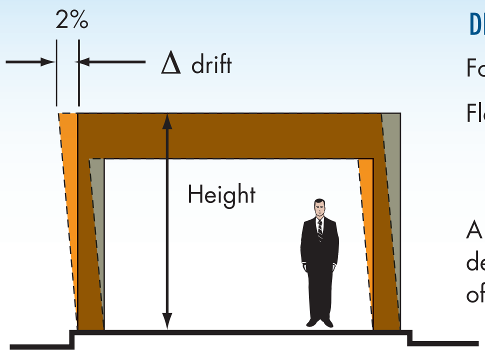


Figure 2-8: The short column problem

2.2.2.6 Drift

Drift is the term used in seismic design to describe the horizontal deflection of structural members in response to seismic forces. In the seismic code, limits are set on the amount of drift permitted. This is done to ensure that the structure will not be designed to be so flexible, even if structurally sound, that its nonstructural components will be unacceptably damaged. Drift is limited on a story basis. The allowable story drift is limited to floor-to-floor height times 0.010 (1 percent of the floor height) for essential buildings and 0.015 (1.5 percent of the floor height) if the nonstructural components have been designed to accommodate drift. A story drift of 0.010 is equivalent to a deflection of 1-½ inches for a floor-to-floor height of 12 feet 6 inches (Figure 2-9).



DRIFT LIMITS

For most buildings, drift is limited to:

Floor-to-floor height x **0.010** to **0.020**

A story drift of 0.010 = deflection of 1-1/2 inches for a height of 12 feet 6 inches

Figure 2-9: Allowable story drift

2.2.2.7 Configuration: Size and Shape

Experience has shown that the architectural form of a building has a major influence on its performance during ground motion. This influence is the result of the three-dimensional interaction of all the structural systems and all architectural components when subjected to earthquake forces. For certain architectural forms, the *response of the building* can become very complex and the earthquake forces can become concentrated and distributed in undesirable ways. The term *building configuration* is used in seismic design to determine the architectural form of the building.

The kinds of unusual conditions that warrant concern are a result of early architectural decisions that determine the configuration of the building. In making these decisions, the architect plays a major role in determining the seismic performance of the building and can make it easy or difficult for an engineer to develop an efficient and cost-effective structural design. For seismic design purposes, configuration can be defined as *building size and shape; the size and location of the structural elements; and the nature, size, and location of nonstructural elements that may affect structural performance.* The latter include such elements as heavy and/or stiff nonstructural walls, staircases and elevator shafts, exterior wall panels, and heavy equipment items.

The seismic significance of the building configuration is that it determines both the way forces are distributed throughout the structure and the relative magnitude of those forces. Seismic codes distinguish between regular and irregular configurations, and it is the latter that may have a detrimental influence on the effectiveness of the seismic engineering and on building seismic performance. Configuration irregularity results in two main undesirable conditions—stress concentrations and torsional forces.

2.2.2.8 Stress Concentrations

Irregularities tend to create abrupt changes in strength or stiffness that may concentrate forces in an undesirable way. Stress concentration means that an undue proportion of the overall forces is concentrated at one or a few points of the structure, such as a particular set of beams, columns, or walls. Those few members may fail, and by chain reaction bring down the whole building. Stress concentration can also be created by vertical irregularity. The most serious condition of vertical irregularity occurs when a building has a soft or weak story, usually the ground floor, which is significantly weaker or more flexible than those above. This design creates a major stress concentration at the points of discontinuity, and in extreme cases may lead to collapse unless adequate design is provided for such points. Figure 2-10 shows some types of soft story design, and Figure 2-11 shows the collapse mechanism that is created.

STRESS CONCENTRATIONS

The most serious condition of vertical irregularity is the **soft or weak story**, in which one story, usually the first with **taller, fewer columns**, is significantly weaker or more flexible than the stories above.

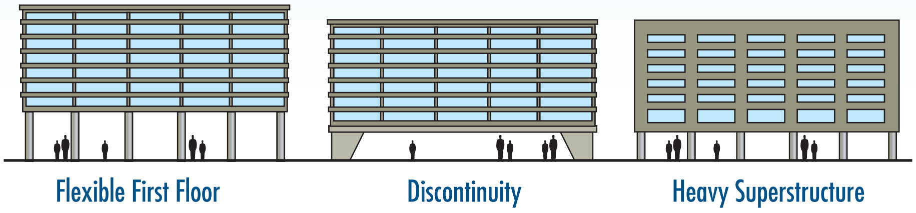


Figure 2-10:
Types of soft and weak story structures

STRESS CONCENTRATIONS

The soft story collapse mechanism.

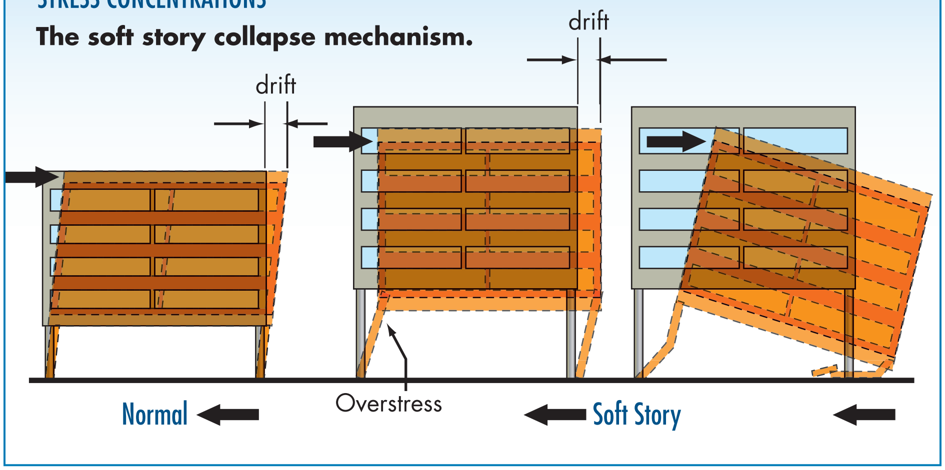


Figure 2-11:
Soft story collapse mechanism

The severe damage to Olive View Hospital in 1971, described in Section 2.3.1.1, was largely the result of a soft first story design. Such soft or weak stories are not permitted in current seismic designs.

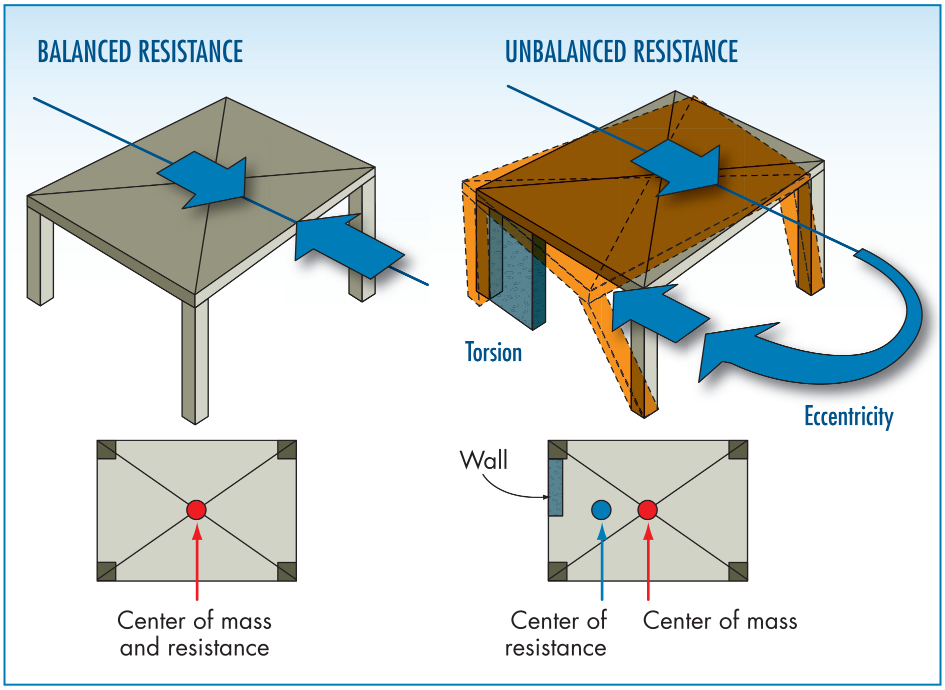
2.2.2.9 Torsional Forces

Irregularities in building configuration may produce torsional forces, which complicates the analysis of building resistance. Torsion is created by a lack of balance between the location of the resisting elements and the arrangement of the building mass. Engineers refer to this as eccentricity between the center of mass and the center of resistance, which tends to make the building rotate around the latter and create torsion within the resisting elements.

The IBC lists a dozen conditions of irregularity (six horizontal and six vertical) for which special design requirements apply. These special requirements either restrict the level of irregularity, amplify forces to account for it, or require more sophisticated analysis. A severe soft first story is specifically prohibited, although it is often encountered in existing buildings.

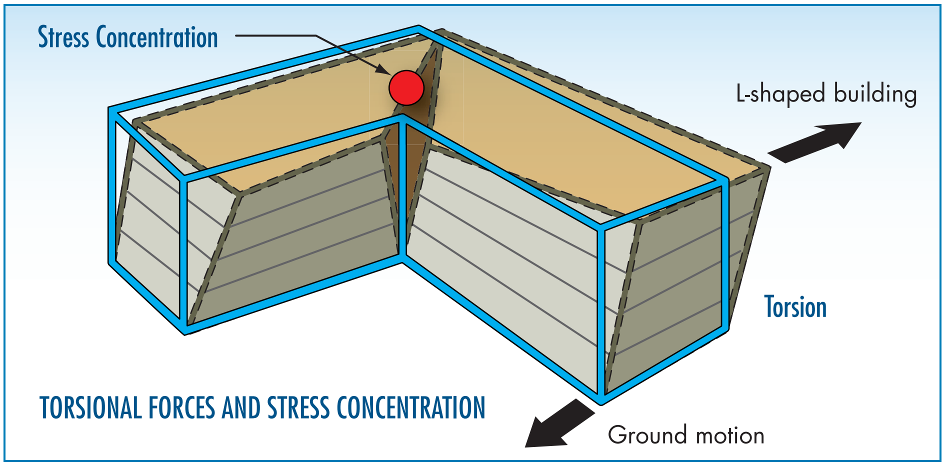
As explained in Section 2.2.1.1, the weight of the floors, walls, and roof contributes to the main lateral forces exerted on the structure through the center of mass, usually the geometric center of the floor plan. If the resistance provided by the building components is exerted through this same point (the center of resistance), then there is no torsion and balance is maintained. As shown in Figure 2-12, conditions of eccentricity—when the centers of mass and resistance are offset—produce torsional forces.

Figure 2-12:
Torsion



One building configuration that is most likely to produce torsion features re-entrant corners (buildings shaped in plan like an "L" or a "T," for example). The wings of such buildings tend to twist and result in torsion and stress concentration at the "notch" where the wings meet, also called a re-entrant corner (Figure 2-13).

Figure 2-13:
The re-entrant corner building



Buildings that have large variations in their perimeter resistance on different facades of the building also tend to produce torsion. Such variations often occur when some facades have large areas of glazing while the others have solid walls.

Irregular configurations generally arise because of functional planning and programming requirements, or sometimes because of the architect's or owner's desire to create an original or striking architectural form.

Hospitals often have irregular and complicated configurations as a result of their functional complexity. Broadly speaking, smaller hospitals are usually planned in one or two stories with horizontal-planned layouts; large hospitals often have a vertical tower for patient rooms elevated above horizontally planned floors for the diagnostic, treatment, and administrative services. Emergency services are generally placed at the ground floor level, with direct access for emergency vehicles. However, new developments in hospital design (see Section 1.2.4) represent a radical departure from this traditional hospital morphology. The new designs are based on decentralization of functions, and the introduction of natural environment into hospital buildings. New hospital buildings have even more complex configurations consisting of fragmented blocks interspersed with courtyards and gardens, where different blocks frequently have not only different shapes, but different structural systems as well.

The structural design for a hospital, however, should still focus on reducing configuration irregularities to the greatest extent possible and ensuring direct load paths. Framing systems need careful design to provide the great variety of spatial types necessary without introducing localized irregularities (Figure 2-14).

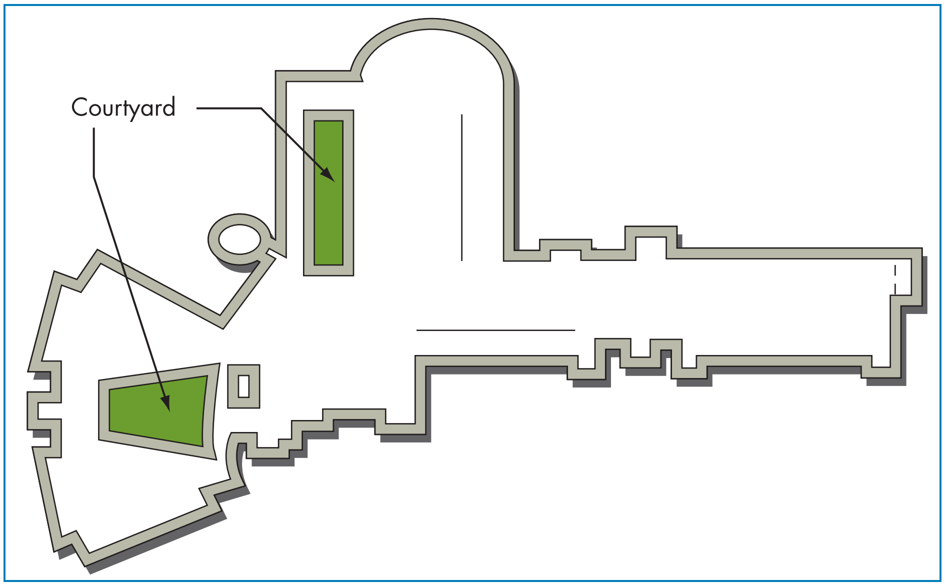


Figure 2-14: Complex footprint of a large community hospital. Shaded areas represent open courtyards.

2.2.3 SPECIFICATIONS FOR PERFORMANCE-BASED SEISMIC DESIGN

Beginning with the 1989 Loma Prieta earthquake in the San Francisco Bay Area, the importance of the consequences of damage, other than endangering life safety, has been increasingly recognized, not only in hospitals and other critical facilities, but in all buildings. A major effort to develop guidelines for seismic rehabilitation of buildings was funded by FEMA in 1992, and published as FEMA 273 (1997). Subsequently, this guideline was improved and republished as FEMA 356 (2000), and in 2007 was made a standard by the American Society of Civil Engineers (ASCE 41).

2.2.3.1 Performance Levels

As a result of the high cost of retrofit and the growing interest in understanding the various performance levels of buildings in earthquakes, FEMA 273 described a variety of seismic performances for both structural and nonstructural systems that could be targeted in design. These performances were summarized in a matrix (see Table 2-1) that allowed specification of a given performance level by combining the desired structural performance with a desired nonstructural performance. Four overall performances levels from that table were highlighted as discussed below. These performance levels were developed to be applicable to any building with any occupancy, as appropriate.

Table 2-1: Combinations of Structural and Nonstructural Seismic Performance

Nonstructural Performance Levels	**Structural Performance Levels and Ranges**					
	S-1 Immediate Occupancy	**S-2 Damage Control Range**	**S-3 Life Safety**	**S-4 Limited Safety Range**	**S-5 Collapse Prevention**	**S-6 Not Considered**
N-A Operational	Operational 1-A	2-A	Not recommended	Not recommended	Not recommended	Not recommended
N-B Immediate Occupancy	Immediate Occupancy 1-B	2-B	3-B	Not recommended	Not recommended	Not recommended
N-C Life Safety	1-C	2-C	Life Safety 3-C	4-C	5-C	6-C
N-D Hazards Reduced	Not recommended	2-D	3-D	4-D	5-D	6-D
N-E Not Considered	Not recommended	Not recommended	Not recommended	4-E	Collapse Prevention 5-E	No rehabilitation

Operational Building Performance Level (1-A)

Buildings meeting this target building performance level are expected to sustain minimal or no damage to their structural and nonstructural components. The building would be able to continue its normal operations, possibly with only slight adjustments, mainly with respect to power, water, and other utilities that may need to be provided from emergency sources.

Under low levels of earthquake ground motion, most hospitals should be able to meet or exceed this target building performance level. However, it would not be cost-effective to design buildings for this target building performance level under very rare, intense ground shaking, except for buildings that offer unique services or that contain exceptionally hazardous material.

Full functionality is normally considered difficult to achieve in the immediate aftermath of strong earthquake shaking. Offsite issues, such as staff availability and potential loss of utilities that are not under the control of the facility, may impair operations. In addition, relatively minor onsite damage to key components can significantly affect overall functionality. A single anchorage failure of the emergency generator, or a leak in one of the many pressurized water systems, can significantly disrupt hospital operations.

Immediate Occupancy Building Performance Level (1-B)

Buildings meeting this target building performance level are expected to sustain minimal damage to their structural elements and only minor damage to their nonstructural components. While it would be safe to reoccupy a building meeting this target building performance level immediately following a major earthquake, nonstructural systems may not function, either because of the lack of electrical power or damage to fragile equipment. Therefore, although immediate occupancy is possible, it may be necessary to perform some cleanup and repair and await the restoration of utility services before the building can function in a normal mode. The risk of casualties at this target building performance level is very low.

Many building owners may wish to achieve this level of performance when the building is subjected to moderate earthquake ground motion. In addition, some owners may desire such performance for very important buildings under severe earthquake ground shaking. This level provides most of the protection obtained under the Operational Building Performance Level, without the cost of providing full standby utilities and performing rigorous seismic qualification of equipment performance.

Immediate Occupancy is more realistic than the Operational performance level for most buildings, and at a minimum, should be the goal of all new hospital buildings. However, since even the smallest disruption of non-structural systems may be too detrimental for continued operation of a hospital, the owners and designers should consider a higher level of protection for critical hospital functions. For instance, it is recommended that provisions be made for independent operation of critical utilities for a minimum of 4 days. Critical utilities usually include electric power; water; the sanitary sewer; and, depending on the local weather conditions, fuel for heating and cooling.

Life Safety Building Performance Level (3-C)

Buildings meeting this performance level may experience extensive damage to structural and nonstructural components. Repairs may be required before re-occupancy of the building is allowed, although in some cases the repair may not be deemed cost-effective. The risk of casualties in buildings meeting this target building performance level is low.

This target building performance level entails somewhat more extensive damage than anticipated for new buildings that have been properly designed and constructed for seismic resistance.

The Life Safety level should prevent significant casualties among able-bodied hospital occupants, but may not protect bed-ridden patients. In these circumstances, life safety level of protection is not appropriate for new hospitals.

Collapse Prevention Building Performance Level (5-E)

Although buildings meeting this target building performance level may pose a significant hazard to life safety resulting from failure of nonstructural components, significant loss of life may be avoided by preventing collapse of the entire building. Many buildings meeting this performance level may, however, be complete economic losses.

This level has been sometimes selected as the basis for mandatory seismic rehabilitation ordinances enacted by municipalities, as it results in mitigation of the most severe life-safety hazards at the lowest cost. Collapse Prevention is intended to prevent only the most egregious structural failures, and includes no consideration for continued occupancy and functionality of a hospital, the economics of damage repair, or damage to nonstructural components.

2.2.3.2 New Developments in Performance-Based Design

Although developed for use in the process of seismic rehabilitation of older buildings, the aforementioned damage descriptions have filled a void and have become an interim standard for describing seismic performance of both new and existing buildings.

The goal of performance-based earthquake engineering has thus become the development of methods to predict the expected losses adequately, measured by the risk of casualties, the cost of damage repair, and the length of building downtime. These losses are to be calculated on a cumulative and probabilistic basis, allowing communication with stakeholders based on losses in a given scenario earthquake, the losses due to a probabilistically determined event, or the average annual losses over a given time period.

Since the publication of FEMA 273, performance-based earthquake engineering has continued to develop, particularly through research performed at the Pacific Earthquake Engineering Research Center, one of three major earthquake research centers funded by the National Science Foundation, and through the FEMA funded project, *Next Generation Performance-Based Seismic Design Guidelines*, FEMA 445 (2006). When this work is completed, the global performance states used by FEMA 356 will be redefined better to reflect current knowledge and to communicate the potential losses to stakeholders more effectively.

The example of California shows how earthquake damage affects legislation. The 1971 San Fernando earthquake was particularly damaging to hospital buildings, most notably the Olive View Medical Center, a brand new facility that was damaged so badly that it was eventually demolished. Based on similar experiences with schools, the legislature passed the Hospital Seismic Safety Act (HSSA) in 1972. The intent of the law was both to protect acute care patients and to provide post-earthquake medical care. The law was patterned after the Field Act covering schools in California, specifying the same State review agency, and stipulating design by specially experienced and approved “Structural Engineers.” It covered new buildings only and provided for a “Building Safety Board” of industry design professionals and facility experts, appointed by the Director of Health Services, to advise the State on implementation of requirements.

The law and regulations included four main considerations:

- Geologic hazard studies for sites
- Structural design forces in excess of those used for “normal” buildings (initially a “K-factor” of 3.0; later, an importance factor, I, of 1.5)

(continued)

- Specific design requirements for nonstructural elements
- Strict review of design and inspection of construction

Surprisingly, only 23 years after the San Fernando earthquake, another damaging event occurred in almost the same spot. In January of 1994, the Northridge earthquake produced very large ground motions in the San Fernando Valley just north of Los Angeles. Just as the San Fernando event, the Northridge earthquake had a profound effect on hospital design in California. Although there were no failures in hospitals comparable to the Olive View disaster, several hospitals required evacuation as a result of failures of both structural and nonstructural systems. These high-profile evacuations once again put the hospital building inventory in the spotlight. Analysis and comparison of the performance of buildings in Northridge built before and after the HSSA clearly indicated its effectiveness. This analysis also indicated that further improvements were needed in the performance of nonstructural systems.

Senate Bill 1953, which introduced a plan to bring all pre-Act hospital buildings into compliance with the HSSA by the year 2030, was signed into law by the governor of California in September, 1994. Standards and regulations needed to implement the law included:

- Definition of structural vulnerabilities and evaluation standards
- Definition of nonstructural vulnerabilities and evaluation standards
- Standards for retrofit
- Building evaluations and facility compliance plans shall be submitted to the Office of Statewide Health Planning and Development (OSHPD) by January 1, 2001; Facility owners, 60 days after approval by OSHPD, shall submit building performance categories to local emergency service agencies and use the performance information to improve emergency training, response, and recovery plans
- Hospital buildings with a high risk of collapse cannot be used for acute care purposes after January 1, 2008. These buildings must be retrofit (to a “life safe” performance), demolished, or abandoned for acute care use by that date
- High-risk nonstructural systems (pre- and post-Act) shall be mitigated in accordance with priorities and timelines to be set in regulation by OSHPD, in consultation with the Hospital Building Safety Board
- All facilities shall be in substantial compliance with the intent of the HSSA by January 1, 2030

2.3 EARTHQUAKE DAMAGE TO HOSPITALS

Although earthquakes damage most manmade structures in similar ways, to understand the true consequences of damage to buildings with special occupancies and functions requires a much more detailed and accurate damage description than may be needed for other buildings. The effects of earthquake damage on hospital operations and the safety of occupants have been described below based on the experiences of hospitals in the United States and around the world.

Historically, buildings have been engineered to provide adequate life safety to occupants and passers-by from earthquake hazards. For most buildings, life safety is primarily threatened by building collapse or the debris falling into the street and neighboring buildings. A higher level of performance is required to address the life safety issues of hospitals, since patients often have limited mobility and are dependant on caregivers or specialized medical equipment.

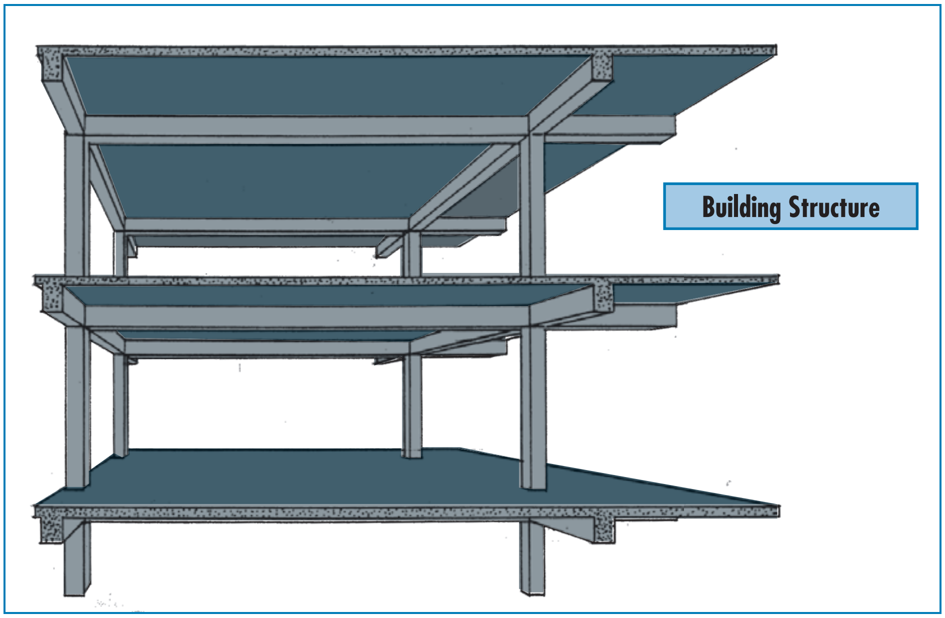


Figure 2-15a: Structural and nonstructural elements of a building

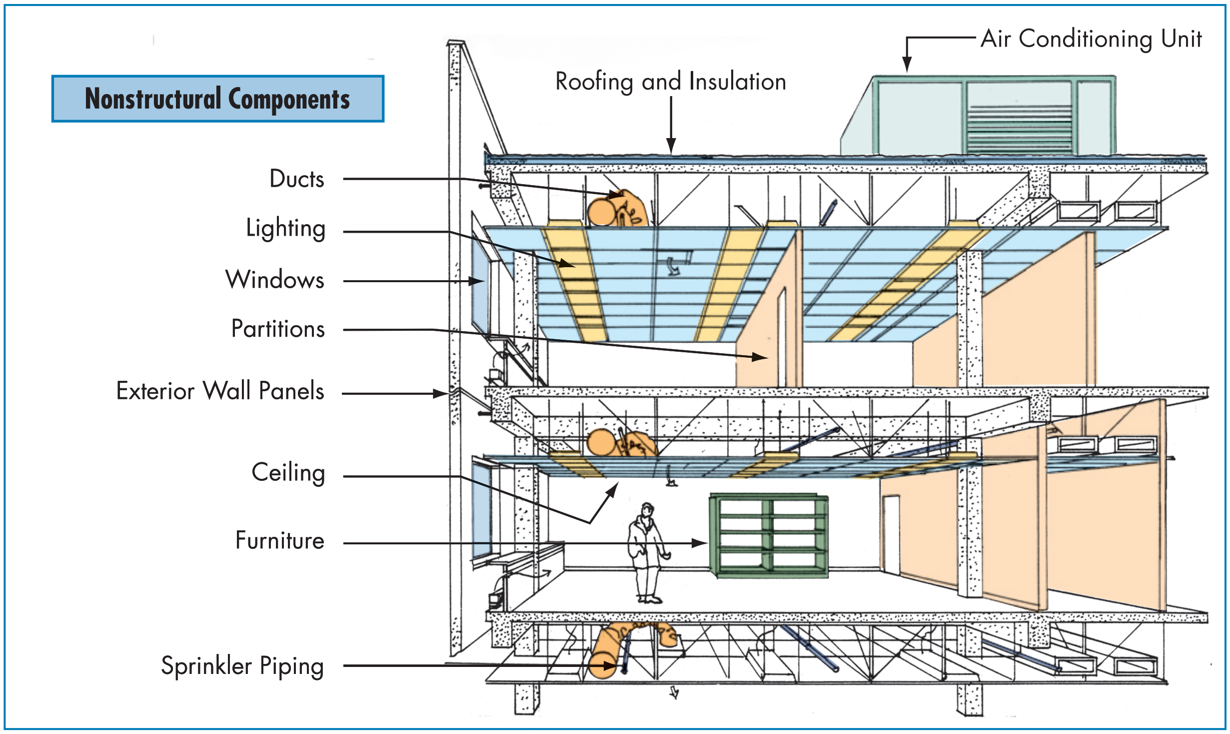


Figure 2-15b: Structural and nonstructural elements of a building

Figure 2-15 shows typical building components and systems present in hospital facilities. The structural elements consist of the foundations, columns, beams and slabs, walls, and braces that hold the building up against vertical gravity forces and horizontal wind and earthquake forces. The nonstructural elements include building service systems, such as electricity and lighting, heating and cooling, plumbing, and interior architectural systems, such as ceilings, floors, partitions, and other interior components. The building envelope includes the systems that separate the interior spaces from the exterior, both structural and nonstructural. It includes exterior walls and cladding, roof systems, doors and windows, and floors or slabs that separate the building interior from the ground. Contents and equipment are completely dependent on the type of occupancy and the function of the space, and range from items such as furniture encountered in a lobby or a waiting room, to highly technical equipment commonly present in treatment rooms. In addition, laboratories, pharmacies, bulk storage areas, and large central energy plants have highly specialized and frequently very sensitive equipment.

In general, both the building service systems and the contents of hospitals rank among the most complex and expensive of any building type. Furthermore, both the structural system and most of the nonstructural systems are required to perform without interruption after an earthquake to enable adequate functionality.

2.3.1 TYPES OF STRUCTURAL DAMAGE

When the ground shakes in an earthquake, the shaking is transferred to the building, potentially causing structural damage. The damage can consist of cracks in structural walls, bent or broken braces, or damage to columns and beams. Damage can range from minor (a few cracks), to major (parts of the structure rendered ineffective and potentially unsafe), to complete collapse. See Figures 2-16, 2-17, 2-18, and 2-19 for examples of structural damage.

Figure 2-16:
This concrete building suffered severe damage to the columns at the second floor level. It was deemed unsafe by the local jurisdiction and later demolished.

Figure 2-17:
A steel frame building with a post-earthquake "lean" to the right, seen particularly at the first floor. Severe damage was found in its beam-column joints and it was later demolished.

Figure 2-18: Severe damage to a poorly reinforced masonry wall on a steam plant

Figure 2-19: Damage to an exterior concrete wall. This hospital building was evacuated.

2.3.1.1 The Case of the Olive View Medical Center

The Olive View Hospital in the northern San Fernando Valley, owned by Los Angeles County in Southern California, was severely damaged on February 9, 1971, when the San Fernando earthquake damaged the almost-new facility so severely that it was later demolished. Over 500 patients were evacuated immediately after this event.

The 850-bed Olive View Hospital campus comprised over 30 buildings of various ages, but most notably featured a complex of buildings completed in 1970, only months before the 1971 San Fernando earthquake. These "new" buildings included the five-story Medical Care Facility, the two-story Psychiatric Unit, the Heat and Refrigeration Plant, and several other smaller ancillary buildings such as a warehouse, assembly building, walkway canopy, and ambulance canopy. The 1970 buildings were all made of reinforced concrete and designed under the 1965 Los Angeles Building Code, which included seismic provisions. However, neither of these buildings had any special seismic protection features. In fact, the poor performance of this facility was one of the prime reasons for passage of California's Hospital Seismic Safety Act (HSSA). The shaking experienced in the 1971 San Fernando earthquake was extreme; however, structural performance of these buildings was worse than the engineering community had expected. Subsequent investigations indicated that the buildings technically met the requirements of the code, but included features that made them particularly vulnerable to earthquake damage. Seismic codes were subsequently refined to prevent this type of vulnerability in future buildings.

The damage to Olive View Hospital buildings was nearly catastrophic. The first story of the medical treatment and care unit was over 15 inches out of plumb and near collapse (Figure 2-20). Three of the four exterior stair towers pulled away from the main building or collapsed completely, rendering them useless for egress (Figure 2-21). The Ambulance Canopy collapsed onto the parked ambulances and destroyed them. The first story of the Psychiatric Unit collapsed, but all the occupants were on the second floor at the time.

Almost immediately after the event, the patients in the Psychiatric Unit began assembling in a parking lot adjacent to their facility. The need to evacuate was obvious, and the second floor wards were only feet from the ground after the first floor collapse (see Figure 2-22). Controlling and tracking these patients was nearly impossible, particularly in the first few hours. Within 5 hours, evacuation was underway in the main building using interior stairwells. The building had no power and therefore no elevators or lights. The nurses evacuated their own units, ambulatory patients first, and, when sufficient assistance was available, non-ambulatory patients. By that time, a network of ambulances and helicopters had been set up for transfer to other facilities (Arnold, 1983; Lew, 1971; NOAA, 1973).

Subsequent analysis of the effects of this earthquake on the hospital noted, as particularly troublesome, the lack of functioning communications, either internal or external, the lack of an effective evacuation plan or identified assembly area, and the lack of any control or tracking of medical records.

Figure 2-20:
Aerial view of 1971 Olive View Hospital
SOURCE: NOAA, 1973

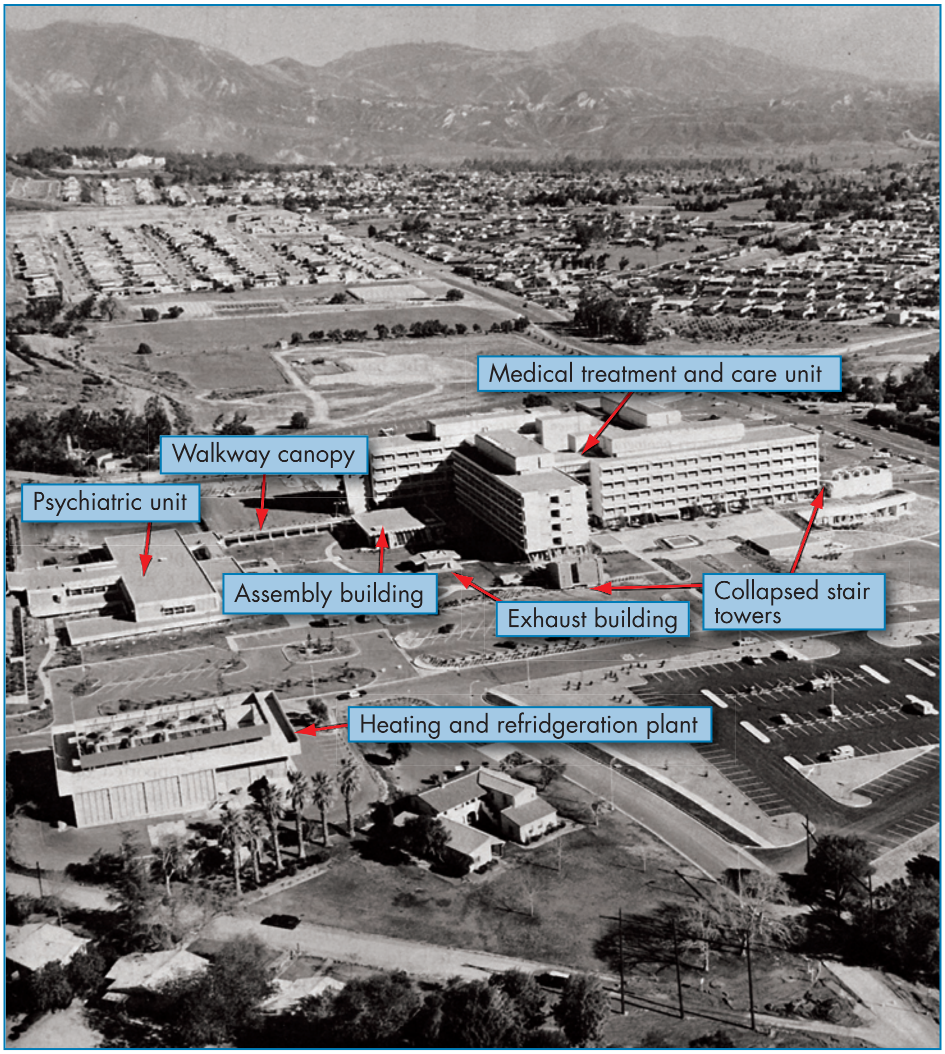


Figure 2-21:
Collapsed stair tower in main building of Olive View Hospital

Figure 2-22: Completely collapsed first level (not visible) of Psychiatric Unit

2.3.2 NONSTRUCTURAL DAMAGE

When the ground shakes the structure, the structure shakes everything that is in it or on it, including the building envelope and components of the interior nonstructural systems. This shaking can damage most components directly. Indirect damage, resulting from structural deformation between floors, can cause damage to all the systems connected to these structural components.

Damage to architectural systems consists of broken windows and cracked exterior walls and interior partitions. In extreme cases, exterior walls and partitions topple completely. Ceilings are also vulnerable to damage and can break into small pieces or fall to the floor (see Figure 2-23).

Figure 2-23: A damaged exit corridor—dark and barely passable

Damage to the building service systems can consist of sliding or overturning of equipment like boilers, generators, and fans, or swaying and possible fracture of mechanical ducts, pipes, and electrical conduit (see Figures 2-24, 2-25, and 2-26).

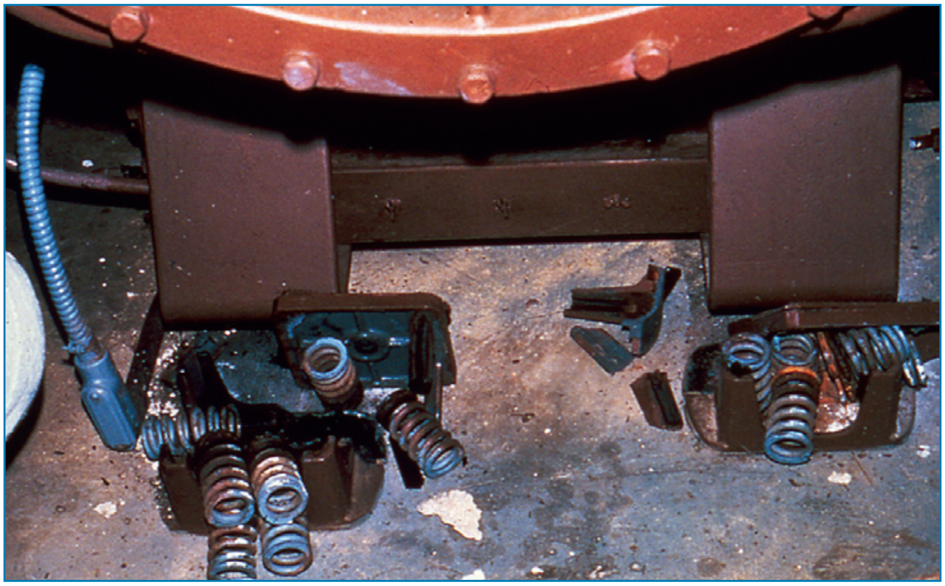


Figure 2-24: Vibration isolation bearing assemblies on mechanical equipment collapsed due to seismic shaking—such movement breaks pipe or electrical connections to the equipment.

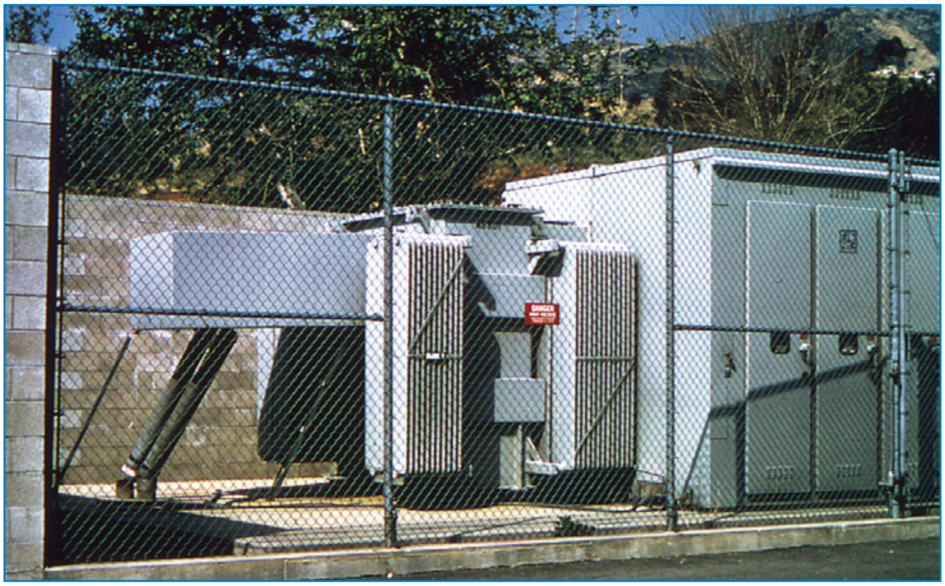


Figure 2-25: A heavy transformer that moved several feet, breaking all connections

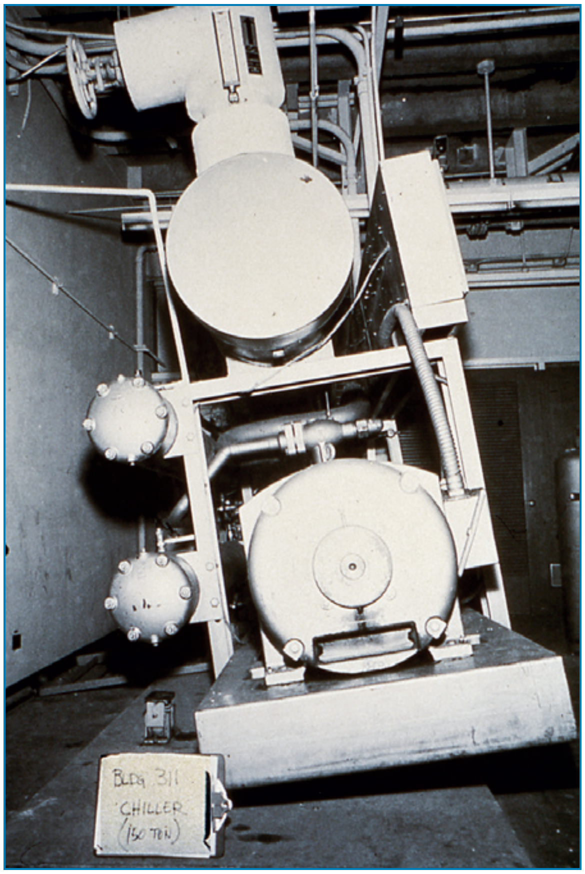


Figure 2-26:
A large chiller almost tipped over.

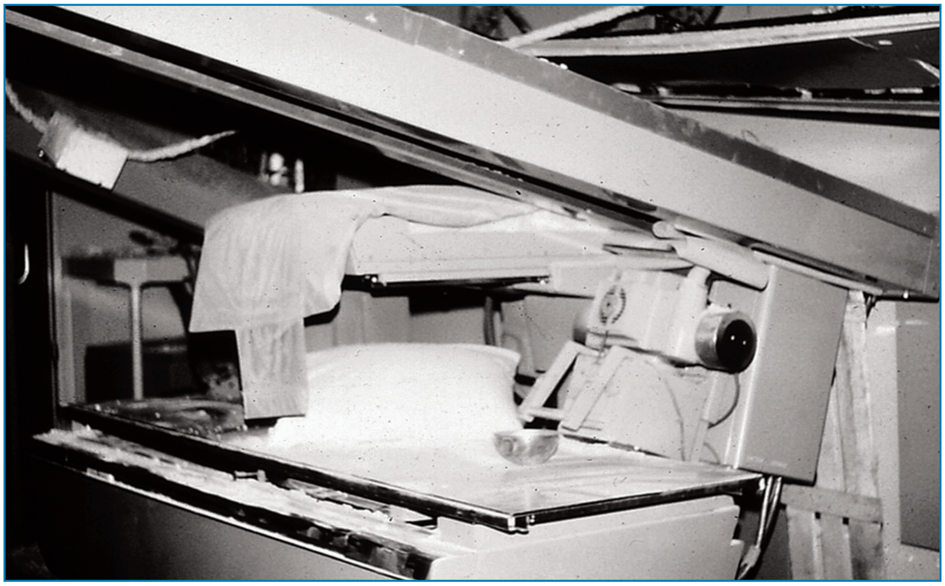


Figure 2-27:
Damaged radiology equipment that not only will not function, but has become a life-safety risk

Because of the wide variation of contents and equipment in a typical hospital, the type of damage experienced by these systems varies widely. For example, medical equipment, such as operating tables and lights, radiation and x-ray units, sterilizers, and patient monitors, is often heavy and not well anchored to the structure (see Figure 2-27). Offices and storage rooms, such as the areas used to store critical supplies, medicine, medical records, chemicals, and fuel, can also be severely damaged by shaking (see Figures 2-28, 2-29, and 2-30).

Figure 2-28:
Chaos in a storage area similar to central storage or medical records

Figure 2-29:
Jumbled contents of a typical office

Figure 2-30:
Overturned tank similar to medical gas storage

2.3.2.1 The Case of New Olive View Medical Center

Nearly 15 years after the 1971 earthquake event that destroyed the Olive View Medical Center (see Section 2.3.1.1), a new hospital was opened on the same site in 1986 (see Figure 2-31). Built even stronger than required under the HSSA of 1972, the building has no basement and features a seismic system of concrete shear walls and steel plate shear panels. The building was also equipped with instruments to record its response in future earthquakes.

Figure 2-31:
Aerial view of "new" Olive View Hospital (1986)

Early in the morning of February 17, 1994, a Magnitude 6.7 earthquake occurred on a little known fault not generally considered dangerous, located near Northridge, about 10 miles from the hospital. The recorders captured exceptionally high accelerations of 0.82 g at the first floor and 1.7 g at the roof. The structure suffered little or no structural damage, but its stiffness and strength contributed to the transfer of unprecedented accelerations through the building, in some cases overwhelming the seismic anchorage and bracing provided for the building's nonstructural systems. Some of these components and systems were not considered sufficiently vulnerable to require special bracing.

Damage included the following (see Figures 2-25, 2-26, and 2-27):

- Shifting, and in some cases, failure, of anchorages of equipment at the roof level, where accelerations were the highest. This movement broke one or more chiller water lines, causing flooding in the top floors (see Figure 2-32).

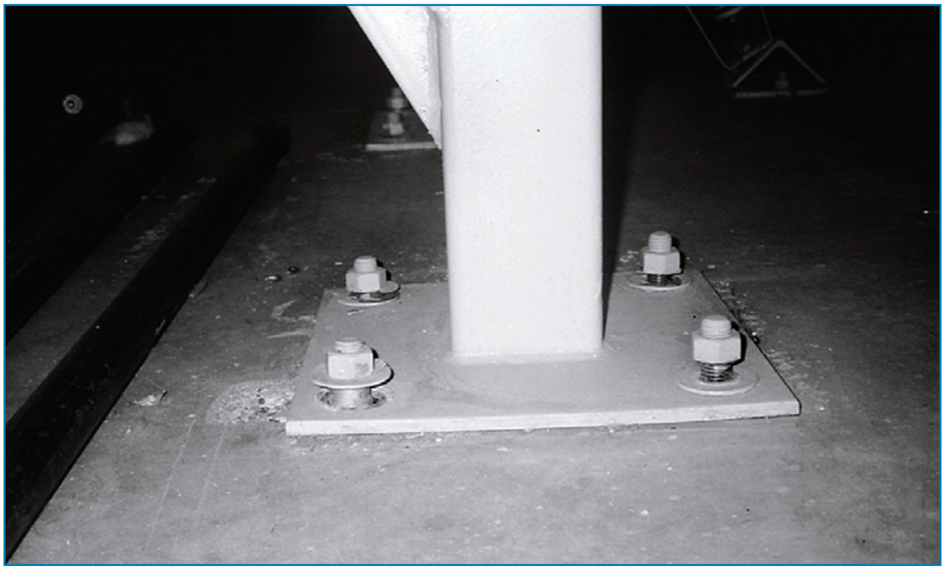


Figure 2-32: Anchor bolts stretched by large seismic accelerations at roof level

- Excessive movement and failure of wall-mounted television brackets, causing some television units to fall.
- Extensive damage to suspended panelized ceilings, some exacerbated by leaks from water pipes from above.
- Excessive movement and interaction between gypsum board and other fire-rated ceilings and sprinkler lines, causing additional leaks.
- Movement at the copper tube reheat coils in the ceiling spaces, almost universally at the third through the sixth floor, causing leaks (see Figures 2-33 and 2-34).

Figure 2-33: Damage to ceiling and fixtures from sprinkler breaks

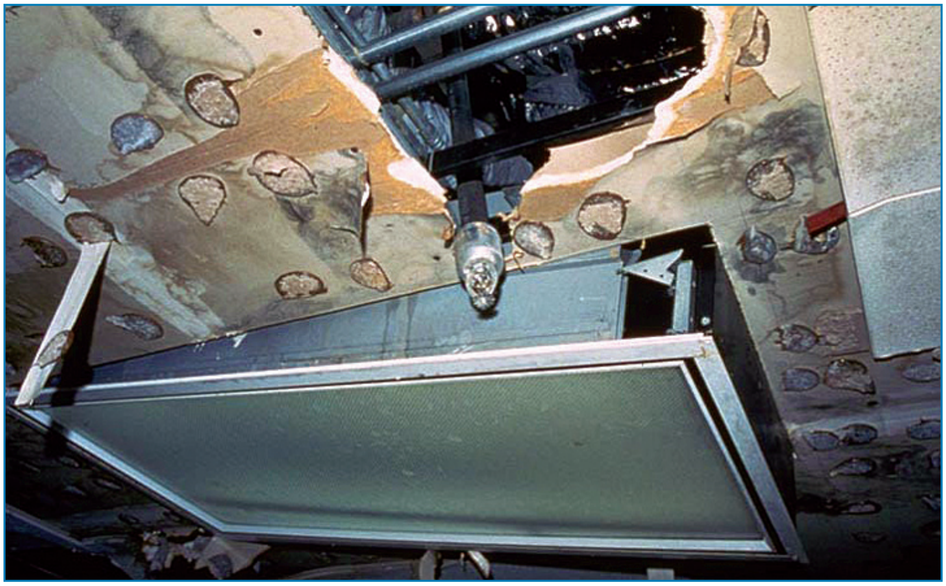


Figure 2-34: Detail of water damage to ceiling

- Damage to some equipment anchorage in the Central Plant and at the bulk oxygen tank.

- Damage to elevators, seven of which were temporarily out of service. Four had sustained severe damage as a result of derailed and bent counterweight frames.

Right after the earthquake event, administrators planned a partial evacuation of 79 patients, but by the afternoon, they decided to transfer all 377 patients to other facilities, despite the dangers associated with such a move. The evacuation was prompted primarily by water damage and lasted 41 hours (EERI, 1995; LACDHS, 1994; URS, 1996).

Despite vastly improved structural performance and compliance with the requirements for anchorage and bracing of nonstructural components and systems compared to the conditions in 1971, the hospital's operations were severely compromised. It was not ready to accept local casualties, but actually increased the load of neighboring facilities by requiring evacuation. The unexpectedly poor performance was caused by extraordinary ground motions, probably made more damaging to nonstructural systems and contents by the very stiff and strong structure of the hospital.

2.3.2.2 The Case of Kona Community Hospital, Hawaii

The Kona Community Hospital (KCH) is located in Kealakekua, Kona, on the central west coast of the Big Island of Hawaii. It was originally a county hospital but became part of the State-owned Hawaii Health Systems Corporation in 1996. KCH is a full service medical center and is the primary health care facility serving West Hawaii. The facility has 33 acute medical-surgical beds, a 9-bed intensive care unit, 7 obstetric beds, an 11-bed behavioral health unit, and a 34-bed skilled nursing/long term care wing.

The KCH campus includes several buildings, but the primary medical facility occupies a three-story L-shaped building that consists of the original 60,500-square-foot block built in 1972, and an 18,300-square foot addition built in 1989. Both structures are concrete, rectangular in plan, and each forms one leg of the L shape. The site slopes east to west creating two stories above grade and one basement floor on the east, and three stories above grade on the west face. The lateral force (wind and earthquake) resisting system of the original building consists of concrete pier shear walls that are part of the exterior wall and concrete walls around the elevators and stairs. The lateral force resisting system of the addition is a ductile concrete frame, which consists of the beams and columns rigidly tied together in a manner that resists lateral motion. The addition is notable in that the two bays of the western end are open at the ground floor and serve as a drive-through to the back of the campus and as an ambulance entrance.

Seismic Characteristics of the Facility

A technical evaluation of the facility, performed in 1993 by the Hawaii State Earthquake Advisory Board, identified several seismic deficiencies. It was found that the layout of the lateral-force-resisting shear walls in the original 1972 building and the outdated pattern of column reinforcement were of the type that previously contributed to unacceptable levels of damage in similar buildings. Conditions that presented potential seismic deficiencies were also found in the 1989 addition, including:

- The eccentric location of the stair and elevator core, which could potentially create torsional response
- Inadequate connection of the floor slabs to the core, which could cause moderate damage
- The potential for nonstructural plaster cracks in the upper floors,
- The potential for local damage at the connection between new and original wings during shaking

As part of the evaluation, the torsion issue (related to the stair and elevator) was checked and found not to represent a significant problem. No specific recommendations related to the other problems were included in the evaluation. The structural evaluation concluded with a recommendation to retain a local structural engineer to review the seismic adequacy of KCH in more detail. The evaluation also covered the seismic protection of nonstructural systems and equipment, but included no specific recommendations for KCH.

The evaluation categorized nonstructural components and systems as:

- Systems and elements which are essential to hospital operations and without which the hospital cannot function (Essential)
- Nonessential elements whose failure could compromise hospital operations (Nonessential)

In fact, when considering seismic preparedness of hospital facilities, there is little consensus about the types of nonstructural systems that should be considered essential. These classifications vary from facility to facility and are closely tied to elements of the emergency response plan. For example, unbraced, suspended panelized ceiling systems typically used in hospitals on the island were noted as a deficiency, but consistent with standard seismic evaluation procedures for hospitals, these systems were classified as nonessential. However, as described below, damage to these ceilings proved critical when a real event struck.

Most of the larger equipment categorized as “essential” in the evaluation, including the emergency generator, the bulk oxygen tank, the chiller, and the rooftop cooling tower were seismically anchored and continued to function during the earthquake.

Damage

The Hawaii Earthquake of October 15, 2006, had a magnitude 6.7 and was centered about 35 miles north of the KCH. It was followed by a second shock of magnitude 6.0. The shaking caused moderate damage over much of the Big Island and was felt as far away as Oahu. Shaking on the island of Hawaii, as recorded on several instruments installed by the USGS, featured relatively high accelerations, but the energy was restricted to very high frequency (short period), which proved damaging to stiff, brittle structures. Several unreinforced masonry buildings suffered severe damage, many ungrouted stone masonry fences and walls partially collapsed, and landslides and rockslides were common, which is consistent with this kind of motion.

The Special Services Building at KCH (seen in Figure 2-35 behind the small single-story building on the left) contained such an instrument. The response spectrum for one component of motion is shown in Figure 2-36 in blue. Note the rapid decline of spectral acceleration values for very short periods, much less than 0.5 seconds. The orange curve shows a spectral shape that might be expected in association with such high ground accelerations, and is included in building codes. High values of spectral acceleration between the periods of 0.5 seconds and 2.0 seconds, as shown in this standard curve, are usually associated with much greater building damage.

Figure 2-35:
Kona Community Hospital. Addition (1989) supported on isolated columns in the foreground. The original building (1972) is in the left background.

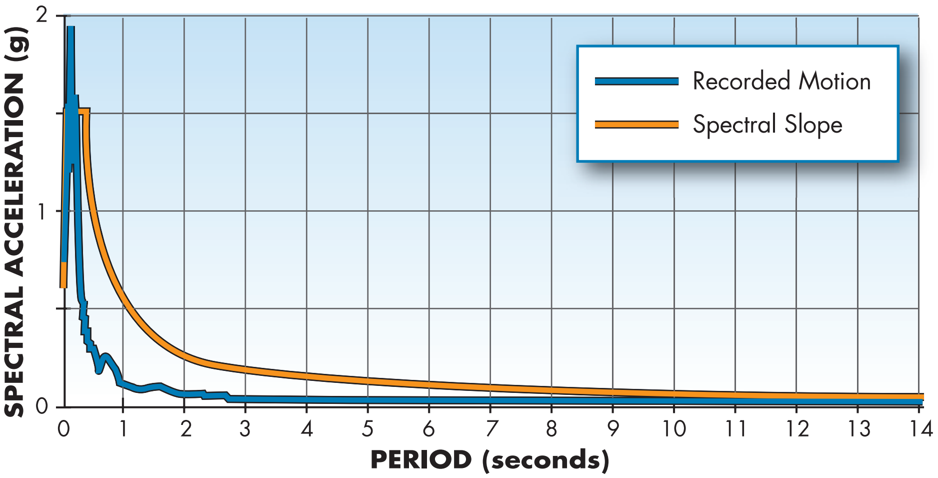


Figure 2-36: Response spectra for one of the orthogonal components recorded at the site of the KCH. The blue line is for the recorded motion. The orange line represents the spectral shape more commonly expected and contained in building codes.

(GRAPH COURTESY OF WWW.COSMOS-EG.ORG)

The high acceleration motion caused the unbraced, suspended panelized ceilings (see Figure 2-37), found almost everywhere at KCH, to strike partitions that demarcated rooms and corridors. The partitions were constructed of steel studs and gypsum board, and the studs run from the structural floor to the underside of the structure above, making them very strong and stiff. The impact of the panelized ceilings caused the lightweight support tees either to buckle or pull off of a typical perimeter trim angle (Figure 2-38). In the absence of vertical support wire, the tees collapsed, allowing the ceiling tiles to fall. Many of the florescent light fixtures, also supported on the tees, became dangerously unstable, though few fell to the floor. This type of damage was concentrated at the perimeter of rooms, adjacent to the partition walls, but it was not completely limited to these locations (see Figures 2-39). When ceiling tiles became dislodged, decades of accumulated dust on the top of the tiles came down, adding to the general disarray and threatening the health of patients and other occupants.

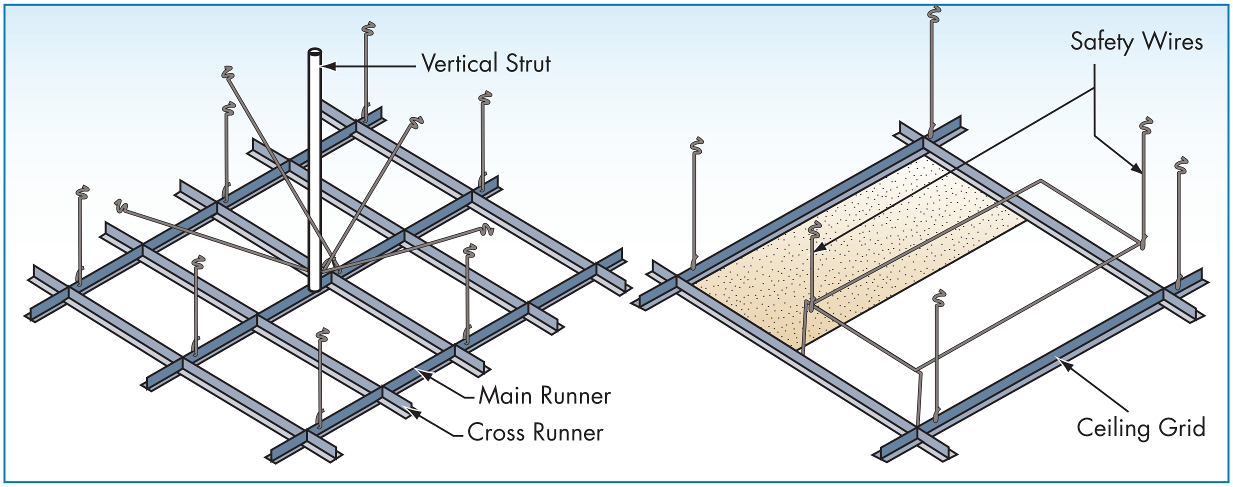


Figure 2-37: Typical suspended panelized ceiling system showing seismic bracing (according to the 1993 seismic evaluation report, this system was not used in the hospitals reviewed at that time).

Figure 2-38:
Typical damage at the perimeter of a room from loss of support from the partition-mounted perimeter angles to the ceiling system tees or from contact with the ceiling system and the partitions.

Figure 2-39:
Ceiling damage in the operating room. The round operating lights on the right were not damaged.

Almost simultaneously with the first shock, the power went out. The emergency generator was seismically protected and provided power for the emergency circuits. Eight minutes after the main shock, about the time some semblance of order was being restored, the second shock hit. With equipment and contents as well as ceiling tiles and metal tees littering the floor or hanging precariously over patients' beds, a decision was made to evacuate the most disrupted areas.

At the time of the earthquake KCH had 69 patients, including 31 in the long-term care unit. These 31 long-term care patients were taken to a local hotel; 27 patients were discharged; 5 were airlifted to an acute care facility in Hilo, and one was transported to a local long-term care facility. The remaining five patients were more difficult to move and were placed in usable rooms in the obstetrics or the intensive care unit (ICU) on site.

The potential torsional response of the building addition, identified in the 1993 evaluation, proved prophetic, as the column-supported west end attempted to rotate around the stiffly supported east end. As shown in Figure 2-40, the two beam connections tending to restrain the motion spalled. Similarly, in the partially enclosed penthouse, the embedded connection of a steel beam spanning between two exterior concrete walls pulled out due to a stiffness incompatibility. This damage was not considered serious enough for the structure and did not affect the occupancy status.

Figure 2-40: Spalling at beam connections

Exterior and interior nonstructural plaster or stucco walls had many cracks, especially around some door frames. This damage was costly, but did not affect operations.

Emergency generators and medical gas storage were seismically anchored and survived the tremor undamaged. The communications were disrupted for the first hour or so, because the telephone main switching equipment, which was not anchored, failed. The radio-repeater mast on the roof fell over and dislodged the coaxial cable, limiting the use of that system. The hospital has subsequently decided that their radio system does not have sufficient channels for emergency use and intends to upgrade the system. Ham radio was also available on the site but was not used.

The hydraulic elevators, which are not as susceptible to damage as the traction elevators used in taller buildings, sustained no major damage but were not functional as a result of power outage. Elevators can be very valuable after earthquakes for moving bed-ridden patients, provided special seismic anchorage and controls are installed and emergency power is available. The pressurized water systems (including sprinklers, domestic, and chilled water), considered by many the most likely to break or leak and disrupt operations, suffered no damage.

The experience of KCH highlighted the vulnerability of unbraced suspended panelized ceilings, which are often given a low retrofit priority because they are not considered a serious life safety hazard. It was also thought that the benefits of bracing do not warrant the extreme disruption that such a retrofit usually causes for hospital operations. It is very likely that lessons from Kona Community Hospital's experience will help change this view.

2.3.3 CONSEQUENCES OF BUILDING DAMAGE

The uninterrupted operation of hospitals is crucial in the aftermath of an earthquake, because of a potentially large number of casualties. Damage to these facilities and a possible need for an evacuation not only hampers the emergency response but can also compound the disaster by adding casualties. The most obvious risk to life safety is serious structural failure of a hospital, similar to the experience of the original Olive View hospital. In the aftermath of an earthquake the local building authority typically determines which buildings are unsafe for use based on the level of damage. For this purpose, a simple "tagging" procedure has been developed in California that uses colored placards or "tags" affixed to buildings that show that the building has been inspected and indicate the level of safety. The evacuation is inevitable when the hospital buildings are "red tagged," i.e. when the building is in imminent danger of collapse in an aftershock. In such circumstances, a hospital becomes unavailable for emergency services and the staff can only provide medical care in parking lots or other ancillary facilities, as has happened in the past.

TAGGING

🟥 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 a 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.

Even in cases where hospitals have avoided major damage, their operations may be sufficiently disrupted to require complete evacuation, which can be very dangerous for many patients. Failures in nonstructural systems, such as broken pipes that cause extensive flooding, failed emergency generators, lack of water, or general chaos created by contents that have been thrown about have all created conditions that have forced hospital administrators or local jurisdictions to order an evacuation. Minor nonstructural damage, especially if essential equipment or other contents are affected, can still cause considerable disruption in hospital operation, even if global evacuation is not deemed necessary.

Finally, almost all hospitals have financial constraints. The cost of repairs and/or the partial loss of capacity will affect the financial well-being of any facility and must be considered as a significant potential consequence of earthquake damage.

2.3.4 SEISMIC VULNERABILITY OF HOSPITALS

Seismic vulnerability of a hospital facility is a measure of the damage a building is likely to experience when subjected to ground shaking of a specified intensity. The response of a structure to ground shaking is very complex and depends on a number of interrelated parameters that are often very difficult, if not impossible, to predict precisely. These include: the exact character of the ground shaking the building will experience; the extent to which the structure will respond to the ground shaking; the strength of the materials in the building; the quality of construction, the condition of individual structural elements and of the whole structure; the interaction between structural and nonstructural elements; and the live load in the building at the time of the earthquake.

Frequently, seismic activity causes insignificant damage to the structure of a hospital, yet its operations are impaired or disrupted because of damage to nonstructural elements. Even a low-magnitude seismic event can affect vital functions of a hospital and cause its evacuation and closure. This was evident in some recent earthquakes, whereby structures designed in accordance with modern seismic resistance criteria performed well, while the poor performance of the nonstructural elements caused serious disruption of hospital operations.

A variety of methods for assessing seismic vulnerability of buildings exist that differ in cost and precision. The type of method to be used depends on the objective of the assessment and the availability of data and appropriate technology. Typically, quicker and less sophisticated methods, like the commonly used rapid visual screening, are used for larger areas and large number of buildings. They often form the first phase of a multiphase procedure for identifying hazardous buildings, which must then be analyzed in more detail to determine upgrading strategies. Detailed assessment procedures use computer models and various forms of engineering analysis that are time consuming and expensive and require a high degree of analytical expertise to obtain reliable results. Consequently, they are used for detailed verification of the safety of structural and nonstructural elements, including proposals for specific mitigation measures.

A simple preliminary vulnerability assessment of existing hospitals can be performed using the results of the historical study of hospital performance in a variety of seismic events. This method is described below in greater detail.

2.3.4.1 Seismic Vulnerability of Hospitals Based on Historical Performance in California

A recently completed study on "*Seismic Vulnerability of Hospitals Based on Historical Performance in California,*" (Holmes and Burkett, 2006) analyzed the historical record of losses to hospitals damaged in major California earthquakes since 1971. The data base contained two hundred eighteen cases, each representing a hospital (potentially one or more buildings) that experienced earthquake ground shaking in the earthquakes of San Fernando (1971), Imperial Valley (1979), Coalinga (1983), Whittier (1987), Loma Prieta (1989), Sierra Madre (1991), and Northridge (1994). Damage reports varied from brief, one-paragraph summaries to elaborate narratives of the damage patterns and the consequences. Evacuations or shut-downs of facilities were always noted. These descriptions were used to categorize hospital damage into one of the structural and nonstructural performance categories shown in Table 2-2.

Table 2-2: The description of performance categories in terms of structural and nonstructural building damage

Performance category (damage level)	Type of Structural Damage	Type of Nonstructural damage
None		
Minor	Minor structural damage (light concrete cracking, etc.)	Minor damage to nonstructural components or systems (plaster cracking, ceiling damage, some equipment shaken off supports)
Affecting hospital operations	Damage requiring immediate evacuation due to dangerous conditions or concern for collapse in an aftershock	Nonstructural damage that prevents full functioning of the hospital (loss of emergency generator, local pipe breaks and causes flooding, computer system down)
At least temporary closure	Closure could be temporary or permanent	Temporary Closure based on major nonstructural damage (long-term power or water outage, extensive ceiling and light fixture damage, major flooding)

The study related the recorded levels of damage experienced by hospitals and ground motion data for each seismic event, determined on the basis of recorded ground motion at the site during the earthquake and USGS data. The intensity of ground motion was represented by spectral acceleration at short periods (S_{DS}), measured in units of the acceleration of gravity "g" in order to match building code information that can be obtained locally (see Section 2.2.2.1). In this study, the spectral acceleration at short periods for each case in the historical record was labeled S_{HS}, which stands for historical short period spectral acceleration. By matching spectral acceleration data with performance categories, a relationship was established between the damage (and the consequences of damage) and the ground motion intensity that caused it. All buildings were divided into two groups according to the level and quality of seismic design and construction. The adoption of the HSSA in 1972 was used as a divide between pre-Act buildings and post-Act buildings. The results of this study presented the differences in performance of hospital buildings in California in graphic form on Figures 2-41 for pre-Act buildings and in Figure 2-42 for post-Act buildings.

The measure of ground motion intensity is different in the two figures. For pre-Act buildings, S_{HS} represents accelerations recorded at the time, while post-Act building performance was categorized according to ground motion expressed as the percentage of S_{DS} typically used in California for seismic design in the post-Act period. Post-Act buildings in the database were designed for the higher seismic zones of California, typically with an S_{DS} of about 1.0. To use this data to estimate potential damage to newer buildings in other parts of the country that have incorporated thorough seismic design with other values of S_{DS}, it is necessary to normalize the data to an S_{DS} of 1.0. The ground motion in Figure 2-42 is thus represented as a percentage of the S_{DS} used to design the building. "S_{HS} = 0.25–0.50 of S_{DS}" shows expected damage to a relatively new building when it is shaken with an intensity of 25 to 50 percent of its code design, as measured by S_{DS}. Since damage occurs even at levels considerably below the code earthquake, the data is still very useful for planning purposes. The probability of occurrence of shaking different from the code level can be estimated by local seismologists or engineers.

This study, based on past damages, provided a clearer picture of the vulnerability of hospitals and established a benchmark for vulnerability assessments of all the existing hospitals. Among other things, the analysis indicated that the threshold for potentially significant seismic damage coincided with the current, lower-bound ground motion intensity requiring seismic design for new buildings (S_{DS} greater than 0.167 g). The pre-Act charts indicated a slight possibility of significant structural damage, but a strong possibility of nonstructural damage at low shaking levels. It should be noted however, that structural damage requiring building closure has been recorded even at the S_{DS} level just above 0.4 g. The analysis of the post-Act data indicated that hospital buildings built in accordance with the 2000 IBC (or later edition) are unlikely to suffer serious structural damage for events up to, and including, the intensity of the code earthquake. However, as previously discussed, new hospital buildings may not perform as well as indicated on the post-Act charts, since most regions of the country do not have as strict design and construction codes and code enforcement as California. Nonstructural damage, which can reduce hospital effectiveness or even cause evacuation, remains a significant vulnerability, even in new buildings.

2.3.4.2 Vulnerability Assessment of Hospital Buildings

Although the above-mentioned study was based on data from California, where the ground motions have slightly different characteristics than in other parts of the country, the vulnerability to damage for certain building types at given levels of ground motion is comparable to any location. Prior to obtaining the detailed site-specific seismic evaluations, the expected damage from a given ground motion can be estimated on the basis of historical data. The results of the study, therefore, can be used effectively to make preliminary assessments of the vulnerability of hospitals in any seismic region of the country. While this type of analysis will not take the place of a formal seismic building evaluation performed by experienced design professionals, it can be very helpful in raising the awareness of potential earthquake risks, in determining whether a more detailed study of vulnerability is justified, and whether to incorporate more realistic damage projections in a disaster plan or emergency exercise.

For example, a hypothetical hospital near Charleston, SC, may determine from the local building code that the seismic spectral acceleration value for short periods at the site is 0.8 g. If one or more of their buildings are 20 or more years old and were designed without seismic provisions or with out-of-date seismic provisions, the pre-Act columns of Figure 2-41 should be consulted. The chart on Figure 2-41 for the range of S_{DS} between 0.6-0.8 g shows that, unless building-specific studies are done to prove otherwise, it should be assumed that a code earthquake will cause sufficient damage to hinder the full operations (about a 33 percent chance) or require closure of a building (about a 13 percent chance). Perhaps more importantly, the right column of Figure 2-41 indicates a high probability that hospital operations will be interrupted by nonstructural damage. In fact, for such a facility, even very low shaking levels of S_{DS} 0.2 g to 0.4 g could be expected to cause nonstructural damage resulting in significant disruption of hospital operations.

In contrast, a brand new hospital in northern Utah, on a site with S_{DS} of about 0.7 g, is unlikely to suffer significant structural damage (as shown on the post-Act charts, left column of Figure 2-42). However, if such a hospital was not constructed according to the best design and construction standards, it can be expected to suffer a more significant nonstructural damage than the post-Act data shown in Figure 2-42. A prudent disaster plan would in such a case consider the possibility that nonstructural damage could cause a temporary closure.

2.3.4.3 Comparability of Hospital Buildings

The structural performance of hospital buildings built anywhere in the country without any seismic design provisions is most likely comparable to the performance of pre-Act buildings as shown on Figure 2-41. All buildings in the pre-Act group were either constructed with no seismic design, or with the archaic seismic design rules of the 1960s or earlier. Most of these buildings were constructed with concrete, steel, reinforced masonry, or wood construction. Unreinforced masonry buildings are rare in California because most of these buildings have either been abandoned or retrofitted. However, it should be assumed that older buildings of unreinforced masonry bearing wall construction, that are still common in other parts of the country, would perform at the low end of the ranges recorded for pre-Act buildings.

Buildings with seismic designs completed in the 1970s and 1980s can be expected to perform somewhere between pre- and post-Act levels, but probably closer to the pre-Act data. Buildings classified as post-Act are exceptionally strong, because the designs were thoroughly checked and the construction monitored in detail. Due to the State-of-California-mandated scrutiny given design and construction, there are few hospital buildings outside of that area that would be equivalent to the post-Act category. However, the structural performance of hospitals built since the early 1990s that incorporated full seismic design, including an importance factor of 1.5, can be compared to the post-Act category.

The vulnerability assessment of existing hospitals with respect to nonstructural building components is different from the assessment of potential structural damage. Unless a significant emphasis was placed on the design and installation of nonstructural anchorage and bracing, and unless the construction was monitored and inspected regularly, the potential for damage to ceilings, partitions, pipes, ducts, equipment, and other nonstructural systems should be estimated using the pre-Act column and charts. Since it is unlikely that nonstructural systems have been adequately protected in areas outside of California, it is recommended to assume that

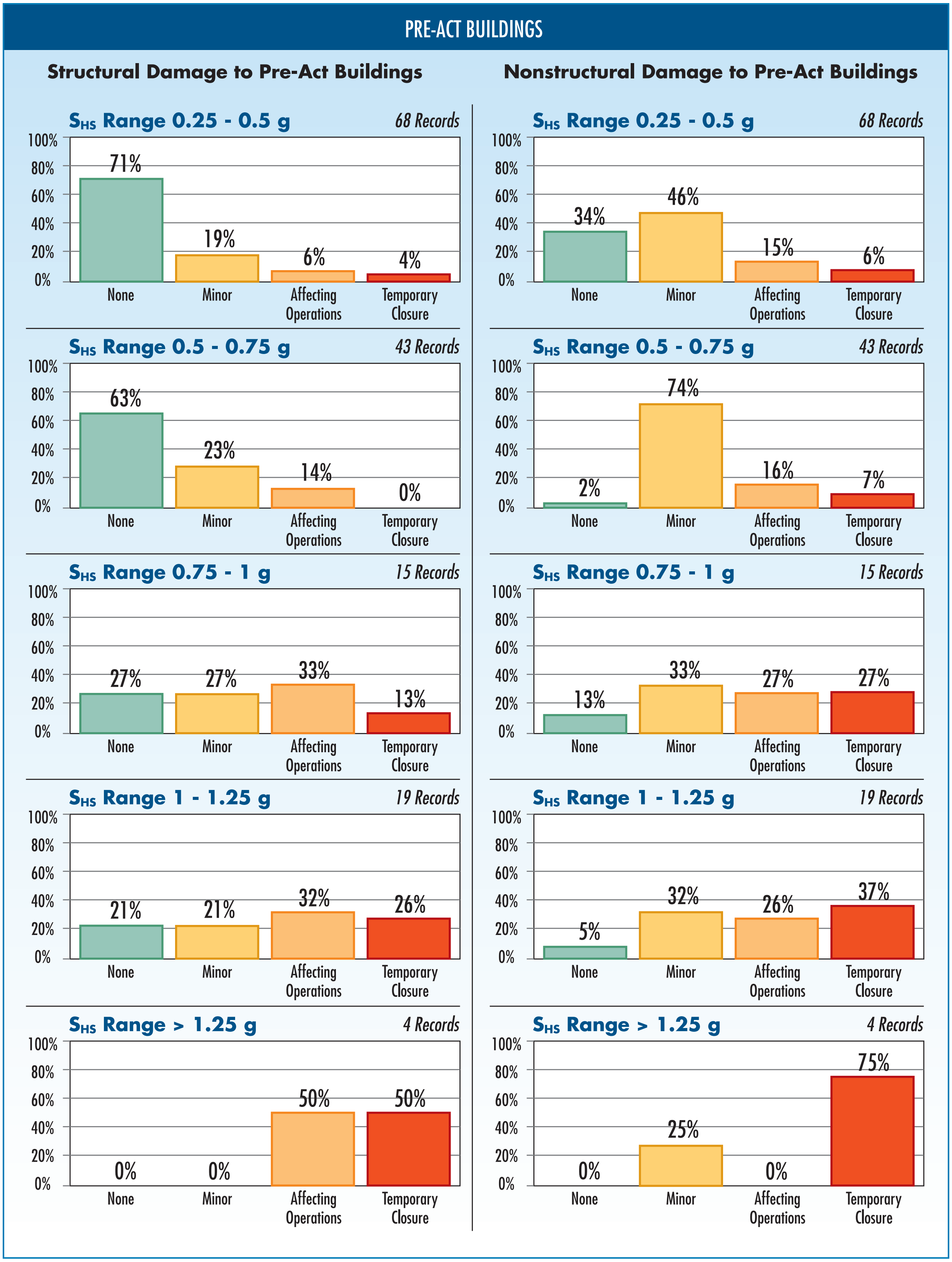


Figure 2-41: Charts showing performance categories for pre-Act buildings for various ground motions

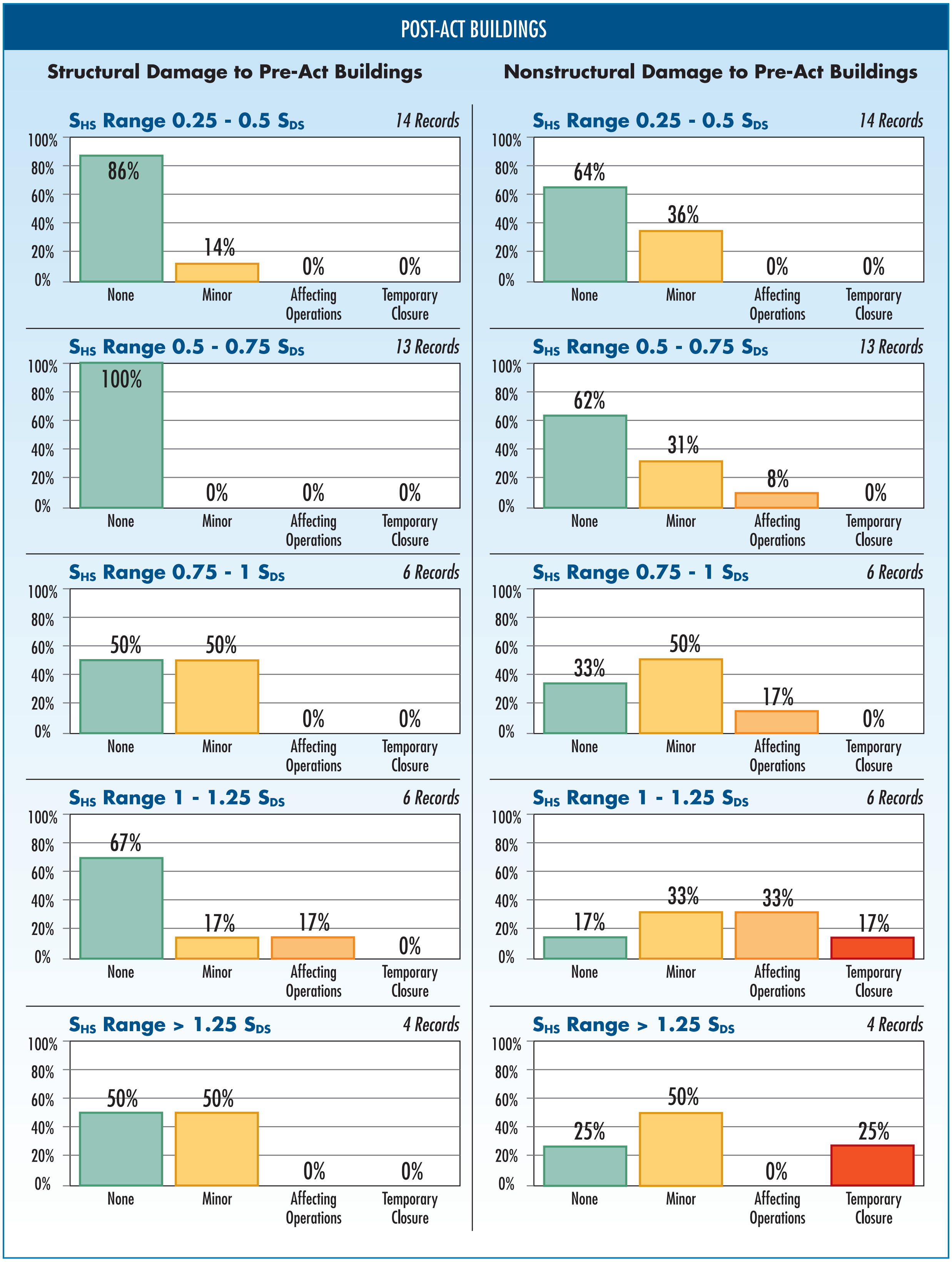


Figure 2-42: Charts showing performance categories for post-Act buildings for various ground motions

substantial damage to these systems would be a certainty in moderate to high levels of shaking. Even with the extraordinary measures taken in California to assure thorough seismic protection of nonstructural systems, the level of nonstructural damage recorded indicates that the potential disruption of hospital operations can happen at shaking of about 50 percent S_{DS}. The shaking above 80 percent S_{DS} would most likely result in nonstructural damage that would require immediate closure and total evacuation of the hospital.

This type of vulnerability analysis should be used for preliminary assessments or for the purpose of awareness training or emergency planning. It cannot replace a formal seismic building evaluation performed by experienced design professionals. The type and the extent of seismic risk exposure for hospitals can only be identified by expert analysis.

2.4 RISK REDUCTION MEASURES

This section outlines some of the basic approaches and techniques of mitigating earthquake hazards. Since the theory and practice of seismic design are well established and have largely been incorporated into the current model building codes, this section starts with the review of basic steps in the process of planning and design of hospitals. It also highlights some of the well-established seismic design and construction techniques and specialized building systems designed specifically to address the seismic forces. Although the general principles of design are similar for new and existing hospitals, this section highlights the differences in code requirements and overall project delivery processes that reflect the opportunities and constraints of seismic design for new and existing buildings.

2.4.1 SITE SELECTION BASICS

The first priority for owners of existing hospitals and planners and designers of new facilities is to understand the seismic hazard risk. The location and the physical characteristics of the site determine the extent of seismic hazards, which include the potential intensity of ground shaking, the possibility of liquefaction, earthquake induced landslide, or more rarely, the potential of a tsunami or seiche. If ground motion is the only or predominant hazard, site seismicity can be determined from the local building code by a local structural engineer or a building department official. More detailed information can be obtained from the USGS Web site, which provides seismological information for any zip code in the nation. When hazards in addition to ground motion exist, seismic experts are needed to determine the probability and extent of these risks and possible mitigation techniques.

The selection of hospital sites is generally based more on factors associated with availability of land, proximity to service area, cost, convenience of access for patients, visitors, and staff, or general demographic concerns than on the exposure of these sites to natural hazards, particularly earthquakes. Careful site selection, however, is a critical first step in risk reduction, because the potential ground motion from a single earthquake may vary considerably depending on the nature of the soil and the distance of the site from known earthquake faults. A large medical center that is developing a plan for new multi-building facility should include comprehensive analysis of the site characteristics and its exposure to natural hazard as an important factor in evaluating alternative sites.

- Consider seismic constraints in site selection. Although it would be very rare for a hospital district to make a site selection decision based solely on seismic risk, moving a hospital even a few miles in some cases can make a big difference to its exposure to seismic hazard. An example is locating a hospital 5 to 10 miles away from a major earthquake fault, rather than locating it within 1 mile of the fault.

- Locate the building on a soil type that reduces the risk. 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 damage from liquefaction, land sliding, or lateral spreading of the soil.

- Since hospitals should be designed to performance-based criteria that include minimum disruption and continued operation, the location of the site within the region may play a critical role in achieving the required performance. The definition of "site" becomes the region within which the facility is located, and assessments should be made with respect to its access to materials, personnel, and utilities, as well as its position in the regional transportation grid.

In most cases, however, it is probable that a site with optimal characteristics (other than seismic considerations) will be selected and that seismic issues will be mitigated as part of planning and design of the facility. A proposed construction site located directly over a fault is probably the only location characteristic that would lead to rejection of an otherwise suitable site.

2.4.2 SEISMIC DESIGN BASICS

Minimum standards and criteria for seismic design are defined in the seismic section of 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. The seismic provisions in building codes are adopted by State or local authorities, so it is possible for a seismically-prone region to be exempt from seismic building code regulations if the local community decides that the adoption of such provisions is not required. Hospital board officials and designers should not ignore seismic design requirements irrespective of whether local communities have adopted seismic code regulations or not.

Budgeting extra costs for seismic design is a difficult issue, because although the risk may appear to be minimal, the effects could be catastrophic if a significant event were to occur. The very fact that such an event is rare means that the community may have no history of designing for earthquakes, and the building stock in general would be especially vulnerable. Hospital buildings are an important community resource (along with other essential buildings, such as schools and fire and police stations) that must be protected as much as possible.

2.4.3 STRUCTURAL SYSTEMS

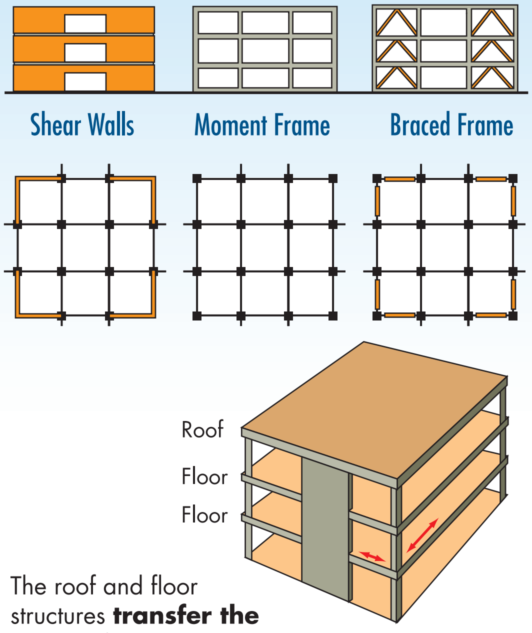
Health care facilities occupy buildings of different sizes, configurations, and structural systems. Additionally, hospitals differ in the level of services they provide. Some hospitals are distinguished by high occupancies, while others emphasize outpatient services. The mixture of functions and services is such that hospitals frequently require building systems that can accommodate very diverse functions. These can vary from acute care with many diagnostic, laboratory, and treatment areas requiring high-tech facilities and services to support functions such as laundry, food service, receiving, storage, and distribution.

Smaller healthcare facilities may encompass one or more of these functions, such as predominantly longer residential care, or specialized treatment such as physical rehabilitation or dialysis. This functional variety may influence some structural choices, but the structure, as in all buildings, plays a primary role in providing a safe and secure support for the facility activities. Since continued operation is the preferred performance objective, structural design that goes beyond life safety standards is necessary, which requires special attention.

2.4.3.1 Basic Types of Lateral Force Resisting Systems

Figure 2-43 shows the basic types of structural lateral force resisting systems. These systems compose the three basic alternatives for providing lateral resistance: shear walls, braced frames, and moment-resistant frames. Each of these has specific characteristics, such as stiffness, relationship to spatial requirements, and cost-effectiveness that must be evaluated for each project. Diaphragms connect horizontal and vertical elements and transfer the seismic loads to the lateral force resisting system. This concept is shown in Figure 2-43. Structural material alternatives—steel, reinforced concrete, reinforced concrete masonry, and wood, provide further options that must be evaluated. Figures 2-44, 2-45, and 2-46 show the three systems and materials that can be used to resist seismic forces in more detail.

HOW BUILDINGS RESIST EARTHQUAKES



The roof and floor structures **transfer the lateral forces** to the columns and shear walls

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.

Figure 2-43: Basic types of lateral force resisting systems

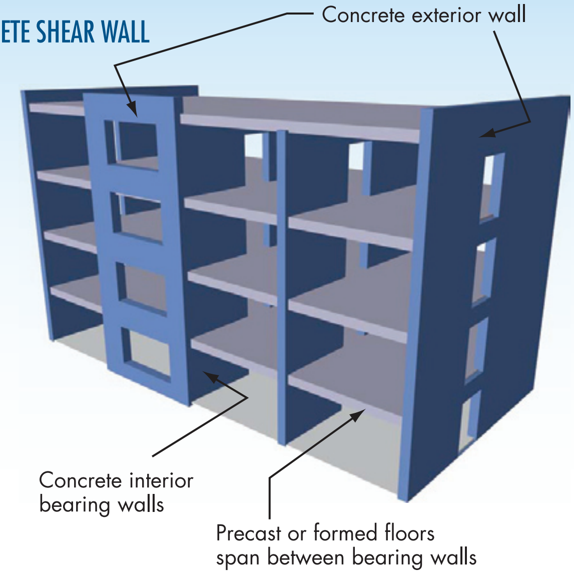
SOURCE: *BSSC: PRESENTATIONS TO THE ARCHITECTURAL COMMUNITY*, 2001, CHRIS ARNOLD AND TONY ALEXANDER

Figure 2-44:
Reinforced concrete shear wall structure

FEMA BUILDING TYPE C2 – CONCRETE SHEAR WALL

with Bearing Walls

Concrete shear walls are concrete walls in a building design to provide lateral stiffness and strength for lateral loads. There are two main types of shear wall buildings, those in which the shear walls also carry the gravity loads (with bearing walls), and those in which a column-supported framing system carries the gravity loads (with gravity frame). In the bearing wall type, all walls usually act as both bearing and shear walls.



FEMA BUILDING TYPE S2 STEEL BRACED FRAMES

These buildings consist of a frame assemble of steel columns and beams. Lateral forces are resisted by the diagonal steel members placed in selected bays. Floors are cast-in-place concrete. These buildings are typically used for buildings similar to Steel Moment Frames, although are more often low rise.

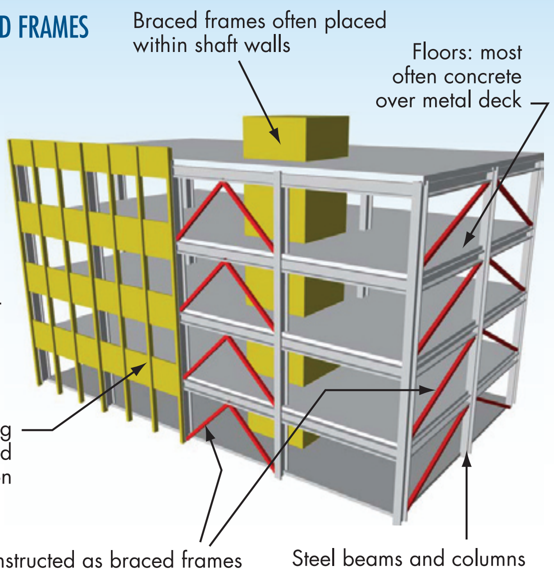


Figure 2-45: Steel braced frame structure

FEMA BUILDING TYPE S1 – STEEL MOMENT FRAMES

These buildings consist of an essentially complete frame assembly of steel beams and columns. Lateral forces are resisted by moment frames that develop stiffness through rigid connections of the beam and column created by angles, plates, and bolts, or by welding. Moment frames may be developed on all framing lines or only in selected bays. It is significant that no structural wall are required. Floors are cast-in-place concrete or slabs or metal deck and concrete. The building is used for a wide variety of occupancies such as offices, hospitals, laboratories, academic and government buildings.

The S1A building type is similar but has floors and roof that act as flexible diaphragms such as wood or uptopped metal deck.

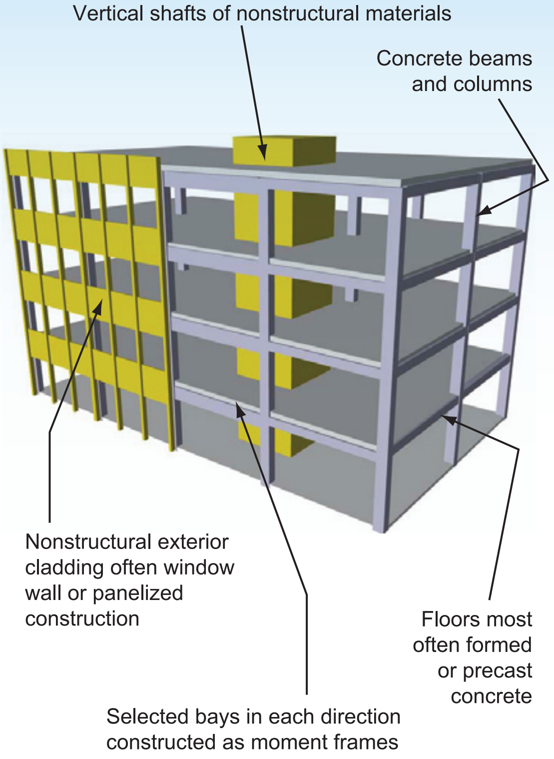


Figure 2-46: Steel moment resistant frame

Many variations of these types are possible, together with other structural types such as wood frame, light steel, reinforced masonry, and tilt-up reinforced concrete. The seismic codes expand these three basic systems into six categories by the addition of two categories of dual systems (composite steel and reinforced concrete) and inverted pendulum systems (such as cantilevered water tanks).

For each of the three basic systems, four coefficients and factors are provided, of which the most unique is the response modification, or "R" factor. This is a coefficient related to the overall behavior and ductility of the structural system. R has values from 1.25 to 8, and is a divisor that modifies the base shear value obtained in the ELF procedure by reducing the design forces. The higher the number assigned to R, the greater the reduction. Thus, the highly ductile and better-understood moment resisting frame has a value of 8, while an unreinforced masonry structure has a value of 1.5. Using the R reduction is justified because experience and research confirm the expected performance of these systems and their ability to accept overloads.

2.4.3.2 Innovative Structural Systems

In recent years, a number of new approaches to the seismic protection of buildings have been developed that are now seeing increased use. These systems depend on modifying either the seismic loads that are transmitted from the ground to the building, or the building response. In both instances, the strategy is to let the building "ride with the punch," rather than relying on resistance alone to protect the building.

Seismic isolation, generally referred to as *base isolation*, is a design concept that reduces the earthquake motions in the building superstructure by isolating the building from ground motions. This is accomplished by supporting the building on bearings that greatly reduce the transmission of ground motion (see Figure 2-47). Both the structure and the nonstructural systems are subjected to reduced shaking levels, so the system is well suited for essential facilities, like hospitals that need to remain functional following an earthquake. Many emergency management centers and a few hospitals in the United States have employed this technique. It has also been used by private industry on buildings of high importance, and as a retrofit technique, mostly for significant historic buildings.

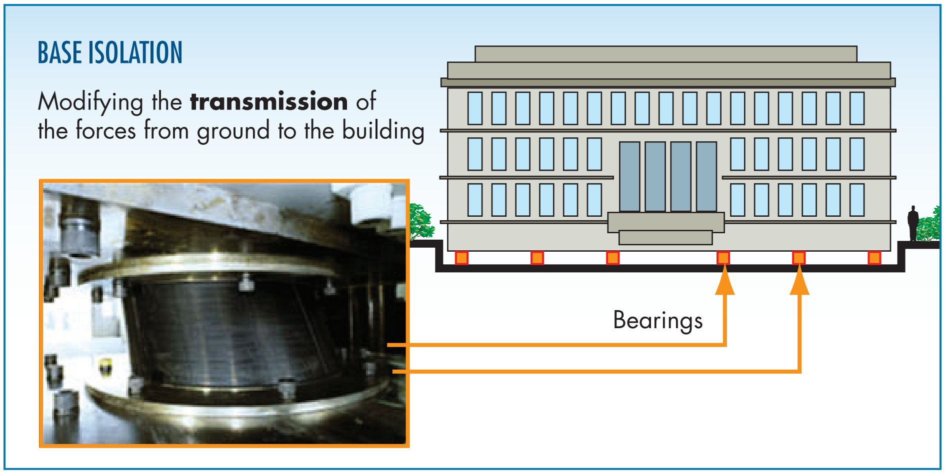


Figure 2-47: Seismic isolation

Passive energy dissipation is another concept in which the earthquake forces in the building are reduced by the introduction of devices that are designed to dissipate the earthquake energy in a controlled manner using friction, hydraulics, or deformation of material specially placed for this purpose (see Figure 2-52). These devices usually take the form of a bracing system that connects the vertical structural members together. These devices also increase the damping of the structure and reduce the drift. The Bremerton Naval Hospital provides an example of successful rehabilitation that used these devices (see Section 2.4.6.2).

2.4.3.3 Structural Systems Selection

The seismic code prescribes the analysis procedures for a number of different types of structural systems. The engineer, however, must choose the system that is appropriate for the type of building and its use. Structural systems vary greatly in their performance attributes, even though they may all meet the requirements of the seismic code if correctly designed and constructed.

The critical initial step in selecting a structural system is to establish performance goals for the project. Because hospitals are classified as essential buildings, the seismic code requirements imply a requirement for a certain level of performance. An informed performance-based design procedure is necessary. This procedure should involve the owner, the full design team, and any other stakeholders. The process should cover all steps, from determining performance goals to the detailed design and construction of the project.

On the technical side, the most important measure of good earthquake-resistant design is the effect on the structure after the earth has stopped shaking. With little building damage, there is a good chance that the building will be functional and repair costs will be low. With significant damage, it is unlikely that the building would be functional and repair or replacement costs would be high. The measure of success in seismic design of a hospital is the extent to which a building can avoid significant damage and retain a reasonable level of functionality without the need to evacuate patients. The behavior of each structural system and building configuration differs with earthquake ground motions, soil types, duration of strong shaking, etc., but past observations of damage can inform the decisions about the most appropriate systems.

The best performing structural systems will do the following:

- Possess stable cyclic behavior. Will not be prone to sudden structural failure or collapse
- Control lateral drift. Will keep drift (lateral distortion between floors) to reasonable dimensions to reduce damage to nonstructural components, such as glazing, partitions, and cladding
- Dissipate seismic energy without failing. Absorb the earthquake energy in a controlled manner without causing structural members to fail
- Create a good chance of functionality and a low post-earthquake repair cost

2.4.4 NONSTRUCTURAL COMPONENTS AND SYSTEMS

For a long time, seismic building codes focused exclusively on the structural components of building. Although this focus still remains dominant, experience in recent earthquakes has shown that damage to nonstructural components and systems is also of great concern. Continued hospital operation is increasingly dependent on nonstructural components and systems, including medical and building equipment. Hospital operations also depend on specialized services, some of which involve storing of hazardous substances, such as pharmaceuticals, toxic chemicals, oxygen, and other gases, that must be protected against spilling. Distribution systems for hazardous gases must be well supported and braced. Unlike most buildings, hospitals require a very extensive plumbing network to supply water throughout the building, and an adequate piping network to supply water for fire sprinklers, which increases the risk of secondary water damage in case of failure of these systems during earthquakes.

In a typical hospital, not only do the nonstructural components play a major role in operations, they also account for large share of the cost. Typically, for a medium-size hospital, the structure accounts for around 15 percent of the total cost, and the nonstructural components for the remaining 85 percent. Of the latter, the mechanical, electrical, and plumbing systems alone account for approximately 35 percent of the total building cost.

Even though the building structure may be relatively undamaged after an earthquake, excessive structural motion and drift may cause damage to ceilings, partitions, light fixtures, service piping, and exterior walls and glazing. In addition, storage units, medical equipment, and filing cabinets may topple and cause injuries if not properly anchored or braced. Excessive drift and motion may also lead to damage to rooftop equipment, and localized damage to water systems and fire suppression piping and sprinklers. Heavy equipment, such as shop machinery, kilns, and heavy mechanical and electrical equipment, may also be displaced and become non-functional.

2.4.4.1 Code Regulated Nonstructural Systems

The seismic code categorizes nonstructural components as architectural components or mechanical and electrical components. Many of the hospital contents, such as furnishings and specialized equipment, which may be critical to hospital function, are not subject to regulation.

Table 2-3 shows the list of nonstructural components and systems that are subject to code regulation.

Table 2-3: Code Regulated Architectural, Mechanical, and Electrical Components

Architectural Components	Mechanical and Electrical Components
Interior Nonstructural Partitions	**General Mechanical**
Plain unreinforced masonry	Boilers and furnaces
Other walls and partitions	Pressure vessels
Cantilever Elements, Unbraced	Stacks
Parapets	Cantilevered chimneys
Chimneys and stacks	Other
Cantilever Elements, Braced	**Manufacturing And Process Machinery**
Parapets	General
Chimneys and stacks	Conveyors (non-personnel)
Exterior Nonstructural Wall Elements	**Piping Systems**
Wall elements	High deformability
Body of panel connections	Limited deformability
Fasteners of connecting systems	Low deformability

Table 2-3: Code Regulated Architectural, Mechanical, and Electrical Components (continued)

Architectural Components	Mechanical and Electrical Components
Veneer	**HVAC System Equipment**
Limited deformability	Vibration isolated
Low deformability	Non-vibration isolated
Penthouses, Not Part of Main Structure	Mounted in-line with ductwork
Ceilings	Other
Cabinets	**Elevator Components**
Storage cabinets and lab equipment	**Escalator Components**
Access Floors	**Trussed Towers (Free-standing or Guyed)**
Special access floors	**General Electrical**
All others	**Lighting Fixtures**
Appendages and Ornamentation	
Signs and Billboards	
Other Rigid Components	
High deformability elements	
Limited deformability elements	
Low deformability elements	
Other Flexible Components	
High deformability elements	
Limited deformability elements	
Low deformability elements	

Figure 2-48 is an example of a cable tray with a braced support system designed in conformance with the seismic code.

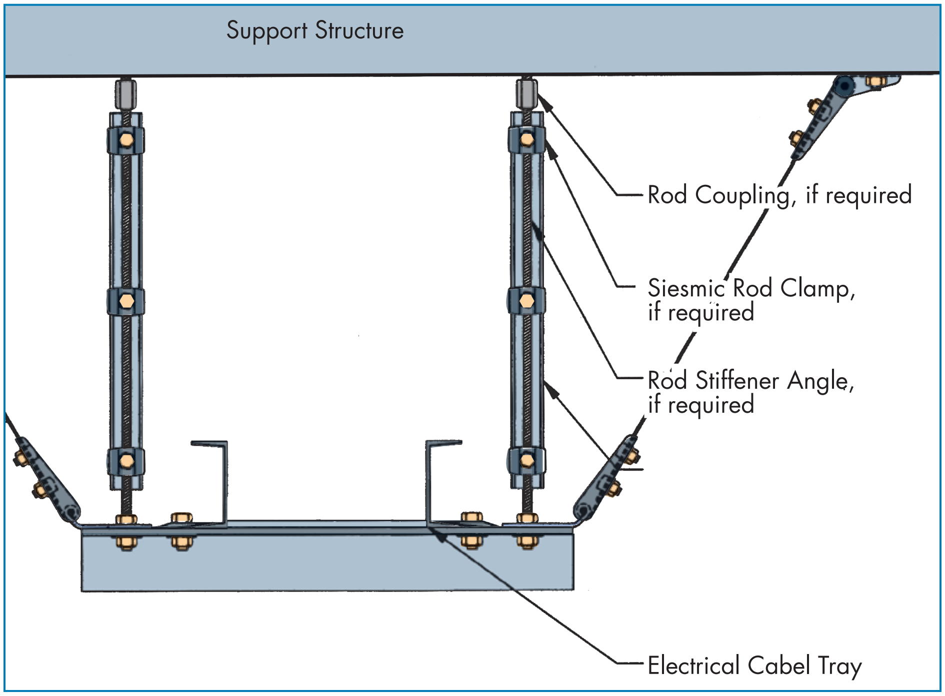


Figure 2-48: Seismically braced cable tray support

2.4.4.2 Interstitial Space for Utility Installations

Developments in medical technology frequently require hospitals to add or re-route utility and medical services infrastructure and add electrical capacity to various parts of the building, often with consequent disruption of the operations and difficulties caused by limited available space above the ceiling. In response to these problems, a number of hospitals have been designed with interstitial service space. In some designs, the interstitial floor is a nonstructural floor hung from the structural floor above (Figure 2-49).

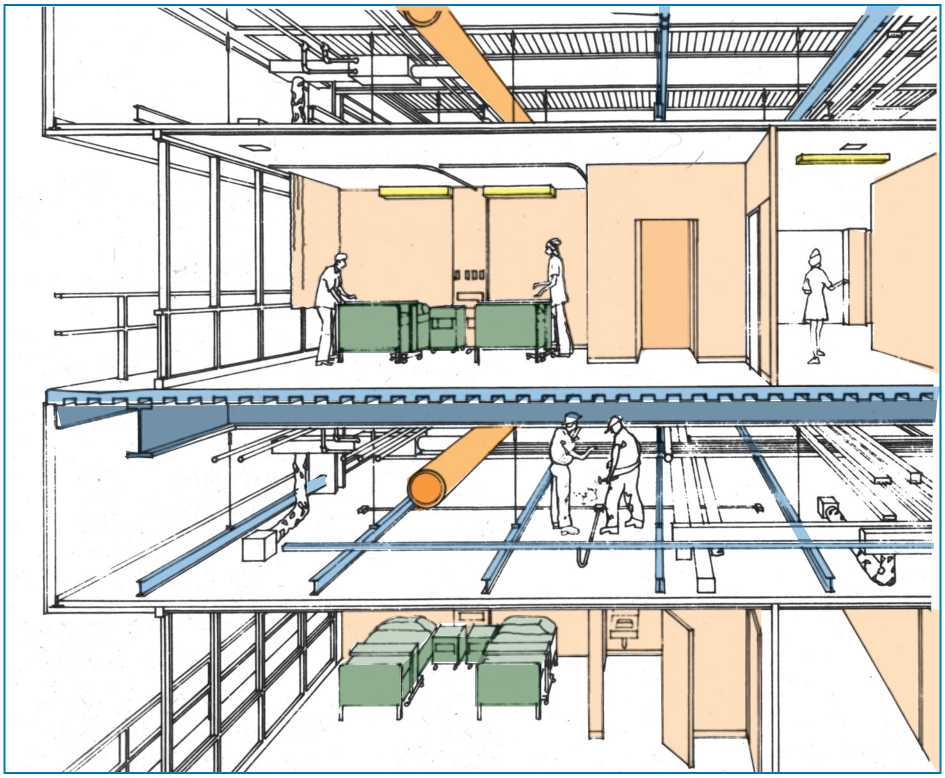


Figure 2-49: Interstitial floor system hung from the floor above

The interstitial space concept provided a full floor above the functional space where service personnel can work to add or modify installations without disturbing the space below, or disrupting hospital operations. The main structural effect of an interstitial floor is to increase the floor-to-floor height of the occupied floors and the building as a whole, with some increase in the amount of structural material. Any of the common steel and concrete frame systems can be used to provide the interstitial floor arrangement. The interstitial space concept was used in the Loma Linda Veterans Hospital (see Section 2.4.5.1)

2.4.5 MITIGATION MEASURES FOR NEW BUILDINGS

If mitigation measures are instituted in the planning stage, a high level of seismic protection can be achieved in a new building with the following steps:

- ❍ Assure that the latest model building code is used, using the appropriate importance factor.
- ❍ Include provisions in the design to allow the facility to function on its own for 4 days. This would require storage of sufficient fuel for emergency standby power supply system, reserve water supply, and provisions for waste water storage. Assure that access to the site will not be impaired by earthquake damage.
- ❍ Although seismic isolation should be considered for all buildings that are intended to be functional after an earthquake, this measure should be considered as a realistic alternative only for sites with S_{DS} over 0.8 g.
- ❍ Consider a peer review of the structural design, particularly in jurisdictions that do not require a thorough plan check to obtain a building permit. A peer review is essential if innovative structural systems, such as isolation or structural dampers, are used.
- ❍ Assure that the seismic design for nonstructural elements and systems regulated by the building code are the responsibility of the design team. A list of such responsibilities is given in FEMA 356. One method of gaining such assurance is to create the position of a Nonstructural Seismic Coordinator (NSC), whose responsibility is to review the specifications, drawings, or other methods proposed to attain adequate seismic anchoring and bracing of all systems. Further, the NSC will follow the submittals and construction processes to assure appropriate implementation.
- ❍ Put in place a comprehensive system to monitor construction quality and to track significant change orders that might imply subtle reductions in structural or nonstructural seismic performance.

2.4.5.1 The Case of Loma Linda Veterans Hospital

The 500-bed Veterans Administration Hospital in Loma Linda, CA, opened in September 1977. Designed as a replacement facility for the Veterans Administration Hospital lost in the 1971 San Fernando earthquake, it was built in the area of extremely high seismicity, and represents an interesting case of careful seismic design.

The project was remarkable because of the extent to which the configuration of a large and complex building was influenced by seismic design concerns. At the same time, the project provides a lesson in showing that early recognition of seismic design determinants by the whole design team, and a serious interdisciplinary approach from the inception of design, can enable requirements of both seismic design and hospital planning and economy to be achieved with equal effectiveness.

The San Bernardino Valley is seismically very active, and the final site selected for the new hospital had 11 known active faults within a 65-mile radius, including the San Jacinto fault and two segments of the San Andreas fault. The potentially active Loma Linda fault was also believed to be located near the site, and after intensive studies, it was concluded that the most likely location of the fault was 200 to 400 feet southwest of the site, but that surface rupture at the site was not likely. The risk of soil amplification was significant.

The consultants recommended that design earthquakes of magnitude 8+ and duration of 35–40 seconds on the San Andreas fault, and magnitude 6.5–7.25 and duration of 20 seconds on the San Jacinto fault, should be considered. The building structure was to be designed for a peak acceleration of 0.5 g, while the essential and potentially damaging nonstructural components were to be designed for an acceleration of 2.0 g.

Some of the design force determinants evaluated were dependent on a building configuration concept.

1. **Site geometry:** The large 40-acre site enabled the designers to consider a freestanding building unconstrained by site geometry. The site area was sufficiently large to allow consideration of a relatively low, horizontally planned building.

2. **Design Program:** Research studies on hospital organization and planning had established some general benefits of horizontal planning—defined as plans in which clinical and diagnostic areas are placed on the same floor as nursing areas, rather than being concentrated into a base structure with a vertical connection to the bed-related functions. Experience in vertically planned hospitals had indicated some problems in ensuring adequate circulation, since the concentration of vertical circulation into a single tower tended to result in over- or under-capacity, depending on the time of the day. There were also indications of a general preference by staff for horizontal movement over vertical, and an indication that a reduction of vertical circulation for severely ill patients would be desirable.

3. **Aesthetics:** The design of hospitals tends to be dominated by the solution of very complex planning, service, and equipment problems, and appearance tends to be a secondary concern. The city of Loma Linda was anxious that the setting of the hospital should be "parklike." In response to this desire, and to the generally small scale of the immediate site surroundings, the image of a low, nonassertive building, placed toward the center of the site, seemed appropriate. Although very large in size, the building's relatively low height and the considerable size of the site was to help reduce the visual effect of the building on the neighboring community

4. **Building system:** The Loma Linda Hospital was intended as a demonstration of the Veterans Administration Hospital Building System, which had been developed over a period of several years by the same team that was responsible for the hospital design. The building system consisted of a carefully conceived set of design concepts intended to rationalize and organize the preliminary hospital design.

The structural design comprised moderate-span simple post and beam shallow floor framing system, large floor-to-floor heights, and lateral force resistance elements concentrated in the service tower at the end of each of the service modules. The planning and aesthetic requirements of a low, deep plan building coincided well with a stiff seismic design that would minimize story drift; consequent architectural, mechanical, electrical, and contents damage; and loss of operational capability. In addition, the low, stiff building would have a shorter period and possibly a lower response than the projected response spectra peaks of 0.3 and 0.8 seconds from the two nearby faults. The only way of moving the building response well away from the ground response would be to develop a flexible high-rise structure that would be undesirable from all the other viewpoints considered.

The chosen configuration was the simplest of all those studied: a simple block, almost square in plan, with no basement and with a symmetrical pattern of four courtyards within the block. The courtyards were relatively small. The plan had an even distribution of shear walls throughout, running uninterrupted from roof to foundation and having direct continuity in plan with the structural framing members.

The planning and circulation of the building were carefully related to shear wall layout to achieve minimum shear wall penetration with clearly defined, highly accessible public and departmental planning. The eight service towers (four at each end) provided a location for major shear walls. Each tower provided two shear walls in the east-west direction and one in the north-south direction.

The general lateral resisting system used concrete shear walls and a ductile moment-resistant “backup” frame. The stiff primary shear wall system was designed for a high force level, so that the structure will tend to have low lateral deflections for the design earthquakes described earlier. The calculated maximum story-to-story drift was well within presently accepted desirable ranges for hospitals.

The backup frame was intended to form a stable and reliable backup system for lateral force resistance and redistribution of forces should one or more of the shear walls become seriously damaged. The chances of the backup frame being forced to work to its full capacity were considered small, but considering the size and importance of the facility, and the uncertainties of estimating the nature of ground motion, the possibility could not be ignored.

Shear walls were always placed at the perimeter of service modules to minimize interference. Interior girders were dropped below the beams to minimize interference with plumbing service and to allow beam continuity across the module. As a result of the service organization, all beams and girders are free of penetrations. These framing characteristics were the product of the research study that determined the system’s design.

The shear walls are collocated with frame lines. The advantages of this arrangement were:

- Beams or girders were always parallel and lined up with the walls, to serve as lateral force collectors.
- The continuation of these members through the wall allowed direct transfer of forces from the diaphragm to the wall.
- The columns at the end of walls formed the required ductile flange members.
- Frame members were in the correct position to provide vertical support for shear wall dead loads.

Complete calculations and designs were completed for all nonstructural components and systems. The bracing of utility distribution systems, ceilings, partitions, and lights was made easier and less expensive by the presence of the interstitial floor system shown in Figure 2-49.

2.4.6 MITIGATION MEASURES FOR EXISTING BUILDINGS

Engineering of structural and nonstructural risk reduction measures is similar for new and existing hospitals. New hospital design offers the possibility to minimize the risk by selecting a site subject to less ground motion, with better soil conditions, or located farther from a fault. It 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 hospital. The existing building may have been designed to an obsolete seismic code or no code at all, its materials may be questionable, or the building configuration and structural system may be inappropriate. Therefore, protecting an existing hospital must start with a detailed evaluation of its vulnerability, because seismic retrofitting is both disruptive and expensive, and should not be implemented without careful study.

2.4.6.1 Procedures and Design Strategies for Rehabilitation of Structural Systems

Additions to an existing hospital must meet all the code requirements for a new building. With the exception of California, there are currently no seismic codes that apply to the retrofit of existing hospitals. Typically, the standards to be applied are derived from the code for new buildings and negotiated with the applicable building department. It is generally recognized that it is difficult, or almost impossible, to bring an existing structure to full compliance with a current code, and so some compromises have to be made. There is, however, no general agreement as to how the code for new buildings shoul be applied to the retrofit design of existing ones.

FEMA has developed many such documents and several have been adopted by ASCE as standards suitable for adoption by building codes (see ASCE 31 and ASCE 41). The planning process for retrofits should begin with an evaluation procedure, such as Tier 1 of the ASCE 31 *Seismic Evaluation of Existing Buildings* (ASCE, 2003). If the evaluation results require a retrofit of an existing building, ASCE 41, *Seismic Rehabilitation of Buildings* (ASCE, 2007) is the authoritative source document and can be used to help a hospital design team select seismic protection criteria. The architect and engineer can also use the document for the design and analysis of the seismic rehabilitation project.

ASCE 41 provides methods and design criteria for several different levels of seismic performance. The document also recommends a thorough and systematic procedure for performance-based seismic design, intended to produce a design responsive to the owner's level of acceptable risk and available resources. This process starts with a requirement to select specific performance goals (Rehabilitation Objectives) as a basis for design. In this way, users can directly determine the effect of different performance goals on the design requirements, including their complexity and cost. See Section 2.2.3 for a further description of performance-based seismic design.

Typical basic design concepts for improving the structural seismic performance of an existing hospital include:

- Modifying and improving local components or materials, such as beam/column connections. This involves retrofitting connections and strengthening structural members by such methods as adding, reinforcing, or replacing them with new components.

- Adding new lateral force resisting elements, such as shear walls or braced frames.

- Removing or reducing configuration irregularities. This involves providing seismic separations in irregular configurations, or adding shear walls or bracing to reduce torsional effects. Mass can also be removed by removing stories.

- Modifying the basic seismic response of a structure by adding dampers or installing seismic isolation systems.

2.4.6.2 The Case of Naval Hospital Bremerton

Naval Hospital Bremerton, located in Bremerton, WA, not only serves military personnel and their families in the area—up to 60,000 people—but could also be called on to serve more than 250,000 people on Washington's Kitsap Peninsula after a major earthquake. The facility is spread over 40 acres, and includes 20 buildings, some of which are 70 years old. Being one of only two major hospitals in the region, the Navy was concerned about its response capability to moderate-to-strong seismic ground shaking expected at the site (Wilson, 2005).

To obtain a broad understanding of the vulnerability of the facility and the relative risk among the many buildings, a rapid visual screening was completed by the Navy's consultant, Reid Middleton, using FEMA 154 (FEMA, 2002), which considers structural type, basic seismic characteristics, building use, and occupancy load. This relatively modest effort provided an overview of the seismic risk at the campus, as well as a preliminary relative ranking among buildings. It made it obvious that the main hospital building, a nine-story, 250,000-square-foot building that housed most of the essential medical functions, should be a priority (see Figure 2-50).

The building is a steel moment frame, constructed in the 1960s, that employed welded beam-to-column connections, now known to be prone to cracking when subjected to large seismic deformations. A more detailed structural analysis and evaluation was performed using FEMA 356 (FEMA, 2000). It was found that although the frame does not pose a significant threat of collapse, the building's ability to function after an earthquake could be severely limited by damage to structural joints, and by nonstructural damage.

In February 2001, while the Navy and the design team were considering their options, the Magnitude 6.8 Nisqually earthquake struck the area. The earthquake occurred deep below the surface and approximately 30 miles from the site. The ground motions at the site were below the design shaking for the site, but nevertheless caused significant nonstructural damage—particularly in the upper floors (see Figure 2-51). Such nonstructural damage always causes concern about the integrity of the structure—and often requires destructive exploration to verify. Based on preliminary structural inspections, aided by recordings of the response from instruments in the building, the Navy decided to stay in the building while more extensive exploration and analysis were performed. It took several months before nonstructural repairs were completed and the building returned to full use. Subsequent structural review indicated no structural damage.

Figure 2-50:
The main building at Naval Hospital Bremerton

SOURCE: REID MIDDLETON, INC.

Figure 2-51:
Disruption in the upper floors at Naval Hospital Bremerton from the Nisqually earthquake

SOURCE: REID MIDDLETON, INC.

The data on the response of the building to the Nisqually earthquake provided an opportunity to simulate, by computer analysis, a design event. This simulation revealed that shaking at the design level could cause unacceptable damage, both to the beam-column joints and to nonstructural systems. The team found that traditional, code-based retrofits, such as local modification of the 1,550 beam-column connections, or introduction of braced frames to meet current standards, were too costly and disruptive. Solutions were investigated using the more finely tuned, performance-based design methodologies of FEMA 356, and a more innovative scheme, based on the introduction of supplemental seismic dampers, appeared feasible.

Several styles of dampers are available for use in buildings, including those employing controlled yielding of steel elements, those based on friction (similar to a brake shoe), and more sophisticated hydraulic dampers (similar to a shock absorber). Dampers are normally placed in a building in a configuration similar to diagonal braces, and work against the movement between floors (see Figure 2-52). This action reduces inter-story drift and, to a lesser extent, reduces floor accelerations that cause sliding and overturning of equipment and contents. Although dampers should be evenly distributed throughout the building, they allow greater flexibility in placement than braced frames or other standard lateral force resisting systems. The flexibility in placement of the dampers means that critical locations, those that would reduce usefulness of the intended space or cause operational shutdowns during installation, can be avoided. Using performance-based design concepts, the team set the target structural performance levels for Immediate Occupancy (see Section 2.2.3.1) for the design earthquake shaking, and Collapse Prevention for a reasonable estimate of the worst shaking expected at the site. Structural analysis indicated that adding a total of 88 fluid viscous dampers, spread through the facility, would deliver the desired performance within the bounds of the current analysis and prediction capability. The cost of the structural retrofit was projected to be less than 10 percent of the replacement cost, a value that would yield a favorable life cycle cost (from damage avoided) on most sites in the country.

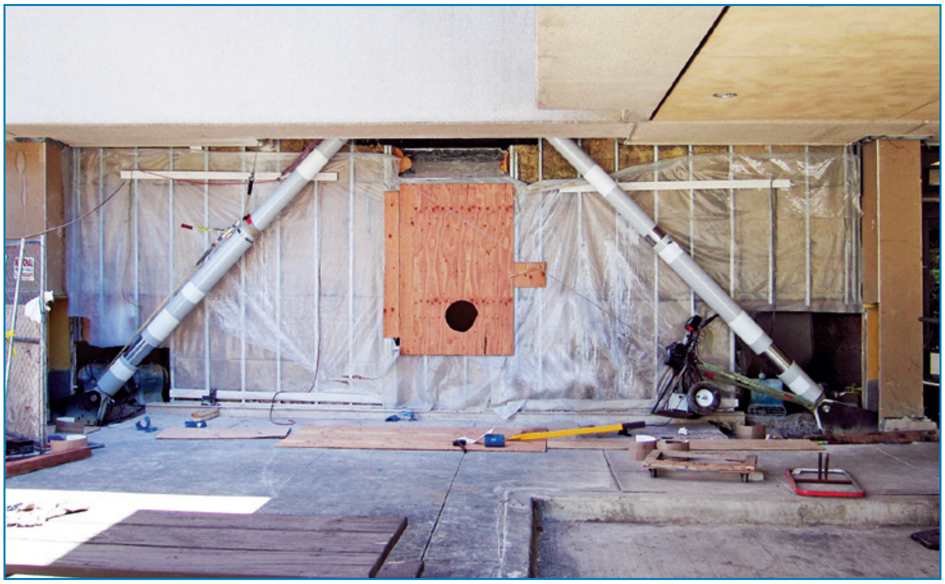


Figure 2-52:
Installation of dampers at Naval Hospital Bremerton. The configuration is similar to steel braced frames.

SOURCE REID MIDDLETON, INC.

In parallel with the retrofit design, the team developed an inexpensive and innovative program (called REACH—Rapid Evaluation and Assessment CHecklist) to improve the speed and effectiveness of future building safety evaluation following a seismic event. For many structural types, the seismic structural damage is covered and not obvious; concern about the extent of structural damage can sometimes delay decisions about building safety, or even cause an unneeded evacuation. The building-specific REACH program incorporates real-time data from the building's seismograph network. Threshold values for acceleration and displacement are pre-determined by the design team, and actual building motion is then compared with these threshold values to allow more accurate and informed decisionmaking regarding the ability of the building to sustain the safe delivery of medical services after earthquakes. The REACH checklist contains additional information, such as a description of the structural system, structural drawings, recommended structural inspection sites, and other information of use to the facility engineer and building inspectors. The REACH documents are stored in the facility department's disaster response locker, and are reviewed by facility staff during routine emergency drills.

Recognizing the significant effect that damage to nonstructural systems can have on post earthquake functionality, the facility has begun retrofit of nonstructural elements, including bracing of acoustic tile ceiling and light grids, mechanical system piping, as well as cabinetry and furniture. Future analysis and reinforcement of bracing for critical equipment (such as radiology and laboratory) is planned.

2.4.6.3 Procedures and Design Strategies for Rehabilitation of Nonstructural Systems

Complete, nonstructural seismic rehabilitation of an existing hospital in operation is disruptive and very expensive. However, it is relatively easy to incorporate seismic bracing and anchoring during ongoing renovation or rehabilitation work. A more active and aggressive program requires developing databases of components and systems, and developing a process for prioritizing. Priorities can be set by considering importance to life safety, importance to overall functionality, associated cost and disruption, component vulnerability, or by cost-benefit considerations (see FEMA 274 for more information).

Components commonly found to be of high priority because of their importance, high level of vulnerability, and relatively low cost include anchorage of standby generators, medical gas storage, pressurized piping, and communications systems. Although not normally considered a dangerous or high-priority system, damage to lightweight suspended panelized ceiling and light systems can disrupt hospital operations, as happened in Hawaii where such damage forced the KCH to evacuate (see Section 2.3.2.2). It is important that the key vulnerabilities of each facility be identified and considered in emergency planning and mitigation programs.

2.4.6.4 Summary of Risk Reduction Measures for Existing Buildings

Achieving cost-effective improvements in seismic performance of existing facilities is far more complex than improving expected performance for proposed new buildings in the planning and design stage. First, and most obvious, it is always far less expensive to include relatively small changes in a new design to create seismically resistant structural and nonstructural systems than it is to retrofit—or sometimes replace—existing systems. The complexity and expense of retrofitting is exacerbated when such work is not done in conjunction with complete renovation—that is, if the building has to remain mostly occupied and operational.

Following the recommended seismic evaluations, careful analysis is needed to identify significant life safety risks from potential structural collapse; to identify and achieve short-term, high benefit-cost mitigation measures; and to plan for longer-term overall mitigation. The following steps are recommended:

- Engage a structural engineer experienced in seismic evaluation and design to perform a seismic structural evaluation of existing buildings on the campus that contribute to the hospital function. The primary purpose of such an analysis is to quickly identify buildings that may be seriously damaged or even collapse in a code-level earthquake. A secondary purpose is to gain an understanding of the probable performance of the structural and nonstructural systems of each building by using the data charted in Figures 2-41 and 2-42.

- Engage an architect, mechanical and electrical engineer, and structural engineer, as needed, to evaluate the probable seismic performance of nonstructural components and systems.

- Update the emergency response plan, considering the results of the seismic evaluations.

- If significant life safety risks are identified from review of either structural or nonstructural systems, make plans to minimize occupancy of the building, replace the building, or retrofit to an acceptable level of performance.

- In most cases, shaking of less than code intensity, which may cause minor or no structural damage, can cause serious nonstructural damage. The most vulnerable elements that can affect the functions of the hospital have been identified from past earthquakes. They are the emergency generator, the bulk oxygen storage tank, the internal and external emergency communication systems, and the patient elevators. These elements, other than the elevators, normally can be anchored and braced against seismic damage rather inexpensively and quickly. The elevators may require extensive retrofit to assure operation after strong shaking. However, to assure safe patient relocation immediately after an event, it is recommended that one patient elevator serving each floor be retrofitted to at least the capacity of the structural system and to current standards for essential facilities. Automatic seismic switches that demobilize elevators at low shaking levels should be used with caution, as the switch may defeat the purpose of the strengthened elevator.

- Mechanical equipment on vibration isolators that are not designed for seismic forces are extremely vulnerable to seismic damage. This equipment should be identified and fitted with appropriate anti-seismic isolators, or seismic snubbers, as soon as possible.

- Nonstructural elements affected by or exposed by normal renovation should be upgraded to current standards.

- The expected seismic structural performance of all buildings on the campus should be considered as part of master planning. Planning should also consider opportunities to provide 4 days of self reliance, (See Section 2.4.5).

- Vulnerable medical buildings that can lose full functionality after a code earthquake should be studied for retrofit or replacement. Improvements in seismic structural performance can often be combined with major renovations. Adjacent additions can sometimes be made sufficiently strong to buttress an existing building.

- Incremental seismic rehabilitation, as described in FEMA 396 (2003), should also be considered for applicability.

- An emergency plan that considers the care of the patients and staff of the facility, as well as the surrounding community, should be kept up to date and should include a realistic estimation of the seismic performance of the structural and nonstructural systems in each building, and on the site in general.

- The Hospital Seismic Safety Evaluation Checklist (Table 2.4) should be applied.

2.5 CHECKLIST FOR SEISMIC VULNERABILITY OF HOSPITALS

The Checklist for Seismic Vulnerability of Hospitals (Table 2-4) is a tool that can be used to help assess site-specific seismic hazards and building vulnerability. The checklist is useful during site selection, preliminary design of a new building, or when considering rehabilitation of an existing facility. In addition to examining building design issues that affect vulnerability, the checklist also helps users to examine the functionality of the critical and emergency systems upon which most hospitals depend. The checklist is organized into separate sections, so that each section can be assigned to a subject expert for greater accuracy of the examination. The results should be integrated into a master vulnerability assessment to guide the design process and the choice of appropriate mitigation measures.

Table 2-4: Hospital Seismic Safety Evaluation Checklist

Vulnerability Sections	Guidance	Observations
Site Condition		
Is there an active fault on or adjacent to the site?	If suspected, site-specific geologic investigations should be performed. Consult local building department, State geologist, local university, or local geotechnical expert.	
Does the site consist of soft, stiff, or dense soil or rock?	If the presence of softer soil that can lead to force amplification or liquefaction is suspected, site-specific geologic investigations should be performed.	
Are post-earthquake site egress and access secured?	Alternative routes—unlikely to be blocked by falling buildings, power lines, etc.—are desirable.	
Are utility and communications lifelines vulnerable to disruption and failure?	Security of the entire utility and communications network is the issue: the facility may be affected by offsite failures.	

Table 2-4: Hospital Seismic Safety Evaluation Checklist (continued)

Vulnerability Sections	Guidance	Observations
Site Condition (continued)		
Are there alternate or backup sources for vital utilities such as water and power?	Redundant systems increase the probability of the hospital remaining functional after an event.	
Architectural		
Is the architectural/structural configuration irregular?	Irregular vertical and horizontal configurations, such as set backs, open first stories, or L- or T-shaped plans, may lead to significant stress concentrations.	
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. If waterproofing of these systems is compromised, rain following an earthquake could cause parts of the building to be closed.	
Are heavy veneers, 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.	
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 to accommodate drift	
Are light, suspended grid ceilings and lights braced and correctly attached at walls?	Suspended ceilings, if not braced, easily distort (particularly in light and flexible frame structures), thus causing ceiling panels to fall out.	
Are heavy plaster suspended ceilings securely supported and braced?	Heavy lath and plaster ceilings in older facilities are very dangerous if poorly supported.	
Are partitions that terminate at a hung ceiling braced to the structure above?	Partitions need support for out-of-plane forces, and attachment to a suspended ceiling grid only is inadequate.	
Are masonry or hollow tile partitions reinforced, particularly those surrounding exit stairs?	Heavy partitions attract strong earthquake forces because of their stiffness and mass, and are prone to damage. They are particularly dangerous around stairs and exit ways.	
Are parapets and other appendages securely braced and attached to the building structure?	Unreinforced masonry parapets are especially vulnerable. Brace items such as cornices, signs, and large antennas.	
Structural System		
When was the existing structure designed?	Buildings with no, or outdated, seismic design are unlikely to perform adequately in strong shaking. Verify that the Importance Factor was used in design.	

Table 2-4: Hospital Seismic Safety Evaluation Checklist (continued)

Vulnerability Sections	Guidance	Observations
Structural System (continued)		
Has the local seismic zoning changed significantly since the building was designed?	Local expectation of shaking intensity can change as scientific knowledge increases	
Is there a continuous load path from all components of the building to the foundation?	A continuous load path assures that the structure will act together as a whole when shaken. Connections from walls to floors and roofs should also form part of this load path.	
Is all load-bearing structural masonry reinforced according to code?	Older unreinforced masonry has proven very vulnerable in strong shaking.	
Are horizontal diaphragms correctly designed and constructed with necessary chords and collectors?	Large diaphragm openings and the edges of diaphragms need careful design to ensure forces are properly transmitted to walls and frames.	
Nonstructural Systems		
Are there backups for critical municipal utilities?	Municipal utilities such as water, power, and gas, are often disrupted in strong shaking. Onsite backups should provide 48 hours of use.	
Are ducts, piping, conduit, fire alarm wiring, and communication systems that pass through seismic joints 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.	
Is heavy mechanical equipment adequately secured?	Heavy equipment may slide and break utility connections.	
Are vibration isolators for vibrating equipment designed for seismic forces?	Equipment may jump off very loose isolators and may break restraints designed for wind only.	
Is the piping properly braced and provided with expansion joints?	See Section 2.4.4.	
Is ductwork properly supported and braced?	See Section 2.4.4.	
Are boilers and other tanks securely braced?	Gas heaters or tanks with flammable or hazardous materials must be secured against toppling or sliding.	
Are plumbing lines adequately supported and braced?	Leaks in pressure pipes can cause damage over a large area. Protection of joints is especially important. See Section 2.4.4.	
Is fire protection piping correctly installed and braced?	See Section 2.4.4.	

Table 2-4: Hospital Seismic Safety Evaluation Checklist (continued)

Vulnerability Sections	Guidance	Observations
Nonstructural Systems (continued)		
Is heavy electrical equipment adequately secured?	Switch gear and transformers are heavy and sliding or movement failure can shut down the electrical system. See Section 2.4.4.	
Is emergency generator and associated equipment secured against movement?	The generator, muffler, batteries, day tank, and other electrical equipment may be necessary for emergency operation. See Section 2.4.4.	
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. See Section 2.4.4.	
Are light fixtures supported in an integrated 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. See Section 2.4.4.	
Are the elevator cars, counterweights, and equipment anchored for seismic forces?	Elevators are important for patient movement, particularly in an emergency. After strong shaking, elevators and shafts should be checked for safety before use. See Section 2.4.4.	
Is at least one elevator in each wing connected to the emergency power system?	Even if properly anchored and undamaged, the elevator needs power to enable vertical patient movement. See 2.4.4.	
Is the bulk oxygen tank and associated equipment secured?	The legs, anchorage, and foundations of large tanks need to be checked for adequacy.	
Is nitrogen storage secured?	Loose tanks may fall and break connections.	
Are small natural gas lines to laboratories or small equipment vulnerable?	Incompatibility of large and small lines and equipment movement can cause dangerous leaks.	
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.	
Is significant fire alarm equipment secured against movement?	Equipment can slide or topple, breaking connections. See FEMA 74.	
Communications and IT Systems		
Are communications components, including antennas, adequately braced and supported?	Post-event communications are vital for post-earthquake operations. See FEMA 74.	
Are plans in place for emergency communication systems, both within the facility and to outside facilities?	Planning must consider likely post-earthquake conditions at the site and offsite.	

2.6 REFERENCES AND SOURCES OF ADDITIONAL INFORMATION

Note: FEMA publications may be obtained at no cost by calling (800) 480-2520, faxing a request to (301) 497-6378, or downloading from the library/publications section online at http://www.fema.gov.

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