CHAPTER 1

OVERVIEW

> *As usual in our vibrant, free society, it is up to us to decide whether to face the reality of the seismic threat and embrace the availability of the solutions or to continue to lie helpless before quakes which can flatten our houses, destroy our employers, damage our national economy and national defense, and wipe out the financial equity of a lifetime in a mere thirty seconds of groundshaking.*
>
> John J. Nance, *On Shaky Ground,* Morrow & Co., New York, 1988

1.1. INTRODUCTION

During an earthquake an individual could be thrown out of bed at night, be unable to stand upright and be forced to kneel on the ground, fall down stairs, or even be tossed out of the swimming pool by the violent sloshing of the water. In the aftermath of the 6.7-Richter-magnitude Northridge earthquake of January 17, 1994 (Figure 1.1), the author spoke with the resident of a two-story house who had been through a similar experience during the 1971 San Fernando earthquake. At that time she was repeatedly knocked down while attempting to reach her baby daughter downstairs. Twenty-three years later, living in a different location but still near the epicenter, the violent quaking of Northridge prevented her once again from reaching the ground floor. Both seismic events happened in the early morning.

The author collected these and other personal accounts in the course of inspections of nearly 100 homes damaged by the Northridge earthquake.

There are ways of making structures safer than the current ones. Researchers and the engineering community have mobilized to achieve that goal, working on removing shortcomings in the design of structures that have not

Figure 1.1 Parking structure that collapsed during the 1994 Northridge earthquake, California State University, Northridge Campus.

performed well in seismic events and coming up with improved versions capable of standing up to a certain level of earthquakes. (See Figures 1.2 and 1.3.)

One option is to build or retrofit on seismic isolators or structural dampers. An example is the Los Angeles City Hall, retrofitted with a *viscous-device* type of supplemental damping to improve seismic response. However, placing such a massive stone building and historic landmark on an earthquake damage control system comes at a cost that not all areas can afford.

1.2 CONCEPTS, TERMINOLOGY, AND SOURCE OF EARTHQUAKES

Specific Gravity

The specific gravity of a substance refers to how much heavier than water a unit volume of the substance is. Some specific gravities related to earthquake engineering are as follows:

Earth's crust	2.7–3.0
Mantle (inner periphery)	5.7
Core (periphery)	9.7
Center	12.3

The earth's crust *floats* on the surface of the mantle (Figure 1.4), which possesses a viscoelastic character. This equilibrium is called *isostasy*.

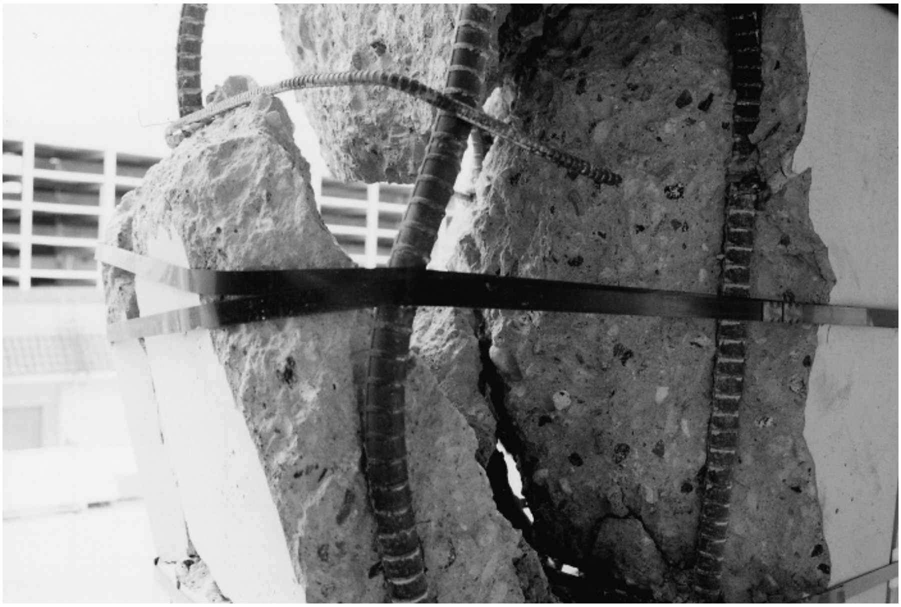

Figure 1.2 Straps are holding the crumbled lightweight concrete in a multistory residential building in Santa Monica, California, severely damaged by the Northridge earthquake.

Orogenic Movements and Crust Convection (Conveyor Belt)

Orogenic movements and crust convection are mainly responsible for mountain building and valley forming—in other words, the constant changes affecting the surface of the earth.

In the first half of the twentieth century Alfred Wegener asserted that at one time continents such as Africa and South America were connected and then drifted away from each other. Wegener, who was ridiculed at the time for his *continental drift* concept, perished on an expedition to the North Pole. Since then, fossil and geological evidence has substantiated the fact that these continents were once one massive piece. High-technology developments of the 1960s and deep-diving submarines have produced interesting findings about ocean floor fissures and left-and-right movements that, like a giant conveyor belt, have the power of moving continents that float on the viscous mantle. A similar movement at Lake Victoria in Africa is slowly splitting the African continent.

Subduction Zones

As the ocean floor exerts pressure on the coastline of the continent, the leading edge of the ocean floor is pushed under the continent, carrying down sea deposits, including the remains of organisms (Figure 1.5). The matter reaches

Figure 1.3 Detail of parking structure that collapsed during the Whittier Narrows earthquake of 1987.

intensive heat under the continent and produces geothermal irregularities—gases and molten matter that tend to rise to the surface. This *subduction* process can be seen in the series of active volcanoes along the Pacific shoreline of the American continent from Alaska to Chile, and is responsible for the earthquakes that affected Chile, Colombia, California, and Washington State.

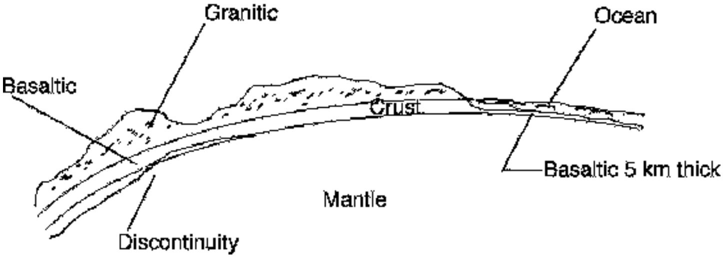

Figure 1.4 Discontinuity of seismic waves, named the *Mohorovicic discontinuity.*

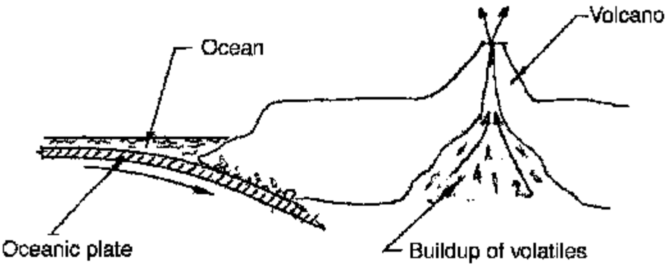

Figure 1.5 Subduction process.

Volcanoes

Around 900 years ago the Sunset Crater volcano eruption coupled with strong ground motion caused panic among the native population in what is today Flagstaff and the surrounding areas of Arizona. We can still see the geologically fresh lava flow. In northern California, Mount Shasta bombarded the neighboring region with boulders that scattered for miles, some weighing about 5 tons. The upheaval was accompanied by severe ground motion.

Land Erosion

The 1812 New Madrid earthquake in Missouri is considered the largest earthquake in what is regarded a *low-seismicity* area. What could have caused such an event was the mighty Mississippi constantly eroding the land mass and making the earth's crust lighter. Since the earth's crust cannot adjust immediately to the river's action, from time to time it springs up.

Summary of Main Sources of Earthquakes

1. Orogenic movements such as mountain building
2. Subduction and plate convection followed by geothermal and mechanical disturbances
3. Volcanic activity
4. Land erosion

1.3 WAVE PROPAGATION AND VELOCITIES

Wave Propagation

The focal point of an earthquake under the surface of the earth is called the *hypocenter* and its corresponding point on the surface the *epicenter*. It is customary to refer to earthquakes with relation to the epicenter.

When an earthquake hits the hypocenter, it sends out shock waves. There are two types of shock waves:

Push waves—denoted p

Shock waves or *shear* waves that produce transverse vibration with respect to the direction of travel, also named s waves

The p waves are faster than s waves and arrive first, produce a relatively mild vibration, and cause less damage. They are messengers of the severe ground shaking that will follow. The moment the s waves arrive, seismographic diagrams start recording the magnitude of ground shaking (Figure 1.6).

If the distance from a given observation point to the hypocenter is s, the propagation velocity of the transverse waves is v_s and the propagation velocity of the longitudinal (push waves) is v_p. Then T, the time difference between the arrival of p and s waves, is given as

$$T = \frac{s}{v_s} - \frac{s}{v_p} = s\left(\frac{1}{v_s} - \frac{1}{v_p}\right)$$

where the distance $s = (1/v_s - 1/v_p)^{-1}\, T$ from simple arithmetic. We need three observation points to use triangulation *and* the geology of the ground, which determines v_s and v_p by measurement. The 1997 UBC gives some rough values for v_s and v_p. Nonetheless, it is advisable to have a good geotechnical report for accuracy.

Wave Velocities (Body Waves)

$$v_p\sqrt{\frac{E(1 - \sigma)}{\rho(1 + \sigma)(1 - 2\sigma)}}$$

where E = Young's modulus
σ = Poisson's ratio (usually 0.25)
ρ = density

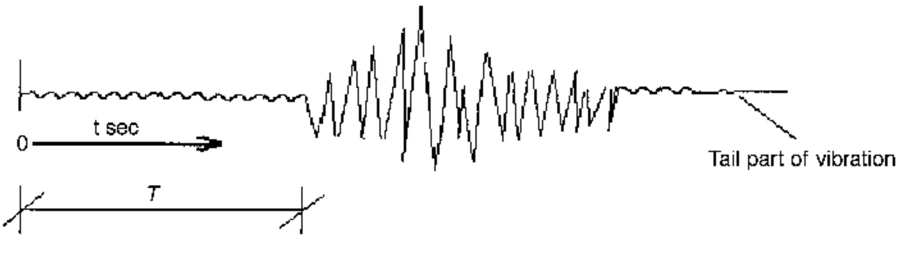

Figure 1.6 Seismograph reading of ground vibration caused by an earthquake.

and

$$v_s\sqrt{\frac{E}{2\rho(1 + \sigma)}}$$

Velocities v_s of typical transverse waves to propagate through the ground for selected materials are as follows (in meters per second):

Sand	60
Reclaimed sand	100
Clay	250
Gravel	600
Tertiary rock	1000 and up

1.4 MAGNITUDE OF EARTHQUAKES

To compare earthquakes, we need some yardstick or scale such as the one created by C. F. Richter. Using a standard horizontal Wood–Anderson seismograph, the magnitude

$$M = \log_{10} A$$

where A denotes the *trace* amplitude in micrometers for an epicentral distance of 100 km. When the distance from the epicenter is other than 100 km,

$$M = M_\Delta - \frac{1.73 \log_{10} 100}{\Delta}$$

where M_Δ is the magnitude at a distance Δ calculated from the basic Richter formula. The magnitudes of significant earthquakes in the United States are given in Table 1.1.

1.5 BUILDING DAMAGE

As a measure of the magnitude of destruction caused by the 1994 Northridge earthquake, following is a summary of the structural damaged suffered in a densely populated area, the City of Los Angeles:

Total Number of Buildings Damaged 93,200 (1900 *red,* 8800 *yellow,* 82,500 *green*). Of these, 3000 buildings suffered moderate to major damage.

TABLE 1.1 Significant U.S. Earthquakes

Location	Date	Magnitude
Cascadia Subduction Zone[a]	1700	~9.0
New Madrid, Missouri	1811, December 16	8.1
	1812, February 7	~8.0
Ventura, California	1812	7.1
Fort Tejon, California	1857	7.9
Ka'u District, Island of Hawaii	1868	7.0
Lanai, Hawaii	1871	6.8
Owens Valley, California	1872	7.4
California/Oregon coast	1873	7.3
Denver, Colorado	1882	6.2
Charleston, South Carolina	1886	7.3
Imperial Valley, California	1892	7.8
Cape Yakataga, Alaska	1899	7.9
Yakutat Bay, Alaska	1899	8.0
Eureka, California	1899	7.0
San Andreas, California	1906	8.3
San Francisco, California	1906, April 18	7.8
Oregon	1910	6.8
Pleasant Valley, Nevada	1915	7.1
Eureka, California	1922	7.3
Humboldt County, California	1923	7.2
Santa Barbara, California	1925	6.3
Clarkston Valley, Montana	1925	6.6
Lompoc, California	1927	7.1
Fox Islands, Aleutians, Alaska	1929	7.8
Valentine, Texas	1931	5.8
Cedar Mountain, Nevada	1932	7.3
Long Beach, California	1933	6.4
Excelsior Mountain, Nevada	1934	6.5
Hansel Valley, Utah	1934	6.6
Helena, Montana	1935	6.25
Central Alaska	1937	7.3
East of Shumagin Islands, Alaska	1938	8.2
Imperial (El Centro), California	1940	7.1
Ossipee Lake, New Hampshire	1940	5.5
Skwenta, Alaska	1943	7.4
Unimak Islands, Alaska	1946	8.1
Wood River, Alaska	1947	7.2
Southwest Montana	1947	6.25
Manix, California	1947	6.4
Seattle, Washington	1949	7.1
White Wolf, California	1952	7.7
Kern County, California	1952	7.3
Near Islands, Alaska	1953	7.1
Rainbow Mountain, Nevada	1954, August	6.8
Fairview Peak, Nevada	1954, December	7.1
Andreanof Islands, Alaska	1957	8.6

TABLE 1.1 (*Continued*)

Location	Date	Magnitude
Fairweather, Alaska	1958	8.0
Wyoming	1959	6.5
Hebgen Lake, Montana	1959	7.3
Prince William Sound, Alaska	1964, March 27	9.2
Rat Islands, Alaska	1965	8.7
Puget Sound, Washington	1965	6.5
Rat Islands, Alaska	1966	7.61
San Fernando, California	1971	6.7
Sitka, Alaska	1972	7.6
Near Islands, Alaska	1975	7.6
Eastern Idaho	1975	6.1
Kalapana, Hawaii	1975	7.2
Mount St Elias, Alaska	1979	7.6
Imperial Valley, California/Mexico border	1979	6.4
Eureka, California	1980	7.4
Coalinga, California	1983	6.5
Borah Peaks, Idaho	1983	7.0
Andreanof Islands, Alaska	1986	8.0
Chalfant Valley, California	1986	6.4
Whittier, California	1987	6.0
Gulf of Alaska	1987	7.9
Gulf of Alaska	1988	7.8
Loma Prieta, California	1989	6.9
Crescent City (offshore) California	1991	7.0
Sierra Madre, California	1991	5.8
Joshua Tree, California	1992	6.2
Big Bear, California	1992	6.5
Cape Mendocino, California	1992	7.2
Landers, California	1992	7.3
Bishop. California	1993	6.2
Northridge, California	1994	6.7
Cape Mendocino, California	1994	7.0
Northern California (off coast)	1994	7.1
Andreanof Islands, Alaska	1996	7.9
Hector Mine, California	1999	7.2
Seattle, Washington	2001	6.8
Denali Fault, Alaska	2002	7.9
Rat Islands, Aleutians, Alaska	2003	7.8
Offshore Oregon	2003	6.2
San Simeon, California	2003	6.5
Central California	2004	6.0
Northern California (off coast)	2005	7.2
Gulf of California	2006, January 4	6.6

[a] A 600-mile-long region that covers northern California, Oregon, Washington, and southern British Columbia. The earthquake triggered off a tsunami that reached Japan. Written records place the earthquake in the evening of January 26, 1700.

Source: U.S. Geological Survey.

Failures by Building Class

Wood-framed homes: 1650
Wood-framed apartments, condominiums, and hotels: 630
Tilt-ups, masonry: 350
Unreinforced masonry retrofitted: 213
Structural steel buildings: 100

1.6 STRUCTURAL FAILURES: OVERALL FAILURE

Structural failures may be categorized as *overall failure* and *component failure.* Overall failure involves collapse or overturning of the entire structure. The choice of the type of structure is instrumental and often a predetermining factor for failure.

1. *Moment Frame in Longitudinal Direction, Shear Walls at Each End in Short Direction* This structural system was approved as a major structural category to resist earthquakes by Structural Engineers Association of California (SEAOC), which influenced the Uniform Building Code (UBC) and the 2000 and 2003 International Building Codes (IBCs). This type of structure, however, fared badly in the January 17, 1994, Northridge earthquake. Figure 1.7 shows the collapsed wing of an office building in the 1994 Northridge earthquake. The longitudinal moment frame underwent large lateral oscillation imposed by the longitudinal component of the quake.

The moment frame pushed over and destroyed the shear wall, leaving the structure defenseless against the lateral force component in the short direction, which caused the building to collapse. Each new UBC edition and its IBC successors adopted this type of building system, granting it a *prequalified status* design category. Such structures, they reasoned, would be able to resist earthquakes, along with a few recognized structural types, such as moment frames, braced frames, shear wall structures, and hybrid combinations of these.

The basic concept behind the moment frame–shear wall combination advocated by SEAOC is that the end shear walls will take care of the earth force component in the short direction while the moment frame will resist the longitudinal component acting in the longitudinal direction of the structure (Figure 1.8). As explained below, the laws of nature challenge such an assumption.

When an earthquake hits, the structure undergoes lateral oscillations that amplify in the longitudinal direction. The springlike response of the moment frame and the large floor mass contribute to the excitation. Measured lateral floor displacements—*story drift*—can be on the order of 10 in. This fact has been verified by the author while performing a dynamic analysis on

Figure 1.7 Northridge earthquake, 1994. Collapsed end shear wall, Kaiser Permanente Office Building, Granada Hills, CA. (Photo courtesy of the University of California Library at Berkeley.)

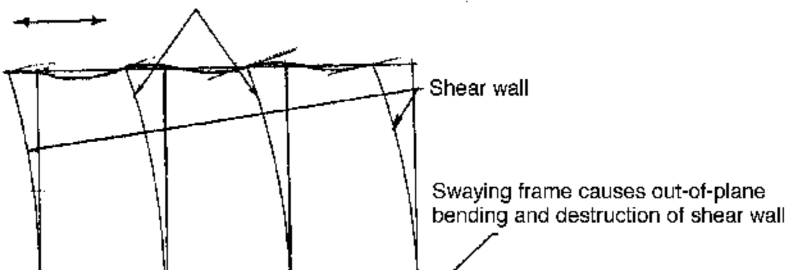

Figure 1.8 Moment frame and end shear wall, a bad combination to counter earthquakes.

earthquake-generated ground acceleration data at the base of an actual structure. Rapid and violent oscillations of the moment frame exceeding 2 Hz (cycles per second) will cause the end shear wall to bend back and forth until it breaks at the base. This was the case of the Kaiser Office Building in Granada Hills during the 1994 Northridge earthquake. Once the end shear walls are destroyed, the building is susceptible to catastrophic failure. It is estimated that 80% of high-rise hospital structures in California have this type of construction.

Champagne Towers, an upscale high-rise apartment building overlooking the Santa Monica Bay in Southern California was built utilizing a similar system, that is, end shear walls in the short direction and reinforced-concrete moment frames acting in the long direction of the structure. When the 1994 Northridge earthquake hit, residents of the towers woke up to a frightening sound and violent ground shaking accompanied by lateral sway. Initially not all that significant, within seconds the sway turned violent and uncontrollable followed by the sound of an explosion when the concrete columns broke up (Figure 1.9). The alarmed residents fled the building. The first daylight revealed severe damage to the main load-bearing columns with diagonal cracks up to $\frac{1}{2}$ in. Within hours the building was declared dangerous, uninhabitable, and condemned.

Mechanism of Destruction of Moment Frame–End Shear Wall Construction. Shear walls are sensitive to out-of-plane bending. Normally just a

Figure 1.9 Reinforced-concrete columns severely damaged in the Northridge earthquake, Champagne Towers, Santa Monica, CA.

single layer of vertical reinforcement is provided for the wall and it is traditionally placed at the theoretical elastic centerline of the wall, thereby offering poor resistance to out-of-plane bending (Figure 1.10).

When the moment frame undergoes lateral sway in the longitudinal direction, it causes serious out-of-plane flexural deformation to the shear wall. As the shear wall begins to sway back and forth, it crushes the outer and inner fibers of the concrete until there is no concrete left to support the rebars. Once the rebars are deprived of the confining effect of the concrete, they buckle under the load imposed by the shear wall. The process develops very fast, the sway occuring at 2–3 Hz. The deformation of the wall can be very large and the lateral floor displacement or story drift can reach a magnitude of 10 in. or more.

Exceedingly large sway of frame structures occurred during the San Fernando earthquake of 1971 in California. The stair/elevator towers of the Veterans Hospital swayed out, acting like a sledgehammer against the wings of the main building and destroying it.

By now it should be clear to the reader that moment frame–end shear wall construction is a dangerous combination based on static force considerations that ignore the dynamic response of the entire structure. Unfortunately this type of construction was (and is) stated as accepted practice in successive editions of the UBC and its successors, the IBC 2000 series.

Figure 1.10 It is estimated that 80% of hospital structures in California are of the moment frame–shear wall type of construction, a bad design arrangement to resist a strong earthquake.

2. *Multistory Buildings with First-Story Shear Walls Not Aligned with Upper Story Shear Walls* When first-story walls are not aligned with upper story shear walls, they create an unnatural configuration that severs the continuity of the vital lateral force resisting system. Figures 1.11–1.13 show a cross section and a side elevation of a building with the type of design forces normally—but erroneously—applied to the main cantilever structure corbels or cantilevered beams. These forces include gravity loads but ignore dynamic impact by seismic forces.

While numerous engineering seminars teach that the floor of a structure transfers the seismic shear to the nonaligned shear wall below, reality contradicts this concept. In addition to horizontal shear, the cantilever floor transfers the overturning moment, which is greatly amplified by the rocking motions induced by the *dynamic impact* of the earthquake.

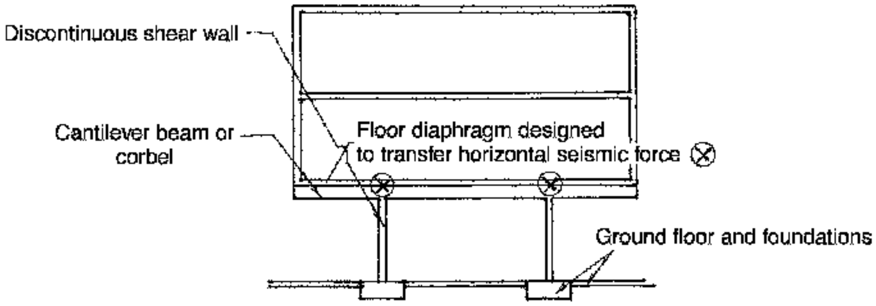

Figure 1.11 Cross section of building with discontinuous shear walls.

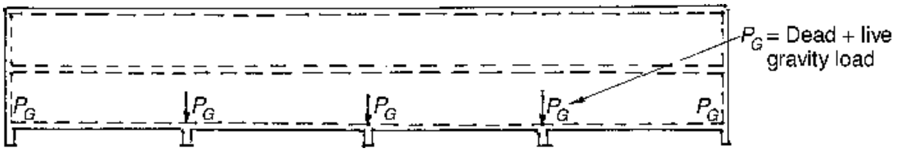

Figure 1.12 Side elevation showing incomplete cantilever design forces. Dynamic force caused by rocking motion can exceed P_G gravity load for which the building is normally designed.

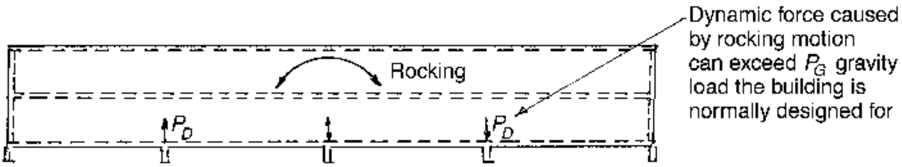

Figure 1.13 Side elevation showing seismic reaction forces on cantilever ends.

The cantilever element, not designed for dynamic forces that may well exceed dead- and live-load gravity, will be underdesigned and prone to failure. Such was the case at the chemistry-physics building of the Santa Monica Community College (SMCC) in Santa Monica, California, destroyed by the 1994 Northridge earthquake. The damage was so severe that the building collapsed in a heap of rubble and no attempts were ever made to repair and/or rehabilitate it. Instead, the building was demolished before the restoration of the majority of the other damaged buildings even began.

Numerous high-rise hospitals and hotel structures built using this system are in danger of collapsing if a significant earthquake hits them. An example is the Santa Ana Tustin Hospital in Santa Ana, California, where shops occupy the first story space provided by the offset shear wall system.

3. *Dry-Jointed Connections in Precast Parking Structures without Monolithic Connections* An example of this type of construction was the California State University precast parking structure located near the epicenter of the 1994 Northridge earthquake (Figure 1.14). Being dry jointed, that is, the precast beams were supported on corbels of the equally precast concrete columns without monolithic connection, the structure relied on friction of the support reaction created by gravity forces (mostly dead weight) across a few inches of seating.

Figure 1.14 California State University parking structure. A corner of the cast-in-place framework was pulled in by the collapsed interior of the multistory structure during the 1994 Northridge earthquake.

During an earthquake of relatively large magnitude, such as the 1994 Northridge earthquake, the several-feet-long lateral movement of the ground tends to pull the beams off the inadequate support. Worse, the vertical ground acceleration makes the structure weightless, thus overcoming any attempt to rely on friction connection.

Regrettably, a moratorium has never been declared on these potentially dangerous structures. Paradoxically, just a few months after the 1994 Northridge earthquake another precast parking structure was built at a sister campus, the *California State University Long Beach,* using the same system as the collapsed Northridge parking structure.

Some California *freeway bridges* are perfect examples of ill-fated uses of dry-jointed connections. An expansion joint is provided for the otherwise continuous bridge deck, separating a main span into a short cantilever (the supporting portion) and a long span (the supported portion). The main span rests on a few-inch-wide seating. When an earthquake hits, it causes several feet of measured lateral movement between adjacent or dry-joint connected structural components. As the long span springs up, its support, the initially continuous system breaks and suddenly converts into one short and one large span cantilever element no longer capable of supporting their own weight. The I-14/I-5 interchange near the town of San Fernando, California, crushed a motorist to death when it collapsed in the 1971 San Fernando earthquake. Yet the bridge was rebuilt using the same structural system, only to kill a highway patrol officer that was on the bridge when the Northridge earthquake hit.

It is estimated that more than 90% of the major California freeway bridges are built using the same faulty concept and construction method. Following the Loma Prieta and Northridge earthquakes, CALTRANS attempted to retrofit the joints by locking the two bridge segments with high-strength steel tendons. The tendons were inserted through holes drilled into the supporting joints. However, the soft concrete matrix has a Brinell hardness of about 10 with the high-strength steel at about 100 on the Brinell hardness scale. Thus, when a strong earthquake occurs, there is likely to be a cheese-cutter effect that will cause the cable to cut through the concrete and separate the joints. Once good construction is compromised, it seems virtually impossible to reverse the inevitable course of events, such as earthquakes exposing inherent structural weaknesses.

Is there any other way to create expansion joints in continuous structures? Perhaps doubling the columns would create safer expansion gaps between separable bridge components.

4. *When a Structure Is Too Strong to Break Up* A solid, several-story apartment structure built as a monolithic box of cast-in-place concrete tilted without structural damage in the 1964 Niigata earthquake in Japan. Evidently the rocking motion of the building, generated by the earthquake, created a pumping action to the partially saturated soil, increasing its potential for liquefaction.

1.7 COMPONENT OR JOINT FAILURE

Component failure refers to failure of one or more structural elements, mostly joints, due to a type of damage that makes the structural component or joint unusable. Such a condition necessitates repair or replacement. Because the failure mechanism differs according to the choice of material and type of structure, it seems best to categorize the structure by the construction materials used, especially *steel* and *concrete,* and then create subcategories.

Steel Structures

Apart from hybrids, *two major lateral force-resisting systems exist:* (1) *moment-resisting frames* and (2) *braced frames.*

1. *Moment-Resisting Frames* The most frequently observed damage to these structures is beam–column joint failure. To ensure continuity and moment transfer, the solution by the construction industry has been to butt weld the beam flanges to the column. Shear transfer from beam to column (and column to beam!) is provided by the shear tab, a vertical steel plate welded to the column. The shear tab and the beam web provided with boltholes allow prompt and easy erection. By tightening the bolts between the beam web and the plate, the beam is kept in place until the beam flanges are welded to the column flanges (or webs).

Several California earthquakes have proven that such a construction method is defective. The lateral oscillations caused by ground motion on a highly elastic steel frame create large internal forces that correspond to the mass times acceleration of the massive concrete floor acting as the driving force.

The amplification of dynamic lateral displacements often goes out of control, overtaxing the joint. During the rapid cycle, reversed stresses observed by the author far exceeded the nominal yield strength of the steel. In fact, often even the nominal ultimate strength (F_u) of the metal was exceeded. Under such conditions, the structure had to depend upon additional reserves.

Such reserves are provided by the moment of resistance of the shear tab by utilizing resistance of the bolts. When the *friction grip bolts* slip to form a couple, the bolts begin exerting an excessive force on the shear tab. Not meant for such extreme use (or misuse), the hardened high-strength bolts split the shear tab. The author observed such damage during the postearthquake retrofitting of the Anthony Building, head office and control building for the Los Angeles County Water and Power utility (Figure 1.15).

A fully welded web joint, the shear tab was welded to the beam web instead of being bolted. It could have performed better if it had utilized the full flexural resistance of the entire beam section consisting of flange and web. Yet this method was compromised in favor of a fast and easy erection.

Figure 1.15 Left: crack in beam web during the Northridge earthquake, Anthony Building, Department of Water and Power, Los Angeles County.

Needless to say, tearing up the shear tab represents the last phase of the integrity of a structure.

When the destroyed shear tabs can no longer carry the vertical reaction, the floor will collapse on the floor below, which could create a catastrophic chain reaction of progressive failure (*pancaking*) that could eventually wipe out the entire building. Fortunately, in the case of the Anthony Building, the January 1994 Northridge earthquake was of relatively short duration. Had it lasted longer, it would have caused a floor collapse and possibly catastrophic failure of the entire control building.

2. *Braced Frames* Concentric braced frames that proved their value in situations involving static loads have a rather poor performance in an earthquake. Being a rather rigid structure, its shock absorption under dynamic impact is almost negligible.

The damage to the concentric braced frames of the Oviatt Library Annex in the California State Northridge Campus, California, is a clear demonstration of the lack of shock-absorbing properties of this type of structure (Figures 1.16 and 1.17).

The 4-in.-thick base plates connecting the Oviatt Library Annex structure to its foundation, behaving like glass, cracked and failed in brittle fracture. In addition to splitting the plates horizontally, as shown in Figure 1.16, a punching shear failure started to develop around the perimeter of the frame

Figure 1.16 Cracks in 4-in.-thick base plates during the Northridge earthquake, Oviatt Library Annex Building.

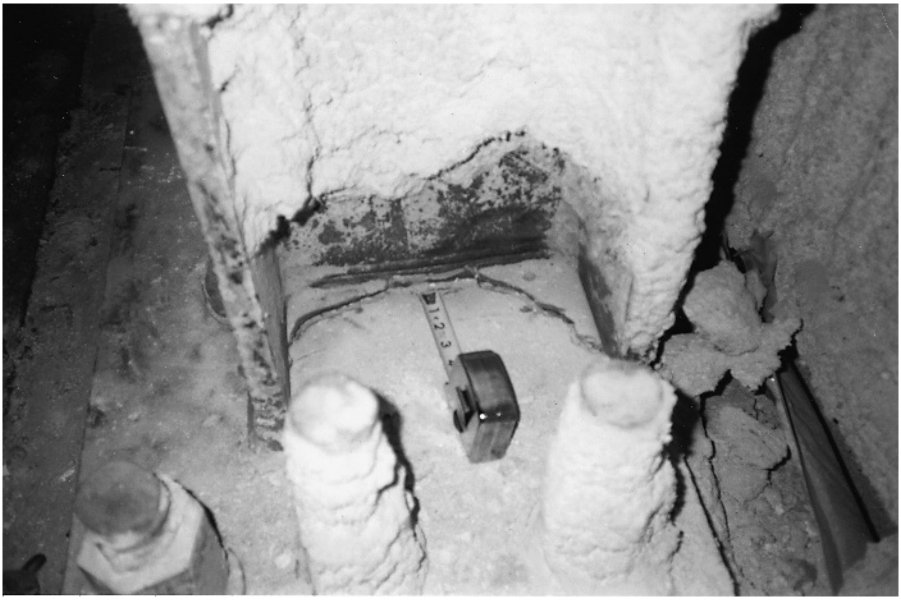

Figure 1.17 Shear failure at perimeter of frame leg–base plate solidly welded connection, Oviatt Library Annex Building. Note the crack in the center and the initial stage of shear failure on the left.

leg–base plate solidly welded connection. Torn from its footings, this rather slender structure would have overturned had the earthquake lasted a bit longer.

An alternative to the concentric braced frame which offers improved shock absorption properties is the hybrid eccentric braced frame, which has members eccentrically connected at the joints. However, there is a trade-off for improved shock absorption. During the time-dependent impacts of the earthquake, the beam providing eccentric connection for the braces will bend and undergo permanent deformation. Should the deformation be of significant magnitude, it will affect the entire structure and leave an out-of-alignment building that is difficult and expensive to repair or a permanently damaged building that is impossible to repair. Developed alternatives for added safety that do not compromise serviceability are presented at the end of this book.

Although there has been much debate about this structure, the improved shock absorption is at the expense of sizable and permanent deformations that make the entire building unacceptable for future use.

Reinforced-Concrete Structures: Moment-Resisting Frames

Of all structures, perhaps the *reinforced-concrete moment-resisting frame* is the most vulnerable to earthquakes. Initially named *ductile moment-resisting frame* by SEAOC and in several UBC editions, it was renamed *special moment-resisting frame* in the 1997 edition of the Code. It was the preferred structural design category and enjoyed a special low lateral coefficient as compared to other structures. The problem is that there is nothing *ductile* about this type of structure.

An example of the nonductile performance of the reinforced-concrete moment-resisting frame was a fashion center parking structure in the Whittier Narrows earthquake of 1987 in California (Figures 1.18–1.20). The author established that, during each aftershock, the large, rapidly reversed horizontal shear forces produced a grinding action at the beam–column joint that pulverized the concrete until it totally disappeared. Once the concrete was gone, the slender rebars, lacking lateral confinement, could no longer support the weight of the massive concrete floor structure and buckled.

The mechanism of beam–column joint failure can be described in the following manner. As the significant mass of the floor (or roof) deck starts swaying back and forth, the frame columns attempt to resist the movement. This causes the acceleration and dynamic forces to be imparted by the floor beam to the beam–column joint. The dynamic response characteristics of a deck are normally different from the frame column. The reversal of dynamic forces, with their back-and-forth movement, grinds the concrete between beam and column until it entirely disappears from the joint, leaving the column rebars exposed. The rebars, no longer confined, behave like slender columns and buckle under a large vertical beam reaction that they were not meant to support. A progressive failure mechanism then results in collapse of the entire structure.

Figure 1.18 Initial stages of column joint degradation in the progressive failure of a fashion center parking structure in the Whittier Narrows earthquake, 1987.

What went wrong with the Whittier fashion center parking structure and the numerous other earthquake-damaged reinforced-concrete moment frames that complied with UBC and SEAOC *Blue Book* requirements? According to the SEAOC–UBC concept, the column joint was supposed to yield under the sway action of the frame. Since moment frames are referred to as *rigid frames* in most textbooks, it seems odd to adopt them in earthquake areas, thereby endowing them with qualities they do not possess. Such attributes are joint yielding, plastic joint rotation beyond 3 rad, and excessive strength reserve under the dynamic load of successive strain reversals caused by an earthquake.

Another major problem is underestimating earthquake-generated forces in the UBC and IBC codes, as discussed next.

1.8 CODE DESIGN FORCES: RESERVE STRENGTH TO COUNTER EXTREME FORCES

The author has analyzed actual forces acting upon a newly built, Code-complying structure damaged by the Northridge earthquake. By reconstructing time deformations, frequency of internal forces, and characteristics of

Figure 1.19 Exterior columns that supported the second floor broke at the second-floor beam–column intersection, fashion center parking structure.

structural vibration caused by the earthquake, it was determined that the *large internal forces exceeded several times the UBC-predicted forces.*

At this point it is important to evaluate and compare the UBC-recommended design forces with actual earthquake forces as measured at the site. The 1979 UBC *lateral coefficient for base shear* (the maximum lateral force coefficient) was 0.094 *g* at *working stress level,* or 13% at *strength level,* using the 1.4 UBC 1997 load factor for conversion. The 1988 UBC lateral coefficient for base shear was a mere 11.3% *g* at strength level, to be increased again to 13% by the 1997 UBC.

How do these predictions compare to actual field measurements? The *lateral and vertical* earthquake force was 100% *g* during the 1971 San Fernando earthquake, measured at the Pacoima Dam. It was nearly 200% *g* near the epicenter of the 1994 Northridge earthquake, at a nursery north of the California State University Northridge Campus.

The effects on buildings with a disproportion between projected or *design forces* and actual forces are clearly obvious. In addition, building code regulations are prescriptive. As such, design professionals are expected to follow somewhat rigid design rules based on the *law of man* rather than the *law of*

Figure 1.20 Collapsed upper floor and a large portion of the collapsed parking structure, later demolished, Whittier Narrows earthquake, 1987.

physics. The latter is inherent in the nature of earthquakes, based on proportions of predictable forces and actual structural resistance.

If the gap between actual and predicted design forces were not too large, it could be assumed that a structure would remain safe by applying a bit of additional resistance as an adjustment. However, if the actual forces were in excess of approximately 15 times the UBC's predicted design forces, something drastic is destined to happen. Fortunately the duration of California earthquakes has been short as compared to other U.S. regions such as Alaska. Time plays an essential role: The longer the duration of an earthquake, the more damage it will cause, such as the 1964 Great Alaska earthquake, which lasted more than 3 min.

The UBC lateral coefficient, applied horizontally to a ductile moment frame, was between 12 and 18% g depending on height, geometry, and other factors. This is a markedly underestimated value as compared to the 100% g lateral ground acceleration measured at the Pacoima Dam during the 1971 San Fernando earthquake, that is, more than five times the UBC-estimated equivalent static force that overlooks the *magnifying dynamic impact factor due to structural response.*

As mentioned earlier, the horizontal and vertical ground accelerations measured almost 200% *g*—the strongest ground movement recorded in the Northridge earthquake—at the Cedar Hills nursery in Tarzana,* near the epicenter. Such readings substantiate the fact that structures engineered following UBC regulations in force at the time were about 10 times underdesigned.

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* **The Tarzana Shake.** The strong-motion accelerograph in this location recorded 1.82 g vertical accelerations for approximately 8 seconds *after* the Northridge earthquake. The puzzling readings and unrelenting shaking intrigued seismologists around the world and attracted them from Africa, England, Japan, and New Zealand. It was the strongest measurement recorded in seismic history. Equally inexplicable was the fact that Tarzana houses did not suffer significant damage and people in the community were fine.

The accelerograph was implanted into a rock close to the ground, on top of a hill in a ranch once owned by author Edgar Rice Burroughs, creator of Tarzan, now the grounds of Cedar Hills Nursery. The fact that the measuring instrument was on shallow rock proves that the readings were not augmented. Site and instrument evaluations done afterward also confirmed the validity of the readings.