The Built Environment 3

Earthquake hazards exist throughout the United States. The primary hazard associated with earthquakes is ground shaking, which damages and destroys buildings, bridges, and other structures. Ground shaking also causes liquefaction, landslides, and other ground failures that also damage and destroy structures. This damage can cause massive immediate financial losses, casualties, disruptions in essential services such as water and electricity, and severe long-term economic and social losses. Although the location, timing, and magnitude of future earthquakes are uncertain, there is little doubt that potentially damaging earthquakes will strike U.S. metropolitan areas in the next few decades.

Although earthquakes are unavoidable, the losses they cause are not. This chapter reviews technologies and practices to reduce the societal losses[1] of earthquakes. The focus is on *the built environment*—the buildings, bridges, pipelines, and other structures that bear the brunt of earthquake damage. The chapter first discusses deaths and injuries from earthquakes, focusing on what causes them and how they can be reduced. This is followed by a discussion of buildings—how they are damaged by earthquakes, and what technologies and practices are available to increase the seismic resistance of both new and existing buildings. Technologies for reducing damage to lifelines, such as bridges, water and sewer systems, and energy systems, are then reviewed. Finally,

[1] *Damage* refers to the direct financial costs of earthquakes. *Losses* denotes all of the societal effects of earthquakes, including deaths, injuries, direct financial costs, indirect costs (e.g., those resulting from business interruptions), and social impacts such as increased homelessness. Reducing damage by strengthening the built environment will reduce losses as well.

TABLE 3-1: Major Earthquakes Worldwide, 1980-90

Yea	oca on	Magn ude	Dea hs
1980	Algeria	7.7	3,500
1980	Italy	7,2	3,000
1981	Iran	6.9	3,000
1981	Iran	7.3	1,500
1982	Yemen	6.0	2,800
1983	Japan	7.7	107
1983	Turkey	6.9	1,342
1985	Chile	7.8	177
1985	Mexico	7.9	9,500
1986	El Salvador	5.4	1,000
1987	Colombia, Ecuador	7.0	1,000
1988	Nepal, India	6.6	1,450
1988	Burma, China	7.0	730
1988	Armenia	7.0	25,000
1989	West Iran	5.8	90
1989	U.S.—California	7.0	63
1989	Australia	5.6	13
1990	Iran	7.7	40,000+
1990	Philippines	7.8	1,700
TOTAL			~96,000

SOURCE: Bruce A. Bolt, *Earthquakes (New* York, NY: W. H. Freeman and Co., 1993), pp. 272-273,

the chapter discusses key research needs for ensuring that the built environment is well protected from future earthquake damage.

CASUALTIES

Deaths

A single earthquake can cause thousands of deaths and tens of thousands of injuries. As shown in table 3-1, in just 11 years-1980 to 1990-earthquakes killed almost 100,000 people worldwide. About two-thirds of these deaths occurred in just two catastrophic earthquakes-25,000 in Armenia in 1988 and 40,000 in Iran in 1990.

The historical record of U.S. earthquake fatalities is less unfortunate. About 1,200 people have died in U.S. earthquakes since 1900 (table 3-2). Most of these earthquakes occurred in regions that were, at the time, sparsely populated; so the low fatality figures for 1900 to 1950 earthquakes are not surprising. However, even those earthquakes occurring since 1950 in heavily populated areas of California have had relatively low fatalities, largely because many of its buildings and other structures are built to resist seismic collapse.[2]

Casualties from future earthquakes are very uncertain. In California, most deaths from future earthquakes will likely be caused by the collapse of older, seismically vulnerable structures. One estimate found that a repeat of the 1906 San Francisco earthquake would cause 2,000 to 6,000 deaths.[3] In the Pacific Northwest and the eastern United States, the potential for large numbers of deaths may be higher than in California. Although the probability of a major earthquake is relatively low, the building stock is more vulnerable, as even new structures often do not use known technologies and practices to reduce seismic damage.[4] One study found that a large earthquake striking the New Madrid region of the central United States would cause 7,000 to 27,000 deaths.[5]

Deaths that occur in earthquakes are due largely to the collapse of structures. In Armenia, most of the deaths were caused by people being crushed under collapsing concrete buildings. All but one of the deaths in the Loma Prieta earthquake were

[2] There is an element of luck here as well. The Loma Prieta earthquake, for example, struck during the World Series baseball game when the roads were relatively empty. Fatalities would have been in the hundreds, perhaps higher, if traffic levels were at more typical weekday levels.

[3] See "'Repeat' Quakes May Cause Fewer Deaths, More Damage," Civil *Engineering,* November 1994, pp. 19-21.

[4] As noted in chapter 1, many states in lower risk areas do not have or do not enforce seismic building codes for new construction.

[5] National Academy of Sciences, *The Economic Consequences of a Catastrophic Earthquake,* Proceedings of a Forum, Aug. 1 and 2, 1990 (Washington DC: National Academy Press, 1992), p. 68.

TABLE 3-2: Major U.S. Earthquakes, 1900-94

Year	Location	Deaths	Damages (million $1994)
1906	San Francisco, California	700	6,000
1925	Santa Barbara, California	13	60
1933	Long Beach, California	120	540
1935	Helena, Montana	4	40
1940	Imperial Valley, California	8	70
1946	Aleutian Islands, Alaska	n/a	200
1949	Puget Sound, Washington	8	220
1952	Kern County, California	12	350
1952	Bakersfield, California	2	60
1959	Hebgen Lake, Montana	28	n/a
1964	Anchorage, Alaska	131	2,280
1965	Puget Sound, Washington	8	70
1971	San Fernando, California	65	1,700
1979	Imperial County, California	n/a	60
1983	Coalinga, California	0	50
1987	Whittier Narrows, California	8	450
1989	Loma Prieta, California	63	6,870
1992	Petrolia, California	0	70
1992	Landers, California	1	100
1993	Scotts Mills, Oregon	n/a	30
1993	Klamath Falls, Oregon	2	10
1994	Northridge, California	57	20,000
TOTAL		1,225	39,160

KEY: n/a = not available.

SOURCE: Office of Technology Assessment, 1995.

due to structural failure.[6] Other earthquakes generally show the same pattern: people are killed in earthquakes when structures collapse. The second major cause of death in earthquakes is fire. In the 1923 Tokyo earthquake, for example, many of the 143,000 deaths were caused by the firestorms that occurred after the earthquake.[7]

Further reductions in fatality levels will come largely from incorporating seismic design principles into new construction (this is not done in many areas of the United States), retrofitting existing structures to improve their seismic resistance, and ensuring adequate fire and emergency response.

▮ Injuries

Earthquake-related injuries, in contrast to deaths, often result from nonstructural damage. Damages

[6] M. Durkin and C. Thiel, "Improving Measures To Reduce Earthquake Casualties, " *Earthquake Spectra,* vol. 8, No. 1, February 1992, p. 98.

[7] Bruce A. Bolt, *Earthquakes* (New York, NY: W. H. Freeman and Co., 1993). PP. 2197271.

[8] This report uses *retrofitting* to mean adding seismic resistance features, such as bracing, to an existing building to reduce the damage if an earthquake occurs. Some reports use the term *rehabilitation* instead.

TABLE 3-3: Injuries from the Loma Prieta Earthquake, 1989

Source	Percent of Injuries
Hit by falling object	13
Hit by overturning object	11
Thrown into object	18
Fall-related injuries	27
Strained taking evasive action	7
Structural collapse	5
Other	19

SOURCE: M. Durkin and C. Thiel, "Improving Measures To Reduce Earthquake Casualties, " *Earthquake Spectra,* vol. 8, No. 1, February 1992, p 99.

can occur, and people in or near buildings can be injured, even when there is no structural failure. In Loma Prieta, for example, 95 percent of the injuries did not involve structural collapse (table 3-3). These injuries were caused by falls, being struck by falling or overturned objects, or being thrown into objects.

Some simple, low-cost measures that can reduce these injuries include anchoring bookcases to walls, using chains to secure books in bookcases, securing kitchen appliances to the floor, bolting computers to desks, and tying lights to ceilings.

DAMAGE TO BUILDINGS

When the ground moves in an earthquake, the basement and the first floor will move with it. The top floor, or in a multistory building the upper floors, however, tend to stay put because a building is not perfectly rigid. The movement of the bottom of the building relative to the top puts great stress on the walls. The stress and resulting damage vary depending on the building itself. A simple wood house on a concrete foundation maybe knocked off its foundation in an earth quake, because the foundation moves with the ground but the house is left behind. A three-story brick building can be turned into a pile of rubble because the bricks are not rigidly attached to each other; the walls collapse outward leaving the floor unsupported. A tall steel-framed building may show little or no damage, because steel bends and sways to absorb the movement of the lower floors.[9]

The most dramatic, widely feared, and best understood type of damage is *collapse* (also called structural failure)-destruction of an entire building by an earthquake, often killing most of its occupants. A second type of damage is *structural damage*— broken or twisted beams, failure of structural members, and other damages that leave a building standing but often unsafe. In some cases costs of repair approach those of replacement. *Nonstructural damage+ racks* in walls, broken water pipes, broken windows—is rarely life-threatening but is often dauntingly expensive to repair. A final type of damage is *contents damage*--computers sliding off desks, pictures knocked off the wall, dishes smashed, merchandise tossed off shelves in stores, and so on. A useful rule of thumb is that contents are typically worth about 50 percent of the cost of the building

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Earthquakes can severely damage buildings.

[9] However, the 1994 Nothridge earthquake resulted in unexpected damage to steel buildings, which is discussed later in this chapter.

TABLE 3-4: Expected Damage to New Buildings That Meet Seismic Codes

Magnitude		Damage (percent of buildings)			
6.0-6.5	7.5-8.0				
Distance to fault (miles)		Minor only	Nonstructural	Structural	Collapse
30	50	10-40	1-5	<1	0
5	40	35-45	10-30	<5	<1
1	30	25-40	20-40	3-10	<2
—	3	5-25	40-70	10-30	<5

NOTE: These estimates are for new buildings that meet the 1991 Uniform Building Code; they do not apply to existing building stock.

SOURCE: Adapted from Earthquake Engineering Research Institute, "Expected Seismic Performance of Building s," February 1994, p. 15.

itself.[10] Therefore, damage to contents, although rarely life-threatening, can be a significant expense and can cause many injuries as well.

After an earthquake, one typically finds many buildings with nonstructural damage and progressively fewer buildings with greater damage. The degree of damage tends to increase as one moves closer to the fault (see table 3-4).

The type and amount of building damage caused by an earthquake depend on several factors. Liquefaction, in which the soil loses its ability to support weight, can cause a building to sink or topple. Ground-shaking damage will vary depending on the magnitude and frequency of the shaking. In general, long, slow ground movement is more damaging to taller buildings because the ground movement is closer to the building's natural frequency. In contrast, short, rapid ground movements are generally more damaging to shorter buildings. The design and materials used in the building are important as well. Buildings with carefully designed bracing, reinforcements in concrete columns, tightly connected walls and floors, and other seismic design features can ride out even large earthquakes; but those designed without consideration of seismic forces are likely to be damaged. Finally, the material used in construction (e.g., unreinforced masonry, wood, and steel) has a strong influence on a building's response to an earthquake (see box 3-l).

New Construction

Incorporating seismic considerations into the design and construction of buildings is much less expensive than attempting to retrofit an existing structure. Furthermore, if new construction incorporates such features, eventually all buildings will have them as older buildings are demolished. This section reviews the state of the knowledge of designing new buildings to resist seismic forces. The principal tool that determines the seismic performance of new buildings—building codes—is discussed, and several promising new technologies are reviewed.

State of *the Knowledge*

Numerous technologies and practices for new construction can reduce dramatically the risk of structural failure. These range from relatively simple design features, such as avoiding the use of soft stories (i.e., large open spaces in the first

10 Risk Engineering, Inc., "Residential and Commercial Earthquake Losses in the U.S.," report prepared for the National Committee on Property Insurance, Boston MA, May 3, 1993, p. 2.

BOX 3-1: Building Materials and Earthquakes

Unreinforced Masonry

Among the most dangerous buidings in an earthquake are those built of unreinforced masonry (URM). These buildings are dangerous for two reasons 1) the floors and roof are often not strongly attached to the walls and therefore the walls tend to collapse outward in an earthquake, and 2) the walls are often not strong enough to absorb the shear forces experienced in an earthquake (masonry is very weak in tension, meaning it has little resistance to being pulled apart). A relatively mild earthquake can turn a URM building into a pile of rubble quite easily. URM is also one of the least expensive building techniques—leading to the unfortunate outcome that lower income groups are often hardest hit by earthquakes. URM buildings are dangerous both to occupants and to those nearby, who can be hit by falling masonry. For example, eight people were killed by falling bricks in the Loma Prieta earthquake, all were killed outside a URM building.1

Concrete and Reinforced Masonry

A second type of building—made with reinforced masonry (in which steel reinforcing bars are used for strengthening), concrete frames, or precast concrete—can be dangerous as well, although less so than those built from URM. Concrete frame buildings—typically built in the 1950s to 1970s—are often large, multistory commercial or office buildings. Even when these buildings have walls to absorb some of the stress of an earthquake (called shear walls), the frame itself can fail. Precast concrete is often used for single-story warehouse, light industrial, or commercial buildings. The concrete panels can simply fall away from the building in an earthquake, due to inadequate connections between roof, floors, and walls,

Wood

Wood is often used as a structural material in single-family residences. It is the preferred construction material for smaller buildings in high earthquake risk areas because, unlike concrete, it is flexible and can bend without breaking. In an earthquake, a wood frame building will typically sway and bend, but will not fail. It is rare for a wood frame building to suffer structural collapse in an earthquake. However, wood residences can be damaged, sometimes severely, by an earthquake. Unanchored wood houses sitting on concrete foundations can be knocked off their foundations, Short walls (called cripple walls) that provide support between the floor and the ground can tip, moving the house off the foundation and severing gas lines and utility wires. These dangers can be reduced at reasonable cost by, for example, bolting houses to foundations and bracing cripple walls.

[1] California Seismic Safety Commission, *The Commercial Property Owner's Guide to EQ Safety, SSC 93-01* (Sacramento, CA January 1993), p, 8,

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floor) in apartment buildings, to the use of complex computer models to assist in the design and location of structural members in a large office building. Although considerable uncertainties exist in building performance under seismic stress, [11] it is generally agreed that **the knowledge exists to** design and construct buildings that are unlikely to collapse in an earthquake. Years of research have yielded a knowledge base that, *if applied properly,* would result in buildings that are unlikely to collapse in an earthquake. However such knowledge may not always be applied

[11] Examples include the steel weld issue (see box 3-1), and recent modeling suggesting that large buildings maybe vulnerable to collapse from large ground motions. T. Heaton et al., "Response of a High-Rise and Base-Isolated Buildings to a Hypothetical Mw 7.0 Blind Thrust Earthquake," Science, vol. 267, Jan. 13, 1995, pp. 206-211.

BOX 3-1 (cont'd.): Building Materials and Earthquakes

Steel

Steel has long been considered the ideal material for large buildings in high earthquake risk areas. It is extremely strong, durable, flexible, and ductile (i.e., it will bend slowly, rather than snap, if overstressed). A steel-framed building is very unlikely to fail structurally from ground shaking in an earthquake. However, faith in steel as a structurally sound material was shaken by the 1994 Northridge earthquake. In this quake, more than 100 steel-framed buildings—including some under construction—exhibited a severe and costly vulnerability not seen before: the steel beams themselves cracked at or near where they were welded to steel columns. Although none of these buildings collapsed, repair will be very expensive. Furthermore, these buildings were built to modern design standards. Presumably if they are rebuilt to these standards they will be susceptible to the same damage if they are subjected to the same shaking forces. This unexpected vulnerability has international Implications because large buildings all over the world are similarly built, and are presumably just as vulnerable to this type of damage.

What has become known as the steel-weld problem refers, in most cases, to cracks in steel supporting members at or near welds that joined horizontal beams and vertical columns. In tall buildings, these beams and columns are the backbone of the building. The discovery of cracks in these members usually leads to immediate evacuation due to fear of structural collapse. This problem was discovered in a few buildings in routine post-earthquake inspections; as awareness of the problem spread, cracks were found in more than 100 buildings. Since these cracks were in most cases found only by tearing down walls or other covering material, many were not discovered until inspectors went looking for them.

There is as yet little agreement on why these failures occurred. Fears of financial liability have made all parties sensitive to placing or accepting responsibility. Among the possible reasons raised are poor welding quality, poor steel quality, improperly designed connections, and inherent limitations of the beam-column design.

The first proposed technical fix was to reinforce the welds; however, tests of these reinforced welds showed that they too would fail in a major earthquake.[2] A second reinforcing method appears to perform better in preliminary testing, but costs three times as much as a standard connection.[3] Efforts to find effective and affordable solutions are continuing.

[2] "Weld Test Failures Shock L.A,," *Engineering News-Record,* June 13, 1994, p 9.

[3] "Test Results Kick Off More Debate on Steel, " *Engineering News-Record,* Sept 19, 1994, p. 8

properly because of lack of training, costs, and other reasons (these issues are discussed in chapter 4).

There are numerous examples of the ability to build structures that can resist seismic collapse. In the 1989 Loma Prieta earthquake, "well-designed and well-constructed buildings performed well."[12] In the 1994 Northridge earthquake, damage was most severe in older and poorly engineered buildings.[13] The 1995 earthquake in Kobe, Japan,[14] also suggests that current designs can yield build-

[12] National Research Council, *Practical Lessons from the Loma Prieta Earthquake* (Washington DC: National Academy Press, 1994), p. 70.

[13] J.D. Goltz (ed.), National Center for Earthquake Engineering Research, "The Northridge, California Earthquake of January 17, 1994: General Reconnaissance Report," Technical Report NCEER-94-0005, Mar. 11, 1994, p. 3-19.

[14] This earthquake is sometimes called the Hyogo-Ken Nanbu earthquake to denote the three regions involved.

ings unlikely to collapse. Although the earthquake caused massive losses and more than 5,000 deaths, new structures reflecting current building codes performed quite well.[15]

Our knowledge and implementation of technologies and practices to reduce *nonstructural* and contents damage is poor. Very little research has been done in these areas, and building codes are for the most part directed at protecting life safety by avoiding structural damage.[16] An analysis of residential insurance claims from recent California earthquakes found little correlation between the age of a building and the claim amount: newer buildings, although much less likely to collapse, were just as vulnerable to nonstructural damage.[17]

Building Codes

The knowledge of how to construct new buildings to avoid structural failure is laid out in building codes—detailed documents that summarize consensus design principles. Building codes are the most important policy lever for incorporating seismic considerations into new buildings; some of their key features and constraints are summarized here. A detailed discussion of building codes may be found in chapter 4.

In the United States, the local political jurisdiction typically regulates the design and construction of new buildings through the use of building codes. These codes are intended to ensure the health and safety of occupants. The codes typically set requirements for structural soundness, fire safety, electrical safety, and in some areas, seismic resistance as well. Most local building codes are based on model codes. The three national model codes are: the Uniform Building Code, which has been adopted in part by much of the western United States; the Building Officials and Code Administrators code, generally used in the northeast United States; and the Southern Building Code Congress International, adopted in the southeastern United States. The seismic provisions of these three model codes are based in part on what is known as the NEHRP (National Earthquake Hazards Reduction Program) Provisions.[18] These NEHRP Provisions are produced by an independent organization (the Building Seismic Safety Council) with NEHRP funding.

Codes have strengths and weaknesses that should be recognized. First, building codes are consensus documents. They are the results of negotiation and discussion among interested parties, and they reflect a balance of safety, first-cost, performance uncertainty, and other concerns. Second, codes are intended to provide a minimum, not an optimal, performance level. Although codes are unfortunately often taken as prescriptive, they are intended to define a minimum acceptable level of safety. Third, codes are technologically conservative. The process for updating and modifying codes is complex and time consuming. The result is that new technologies and practices can take years to make it into the model codes. From there, many more years are often necessary before a new model code is adopted by localities. Fourth, codes are intended primarily to prevent structural collapse. They have few requirements for nonstructural damage

[15] See, e.g., National Science Foundation, “Modern Buildings Fared Well in Kobe Quake, According to Preliminary Report,” press release, Feb. 23, 1995; and “Kobe High-Rise Rebuilding on Hold,” *Engineering News-Record*, Feb. 20, 1995, p. 12. This second reference reports on a post-earthquake survey in Kobe that found more than one-third of pre-1971 buildings were unsafe, while only 6 percent of buildings meeting current codes were unsafe.

[16] “The primary intent (of the Uniform Building Code seismic provisions) is to protect the life safety of building occupants and the general public.” Earthquake Engineering Research Institute, *Expected Seismic Performance of Buildings* (Oakland, CA: February 1994), p. 6.

[17] Confidential insurance industry data.

[18] “Two Model Codes Stiffen Protection,” *Engineering News-Record*, Jan. 6, 1992, p. 7.

TABLE 3-5: Costs of Seismic-Resistant Features in New Buildings

Building type	Number of cases	Estimated change in construction costs (percent)
Low-rise residential	9	0.7
High-rise residential	12	3.3
Office	21	1.3
Industrial	7	0.5
Commercial	3	1.7
Average	—	**1.6**

SOURCE: S Weber, National Institute of Standards and Technology, “Cost Impact of the NEHRP Recommended Provisions on the Design and Construction of Buildings, ” 1985, p. 1-11,

or for protecting contents. Finally, they generally apply only to new construction.[19]

Costs of Incorporating Seismic Provisions in New Construction

The cost of incorporating seismically resistant features into new buildings is frequently raised as a barrier to greater use of these features, especially in lower risk areas. These costs are heavily dependent on the design, location, and features of the building, as well as the local costs of labor and materials. Several studies have tried to estimate these costs through the use of representative case study buildings. These studies found that **incorporating seismic resistance features into new buildings increases construction costs by about 1 to 2 percent.**

One study by the National Institute of Standards and Technology estimated the costs of complying with the NEHRP Provisions, relative to building to the existing code. The study found an average increase in *construction* costs of 1.6 percent (see table 3-5).[20] A separate study estimated these costs for new single-family residential buildings. This study found that the costs of complying with the NEHRP Provisions, relative to existing practice, varied from O (some houses did not need any changes) to 1.6 percent of construction costs.[21] As in the previous study, these costs would be higher as a percentage of structural costs and lower as a percentage of total costs.

New Technologies

The traditional method of designing a building to resist seismic damage is by strengthening the structure. Although this is often effective at reducing the chances of structural collapse, significant nonstructural and contents damage can still resuit.[22] Furthermore, it is difficult and expensive to retrofit existing buildings to make them suffi-

[19] It is possible, however, to have building codes apply when existing buildings are extensively modified or expanded.

[20] S. Weber, National Institute of Standards and Technology, “Cost Impact of the NEHRP Recommended Provisions on the Design and Construction of Buildings,” 1985, p. 1-11. The choice of denominator in such an estimate is crucial. Construction costs include structural, material, labor, and all other costs associated with actual construction. They do not include land, site development, and other nonconstruction costs. Costs as a percentage of structural costs would be three to four times higher; as a percentage of total costs they would be roughly half of those shown in table 3-5.

[21] NAHB Research Center, “Estimated Cost of Compliance with 1991 Building Code Seismic Requirements,” prepared for the Insurance Research Council, Oak Brook IL, August 1992, p. 3.

[22] The contents of a building are typically worth about half as much as the building itself. Risk Engineering, Inc., see footnote 10, P. 2.

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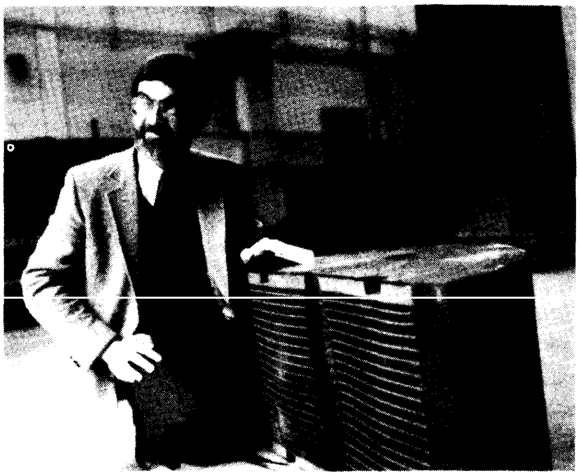


A base isolator cut in half to show its construction.

ciently strong to withstand a major earthquake. Two new technologies that may be able to reduce damages in both new and existing buildings—base isolation and active control systems—are reviewed here, promising information technologies are discussed in box 3-2.

Base isolation

Rather than the usual method of stiffening a building to resist seismic damage, base isolation in effect disconnects the building from the ground. This allows the ground to move underneath the building while the building stays relatively still. If successful, base isolation can protect both the building and its contents. There are two principal techniques for base isolation:

1. Installing rubber or rubber and steel pads, called elastomeric bearings, between the building and the ground: when the ground moves in an earthquake, the bushing bends and gives; the building, however, stays relatively still.
2. Using a bearing and a concave surface: the building's columns are attached to a bearing or other low-friction material, which in turn sits in a concave surface. In an earthquake, the concave surface (which is attached to the ground) slides around while the building stays still.

There are currently at least 30 base-isolated buildings in the United States, and more than 65 in Japan.[23] Applications of base isolation include new buildings such as the Foothill Communities Law and Justice Center in southern California, opened in 1986, which uses 98 rubber bearings; retrofits to existing buildings such as the U.S. Court of Appeals in San Francisco, originally built in 1905; and other structures such as a water tower in Seattle and art objects in the J.P. Getty Museum in Malibu, California.

Key questions of base isolation are:

- How well does it protect buildings and their contents?
- How does its cost compare to conventional techniques?

Computer modeling and laboratory testing of base isolation suggest that it works quite well. Laboratory tests of a base isolation system built to protect a large statue indicate that the system reduces accelerations 35 to 45 percent at the top of the statue.[24] Computer modeling of a base isolation retrofit to a historic brick tower in Seattle predicted a 75 percent reduction in base shear.[25] A much better test of base isolation would be its performance during a real earthquake. Although no base-isolated structures in the United States have yet experienced a large earthquake, several have been exposed to moderate ground shaking in recent years. Although data are still sparse, it ap-

[23] D. Trummer and S. Sommer, Lawrence Livermore National Laboratory, "Overview of Seismic Base Isolation Systems, Applications, and Performance During Earthquakes," UCRL-JC-1 15114, August 1993, p. 2.

[24] W. Haak, "Base Isolation System for Large Scale Sculptural Works of Art," in *Proceedings of the Fifth U.S. National Conference on Earthquake Engineering,* July 10-14, 1994, Chicago IL, vol. 1 (Oakland, CA: Earthquake Engineering Research Institute), p. 590.

[25] D. Bleiman et al., "Seismic Retrofit of a Historic Brick Landmark using Base Isolation," in *Proceedings of the Fifth U.S. National conference on Earthquake Engineering, see* ibid., p. 616.

BOX 3-2: Earthquake Notification and Early Warning Systems

Additional tools in the mitigation of seismic risks are post-earthquake notification and early warning systems (EWS). Notification systems use automated analysis of seismic data to estimate earthquake location, magnitude, and the geographic distribution of potentially damaging ground motion within minutes of a quake's occurrence. Because electronic signals travel faster than seismic waves through the earth, EWS can warn of approaching ground motion. Initial applications of future EWS include automated shut off of valves and opening of firehouse doors; these actions impose low to moderate costs if the warning is a false alarm. Should 30 to 60 seconds of warning be available, more applications are possible, including turning off computers or halting manufacturing processes and initiating personal safety precautions in schools, homes, or offices.

Development of Earthquake Notification Systems and EWS in California

In 1988, the California Division of Mines and Geology (CDMG) studied earthquake warning systems and their potential benefits and costs in California. The agency concluded that, with existing technologies and knowledge of earthquake hazards, construction of an EWS in California would not be justifiable on a cost-benefit basis.[1]

Within three years of this report's release, however, the California Institute of Technology (Caltech) and the U.S. Geological Survey (USGS), Pasadena—with the participation of local governments and the private sector—began providing automated broadcasts of southern California earthquake magnitude and location in near real time. Today, the Caltech-USGS Broadcast of Earthquakes (CUBE) system disseminates this Information to the scientific community, public officials, electric utilities, and railroad operators via pagers, electronic access to the Southern California Earthquake Data Center at Caltech, and direct phone lines. Another notification system, the Rapid Earthquake Data Integration (REDI) system, has been operating in northern California since 1993. It uses data from University of California at Berkeley and USGS, Menlo Park, seismographic stations located throughout northern and central California.

Factors contributing to the change of heart toward implementing EWS included:

- The National Research Council issued a report that delineated the benefits of real-time analysis of seismological data.[2]
- There were rapid advances in seismic data digitizers and sensors and satellite telecommunications capabilities.

[1] See Richard Holden et al., *Technical and Economic Feasibilityofan Earthquake Warning System in California, Special* Publication 101 (Sacramento, CA, California Department of Conservation, Division of Mines and Geology, March 1989).

[2] See National Research Council, Committee on Seismology, *Real-Time Earthquake Monitoring: Ear/y Warning and Rapid Response* (Washington, DC: National Academy Press, 1991)

(continued)

pears that base isolation systems reduced large accelerations yet had little effect on small accelerations.[26] In one study in Japan, two identical buildings, one with base isolators and one with conventional technology, were built side by side in an active seismic area. The building with base isolators experienced, on average, about 75 percent lower acceleration than the conventional building during a series of moderate earthquakes.[27] There is some evidence, however, that

[26] Trummer and Sommer, see footnote 23, p. 3.

[27] T. Kuroda et al., Argonne National Laboratory, "Comparison of Seismic Response of Ordinary and Base-Isolated Structures," ANL/CP—75357, 1992.

BOX 3-2 (cont'd.): Earthquake Notification and Early Warning Systems

- Increased attention was given to the earthquake threat, facilitated by the 1989 Loma Prieta earthquake in the San Francisco Bay area and the 1992 Landers earthquakes in southern California.
- There was improved perception by the private sector and local governments of the usefulness of ground-motion information and early warning.[3]

REDI and CUBE coordinate to provide complete statewide coverage and to automatically notify the state Office of Emergency Services, Department of Transportation, CDMG, utilities, telecommunications providers, and transportation companies of significant events. Second, strong-motion estimates (for earthquakes of magnitude 5.5 or greater) are broadcast via the paging system and maps of strong-motion distribution are made available on the Internet. After initial source data and strong-motion estimates are released, the systems automatically calculate the seismic moment and moment tensor for the earthquake. This helps to determine which fault planes are involved, to refine magnitude calculations, and to better characterize rupture processes that determine the degree of severe shaking.[4]

Future Directions

Besides developing EWS capabilities, goals for the existing notification systems include reducing analysis time and developing quick damage assessment capabilities to aid in emergency response and aftershock preparedness. For example, university and government researchers are working to include soil amplification and other site effects, and to integrate building inventories into the systems in order to rapidly estimate zones of highest damage and casualties.

In a similar vein, work is under way to develop an automated rapid damage assessment capability intended to alleviate much of the uncertainty, delays, and inaccurate information associated with traditional post-quake intelligence gathering.[5] Data on the built environment are being collected and vulnerability assessment software is being developed that will accept CUBE and REDI data and predict both damage areas and overall impact.

[3] Egill Hauksson, Seismological Laboratory, California Institute of Technology, personal communication, June 28, 1995

[4] Lind Gee, Selsmographic Station, University of California at Berkeley, personal communication, June 28, 1995

[5] Ronald T Eguchi et al , "Real-Time Earthquake Hazard Assessment in California: The Early Post-Earthquake Damage Assessment Tool and the Caltech-USGS Broadcast of Earthquakes, " paper presented at the Fifth U S National Conference on Earthquake Engineering, July 10-14, 1994, Chicago, Illinois, p. 2.

base isolation systems as currently designed may be overwhelmed by large earthquakes that produce very large ground displacements.[28]

The costs of base isolation are not well known. A commonly used estimate is that base isolation adds about 5 percent to the construction costs of a new building. One cost analysis of a new building in southern California found that base isolation would be about 6 percent cheaper than conventional design, with much of the savings coming from eliminating the need for measures to protect computers and other sensitive equipment.[29]

[28] Heaton et al., see footnote 11.

[29] S. Sommer and D. Trummer, "Issues Concerning the Application of Seismic Base Isolation in the DOE," in *Proceedings* of the Fifth U.S. *National Conference on Earthquake Engineering, see* footnote 24, p. 603.

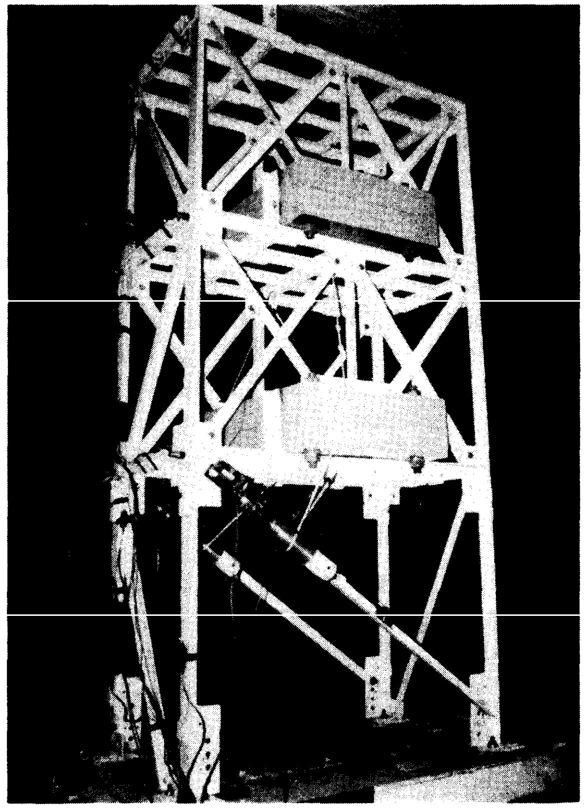
Another study found the life-cycle costs of base isolation to be comparable to conventional technology.[30]

Although these studies suggest that the costs of base isolation are competitive with conventional design, costs are still uncertain. Most applications to date of base isolation have been in buildings where noncost attributes are crucial: experimental buildings, historic retrofits where major interior renovations were impossible, and buildings where continuance of building function after an earthquake was critical.

Active control systems

Another approach to minimizing earthquake damage is the use of active control systems, which detect earthquakes and respond to them. Although many ideas for active control are still at the conceptual stage, some are beginning to be applied in buildings. Perhaps the simplest example of active control is the use of a large weight on the top of a building; the weight is computer-controlled to move so as to counteract the earthquake-induced sway of a building. This technique, known as "active mass damping," is already used in some tall buildings, including the John Hancock Building in Boston, to reduce occupant discomfort from wind-induced building sway.[31] Such a system has been installed in an office building in Japan to resist seismic damage.[32]

A more advanced approach is the use of "active tendons' '-electronically controlled actuators that can be instructed to shake the frame of a building so as to minimize earthquake-induced movement. These systems, although still far from commercial application, have the potential to reduce both structural and contents damage by minimizing building movement in an earthquake. They could in theory be used in both new and retrofit applications. An active tendon system has been installed in an experimental building in Tokyo, Japan.[33]



Active control systems being tested.

Issues affecting the development and use of these systems include:

- Cost. Most systems to date have been experimental and designed with little attention to cost. The costs of commercial systems are as yet unknown.

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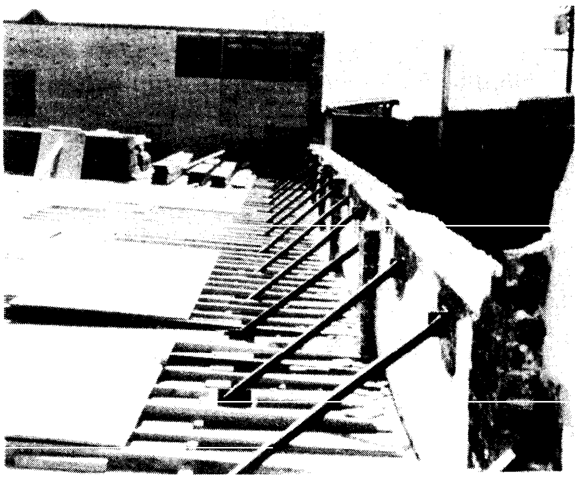
[30] S. Pyle et al., "Life-Cycle Cost Study for the State of California Justice Building," in *Proceedings of Seminar on Seismic lsolation, Passive Energy Dissipation, and Active Control,* ATC 17- I (Redwood City, CA: Applied Technology Council, 1993), p. 58.

[31] V. Vance, Langley Research Center, "Active Control of Buildings During Earthquakes," NASA Technical Memorandum, December 1993, p. 3.

[32] "Structures Tuned to the Rhythm of a Quake," *New Scientist,* Feb. 16, 1991, p. 33.

[33] Vance, see footnote 31, p. 5.



Bracing parapets can reduce damage and injuries.

- *Reliability.* These systems will be inactive most of the time, but must work properly when called on. Reliability is critical, and ensuring it will increase cost.
- *External energy requirements.* Active systems require energy, and energy systems can be interrupted in an earthquake. If energy storage is needed, costs will increase.
- *Potential for future applications.* Since a well-designed building is likely to avoid structural damage in all but the largest earthquakes, the value of active control systems will be largely in their ability to reduce nonstructural and contents damage. This value has not been well-quantified.

Existing Buildings

Most buildings in existence today were constructed before our current understanding of how to build them to reduce seismic damage. These older structures were built to earlier, less stringent building codes. This section reviews technologies and practices for reducing earthquake damage in existing buildings. It discusses the costs of doing so and some associated policy issues.

State of the Knowledge

Our understanding of how to retrofit existing buildings to improve their seismic performance has improved in recent years, due in part to NEHRP-sponsored programs, yet numerous knowledge gaps and uncertainties remain. Retrofitting is a more difficult task than new building design for several reasons: the original plans of the building may be missing or inaccurate; it maybe necessary to allow the building to remain occupied while it is being retrofitted; owners may want to preserve the appearance of a building (e.g., exterior seismic braces may be unacceptable); and, as always, costs are a concern. Designing retrofit methods that can overcome these obstacles is a continuing challenge.

There are generally agreed-on principles that can guide retrofitting. For example, typical steps to reduce damage include bracing parapets; improving connections among walls, floors, and roofs; strengthening the walls themselves; adding structural framing to support exterior walls; and modifying the building design to reduce asymmetry (symmetric buildings are generally stronger). Work to refine these techniques is ongoing. Its goal is to develop a set of comprehensive guidelines on seismic retrofitting of existing buildings.[34]

Costs of Retrofit

The costs of retrofitting buildings to improve seismic resistance are uncertain, but are generally much higher than incorporating seismic design into new construction. The uncertainty is due to several factors: seismic retrofits are often done in conjunction with other building improvements, such as appearance and fire safety, which makes it

[34] The Federal Emergency Management Agency has published a number of related guidebooks and reports, and plans to complete retrofit guidelines in 1997.

difficult to separate the cost of seismic actions alone;[35] buildings and retrofit techniques differ widely, leading to wide variations in costs; and there is little agreement on the appropriate level of retrofit (i.e., the level of safety a retrofitted building should provide).

Unreinforced masonry (URM) buildings have received the most retrofit attention since they are often the buildings at greatest risk for life safety. Costs of URM retrofits are typically $7 to $18 per square foot.[36] To put these costs in perspective, typical construction costs for new masonry buildings are $40 to $70 per square foot.[37] Combining these estimates yields a range of 10 to 45 percent, with a midpoint of 23 percent: that is, **retrofit of URM buildings typically costs about 23 percent as much as new construction** (although costs will vary considerably). When this is compared with the 1 to 2 percent additional cost of incorporating seismic design into new construction (discussed above), it is clear that retrofitting is much more expensive.[38]

Other Retrofit Issues

Few buildings in the United States have been retrofitted to improve seismic performance, even though they represent a significant risk.[39] Why are retrofits so difficult to implement? Part of the answer is their high cost. As noted above, retrofits of URM buildings typically cost about 23 percent as much as new construction, and costs of retrofits for other building types are comparably high. Perhaps more important, however, is that these retrofits offer little in the way of near-term market benefits (which are typically a function of size, location, amenities, and so forth). Not surprisingly, therefore, the retrofits that have occurred have been largely in response to regulations requiring them (chapter 4 discusses these issues in more detail).

A second issue complicating retrofits is determining the appropriate level of safety. Increased safety comes at an increased cost. For new buildings, the minimum safety level is set by the building code. There is however no such generally accepted code for existing buildings (although guidelines are now available),[40] and requiring them to meet the same safety levels as new buildings would be extremely expensive.

A third issue is how well retrofits work. Data on retrofit performance in earthquakes are rare; however, there is some evidence that retrofitted URMs

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[35] Performing a seismic retrofit may "trigger" other code requirements, such as fire safety upgrades.

[36] Much of the variation can be explained by the level of seismicity to which the building is retrofitted and by the size of the building (larger buildings have lower retrofit costs per square foot). Retrofit costs for non-URM buildings are in the same range—for example, retrofitting precast concrete tilt-up walls is estimated to cost $5 to $19 per square foot. Federal Emergency Management Agency, *Typical Costs for Seismic Rehabilitation of Existing Buildings*, 2nd Ed., FEMA 156 (Washington, DC: December 1994), pp. 1-15 to 1-18.

[37] OTA estimate, based on Federal Emergency Management Agency, *Typical Costs for Seismic Rehabilitation of Existing Buildings*, vol. 2, FEMA 157 (Washington, DC: September 1988), p. 3-72.

[38] Retrofitting, although more expensive than incorporating seismic considerations into new construction, can still be a worthwhile investment if the risk is high (e.g., in an area with a high probability of a damaging earthquake or in a critical building such as a hospital).

[39] For example, a 1994 review of California's seismic risk found, "we still have many earthquake-vulnerable buildings. . . ." California Seismic Safety Commission, "California at Risk," 1994 Status Report, SSC 94-01, p. 1. In the central United States, some states have just begun to identify hazardous structures. R. Olshansky, "Earthquake Hazard Mitigation in the Central United States: A Progress Report," in *Proceedings of the Fifth U.S. National Conference on Earthquake Engineering*, see footnote 24, p. 992.

[40] These guidelines, known as the Uniform Code for Building Conservation (UCBC), are intended not to ensure life safety but to decrease seismic risk. For example, 15 to 25 percent of *retrofitted* URMs located near the epicenter of a major earthquake are expected to collapse in a moderate earthquake. Earthquake Engineering Research Institute, see footnote 16, p. 16. In addition, as noted above, FEMA is working to develop comprehensive retrofit guidelines.

did not perform as well as hoped.[41] Evaluation of retrofit methods is clearly needed.

One major technical issue that makes such retrofits difficult is the analysis of existing buildings. Deciding on a retrofit technique requires an understanding of the strengths and weaknesses of the building as it stands. For many older buildings, however, the original plans are not available; the building has been modified several times since its original construction; and structural details of the building are hidden by nonstructural components. Some work has been done by the National Institute of Standards and Technology (NIST) in applying nondestructive testing techniques, such as sensors that can detect reinforcing rods in concrete, to seismic retrofit problems. The Federal Emergency Management Agency (FEMA) has also sponsored research into "rapid screening methods"—methods to quickly estimate a building's seismic hazard without performing a detailed engineering analysis. These are promising research directions.

DAMAGE TO LIFELINES

Lifelines (i.e., bridges, mass transit systems, overpasses, roads, electric and gas supply systems, water and sewer systems, and telecommunication networks) are often damaged by earthquakes. Much of what has been discussed about buildings applies to lifelines as well:

- most fatalities associated with lifelines are caused by structural collapse;
- the knowledge of how to build new lifeline facilities to minimize structural collapse is available, although this knowledge, for economic or other reasons, may not be used;
- much of the remaining life safety risk lies with existing facilities; and
- existing facilities can be retrofitted, but the costs are high.

There are, however, some key ways in which lifelines differ from buildings. The most important difference is **the high cost of outage**. If a building is damaged, only the functions in that building are lost. If a lifeline is interrupted—even for a brief time—the costs can be massive. The most extreme example would be loss of a water supply system after an earthquake, which occurred in San Francisco in 1906, leading to massive fires. In the longer term, interruptions in water or sewer service can lead to public health problems, breaks in key transportation links can snarl commuting, and the loss of natural gas systems can force otherwise undamaged businesses to close. Thus "success" in lifeline seismic design is often defined as retaining functionality rather than simply reducing damage.

The second major difference is that **lifelines are usually owned and operated by public agencies** (exceptions are electricity and natural gas supply systems, which in most areas are owned and operated by publicly regulated, privately owned companies). Therefore, responsibility for their continued operation, and decisions about their earthquake resistance, often lie entirely with the government.

Bridges

Bridges, overpasses, and elevated highways are often damaged by earthquakes, and the costs of damage to these critical lifelines are high. Catastrophic failure can result in many deaths. Of the 63 deaths in the 1989 Loma Prieta earthquake, for example, 42 were caused by the collapse of one elevated highway.[42] Repair of damaged bridges can be very expensive: the reconstruction of the

[41] For example, many retrofitted masonry structures suffered severe damage in the Northridge earthquake. Goltz, see footnote 13, p. 3-36.

[42] M. Durkin, "Improving Earthquake Casualty and Loss Estimation," paper presented at the Earthquake Engineering Tenth World Conference, Balkema, Rotterdam, 1992, p. 559.

Santa Monica Freeway in Los Angeles, which was damaged in the Northridge earthquake, cost $29.4 million.[43] Also, interruption of transport services can disrupt the local economy; the 1989 Loma Prieta earthquake caused the partial collapse of the San Francisco-Oakland Bay Bridge, which disrupted the passage of 243,000 vehicles per day.[44]

Bridges can be damaged in several ways, including:

- They can simply be "unseated." Sections of bridges typically sit on horizontal supports, called seats; if the support moves far enough in an earthquake it can simply drop the bridge section.
- The columns holding up sections of a bridge may collapse under the lateral (side) forces caused by an earthquake.
- The soil providing support for a bridge may settle or shift.

Known technologies and practices can do much to reduce the risk of major damage to or collapse of bridges. The primary constraint is the high cost of implementing these technologies and practices, especially when such long-term investments must compete with other public investments for scarce capital.

New Construction

Like buildings, bridges built to current standards of seismic resistance have performed quite well in recent earthquakes. In the Loma Prieta earthquake, only one of the 100 bridges damaged was designed after 1972, when seismic design requirements were revised significantly.[45] Similarly, the two major freeway collapses in the 1994 Northridge earthquake—the Santa Monica Freeway and the I5-SR14 interchange—were due primarily to the failure of supporting columns designed and built before 1971.[46] A total of seven highway bridges collapsed in the 1994 Northridge earthquake; none were built to current codes.[47] The elevated highway that collapsed during the 1995 quake in Kobe, Japan, did not incorporate current knowledge on designing columns to resist seismic damage.[48]

Some design features in new bridges that resist seismic damage include: using continuous spans and thereby eliminating joints that can separate and collapse, using longer seat widths that allow for more horizontal movement without unseating, improving soil strength to avoid liquefaction, designing all bridge components for horizontal loads, and confining (wrapping) columns.[49]

Retrofits

About 345,000 bridges in the United States were built before 1970, with little or no consideration of seismic resistance.[50] Although not all of these are located in areas of seismic concern, retrofitting these bridges remains a major technical, financial, and policy challenge.

Much of the bridge retrofit activity in the United States has been in California. The 1971 San Fernando earthquake in southern California

[43] "Quake-Damaged Freeway Reopening Ahead of Time," *New York Times*, Apr. 12, 1994, p. A12. About half the cost was a bonus to the contractor for early completion.

[44] U.S. Geological Survey, "The Loma Prieta, California, Earthquake of October 17, 1989—Fire, Police, Transportation, and Hazardous Materials," 1553-C, 1994, p. C18.

[45] National Research Council, see footnote 12, p. 169.

[46] J. Cooper et al., "The Northridge Earthquake," *Public Roads*, summer 1994, p. 32.

[47] I.G. Buckle, National Center for Earthquake Engineering Research, "The Northridge, California Earthquake of January 17, 1994: Performance of Highway Bridges," Technical Report NCEER-94-0008, Mar. 24, 1994, p. 1-1.

[48] Earthquake Engineering Research Institute, *The Hyogo-Ken Nanbu Earthquake*, Preliminary Reconnaissance Report (Oakland, CA: February 1995), p. 44.

[49] Cooper et al., see footnote 46, p. 34.

[50] Ibid.

damaged more than 60 bridges, and led both to revision of standards for new bridge construction and to an ambitious bridge retrofit program. Retrofitted bridges performed very well in the 1989 Loma Prieta earthquake: 350 bridges retrofitted with hinge restrainers were in the area impacted by the quake, and none were damaged.[51] Similarly, retrofitted bridges performed very well in the 1994 Northridge earthquake.[52] Although some hinge restrainers failed, no steel-jacketed column retrofits showed signs of distress.[53]

The technical knowledge of how and what to retrofit is good, but not faultless. The 1989 Loma Prieta earthquake caused the partial collapse of the San Francisco Bay Bridge; this bridge had been retrofitted in the 1970s, and the section that collapsed was not considered vulnerable.[54]

In addition to determining the best technologies and practices for bridge retrofits, funding these retrofits remains a major challenge. The I-880 elevated highway that collapsed in the Loma Prieta earthquake, killing 42 people, was scheduled for retrofit but had not been because of budget limitations.[55] A General Accounting Office survey of state bridge retrofit activity found that very few states had retrofitted their bridges; limited funding was identified as a major barrier.[56]

Water and Sewer Systems

Ground motion and ground failure due to earthquakes can cause water and sewer pipes to break; this can be especially dangerous if fire follows an earthquake. Also, since almost all of these pipes are underground, repair is expensive and time consuming. The 1989 Loma Prieta earthquake caused 748 water supply pipeline breaks; the total cost of repairs was in the tens of millions of dollars.[57] This earthquake also severely damaged San Francisco's auxiliary water supply system.[58] The 1987 Whittier Narrows earthquake caused 17 major water supply pipeline breaks, with the result that water pressure in the system was at half its usual level for two days following the earthquake.[59] The loss of water supply contributed to the severity and duration of fires in the 1995 Kobe, Japan, earthquake.

Recent experiences with the performance of water systems in earthquakes suggest several design principles to reduce future disruptions. The Loma Prieta and Northridge experiences point to the importance of redundancies in water supply systems. In the Loma Prieta earthquake, liquefaction in the South of Market area of San Francisco caused a break in a major pipeline of the city's backup water supply system. Fortunately, other backup systems, including cisterns and a fire boat, were available. Water supply systems should build in redundancies (e.g., multiple pipelines and independent power supplies for pumping) to reduce the probability of the system's being disabled from the loss of any one component. In the Northridge earthquake, a number of water leaks resulted from the breakage of pipes and valves

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[51] National Research Council, see footnote 12, p. 168.

[52] Cooper et al., see footnote 46, p. 32.

[53] Buckle, see footnote 47, p. 1-1.

[54] U.S. Congress, General Accounting Office, *Loma Prieta Earthquake: Collapse of the Bay Bridge and the Cypress Viaduct*, GAO/RCED-90-177 (Washington, DC: June 1990), p. 5.

[55] Ibid., p. 2.

[56] U.S. Congress, General Accounting Office, *The Nation's Highway Bridges Remain at Risk from Earthquakes*, GAO/RCED -92-59 (Washington, DC: January 1992), p. 13.

[57] National Research Council, see footnote 12, pp. 138, 146.

[58] "Keeping Lifelines Alive," *Civil Engineering*, March 1990, p. 59.

[59] A. Schiff, "The Whittier Narrows, California Earthquake of October 1, 1987—Response of Lifelines and Their Effect on Emergency Response," *Earthquake Spectra*, vol. 4, No. 2, 1988, p. 344.

where they connect to water tanks. Use of flexible connections that would allow differential movement of pipes and tanks would reduce such leaks. A $17-million evaluation and retrofit of Seattle's water supply system found that elevated water tanks were among the most vulnerable components of the system.[60] Ensuring that such tanks have sufficient anchors and braces will reduce the chances of collapse.

Electricity Systems

In recent earthquakes in the United States, the damage to electricity systems has been relatively minor. Redundancies in transmission and distribution systems, coupled with the inherent flexibility of wires (i.e., compared to rigid pipes), suggests that electricity is not the most vulnerable lifeline. In the Loma Prieta earthquake, several electrical switchyards were moderately damaged.[61] In the Northridge earthquake, about 2 million customers lost electrical power due mainly to substation problems; however, most service was restored within a day.[62]

Fortunately most critical facilities that use electricity—such as hospitals, telecommunications systems, and computer facilities—have backup electricity-generating facilities. However, since most backup systems such as batteries and on-site generators are designed to supply limited power for only a short time (typically hours or tens of hours), longer term electricity system damage can be a serious problem.

Natural Gas Systems

Natural gas is transported through underground pipelines, which are vulnerable to fracture in earthquakes. Resulting natural gas leaks are a dangerous fire and explosion hazard. In the Northridge earthquake, a broken natural gas transmission pipeline caused a fire that destroyed five houses.[63] Analysis of the performance of natural gas transmission pipelines in California earthquakes found that most damage could be traced to pre-1930 welds, which were generally of poor quality. Pre-1930 pipes had a damage rate 100 times that of post-1930 pipes.[64] Modern pipes with high-quality welds are still vulnerable to ground deformation, but are very resilient to damage from traveling ground waves.

Although modern natural gas transmission systems generally perform quite well in earthquakes, leaks and other problems in the distribution system and at or near the service connection are common. In the 1987 Whittier Narrows earthquake, for example, there was only one leak in the transmission system (due to a cracked cast iron pipe) but there were 1,400 leaks on customer property. Three-quarters of these resulted from failures at appliance connections, primarily water heaters.[65] In the Loma Prieta earthquake, the natural gas transmission system was undamaged, but the distribution system suffered extensive damage. Repairs in many cases were made by inserting flexible plastic piping into damaged cast iron pipes.[66] In the Northridge earthquake, 120 mobile

[60] W. Anton et al., "Seattle Plays It Safe," *Civil Engineering*, August 1992, p. 39.

[61] National Research Council, see footnote 12, p. 142.

[62] Goltz (ed.), see footnote 13, p. 4-11.

[63] Ibid., p. 4-21.

[64] T. O'Rourke and M. Palmer, National Center for Earthquake Engineering Research, "The Northridge, California Earthquake of January 7, 1994: Performance of Gas Transmission Pipelines," Technical Report NCEER-94-0011, May 16, 1994, pp. 2-32, 2-35.

[65] Schiff, see footnote 59, p. 348.

[66] National Research Council, see footnote 12, p. 140-141.

homes were destroyed by fires triggered by natural gas valve leaks.[67]

ACCOMPLISHMENTS AND NEEDS OF FEDERALLY SPONSORED RESEARCH

Accomplishments

Considerable progress has been made in understanding how the built environment is affected by earthquakes and how structures can be designed to reduce structural failure. **NEHRP has done much to expand our knowledge of earthquake engineering**. Although a rigorous evaluation of NEHRP has not been undertaken (and would be very difficult, since much of NEHRP involves research, which is inherently difficult to evaluate), there are numerous examples in which NEHRP-funded programs have had considerable societal benefits.

A 1993 workshop defined some key contributions made to earthquake engineering by the National Science Foundation's funding of research under NEHRP. These include:

- advances in analytical and modeling techniques, permitting seismic structure design on inexpensive computers;
- improved understanding of how structures behave under earthquake-induced stress, which has led to better building codes in such areas as bracing systems for steel structures;
- advances in new technologies such as base isolation and active control;
- better reliability and risk assessment techniques for lifelines and structures; and
- improved disaster response planning from social science research that sheds light, for example, on cultural differences in perceptions of disaster.[68]

NEHRP-funded work by NIST, although a small fraction of total program funding, has also addressed some key applied earthquake engineering problems. Examples include testing of base isolation systems, development of methods to evaluate the strength of existing buildings, and evaluation of building retrofit techniques.[69] Additional relevant NIST activities include, for example, development of seismic standards for existing federal buildings and management of a United States-Japan annual meeting on earthquake engineering.

Implementation of this knowledge is a continuing concern; yet there are successes here as well. For example, development of the NEHRP Provisions, a resource document for model codes, and their adoption by model code agencies, is a significant accomplishment. Retrofitting of existing buildings is still a difficult and expensive task, yet FEMA's work in this area has made some progress toward consensus on methods and costs.

These examples of NEHRP successes are not the result of a thorough evaluation of that program, nor do past successes ensure future contributions. However, it is clear that NEHRP has made a significant contribution to improving understanding of how to build structures that will resist seismic damage. (A more detailed description of the current activities of NEHRP agencies can be found in appendix B.)

Future Needs

Knowledge of how to design and build structures so as to reduce earthquake-induced damage has improved considerably. However, the problem is far from solved. The 1994 Northridge earthquake occurred in probably the most well-prepared area of the United States. Nevertheless, it caused 57

[67] Goltz (ed.), see footnote 13, p. 6-5.

[68] National Science Foundation, "Directions for Research in the Next Decade," Report on a Workshop, June 1993.

[69] Richard N. Wright, Director, Building and Fire Research Laboratory, National Institute of Standards and Technology, testimony at hearings before the Senate Committee on Commerce, Science, and Transportation, Subcommittee on Science, Technology and Space, May 17, 1994, on NEHRP reauthorization.

deaths and about $20 billion in losses. Scenarios of future earthquakes across the United States suggest that large losses are likely.

Greater use of existing knowledge, practices, and technologies could reduce these losses. For example, the 1989 collapse of the I-880 elevated highway in Oakland, which resulted in 42 deaths, could have been prevented with the use of known technologies. The implementation (or lack thereof) of these technologies to date has been determined largely by economic, behavioral, institutional, and other factors, not by the state of the knowledge (these issues are addressed in chapter 4).

Nevertheless, improved knowledge could have several benefits. First, although current knowledge of how to build new structures to resist seismic damage is good, it is far from perfect (consider the steel weld failures in new buildings in the Northridge earthquake). Second, many of the financial losses in recent earthquakes resulted from nonstructural and contents damage—areas that have received little research attention. Third, much of the risk of fatalities lies in existing structures, and retrofit methods are still not well developed. Research into improving retrofits could reduce this risk. Fourth, to the extent that economic factors influence implementation, research to reduce costs could lead to greater implementation.

New Buildings

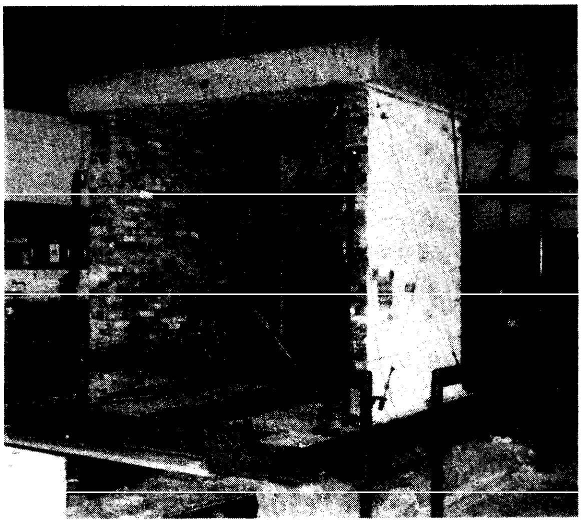
Buildings constructed to comply with today's codes are meeting the goal of providing life safety. Building collapses have been limited largely to older buildings designed to earlier codes. This is a major success, for which NEHRP gets some credit: years of research, and a concerted effort to ensure that the results of this research are incorporated into codes, have resulted in effective new building codes that, if properly applied, will yield a building that is unlikely to suffer structural collapse.

However, several crucial areas of new building seismic design are still not well understood. A new building meeting today's code, although unlikely to suffer structural collapse, will likely suffer expensive nonstructural and contents damage in a major earthquake. This does not indicate inadequate or faulty construction or design. Rather, it reflects the fact that codes are intended primarily to protect life safety by preventing structural collapse and typically have few or no requirements to limit nonstructural or contents damage.[70] It is time for new building seismic engineering research to consider the next problem: **reducing nonstructural and contents damage**. Possible areas of research include:

- data collection and analysis of nonstructural and contents damage from recent earthquakes;
- how to design and build structures to avoid or minimize expensive nonstructural failures such as cracked walls, broken sprinkler systems, and collapsed chimneys;
- analytical methods to measure or predict such damage;
- guidelines for lighting, electrical, water, and other systems design and installation to minimize seismic damage;
- expanding building codes to address nonstructural and contents damage; and
- considering technologies—notably active and passive control—that can reduce these damages.

The major surprise of the 1994 Northridge earthquake was the failure of steel welds. These failures occurred in new buildings and in buildings under construction. Although none of these buildings collapsed, repairing this damage will be very expensive. Since it is not yet clear why such damage occurred or how to prevent it, repairs may

[70] "The primary intent [of the Uniform Building Code seismic provisions] is to protect the life safety of building occupants and the general public." Earthquake Engineering Research Institute, see footnote 16, p. 6.



NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH

Testing of URM retrofit methods

not prevent the recurrence of this problem. Researcg is needed to better understand what caused this failure and how steel frames should be designed, assembled, and modified (in existing buildings) to prevent it from happening again.[71]

Existing Buildings

Much of the risk of collapse and resulting fatalities lies in existing buildings, which do not incorporate current codes and knowledge. Few of these buildings have been retrofitted to reduce risk, and such retrofits have sometimes been expensive, complex, and of uncertain benefit. Additional research is needed to improve understanding of how to best reduce the risk in existing buildings.[72]

The first area of research for existing buildings should be to **better understand the vulnerability of existing buildings.** It is commonly recognized that URM buildings are unsafe. However, for other types of buildings (e.g., precast concrete framed buildings or reinforced masonry buildings), the risk is less well known. Laboratory and field experiments, and collection and analysis of data on how buildings respond during earthquakes, are needed. Improved tools to determine risk in existing buildings—such as nondestructive evaluation techniques—are needed as well. A second area is **the development of low-cost standardized retrofit techniques.** Many retrofits to date have been expensive and have required extensive site-specific design and analysis. Standardized methods, such as those contained in codes for new construction, would reduce costs. These methods could also allow for multiple levels of safety to accommodate different risk preferences. A third research area is to **extend retrofits from structural damage reduction to nonstructural and contents damage reduction.** The bulk of damage to buildings in recent California earthquakes has been nonstructural and contents damage; retrofit methods to reduce this damage could be very beneficial.

Lifelines

Lifelines are expensive to repair if damaged in an earthquake, and service interruptions are at best inconvenient and at times deadly. Like buildings, lifeline facilities built to current design knowledge generally behave quite well in earthquakes. However, the lack of an accepted national standard for the design and construction of lifelines raises costs and reduces performance. The 1990 NEHRP reauthorization directed FEMA and NIST to work together to develop a plan for creating and adopting design and construction standards for lifelines. The legislation directed the agencies to submit this plan to Congress by June 30, 1992. Although some work has been done on the plan, as of this writing it had not yet been submitted to Congress.

Much of the life safety risk associated with lifelines lies in existing facilities. Research is needed to develop methods to better determine the risk in

[71] Fema is currently using supplemental appropriations funds, passed after the Northridge earthquake, to sponsor research and development related to the steel weld problem.

[72] FEMA has an existing buildings program that is addressing some of the issues noted here.

existing facilities, to develop methods to prioritize retrofits, and to develop standardized retrofit methods that can reduce retrofit costs. A goal of preserving functionality, rather than simply minimizing damage, is often appropriate for lifelines. The development of low-cost, easy-to-use procedures to analyze lifelines for weak links would help to ensure their continued function in earthquakes.