

5.1 INTRODUCTION

Improving performance to reduce seismic risk is a multi-faceted issue that requires consideration of a broad range of factors. Previous chapters in this document have introduced and described the overarching concept of seismic risk management (Chapter 2) and two of the fundamental factors affecting improved seismic performance: consideration of the seismic hazards affecting the site (Chapter 3); and consideration of the desired seismic performance of structural and nonstructural components for the range of earthquakes of concern (Chapter 4).

This chapter identifies and addresses related seismic design issues that are fundamentally important to improved seismic performance, regardless of the occupancy type:

- selection of the structural materials and systems (Section 5.2);
- selection of the architectural/structural configuration (Section 5.3);
- consideration of the expected performance of nonstructural components, including ceilings, partitions, heating, ventilation, and air condition equipment (HVAC), piping and other utility systems, and cladding (Section 5.4);
- cost analysis, including consideration of both the benefits and costs of improved seismic performance (Sections 5.5 through 5.7);
- and quality control during the construction process (Section 5.8).

Considerable attention is given to the quantification of benefits and costs of improved seismic performance, given the underlying importance of cost considerations. Benefits include reduced direct capital losses and reduced indirect losses, which are related to the time that a given building is operationally out of service. Cost issues are demonstrated through several means, including the use of (1) graphics showing the relationship between the cost of various options for improving seismic performance versus the resulting benefits; and (2) case studies demonstrating best practices in earthquake engineering.

The Chapter concludes with a set of general recommendations for improving seismic performance during the seismic design and construction process, regardless of occupancy type. The subsequent six chapters focus on seismic design and performance issues related to spe-

cific occupancy types: commercial office buildings (Chapter 6); retail commercial facilities (Chapter 7); light manufacturing facilities (Chapter 8); healthcare facilities (Chapter 9); local schools, kindergarten through grade 12 (Chapter 10); and higher education (university) facilities (Chapter 11).

5.2 SELECTION OF STRUCTURAL MATERIALS AND SYSTEMS

An earthquake has no knowledge of building function, but uncovers weaknesses in the building that are the result of errors or deficiencies in its design and construction. However, variations in design and construction will affect its response, perhaps significantly, and to the extent that these variations are determined by the occupancy, then each building type tends to have some unique seismic design determinants. A building that uses a moment–frame structure will have a different ground motion response than a building that uses shear walls; the frame structure is more flexible, so it will experience lower earthquake forces, but it will deflect more than the shear wall structure, and this increased motion may cause more damage to nonstructural components such as partitions and ceilings. The shear wall building will be much stiffer but this will attract more force: the building will deflect less but will experience higher accelerations and this will affect acceleration-sensitive components such as air conditioning equipment and heavy tanks.

These structural and nonstructural system characteristics can be deduced from the information in the seismic code, but the code is not a design guide and gives no direct guidance on the different performance characteristics of available systems or how to select an appropriate structural system for a specific site or building type.

Table 5-1 illustrates the seismic performance of common structural systems, both old and new, and gives some guidance as to the applicability of systems and critical design characteristics for good performance. The different structural performance characteristics mean that their selection must be matched to the specific building type and its architecture. Table 5-1 summarizes a great deal of information and is intended only to illustrate the point that structural systems vary in their performance. The table is not intended as the definitive tool for system selection; this requires extensive knowledge, experience and analysis.

Table 5-2 shows structural system selections that are appropriate for different site conditions, for different occupancies and various building functions. For example, an important aspect of the building site is that

Table 5-1 Seismic Performance of Structural Systems (adapted from Elseser, 1992)

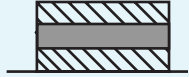


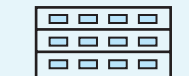


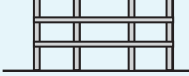
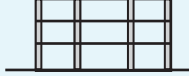

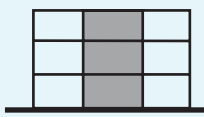
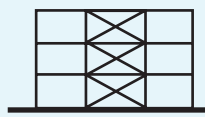
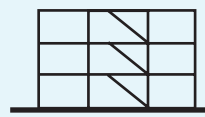

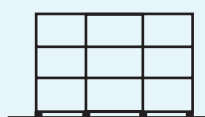
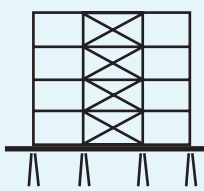
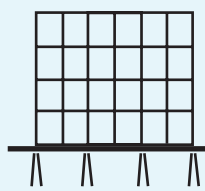
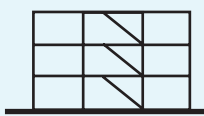
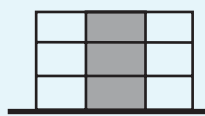
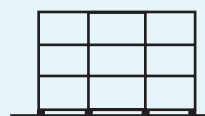
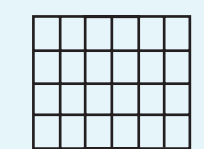
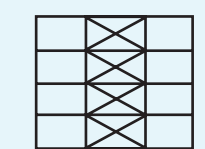
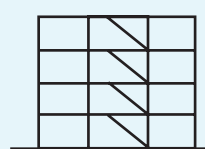
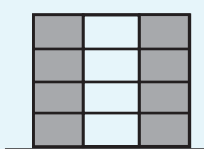
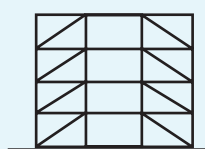
SUMMARY OF SEISMIC PERFORMANCE OF STRUCTURAL SYSTEMS			
Structural System	Earthquake Performance	Specific Building Performance and Energy Absorption	General Comments
<p>Wood Frame</p> 	<p>San Francisco, 1906 Alaska 1964 Other Earthquakes Variable to <i>Good</i></p>	<ul style="list-style-type: none"> ○ San Francisco Buildings performed reasonably well even though not detailed. ○ Energy Absorption is excellent 	<ul style="list-style-type: none"> ○ Connection details are critical. ○ Configuration is significant
<p>Unreinforced Masonry Wall</p> 	<p>San Francisco, 1906 Santa Barbara, 1925 Long Beach, 1933 Los Angeles, 1994 Variable to <i>Poor</i></p>	<ul style="list-style-type: none"> ○ Unreinforced masonry has performed poorly when <i>not</i> tied together. ○ Energy absorption is good if system integrity is maintained. 	<ul style="list-style-type: none"> ○ Continuity and ties between walls and diaphragm is essential.
<p>Steel Frame with Masonry Infill</p> 	<p>San Francisco, 1906 Variable to <i>Good</i></p>	<ul style="list-style-type: none"> ○ San Francisco buildings performed very well. ○ Energy absorption is excellent. 	<ul style="list-style-type: none"> ○ Building form must be uniform, relatively small bay sizes.
<p>Reinforced Concrete Wall</p> 	<p>San Francisco, 1957 Alaska, 1964 Japan 1966 Los Angeles, 1994 Variable to <i>Poor</i></p>	<ul style="list-style-type: none"> ○ Buildings in Alaska, San Francisco and Japan performed poorly with spandrel and pier failure ○ Brittle system 	<ul style="list-style-type: none"> ○ Proportion of spandrel and piers is critical, detail for ductility and shear.
<p>Steel Brace</p> 	<p>San Francisco, 1906 Taft, 1952 Los Angeles, 1994 Variable</p>	<ul style="list-style-type: none"> ○ Major braced systems performed well. ○ Minor bracing and tension braces performed poorly. 	<ul style="list-style-type: none"> ○ Details and proportions are critical.
<p>Steel Moment Frame</p> 	<p>Los Angeles, 1971 Japan, 1978 Los Angeles, 1994 ? <i>Good</i></p>	<ul style="list-style-type: none"> ○ Los Angeles and Japanese buildings 1971/78 performed well. ○ Energy absorption is excellent. ○ Los Angeles 1994, mixed performance. 	<ul style="list-style-type: none"> ○ Both conventional and ductile frame have performed well if designed for drift.
<p>Concrete Shear Wall</p> 	<p>Caracas, 1965 Alaska, 1964 Los Angeles, 1971 Algeria, 1980 Variable</p>	<ul style="list-style-type: none"> ○ Poor performance with discontinuous walls. ○ Uneven energy absorption. 	<ul style="list-style-type: none"> ○ <i>Configuration is critical</i>, soft story or L-shape with torsion have produced failures.
<p>Precast Concrete</p> 	<p>Alaska, 1964 Bulgaria, 1978 San Francisco, 1980 Los Angeles, 1994 Variable to <i>Poor</i></p>	<ul style="list-style-type: none"> ○ Poor performance in 1964, 1978, 1980, 1994 	<ul style="list-style-type: none"> ○ Details for continuity are critical ○ <i>Ductility</i> must be achieved
<p>Reinforced Concrete Ductile Moment Frame</p> 	<p>Los Angeles, 1971 ? <i>Good</i></p>	<ul style="list-style-type: none"> ○ Good performance in 1971, Los Angeles ○ System will crack ○ Energy absorption is good. ○ Mixed performance in 1994 Los Angeles 	<ul style="list-style-type: none"> ○ Details <i>critical</i>.

Table 5-2 Structural Systems for Site Conditions and Occupancy Types (from Elsesser, 1992)

STRUCTURAL SYSTEMS FOR SITE CONDITIONS AND OCCUPANCY TYPES			
Site Conditions	"Soft" Site (Long Period)	Use rigid building with short period	   <p>Shear Wall Steel Brace Eccentric Braced Frame</p>
	Distant Site (short period)	Use rigid building with short period	
	"Hard" Site (Short Period)	Use flexible building with long period	  <p>Ductile Moment Frame Base Isolation</p>
	Poor Soils (Pile Supported)	Use lightweight rigid building	  <p>Steel Braced Frame Steel Tube Frame</p>
Occupancy	High-Tech (labs, computers, hospitals)	Use ductile rigid systems for damage control	   <p>Eccentric Braced Frame Dual Wall / Ductile Moment Frame Eccentric Braced Frame</p>
	Office Buildings	Open Plan	   <p>Steel Ductile Moment Frame Steel Braced Frame Eccentric Braced Frame</p>
	Residential	Cellular Spaces	  <p>Concrete Shear Wall Steel Braced Frame</p>

a major structure must be “de-tuned,” that is, designed such that its fundamental period differs sufficiently from that of the ground so that dangerous resonance and force amplification are not induced. Thus, for a soft, long-period site; it is appropriate to use a rigid short period structural system; this need in turn must be related to other requirements of occupancy and function.

Table 5-2 also illustrates that structures must be matched to the building’s use. For example, a concrete shear wall structure is appropriate for an apartment house because the strong cross walls are an economical way to provide the necessary seismic resistance and, at the same time, provide good acoustics between the apartments. While the purpose of Table 5-2 is to illustrate the way in which structural systems may be matched to the site condition and building design and use, the table is not intended as the definitive tool for system selection; this also requires extensive knowledge, experience, and analysis.

5.3 SELECTION OF THE ARCHITECTURAL CONFIGURATION

The architectural configuration—the building’s size, proportions and three-dimensional form—plays a large role in determining seismic performance. This is because the configuration largely determines the distribution of earthquake forces, that is, the relative size and nature of the forces as they work their way through the building. A good configuration will provide for a balanced force distribution, both in plan and section, so that the earthquake forces are carried directly and easily back to the foundations. A poor configuration results in stress concentrations and torsion, which at their worst are dangerous.

Configuration problems have long been identified, primarily as the result of extensive observation of building performance in earthquakes. However, many of the problem configurations arise because they are useful and efficient in supporting the functional needs of the building or accommodating site constraints. The design task is to create configuration alternatives that satisfy both the architectural needs and provide for structural safety and economy. This requires that the architect and engineer must cooperate from the outset of the design process: first to arrive at an appropriate structural system to satisfy building needs, and then to negotiate detailed design alternatives that avoid, or reduce, the impact of potential problem configurations.

Seismic codes now have provisions intended to deal with configuration problems. However, the code approach is to accept the problems and

attempt to solve them either by increasing design forces, or requiring a more sophisticated analysis. Neither of these approaches is satisfactory, for they do not remove the problem. In addition, many of the code provisions apply only to buildings that are five stories or over 65 feet in height, which leaves a large number of buildings unregulated by the code. The problem can only be solved by design and not by a prescriptive code.

Design solutions for a soft first story condition that the architect and engineer might explore together include (see Figure 5-1):

- The architectural implications of eliminating it (which solves the structural problem);
- Alternative framing designs, such as increasing the number of columns or increasing the system stiffness by changing the design, to alleviate the stiffness discrepancy between the first and adjacent floors; and
- Adding bracing at the end of line of columns (if the site constraints permit this).

A more general problem is the increasing unpredictability of building response as the architectural/structural configuration increasingly deviates from an ideal symmetrical form. This has serious implications for Performance Based Design, which depends for its effectiveness on the ability of the engineer to predict structural performance.

Tables 5-3 and 5-4 illustrate the above points by identifying the common configuration problems- termed “irregularities” that are dealt with in the seismic code. These are classified as vertical or plan irregularities. The tables show a diagram of each condition, illustrates the failure pattern and describes its effects. The designations and numbers of the conditions are identical to the code: the diagrams are not contained in the code but are interpretations of the descriptions of each condition that the code defines.

5.4 CONSIDERATION OF NONSTRUCTURAL COMPONENT PERFORMANCE

As discussed in Section 4.2, the majority of the damage that has resulted in building closure following recent U.S. earthquakes has been the result of damage to nonstructural components and systems. A building designed to current seismic regulations may perform well structurally in a moderate earthquake, but be rendered nonfunctional due to non-structural damage.

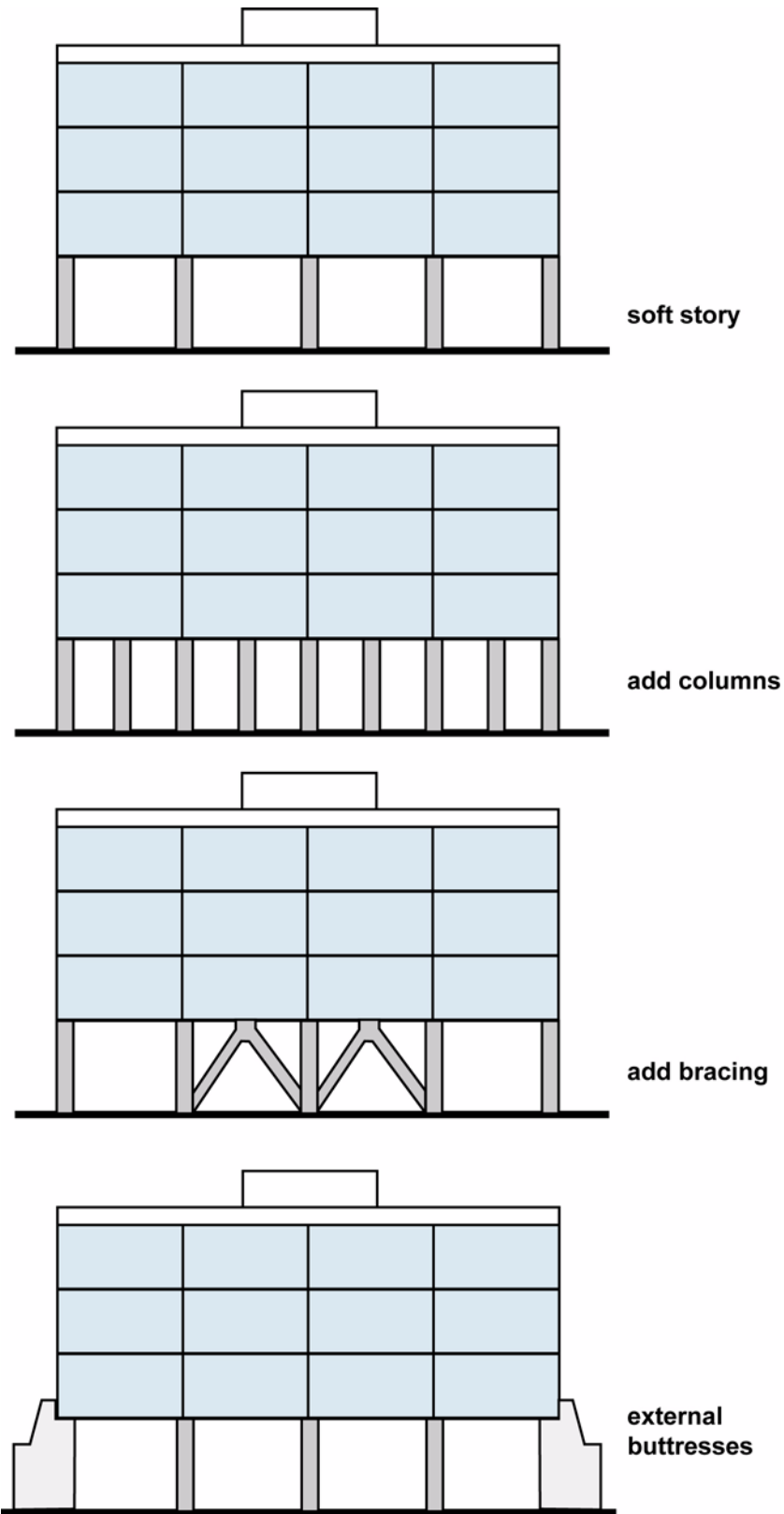


Figure 5-1 Example design solutions for addressing soft story condition.

Table 5-3 Vertical Irregularities, Resulting Failure Patterns, and Performance Implications

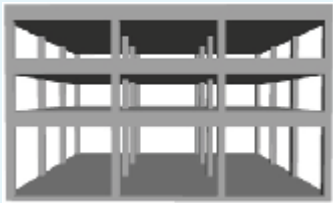

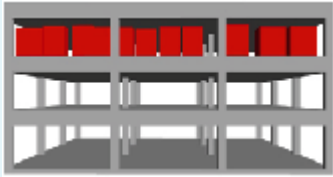
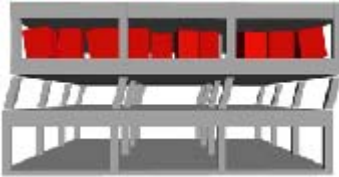






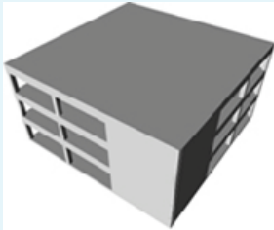
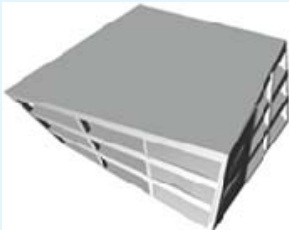
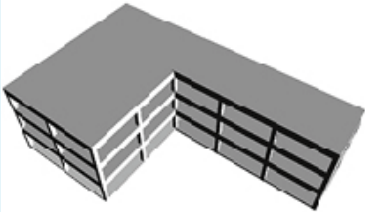
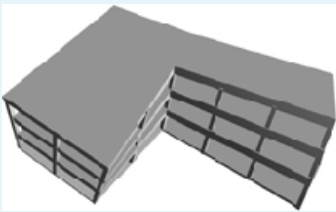
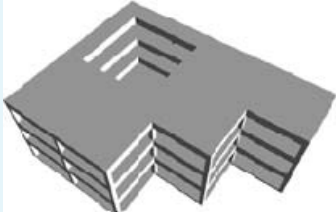
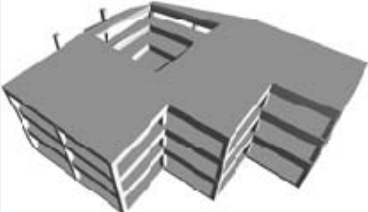


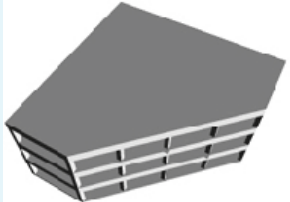
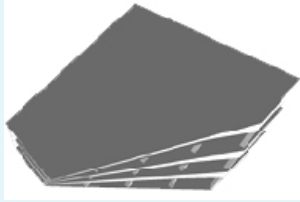
Vertical Irregularities	Resulting Failure Patterns	Performance
		<ul style="list-style-type: none"> ○ Common collapse mechanism. Deaths and much damage in 1994 Northridge earthquake.
V1: Stiffness Irregularity: Soft Story		
		<ul style="list-style-type: none"> ○ Collapse mechanism in extreme instances.
V2: Weight / Mass Irregularity		
		<ul style="list-style-type: none"> ○ Localized structural damage.
V3: Vertical Geometric Irregularity		
		<ul style="list-style-type: none"> ○ Localized structural damage.
V4: In-Plane Irregularity in Vertical Lateral Force-Resisting System		
		<ul style="list-style-type: none"> ○ Collapse mechanism in extreme instances.
V5: Capacity Discontinuity-Weak Story		

Table 5-4 Plan Irregularities, Resulting Failure Patterns, and Performance Implications

Plan Irregularities	Resulting Failure Patterns	Performance
		<ul style="list-style-type: none"> ○ Localized damage. ○ Collapse mechanism in extreme instances.
P1: Torsional Irregularity: Unbalanced Resistance		
		<ul style="list-style-type: none"> ○ Localized damage to diaphragms and attached elements. ○ Collapse mechanism in extreme instances in large buildings.
P2: Reentrant Corners		
		<ul style="list-style-type: none"> ○ Localized damage to diaphragms and attached elements.
P3: Diaphragm Eccentricity and Cut-outs		
		<ul style="list-style-type: none"> ○ Collapse mechanism in extreme instances.
P4: Out-of-Plane Offsets: Discontinuous Shear Walls		
		<ul style="list-style-type: none"> ○ Leads to torsion and instability, localized damage.
P5: Nonparallel Lateral Force-Resisting Systems		

Nonstructural components may also, however, influence structural performance in response to ground shaking. Structural analysis to meet code requirements assumes a bare structure. Nonstructural components that are attached to the structure, and heavy contents, depending on their location, may introduce torsional forces. Characteristic examples of structural/nonstructural interaction are as follows:

- Heavy masonry partitions that are rigidly attached to columns and under floor slabs, can, if asymmetrically located, introduce localized stiffness and create stress concentrations and torsional forces. A particular form of this condition, that has caused significant structural damage, is when short column conditions are created by the insertion of partial masonry walls between columns. The addition of such partial walls after the building completion is often treated as a minor remodel that is not seen to require engineering analysis. The result is that the shortened columns have high relative stiffness, attract a large percentage of the earthquake forces, and fail (Figure 5-2).



Figure 5-2 Elevation views of building with short columns between first and second floors. Upper sketch show the building in an unshaken state; lower sketch shows damage mechanism under earthquake lateral loading.

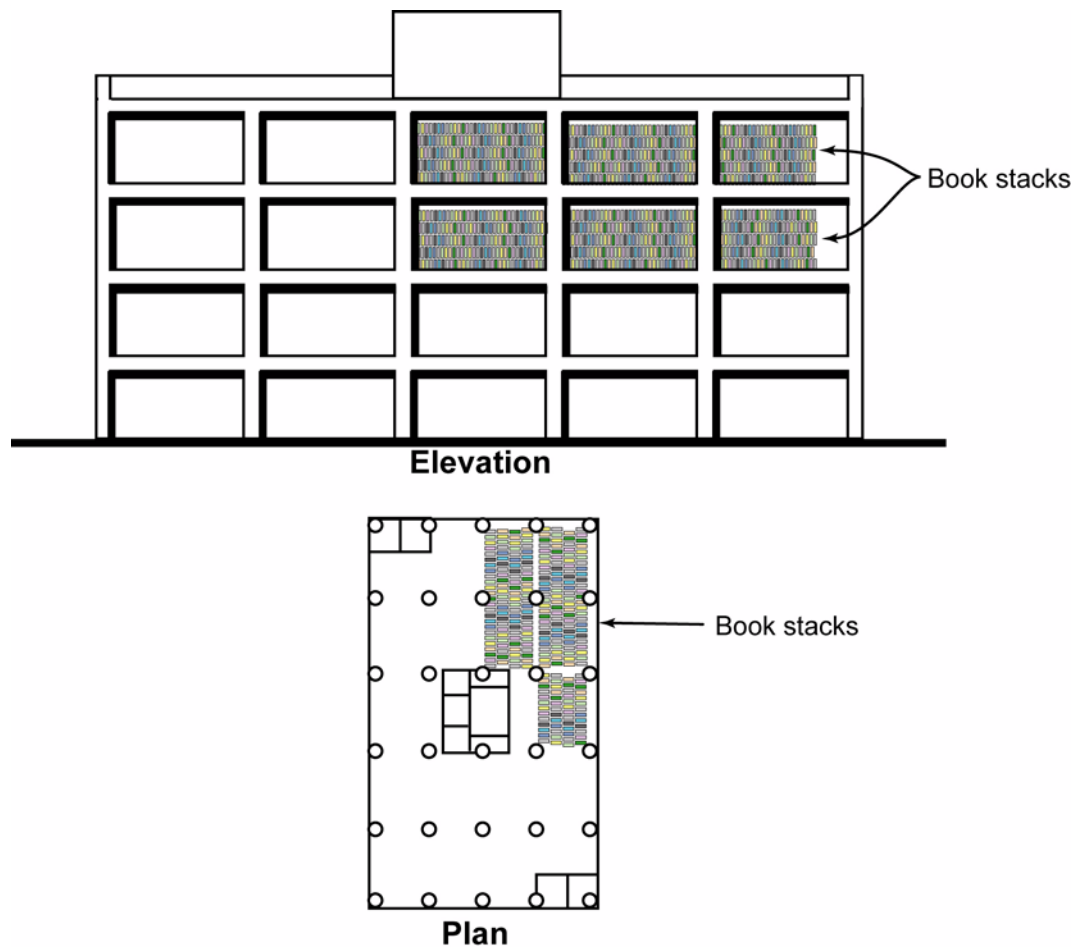


Figure 5-3 Nonsymmetric loading of book stacks in library building. Position and weight of stacks could induce torsional response of building during earthquake shaking.

- In smaller buildings, stairs can act as bracing members between floors, introducing torsion; the solution is to detach the stair from the floor slab at one end to allow free structural movement.
- In storage areas or library stacks, heavy storage items can introduce torsion into a structure. The structure may have been calculated to accommodate the maximum dead load but consideration be lacking for the effect of nonsymmetric loading over time as, for example, when library books are acquired (Figure 5-3).

5.5 QUANTIFYING THE BENEFITS OF IMPROVED PERFORMANCE

The benefits of improved performance are the reduced losses resulting from improved performance. These reduced losses include not only

the reduction in capital losses (as described below), but also the reduction in financial impacts resulting from the loss of operations.

The benefits of improved earthquake performance of a building are quantified differently by the various types of building owners and users. For example, an owner occupant, an owner of a tenant-occupied building, and a tenant will all have different priorities and views regarding the cost-benefit trade-offs associated with improved earthquake performance of the building.

From the point of view of an owner occupant, earthquake performance of a building can be quantified in terms of reducing the probability of:

- deaths and injuries in and around the building caused by an earthquake, and the resultant liability;
- collapse of the building or damage to the building that reduces the building's value;
- disruption of building services (HVAC, plumbing, electrical) and the resultant loss of use of the building or portions of it;
- damage to building contents such as furniture, files, and inventory; and
- disruption of building operation and business as a result of the above.

From the point of view of an owner of a tenant-occupied building, earthquake performance of a building can be quantified in terms of reducing the probability of:

- deaths and injuries in and around the building caused by an earthquake, and the resultant liability;
- collapse of the building or damage to the building that reduces the building's value; and
- disruption of building services (HVAC, plumbing, electrical) and the resultant loss of use of the building or portions of it (tenant business interruption).

From the point of view of a tenant who is not the owner, earthquake performance of a building can be quantified in terms of reducing the probability of:

- disruption of building services (e.g., HVAC, plumbing, electrical) and the resultant loss of use of the building or parts of it;
- damage to building contents such as furniture, files, and contents; and

- disruption of building operation and business as a result of the above.

Quantifying Expected Capital Losses

Capital losses consist of the cost of replacing or repairing earthquake-damaged structural and nonstructural components as well as damaged building contents. When quantifying capital value of damaged building components and contents, the first distinction that needs to be made is between the depreciated value of an asset, its market value, and its replacement cost. The assumption is generally that damaged capital will be replaced. If a 50-year-old building or piece of equipment is damaged to the extent that it is a total loss, it is unlikely that an owner can have a replacement building constructed or purchase a new piece of equipment for the same price as the original cost, nor for the depreciated value of the building or equipment (which may be very low, or zero). One may purchase a replacement building or piece of equipment that is 50 years old. Still, the price of that building or equipment will be based not on the depreciated value, but on the current market value of the asset. When the cost of losing an asset is evaluated, the owner must therefore determine what the cost to replace the asset will be, whether it is new or used.

An owner can use various means to estimate the replacement cost of a building or its contents. Realtors, manufacturers, engineers, and other specialists can research market conditions to estimate costs. If the owner has a large number of facilities or buildings, he/she may have a database of recent capital projects from which to draw information.

If structural and nonstructural building elements suffer less than total loss in an earthquake, they can often be repaired without being replaced. Theoretically, one would never spend more than the replacement cost of the building to repair structural and nonstructural damage. Practically, most owners consider the limit of repair costs to be on the order of 40 to 60 percent of the replacement cost. The older the building or equipment, typically the lower the threshold. The reasoning is that if a building or piece of equipment is old and outdated, repairing it leaves the owner with something that, although functional, is still old and possibly outdated.

Owners may have other constraints which raise or lower this threshold. If short on cash or credit, an owner may have no choice but to repair a



Quantifying Capital Value

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Repair Costs

Most owners consider the limit of repair costs to be on the order of 40 to 60 percent of the replacement cost. The older the building or equipment, typically the lower the threshold. Owners, however, may have other constraints which raise or lower this threshold.

heavily damaged building rather than replace it. If the operations within the building are so valuable that losses from down time far exceed the building's replacement cost, then even if very expensive repairs can be done more quickly than replacement, the threshold of repairable damage may also be high. On the other hand, if an owner has been looking to get rid of an old, poorly configured, structure even small amounts of damage may provide a convenient excuse to replace the building.



Repair Cost Vs Cost of New Construction

It should be clear that unit repair costs are rarely equal to the unit costs of new construction—they are typically higher.

It should be clear that unit repair costs are rarely equal to the unit costs of new construction. The cost of building partition walls in a new building, for example, may be on the order of five dollars per square foot. Repairing heavily damaged partition walls may cost more than twice this amount. Removing and replacing a damaged steel brace within a building may cost several times the cost of installing the brace in a new building.

A key to estimating the cost of repairing structural and nonstructural damage is understanding what the nature of the damage may look like. This is often defined as the “fragility” of the building system. Fragility presents the likelihood of damage as a function of the forces or deformations imposed on the building. Damage may be described in terms that include cracking or spalling of concrete elements; fracturing or buckling of steel beams, columns, or braces; glazing breakage; and partition cracking or failure. Estimating how much damage occurs at a specific stress or deformation has been and continues to be the subject of research. Once estimates of the damage are made, contractors and cost estimators can provide valuable assistance to owners and the design team in estimating repair costs.



Quantifying Replacement Costs

Damage to contents and inventory is usually quantified in terms of the amount of each that needs to be replaced.

Damage to contents and inventory is usually quantified in terms of the amount of each that needs to be replaced. In some cases, with very expensive equipment or inventory, one might consider repairing damage. In most instances, however, damaged items are typically replaced. Damage to non-fixed items typically occurs as a result of high accelerations “flinging” items off shelves or overturning them. Earthquake-induced accelerations vary over the height of a building so that items in upper stories may be more prone to damage than at lower stories. Estimating the amount of damage to contents and inventory involves calculating the acceleration at each level and estimating the capacity of elements at each story to withstand these accelerations. Shelving

should be evaluated as to its overturning capacity and the potential damage of items that are spilled.

Contents such as desks and cabinets are fairly resilient to damage from sliding or falling, and are typically considered as losses only when they cannot be recovered because of substantial structural damage. Therefore, one might consider a threshold of structural damage (say when the building is condemned following an earthquake, or when it reaches its replacement threshold) at which point most of the contents are considered lost.

Quantifying Loss of Operations

Structural and nonstructural damage may require that a building's operations be curtailed or cease altogether for some period during repair or replacement. The loss of operations will have a direct effect on the revenue or "value" of the services or goods that the business produces. It will also, presumably, have a broader impact on its employees, on the customers that it serves, and possibly on the community or region as a whole. Business interruption may also be a factor in how soon, if ever, the business can recover lost opportunities and markets.

The primary impacts caused by loss of operations include:

- Direct loss of revenue or value;
- Indirect losses to employees, customers, and the community at large; and
- Long term business losses.

All three of these impacts are dependent on how long and to what extent the business is out of operation. This is usually a function of structural and nonstructural damage, and may also be a function of contents loss. The impact of loss of operations on two facility types are demonstrated in the two example case studies described on the following page.

The loss of function of any single building is unlikely to cause devastating consequences to people in the affected region; nonetheless, these losses can be severe if the affected facilities are critical to community functions or the local or regional economy. Following are example situations where the loss of a critical facility can negatively affect the community as a whole or have far-reaching consequences:

- In August, the only high school in a city is damaged to the point where it must be replaced. Where do the students go to school for the coming year or more while a new facility is designed and built?



Loss of Operations Case Study: Data Center

Situation.

A tilt-up building used as a data center suffers damage that causes a partial closure such that until cracks in several shear walls are repaired, access can only be allowed for up to four hours a day by no more than ten employees.

Because of the vibration-sensitive equipment contained in the building and the need for constant structural monitoring, the limitation on access essentially means that only 25% of the data center can be operated and maintained until the cracks are repaired.

Repairs take six months after which time the data center is fully functional.

Impacts Resulting from Loss of Operations.

The data center, which provides server space for clients, will lose 75 percent of its revenue initially. Suppose that, after three months, enough of the space is repaired so that 50 percent of the center's capability can be restored. The direct losses could be 75 percent of its revenue for the first three months and 50 percent of its revenue for three additional months. Indirectly, however, the data center company may have to either pay its employees salaries during that time, or temporarily or permanently lay them off. In the latter case, the company may have to pay the expense of rehiring employees once the facility is fully functional. The company may also have to pay damages to clients that lost data because of the loss of operations.

Long term, the data center company may permanently lose the customers it wasn't able to keep while repairs were in process. These customers presumably need server space following the earthquake and during the center's repair, and would look elsewhere for it. Once they find alternate space, they may be reluctant to switch back. The company, therefore, may lose market share for some time until it can recover lost clients or generate new ones.

Loss of Operations Case Study: University Laboratory Building

Situation.

A university laboratory building is badly damaged after an event with losses greater than 60 percent of the replacement cost. The building and laboratory equipment are twenty years old; the university therefore makes the decision to replace the building.

The laboratory is highly specialized, and researchers are unable to proceed with their experimental work for the three-year duration of the building replacement. The new building will, however, contain state-of-the-art facilities.

Impacts Resulting from Loss of Operations.

In the second example, the university would presumably lose the direct revenue in grant funding it received for the research conducted in the laboratory. Because the university is a non-profit organization, and a significant portion (say, 1/3) of the grant revenue pays university overhead costs, which include campus-wide expenses, loss of the laboratory would have consequences that reach far beyond the loss of the laboratory facility. Such loss revenue could cause campus-wide reductions in staffing and other goods and services, depending on the ratio of overhead revenue lost versus overhead revenue amounts from other sources.

Beyond the immediate revenue losses in this example are the additional potential impacts if students, faculty, and staff elect to leave for other institutions if they cannot continue to conduct the research of their choice at the university. This could have a long and lasting impact on the output and future funding for the university, and may hurt its future ability to attract researchers and students. These considerations are not easy to quantify in dollar terms; they should, however, play an important role in determining the willingness to invest in a better performing building.

- The only county hospital with a trauma center is rendered non-functional during an event that causes dozens of life-threatening injuries within the community.
- A pharmaceutical manufacturing plant that produces a popular drug for which the company owns the patent is destroyed in an earthquake. How will patients continue to get the drug?
- An automotive parts manufacturer that provides “just-in-time” supplies to an automobile maker cannot function for three months. How will this affect the automobile company’s ability to produce cars and its ability to keep its employees busy?

It is almost impossible to put a dollar value on the cost of these losses because, like many other events, the repercussions can be difficult to completely define. It is therefore unrealistic to develop a pure cost–benefit study equating additional dollars spent on better performance with savings in terms of these reduced indirect effects.



It is almost impossible to put a dollar value on the cost of indirect losses. One can, however, make comparative studies with respect to other types of risks and establish an equivalent value of tolerating them.

One can, however, make comparative studies with respect to other types of risks and establish an equivalent value of tolerating them. In any of the examples above, the building owner will likely have liability insurance to protect against claims that could have a devastating impact on the entity. A private school might have a catastrophic insurance policy to protect against a student being killed in a sporting event; a public school may have locally- or state-granted legal protections. A hospital certainly has malpractice insurance and an automotive plant will have worker’s compensation insurance. However, insurance policies all have limits on coverage. If losses exceed the coverage limit the result could be bankruptcy. Yet the owner in all cases makes a decision to limit coverage and therefore to accept the remaining risk of catastrophic loss.

Considering the example of the school injury, if a family of an injured student wins a judgment exceeding the school’s insurance policy, the school may have to declare bankruptcy and close its doors. The school may be able to avert this consequence if it buys additional insurance. However, at some point it makes the decision that it is not going to spend more in premiums and is willing to accept the risk of a catastrophic loss. The process to arrive at this limit may have been explicitly or implicitly thought out. Regardless, it can be used as a guide for making other decisions about risk management for earthquakes. The case study icon (see next page) illustrates this hypothetical situation.

When determining the level of performance for which a building should be designed, an owner may want to consider involving those outside the business who will be indirectly affected by the potential loss of operations. A community might be willing to contribute to the cost of a higher performance design of a school if it considers the value of having the building usable after an earthquake sufficiently high. Similarly, an auto maker might contribute to the performance-based design of one of its parts suppliers if it considers an uninterrupted supply of parts crucial to its own operations.



Comparative Risk Tolerance Case Study: Seismic Risk Management Versus Student Injury Liability Insurance

Student injury liability policy:

- Up to \$1,000,000 per incident (excludes earthquakes)
- Annual premium: \$40,000
- Out-of-pocket loss above which would result in school bankruptcy: \$2,000,000
- Total manageable loss: \$1,000,000 (insurance) + \$2,000,000 (out-of-pocket) = \$3,000,000
- Annual likelihood of a \$3,000,000 claim: 1/2%

Risk Tolerance: willing to spend \$40,000 annually to limit risk to a 1/2% chance of a catastrophic loss.

Earthquake risk management situation:

- School is planning to move to a new site and build new facilities.
- Earthquake ground motions with a 1/2% probability of being exceeded per year, (which correspond to a 200-year return period) are expected to cause \$500,000 in capital losses, relocation for six months at a cost of \$500,000, and injury to students at a cost of \$1,500,000 = \$2,500,000 total.
- Risk of 1/2% for a \$2,500,000 loss exceeds threshold (\$2,000,000) established for student injury liability (see above)

Comparable Risk Tolerance: If the premium for earthquake insurance is no more than \$40,000 to cover \$500,000 of capital losses, then spending on earthquake risk reduction is at least as good an investment as the liability policy.

Social and Political Factors Affecting Seismic Risk Management

Emotion and politics are often important factors in the seismic risk management decision-making process. Parents of school children may say, “No price is too high to pay for the safety of my child.” Politicians or business leaders may proclaim, “We have a zero tolerance policy for placing the occupants of our buildings at risk.” While well intended, these positions are not often achieved in practice.

The concept of placing a quantified (dollar) value on the life or safety of each person is a controversial issue that impacts benefit-cost analysis. This approach is implemented by comparing the value of saved lives (the benefit) to the cost of protecting those lives. Political or emotional constraints often make this extremely difficult. If an owner looks beyond life safety, however, and focuses on capital losses or down time, then it is practical and possibly necessary to quantify these losses in terms that can be compared directly to the costs to reduce them. The fact that most new U.S.-code-designed buildings are expected to provide life safety (for the range of earthquakes that may occur over the life of the building) renders the need to assign dollar values to human lives less imperative.

5.6 COSTS OF IMPROVED PERFORMANCE

Building owners incur costs to obtain specified levels of building performance. These costs are considered “first costs” if incurred at the time of building design and construction or purchase. They are considered “operating costs” if incurred over the period of use of the building.

It should be noted that the period of use of a building by its owner might differ from the life of the building. The life of a building may be 60 years or more, while the owner’s use could be much shorter. When considering societal costs of a building, for example energy use, society’s interest in operating costs are spread over the life of the building, regardless of owner turnover. The life of the building is also of interest in the operating cost considerations of certain types of owners, particularly institutional owners such as schools and universities. However, for most commercial owners considering making an investment in a building, operating costs are of interest only over the period that the owner anticipates owning the building.

First Costs

The following are typical of first costs:

- The costs of site selection, including the cost of physical and economic analysis of alternative sites.
- The costs of planning and programming a new building, including the costs of consultants.
- The costs of architectural and engineering design and construction management, in the case of the construction of a new building, or

the transaction costs (e.g., inspection and appraisal), in the case of the acquisition of an existing building.

- The disruption of operations resulting from the move from a currently used building to a new building.

Except for the last item, there is generally a direct relationship between cost and building performance (including seismic performance) – a higher first cost investment typically results in improved performance.

Operating cost analyses often categorize the costs of construction or purchase as first costs. This is short sighted in most cases, since these costs are usually financed through mortgages or bonds, which converts them into continuous operating costs.

Operating Costs

The following are typical operating costs:

- Operation and maintenance of the building, including costs of earthquake response and recovery.
- Replacement of building components and systems, including the cost of disruption of operation related to these activities, both of which can be annualized if converted to a payment into a replacement reserve fund.
- Changing the building to accommodate new functions or technology, and the disruption of operation resulting from such activities (which is analogous to churn rate).
- Insuring the building. Higher costs in this category may improve building performance by reducing unrecoverable losses or they may be inversely related to it, depending on insurance company underwriting practices.
- Building and contents damage resulting from unpredictable events, such as natural and man-made disasters, which can be expressed as a probability of incurring an annual cost.
- Disruption of operation due to building damage resulting from unpredictable events, which can be also expressed as a probability of incurring an annual cost.
- Liability for deaths and injuries from building damage resulting from unpredictable events.

The Relationship Between Cost and Performance

An advantage of performance-based design is that it provides a means for the design team to create a relationship between construction cost and performance. Traditionally (i.e., using existing seismic codes for new building design), to achieve better performance an engineer might simply increase the importance (I) factor from 1.0 to 1.25, thereby raising the design seismic forces by 25%. This may make a building perform better; however, the benefit is not easily quantifiable, even if the cost in increased steel tonnage or concrete volume can be estimated.

A more refined way of achieving a specified performance in a cost efficient manner is to develop “learning curve” type relationships between the two. Consider the example in Figure 5-4. A hypothetical precast concrete tilt-up manufacturing facility is to be constructed in a moderately high seismic zone. The lowest cost for the building is that which meets the minimum requirements of the building code. At this design level, the building will be expected to suffer some loss in the “worst case” earthquake, however that is defined. Additional investments in

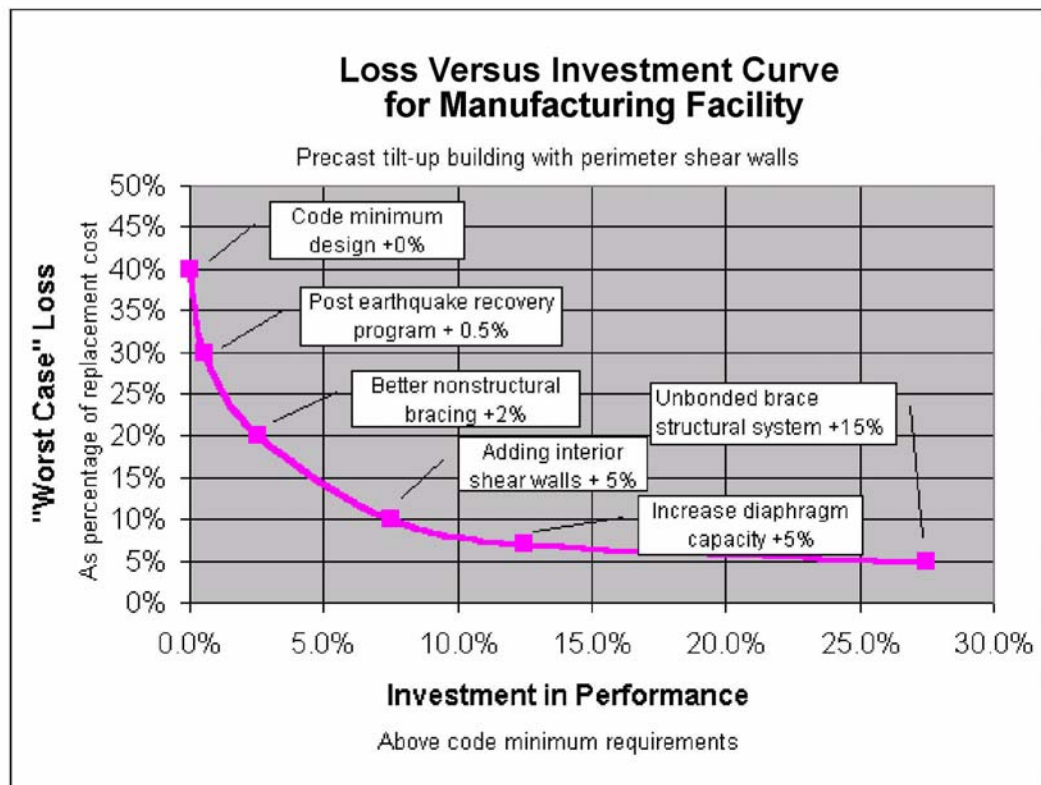


Figure 5-4 Relationship between cost and performance for hypothetical example.

improved performance might be considered by the design team and owner. If the cost for each investment is added cumulatively as each is included in the construction budget then the expected worst case loss should decrease. As this example shows, investments in postearthquake response and nonstructural bracing result in a relatively large benefit in terms of reduced losses. Adding interior shear walls results in a moderate benefit. Increasing diaphragm strength and changing the entire structural system to unbonded braces produce a relatively low benefit.

This example can be taken further by computing the benefit-cost ratio (BCR) for each performance strategy. Suppose the likelihood of the worst case event occurring over a 50-year life of the building is 25%, which corresponds to a 0.58% annual probability of occurrence², and that the code minimum cost is equal to the replacement cost. Assuming a 5% discount rate (rate of return), the resulting benefits and costs are as summarized in Table 5-5.

Table 5-5 Summary of Benefits and Costs for Hypothetical Manufacturing Facility Example

Risk Reduction Strategy	------(As Percent of replacement cost)-----				BCR (Benefit/ Cumulative Cost of investment)
	Cumulative Cost of investment (above Code Minimum)	"Worst Case" Loss	Present Value of Loss ¹	Benefit ²	
Code minimum design	0.0%	40%	4.2%	0.0%	-
Post earthquake recovery program	0.5%	30%	3.2%	1.0%	2.1
Better nonstructural bracing	2.5%	20%	2.1%	2.1%	0.85
Adding interior shear walls	7.5%	10%	1.1%	3.2%	0.42
Increase diaphragm capacity	12.5%	7%	0.7%	3.5%	0.28
Unbonded brace structural system	27.5%	5%	0.5%	3.7%	0.13

Notes:

¹ Computed as: $PV = pmt \left[\frac{1}{r} \cdot \frac{1}{r(1+r)^n} \right]$ where PV = the Present Value of Loss; pmt = Annual Loss ("Worst Case" Loss times the annual probability of occurrence); r = rate of return; and n = life of building in years

² Present Value of Loss for code minimum design less Present Value of Loss with cumulative investment in performance

2. Computed as $(\ln(1 - \text{probability of occurrence in } n \text{ years})) / (-n \text{ years})$

The example suggests that, in this case, the incorporation of a post-earthquake recovery program with a BCR of 2.1 is clearly a good investment. Improving nonstructural bracing in addition results in a BCR of 0.85 suggesting that it is possibly a good investment. The other performance strategies appear not to be economically beneficial.

A careful study of possible design strategies may lead to several cost–performance curves, such as Figure 5-4, incorporating different combinations of performance strategies. These will then allow the owner and the design team to select the one that achieves the greatest expected return on the investment.

5.7 CASE STUDIES OF COST AND PERFORMANCE CONSIDERATIONS

The following five case studies illustrate how different owners have addressed cost and performance considerations in seismic risk management decisions.

Case Study 1: Computer Graphics Equipment Maker in Salt Lake City, Utah

Salt Lake City, Utah is the headquarters of a small computer graphics equipment maker, as shown in Figure 5-5. The company’s main products are high-end simulation systems that sell for nearly \$10 million each. Its new corporate office was to include a large assembly floor in



Figure 5-5 Site of facilities for computer graphics equipment maker in Salt Lake City, Utah.

which eight to ten of these devices would be assembled at one time, as well as a floor of office space above. All of the company’s manufacturing would be housed within the building. The loss of a single simulation device as a result of an earthquake would have caused a catastrophic loss for the company, resulting in possible bankruptcy.

The local structural engineer of record was skilled in performance-based design and well known in Salt Lake City because of his efforts to expand awareness of seismic issues. The engineer was able to develop a relationship with the owner directly, although he was part of a design team headed by an architect. This “access” to the owner was crucial in providing an opportunity for the engineer to explain concepts of performance-based seismic design. He and the owner discussed critical structural issues that could affect building performance and impact repair costs and business restoration.

The code in force at the time of construction would likely have protected the building against most earthquakes. The seismicity in the Salt Lake City region during a typical 30-50 year building life is relatively low. However, considering the consequence of damage and lost functionality, even the relatively low vulnerability still resulted in an intolerably high risk to the owner.

Because of the extremely high value of contents and cost of lost operations, a performance objective was established to limit structural and nonstructural damage in a rare event to a level that would protect the contents and allow operations to continue unimpeded.

To achieve this performance objective, the building was base isolated. The project team justified the additional cost associated with a base isolated building over a conventional structure by noting that the cost of the isolated structure was still less than the value of a single simulator. The vulnerability of the enhanced building was substantially lower than would be for a similar conventional structure. Much of the equipment, including the simulator devices, was braced to prevent tipping or sliding. The overall reduction in risk achieved was dramatic and met the owner’s risk threshold. To reduce the risk any further, the building would likely have to have been re-sited to a region of lower seismicity.



Case Study 2: Salt Lake City, Salt Lake City K-12 School District

The Salt Lake City School District consists of 30-40 sites and contains buildings more than 70 years old, as shown in Figure 5-6. The District



Figure 5-6 Sample existing school building in Salt Lake City K-12 School District.

embarked upon a program of seismically upgrading its buildings to ensure that they would be safe and usable following a major seismic event. The District made the determination that it wanted to achieve a 70-year additional life for its structures.

Its study of the existing school facilities found that when nonstructural rehabilitation costs (e.g., heating, electrical, roofing, and deferred maintenance) were added to the structural costs necessary to achieve the high performance objective, many of the rehabilitations would cost more than the replacement cost of the building. In these cases the decision was made to replace the facilities with new designs such as that shown in Figure 5-7.



Figure 5-7 Sample new school building design in Salt Lake City K-12 School District.

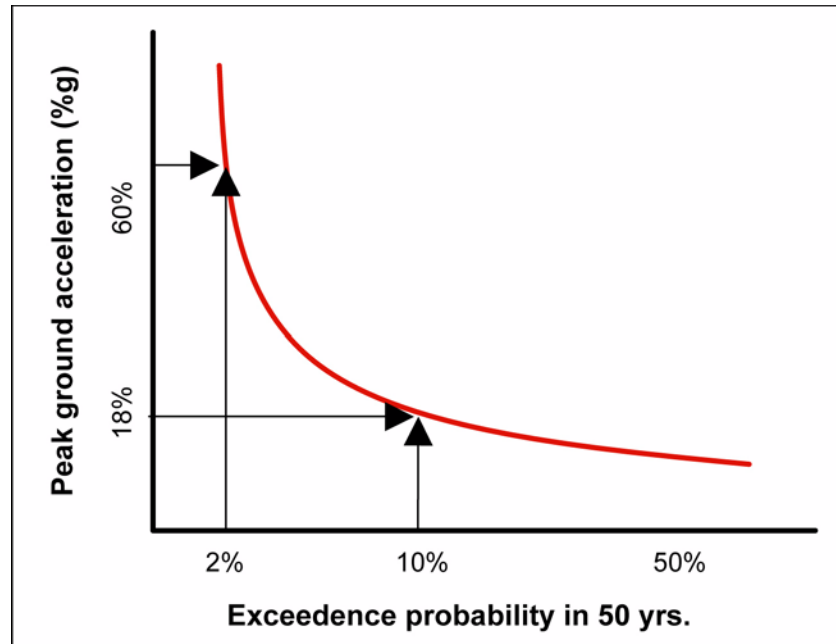


Figure 5-8 Site hazard curve for Salt Lake City K-12 School District seismic risk study.

Recognizing that building codes can change dramatically even over the course of ten to twenty years, the District asked its engineering consultant to evaluate the performance needs with its long lifetime in mind. The engineer crafted simple yet effective graphics similar to the plot shown in Figure 5-8 to help the District determine its risk tolerance. A site hazard curve (see discussion in Section 3.2) was developed (see Figure 5-8) to show the expected ground accelerations plotted against their probability of exceedence in 50 years. Salt Lake City is in *Uniform Building Code* (UBC) Seismic Zone 3, and the vertical line at 10% show the design ground motion specified by the UBC. Over a 70-year period, the probability of exceedence of this level of ground shaking increases from 10% to 14%. Another vertical line is drawn at 2% probability of exceedence in 50 years, representing perhaps the maximum credible event in the area. Over a period of 70 years, the probability of exceedence of this level of ground shaking increases from 2% to approximately 3%. Most notable is the dramatically higher ground motions that would be expected in the 2% probability of exceedence in 50-year event. This analysis showed that designing only for ground motions having a 10% probability of exceedence in 50 years meant there was still a risk of much higher ground motions that could seriously damage the facilities. The District wanted to achieve a higher level of confidence than 14% over the 70-year lifetime that damage would be

kept to a minimum. The design forces for the 2% probability of exceedence in 50-year event compared well to the UBC Seismic Zone 4 design forces. Therefore, the District decided to design all its new facilities to Zone 4 requirements for forces and detailing, pending a cost analysis of the upgraded performance.

The consulting engineer estimated that to enhance a new facility's design from Zone 3 to Zone 4 compliance would add a cost on average of ¼ to 1% of the construction budget. The District quickly realized that amortized over the length of its construction financing and certainly over the length of the 70-year assumed lifetime, this additional cost was negligible and therefore adopted the enhanced design strategy.

Key factors in the owner's decision to use an enhanced performance objective were the expected longevity of the facilities and the number of buildings in the portfolio. The importance to the community of the school district, the large capital investment that was being made over the entire inventory, and the not inconsiderable likelihood of a damaging event occurring over the lives of the buildings were also important considerations in the District's decision.

Case Study 3: Prosthesis Manufacturing Company in Memphis, Tennessee

A prosthesis manufacturing company in Memphis, Tennessee was nearing completion of a 100,000 square foot manufacturing plant in early 2002. The products manufactured within the building generate revenues of nearly \$500,000 per day. The building operations are insured against down time by a large international insurance company.

The building was built to the structural and nonstructural requirements of the 1997 *Southern Building Code* (SBCCI, 1997). The insurer offered to reduce the building's insurance premiums significantly if the nonstructural bracing was brought into conformance with the more severe requirements in the 2000 *International Building Code* (ICC, 2000). The *International Building Code* (IBC) requires that nonstructural bracing be designed to consider site conditions including soil and proximity to faults, and the location of the equipment within the building.

A New York based manufacturer and supplier of mechanical equipment bracing products was hired to assess the additional cost of bracing the equipment to the higher standard. Typically, the IBC design required



Cost-Effectiveness of Nonstructural Bracing

Improving the seismic nonstructural bracing in new buildings located in moderate seismic zones can be very cost efficient in terms of reducing losses

only larger elements (e.g., anchor bolts, clevises, rods) and not a substantial change to the design configuration.

The manufacturer performed a detailed comparison of the two codes and prepared a side-by-side comparison of the cost premium for the IBC design. An excerpt from the comparison is shown in Table 5-6.

Table 5-6 Comparison of Costs for Design to SBCCI and IBC Requirements

EQUIPMENT	FOR SBCCI REQ.	FOR IBC REQ.	SBCCI PRICE	IBC PRICE
Fan Powered Boxes A Thru R	Cable Bracing (Spec 12)	Cable Bracing (Spec 12)	\$92 Each. + \$300 Total for calculation	\$92 Each. + \$300 Total for calculation
Fans F-1,2,3,4, In Line	Isolation Hangers, (Spec 11) Cable Bracing (Spec 12)	Isolation Hangers, (Spec 11) Cable Bracing (Spec 12)	\$408+ \$300 Total for calculation	\$616+ \$400 Total for calculation
F-5 Cabinet	Anchor Bolts (Spec 19), Grommets (Spec 14)	Anchor Bolts (Spec 19), Grommets (Spec 14)	\$56+ \$300 Total for calculation	\$56+ \$300 Total for calculation
F- 6, 7, 11, 12, 13, 14, 15, 17, 18, Rooftop	Mason Rigid Roofcurb	Mason Rigid Roofcurb	\$43/Foot	\$43/Foot
F-8, 9, 10, Wall Fans	Nothing Required	Nothing Required		

The results of the study showed that the additional cost of upgrading the seismic bracing was negligible as a percentage of the overall non-structural costs. The company decided, based on the benefit of reduced insurance premiums, to implement the higher standard.

This example suggests that improving the seismic nonstructural bracing in new buildings located in moderate seismic zones can be very cost efficient in terms of reducing losses. It may also result in the direct benefit of reduced annual insurance costs.



Case Study 4: Stanley Hall, University of California Berkeley

The University of California (UC) at Berkeley is one of the nation’s premier research institutions. In 2003 the university broke ground for a state-of-the-art bio-engineering laboratory building as shown in Figure 5-9. The estimated cost of the project is nearly \$200 million. The building will contain high-end laboratory facilities and house researchers working annually on nearly \$40 million in grants. UC Berkeley sits



Figure 5-9 New bioengineering laboratory building designed for UC Berkeley campus.

astride the active Hayward Fault. In the next thirty years, the USGS predicts there is nearly a 30% likelihood of a magnitude 7 or greater earthquake occurring on the fault (Working Group on California Earthquake Probabilities, 2003).

The University considered the protection of its massive investment in this facility to be extremely important. It asked the engineer of record to consider a higher performance objective than would have been required by the building code in force at the time. The goal was that the facility should remain occupiable after a design level event, and repair time to restore full operability should be measured in weeks not months. The engineer employed a state-of-the-art buckling restrained (unbonded brace) braced frame system to ensure that damage would be kept to a minimum even in a large event that might rupture the entire length of the Hayward Fault.

In order to obtain financing for the project, the University had to justify the added expense of the enhanced structural scheme. The school hired a second engineering firm expert in risk analysis, to help them provide the necessary rationale. The firm developed a “baseline” structural scheme that met only the minimum requirements of the building code. This system employed conventional concentric braced frames. The difference in cost between the two schemes was approximately \$1.2 million, or roughly ½% of the building cost. They then used nonlinear performance-based engineering and risk assessment tools to calculate the expected losses due to earthquakes over the life of the building. The analysis showed that losses were substantially reduced using the enhanced scheme. The overall return on the \$1.2 million investment,

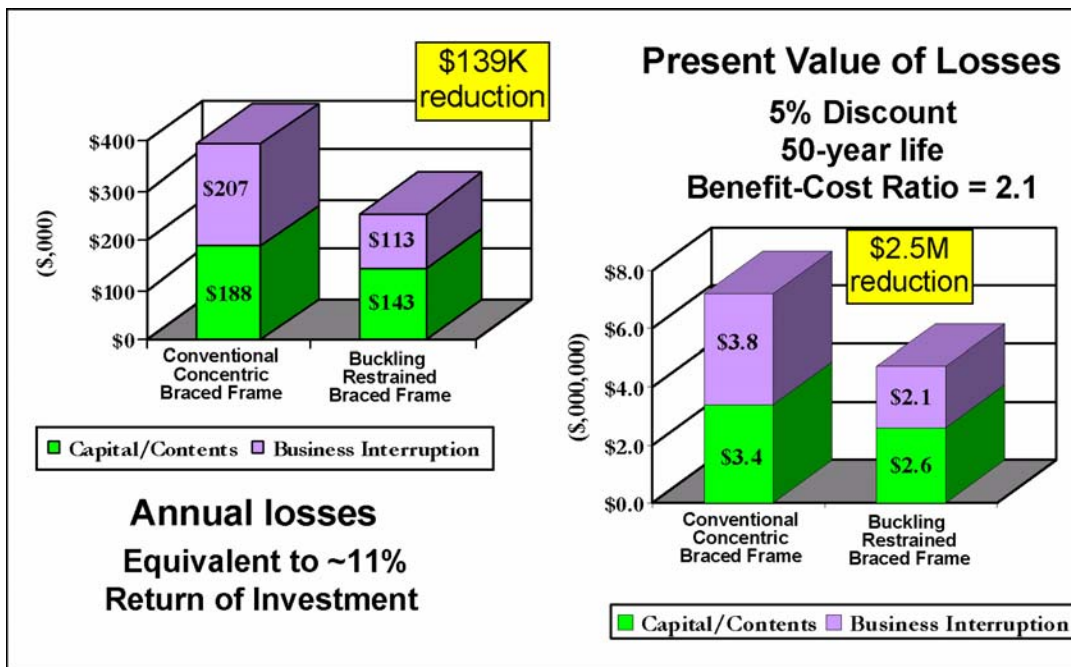


Figure 5-10 Comparison of future losses for two different structural system options for new UC Berkeley laboratory building.

considering reduction of capital, contents and business interruption losses was approximately 11%. Figure 5-10 shows that the reduction in business interruption provided the majority of the projected benefits. Using a 5% discount rate as a benchmark, the benefit-cost ratio (BCR) for the enhancements was over 2 considering a fifty year life. At that discount rate, the BCR reached one at a building life of about 15 years as shown in Figure 5-11.

This example suggests that performance-based design can be a very cost effective risk management strategy for buildings that generate substantial revenue and for which the owner has a long-term interest.

5.8 QUALITY CONTROL DURING THE CONSTRUCTION PROCESS

Quality control is an important aspect of assuring satisfactory seismic performance: the building must be constructed as designed and specified.

Building owners often interpret construction quality primarily in relation to interior and exterior finishes and materials because these are important for “marketing” in the private sector. It is generally assumed that design and construction to meet the applicable building codes will

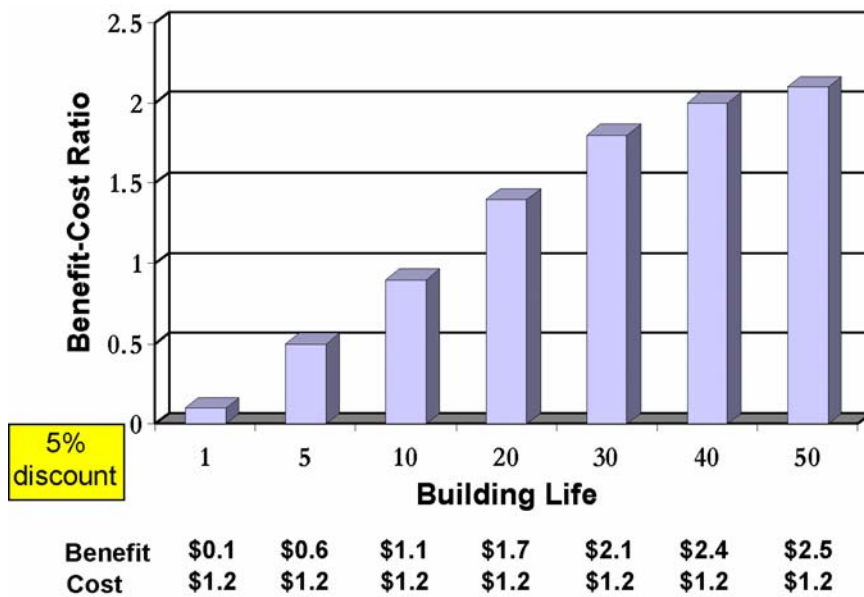


Figure 5-11 Comparison of benefit to cost of using a buckling restrained braced frame, instead of a conventional concentric braced frame, for new UC Berkeley laboratory building. Cost equals cost differential.

assure a durable and safe structure. Since structural elements are usually invisible—concealed behind a suspended ceiling, gypsum board or exterior cladding—they have little bearing on the perception of building quality. The exterior and interior appearance of the building will typically adhere to a company or institutional philosophy; this may be very functional for an industrial facility owner, but market trends or institutional objectives may influence others. The appearance of all facilities may also be influenced by local community design requirements. Decisions about image and quality have a major impact on construction cost, both initial and lifetime. See Section 12.5 for additional guidance on assuring design and construction quality.

5.9 RECOMMENDATIONS FOR IMPROVING SEISMIC PERFORMANCE

In addition to the specific seismic design issues relating to siting, structural systems, and nonstructural systems, there are some general measures that can be employed to help manage seismic risk by reducing either the vulnerability of the facility to earthquake damage, or the consequences of the damage should it occur. These measures include the following.

- Consideration should be given to performance-based design to a level beyond Life Safety (typically the level of performance provided by provisions of the current seismic design codes) to a level of Immediate Occupancy, as discussed in Section 4.3. Institutional, public and corporate owners usually have long-term ownership of their facilities and a desire for continued operation in the post-event period.
- The design professionals in charge of the structural and nonstructural component installation should specify quality assurance requirements; the contractor should be required to exercise a high degree of quality control; and independent inspection should be used to ensure conformance to requirements.
- The design engineer should advise facility owners and manager on technical aspects of obtaining insurance to cover potential losses including service interruption. It may be possible to negotiate reduced premiums with the insurance carrier on the basis of any seismic mitigation measures provided beyond the code-minimum requirements.
- Retainer agreements should be established with engineers and architects to provide building inspection services immediately following an earthquake (see Section 2.6 for additional information).
- Personal protection and evacuation plans should be developed for all staff and students. Regular drills and educational sessions should be conducted to ensure proper execution (see Section 2.6 for additional information).