Earthquake Design of Buildings and Structures:

Beyond Design Codes

Course No: S01-003
Credit: 1 PDH

Chelliah Sundararajan, PhD, MASCE, FASME

CED engineering.com
PDH FOR THE PROFESSIONAL

Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.com

Risk Management Series

Primer for Design Professionals

Communicating with Owners and Managers of New Buildings on Earthquake Risk

January 2004

FEMA

FEMA 389

FEMA 389 / *January 2004*

RISK MANAGEMENT SERIES

Primer for Design Professionals: Communicating with Owners and Managers of New Buildings on Earthquake Risk

PROVIDING PROTECTION TO PEOPLE AND BUILDINGS

FEMA

www.fema.gov

IMPROVING PERFORMANCE TO REDUCE SEISMIC RISK 5

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 specific 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 Elsesser, 1992)

SUMMARY OF SEISMIC PERFORMANCE OF STRUCTURAL SYSTEMS

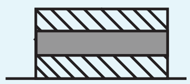
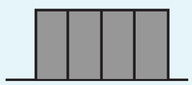
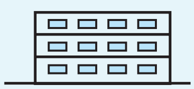
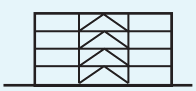
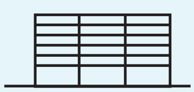
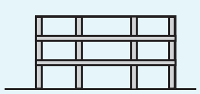
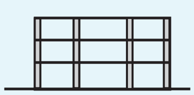
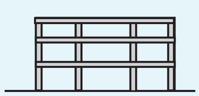
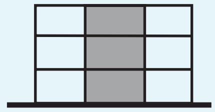
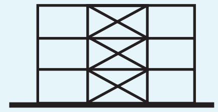
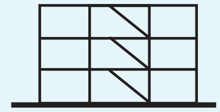
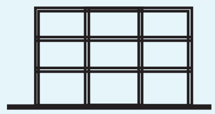
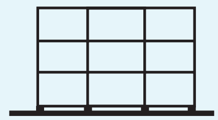
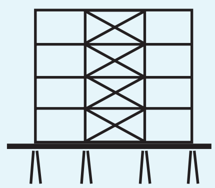
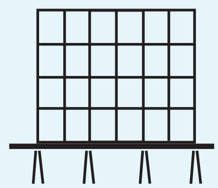
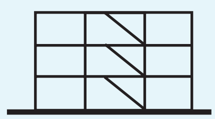
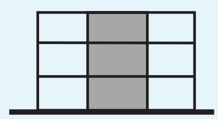
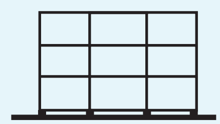
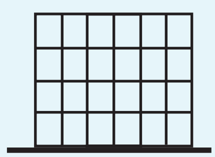
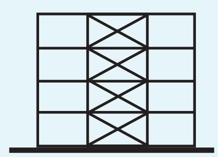
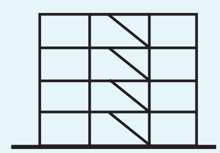
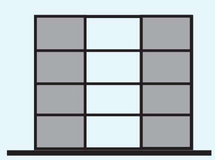
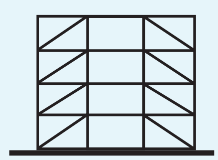
Structural System	Earthquake Performance	Specific Building Performance and Energy Absorption	General Comments
Wood Frame 	San Francisco, 1906 Alaska 1964 Other Earthquakes Variable to *Good*	❍ San Francisco Buildings performed reasonably well even though not detailed. ❍ Energy Absorption is excellent	❍ Connection details are critical. ❍ Configuration is significant
Unreinforced Masonry Wall 	San Francisco, 1906 Santa Barbara, 1925 Long Beach, 1933 Los Angeles, 1994 Variable to *Poor*	❍ Unreinforced masonry has performed poorly when *not* tied together. ❍ Energy absorption is good if system integrity is maintained.	❍ Continuity and ties between walls and diaphragm is essential.
Steel Frame with Masonry Infill 	San Francisco, 1906 Variable to *Good*	❍ San Francisco buildings performed very well. ❍ Energy absorption is excellent.	❍ Building form must be uniform, relatively small bay *sizes.*
Reinforced Concrete Wall 	San Francisco, 1957 Alaska, 1964 Japan 1966 Los Angeles, 1994 Variable to *Poor*	❍ Buildings in Alaska, San Francisco and Japan performed poorly with spandrel and pier failure ❍ Brittle system	❍ Proportion of spandrel and piers is critical, detail for ductility and shear.
Steel Brace 	San Francisco, 1906 Taft, 1952 Los Angeles, 1994 Variable	❍ Major braced systems performed well. ❍ Minor bracing and tension braces performed poorly.	❍ Details and proportions are critical.
Steel Moment Frame 	Los Angeles, 1971 Japan, 1978 Los Angeles, 1994 ? *Good*	❍ Los Angeles and Japanese buildings 1971/78 performed well. ❍ Energy absorption is excellent. ❍ Los Angeles 1994, mixed performance.	❍ Both conventional and ductile frame have performed well if designed for drift.
Concrete Shear Wall 	Caracas, 1965 Alaska, 1964 Los Angeles, 1971 Algeria, 1980 *Variable*	❍ Poor performance with discontinuous walls. ❍ Uneven energy absorption.	❍ *Configuration* is *critical,* soft story or L-shape with torsion have produced failures.
Precast Concrete 	Alaska, 1964 Bulgaria, 1978 San Francisco, 1980 Los Angeles, 1994 Variable to *Poor*	❍ Poor performance in 1964, 1978, 1980, 1994	❍ Details for continuity are critical ❍ *Ductility* must be achieved
Reinforced Concrete Ductile Moment Frame 	Los Angeles, 1971 ? *Good*	❍ Good performance in 1971, Los Angeles ❍ System will crack ❍ Energy absorption is good. ❍ Mixed performance in 1994 Los Angeles	❍ Details *critical.*

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

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 nonstructural damage.

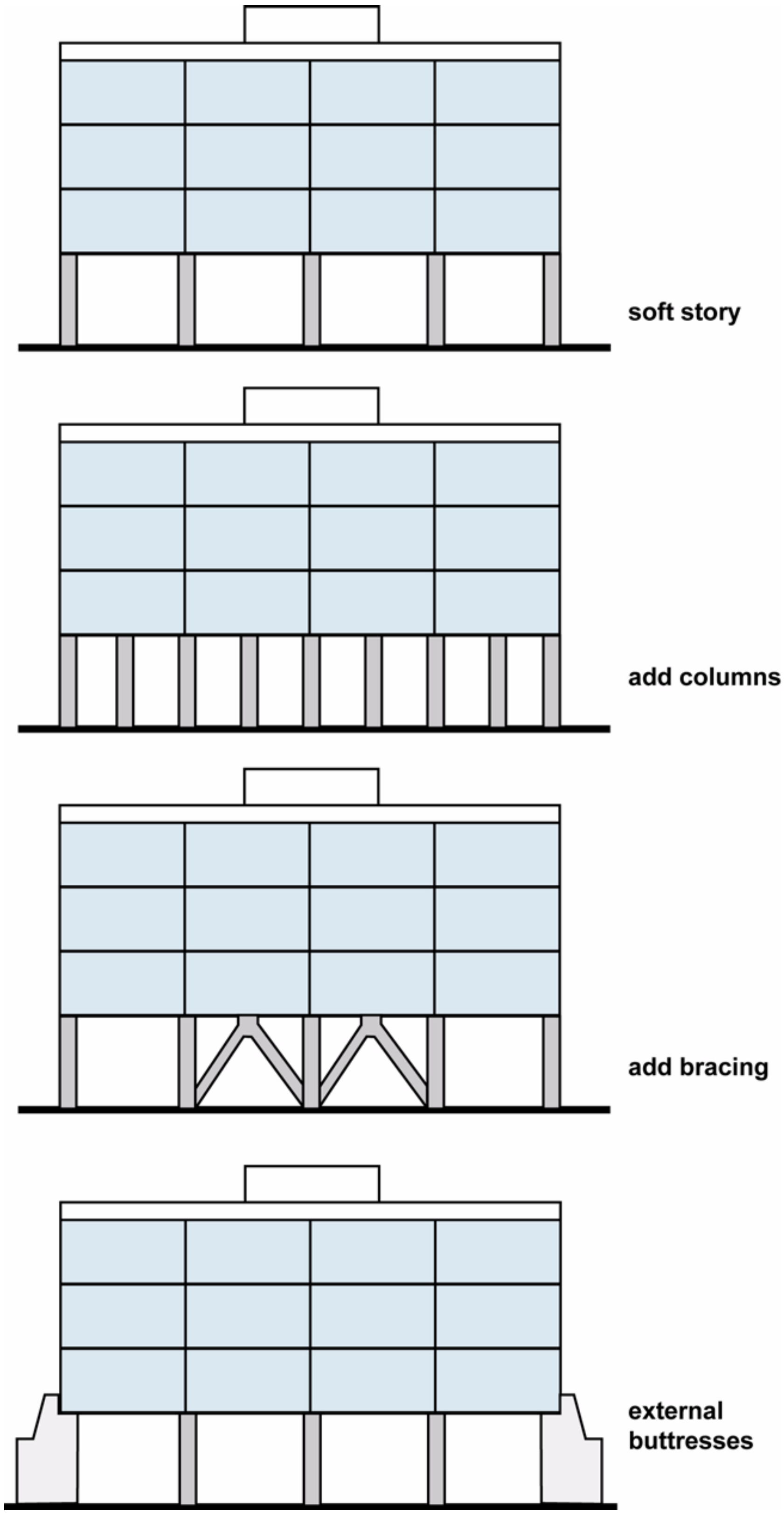


Figure 5-1 Example design solutions for addressing soft story condition.

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

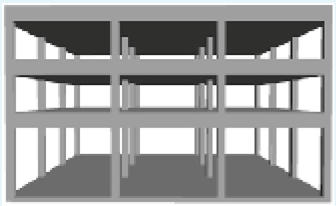
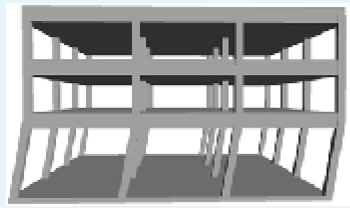
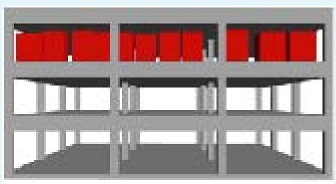
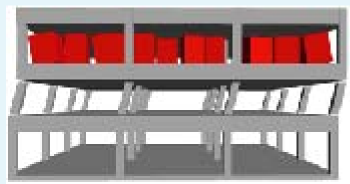
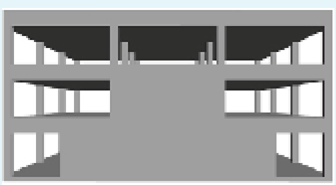
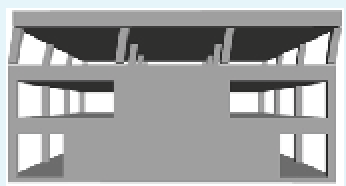
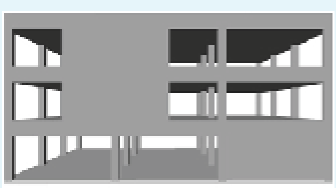
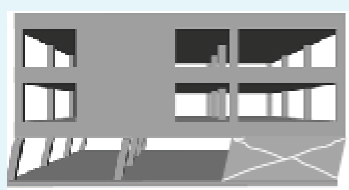
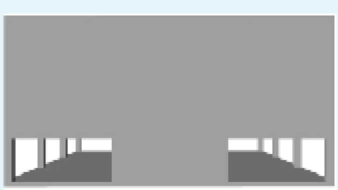
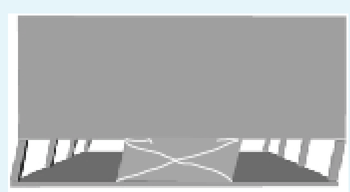
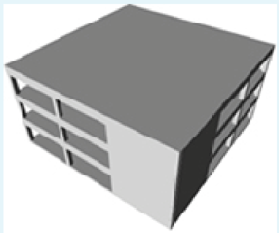
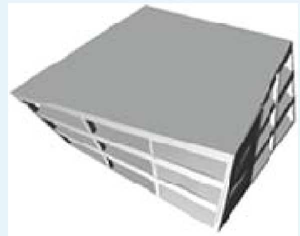
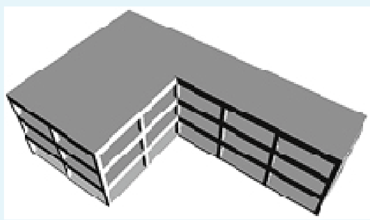
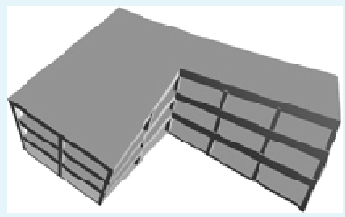
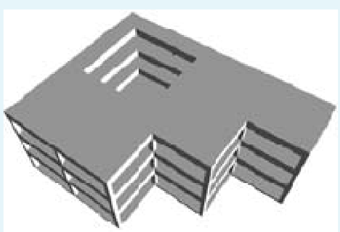
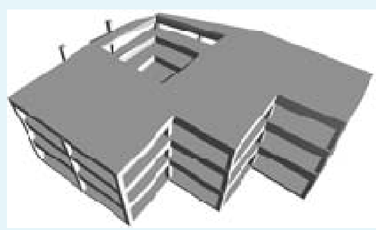
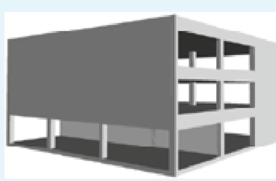
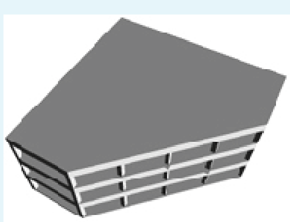
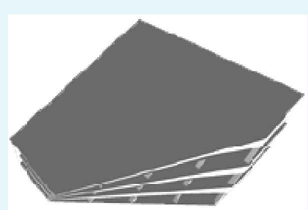
Vertical Irregularities	Resulting Failure Patterns	Performance
		❍ Common collapse mechanism. Deaths and much damage in 1994 Northridge earthquake.
V1: Stiffness Irregularity: Soft Story		
		❍ Collapse mechanism in extreme instances.
V2: Weight / Mass Irregularity		
		❍ Localized structural damage.
V3: Vertical Geometric Irregularity		
		❍ Localized structural damage.
V4: In-Plane Irregularity in Vertical Lateral Force-Resisting System		
		❍ 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
		❍ Localized damage. ❍ Collapse mechanism in extreme instances.
P1: Torsional Irregularity: Unbalanced Resistance		
		❍ Localized damage to diaphragms and attached elements. ❍ Collapse mechanism in extreme instances in large buildings.
P2: Reentrant Corners		
		❍ Localized damage to diaphragms and attached elements.
P3: Diaphragm Eccentricity and Cut-outs		
		❍ Collapse mechanism in extreme instances.
P4: Out-of-Plane Offsets: Discontinuous Shear Walls		
		❍ 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.

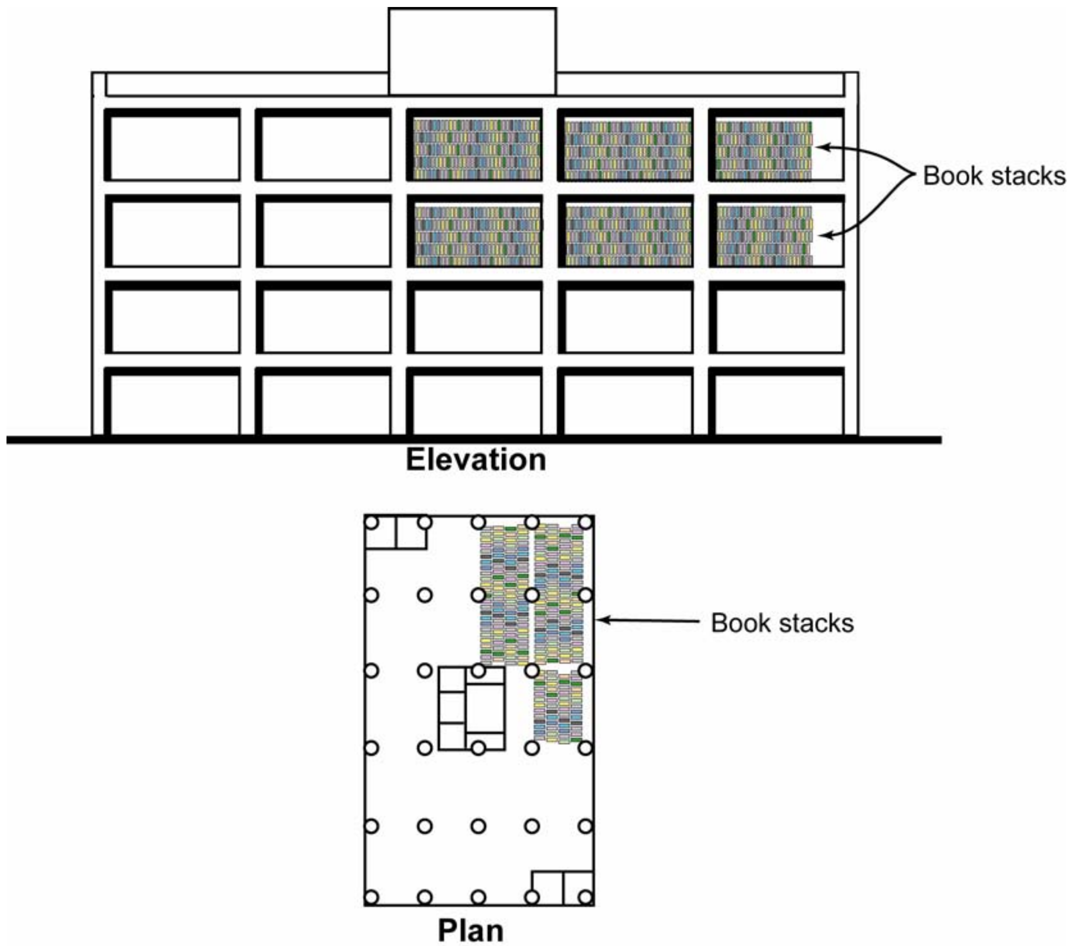


Figure 5-3 Nonsymmetric loading of book stacks in library building. Position and weight of stacks could induce torsional response of building during earthquake shaking.

- 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).