SEISMIC ISSUES IN ARCHITECTURAL DESIGN 5

by Christopher Arnold

5.1 INTRODUCTION

This chapter uses the information in the preceding chapter to explain how architectural design decisions influence a building's likelihood to suffer damage when subjected to earthquake ground motion. The critical design decisions are those that create the building configuration, defined as the building's size and three dimensional shape, and those that introduce detailed complexities into the structure, in ways that will be discussed later.

In sections 5.2 to 5.5, the effects of architectural design decisions on seismic performance are explained by showing a common structural/architectural configuration that has been designed for near optimum seismic performance and explaining its particular characteristics that are seismically desirable. In Section 5.3, the two main conditions created by configuration irregularity are explained. In Section 5.4, a number of deviations from these characteristics (predominantly architectural in origin) are identified as problematical from a seismic viewpoint. Four of these deviations are then discussed in more detail in Section 5. 5 both from an engineering and architectural viewpoint, and conceptual solutions are provided for reducing or eliminating the detrimental effects. Section 5.6 identifies a few other detailed configuration issues that may present problems.

Section 5.7 shows how seismic configuration problems originated in the universal adoption of the "International Style" in the twentieth century, while Section 5.8 gives some guidelines on how to avoid architectural/structural problems. Finally, Section 5.9 looks to the future in assessing today's architectural trends, their influence on seismic engineering, and the possibility that seismic needs might result in a new "seismic architecture."

5.2 THE BASIC SEISMIC STRUCTURAL SYSTEMS

A building's structural system is directly related to its architectural configuration, which largely determines the size and location of structural elements such as walls, columns, horizontal beams, floors, and roof structure. Here, the term **structural/architectural configuration** is used to represent this relationship.

5.2.1 The Vertical Lateral Resistance Systems

Seismic designers have the choice of three basic alternative types of vertical lateral force–resisting systems, and as discussed later, the system must be selected at the outset of the architectural design process. Here, the intent is to demonstrate an optimum architectural/structural configuration for each of the three basic systems. The three alternatives are illustrated in Figure 5-1.

These basic systems have a number of variations, mainly related to the structural materials used and the ways in which the members are connected. Many of these are shown in Chapter 7: Figures 7-2, 7-3, 7-11A and 7-11b show their comparative seismic performance characteristics.

- Shear walls

  Shear walls are designed to receive lateral forces from diaphragms and transmit them to the ground. The forces in these walls are predominantly shear forces in which the material fibers within the wall try to slide past one another. To be effective, shear walls must run from the top of the building to the foundation with no offsets and a minimum of openings.

- Braced frames

  Braced frames act in the same way as shear walls; however, they generally provide less resistance but better ductility depending on their detailed design. They provide more architectural design freedom than shear walls.

  There are two general types of braced frame: conventional concentric and eccentric. In the concentric frame, the center lines of the bracing members meet the horizontal beam at a single point.

  In the eccentric braced frame, the braces are deliberately designed to meet the beam some distance apart from one another: the short piece of beam between the ends of the braces is called a link beam. The purpose of the link beam is to provide ductility to the system: under heavy seismic forces, the link beam will distort and dissipate the energy of the earthquake in a controlled way, thus protecting the remainder of the structure (Figure 5-2).

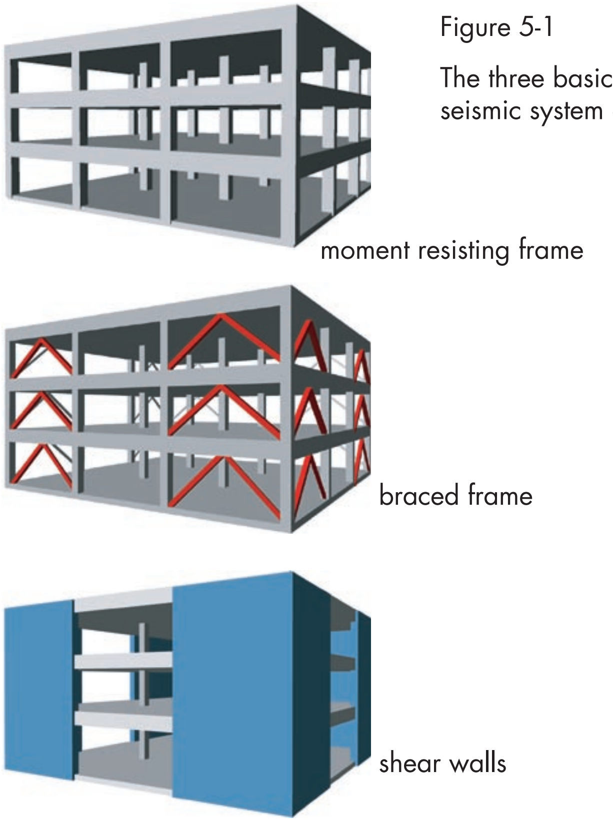


Figure 5-1

The three basic vertical seismic system alternatives.

- Moment-resistant frames

  A moment resistant frame is the engineering term for a frame structure with no diagonal bracing in which the lateral forces are resisted primarily by bending in the beams and columns mobilized by strong joints between columns and beams. Moment-resistant frames provide the most architectural design freedom.

These systems are, to some extent, alternatives, although designers sometimes mix systems, using one type in one direction and another type in the other. This must be done with care, however, mainly because the different systems are of varying stiffness (shear-wall systems are much stiffer than moment-resisting frame systems, and braced systems fall in between), and it is difficult to obtain balanced resistance when they are mixed. However, for high-performance structures,) there is now increasing use of dual systems, as described in section 7.7.6. Examples of effective mixed systems are the use of a shear-wall core together with a perimeter moment-resistant frame or a perimeter steel-moment frame

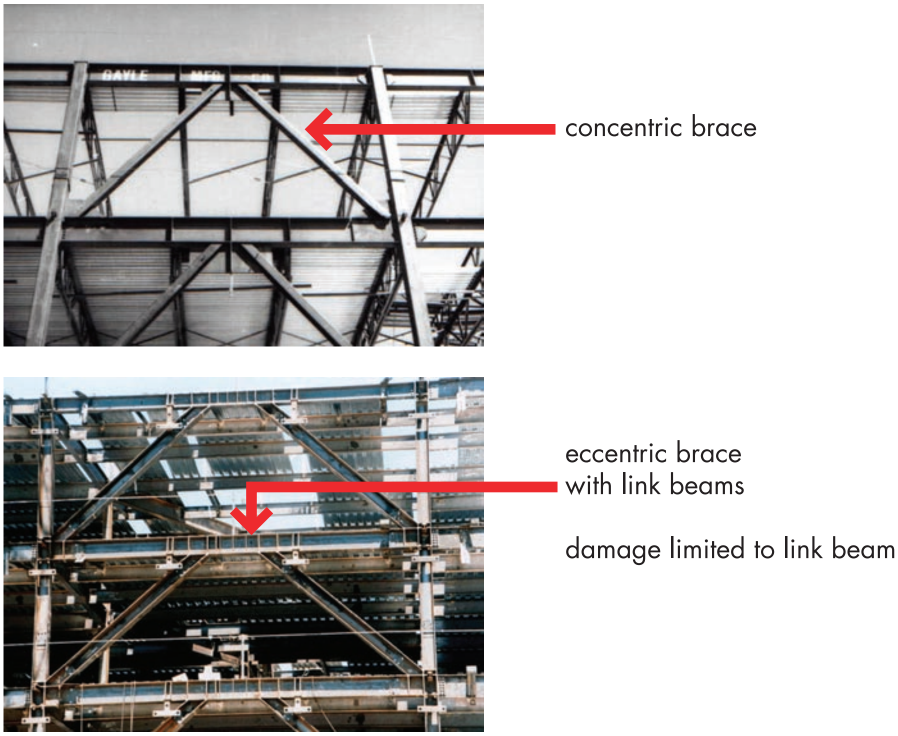


Figure 5-2

Types of braced frames.

concentric brace

eccentric brace
with link beams

damage limited to link beam

with interior eccentric-braced frames. Another variation is the use of shear walls combined with a moment-resistant frame in which the frames are designed to act as a fail-safe back-up in case of shear-wall failure.

The framing system must be chosen at an early stage in the design because the different system characteristics have a considerable effect on the architectural design, both functionally and aesthetically, and because the seismic system plays the major role in determining the seismic performance of the building. For example, if shear walls are chosen as the seismic force-resisting system, the building planning must be able to accept a pattern of permanent structural walls with limited openings that run uninterrupted through every floor from roof to foundation.

5.2.2 Diaphragms—the Horizontal Resistance System

The term "diaphragm" is used to identify horizontal-resistance members that transfer lateral forces between vertical-resistance elements (shear walls or frames). The diaphragms are generally provided by the floor and roof elements of the building; sometimes, however, horizontal bracing systems independent of the roof or floor structure serve as diaphragms. The diaphragm is an important element in the entire seismic resistance system (Figure 5-3).

The diaphragm can be visualized as a wide horizontal beam with components at its edges, termed **chords**, designed to resist tension and compression: chords are similar to the flanges of a vertical beam (Figure 5-3A)

A diaphragm that forms part of a resistant system may act either in a **flexible** or **rigid** manner, depending partly on its size (the area between enclosing resistance elements or stiffening beams) and also on its material. The flexibility of the diaphragm, relative to the shear walls whose

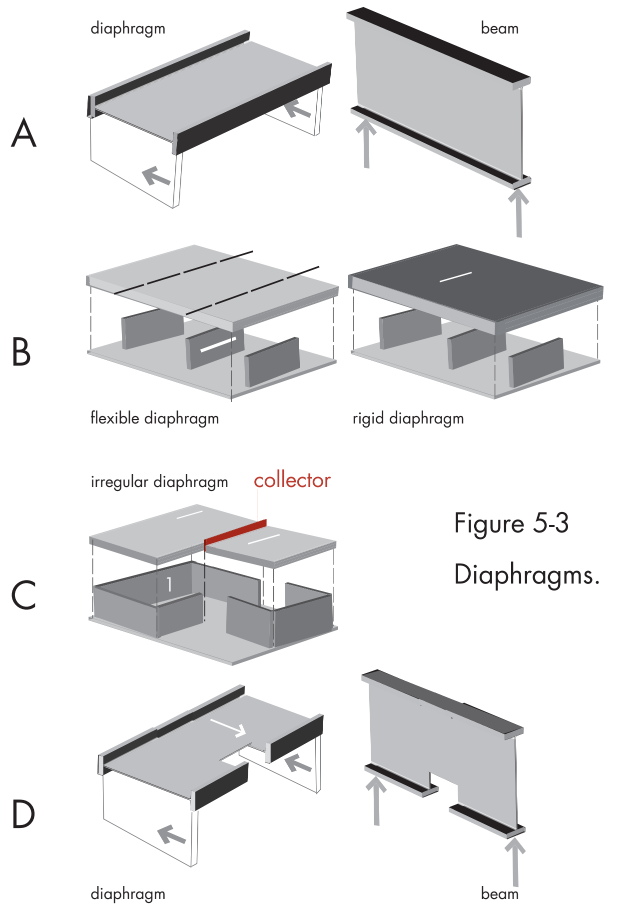


Figure 5-3 Diaphragms.

forces it is transmitting, also has a major influence on the nature and magnitude of those forces. With flexible diaphragms made of wood or steel decking without concrete, walls take loads according to tributary areas (if mass is evenly distributed). With rigid diaphragms (usually concrete slabs), walls share the loads in proportion to their stiffness (figure 5-3B).

Collectors, also called **drag struts** or **ties**, are diaphragm framing members that “collect” or “drag” diaphragm shear forces from laterally unsupported areas to vertical resisting elements (Figure 5-3C).

Floors and roofs have to be penetrated by staircases, elevator and duct shafts, skylights, and atria. The size and location of these penetrations are critical to the effectiveness of the diaphragm. The reason for this is not hard to see when the diaphragm is visualized as a beam. For example, it can be seen that openings cut in the tension flange of a beam will seriously weaken its load carrying capacity. In a vertical load-bearing situation, a penetration through a beam flange would occur in either a tensile or compressive region. In a lateral load system, the hole would be in a region of both tension and compression, since the loading alternates rapidly in direction (Figure 5-3D).

5.2.3 Optimizing the Structural/Architectural Configuration

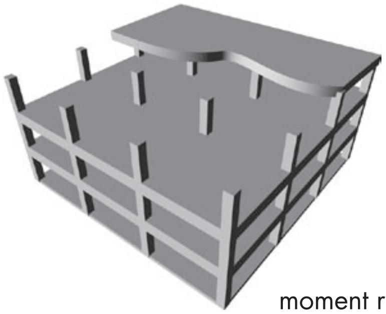
Figure 5-4 shows the application of the three basic seismic systems to a model structural/architectural configuration that has been designed for near optimum seismic performance. The figure also explains the particular characteristics that are seismically desirable.

Building attributes:

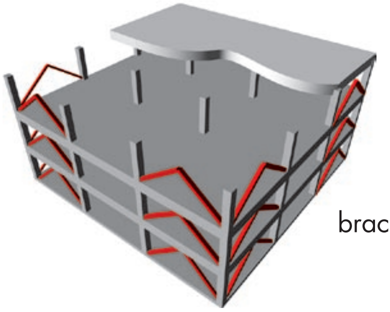
- **Continuous load path.**
  Uniform loading of structural elements and no stress concentrations.
- **Low height-to base ratio**
  Minimizes tendency to overturn.
- **Equal floor heights**
  Equalizes column or wall stiffness, no stress concentrations.
- **Symmetrical plan shape**
  Minimizes torsion.

Figure 5-4

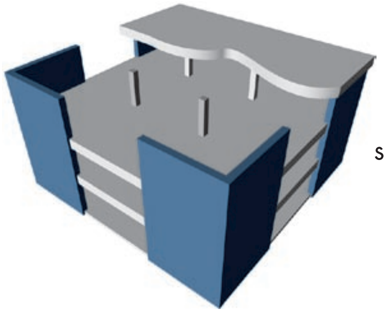
The optimized structural/ architectural configuration.



moment resisting frame



braced frame



shear walls

- **Identical resistance on both axes**
  Eliminates eccentricity between the centers of mass and resistance and provides balanced resistance in all directions, thus minimizing torsion.

- **Identical vertical resistance**
  No concentrations of strength or weakness.

- **Uniform section and elevations**
  Minimizes stress concentrations.

- **Seismic resisting elements at perimeter**
  Maximum torsional resistance.

- **Short spans**
  Low unit stress in members, multiple columns provide redundancy -loads can be redistributed if some columns are lost.
- **No cantilevers**
  Reduced vulnerability to vertical accelerations.
- **No openings in diaphragms(floors and roof)**
  Ensures direct transfer of lateral forces to the resistant elements.

In the model design shown in Figure 5-4, the lateral force resisting elements are placed on the perimeter of the building, which is the most effective location; the reasons for this are noted in the text. This location also provides the maximum freedom for interior space planning. In a large building, resistant elements may also be required in the interior.

Since ground motion is essentially random in direction, the resistance system must protect against shaking in all directions. In a rectilinear plan building such as this, the resistance elements are most effective when placed on the two major axes of the building in a symmetrical arrangement that provides balanced resistance. A square plan, as shown here, provides for a near perfectly balanced system.

Considered purely as architecture, this little building is quite acceptable, and would be simple and economical to construct. Depending on its exterior treatment - its materials, and the care and refinement with which they are disposed- - it could range from a very economical functional building to an elegant architectural jewel. It is not a complete building, of course, because stairs, elevators, etc., must be added, and the building is not spatially interesting. However, its interior could be configured with nonstructural components to provide almost any quality of room that was desired, with the exception of unusual spatial volumes such as spaces more than one story in height.

In seismic terms, engineers refer to this design as a **regular** building. As the building characteristics deviate from this model, the building becomes increasingly **irregular**. It is these irregularities, for the most part created by the architectural design, that affect the building's seismic performance. **Indeed many engineers believe that it is these architectural irregularities that contribute primarily to poor seismic performance and occasional failure.**

5.3 THE EFFECTS OF CONFIGURATION IRREGULARITY

Configuration irregularity is largely responsible for two undesirable conditions-stress concentrations and torsion. These conditions often occur concurrently.

5.3.1 Stress Concentrations

Irregularities tend to create abrupt changes in strength or stiffness that may concentrate forces in an undesirable way. Although the overall design lateral force is usually determined by calculations based on seismic code requirements, the way in which this force is distributed throughout the structure is determined by the building configuration.

Stress concentration occurs when large forces are concentrated at one or a few elements of the building, such as a particular set of beams, columns, or walls. These few members may fail and, by a chain reaction, damage or even bring down the whole building. Because, as discussed in Section 4.10.2, forces are attracted to the stiffer elements of the building, these will be locations of stress concentration.

Stress concentrations can be created by both horizontal and vertical stiffness irregularities. The short-column phenomenon discussed in Section 4.10.2 and shown in Figure 4-14 is an example of stress concentration created by vertical dimensional irregularity in the building design. In plan, a configuration that is most likely to produce stress concentrations features **re-entrant corners:** buildings with plan forms such as an L or a T.) A discussion of the re-entrant corner configuration will be found in Section 5.5.4.

The vertical irregularity of the **soft or weak story** types can produce dangerous stress concentrations along the plane of discontinuity. Soft and weak stories are discussed in Section 5.5.1.

5.3.2 Torsion

Configuration irregularities in plan may cause torsional forces to develop, which contribute a significant element of uncertainty to an analysis of building resistance, and are perhaps the most frequent cause of structural failure.

As described in Section 4.11 and shown in Figure 4-17, torsional forces are created in a building by eccentricity between the center of mass and the center of resistance. This eccentricity originates either in the lack of symmetry in the arrangement of the perimeter-resistant elements as discussed in Section 5.5.3., or in the plan configuration of the building, as in the re-entrant-corner forms discussed in Section 5.5.4.

5.4 CONFIGURATION IRREGULARITY IN THE SEISMIC CODE

Many of the configuration conditions that present seismic problems were identified by observers early in the twentieth century. However, the configuration problem was first defined for code purposes in the 1975 *Commentary to the Strucural Engineers Association of California* (SEAOC) *Recommended Lateral Force Requirements* (commonly called the SEAOC Blue Book). In this section over twenty specific types of "irregular structures or framing systems" were noted as examples of designs that should involve further analysis and dynamic consideration, rather than the use of the simple equivalent static force method in unmodified form. These irregularities vary in importance in their effect, and their influence also varies in degree, depending on which particular irregularity is present. Thus, while in an extreme form the re-entrant corner is a serious plan irregularity, in a lesser form it may have little or no significance. The determination of the point at which a given irregularity becomes serious was left up to the judgment of the engineer.

Because of the belief that this approach was ineffective, in the 1988 codes a list of six horizontal (plan) and six vertical (section and elevation) irregularities was provided that, with minor changes, is still in today's codes. This list also stipulated dimensional or other characteristics that established whether the irregularity was serious enough to require regulation, and also provided the provisions that must be met in order to meet the code. Of the 12 irregularities shown, all except one are configuration irregularities; the one exception refers to asymmetrical location of mass within the building. The irregularities are shown in Figures 5.5 and 5.6. The code provides only descriptions of these conditions; the diagrams are added in this publication to illustrate each condition by showing how it would modify our optimized configuration, and to also illustrate the failure pattern that is created by the irregularity.

For the most part, code provisions seek to discourage irregularity in design by imposing penalties, which are of three types:

- Requiring increased design forces.
- Requiring a more advanced (and expensive) analysis procedure.
- Disallowing extreme soft stories and extreme torsional imbalance in high seismic zones.

It should be noted that the code provisions treat the symptoms of irregularity, rather than the cause. The irregularity is still allowed to exist; the hope is that the penalties will be sufficient to cause the designers to eliminate the irregularities. Increasing the design forces or improving the analysis to provide better information does not, in itself, solve the problem. The problem must be solved by design.

The code-defined irregularities shown in Figures 5-5 and 5-6 serve as a checklist for ascertaining the possibility of configuration problems. Four of the more serious configuration conditions that are clearly architectural in origin are described in more detail in the sections below. In addition, some conceptual suggestions for their solution are also provided, as it may not be possible totally to eliminate an undesirable configuration.

5.5 FOUR SERIOUS CONFIGURATION CONDITIONS

Four configuration conditions (two vertical and two in plan) that originate in the architectural design and that have the potential to seriously impact seismic performance are:

- Soft and weak stories
- Discontinuous shear walls
- Variations in perimeter strength and stiffness
- Reentrant corners

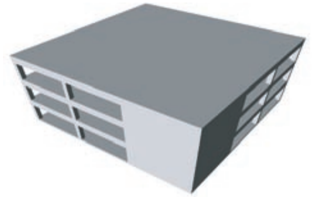
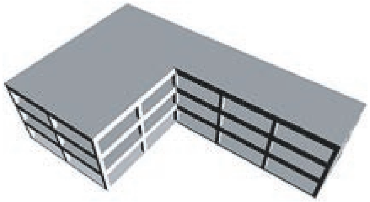
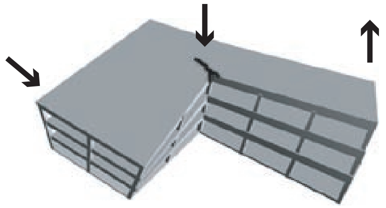
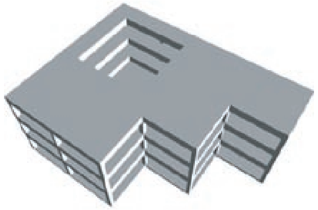
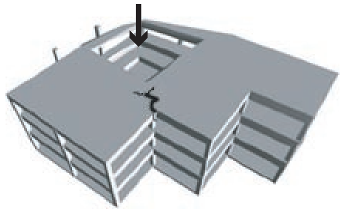
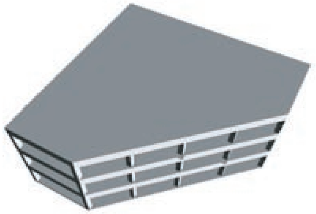
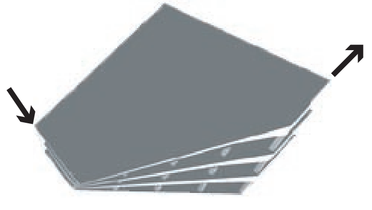
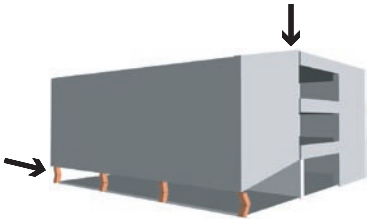
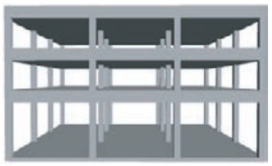
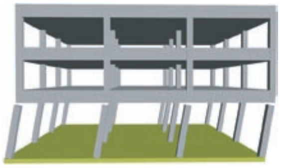
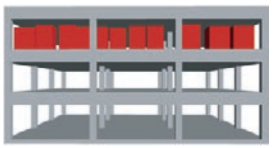
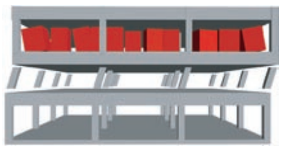
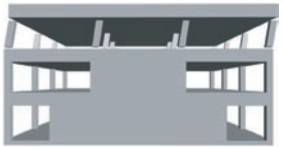
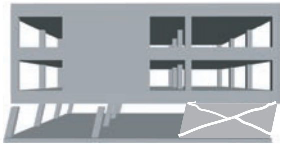
plan conditions	resulting failure patterns	performance	code remedies
		**P1 Torsional Irregularity: Unbalenced Resistance**	
		Localized damage. Collapse mechanism in extreme instances.	Modal Analysis, +65 foot high in SDC D,E, F. 25% increase to diaphragm connection design forces. Amplified forces to max of X3.
		**P2 Re-entrant Corners**	
		Local damage to diaphragm and attached elements. Collapse mechanism in extreme instances in large buildings.	25% increase in diaphragm connection design forces.
		**P3 Diaphragm Eccentricity and Cutouts**	
		Localized structural damage.	25% increase in diaphragm connection design forces.
		**P4 Nonparallel Lateral Force-Resisting System**	
		Leads to torsion and instability, localised damage.	Combine 100% and 30% of forces in 2 directions, use maximum.
		**P5 Out-of-Plane Offsets: Discontinuous Shearwalls**	
		Collapse mechanism in extreme circumstances.	Modal Analysis, +65 foot high in SDC D,E, F. 25% increase to diaphragm connection design forces.

Figure 5-5: Horizontal (Plan) Irregularities (based on IBC, Section 1616.5.1).

Figure 5-6: Vertical Irregularities (based on IBC, Section 1616.5.2).

vertical conditions	resulting failure patterns	performance	code remedies
		**V1 Stiffness Irregularity: Soft Story**	
		Common collapse mechanism. Death and much damage in Northridge earthquake.	Modal Analysis, +65 feet high in SCD D,E,F. Extreme case not permitted in seismic use groups E and F.
		**V2 Weight/Mass Irregularity**	
		Collapse mechanism in extreme circumstances.	Modal Analysis,+65 foot high in SDC D,E,F.
		**V3 Vertical Geometric Irregularity**	
		Localized structural damage.	Modal Analysis,+65 foot high in SDC D,E,F.
		**V4 In-Plane Irregularity in Vertical Lateral Force System**	
		Localized structural damage.	Model Analysis, +65 foot high is SDC D, E, F. 25% increase to diaphragm connection design force. Supporting members designed for increased forces.
		**V5 Capacity Discontinuity: Weak Story**	
		Collapse mechanism in extreme circumstances	Modal Analysis, +65 foot high in SDC D,E,F.

5.5.1 Soft and Weak Stories (Code Irregularities Types V1 and V5)

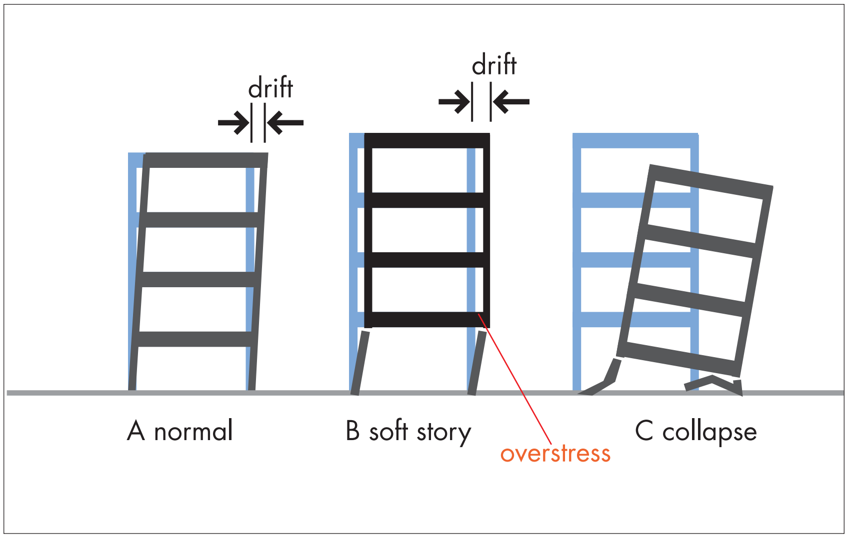
- The problem and the types of condition

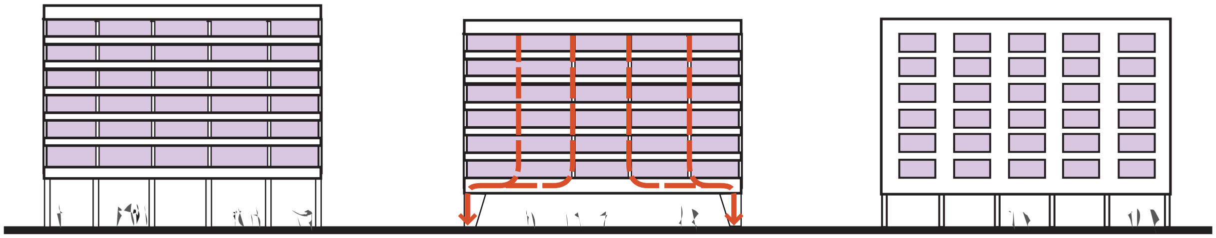
The most prominent of the problems caused by severe stress concentration is that of the “soft” story. The term has commonly been applied to buildings whose ground-level story is less stiff than those above. The building code distinguishes between “soft” and “weak” stories. Soft stories are less stiff, or more flexible, than the story above; weak stories have less strength. A soft or weak story at any height creates a problem, but since the cumulative loads are greatest towards the base of the building, a discontinuity between the first and second floor tends to result in the most serious condition.

The way in which severe stress concentration is caused at the top of the first floor is shown in the diagram sequence in Figure 5-7. Normal drift under earthquake forces that is distributed equally among the upper floors is shown in Figure 5-7A. With a soft story, almost all the drift occurs in the first floor, and stress concentrates at the second-floor connections (Figure 5-7B). This concentration overstresses the joints along the second floor line, leading to distortion or collapse (Figure 5-7C).

Figure 5-7

The soft first story failure mechanism.





A flexible first floor B discontinuity: indirect load path C heavy superstructure

Figure 5-8: Three types of soft first story.

Three typical conditions create a soft first story (Figure 5-8). The first condition (Figure 5-8A) is where the vertical structure between the first and second floor is significantly more flexible than that of the upper floors. (The seismic code provides numerical values to evaluate whether a soft-story condition exists). This discontinuity most commonly occurs in a frame structure in which the first floor height is significantly taller than those above, so that the cube law results in a large discrepancy in stiffness (see Section 4.10.2 and Figure 4-13).

The second form of soft story (Figure 5-B) is created by a common design concept in which some of the vertical framing elements do not continue to the foundation, but rather are terminated at the second floor to increase the openness at ground level. This condition creates a discontinuous load path that results in an abrupt change in stiffness and strength at the plane of change.

Finally, the soft story may be created by an open first floor that supports heavy structural or nonstructural walls above (Figure 5-8C). This situation is most serious when the walls above are shear walls acting as major lateral force-resisting elements. This condition is discussed in Section 5.5.2, since it represents an important special case of the weak- and soft-story problem.

Figure 5-9 shows the Northridge Meadows apartment building after the Northridge (Los Angeles) earthquake of 1994. In this building, most of the first floor was left open for car parking, resulting in both a weak and flexible first floor. The shear capacity of the first-floor columns and the few walls of this large wood frame structure were quite inadequate, and led to complete collapse and 16 deaths.

Figure 5-9

Northridge Meadows apartments, Northridge earthquake , 1994.

Figure 5-10 shows another apartment house in Northridge in which two stories of wood frame construction were supported on a precast concrete frame. The frame collapsed completely. Fortunately there were no ground floor apartments, so the residents, though severely shaken, were uninjured.

Figure 5-10

Apartment building, Northridge earthquake, 1994. The first floor of this three-story apartment has disappeared.

● Solutions

The best solution to the soft and weak story problem is to avoid the discontinuity through architectural design. There may, however, be good programmatic reasons why the first floor should be more open or higher than the upper floors. In these cases, careful architectural/structural design must be employed to reduce the discontinuity. Some conceptual methods for doing this are shown in Figure 5-11.

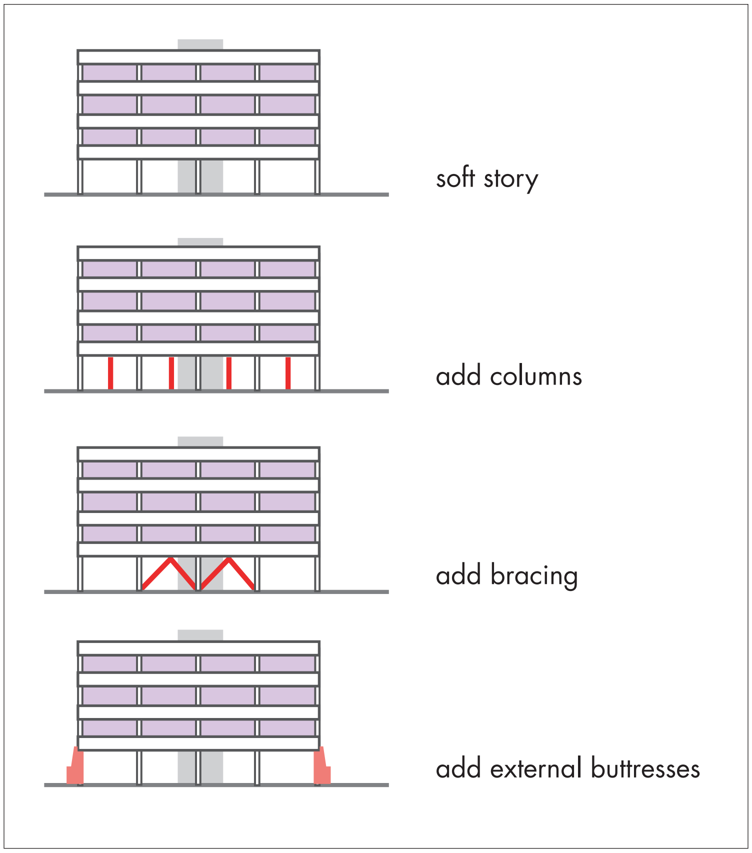


Figure 5-11

Some conceptual solutions to the soft first story.

Not all buildings that show slender columns and high first floors are soft stories. For a soft story to exist, the flexible columns must be the main lateral force-resistant system.

Designers sometimes create a soft-story condition in the effort to create a delicate, elegant appearance at the base of a building. Skillful structural/architectural design can achieve this effect without compromising the structure, as shown in Figure 5-12. The building shown is a 21-story apartment house on the beach in Vina del Mar, Chile. This building was unscathed in the strong Chilean earthquake of 1985.

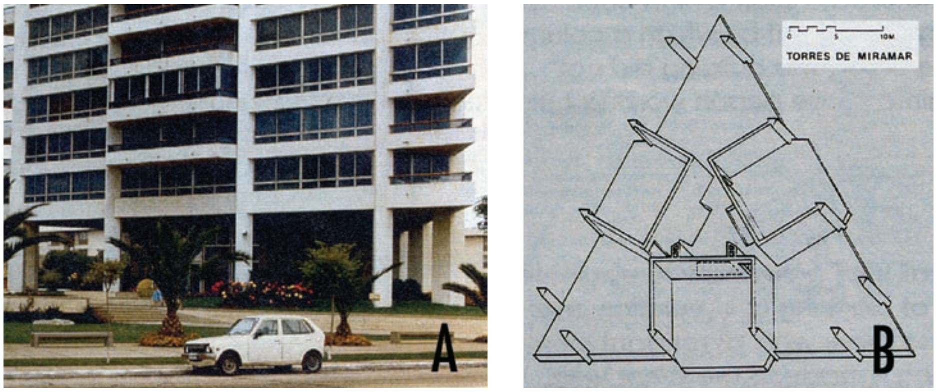


Figure 5-12: This apartment house appears to have a soft first story (Figure 5-12A), but the lateral force-resisting system is a strong internal shear wall box, in which the shear walls act as party walls between the dwelling units (Figure 5-12B). The architect achieved a light and elegant appearance, and the engineer enjoyed an optimum and economical structure.

5.5.2 Discontinuous Shear Walls (Code Type Irregularity V5)

- The problem and the types of condition

When shear walls form the main lateral resistant elements of a structure, and there is not a continuous load path through the walls from roof to foundation, the result can be serious overstressing at the points of discontinuity. This discontinuous shear wall condition represents a special, but common, case of the “soft” first-story problem.

The discontinuous shear wall is a fundamental design contradiction: the purpose of a shear wall is to collect diaphragm loads at each floor and transmit them as directly and efficiently as possible to the foundation. To interrupt this load path is undesirable; to interrupt it at its base, where the shear forces are greatest, is a major error. Thus the discontinuous shear wall that terminates at the second floor represents a “worst case” of the soft first-floor condition. A discontinuity in vertical stiffness and strength leads to a concentration of stresses, and the story that must hold up all the rest of the stories in a building should be the last, rather than the first, element to be sacrificed.

Olive View Hospital, which was severely damaged in the 1971 San Fernando, California, earthquake, represents an extreme form of the discontinuous shear wall problem. The general vertical configuration of the main building was a "soft" two-story layer of rigid frames on which was supported a four story (five, counting penthouse) stiff shear wall-plus-frame structure (Figures 5-13, 5-14). The second floor extends out to form a large plaza. Severe damage occurred in the soft story portion. The upper stories moved as a unit, and moved so much that the columns at ground level could not accommodate such a high displacement between their bases and tops, and hence failed. The largest amount by which a column was left permanently out-of-plumb was 2 feet 6 inches (Figure 5-15). The building did not collapse, but two occupants in intensive care and a maintenance person working outside the building were killed.

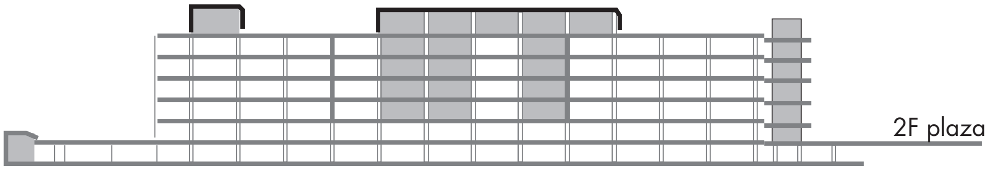


Figure 5-13: Long section, Olive View Hospital. Note that the shear walls stop at the third floor.

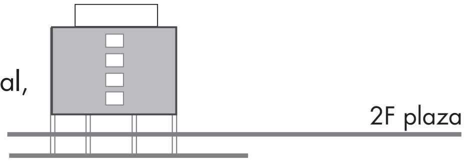


Figure 5-14: Cross section, Olive View hospital, showing the second-floor plaza and the discontinuous shear wall.

Figure 5-15: Olive View hospital, San Fernando earthquake, 1971, showing the extreme deformation of the columns above the plaza level.

Solutions

The solution to the problem of the discontinuous shear wall is unequivocally to eliminate the condition. To do this may create architectural problems of planning or circulation or image. If this is so, it indicates that the decision to use shear walls as resistant elements was wrong from the inception of the design. If the decision is made to use shear walls, then their presence must be recognized from the beginning of schematic design, and their size and location made the subject of careful architectural and engineering coordination early.

5.5.3 Variations in Perimeter Strength and Stiffness (Code Type P1)

The problem and the types of condition

As discussed in Section 4.11, this problem may occur in buildings whose configuration is geometrically regular and symmetrical, but nonetheless irregular for seismic design purposes.

A building's seismic behavior is strongly influenced by the nature of the perimeter design. If there is wide variation in strength and stiffness around the perimeter, the center of mass will not coincide with the center of resistance, and torsional forces will tend to cause the building to rotate around the center of resistance.

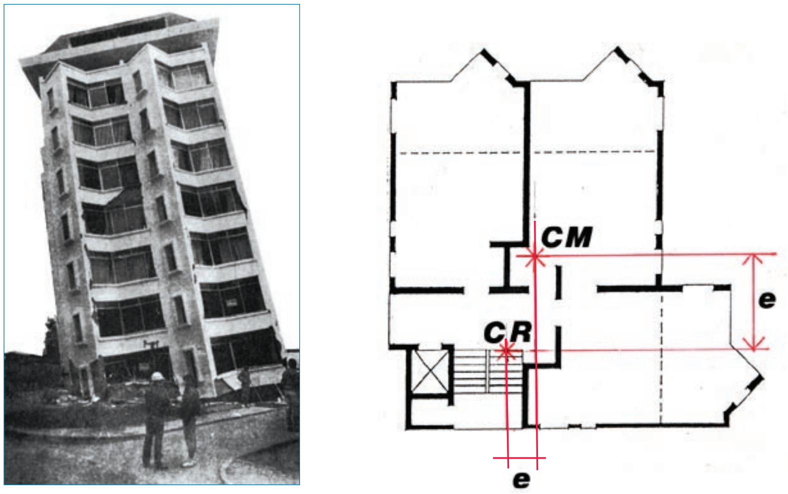


Figure 5-16: Left, the building after the earthquake. Right, typical floor plan showing the Center of Mass (CM), Center of Resistance (CR), and Eccentricity (e) along the two axes. PHOTO SOURCE: EERI

Figure 5-16 shows an apartment house in Viña del Mar, Chile, following the earthquake of 1985. The city is an ocean resort, and beach-front apartments are designed with open frontage facing the beach. This small seven-story condominium building had only three apartments per floor, with the service areas and elevator concentrated to the rear and surrounded by reinforced concrete walls that provided the seismic resistance. The lack of balance in resistance was such that the building rotated around its center of resistance, tilted sharply, and nearly collapsed. The building was subsequently demolished.

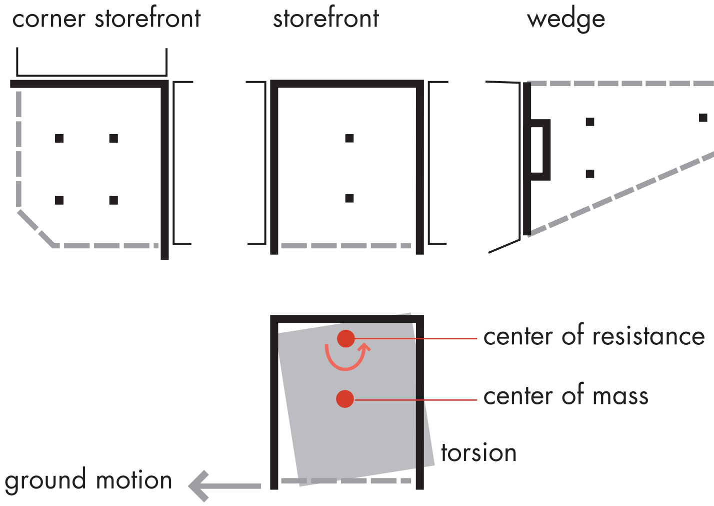


Figure 5-17

Unbalanced perimeter resistance: storefronts and "wedges."

A common instance of an unbalanced perimeter is that of open-front design in buildings, such as fire stations and motor maintenance shops in which it is necessary to provide large doors for the passage of vehicles. Stores, individually or as a group in a shopping mall, are often designed as boxes with three solid sides and an open glazed front (Figure 5-17).

The large imbalance in perimeter strength and stiffness results in large torsional forces. Large buildings, such as department stores, that have unbalanced resistance on a number of floors to provide large window areas for display are also common. A classic case of damage to a large store with an unbalanced-perimeter resistance condition was that of the Penney's store in the Alaska earthquake of 1964 (Figure 5-18).

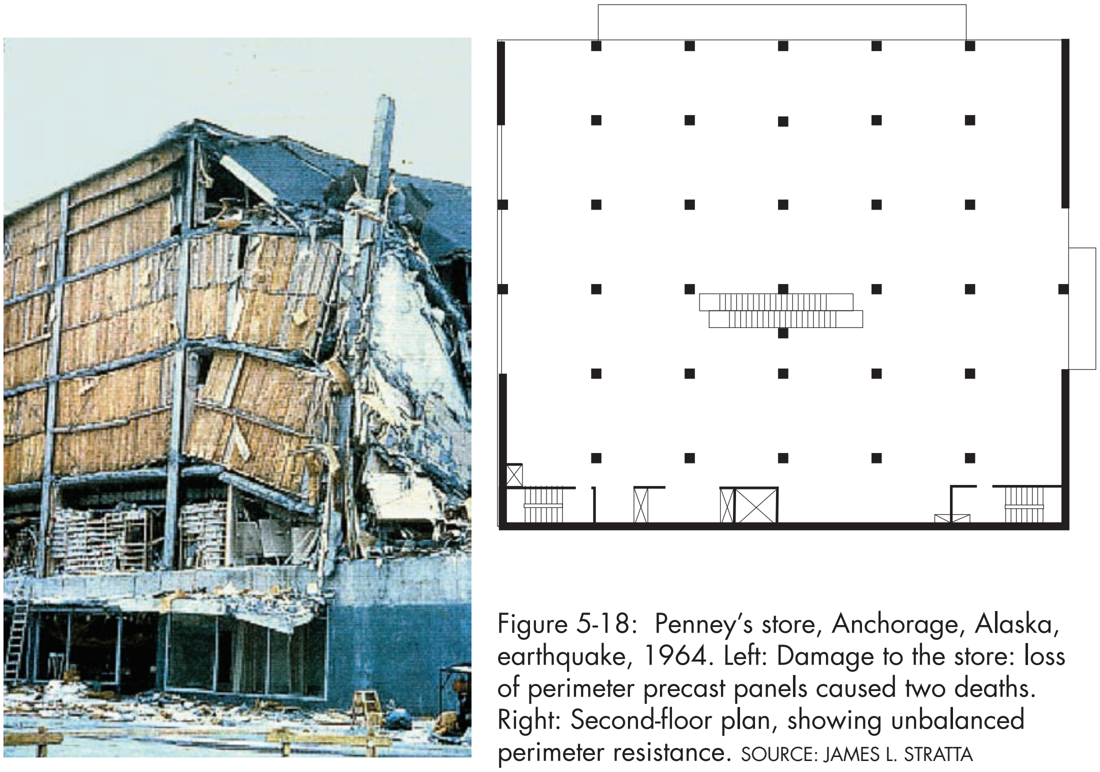


Figure 5-18: Penney's store, Anchorage, Alaska, earthquake, 1964. Left: Damage to the store: loss of perimeter precast panels caused two deaths. Right: Second-floor plan, showing unbalanced perimeter resistance. SOURCE: JAMES L. STRATTA

Solutions

The solution to this problem is to reduce the possibility of torsion by endeavoring to balance the resistance around the perimeter. The example shown is that of the store front. A number of alternative design strategies can be employed that could also be used for the other building type conditions noted (Figure 5-19).

The first strategy is to design a frame structure of approximately equal strength and stiffness for the entire perimeter. The opaque portion of the perimeter can be constructed of nonstructural cladding, designed so that it does not affect the seismic performance of the frame. This can be done either by using lightweight cladding or by ensuring that heavy materials, such as concrete or masonry, are isolated from the frame (Figure 5-19A).

A second approach is to increase the stiffness of the open facades by adding sufficient shear walls, at or near the open face, designed to approach the resistance provided by the other walls (Figure 5-19B).

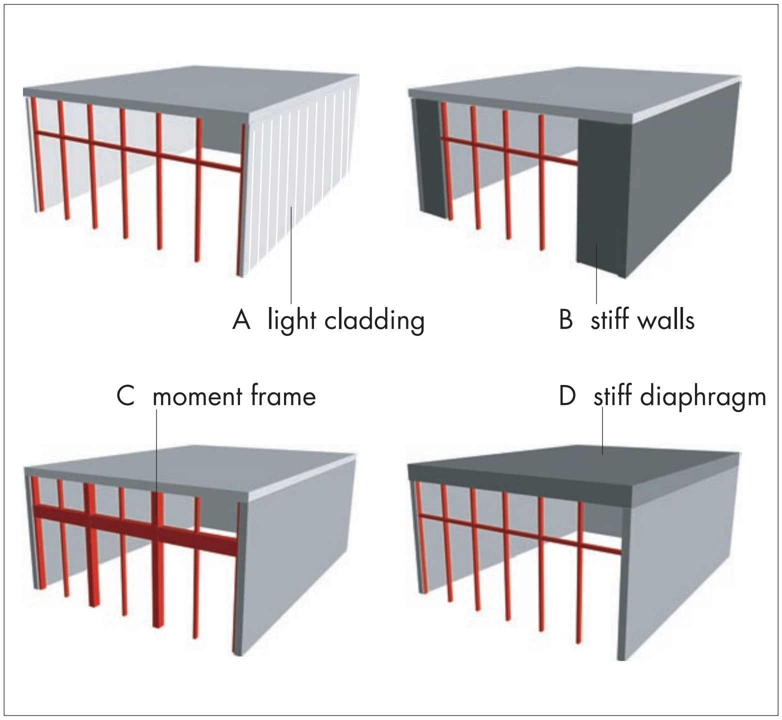


Figure 5-19

Some solutions to store-front type unbalanced-perimeter-resistance conditions

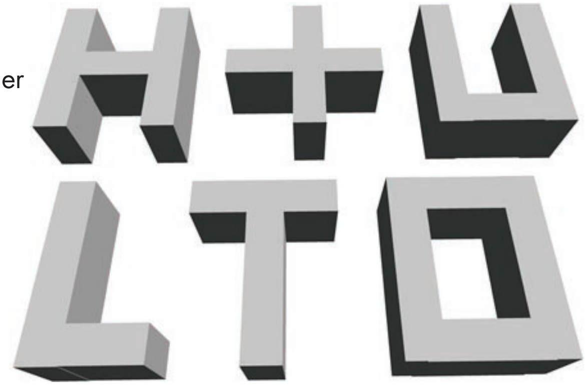
A third solution is to use a strong moment resisting or braced frame at the open front, which approaches the solid wall in stiffness. The ability to do this will depend on the size of the facades; a long steel frame can never approach a long concrete wall in stiffness. This is, however, a good solution for wood frame structures, such as small apartment buildings, or motels with ground floor garage areas, or small store fronts, because even a comparatively long steel frame can be made as stiff as plywood shear walls (Figure 5-19C).

The possibility of torsion may be accepted and the structure designed to have the capacity to resist it, through a combination of moment frames, shear walls,) and diaphragm action. This solution will apply only to relatively small structures with stiff diaphragms designed in such a way that they can accommodate considerable eccentric loading (Figure 5-19D).

Manufacturers have recently produced prefabricated metal shear walls, with high shear values, that can be incorporated in residential wood frame structures to solve the house-over-garage problem.

Figure 5-20

Re-entrant corner plan forms.



5.5.4 Re-entrant Corners (Code Type Irregularitiy H5)

● The problem and the types of condition

The re-entrant corner is the common characteristic of building forms that, in plan, assume the shape of an L, T, H, etc., or a combination of these shapes (Figure 5-20).

There are two problems created by these shapes. The first is that they tend to produce differential motions between different wings of the building that, because of stiff elements that tend to be located in this region, result in local stress concentrations at the re-entrant corner, or "notch."

The second problem of this form is torsion. Which is caused because the center of mass and the center of rigidity in this form cannot geometrically coincide for all possible earthquake directions. The result is rotation. The resulting forces are very difficult to analyze and predict. Figure 5-21 shows the problems with the re-entrant-corner form. The stress concentration at the "notch" and the torsional effects are interrelated. The magnitude of the forces and the severity of the problems will depend on:

- ❍ The characteristics of the ground motion
- ❍ The mass of the building
- ❍ The type of structural systems

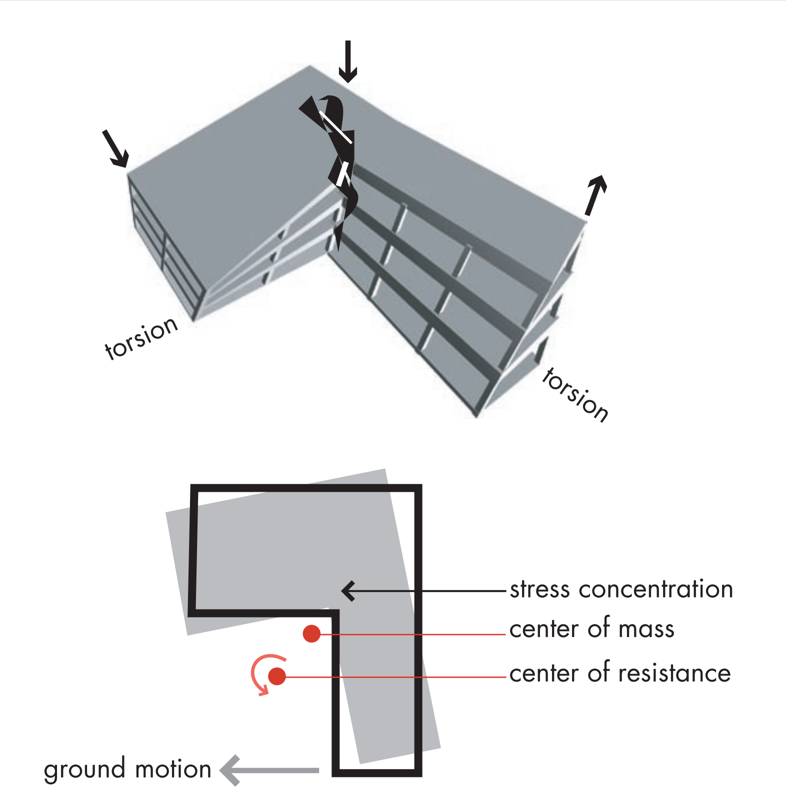


Figure 5-21

Re-entrant corner plan forms.

- The length of the wings and their aspect ratios (length to width proportion)
- The height of the wings and their height/depth ratios

Figure 5-22 shows West Anchorage High School, Alaska, after the 1964 earthquake. The photo shows damage to the notch of this splayed L-shape building. Note that the heavy walls have attracted large forces. A short column effect is visible at the column between the two bottom windows which have suffered classic X –shaped shear-failure cracking and the damage at the top where this highly stressed region has been weakened by the insertion of windows.

Re-entrant corner plan forms are a most useful set of building shapes for urban sites, particularly for residential apartments and hotels, which enable large plan areas to be accommodated in relatively compact form, yet still provide a high percentage of perimeter rooms with access to air and light.

Figure 5-22: West Anchorage High School, Alaska earthquake, 1964. Stress concentration at the notch of this shallow L-shaped building damaged the concrete roof diaphragm.

SOURCE: NATIONAL INFORMATION SERVICE FOR EARTHQUAKE ENGINEERING, UNIVERSITY OF CALIFORNIA, BERKELEY.

These configurations are so common and familiar that the fact that they represent one of the most difficult problem areas in seismic design may seem surprising. Examples of damage to re-entrant-corner type buildings are common, and this problem was one of the first to be identified by observers.

The courtyard form, most appropriate for hotels and apartment houses in tight urban sites, has always been useful; in its most modern form, the courtyard sometimes becomes a glass-enclosed atrium, but the structural form is the same.

● Solutions

There are two basic alternative approaches to the problem of re-entrant-corner forms: structurally to separate the building into simpler shapes, or to tie the building together more strongly with elements positioned to provide a more balanced resistance (Figure 5-23). The latter solution applies only to smaller buildings.

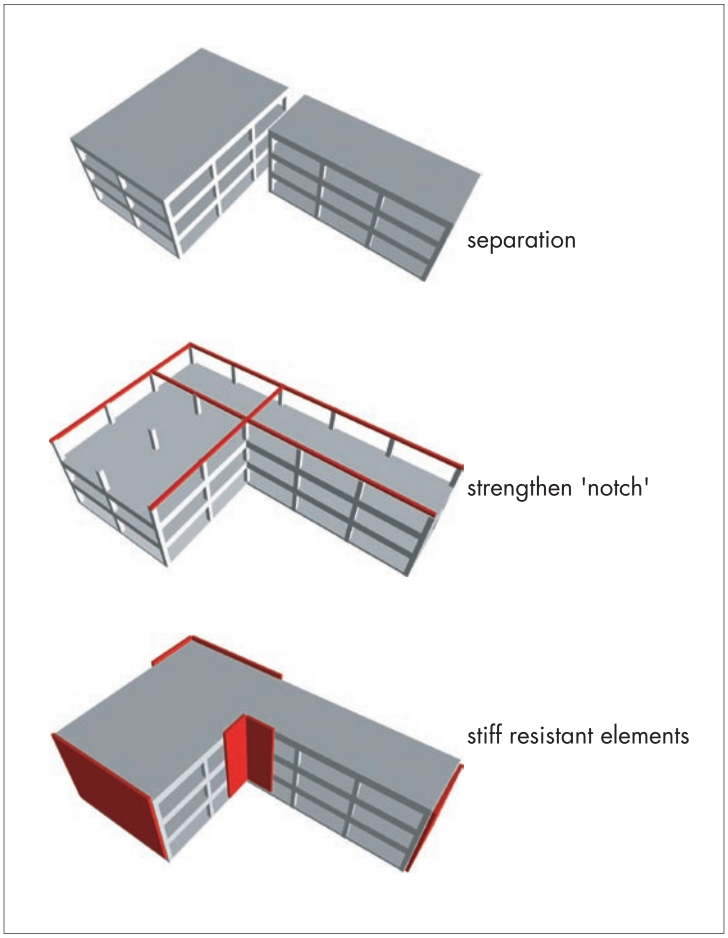


Figure 5-23

Solutions for the re-entrant-corner condition.

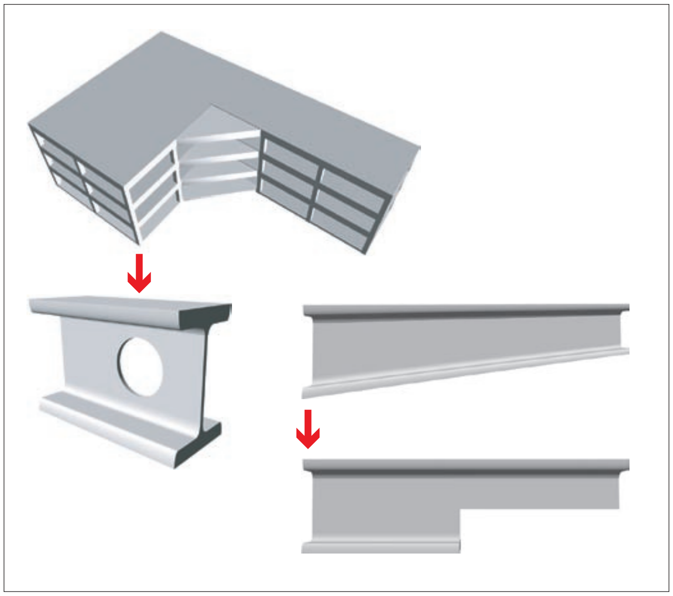
Once the decision is made to use separation joints, they must be designed and constructed correctly to achieve the original intent. Structurally separated entities of a building must be fully capable of resisting vertical and lateral forces on their own, and their individual configurations must be balanced horizontally and vertically.

To design a separation joint, the maximum drift of the two units must be calculated by the structural consultant. The worst case is when the two individual structures would lean toward each other simultaneously; and hence the sum of the dimension of the separation space must allow for the sum of the building deflections.

Several considerations arise if it is decided to dispense with the separation joint and tie the building together. Collectors at the intersection

Figure 5-24

Relieving the stress on a re-entrant corner by using a splay.



can transfer forces across the intersection area, but only if the design allows for these beam-like members to extend straight across without interruption. If they can be accommodated, full-height continuous walls in the same locations are even more effective. Since the portion of the wing which typically distorts the most is the free end, it is desirable to place stiffening elements at that location.

The use of splayed rather than right angle re-entrant corners lessens the stress concentration at the notch (Figure 5-24). This is analogous to the way a rounded hole in a steel plate creates less stress concentration than a rectangular hole, or the way a tapered beam is structurally more desirable than an abruptly notched one.

5.6 OTHER ARCHITECTURAL/STRUCTURAL ISSUES

5.6.1 Overturning: Why Buildings Fall Down, Not Over

Although building mass or weight was discussed as part of the F = MA equation for determining the horizontal forces, there is another way in which the building's weight may act under earthquake forces to overload the building and cause damage or even collapse.

Vertical members such as columns or walls may fail by buckling when the mass of the building exerts its gravity force on a member distorted or moved out of plumb by the lateral forces. This phenomenon is known by engineers as the **P-e** or **P-delta** effect, where P is the gravity force or weight, and "e" or "delta" is the eccentricity or the extent to which the force is offset. All objects that overturn do so as a result of this phenomenon (Figure 5-25).

The geometrical proportions of the building also may have a great influence on whether the P-delta effect will pose a problem, since a tall, slender building is much more likely to be subject to overturning forces than a low, squat one. It should be noted, however, that if the lateral resistance is provided by shear walls, it is the proportions of the shear walls that are significant rather than those of the building as a whole.

However, in earthquakes, buildings seldom overturn, because structures are not homogeneous but rather are composed of many elements connected together; the earthquake forces will pull the components apart, and the building will fall down, not over. Strong, homogeneous structures such as filing cabinets, however, will fall over. A rare example of a large steel-frame building collapse is that of the Piño Suarez apartments in the Mexico City earthquake of 1985. Of the three nearly identical buildings, one collapsed, one was severely damaged, and the third

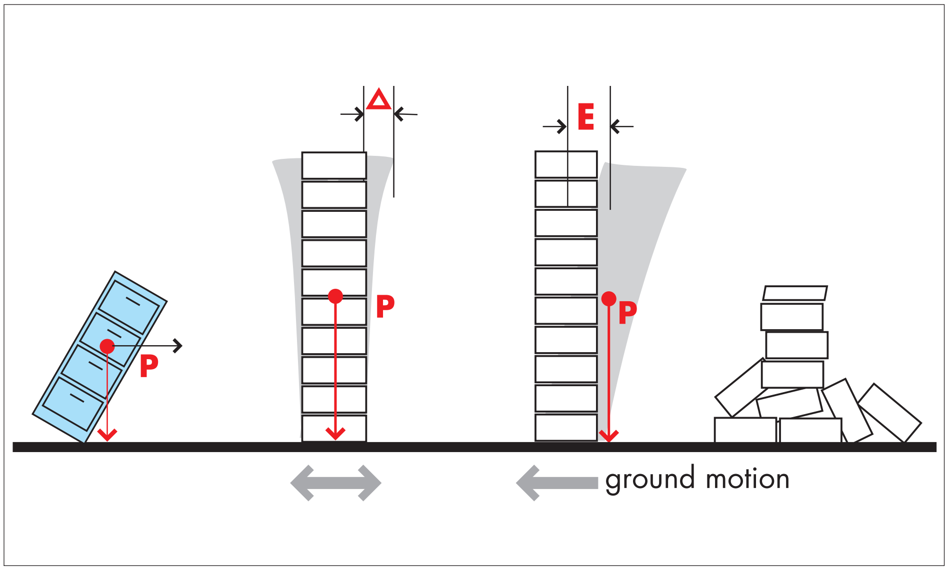


Figure 5-25

Why buildings generally fall down, not over.

Figure 5-26

Piño Suarez apartments, Mexico City, 1985.

SOURCE: NIST

suffered moderate damage. The structures had asymmetrical lateral bracing at their perimeters, and the steel frames were poorly detailed and buckled (Figure 5-26).

The collapse of the Cypress Freeway in Oakland, California, in the Loma Prieta earthquake (though a viaduct rather than building) was a rare example of a low-rise structural collapse (Figure 5-27),

5.6.2 Perforated Shear Walls

Another undesirable condition is when a shear wall is perforated by aligned openings for doors , windows and the like, so that its integrity may be compromised. Careful analysis is necessary to ensure that a continuous load path remains without a significant loss of horizontal shear capacity. Some types of perforated shear wall with unaligned openings have performed well (Figure 5-28).

Figure 5-27

Collapse of large two-story section of the Cypress Freeway, San Francisco, Loma Prieta earthquake, 1989.

Figure 5-28

Shear wall perforated by large opening (at bottom right-hand corner).

5.6.3 Strong Beam, Weak Column

Structures are commonly designed so that under severe shaking, the beams will fail before the columns. This reduces the possibility of complete collapse. The short-column effect, discussed in Section 4.10.2, is analogous to a weak-column strong-beam condition, which is sometimes produced inadvertently when strong or stiff nonstructural spandrel members are inserted between columns. The parking structure shown in Figure 5-29 suffered strong-beam weak-column failure in the Whittier, California, earthquake of 1987.

5.6.4 Setbacks and Planes of Weakness

Vertical setbacks can introduce discontinuities, particularly if columns or walls are offset at the plane of the setback. A horizontal plane of weakness can be created by the placement of windows or other openings that may lead to failure, as in this building in the Kobe, Japan, earthquake of 1995 (Figure 5-30).

Figure 5-29: Damaged parking structure, Whittier Narrows (Los Angeles) earthquake, 1987. The deep spandrels create a strong-beam, weak-column condition.

5.7 IRREGULAR CONFIGURATIONS: A TWENTIETH CENTURY PROBLEM

The foregoing discussion has identified "irregular" architectural/structural forms that can contribute to building damage or even collapse. These irregularities are present in many existing buildings, and the ways in which they affect seismic performance need to be understood by building designers so that dangerous conditions are not created. The ir-

Figure 5-30

Damaged building, Kobe earthquake, Japan, 1995.

regular-configuration problem was made possible by nineteenth-century structural technology and created by twentieth-century architectural design.

5.7.1 A New Vernacular: the International Style and its Seismic Implications

The innovation of the steel and reinforced concrete frame at the end of the nineteenth century enabled buildings to be freed from the restrictions imposed by load-bearing masonry. However, until the early years of the twentieth century, western architectural design culture dictated a historical style even when totally new building types, such as railroad stations or skyscrapers, were conceived. The architectural forms used were all derived from the engineering imperatives of load-bearing masonry structure: these masonry-devised forms survived well into the twentieth century, even when buildings were supported by concealed steel frames, and arches had become stylistic decoration (Figure 5-31).

Figure 5-31

Early twentieth-century steel-frame buildings, Michigan Avenue, Chicago.

This historicism came under attack early in the century from a number of avant-garde architects, predominantly in Europe, who preached an anti-historical dogma in support of an architecture that they believed more fully represented the aspirations and technology of a new age. Later, this movement was termed the **International Style**.

This revolution in architectural aesthetics had many dimensions: aesthetic, technical, economic and political. One result was to give aesthetic validity to a highly economical, unadorned, rectilinear box for almost all building functions. The international style preached the aesthetic enjoyment of the delicacy and slenderness that the steel or concrete frame structure had made possible.

The prototype of the international style was exemplified in the Pavillon Suisse in Paris in 1930 (Figure 5-32).

Figure 5-32

The Pavillon Suisse, Le Corbusier, Paris, 1930: elevated on pilotis, use of a free plan, and curtain walls.

As architects and engineers began to exploit the aesthetics of the building frame, the seeds of seismic configuration problems were sown. In its earliest forms the style frequently created buildings that were close to our ideal seismic building configuration. However, the style often had a number of characteristics not present in earlier frame and masonry buildings that led to poor seismic performance. These were:

❍ Elevation of the building on stilts or pilotis

  This had attractive functional characteristics, such as the ability to introduce car parking under the building, or the building could be opened to the public and its visitors in ways that were not previously possible. It was attractive aesthetically: the building could appear to float airily above the ground.

  However, without full understanding of the seismic implications of vertical structural discontinuity, designers often created soft and weak stories.

- The free plan and elimination of interior-load bearing walls

  Planning freedom was functionally efficient and aesthetically opened up new possibilities of light and space.

  However, the replacement of masonry and tile partitions by frame and gypsum board greatly reduced the energy absorption capability of the building and increased its drift, leading to greater nonstructural damage and possible structural failure.

- The great increase in exterior glazing and the invention of the lightweight curtain wall

  The curtain wall was a significant feature of the new vernacular and was subject to continuous development and refinement. At one end, it became the most economical method of creating an exterior façade; at the other end it led to the apparently frameless glass walls and double-skin energy-efficient curtain walls of today. Like free interior planning, the light exterior cladding greatly reduced the energy-absorption capability of the building and increased its drift.

The post-World War II years saw worldwide explosive urban development, and the new aesthetic, because of its lack of ornamentation, simple forms, and emphasis on minimal structure, was very economical. This ensured its widespread adoption. Unfortunately, seismic design, particularly the need for ductility - as it related to the new, spare, framed buildings - was inadequately understood. Thus the aesthetics and economies of the international style in vogue from about the 50's to the 70's has left the world's cities with a legacy of poor seismic configurations that presents a serious problem in reducing the earthquake threat to our towns and cities.

Configuration irregularities often arise for sound planning or urban design reasons and are not necessarily the result of the designer's whim (or ignorance). The problem irregularities shown in Figures 5-5 and 5-6 represent structural/architectural errors that originate in the architectural design as the result of a perceived functional or aesthetic need. The errors can be avoided through design ingenuity, and mutual understanding and a willingness to negotiate design issues between the architect and engineer. The architect needs to understand the possible implications of the design, and the engineer needs to embrace the design objectives and participate in them creatively.

5.8 DESIGNING FOR PROBLEM AVOIDANCE

Regardless of building type, size, or function, it is clear that the attempt to encourage or enforce the use of regular configurations is frequently not going to succeed; the architect's search for original forms is very powerful. The evolution and recent trends in formal invention are shown in Figure 5-38 in Section 5.9.2.

The seismic code, as illustrated in Figures 5-5 and 5-6, is oriented towards "everyday" economical building and goes a modest route of imposing limited penalties on the use of irregular configurations in the form of increased design forces and, for larger buildings, the use of more advanced analytical methods; both these measures translate into cost penalties Only two irregularities are banned outright: extreme soft stories and extreme torsion in essential buildings in high seismic zones. This suggests a strategy that exploits the benefits of the "ideal" configuration but permits the architect to use irregular forms when they suit the design intentions.

5.8.1 Use of Regular Configurations

A design that has attributes of the ideal configuration should be used when:

- The most economical design and construction is needed, including design and analysis for code conformance, simplicity of seismic detailing, and repetition of structural component sizes and placement conditions.
- When best seismic performance for lowest cost is needed.
- When maximum predictability of seismic performance is desired.

5.8.2 Designs for Irregular Configurations

When the design incorporates a number of irregularities the following procedures should be used:

- A skilled seismic engineer who is sympathetic to the architect's design intentions should be employed as a co-designer from the outset of the design.

- The architect should be aware of the implications of design irregularities and should have a feel for the likelihood of stress concentrations and torsional effects (both the cause and remedy of these conditions lie in the architectural/structural design, not in code provisions).
- The architect should be prepared to accept structural forms or assemblies (such as increased size of columns and beams) that may modify the design character, and should be prepared to exploit these as part of the aesthetic language of the design rather than resisting them.
- The architect and engineer should both employ ingenuity and imagination of their respective disciplines to reduce the effect of irregularities, or to achieve desired aesthetic qualities without compromising structural integrity.
- Extreme irregularities may require extreme engineering solutions; these may be costly, but it is likely that a building with these conditions will be unusual and important enough to justify additional costs in materials, finishes, and systems.
- A soft or weak story should never be used: this does not mean that high stories or varied story heights cannot be used, but rather that appropriate structural measures be taken to ensure balanced resistance.

5.9 BEYOND THE INTERNATIONAL STYLE: TOWARDS A SEISMIC ARCHITECTURE?

Most owners desire an economical and unobtrusive building that will satisfy the local planning department and look nice but not unusual. However, as noted above, the occasional aspiration for the architect to provide a distinctive image for the building is very powerful and is the source of continued evolution in architectural style and art. This thrust is allied to today's "marketing" demand for spectacular forms. The history of architecture shows that design innovation has its own life, fed by brilliant form-givers who provide prototypes that keep architecture alive and exciting as an art form. Thus, like economics, architectural design has its "supply- and demand-sides" that each reinforce one another.

The International Style still exists as a vernacular and can range from everyday economical buildings to refined symbols of prestige. But there are now many competing personal styles. Have the tenets of good seismic design played any role in determining their characteristics? Is it possible that future architectural stylistic trends might seek inspiration in seismic design as an aesthetic that matches the exigencies of physics and engineering with visual grace and intrigue?

5.9.1 The Architect's Search for Forms – Symbolic and Metaphorical

The aesthetic tenets of the International Style—particularly the metal/glass cubistic building—began to be seriously questioned by the mid-1970s. This questioning finally bore fruit in an architectural style known broadly as post-modern. Among other characteristics, post-modernism embraced:

- The use of classical forms, such as arches, decorative columns, pitched roofs in nonstructural ways and generally in simplified variations of the original elements
- The revival of surface decoration on buildings
- A return to symmetry in configuration

In seismic terms, these changes in style were, if anything, beneficial. The return to classical forms and symmetry tended to result in regular structural/architectural configurations, and almost all of the decora-

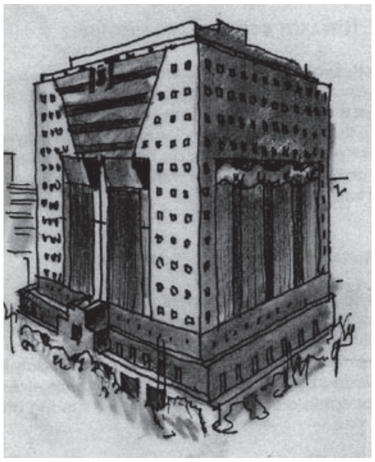


Figure 5-33

Portland Building, Portland, OR.
Architect: Michael Graves, 1982.

tive elements were nonstructural. An early icon of post-modernism, the Portland, Oregon, office building, designed by Michael Graves (Figure 5-33) used an extremely simple and conservative structural system. Indeed, this building, which created a sensation when completed, has a structural/architectural configuration that is similar to the model shown in Figure 5-33. The sensation was all in the nonstructural surface treatments, some proposed exterior statues, and in its colors.

A conventionally engineered steel or concrete member that was supporting the building could be found inside every classical post-modern column. It is clear that an interest in seismic design or structure in general had no influence on the development of post-modernism; it was strictly an aesthetic and cultural movement.

At the same time that post-modernism was making historical architectural style legitimate again, another style began to flourish, to some extent in complete opposition. This style (originally christened “hi-tech”) returned to the celebration of engineering and new industrial techniques and materials as the stuff of architecture. This style originated primarily in Europe, notably in England and France, and the influence of a few seminal works, such as the Pompidou Center in Paris (Figure 5-34).

Although seismic concerns had no influence on the origin and development of this style, it is relevant here because it revived an interest in exposing and celebrating structure as an aesthetic motif.

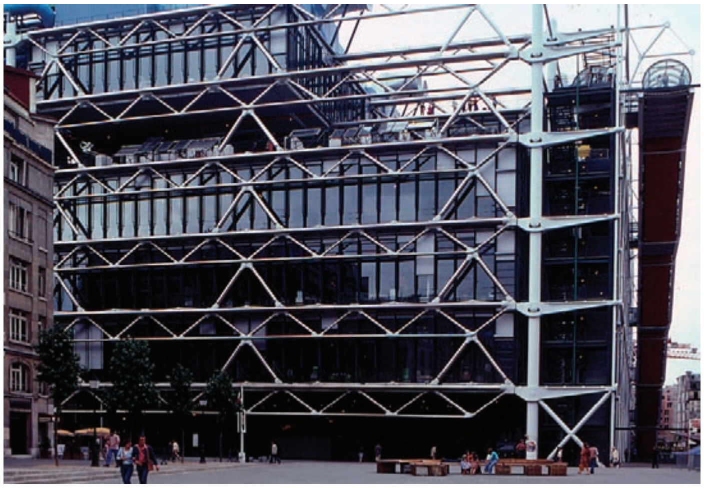


Figure 5-34

Pompidou Center, Paris, Architect: Piano and Rogers, 1976.

Post-modernism died a quick death as an avant-garde style, but it was important because it legitimized the use of exterior decoration and classically derived forms. These became common in commercial and institutional architecture (Figure 5-35). The notion of "decorating" the economical cube with inexpensive simplified historic or idiosyncratic nonstructural elements has become commonplace.

Figure 5-35

Post-modern influences, 2000.

At the same time, in much everyday commercial architecture, evolved forms of the International Style still predominate, to some extent also representing simplified (and more economical) forms of the high-tech style. Use of new lightweight materials such as glass fiber-reinforced concrete and metal-faced insulated panels has a beneficial effect in reducing earthquake forces on the building, though provision must be made for the effects of increased drift on nonstructural components or energy-dissipating devices used to control it.

5.9.2 New Architectural Prototypes Today

The importance of well-publicized designs by fashionable architects is that they create new prototypical forms. Architects are very responsive to form and design, and once a new idiom gains credence, practicing architects the world over begin to reproduce it. Today's New York corporate headquarters high-rise becomes tomorrow's suburban savings and loan office, as shown in Figures 5-36 and 5-37.

Today, however, unlike the era of the International Style and the adoption of "modern" architecture, there is no consensus on a set of appropriate forms. At present, spectacular architectural design is in fashion

gure 5-36

nited Nations Secretariat, New York,
rchitects: Wallace Harrison, Le Corbusier,
Oscar Niemeyer, and Sven Markelius, 1950.

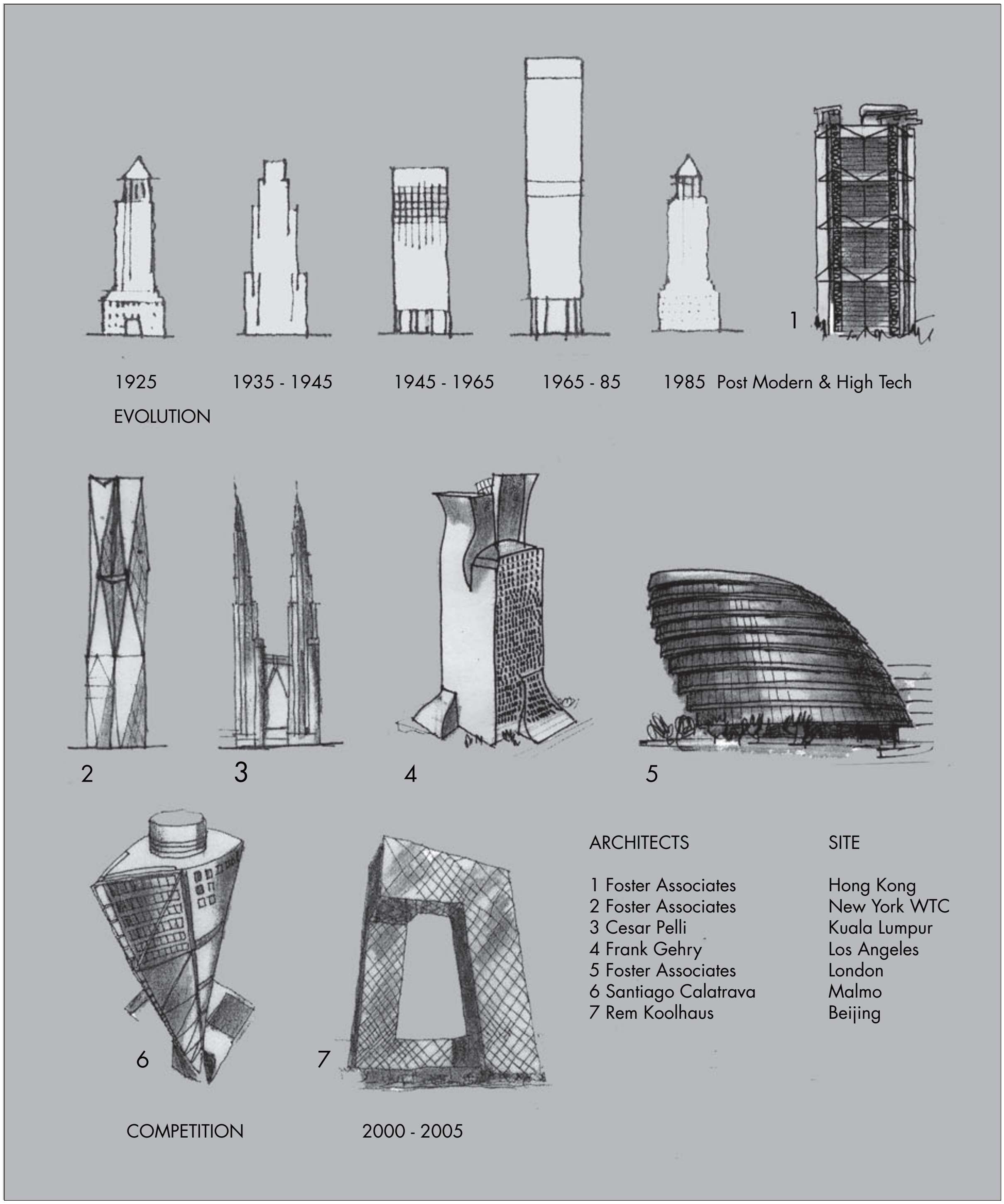
and sought after by municipalities, major corporations, and institutions. So, it is useful to look at today's cutting-edge architecture, because among it will be found the prototypes of the vernacular forms of the future.

Figure 5-38 shows the evolution of the architectural form of the high-rise building from the 1920s to today. There is a steady evolution in which the international style dominates the scenes from about 1945 to 1985. For a brief interlude, post-modern architecture is fashionable, in company with "high-tech." Towards the end of the century, architec-

Figure 5-37

Main street vernacular, anywhere, USA.

Figure 5-38: The evolution of high-rise building form. The twentieth century was a period of evolution.



ARCHITECTS	SITE
1 Foster Associates	Hong Kong
2 Foster Associates	New York WTC
3 Cesar Pelli	Kuala Lumpur
4 Frank Gehry	Los Angeles
5 Foster Associates	London
6 Santiago Calatrava	Malmo
7 Rem Koolhaus	Beijing

The first five years of the 21st century are a period of competition.

tural forms become more personal and idiosyncratic, and evolution is replaced by competition. The first five years of the millenium have seen the emergence of a number of very personal styles, from the jagged forms of Liebskind to the warped surfaces of Gehry. The Foster office in London pursues its own in-house evolution of high-tech design.

In general, today's high-rise buildings remain vertical, and have direct load paths, and their exterior walls are reasonably planar. Some high-rise towers have achieved a modest non-verticality by the use of nonstructural components. A more recent development is that of the "torqued" tower, as in the Freedom Tower at the World Trade Center and Santiago Calatrava's "Turning Torso" tower in Malmo, Sweden, shown in Figure 5-38. For very tall buildings, it is claimed that these twisted forms play a role in reducing wind forces, besides their visual appeal, but their forms are not of significance seismically.

In lower buildings, where there is more freedom to invent forms than in the high rise, planning irregularities (and corresponding three-dimensional forms) are now fashionable that go far beyond the irregularities shown in Figure 5-6. Figure 5-39 shows the extraordinary range of plan forms for art museums conceived by four of today's most influential architects.

Highly fragmented facades now abound, serving as metaphors for the isolated and disconnected elements of modern society. Often-repeated design motifs include segmental, undulating, or barrel-vaulted roofs and canopies, and facades that change arbitrarily from metal and glass curtain wall to punched-in windows.

In all this ferment, there is much originality and imagination, and often high seriousness. It remains to be seen whether any of these forms become attractive to the typical practitioner and their more conservative clients; however, indications of the influence of some of these motifs can now be discerned in more commonplace buildings along the highways and in schools and universities (Figure 5-40).

One may question the extent to which architectural trends look as if they will increase or decrease the kinds of configuration irregularities that manifested themselves in the international style era. The answer appears

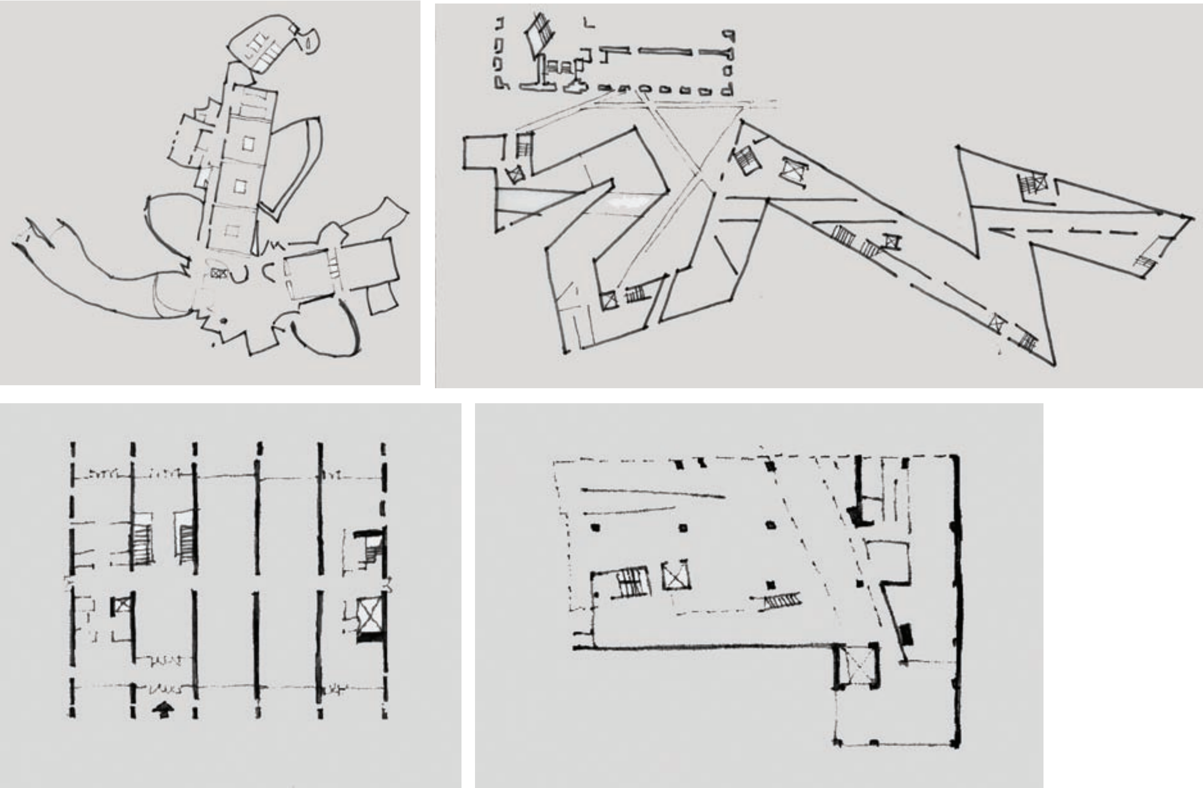


Figure 5-39: Planning variety: four plans of new museums. Top left, Guggenheim Museum, Bilbao, Spain, Architect Frank Gehry, 1998. Top right, Jewish Museum, Berlin, Architect: Daniel Liebskind, 1999. Bottom left, Rosenthal Center for the Arts, Cincinatti, Ohio, Architect: Zaha Hadid 2003, Bottom right, Nasher Sculpture Center, Dallas, Texas ,Architect : Renzo Piano Design Workshop, 2003.

Northern Spain is a low seismic zone. Cincinnati, Berlin, and Dallas are not subject to earthquakes.

Figure 5-40: The influence of prototypes: fragmented facades and tilted walls.

to be that they will increase, because much new architecture is clearly conceived independently of structural concerns or in the spirit of theatrical set design, with the engineer in the role of an enabler rather than collaborator.

5.9.3 Towards an Earthquake Architecture

In the search for meaning in architecture that supersedes the era of International Style and the superficialities of fashion exemplified by much of post-modernism and after, perhaps architects and engineers in the seismic regions of the world might develop an "earthquake architecture". One approach is an architecture that expresses the elements necessary to provide seismic resistance in ways that would be of aesthetic interest and have meaning beyond mere decoration. Another approach is to use the earthquake as a metaphor for design.

5.9.4 Expressing the Lateral-Force Systems

For the low and midrise building, the only structural system that clearly expresses seismic resistance is the use of exposed bracing. There are historical precedents for this in the half-timbered wood structures of medieval Germany and England. This was a direct and simple way of bracing rather than an aesthetic expression, but now these buildings are much prized for their decorative appearance. Indeed, the "half-timbered" style has become widely adopted as an applied decorative element on U.S. architecture, though for the most part at a modest level of residential and commercial design.

Two powerful designs in the 1960s, both in the San Francisco Bay Area, used exposed seismic bracing as a strong aesthetic design motif. These were the Alcoa Office Building and the Oakland Colisem, both designed in the San Francisco office of Skidmore, Owings and Merrill (Figure 5-41).

In spite of these two influential designs and others that used exposed wind bracing, the subsequent general trend was to de-emphasize the presence of lateral-resistance systems. Architects felt that they conflicted with the desire for purity in geometric form, particularly in glass "box" architecture, and also possibly because of a psychological desire to deny the prevalence of earthquakes. However, in the last two decades it has become increasingly acceptable to expose lateral-bracing systems and enjoy their decorative but rational patterns (Figure 5-42).

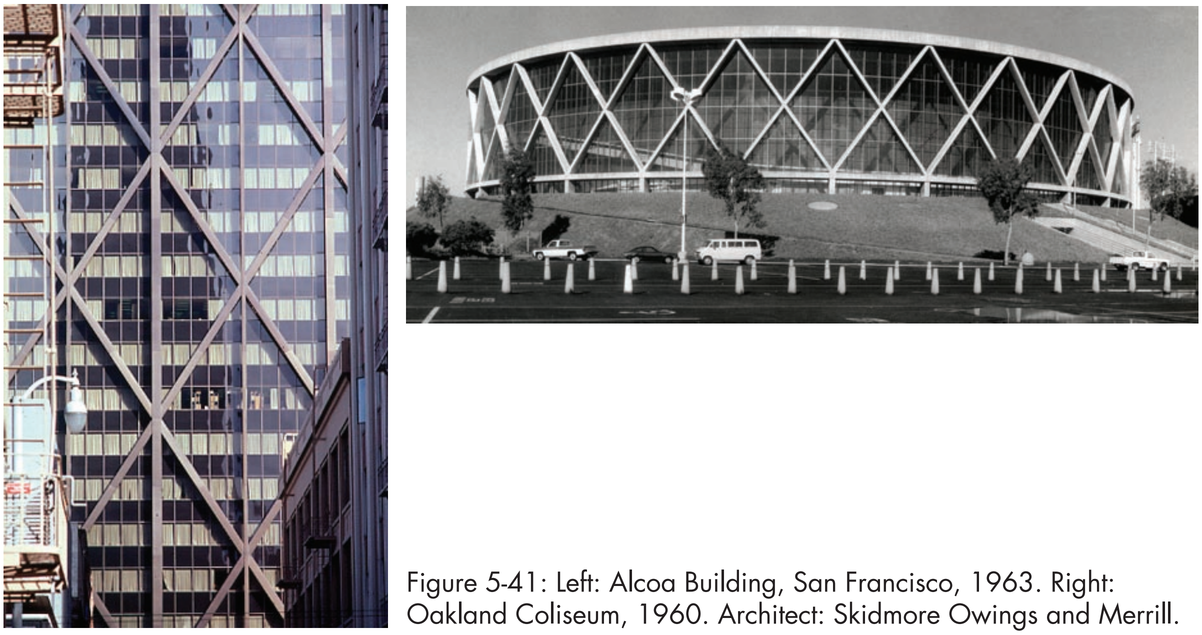


Figure 5-41: Left: Alcoa Building, San Francisco, 1963. Right: Oakland Coliseum, 1960. Architect: Skidmore Owings and Merrill.

Figure 5-42: Exposed cross-bracing examples.

Top left; Pacific Shores Center, Redwood City, CA, Architects DES Architects & Engineers. Top right: Silicon Graphics, Mountain View, Architects: Studios Architects. Bottom left: Sports Arena, San Jose, Architects: Sink, Combs, Dethlefs, (All in California). Bottom right: Government Offices, Wanganui, New Zealand.

Figure 5-43: Left: Retrofitted student residences. Right: University Administration Building, Berkeley California, Architect: Hansen, Murakami and Eshima, Engineers; Degenkolb Engineers.

This new acceptability is probably due to boredom with the glass cube and the desire to find a meaningful way of adding interest to the façade without resorting to the applied decoration of post-modernism. In addition, greater understanding of the earthquake threat has led to realization that exposed bracing may add reassurance rather than alarm.

Exposed bracing is also used as an economical retrofit measure on buildings for which preservation of the façade appearance is not seen as important. A possible advantage of external bracing is that often the building occupants can continue to use the building during the retrofit work, which is a major economic benefit; however, see Chapter 8.5.3.1 for further discussion of this point. External bracing retrofits have also sometimes had the merit of adding visual interest to a number of dull 1960s rectilinear type facades (Figure 5-43).

The movement towards exposed seismic bracing has some parallels with the aesthetic movement of exposing buildings' mechanical systems. Designers who had become bored with expanses of white acoustical ceiling realized that mechanical systems, particularly when color-coded, were of great visual interest and also intrigued those who are fascinated by mechanical systems and devices. Another parallel with seismic design is

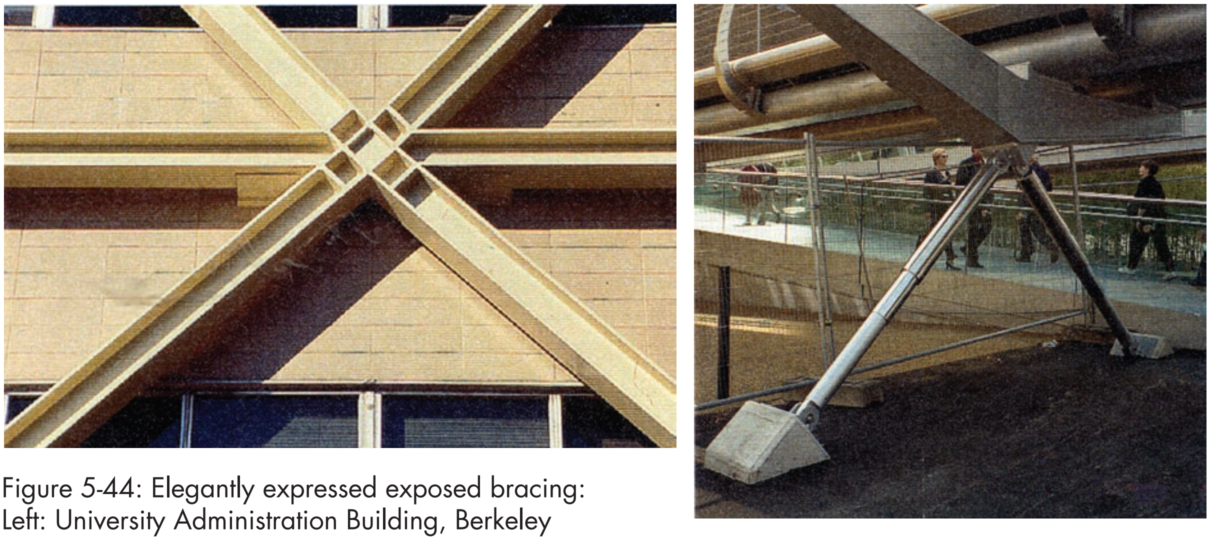


Figure 5-44: Elegantly expressed exposed bracing: Left: University Administration Building, Berkeley California, Architect: Hansen Murakami and Eshima. Right: Millenium Bridge, London, 2000. Architect: Foster Associates; Arup Engineers, Engineer.

that, when mechanical systems were exposed, their layout and detailing had to be much more carefully designed and executed, from an aesthetic viewpoint. In a similar way, exposed bracing has to be more sensitively designed, and this has seen the development of some elegant design and material usage (Figure 5-44).

New innovations, such as base isolation and energy absorbing devices, have sometimes been exploited for aesthetics and reassurance. The designers of an early and ingenious base isolated building in New Zealand (the Union House office building in Auckland) not only exposed its braced-frame, but also made visible its motion-restraint system at its open first-floor plaza (Figure 5-45).

Experiments in linking the rationality of structure to the poetics of form and surface are shown in Figure 5-46, which shows two schemes for advanced systems of perimeter bracing that, if exposed, are perhaps livelier than conventional concealed bracing. The left hand figure shows a 60 story structure with 10 story braced super frame units, restrained by periodic two story moment frame clusters with hydraulic dampers. The right-hand figure shows a 48 story moment frames with random offset toggle hydraulic dampers. The apparent random character of the bracing is based on the load patterns within the structure.

Figure 5-45: Left: Union House, Auckland, New Zealand. Right: detail of energy absorbing system. Architect: Warren and Mahoney; Engineer, Brian Wood

The intent is to exploit an interest in structural expression and its forms, and create a “code” that can be read by anyone that has a sense of how lateral forces operate and must be resisted.

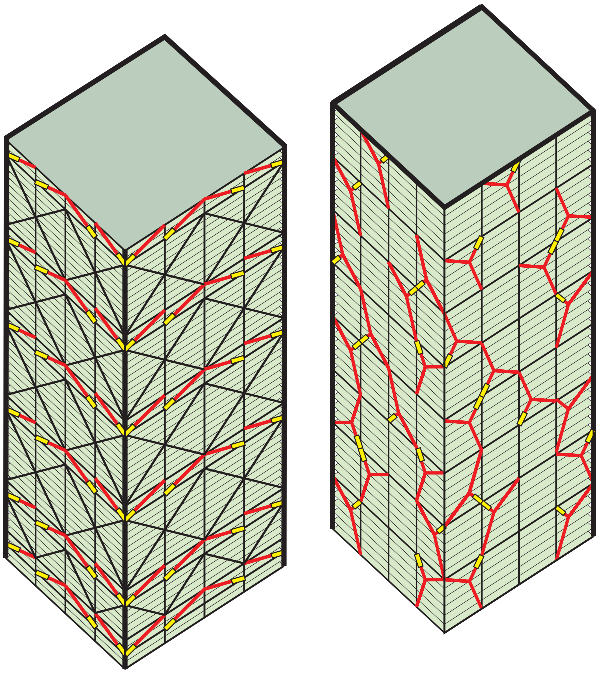


Figure 5-46: Left: 60-story structure with 10 story braced super frame units, restrained by periodic two story moment frame clusters with hydraulic dampers. Right: 48-story moment frames with random offset toggle hydraulic dampers.

5.9.5 The Earthquake as a Metaphor

A more theoretical use of the earthquake as a design inspiration is that of designing a building that reflects the earthquake problem indirectly, as a metaphor. This approach is rare, but has some interesting possibilities for certain building types, such as seismic engineering laboratories.

One of the few executed examples of this approach is the Nunotani Office Building in Tokyo. The architect, Peter Eisenman of New York, says that the building represents a metaphor for the waves of movement as earthquakes periodically compress and expand the plate structure of the region (Figure 5-47).

A listing of ideas for this metaphorical approach has been suggested as part of a student design project at the architecture school, Victoria University, New Zealand (Table 5.1). Figure 5-48 shows a student project in which damage is used as a metaphor, following the example of the Nunotani Building.

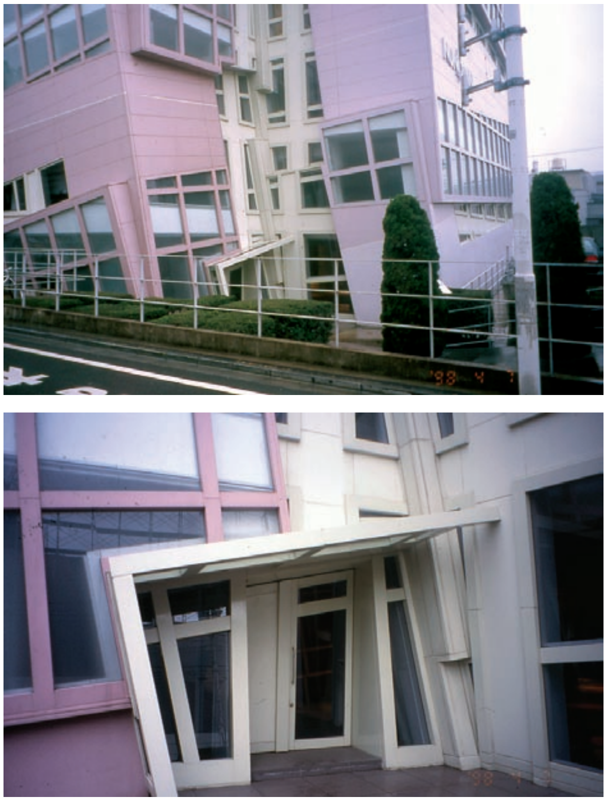


Figure 5-47

Nunotani Office building, Tokyo, Architect: Peter Eisenman 1998

The architect/artist Lebbeus Woods has created imaginary buildings in drawings of extraordinary beauty that explicitly use the representation of seismic forces as a theme (Figure 5-49).

In his project "Radical Reconstruction," Woods was inspired by the 1995 Kobe earthquake to explore the implications of building destruction. Of his many drawings and paintings inspired by San Francisco, Woods has written that these projects "explore the possibilities for an architecture that in its conception, construction and inhabitation comes into new and potentially creative relationships not only with the effects of earthquakes, but more critically with the wider nature of which they are a part."

The expression of seismic resistance and the metaphor of the earthquake could yet provide a rich creative field for a regional architecture that derives at least some of its aesthetic power from the creation of useful and delightful forms that also celebrate the demands of seismic forces and the way they are resisted.

Figure 5-48

Student project, damage as a metaphor.

Designer: L. Allen

Table 5-1: Potential design ideas listed under various headings

Geology & Seismology	Construction Issues	General Concepts or Ideas not Specifically Related to	Other Earthquake Related Items
Seismic waves	Propping	Healing processes such as scabs that form after injury	Temporary buildings for disaster relief
Faulting	Tying elements together	External forces on a building	Seismographs
Earthquake-affected landforms	Post-earthquake ruins	Adaptability	Expression of structural action
Contrast between geologic and seismografic scale	Disassembly	Insecurity	Brittle behavior
	Seismic-resisting technology	Preparedness	Plastic behavior
	Contrast between gravity and lateral load-resisting structure	Engineer & architect relationship	

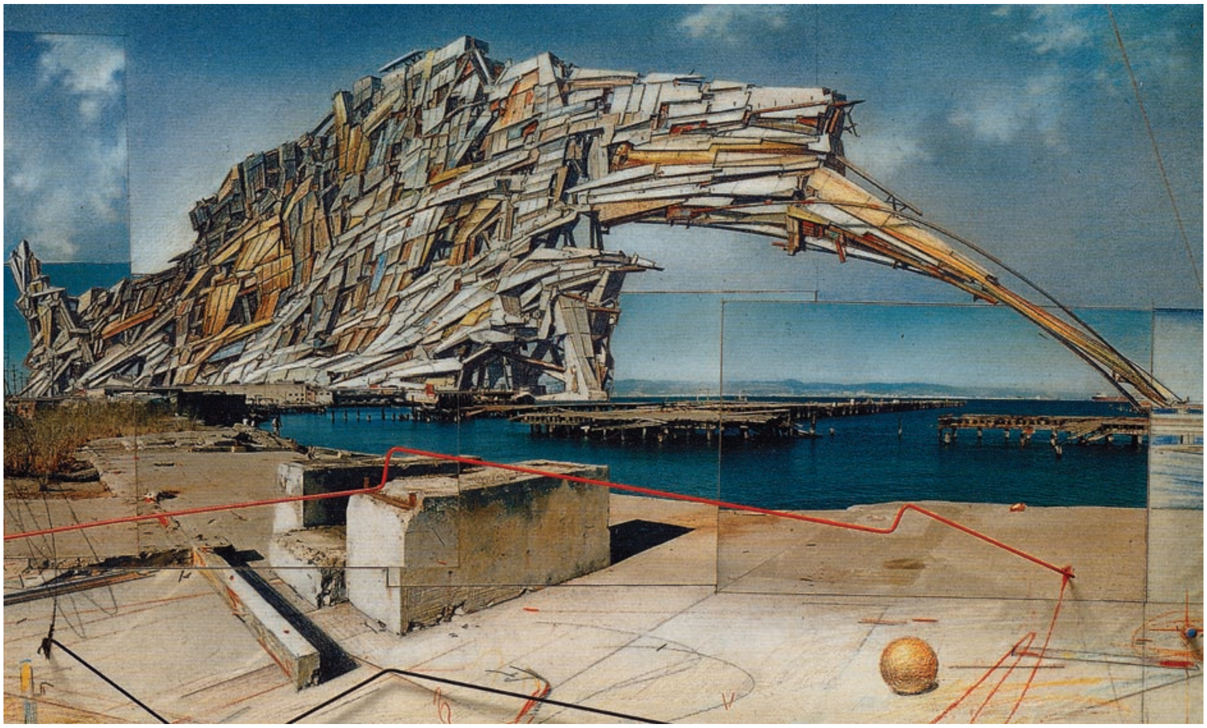


Figure 5-49: Lebbeus Woods: detail of "San Francisco Project: inhabiting the quake WAVE house drawing." 1995. In this theoretical design, "the ball-jointed frames flex and re-flex in the quake: supple metal stems and leaves move in the seismic winds."

SOURCE: LEBBEUS WOODS, *RADICAL RECONSTRUCTUION*, PRINCETON ARCHITECTURAL PRESS, NEW YORK, 1997

5.10 CONCLUSION

This chapter has focused on basic seismic structural systems in relation to architectural configurations, and has looked at architectural design through a seismic "filter." This shows that many common and useful architectural forms are in conflict, with seismic design needs. To resolve these conflicts the architect needs to be more aware of the principles of seismic design, and the engineer needs to realize that architectural configurations are derived from many influences, both functional and aesthetic. The ultimate solution to these conflicts depends on the architect and engineer working together on building design from the outset of the project and engaging in knowledgeable negotiation.

Trends in architectural taste suggest that for the engineer to expect to convince the architect of some of the conventional virtues of seismic design, such as simplicity, symmetry and regularity, is only realistic for projects in which economy and reliable seismic performance are paramount objectives. When the architect and the client are looking for high-style design, the forms will probably be irregular, unsymmetrical, and fragmented. The wise and successful engineer will enjoy the challenges. New methods of analysis will help, but engineers must also continue to develop their own innate feeling for how buildings perform, and be able to visualize the interaction of configuration elements that are quite unfamiliar.

5.11 REFERENCES

Structural Engineers Association of California (SEAOC) *Blue Book*

International Code Council, *International Building Code*, Birmingham AL, 2003

Lebbeus Woods: *Radical Reconstruction*, Princeton Architectural Press, New York, NY, 1997

Andrew Charleson and Mark Taylor: *Earthquake Architecture Explorations, Proceedings*, 13thWorld Conference on Earthquake Engineering, Vancouver, BC 2004

Mark Taylor, Julieanna Preston and Andrew Charleson, *Moments of Resistance*, Archadia Press, Sydney, Australia, 2002

5.12 TO FIND OUT MORE

Christopher Arnold, *Architectural Considerations (chapter 6), The Seismic Design Handbook, Second Edition* (Farzad Naeim, ed.) Kluver Academic Publishers, Norwell, MA 2001

Terence Riley and Guy Nordenson, *Tall Buildings*, The Museum of Modern Art, New York, NY, 2003

Sheila de Vallee, *Architecture for the Future*, Editions Pierre Terrail, Paris, 1996

Maggie Toy, ed. *Reaching for the Sky*, Architectural Design, London, 1995

Yukio Futagawa, ed, *GA Document.* A serial chronicle of modern architecture, A.D.A Edita, Tokyo, published periodically

Garcia, B, (ed.) *Earthquake Architecture*, Loft and HBI an imprint of Harper Collins International, New York, NY, 2000

Sandaker, B. N. and Eggen, A. P. *The Structural Basis of Architecture*, Phaiden Press Ltd., London, 1993