

Chapter 6

Architectural Considerations

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Key words: Configuration, Regular Configurations, Irregular Configurations, Proportion, Setbacks, Plan Density, Perimeter Resistance, Redundancy, Symmetry, Asymmetry, Soft-Stories, Weak Stories, Code Provisions, Plan Irregularities, Elevation Irregularities, Architectural Implications.

Abstract: While the provision of earthquake resistance is accomplished through structural means, the architectural design, and the decisions that create it, play a major role in determining the building's seismic performance. The building architecture must permit as effective a seismic design as possible: at the same time the structure must permit the functional and aesthetic aims of the building to be realized. The three categories are: (1) the building configuration, (2) structurally restrictive detailed architectural design, and (3) Hazardous nonstructural components. This chapter discusses one other issue that bears on the architectural decisions that affect seismic performance: that of the methods by which mutual architectural and engineering seismic design decisions are made during the building design and construction process. This, in turn, leads to some consideration of the architect/engineer relationship as it affects the seismic design problem.

6.1 INTRODUCTION

While the provision of earthquake resistance is accomplished through structural means, the architectural design, and the decisions that create it, play a major role in determining the building's seismic performance. The building architecture must permit as effective a seismic design as possible: at the same time the structure must permit the functional and aesthetic aims of the building to be realized.

The architectural design decisions that influence the building's seismic performance can be grouped into three categories. These categories are not exclusive, and each category of decision may influence the others, but it is useful to structure the decisions in this way because it clarifies the influences and their mutual interactions.

The three categories are:

- **The building configuration:** This is defined as the size, shape and proportions of the three-dimensional form of the building. The terms building concept, or conceptual design, are often also loosely used by architects to identify the configuration, although these terms also refer to architectural characteristics such as internal planning and building organization. Strictly speaking, configuration refers only to the geometrical properties of the building form.
- **Structurally restrictive detailed architectural design:** This refers to the architectural design of building details, such as columns or walls, that may affect the structural detailing in ways that are detrimental to good seismic design practice.
- **Hazardous nonstructural components:** The design of many nonstructural components is the architect's responsibility, and if inadequately designed against seismic forces, they may present a hazard to life. In addition, they may represent a major cause of property loss, and in the case of essential facilities or

other services, their damage may cause loss of building function. Engineering issues in the design of these components are dealt with in Chapter 14.

This chapter discusses one other issue that bears on the architectural decisions that affect seismic performance: that of the methods by which mutual architectural and engineering seismic design decisions are made during the building design and construction process. This, in turn, leads to some consideration of the architect/engineer relationship as it affects the seismic design problem.

6.2 CONFIGURATION CHARACTERISTICS AND THEIR EFFECTS

6.2.1 Configuration Defined

For our purposes building configuration can be defined as building size and shape: the latter includes the characteristic of proportion. In addition, our definition includes the nature, size and location of the structural elements, because these are often determined by the architectural design of the building, and are a subject of mutual agreement between architect and engineer. This extended definition of configuration is necessary because of the interaction of these elements in determining the seismic performance of the building.

In addition, architectural decisions may influence the nature, size and location of nonstructural components that may affect structural performance, either by altering the stiffness of structural members or changing the mass distribution in the building. These elements are generally part of the initial concept of the building but they may be added later, when the building is in operation. This particularly applies to in-fill walls, which may have a dramatic effect on the effective height, stiffness, and load distribution of columns. In this chapter they are discussed later as separate

issues, apart from their relationship to configuration. These include such elements as walls, columns, service cores, and staircases, and also the quantity and type of the exterior wall elements.

6.2.2 Origins and Determinants of Configuration

The building configuration, or concept, is influenced by three main factors:

- urban design, business and real estate issues.
- planning and functional concerns.
- image and style

The selected configuration is the result of a decision process that balances these varying requirements and influences and, within a budget, resolves conflicts into an architectural concept. In very general terms three basic categories of architecture can be distinguished based on their main objective:

- **Economical containers** -the "decorated shed": warehouses, industrial plants, some department stores and commercial buildings
- **Problem/solving, functional facility** -

hospitals, educational, laboratories, residential,

- **Prestigious and/or high-style image** - corporate headquarters, some public buildings and university buildings, museums, entertainment, and some retail stores.

These categories also bear some relationship to the architects, or firms, that design them, for there is much covert specialization in architecture. This can cause client confusion: when the client who wants an economical container goes to a prestige architect, or when the client with a difficult planning problem goes to the container architect.

Building function and planning produce a demand for certain settings and kinds of space division, connected by a circulation pattern for the movement of people, supplies, and equipment. These demands ultimately lead to certain building arrangements, dimensions and determinants of configuration.

Urban design and planning requirements may affect the exterior form of the building. A height limit may set a certain maximum height; the street pattern may, particularly in a dense urban situation, determine the plan shape of the building, at least for its lower floors. City

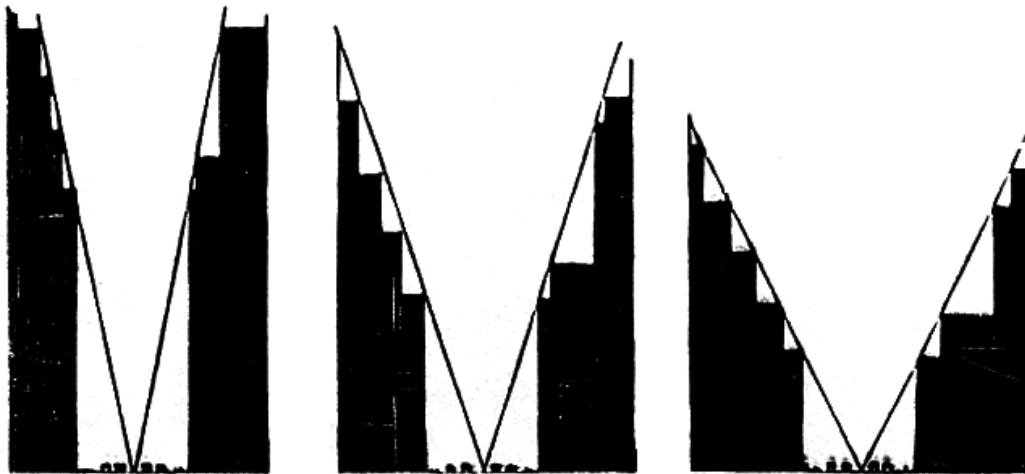


Figure 6-1. Set-back regulations, New York

planning requirements sometimes dictate the need for open first floors, for vertical setbacks, or other characteristics of architectural form. Urban design includes issues such as zoning and planning regulations, which by defining set-backs, height limits and sun-angle requirements often define the building envelope.

For example, recent studies have argued convincingly that early skyscraper form was predominantly determined by local land-use patterns, municipal codes and zoning (Figure 6-1). For example, the striking differences in form between the skyscrapers of Chicago and New York were due to the imposition of a 130 feet height limit on the former, and no limits on the latter. Zoning laws in New York, in 1916, spawned the buildings with "wedding-cake" setbacks, while a 1923 law in Chicago permitted a tower to rise above the old height limit, but restricted its total volume⁽⁶⁻¹⁾.

Engineers can accept the problems of zoning and building function in determining configuration, because they fit into the engineer's rationalist concept of the world. It is the third influence, the need for the building to present an attractive, interesting, unique, or even sensational image to the outside observer, and often the occupants, that engineers feel the trouble begins. Here is where the irrational artist takes over, and the laws of physics and economy may be violated.

It is important to understand the need for the architect sometimes to provide a distinctive image for the building. If this need did not exist the owner might go to an engineer -or contractor- to obtain a simple economical building, and indeed, many owners do so..

Up until the early years of the 20th. century for a Western architect the common acceptance required a historical style -typically mediaeval or renaissance - even when totally new building types such as railroad stations or skyscrapers were conceived. In engineering and materials terms these traditional forms were all derived from masonry structure: the need to keep the blocks of masonry in compression, and the creation of devices such as arches and vaults, to

enable the masonry to achieve larger spans than were possible by using slabs of masonry as beams or lintels. These masonry determined forms survived well into the 20th. century, even when buildings were supported by concealed steel frames, and arches had become a structural anachronism. Moreover, the prevailing historical architectural styles preferred symmetricalness, and decreed that buildings should be massive at the base, with smaller openings, and their mass should decrease with the upper floors.

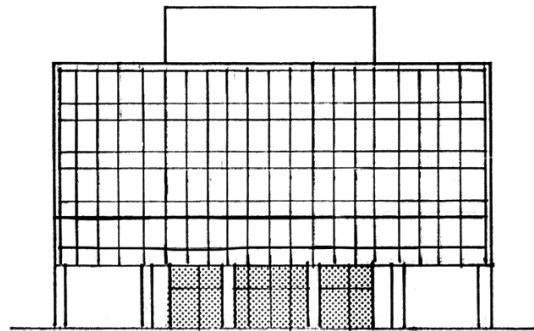


Figure 6-2. The International Style

The revolution in architectural aesthetics that began in the 1920's, and is often called the "International Style" was based on exploiting the forms that could be created by use of frame structures, combined with a desire to strip architecture of its decoration and adherence to historic styles. The International Style in architecture was not alone in extolling the virtues of unadorned structure and absence of decoration in its glorification of the beauties of Euclidean geometry. The same thing was going on in the world of painting and sculpture, and these arts were being stripped of their traditional content in favor of simplicity, geometry, and new materials.

As architects began to exploit the aesthetics of an architecture based on engineered frames, the seeds of seismic configuration problem were sown. Load-bearing masonry buildings were very limited in the extent to which configuration irregularities were possible: with short spans redundancy was always present: the

extensive use of walls, both in exteriors and interiors, meant that, even though the masonry was unreinforced, unit stresses were very low. Large cantilevers and setbacks were not possible.

But with the steel or concrete frame all these limitations were unnecessary: the building structure could be unbelievably slender (because now the columns and beams were analyzed and sized by engineers), first floor walls could be omitted, so that the building seemed to float in space. Lightness and grace were sought, rather than ornamented mass. (Figure 6-2) Buildings could even cantilever out safely so that they could become larger as they rose: the inverted pyramid could be built. These possibilities were eagerly explored by a new generation of architects: with them came other ideas: the rejection of symmetricalness of plan in favor of a more exciting and more rational disposition of elements (rational because the building elements were allowed to occur where planning function was most efficient, instead of being forced into [sometimes] inefficient symmetry).

Examples of the International Style were limited to a few avant-garde buildings in all countries before World War 2, and then bloomed in the rich economic years that began in the 50's. The United States, Western Europe, Latin America, the Soviet Union and Japan exploded in a fury of development, almost all constructed in their regional versions of the International Style. These years of intensive development saw the world's cities grow into huge metropolises: they were also years in which seismic design as it related to the new, spare, framed buildings was inadequately understood, and it took earthquakes in Latin America, Mexico and the United States (in Alaska, 1964, and San Fernando, 1971) to make engineers realize that such buildings were unforgiving and intolerant of the very irregularities that architects had embraced with such enthusiasm.

This architecture of the 50's to the 70's has left us with a legacy of poor seismic configurations that present a serious problem in

reducing the earthquake threat to our cities. The problem is exacerbated when it is allied to the engineering design problem of the use of the non-ductile reinforced concrete frame structure, which was the norm up to about 1975.

This historical discourse is relevant to seismic design, because it shows that:

- the minimalist structural frame provided the basis for an architectural aesthetic which was in tune with the spirit of the age, aesthetically, economically and politically.
- what we now call discontinuities and irregularities were critical elements of the new architectural aesthetic.
- these elements were made possible by the use of the engineered structural frame, and by a new level of architect/engineer collaboration.

It is, however, worth mentioning, that the new style originated, was promoted and developed in Western Europe, predominantly France and Germany, which, of course, are essentially non seismic zones.

A more complete discussion of the origins and influence of the International Style will be found in Reference 6-2.

6.2.3 Configuration Influences in General

Configuration largely determines the ways in which seismic forces are distributed throughout the building, and also influences the relative magnitude of those forces. For a given ground motion, the major determinant of the total inertial force in the building is, following Newton's Second Law of Motion, the building mass (approximated on the earth's surface by its weight). While the size and shape of the building (together with the choice of materials), establish its weight the building square footage and volume are determined by the building program (and the budget): the listing of required spaces and the activities and equipment that they contain. But for any given program an almost infinite variety of

configurations can provide a solution, and it is the variables in these configurations that affect the distribution of inertial forces due to ground shaking .

Thus the discussion of configuration influence on seismic performance becomes the identification of configuration variables that affect the distribution of forces. These variables represent irregularities, or deviations from a "regular" configuration that is an optimum, or ideal, with respect to dealing with lateral forces.

6.2.4 The Optimum Seismic Configuration.

It is easiest to define a regular building by providing an example: the design discussed below represents an essentially perfectly regular building, which in turn represents an "optimum" seismic design. Its characteristics are such that deviations from the design progressively detract from its intrinsic seismic capabilities: these deviations result in "irregularities" and a familiar list of configuration irregularities can be identified. The discussion of these irregularities from an engineering and architectural viewpoint form the main body of this section..

Architecture implies occupancy: thus a solid block of concrete, which might be an optimum seismic design, is sculpture, not architecture. The great pyramid of Gizeh is architecture, and certainly approaches an optimum seismic design, but architecturally it is very uneconomic in its use of space and volume in housing only two small rooms within an enormous volume of unreinforced masonry (Figure 6-3). Our optimal seismic design is compromised by the need also to be reasonably optimal architecturally -that is, in its ability to be a functional and economically viable architectural concept.

Our design shows the three basic ways of achieving seismic resistance, and these are also part of the optimization, so the building is seismically optimized architecturally, in its configuration, and also demonstrates the best arrangement of its seismic resisting elements, in complete harmony with the architecture (Figure

6-4). For convenience, the building is arbitrarily shown as three stories: a one story building might be better seismically, all other things being equal, but with a multi-story building we can show some necessary attributes of such a building.

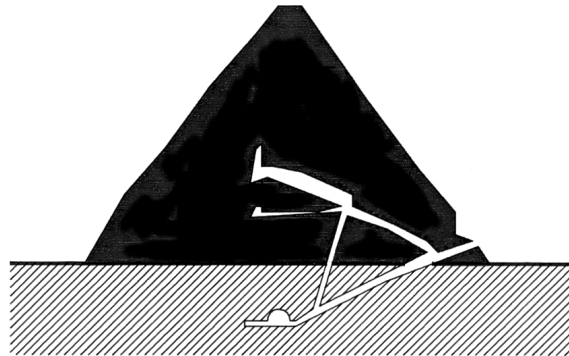


Figure 6-3. The great pyramid of Gizeh

Considered purely as architecture this little building is quite acceptable, and would be simple and economical to construct. It is also a prototypical International Style building. 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 complete, architecturally, of course, because stairs, elevators etc. must be added, and the building is not spatially interesting , although its interior could be configured with nonstructural components to provide almost any quality of room that was desired with the exception of interesting and/or unusual spatial volumes more than one story in height.

What are the characteristics of this design that make it regular, and also make it so good - considering only architectural configuration and the disposition of the seismic resisting elements? Any engineer will recognize them, but it is worth while listing them, because they are specific attributes whose existence or absence thereof can be quickly ascertained in any actual design. These attributes, and their effects, are:

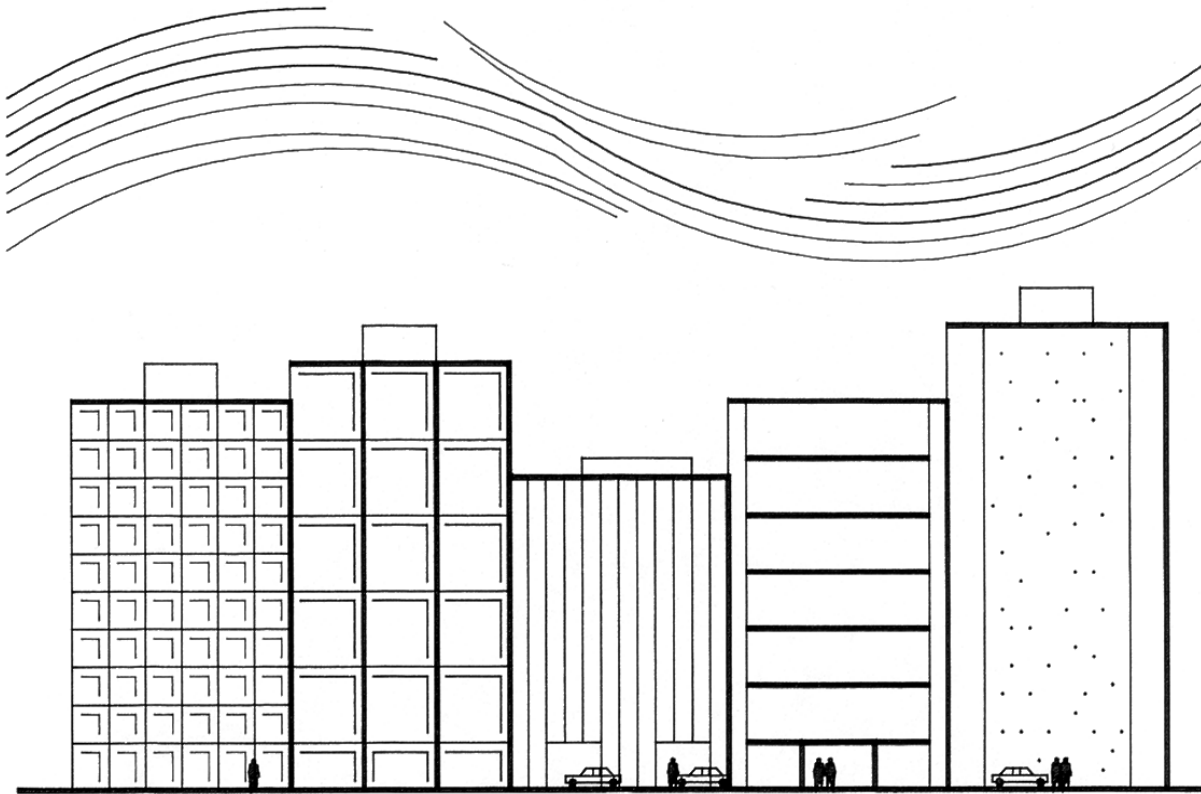


Figure 6-4. The optimal seismic design

- Low height-to base ratio
 - Minimizes tendency to overturn
- Equal floor heights
 - Equalizes column/wall stiffness
- Symmetrical plan shape
 - Reduces torsion
- Identical resistance on both axes
 - Balanced resistance in all directions
- Uniform section and elevations
 - Eliminates stress concentrations
- Maximum torsional resistance
 - Seismic resisting elements at perimeter
- Short spans
 - Low unit stress in members
- Redundancy
 - Toleration of failure of some members
- Direct load paths, no cantilevers
 - No stress concentrations

6.3 METHODS OF ANALYSIS

6.3.1 Methods of Analysis and the Regular Building

An important aspect of a building's response to ground motion is the method of analysis used to establish the seismic forces. The estimate of total forces and their distribution is both a function of and a determinant of the lateral force-resisting system employed in the building. The great majority of designs estimate lateral forces through use of the static equivalent lateral force method (ELF) established in typical seismic codes, which involve estimating a base shear and then distributing the resulting forces through the structural elements of the building. It is

important to recognize that the forces derived from an equivalent force method used according to a typical seismic code and many other code provisions, assume a regular building, comparable to our ideal form described above. This assumption is noted in the Commentary to the 1997 NEHRP Recommended Provisions for Seismic Regulations for New Buildings⁽⁶⁻³⁾: "The Provisions were basically derived for buildings having regular configurations. Past earthquakes have repeatedly shown that buildings having irregular configurations suffer greater damage than buildings having regular configurations. This situation prevails even with good design and construction"

The Commentary to the 1990 Recommended Lateral Force Requirements of the Structural Engineers Association of California (Ref.6-4) discusses the design basis for regular buildings in some detail. Two important concepts apply for regular structures. First, the linearly varying lateral force distribution given by the ELF formulas are a reasonable and conservative representation of the actual response force distribution due to earthquake ground motions. Second, when the design of the elements in the lateral force resisting system is governed by the specified seismic load combinations, the cyclic inelastic deformation demands will be reasonably uniform in all elements, without large concentrations in any part of the system. The acceptable level of inelastic deformation demand for the system is therefore reasonably represented by the R_w value for the system. However, "when a structure has irregularities, then these concepts, assumptions and approximations may not be reasonable or valid, and corrective design factors and procedures are necessary to meet the design objectives".

It is safe to say, based on studies of building inventories, that over half the buildings that have been designed in the last few decades do not conform to the simple uniform building configuration upon which the code is based. For new designs, the simple equivalent lateral force

analysis of the code must often be augmented by engineering judgment based on experience.

Progressive evolution of seismic codes has resulted in increasing force levels and the consideration of additional parameters in estimating force levels, but the impact of configuration irregularity, which was first introduced into the Uniform Building Code in 1973, long remained a matter of judgment. However, starting in 1988 the UBC quantified some configuration parameters, to establish the condition of regularity or irregularity, and laid down some specific analytical requirements for irregular structures.

6.3.2 Irregular Configurations: Code Definitions and Methods of Analysis

In the Commentary to the 1980 SEAOC Recommended Lateral Force Requirements and Commentary⁽⁶⁻⁵⁾, over 20 types of "irregular structures or framing systems" were noted as examples of designs that should involve extra analysis and dynamic consideration rather than use of the normal equivalent lateral force method. These types are illustrated in Figure 6-5, which is a graphical interpretation of the SEAOC list. Scrutiny of these conditions shows that the majority of irregularities are configurational issues within the terms of our definition.

This list of irregularities defined the conditions, but provided no quantitative basis for establishing the relative significance of a given irregularity. These irregularities vary in the importance of their effects, and their influence also varies in accord with the particular geometry or dimensional basis of the condition. Thus, while in an extreme form the reentrant corner is a serious type of plan irregularity, in a lesser form it may have little significance (Figure 6-6). The determination of the point at which a given irregularity becomes serious is a matter of judgment.

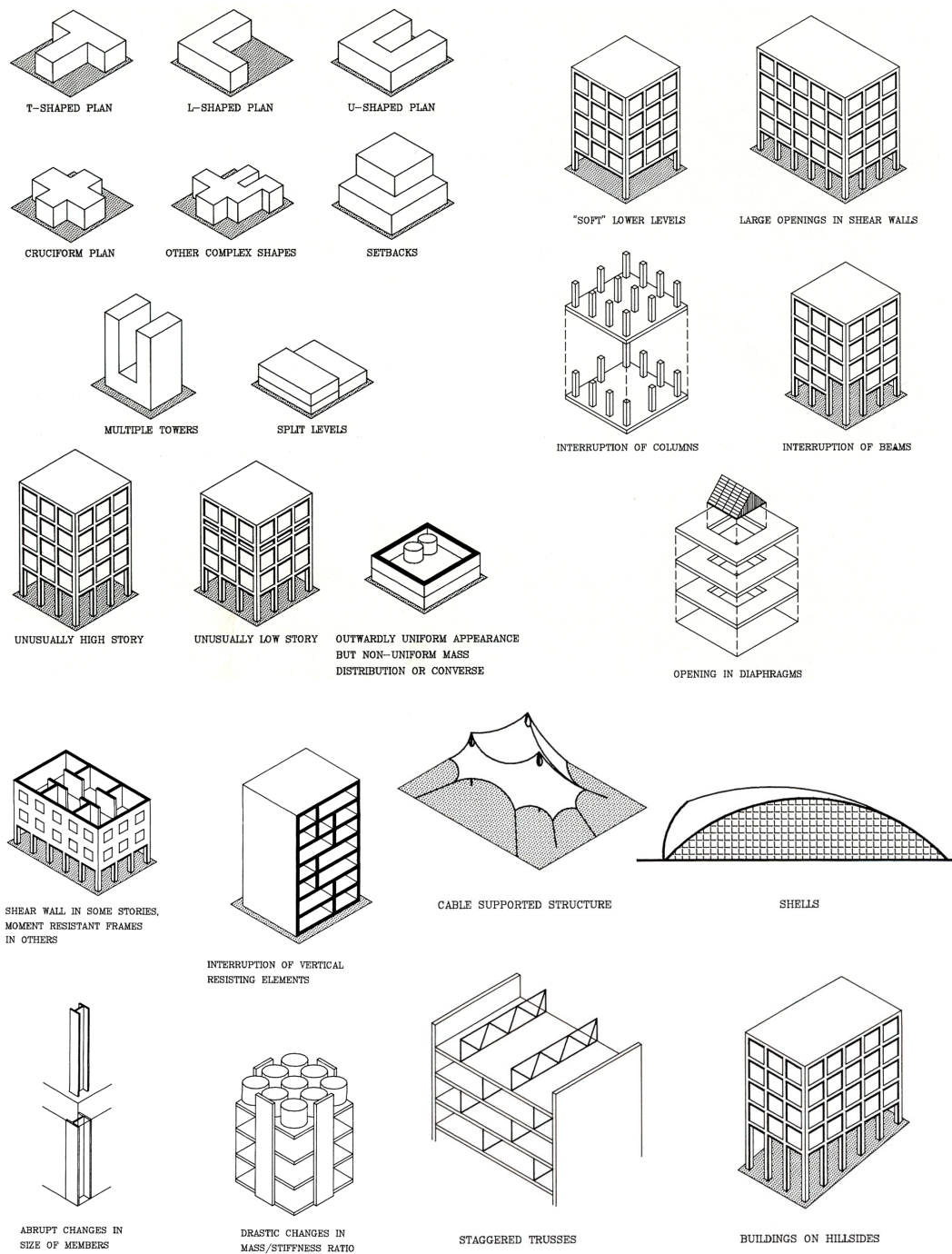


Figure 6-5. Graphic interpretation of "Irregular Structures or Framing Systems" from the commentary to the "SEAOC Recommended Lateral Force Requirements and Commentary" (a) Buildings with Irregular Configuration (b) Buildings with abrupt changes in lateral resistance (c) Buildings with abrupt changes in lateral stiffness (d) Unusual or novel structural features.

The SEAOC Commentary explained the difficulty of going beyond this basic listing as follows:

Due to the infinite variation of irregularities (in configuration) that can exist, the impracticality of establishing definite parameters and rational rules for the application of this Section are readily apparent.

However, in the most recent version of the SEAOC Requirements and Commentary, and starting in the 1988 revisions to the Uniform Building Code, (which is based on the SEAOC document), an attempt has been made to quantify some critical irregularities, and to define geometrically or by use of dimensional ratios the points at which the specific irregularity becomes an issue of such concern that remedial measures must be taken.

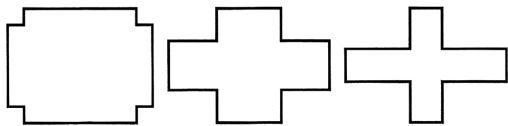


Figure 6-6. The reentrant corner plan : a range of significance

The code approach to reducing the detrimental effect of irregularity is to require more advanced methods of analysis where such conditions occur - more specifically, where the ELF analysis method must be augmented or cannot be used. While this may provide a more accurate diagnosis, and in some instances strengthening of certain members, it does not correct the condition: this must still be done by design means based on understanding of the effects of the condition on building response.

The code requirements relating to the definition of regularity and irregularity, and the determination of the analysis methods required have now become complex, and for design purposes the relevant sections of the applicable code should be referred to. The outline that follows focuses on identifying the irregular conditions for which the ELF method can be

used, must be augmented or where a more complex method is necessary. The irregularity type references are to the 1997 *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings* as illustrated in Figure 6-7. This figure is a graphic interpretation of Table 5.2.3.1 and Table 5.2.3.2 in the *Provisions*. The terminology and configuration requirements in the UBC and the *NEHRP Provisions* are essential similar.

The ELF method can be used for the following irregular structural types, with the noted augmentations:

1. All structures in Seismic Design Category A (in the *NEHRP Provisions* the Seismic Design Category is a classification assigned to a structure based on its seismic use group, or occupancy, and the severity of the design earthquake ground motion at the site).
2. Structures with reentrant corners (plan irregularity type 2), diaphragm discontinuity (type 3) out-of-plane offsets (type 4) , in Seismic Design Categories D, E and F, must provide for an increase in design forces of 25% for connection of diaphragms to vertical elements and to collectors, and connection of collectors to vertical elements.
3. Structures with nonparallel systems (plan irregularity type 5) in Seismic Design Category C,D,E and F, must be analyzed for seismic forces applied in the critical direction, or satisfy the following combination of loads: 100% of forces in one direction plus 30% of the forces in the perpendicular direction.
4. Structures with out-of-plane offsets (plan irregularity type 4) and in-plane discontinuity in vertical lateral force resisting elements (vertical irregularity type 4) must have the design strength to resist the maximum axial forces that can develop in accordance with specially defined load combinations.

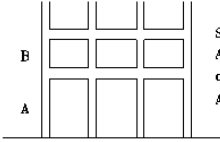
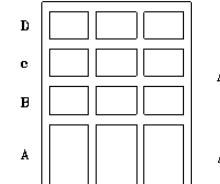
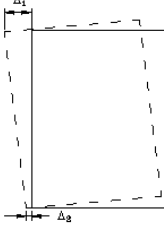
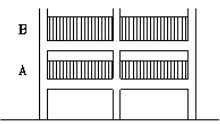
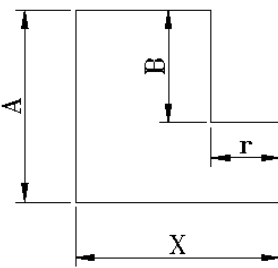
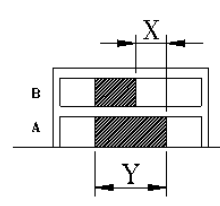
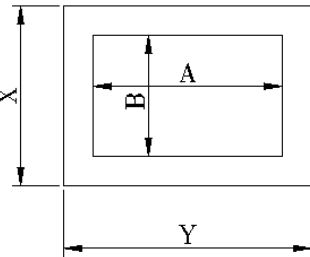
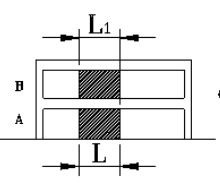
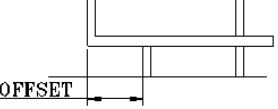
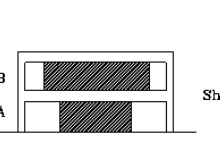
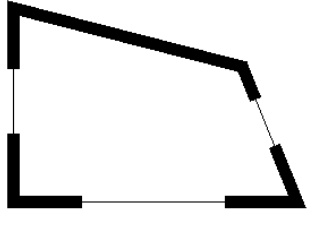
Vertical Irregularities	Plan Irregularities
 <p>STIFFNESS $A < 70\% B$ (1a) or $A < 60\% B$ (1b)</p> <p>Or</p>  <p>STIFFNESS $A < 80\% \frac{(B+C+D)}{3}$ (1a) Or $A < 70\% \frac{(B+C+D)}{3}$ (1b)</p>	 <p>$\Delta_t > 1.2 \times \frac{(\Delta_1 + \Delta_2)}{2}$ (1a) or $\Delta_t > 1.4 \times \frac{(\Delta_1 + \Delta_2)}{2}$ (1b)</p>
<p>1a Stiffness irregularity - Soft Story and 1b Stiffness Irregularity - Extreme Soft Story</p>	<p>1a Torsional Irregularity With Stiff Diaphragm 1b Extreme Torsional Irregularity With Stiff Diaphragm</p>
 <p>MASS $B > 150\%$ MASS A</p>	 <p>Projections $Y > 15\% X$ $B > 15\% A$</p>
<p>2 Weight (mass) Irregularity</p>	<p>2 Reentrant Corners</p>
 <p>$X > 30\% Y$</p>	 <p>AREA $AE > 50\% XY$</p>
<p>3 Vertical Geometric Irregularity</p>	<p>3 Diaphragm Discontinuity</p>
 <p>Offset $L1 > L$</p>	 <p>OFFSET</p>
<p>4 In-Plane Discontinuity in Vertical Lateral Force Resisting System</p>	<p>4 Out-Of-Plane Offsets</p>
 <p>Shear Strength $A < 80\% B$</p>	
<p>5 Discontinuity in Capacity - Weak Story</p>	<p>5 Nonparallel Systems</p>

Figure 6-7. Irregularities defined in the 1997 NEHRP Provisions

Other buildings with plan or vertical irregularities as defined in the Tables, that are not required to use modal analysis as identified below, may use the ELF procedure with "dynamic characteristics given special consideration" : the engineer must use judgment in computing forces.

Buildings with certain types of vertical irregularity may be analyzed as regular buildings in accordance with normal ELF procedures. These buildings are generally referred to as setback buildings. The following procedure may be used:

1. The base and lower portions of a building having a setback vertical configuration may be analyzed as indicated in (2) below if all of the following conditions are met:
 - a. The base portion and the tower portion , considered as separate buildings, can be classified as regular and.
 - b. The stiffness of the top story of the base is at least five times that of the first story of the tower.

Where these conditions are not met, the building shall be analyzed using modal analysis.

2. The base and tower portions of the building may be analyzed as separate buildings in accordance with the following:
 - a. The tower may be analyzed in accordance with the usual ELF procedure with the base taken at the top of the base portion.
 - b. The base portion then must be analyzed in accordance with the ELF procedure using the height of the base portion of h_n and with the gravity load and base shear of seismic forces the tower portion acting at the top level of the base portion.

Modal Analysis is required in the following instances:

1. Buildings which are in Seismic Design Category D, E or F, are over 65 feet in height, and have:

soft stories (vertical irregularity type 1a)
 extreme soft stories (vertical irregularity type 1b)
 mass irregularities (vertical irregularity type 2)
 vertical geometrical irregularity (vertical irregularity type 3)

Exceptions: vertical structural irregularities of types 1a, 1b or 2 do not apply where no story drift ratio under design lateral load is greater than 130 percent of the story drift ratio of the next story above

- 2 Buildings , with torsional irregularity (plan irregularity type 1a) in Seismic Design Category D, E or F and extreme torsional irregularity ((plan irregularity type 1b) in Seismic Design Category D. In addition an increase in design forces of 25% is required for connection of diaphragms to vertical elements and to collectors, and connection of collectors to vertical elements, and a torsion amplification factor.
3. All structures over 240 feet in height.

The following irregular structures are not permitted:

Weak story structures (vertical irregularity type 5) over 2 floors or 30 feet in height with a weak story less than 65% of the strength of the story above, in Seismic Design Categories, B, C, D, E and F.

Extreme soft story structures (vertical irregularity type 1b) and extreme torsional irregularity structures (plan irregularity

type 1b) in Seismic Design categories E and F.

The Commentary to the NEHRP *Provisions* also provides a procedure which may reduce the need to perform modal analysis.

"The procedures defined in the *Provisions* include a simplified modal analysis which takes account of irregularity in mass and stiffness distribution over the height of the building. It would be adequate, in general, to use the ELF procedure for buildings whose seismic resisting system has the same configuration in all stories and all floors, and whose floor masses and cross sectional areas and moments of inertia of structural members do not differ by more than 30% in adjacent floors and in adjacent stories.

For other buildings, the following criteria should be applied to decide whether modal analysis procedures should be used:

1. The story shears should be computed using the ELF procedure.
2. On this basis, approximately dimension the structural members, and then compute the lateral displacement of the floors.
3. Replace the h_x^k term in the vertical distribution of seismic forces equation with these displacements and recompute the lateral forces to obtain new story shears.
4. If at any story the recomputed story shear differs from the corresponding value as obtained from the normal ELF procedure by more than 30%, the building should be analyzed using the modal analysis procedure. If the difference is less than this value, the building may be designed for the story shear obtained in the application of the present criterion and the modal analysis procedures are not required."

This procedure greatly reduces the likelihood that the considerably more complex modal analysis procedure will be required for the building analysis: this is of major importance because building irregularity is quite likely to be present in buildings of modest size and tight budget, and costly analysis procedures are not welcome to the owner.

In addition, the 1997 NEHRP *Provisions* make further predominantly nonquantitative comments about the use of the Equivalent Lateral Force procedure for irregular buildings:

"The ELF procedure is likely to be inadequate in the following cases:

1. Buildings with irregular mass and stiffness properties in which case the simple formulas for vertical distribution of lateral forces may lead to erroneous results:
2. Buildings (regular or irregular) in which the lateral motions in two orthogonal directions and the torsional motions are strongly coupled, and
3. Buildings with irregular distribution of story strengths leading to possible concentration of ductility demand in a few stories of the building.

In such cases, a more rigorous procedure which considers the dynamic behavior of the structure should be employed.

The *Provisions* Commentary points out that the ELF procedure, and both versions of the modal analysis procedure (a simple version and a general version with several degrees of freedom per floor which are described in the *Provisions*) are all likely to err systematically on the unsafe side if story strengths are distributed irregularly over height. This points to the importance of eliminating such irregularities if possible, but often they will be present because of detailed architectural requirements: if they cannot be eliminated, the engineer must use his judgment to assess their effects on the analysis

Even if the modal analysis procedure is used there are limitations to the information that the analysis provides. The procedure adequately addresses vertical irregularities of stiffness, mass or geometry. Other irregularities must be carefully considered on a judgmental basis, and so the engineer must rely on his experiential and conceptual knowledge of the building's response in order to effectively accommodate all irregularities.

6.4 GENERAL BUILDING CHARACTERISTICS

6.4.1 Introduction

These are issues relating to the building configuration as a whole and apply to all configurations.

Irregularity as defined in current seismic codes, and as discussed above, covers the majority of configuration variables that have a significant effect on the seismic performance of the building. Although definitions vary, there is general agreement on those configuration irregularities that are important.

However, the code listing is not complete: issues of building proportion and size are not included, nor are issues such as the building plan density or its redundancy the subject of code provisions, although the latter is briefly mentioned. These are discussed below. The problem of pounding, which combines the issue of drift with that of building adjacency, and as such may present an architectural problem, is discussed in Section 6.9 below.

6.4.2 Size, Proportion and Symmetry

- **Building size:**

It is possible to introduce configuration irregularities into a wood frame house that would be serious problems in a large building, and yet produce a safe structure with the inclusion of relatively inexpensive and unobtrusive provisions. This is because a small

wood frame structure is light in weight and inertial forces will be low. In addition, spans are short and relative to the floor area, there will probably be a large number of walls to share the loads.

For a larger building, the violation of basic layout and proportion principles exacts an increasingly severe cost, and as the forces become greater, good performance cannot be relied upon as in an equivalent building of better configuration.

As the absolute size of a structure increases, the number of alternatives for the arrangement of its structure decreases. A bridge span of 300ft. may be built as a beam, arch, truss, or suspension system, but a span of 3000 ft. can only be designed as a suspension structure. And as the size increases the structural discipline becomes more rigorous: architectural flourishes that are perfectly acceptable at the size of a house become physically impossible at the size of a suspension bridge.(Figure 6-8).

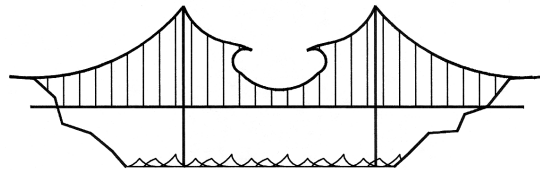


Figure 6-8. The designer's suspension bridge

In looking at the influence of building size on seismic performance, the influence of both the dynamic environment and the characteristics of ground motion result in more complexity than does the influence of size on vertical forces. Increasing the height of a building may seem equivalent to increasing the span of a cantilever beam, and so it is (all other things being equal). The problem with the analogy is that as a building grows taller its period will tend to increase, and a change in period means a change in the building response.

The effect of the building period must be considered in relation to the period of ground motion, and if amplification occurs, the effect of an increase in height may be quite disproportionate to the increase itself. Thus

doubling the building height from 6 to 10 stories may, if amplification occurs, result in a four or fivefold increase in seismic forces. The earthquake in Mexico City in 1985 resulted in major response and amplification in buildings in the 6 to 20 story range, with generally reduced response in well-built buildings below and above these heights.

Although a 100-ft. height limit throughout Japan was enforced until 1964, a 150-ft 13 story limit was the maximum in Los Angeles until 1957, and the limit was 80 ft and later 100 ft on San Francisco, height is rarely singled out as a variable to be used to reduce the building response. Two recent exceptions to this may be noted. After the Armenian earthquake of 1988, planners of the reconstruction of the city of Leninakan limited the height of new buildings to three stories, because of the ground conditions and the bad experience with taller buildings. This decision is especially interesting because it required a major shift in planning and architectural thinking: prior to this, almost all Soviet-style housing consisted of medium to high-rise blocks. After the Mexico City earthquake of 1985 a number of damaged buildings were "topped" as part of the repair strategy: a number of floors were removed, thus changing the building period to something less in tune with the long period ground motions that the city experiences.

The present approach is generally not to legislate seismic height limits (except insofar as seismic codes impose height limits relating to types of construction), but to enforce more specific seismic design and performance criteria. Generally, urban design, real-estate or programmatic factors will be more significant, and earthquake performance must be engineered with the height predetermined by these factors.

It is easy to visualize the overturning forces associated with height as a seismic problem (although the issue is more that of the aspect ratio of shear walls rather than the building as a whole), but large plan areas can be detrimental also. When the plan becomes extremely large, even if it is symmetrical and of simple shape,

the building can have trouble responding as one unit to the ground motion. Unless there are numerous interior lateral-force resisting elements, large-plan buildings impose unusually severe requirements on their diaphragms, which have large lateral spans, and can build up large forces to be resisted by shear walls or frames. The solution is to add walls or frames to reduce the span of the diaphragm, although it is recognized that this may introduce problems in the use of the building. In a very large building, seismic separations may be necessary to subdivide the building and keep the diaphragm forces within bounds, in which case the seismic separations may also act as thermal expansion joints.

An interesting example of a correct "intuitive" response to this problem is that of the design of the Imperial Hotel, Tokyo, by the architect Frank Lloyd Wright in the early 1920s. He subdivided this large complex building, with long wings and many reentrant corners, into small regular boxes, each about 35 ft. by 60 ft in plan. In doing this, he appears to have been concerned about the possibility of differential settlement caused by a travelling wave on the site. In the use of this concept, to which he attributed in large measure the success of the building in surviving the 1923 Kanto earthquake, Wright was well ahead of his time. The short-pile foundation scheme, which Wright claimed as a major invention, probably had much less to do with the building's good performance⁽⁶⁻⁶⁾.

• Building Proportion

In seismic design, the proportions of a building may be more important than its absolute size. For tall buildings, the slenderness ratio (height/least depth) of a building, calculated in the same way as for an individual member, is a more important consideration than just height alone. Dowrick⁽⁶⁻⁷⁾ suggests attempting to limit the height/depth ratio to 3 or 4, explaining:

"The more slender a building the worse the overturning effects of an earthquake and the greater the earthquake stresses in the outer columns, particularly the overturning compressive forces which can be very difficult to deal with."

As urban land becomes more expensive, there is a trend towards designing very slender "sliver" buildings which, although not necessarily very high, may have a large height/depth ratio. Nowhere is this trend more apparent than in Japanese cities, where multistory buildings may be built on sites that are of the order of 15 to 20 ft wide (Figure 6-9). However, the same economic forces often dictate that these buildings will be built very close together, so that they will tend to respond as a unit rather than as individual free-standing buildings, although more recent Japanese

buildings have incorporated relatively large separations to reduce the risk of pounding.

● Building Symmetry

The term symmetry denotes a geometrical property of building plan configuration. Structural symmetry means that the center of mass and center of resistance are located at, or close to, the same point (unless live loads affect the actual center of mass). The single admonition that appears in all codes and in textbooks that discuss configuration is that symmetrical forms are preferred to asymmetrical ones. The two basic reasons are that eccentricity between the centers of mass and resistance will produce torsion and stress concentrations.

However, a building with reentrant corners is not necessarily asymmetrical (a cruciform



Figure 6-9. Slender buildings, Tokyo, Japan



Figure 6-10. False symmetry: offset structural core

building may be symmetrical) but it is irregular, as defined, for example, in current seismic codes. Thus symmetry is not sufficient on its own, and only when it is combined with simplicity is it beneficial.

Nevertheless, it is true that as the building becomes more symmetrical, its tendency to suffer torsion and stress concentration will reduce, and performance under seismic forces will tend to be less difficult to analyze. This suggests that when good seismic performance must be achieved with maximum economy of design and construction, the symmetrical, simple shapes are much to be preferred. But these tendencies must not be mistaken for an axiom that a symmetrical building will not suffer torsion.

The effects of symmetry refer not only to the overall building shape, but to its details of design and construction. Study of building performance in past earthquakes indicates that performance is sensitive to quite small variations in symmetry within the overall form.. This is particularly true in relation to shear-wall design and where service cores are designed to act as major lateral resistant elements. It is possible to have a building which is geometrically symmetrical in exterior form, but highly asymmetrical in the arrangement of its structural systems. The most common form of this condition (sometimes termed "false symmetry") is the building with interior structural cores that, for planning reasons, are unsymmetrically arranged. This can be a major

source of undesirable torsional response. (Figure 6-10)

Experience in the Mexico City earthquake of 1985 showed that many buildings that were symmetrical and simple in overall plan suffered severely because of asymmetrical location of service cores and escape staircases. Moreover, as soon as a structure begins to suffer damage (cracking in shear walls or columns, for example), its distribution of resistance elements changes, so that even the most symmetrical of structures becomes dynamically asymmetrical and subject to torsional forces.

Finally, it must be recognized that architectural requirements will often make the symmetrical design impossible. In these circumstances, it may be necessary, depending on the size of the building and the type of asymmetry, to subdivide the building into simple elements.

There is a tendency, as noted above, for the very tall building to tend towards symmetry and simplicity. The seismic problems are most apparent in the low to medium-height building, where considerable choice exists as to plan form and the disposition of the major masses of the building.

6.4.3 Plan Density, Perimeter Resistance, and Redundancy

The size and density of structural elements in the buildings of former centuries is strikingly greater than in today's buildings. Structural

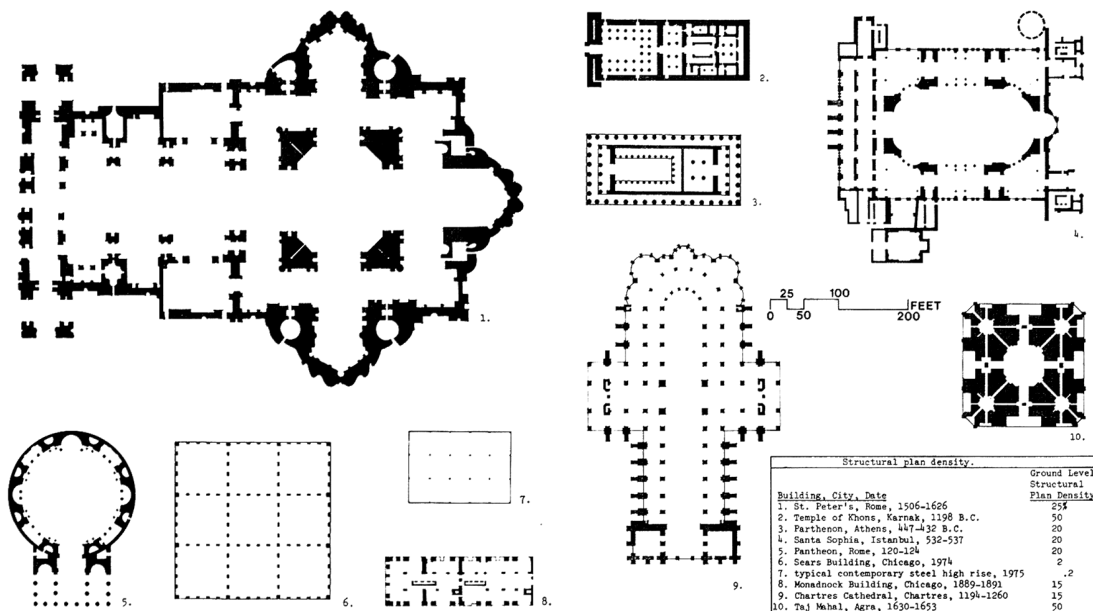


Figure 6-11. Structural plan density

technology has allowed us to push this trend continually further.

Earthquake forces are generally greater at the base of the building. The bottom story is required to carry its own lateral load in addition to the shear forces of all the stories above, which is analogous to the downward build-up of vertical gravity loads. At this same lowest level, programmatic and aesthetic criteria are often imposed on the building that demand the removal of as much solid material as possible. This requirement is the opposite of the most efficient seismic configuration, which would provide the greatest intensity of vertical resistant elements at the base, where they are most needed.

An interesting statistical measure in this regard is the ground level vertical plan density, defined as the total area of all vertical structural elements divided by the gross floor area. The most striking characteristic of the modern framed building is the tremendous reduction of structural plan density compared to historic buildings.

For instance, a typical 10- to 20- story, moment resistant steel frame building will

touch the ground with its columns over 1% or less of its plan area, and combined frame shear-wall designs will typically reach structural plan densities of only 2%. The densely filled-in "footprints" of buildings of previous eras present a striking contrast: the structural plan density can go as high as 50%, in the case of the Tag Mail: the ratio for St. Peter's in Rome is about 25%, and for Chartres Cathedral 15%. The 16-story Monadnock Building in Chicago, which used exterior bearing walls of brick 6 ft. thick at the ground level, has a ratio of 15% (Figure 6-11).

Analogous to structural plan density is the measure of the extent of walls in a structure. Surveys of damaged buildings in Japan and Turkey have indicated a clear relationship between the length of walls in a box-type system building and the extent of damage. This relationship has been incorporated in the seismic codes of these and other countries to provide prescriptive guidance for the design of simple structures.

In Figure 6-12, although both configurations are symmetrical and contain the same amount of shear wall, the location of walls is

significantly different. The walls on the right form greater lever arms for resisting overturning and torsional moments. In resisting torsion, with the center of twist of a symmetrical building located at or near the geometrical center, the further the resisting material is placed from the center, the greater the lever arm through which it acts, and hence the greater the resisting moment that can be generated. Placing resisting members on the perimeter whenever possible is always desirable, whether the members are walls, frames, or braced frames, and whether they have to resist direct lateral forces, torsion, or both.

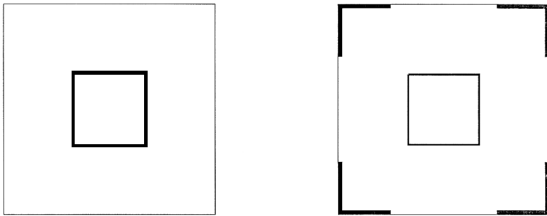


Figure 6-12. Location of lateral resistance elements

The design characteristic of redundancy plays an important role in seismic performance, and is significant in several aspects, most especially because the redundant design will almost certainly offer direct load paths and in this it tends to result in higher plan density as discussed above. In addition, historic buildings tended to be highly redundant, because short spans required many points of support, and thus each supporting member incurs much lower stresses, often even within the capability of unreinforced masonry. Thus, the very limitations of traditional materials forced the designers into good design practices such as redundancy, direct load paths and high plan density.

The detailing of connections is often cited as a key factor in seismic performance, since the more integrated and interconnected a structure is, the more load distribution possibilities there are.

6.5 SEISMIC SIGNIFICANCE OF TYPICAL CONFIGURATION IRREGULARITIES

6.5.1 Introduction

The discussion of configuration issues that follows incorporates all the code-defined issues but, in going back to our original definition of configuration, categorizes configuration problems in ways that relates the seismic implications to those of their architectural origins as decisions made at the conceptual stages of the design.

For each configuration issue, five issues are outlined: definition of the condition, its seismic effects, its architectural implications, historical performance in past earthquakes, and solutions. The notes on architectural effects discuss the origin and purpose of the condition in architectural terms: the discussion of solutions deals with conceptual design approaches, and is most relevant for the consideration of existing buildings.

6.6 PLAN CONFIGURATION PROBLEMS

6.6.1 Reentrant Corners

• Definition

The reentrant , or "inside" corner is the common characteristic of overall building configurations that, in plan, assume the shape of an L, T, H, +, or combination of these shapes.

• Seismic Effects

There are two related problems created by these shapes. The first is that they tend to produce variations of rigidity, and hence differential motions, between different parts of the building, resulting in a local stress concentration at the "notch" of the reentrant

corner. In Figure 6-13, if the ground motion occurs with a north-south emphasis at the L-shaped building shown, the wing oriented north-south will, for geometrical reasons, tend to be stiffer than the wing oriented east-west. The north-south wing, if it were a separate building, would tend to deflect less than the east-west wing, but the two wings are tied together and attempt to move differentially at their notch, pulling and pushing each other. (Figure 6-14). For ground motions along the other axis, the wings reverse roles, but the differential problem remains.

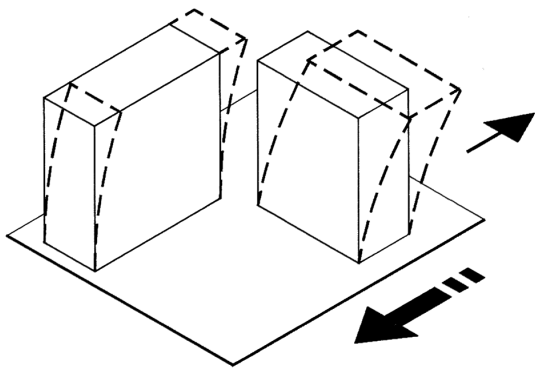


Figure 6-13. Separated buildings

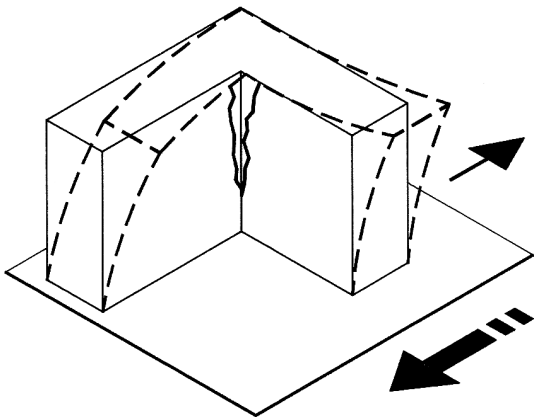


Figure 6-14. The L-shaped building

The second problem is torsion. This is because the center of mass and center of rigidity in this form cannot geometrically coincide for all possible earthquake directions.

The result is rotation, which tends to distort the form in ways that will vary in nature and magnitude depending on the nature and direction of the ground motion, and result in forces that are very difficult to analyze and predict.

The stress concentration at the notch and the torsional effects are interrelated. The magnitude of the forces and the seriousness of the problem will be dependent on:

- the mass of the building
- the structural systems
- the length of the wings and their aspect ratios
- the height of the wings and their height/depth ratios

In addition, it is not uncommon for wings of a reentrant corner building to be of different height, so that the vertical discontinuity of a setback in elevation is combined with the horizontal discontinuity of the reentrant corner, resulting in an even more serious problem.

The reentrant corner is perhaps the major irregularity that will be found in older buildings, including unreinforced masonry. In addition, in such buildings it is rare to find seismic separations at the intersections of the wings, so the prospects for torsion and stress concentration are high, when the wings are long and tall.

• Architectural Implications

Reentrant corners create a useful set of building shapes, enabling large plan areas to be accommodated in compact form, while still providing a high percentage of perimeter rooms with access to light and air. Thus such configurations are common for high-density housing and hotel projects, in which habitable rooms must be provided with windows.

Concerns for daylighting and natural ventilation that were prevalent during the energy crisis of the 1970's resulted in something of a revival of interest in the increased use of narrow buildings and the traditional set of reentrant corner

configurations. The courtyard form, most appropriate for hotels and apartment houses in tight urban sites, has always remained useful. In its contemporary form the courtyard often becomes a glass-covered atrium, but the structural form is the same.

• Historical Performance

Examples of damage to reentrant corner buildings are common, and this problem was one of the first to be identified by observers. It had been identified before the turn of the century, and by the 1920s was generally acknowledged by the experts of the day. Naito⁽⁶⁻⁸⁾ attributed significant damage in the 1923 Kanto earthquake to this factor. The same damage phenomena were reported for the 1925 Santa Barbara and 1964 Alaska earthquakes (Figure 6-15), and for the 1985 Mexico City earthquake. Large wood frame apartment houses with many reentrant corners are common in Los Angeles and suffered badly in the Northridge earthquake of 1994.

• Solutions

There are two basic alternative solutions to this problem: to separate the building structurally into simple shapes, or to tie the building together strongly at lines of stress concentration and locate resistance elements to reduce torsion.

If a decision is made to use separation joints, they must be designed and constructed correctly to achieve the intent. Structurally separated entities of a building must be fully capable of resisting vertical and lateral forces on their own. To design a separation joint, the maximum drift (or some reasonable criterion) of the two units must be calculated by the structural engineer. The worst case is when the two units would lean towards one another simultaneously, and hence the dimension of the separation space must allow for the sum of the deflections. In a tall building the relative motion between portions of the building will become very large, and create major problems of architectural detailing.



Figure 6-15. Damage concentrated at the intersection of two wings of an L-shaped school, Anchorage, Alaska, 1964

One of these is to preserve integrity against fire and smoke spread. The MGM Grand Hotel in Las Vegas is a T-shaped building in plan, with seismic joints approximately 12 in. in dimension. In the fire of 1983 these joints allowed smoke to propagate to the upper floors, resulting in many deaths.

Several considerations arise if it is decided to dispense with separation joints and tie the building together. Collectors at the intersection can transfer forces across the intersection areas, but only if the design allows for these beam like members to extend straight across without interruption. Walls in this same location are even more efficient than collectors. (Figure 6-16).

Since the free end of the wing tends to distort most under tension, it is desirable to place resisting members at this location.

The use of splayed rather than right-angle reentrant corners lessens the stress concentration at the notch, which is analogous to the way a rounded hole in a steel beam creates less stress concentration problems than a rectangular hole, or the way a tapered cantilever beam is more desirable than one that is abruptly notched (Figure 6-17).

6.6.2 Variations in Perimeter Strength and Stiffness

• **Definition**

This section discusses the detrimental effects of wide variations in strength and stiffness in building elements that provide seismic resistance and are located on the building perimeter

• **Seismic Effects**

If arranged to provide balanced resistance perimeter resistance elements are particularly effective in reducing torsional effects because of their long lever arm relative to the center of resistance. If the resistance is not balanced, the detrimental effects can be extreme.

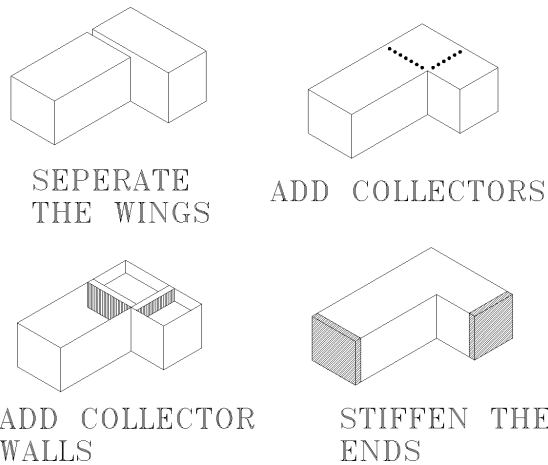


Figure 6-17. Solutions to the L-shaped building

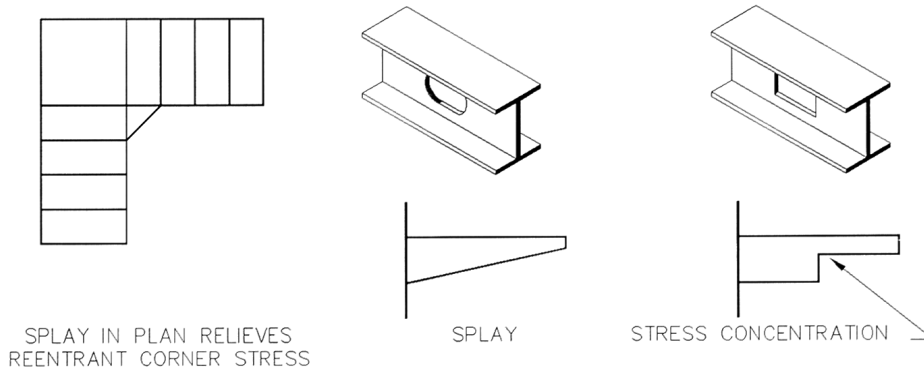


Figure 6-16. Splay in plan relieves reentrant corner problem: analogies to beam

This problem may occur in buildings whose configuration is geometrically symmetrical and simple, but nonetheless irregular for seismic design purposes. If there is wide variation in strength and stiffness around the perimeter, the centers of mass and resistance will not coincide, and torsional forces will tend to cause the building to rotate around the center of resistance. This effect is illustrated in Figure 6-18.

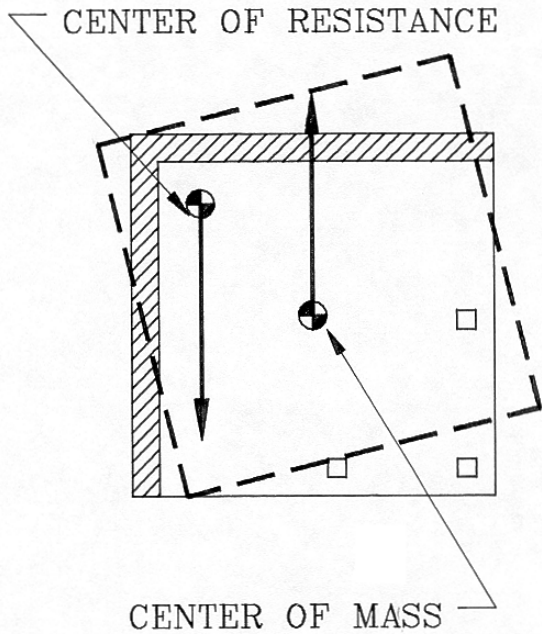


Figure 6-18. Torsional response

A common instance of this problem is that

of the open-front building. The weaknesses of open-front designs have been discussed by Degenkolb⁽⁶⁻⁹⁾:

Figure 6-19 shows the plans of three similar buildings, each with three shear walls so arranged that there is an open end and therefore major torsions in the building. If the buildings are similar, with uniform shear elements (uniform distribution of stiffness) and considering only shear deformations, it can rather simply be proved that the torsional deflection of the open end varies as the *square* of the length of the building.

• Architectural Implications

A common example of this condition occurs in store front design, particularly on corner lots, and in free-standing commercial and industrial buildings with varied openings around the perimeter. A special case is that of fire stations that require large doors for the movement of equipment. In these buildings it is particularly important to avoid major distortion of the front opening, for example if the doors jam and cannot be opened, the fire station is out of action at a time when its equipment is most needed.

Tilt-up concrete industrial and warehouse buildings, in which lateral resistance is provided by the perimeter walls, often also require a variety of openings for entrances, loading docks, and office windows, with a

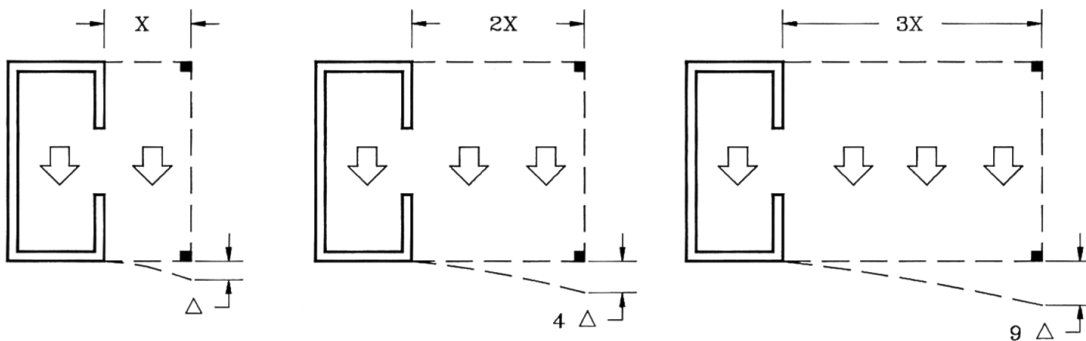


Figure 6-19. Open front design: torsional deflection varies as the square of the length

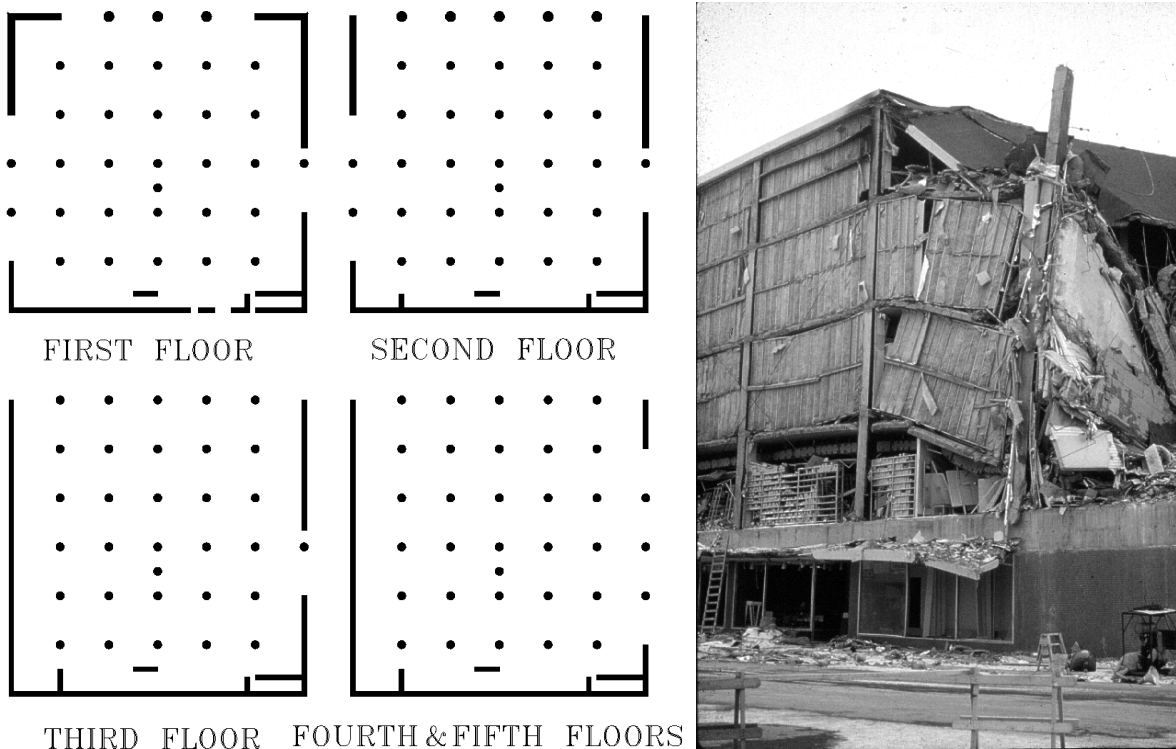


Figure 6-20. J.C.Penney department store, Anchorage, Alaska, 1964 Note: unbalanced location of perimeter walls, particularly on third, fourth and fifth floors, leading to severe torsional forces and near collapse.

consequent variation in seismic resistance around the perimeter.

• Historical Performance

A classical instance of this problem occurred in the J.C.Penney Department Store in Anchorage, Alaska, in the 1964 earthquake. The building was so badly damaged that it had to be demolished. The store was a five-story building of reinforced-concrete construction. The exterior walls were a combination of poured-in-place concrete, concrete block, and precast concrete nonstructural panels which were heavy, but unable to take large stresses. The first story had shear walls on all four elevations. The upper stories, however, had a structurally open north wall, resulting in U-shaped shear wall bracing system (similar to a typical open-front store) which, when subjected to east-west lateral forces, would result in large torsional forces (Figure 6-20).

A special case is also that of apartment house and hotels that are oriented to a view, such as a beach, which implies the need for large openings on the view elevation. The El Faro building was a small apartment house located facing the beach in the Chilean resort town of Vina del Mar. In order to exploit the view, two elevations are open: the stairs and elevator shaft are concentrated to the rear of the building and their walls provide the seismic resistance. The result is a wide eccentricity between the centers of mass and resistance. In the Chilean earthquake of 1985, this building rotated and very nearly collapsed: it was subsequently demolished. (Figure 6-21)

• Solutions

The objective of any solution to this problem is to reduce the possibility of torsion, and to balance the resistance around the

perimeter. Four alternative strategies can be employed, and are shown in Figure 6-22.



Figure 6-21. El Faro apartments, Vina del Mar, Chile, 1985

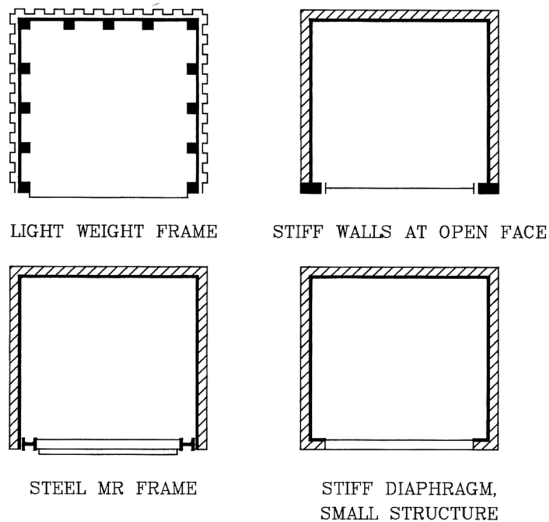


Figure 6-22. Solutions to open front buildings

The first approach is to design a frame structure with approximately equal strength and stiffness for the entire perimeter. The opaque portions of the perimeter can be constructed of nonstructural cladding material that will 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.

A second approach is to increase the stiffness of the open facades by adding shear walls at or near the open face. This solution is, of course, dependent on a design which permits this solution.

A third solution is to use a very strong moment-resisting or braced frame at the open front, which approaches the solid walls in stiffness. The ability to do this will be dependent on the size of the facades: along steel frame can never approach a long concrete wall in stiffness. This is, however, a good solution for wood frame structures, such as apartment houses with a ground floor garage space, because even a rather long steel frame can be made to approach plywood walls in stiffness.

Finally, the possibility of torsion may be accepted and the structure designed to resist it. This solution will only apply to small structures with stiff diaphragms, which can be designed to act as a unit.

6.6.3 Nonparallel Systems

• Definition

The vertical load resisting elements are not parallel or symmetric about the major orthogonal axes of the lateral-force resisting system.

• Seismic Effects

This condition results in a high probability of torsional forces under a ground motion, because the centers of mass and resistance cannot coincide for all directions of ground motion. Moreover, the narrower portions of the

building will tend to be more flexible than the wider ones, which will increase the tendency to torsion.

The problem is often exacerbated by perimeters with variations of strength and stiffness (Figure 6-23). A characteristic form of this condition is the triangular or wedge-shaped building that results from street intersections at an acute angle. These forms often employ a solid, stiff party wall in combination with more open flexible facing the street. The result is a form that is very prone to torsion.

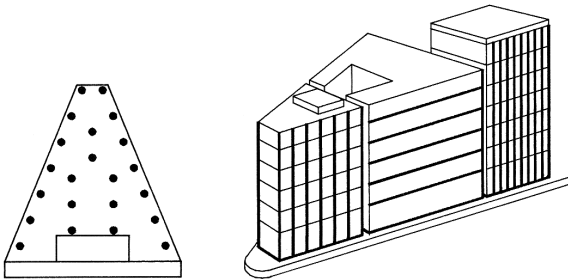


Figure 6-23. Wedge shaped plan: invitation to torsion

• Architectural Implications

Non-rectilinear forms have become increasingly fashionable in the last few years as a reaction against the rectangular "box". Forms that are triangular, polygonal, or curved have become commonplace, even in very large buildings. However, in some instances the desired forms can be achieved by nonstructural elements attached to a structure which may be essentially regular and rectilinear. (Figure 6-24) Extreme forms of non-rectilinearity are a feature of "deconstructionist" architecture, which is discussed in Section 6.11.

The traditional, trapezoidal or "flatiron" form resulting from the street-layout constraints is still common in high-density urban locations.

• Historical Performance

This form has been fairly recently identified as a problem configuration. The form was not identified as irregular in the 1890 SEAOC

Commentary, but it is identified as irregular in the 1988 UBC, the 1990 SEAOC Commentary, and subsequent codes and provisions.

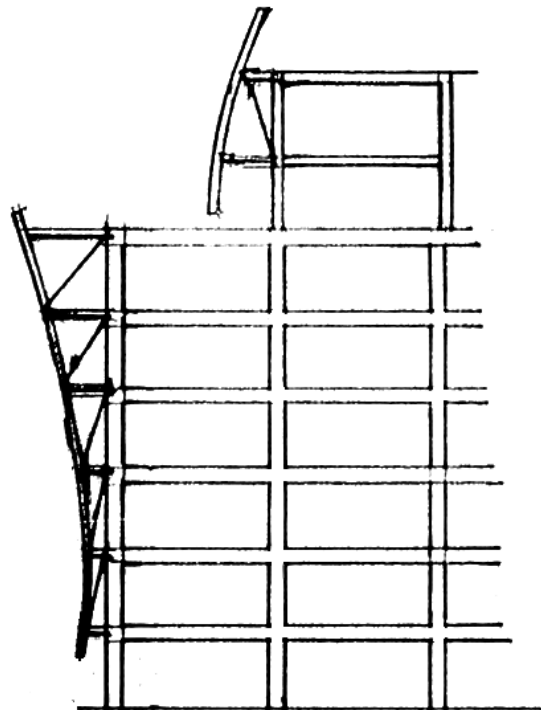


Figure 6-24. Form achieved by nonstructural attachments to main

Many buildings of this type were constructed in Mexico City, resulting from the high density and street layout of the city, and instances of poor performance were observed in the 1985 earthquake. Many buildings suffered severe distortion, particularly wedge-shaped buildings with stiff party walls opposite the apex of the triangular form (Figure 6-25). In many cases the condition was exacerbated by other irregularities such as a soft story.

• Solutions

Since 1988 the UBC and the NEHRP *Provisions* place some special requirements on the design of these types of configuration. Particular care must be exercised to reduce the effects of torsion. In general, opaque walls should be designed as frames clad in



Figure 6-25. Distortion in wedge-shaped building, Mexico City, 1985

lightweight materials, to reduce the stiffness discrepancy between these walls and the rest of the structure.

Alternatively, special design solutions may be introduced to increase the torsional resistance of the narrow parts of the building, although this may be difficult to achieve while still retaining open facades or internal areas.

6.6.4 Diaphragm Configuration

- **Definition**

The diaphragm configuration is the shape and arrangement of horizontal resistance elements that transfer forces between vertical resistance elements.

- **Seismic Effects**

Diaphragms perform a crucial role in distributing forces to the vertical seismic-resisting elements. The diaphragm acts as a horizontal beam, and its edges act as flanges. Diaphragm penetration and geometrical irregularities are analogous to such irregularities in other building elements, leading to torsion and stress concentration.

The size and location of these penetrations is critical to the effectiveness of the diaphragm. The reason for this is not hard to see when the diaphragm is visualized as a beam: it is obvious that openings cut in the tension flange of a beam will seriously weaken its load-carrying capacity. In a vertical load system, a penetration in a beam flange would occur in either a tension or a compression area: in a lateral load system, the hole will be in a region of both tension and compression, since the loading alternates in direction.

When diaphragms form part of a resistant system, they may act in either a flexible or stiff manner. This depends partly on the size of the diaphragm (its area between enclosing resistance members or stiffening beams), and also on its material. The flexibility of a diaphragm, relative to the shear walls whose forces it transmits, also has a major influence on the nature and magnitude of those forces.

• Architectural Implications

Diaphragms are generally floors or roofs, and so have major architectural functions aside from their seismic role. The shape of the diaphragm is dependent on the overall plan form of the building, and how it can be subdivided by walls or collectors.

In addition, however, architectural requirements such as staircases, elevators and duct shafts, skylights, and atria result in variety of diaphragm penetrations. In some cases, as in the need for elevators in an L-shaped building, the logical planning location for elevators (at the hinge of the L) is also the area of greatest seismic stress.

• Historical Performance

Failures specifically due to diaphragm design are difficult to identify, but there is general agreement that poor diaphragm layout is a potential contributor to failure.

• Solutions

Diaphragm penetrations are a form of irregularity specifically called out in the 1990 SEAOC Commentary that requires engineering judgment. In addition, current codes and provisions specifically define such penetrations, and impose some additional requirements on the diaphragm design in such cases.

The general approach to the design of penetrations in diaphragms is to:

- Ensure that penetrations do not interfere with diaphragm attachment to walls or frames.

- Ensure that multiple penetrations are spaced sufficiently far from one another to allow reinforcing elements to develop their required capacity
- Ensure that collectors and drag struts are uninterrupted by openings

6.7 Vertical Configuration Problems

6.7.1 Soft and Weak Stories

• Definition

A soft story is one that shows a significant decrease in lateral stiffness from that immediately above. A weak story is one in which there is a significant reduction in strength compared to that above.

• Seismic Effects

The condition may occur at any floor, but is most critical when it occurs at the first story, because the forces are generally greatest at this level.

The essential characteristics of a weak or soft first story consist of a discontinuity of strength or stiffness, which occurs at the second-story connections. This discontinuity is caused because lesser strength, or increased flexibility, in the first story structure results in extreme deflections in the first story, which, in turn, result in a concentration of forces at the second story connections.

If all the stories are approximately equal in strength and stiffness, the entire building deflection under earthquake forces is distributed approximately equally to each story. If the first story is significantly less strong or more flexible, a large portion of the total building deflection tends to concentrate there, with consequent concentration of forces at the second-story connections. (Figure 6-26)

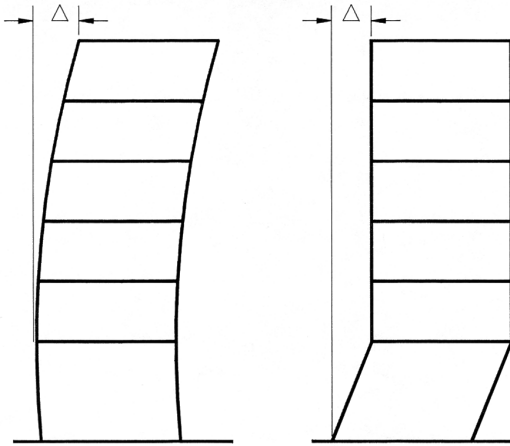


Figure 6-26. The soft-story effect

In more detail, the soft-story problem may result from four basic conditions. These are diagrammed in Figure 6-27 and are:

- A first-story structure significantly taller than upper floors, resulting in less stiffness and more deflection in the first story.
- An abrupt change of stiffness at the second story, though the story heights remain approximately equal. This is caused primarily by material choice: the use, for instance, of heavy precast concrete elements above an open first story.

- The use of a discontinuous shear wall, in which shear forces are resisted by walls that do not continue to the foundations, but stop at second floor level, thus creating a similar condition to that of the second item above.
- Discontinuous load paths, created by a change of vertical and horizontal structure at the second story.

The above characteristics, individually or in combination are readily identifiable in existing buildings provided that the building structure can be studied in its entirety, either in the field or by reference to accurate as-built construction documents.

• Architectural Implications

A taller first story often has strong programmatic justification, when large spaces, such as meeting rooms or a banking hall, must be provided at ground level. Similarly, an open ground floor often meets urban design needs by providing both real and symbolic access to a plaza or street, or by providing space at the base of a building. The changes in proportion provided by a high story, or the "floating box" concept (now somewhat outdated), are very real aesthetic tools for the architect, although engineers may find such concepts hard to rationalize in their terms.

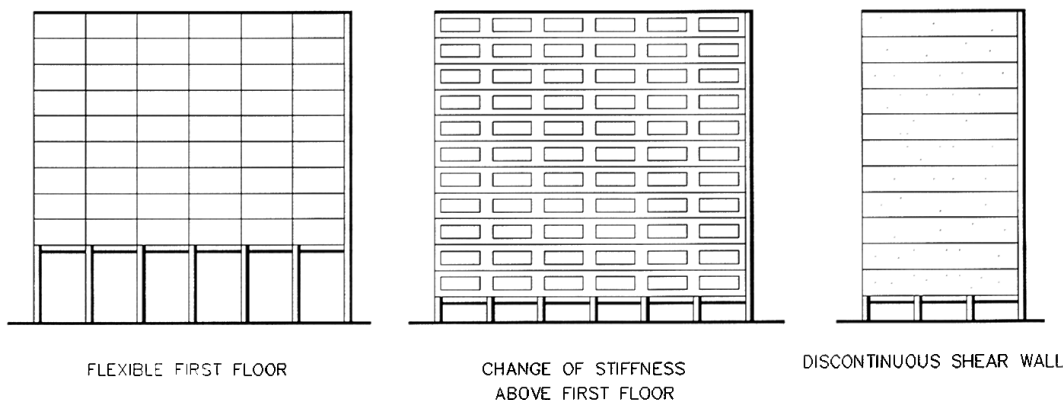


Figure 6-27. Types of soft story

Engineers must accept that some form of variation in the first story will remain a desirable architectural characteristic for the foreseeable future: whether it is "soft" or "weak" in seismic terms is a matter for the architect and engineer to resolve.

• Historical Performance

The general type of soft first story configuration was early identified as a problem. Failures in masonry buildings in the 1925 Santa Barbara earthquake were identified by Dewell and Willis⁽⁶⁻¹⁰⁾ as soft-first-story failures.

In more recent times, with extensive use of frame structures, damage to reinforced-concrete buildings in Caracas (1967) clearly identified the risk to tall buildings with this condition. In the Mexico City earthquake of 1985, researchers determined that soft first stories were a major contributor to 8% of serious failures, and the actual percentage is probably greater because many of the total collapses were precipitated by this condition.

The particular case of the discontinuous shear wall has led to clearly diagnosed failures in United States buildings. Olive View hospital, a new structure that was badly damaged in the 1971 San Fernando earthquake, represents a classic case of the problem.

The vertical configuration of the main building was a two-story layer of rigid frames on which was supported a four-story shear wall-frame structure (Figure 6-28). The second floor extended out to form a large plaza.

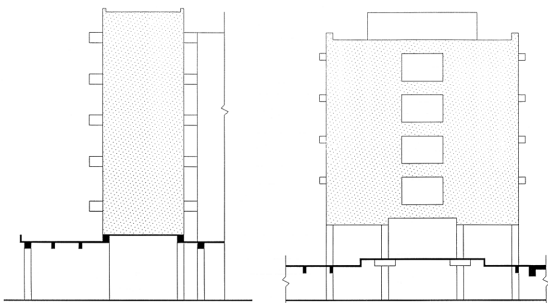


Figure 6-28. Olive View hospital, San Fernando, 1971 (a) elevation of stair towers (b) section through main building

The severe damage occurred in the soft-story portion: the upper floors moved so much as a unit that the columns at ground level could not accommodate such a huge displacement between their bases and tops and failed. The largest amount by which a column was left permanently out of plumb was 2 1/2 feet.

Though not widely identified, the stair towers at Olive View also show a clear and separate example of a discontinuous shear-wall failure. These seven-story towers were independent structures, and proved incapable of standing up on their own: three stair towers overturned completely, while the fourth leaned outwards 10 degrees. The six upper stories were rigid reinforced-concrete walls, but the bottom story was composed of six free-standing reinforced-concrete frames, which failed. The exception was the north tower, whose walls came down to the foundation directly without any discontinuity; this was the only tower to remain standing. Olive View hospital was demolished after the earthquake, and a new hospital built on the same site.

The performance of the Imperial County Services Building, El Centro, in the Imperial Valley Earthquake of 1979, provides another example of the effects of architectural characteristics on seismic resistance. The building was a reinforced-concrete structure built in 1969. In this mild earthquake the building suffered a major structural failure, resulting in column fracture and shortening (by compression) at one end—the east-of the building. (Figure 6-29). The origin of this failure lies in the discontinuous shear wall at that end of the building.

The fact that this failure originated in the configuration is made clear by the architectural difference between the east and west ends: this is an example of the large effect on seismic performance of a relatively small design variation between the two ends of the building.. The difference in location of the small ground-floor shear walls was sufficient to create a major difference in response to the rotational forces on the large end shear walls (Figure 6-30).

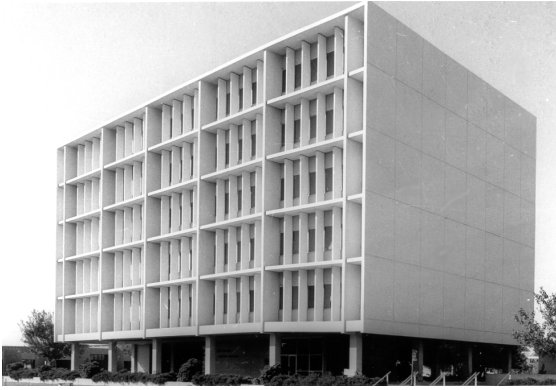


Figure 6-29. Imperial County Services Building, El Centro, California. failure of end bay at discontinuous shear wall, (Imperial valley earthquake of 1979)

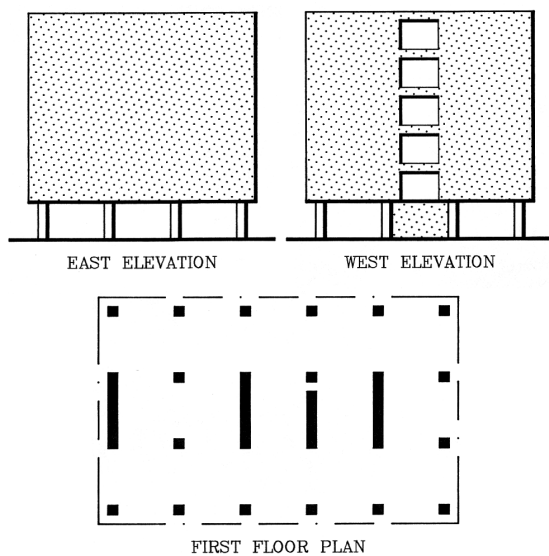


Figure 6-30. Imperial County Service Building, plan and elevations

A more recent instance is that of a medical office building in the Northridge earthquake of 1994, constructed at about the same time as the previous two buildings discussed. The simple rectangular building had discontinuous shear walls at each end. These proved inadequate to deal with the forces, with consequent severe torsional damage at each end of the building, (Figure 6-31) This building also had a structural discontinuity at the second floor that caused the "pancaking" of the second floor.

• Solutions

If a high first story is desired, either:

- Introduce bracing that stiffens the columns up to a level comparable to the superstructure.
- Add columns at the first story to increase stiffness, or
- Change the design of the first-story columns to increase stiffness.

If a large opaque wall is required in a location that could create a soft first story:

- Insure that such a wall is not part of the lateral load resisting system
- Reduce the mass of the wall by use of light material and hollow construction
- If a heavy wall is necessary, then insure that the wall is detached in such a way that the superstructure is free to deflect in a comparable way to the first floor

If the architect insists on such material and design constraints that a major discontinuous shear wall is the only solution, the engineer should refuse to do it. The liabilities involved in using such a proven failure mechanism are too great.

If the lateral resistance system is based on the use of an interior core (for a high-rise office building, for example), the perimeter columns may be tall, but there is no soft first story, provide the core is brought down to the ground. In such a building it is not difficult, if the core-plan dimensions are sufficient, to insure that the stiffness of a tall first story is adequate to prevent structural discontinuity at the second floor. One condominium building a good example of architect- engineer collaboration. That building achieved an elegant exterior appearance which appeared to be a soft first floor. However, the seismic resistance was provided by a strong interior box shear wall structure that enabled the taller first floor to be accommodated with ease. The building suffered



Figure 6-31. Discontinuous shear wall failure, office building, Northridge

virtually no damage in the strong Chilean earthquake of 1985.

It should be noted that in the 1997 NEHRP *Provisions* structures with a weak-story discontinuity in capacity that is less than 65% of the story above are not permitted over 2 stories or 30 feet in height in Seismic Design Categories B,C,D,E and F.

6.7.2 Columns: Variations in Stiffness, Short Columns, and Weak Column/Strong Beam.

• Definition

This section considers the use of columns of varying stiffness, by reason of either differences in length or deliberate or inadvertent bracing: the use of columns that are significantly weaker than connecting beams: and the use of columns

in one floor that are significantly shorter than those on other floors.

• Seismic Effects

Seismic forces are distributed in proportion to the stiffness of the resisting members. Hence, if the stiffness of the supporting columns (or walls) varies, those that are stiffer (usually shorter) will "attract" the most forces. The effect of this phenomenon is explained in Figure 6-32. The important point is that stiffness (and hence forces) varies approximately as the cube of the column length.

Similarly, a uniform arrangement of short columns supporting a floor will attract greater forces to that floor, with a corresponding possibility of failure. Typically such an arrangement may also involve deep and stiff spandrel beams, making the columns significantly weaker than the beams.

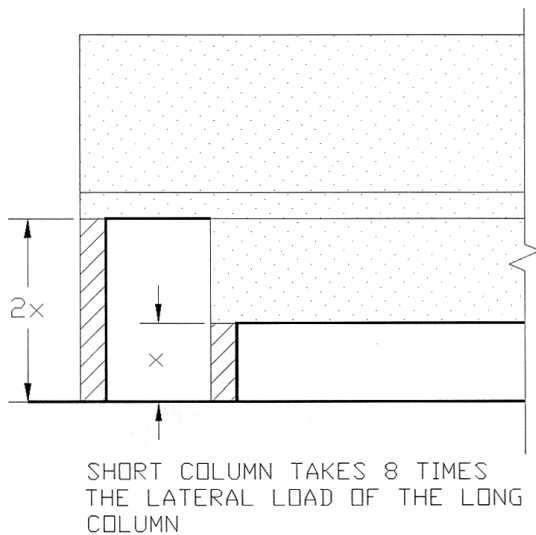


Figure 6-32. Effect of variations of column stiffness

Such a design is in conflict with a basic principle of seismic design, which is to design a structure in such a way that under severe seismic forces, *beams will deform plastically before columns*. This is based on the reasoning that as beams progress from elastic to inelastic behavior they start to deform permanently. This action will dissipate and absorb some of the seismic energy. Conversely, if the column fails first and begins to deform and buckle, major vertical compressive loads may quickly lead to total collapse.

Mixing of columns of varying stiffness on different facades may also lead to torsional effects, since the building assumes the attributes of varying perimeter resistance discussed above.

• Architectural Implications

The origin of variations in column stiffness generally lies in architectural considerations. Hillside sites, infilling of portions of frames with nonstructural but stiff material to create high strip windows, desire to raise a portion of the building of the ground on tall "pilotis", while leaving other areas on shorter columns, or stiffening some columns with a mezzanine or a

loft, while leaving others at their full, unbraced height.

These issues are important because their effects may be counterintuitive. For example, infilling may be done as a remodel activity later in the building life for which the engineer is not consulted, because intuition may suggest to the designer that he is strengthening it in the act of shortening it rather than introducing a serious stress concentration for which the structure was not designed. For vertical forces a reduction in the effective length of a column is beneficial because it reduces the likelihood of buckling, but the effect under lateral forces is quite different.

Variations in openings in different facades are often required from a daylighting or energy-conservation requirement. Where openings are created by variations in structural arrangement, rather than by variations in cladding, some of these conditions may well arise.

• Historical Performance

Significant column failures, sometimes leading to collapse, have been attributed to these conditions in a number of recent earthquakes, particularly in Japan, Latin America, and Algeria.

Many Japanese schools, employing short columns on one side of an elevation, or using a weak-column, strong-beam configuration, suffered severe damage in the Tokaichi-oki earthquake in 1968 and the 1978 Miyagi-ken-oki earthquake. (Figure 6-33)

In Latin America, the problem has frequently been caused by inadvertent stiffening of columns through nonstructural infill which, when combined with high glazing, creates short columns.

In the El Asnam (Algeria) earthquake of 1980, many apartment structure failures were caused by short columns used at ground level to provide a ventilated open space (called a "vide sanitaire") in a semi-basement location. The significant failure of a large condominium and hotel structure in the Guam earthquake of 1993 has been ascribed in part to the creation of a



Figure 6-33. Short column failure, school, Japan: Miyagi-ken -oki, 1978

short column condition by the introduction of nonstructural stiffening elements⁽⁶⁻¹¹⁾ (Figure 6-34)

• Solutions

The general solution is to match the detailed seismic design carefully to the architectural requirements. The weak-column, strong-beam condition can be avoided by insuring that deep spandrels are isolated from the columns; in the same way the lengths of columns around a facade can be kept approximately equal.

Horizontal bracing can be inserted to equalize the stiffness of a set of columns of varying height (Figure 6-35). Heavy nonstructural walls must be isolated from columns to insure that a short-column condition is not created. (Figure 6-36).

6.7.3 Vertical Setbacks

• Definition

A vertical setback is a horizontal, or near horizontal, offset in the plane of an exterior facade of a structure.

• Seismic Effects

The problem with this shape lies in the general problem of discontinuity: the abrupt change of strength and stiffness. In the case of this complex configuration, it is most likely to occur at the line of the setback, or "notch".

The seriousness of the setback effect depends on the relative proportions and absolute size of the separate parts of the building. In addition, the symmetry or



Figure 6-34. Short column failure, Guam, 1993



Figure 6-35. Horizontal bracing to stiffen a high open end entrance

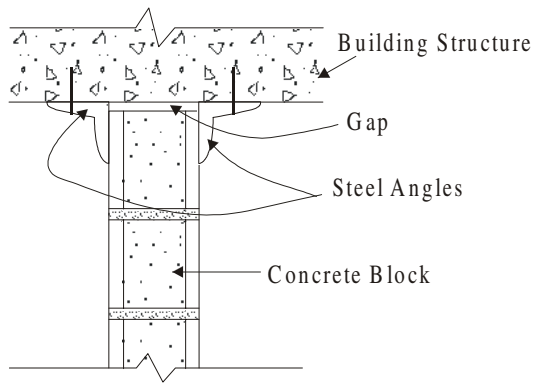


Figure 6-36. Heavy nonstructural wall isolated from structure at top and side

asymmetry in plan of the tower and base affect the nature of the forces. If the tower or base or both are dynamically asymmetrical, then torsional forces will be introduced into the structure, resulting in great complexity of analysis and behavior.

The setback configuration can also be visualized as a vertical reentrant corner. Stresses must go around a corner, because a notch has been cut out, preventing a more direct route. Hence, the smaller the steps or notches in a setback, the smaller the problem. A smooth taper avoids the notch problem altogether. A tapering beam will not experience stress concentrations, whereas a notched beam will.

Setbacks with shear walls in the tower portion that are not continued to the ground are highly undesirable. Besides the change of stiffness where the shear wall enters the base structure, the shear wall will transmit large forces to the top diaphragm of the base.

Although, typically, setbacks occur in a single building, the condition can also be created by adjoining buildings of different heights which have inadequate or nonexistent seismic separations.

• Architectural Implications

Setbacks may be introduced for several reasons. The three most common are zoning requirements that require upper floors to be set back to admit light and air to adjoining sites, program requirements that require smaller

floors at the upper levels, or stylistic requirements relating to building form.

Setbacks relating to zoning were common a few decades ago when daylighting was a major concern, and resulted in characteristic shapes of older high-rise buildings in New York and other large cities. Stylistic fashions replaced these forms with those of simple rectangular solids, made possible by advances in artificial lighting and air-conditioning. Now, there is a renewed interest in set-back shapes for stylistic reasons, while at the same time energy conservation requirements have reinstated a functional interest in setbacks for daylighting reasons.

An interesting example of this stylistic trend is that of the new planning code for San Francisco, which specifically mandates setbacks for large buildings in the downtown area. These represent relatively minor variations in the vertical plane of the facade, rather than the abrupt rising tower on a base, which is of more serious seismic consequence. The trend is, however, away from vertical structural continuity at the perimeter and thus introduces complexity and cost into the structural solution.

A type of setback configuration only made possible by modern framed construction is that of the building that grows larger with height. This type is termed *inverted setback* or *inverted pyramid* depending on its form. Its geometrical definition is the same as that of the setback, but, because of the problems of overturning, its extremes of shape are less. Nevertheless, some surprising demonstrations of this shape have appeared, and it appears to be one whose image has a powerful design appeal (Figure 6-37).

• Historical Performance

Although commonly identified as a configuration problem, severe failures of modern buildings attributed to this condition are few. While traditional towers, primarily churches, have suffered their share of failures, the number of those that have survived severe



Figure 6-37. Dallas City Hall : an inverted pyramid

damage is remarkable. An example from the Kobe earthquake of 1995 shows a failure in a setback building at the plane of weakness created by a combination of the setbacks and adjoining openings in the wall (Figure 6-38)

While there have been recorded failures of inverted-setback buildings, notably in the Agadir (Morocco) earthquake of 1960, some of the more striking examples have performed well. This is probably because the appearance of instability inherent in this form results in special attention being paid to its structural design. Typically, such buildings devote a much larger percentage of their construction cost to structure than more conventional buildings.

• Solutions

Setbacks have long been recognized as a problem, and so the Uniform Building Code has attempted to mandate special provisions for them currently, the earthquake regulations of the Code refer to setback configurations as follows:

Buildings having setbacks wherein the plan dimensions of the tower in each direction is at least 75% of the corresponding plan dimension of the lower part may be considered as uniform buildings without setbacks, provided other irregularities as defined in this section do not exist.

An appendix to the 1990 SEAOC Commentary to this section includes a lengthy discussion of the setback problem and an approach to its analysis .:

In general, conceptual solutions to the setback problem are analogous to those for its horizontal counterpart, the reentrant corner plan. The first type of solution consists of a complete seismic separation in plan, so that portions of the building are free to react independently. For this solution, the guidelines for seismic separation, discussed elsewhere, should be followed.



Figure 6-38. Failure of set-back building along a plane of weakness

When the building is not separated, the analysis proposed in the appendix to the 1990 SEAOC Commentary provides the best guidelines, with some necessary interpretations to fit the particular case. Particular attention should be paid to avoiding vertical column discontinuity, so that setbacks should be arranged to coincide with normal bay sizes (which may result in a series of small bays).

Any large building with major setback conditions should be subjected to special analysis, or at least to careful investigation of probable dynamic behavior. Finally, the inverted setback configuration of any extreme form and size should be avoided in seismic areas, unless the owner is willing to assume the considerable additional structural costs that will be incurred.

The 1997 NEHRP *Provisions*, as noted earlier, permit vertical setback configurations to be analyzed using the simple ELF method if the stiffness on the top story of the base is at least

five times that of the first story of the tower. The UBC permits use of the standard ELF method for a two-stage analysis of tower and base if the average story stiffness of the base is at least 10 times greater than the average story stiffness of the tower.

6.8 STRUCTURALLY RESTRICTIVE ARCHITECTURAL DETAILING

6.8.1 Components and Connections

• Definition

By *structurally restrictive detailing* we mean detailed architectural design of a component that prevents good seismic design practice in the structural design.

• Seismic Effects

This problem represents a micro version of typical overall building configuration problems. Architectural detailing may place dimensional or location constraints on structural design resulting in weakness or eccentricity of force actions that can lead to stress concentration or local torsion. The problem is most critical at beam-column connections, which are highly stressed, but often represent a critical element in the aesthetic scheme of the building.

Structural detailing ideally provides for direct load transfer and minimum local eccentricity, with forces resolved at a point. Architectural detailing may result in inadequate size and eccentric or discontinuous load paths (Figure 6-39). The problem is particularly critical for reinforced-concrete structures, where constraints may provide inadequate room for proper placing of reinforcing.

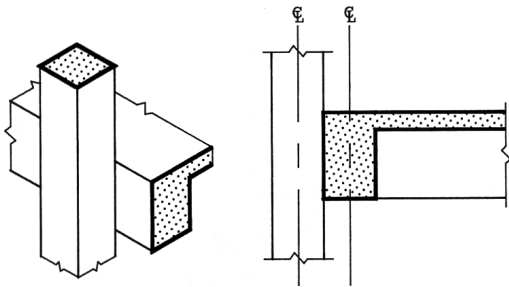


Figure 6-39. Eccentric load paths created by architectural detailing of structural connection

• Architectural Implications

Detailed design is an important element in architectural expression. As an example, the design of the perimeter beam-column connection can provide the building with a predominantly horizontal, vertical, or neutral emphasis. (Figure 6-40). But the structural implications of these variations may not be understood by the architect. Another example is the use of taper or the insertion of recesses in columns. Tapered columns may be a correct

expression of structural forces, and be easy to accommodate, or they may directly contradict structural action and lead to weakness. Recesses are often designed by architects to accentuate the line at which materials meet one another, particularly when the materials are different or meet at right angles, as in a column-slab junction.

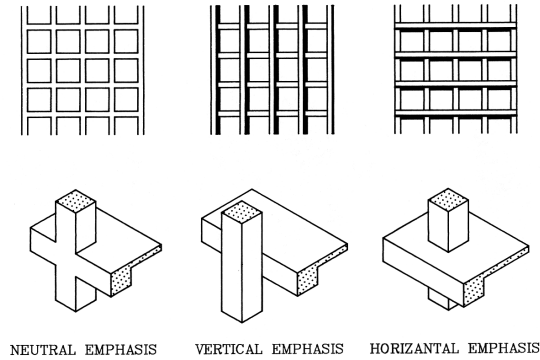


Figure 6-40. Facades: differences in architectural emphasis

• Historical Performance:

Specific performance attributable to this condition is difficult to document but the problem is generally recognized by engineers. Two well documented cases do exist where architectural detailing contributed to failure.

The first is that of the column design of the Olive View Hospital, damaged in the 1971 San Fernando earthquake (discussed previously as an example of soft-first-story failure.). A significant difference in performance was observed between corner and internal columns in this building. The twelve L-shaped corner columns were completely shattered and their load-carrying capacity reduced almost to zero. The interior columns, of square section, had spiral ties, and although they lost most of their concrete cover, they retained load-carrying capacity and probably saved the building from collapse. Because of their architectural form, it was not possible for the corner columns to use spiral ties (Figure 6-41). Higher stress and torsion in the corner columns may also have contributed to their poor performance.

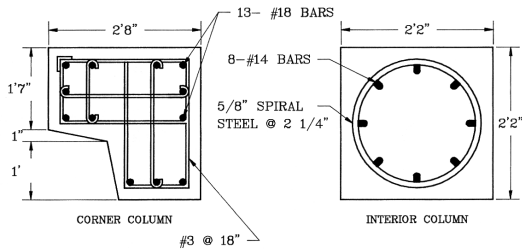


Figure 6-41. Exterior column sections at Olive View Hospital, San Fernando, California. Due to their shape, corner columns could not be spirally reinforced

The Imperial County Service Building at El Centro, California, suffered severe damage in the 1979 Imperial Valley earthquake, and four columns at one end of the building were badly shattered. Detailed study of these columns showed that an architectural recess had been placed at the line where the columns met the ground. (Figure 6-42). This recess caused a reduction in sectional area of the column and a reduction in axial load-carrying capacity. Analytical and experimental studies have shown that this change in column section accentuated the undesirable performance of these columns⁽⁶⁻⁷⁾.

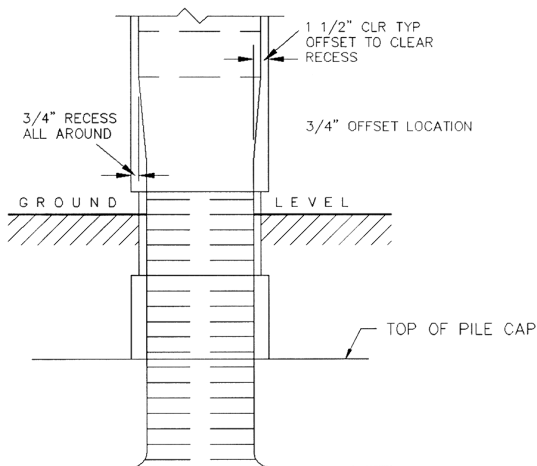


Figure 6-42. Column detail, Imperial County Services Building, El Centro, California. Note architectural recess affecting reinforcement continuity

• Solutions:

Close coordination between architect and engineer is necessary to insure that architectural detailing does not result in undesirable structural design constraints.

6.9 PROBLEMS OF ADJACENCY

6.9.1 Pounding

• Definition:

Pounding is damage caused by two buildings, or different parts of a building, hitting one another.

• Seismic Effects:

Pounding as characterized in Codes and Guidelines and in most analytical research studies takes the form of in plane displacements of two adjacent buildings, as in the investigation of a row of adjacent buildings by Athanassiadou et al⁽⁶⁻¹²⁾. Empirical observation shows that building separations are complex in their basic conditions and in their effects, and lack of separation is not necessarily detrimental.

Observation has shown that the end buildings of a row of adjacent buildings tend to suffer more damage than interior buildings. Analytical pounding studies consider regular buildings in elevation. In fact, the sway characteristics of buildings are much influenced by irregularities, particular that of soft first stories, that can lead to extreme displacements or even collapse. Some of these characteristics are shown in Figure 6-43. Similarly, analytical studies have always assumed regular buildings in plan. Since adjacent buildings with little or no separation will generally be found in the older sections of down town, building plans are often very irregular, leading to torsional effects under ground motion. These characteristics are shown in Figure 6-44.

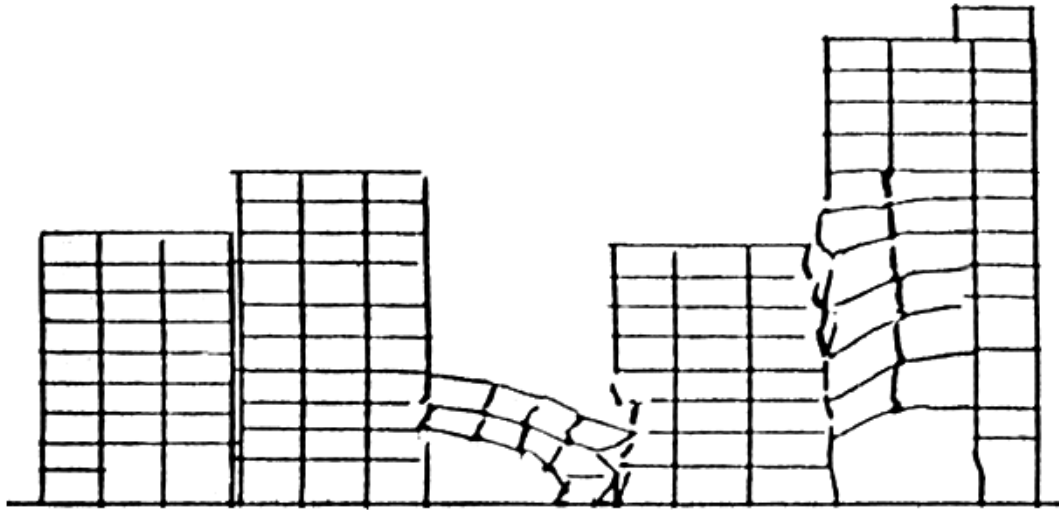


Figure 6-43. Irregularities may create extreme displacements or collapse

Study of pounding damage in Kobe in 1995 showed that very large deflections were often caused by design flaws (such as a soft first story) or near source extreme shaking velocities, or a combination of the two. In addition, many instances of large building deflections (or "leaning") related to ground/foundation failures. These effects are not accounted for in code type separation requirements, which assume a uniform deflection for the height of the building, related only to ground motion.

Observation has also shown that, in some cases, the close proximity of buildings may act as a support, particularly for buildings in mid-block, and increasing the space between buildings might serve, in some cases, to increase deflections and damage rather than reducing them. A probable instance of this was observed by the author in Mexico City, in 1985. In this instance, a tall slender building with an apparent serious soft first story problem, appeared to be restrained by low, stiff buildings on either side. (Figure 3). Several instances of this phenomenon were observed in Kobe.

This point is very difficult to assess. The response to shaking of a number of adjacent buildings with essentially no separation between them must be equivalent to the response of a large building with a variety of strengths, stiffness and other structural characteristics which would be very difficult to analyze.

The possibility of pounding is a function of the vertical deflection or drift of adjoining buildings (or parts of a building). Drift is calculated by applying the code design forces to the building and then observing the deflections that result. Since these estimated forces will be less than what we know can occur, calculated deflections must be corrected to obtain a more realistic estimate of how much the building may actually move. Alternatively, an accurate estimate of drift may be made that accounts for all foreseeable factors.

Potential pounding presents some particular problems of a socio-economic nature where existing buildings are concerned. The socio-economic problems consist of how to involve the adjoining building owner in possibly costly studies, design and construction work that the owner may not wish to participate in or may

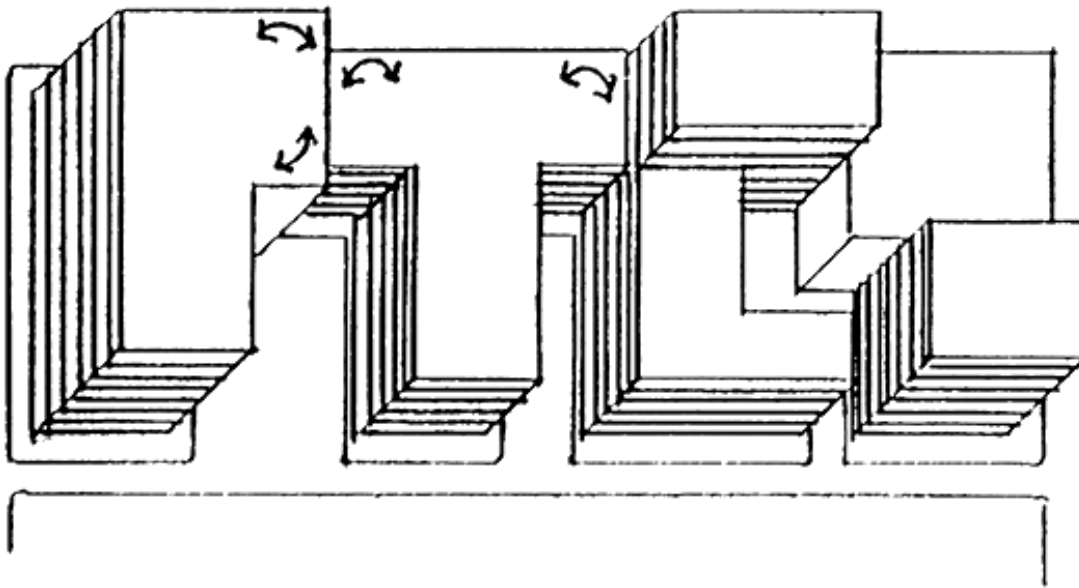


Figure 6-44. Irregularities in plan may create additional torsional effects that impact adjoining buildings

even actively oppose them. The problems are particularly critical in the case of common structure, because rehabilitation is very difficult, if not impossible, without the neighbor's involvement and probably some degree of rehabilitation to his property. In the case of falling hazards, it would be desirable for the neighbor to mitigate them, but the extent to which the federal owner can require this are not clear. The problem of pounding is traditionally dealt with by requiring a large gap between buildings. This can, in theory, be achieved without impacting the adjoining owner.

While in engineering terms it may seem obvious that it is in the adjoining owners best interest to cooperate in evaluation and mitigation, in socio-economic terms there may be many reasons, valid or otherwise, for reluctance. The owner may have real economic constraints in incurring any costs of evaluation or mitigation, and be quite ready to accept the possible risks of inaction. In addition, the owner may have short term intentions of redeveloping or selling his property, and so not wish to incur

expenses that will be of no conceivable benefit to him. Thus, the possibility of cooperative rehabilitation will be much conditioned by how the adjoining owner sees his economic future and views unsolicited action by a neighbor that might impact it.

• Architectural Implications

Pounding is included in this discussion of configuration issues because it is a matter of where buildings are located relative to other structures, which is an early architectural decision. The problem has considerable architectural implications for the construction of buildings on constricted urban sites, because to make provision for the worst case condition could result in large building separations and significant loss of usable space.

While building codes place modest limits on drift (for example, 0.005 time story height) based on static analysis, actual experience with drift and calculations of realistic figures provide some startling numbers. Freeman⁽⁶⁻¹³⁾ calculated

the actual drift on flexible buildings up to 20 stories under 0.4 g acceleration as being 0.020 - 0.055 times the story height. For a 12 -story building this translates into 40-110 in. for a 14-ft story height. A separation that could accommodate two such buildings vibrating out of phase would have to be 18 ft. 4 in. wide.

Clearly compromise is necessary, but nonetheless, loss of usable space measured in lineal feet becomes serious. In addition, the idea of urban buildings with spaces of 2 - 3 feet between them suggests a very difficult maintenance problem.

● Historical Performance:

Problems of adjacency have been routinely noted by earthquake investigators over the past several decades. In the 1972 Managua earthquake, the five-story Grant Hotel suffered a complete collapse of its third floor when battered by the roof level of the adjacent two-story building.

In the 1964 Alaska earthquake, the 14-story Anchorage Westward Hotel pounded against its low rise ball room and an adjoining six-story wing, although separated by a 4-in. gap. The pounding was severe enough in the high rise to dislocate some of the metal floor decking from its steel supports.

In recent earthquakes, pounding has continued to be a serious issue. The earthquake that struck Mexico City in 1985 has revealed the fact that pounding was present in over 40% of 330 collapsed or severely damaged buildings surveyed, and in 15% of all cases it led to collapse. Many instances of pounding were observed in the Kobe earthquake of 1995.

● Solutions:

Perhaps due to the high incidence of pounding damage observed in the 1985 Mexico City earthquake a number of researchers have studied pounding problems in recent years. Two recent studies, by Jeng et al.⁽⁶⁻¹⁴⁾ and the study by Athanassiadou et al.⁽⁶⁻¹²⁾ are representative, and both contain a full set of references to other

studies of the problem. Jeng et al. present a new method for estimating the likely minimum building separation necessary to preclude seismic pounding: two 10 story concrete frame buildings are analyzed by way of example.

Athanassiadou et al. studied the seismic response of adjacent buildings in series, with similar or different dynamic characteristics, using SDOF systems subjected to base motions.

These, and other studies, confirm the results of empirical surveys, and to provide quantitative information that is necessary for code and design practice development, although as yet the quantitative data is not readily transferable to code values.

To assume that code limits on drift provide an accurate estimate of possible drift is unrealistic, but accurate estimates may provide very large worst case figures. Blume, Corning and Newmark suggest an alternative method⁽⁶⁻¹⁵⁾:

Compute the required separation as the sum of the deflections computed for each building separately on the basis of an increment in deflection for each story equal to the yield-point deflection for that story, arbitrarily increasing the yield deflections of the two lowest stories by multiplying them by a factor of 2.

An earlier edition of the Uniform Building Code contained a rule of thumb intended for the relatively stiff structures of that day⁽⁶⁻¹⁶⁾: separations should be " one inch plus one half inch for each ten feet of height above twenty feet".

It should be noted that, notwithstanding the high cost of land in Japanese cities, new structures in Kobe seem to be providing a generous allowance for differential drift.

A possible alternative approach is to place an energy-absorbing material between the buildings; this obvious simple approach seems to have been little studied.

Many buildings in Mexico City were, in fact, protected from collapse because they were erected hard up against adjoining buildings on

both sides, so that whole blocks of buildings acted as a unit, and the group was stronger than the individual structures. As evidence of this, Mexican studies showed that 42% of severely damaged buildings were corner buildings, lacking the protection of adjoining structures. This finding suggests the need for serious research on the subject of allowable drift, pounding, and the design and construction of closely spaced buildings.

6.9.2 Other Adjacency Problems

Two other problems of adjacency give cause for concern: one is that of damage caused to a building by falling portions of an adjoining building: in the 1989 Loma Prieta earthquake a death was caused in downtown Santa Cruz when a portion of unreinforced masonry wall fell through the roof of a lower adjoining building, and six deaths were caused in San Francisco when part of a masonry wall fell on some parked cars. The other adjacency problem is that created by structural elements - generally walls or columns - that are common to adjoining buildings: while instances of damage caused by this condition are not specifically identified, there is a clear problem when an owner wishes to rehabilitate a building which has structural elements common to an adjoining building that is not undergoing related rehabilitation.

6.10 THE ARCHITECT/ENGINEER RELATIONSHIP

6.10.1 Architect-Engineer Interaction

In the United States the architect/engineer relationship is delicate because typically the engineer is employed by the architect, and if he complains too much about the architect's design he may be replaced. An architect who finds his design criticized by his engineer can generally find an alternative engineer who will

accommodate him. It is extremely hard to ascertain whether this second engineer reaches this accommodation because he is more ignorant than his colleague, more of a gambler, or more inventive and clever.

There are, of course, many instances where architects and engineers have built up close relationships and communicate fruitfully, with the engineer participating at an early stage of design. However, even in these instances the pressure of business often means that, for financial reasons, the engineer is not employed until the building schematic design is complete. This applies particularly to private work, where the developer must have a design- perhaps only a three dimensional sketch -in order to procure financing, and he does not want to incur additional consultant costs until the financing is secured.

The following description is of the preliminary design process of a large U.S. architectural for a client in the Pacific Rim:

".. we developed a method whereby we would send a team of three people for a week, working in the client's office, or from a hotel room, but having client input into daily charettes, lots of alternatives in sketch form, not spending many hours of presentation, but spending the hours on design. At the end of the week we would generally have a viable concept that the client had signed off."⁽⁶⁻¹⁷⁾

Thus the schematic design for a multi-million dollar project is completed in a week: presumably the design is then brought to the engineer for him to insert a structure.

Obviously, in this instance, much depends on the knowledge and experience of this three person team to ensure that the design is structurally reasonable. More risky is when analogous processes are conducted by a single architect with a desire to produce a design that will amaze his client.

In seeking improved architect/engineer interaction a number of conditions must apply:

- The engineer must communicate directly with the architectural design person or team
- The architect must take seriously his shared responsibility with the engineer for the seismic performance of the building. Recent experiences, such as Northridge and Kobe, should encourage this attitude.
- Mutual respect and cooperation: an adversarial relationship will not be productive.
- Common language and understanding:

The architect must have some understanding of seismic engineering terms -such as acceleration, amplification, base shear, brittle failure, damping (and so on through the engineering glossary). At the same time the architect should have a general understanding of the characteristics of typical seismic structural concepts: shear walls, bracing, moment frames, diaphragms, base-isolation etc. The new concepts of performance -based seismic design should also be understood. In turn the engineer must understand the architect's functional needs and aspirations.

- Collaboration must occur at the onset of a project: before architectural concepts are developed or very early on in their conception
- Business conditions that restrict early architect/engineering interaction must be alleviated (by the use of a general consulting retainer fee, for example, recovered from those projects that are achieved).
- If the architect does not want to interact with his engineer, or if for some reason is prevented from doing so, then he should work with simple regular forms, close to the optimal seismic design

While it is reasonable for engineers to ask that architects become better informed about seismic design and the consequences of their configuration decisions, the engineer must understand that while for them seismic design is

of paramount importance, for architects and their clients it takes very low priority as far as their own interests. For the architect, seismic design and safety is taken care of by the engineer: it is no more a subject of concern than provision for vertical forces, which never comes up for discussion between owner and architect, and seldom between architect and engineer. The architect is preoccupied with issues of codes and regulations relating to planning and design far removed from seismic problems, but of great importance and interest to his client. Similarly, the architect is continuously evaluating planning options, materials issues and both functional and aesthetic concerns upon which his client is constantly questioning him. Above all, the work must be done on time and on budget, and the architect would also like the job to be profitable.

Architects vary greatly in their interests: the stereotype of the architect as an unworldly aesthete is seldom true. Some architects are brilliant salespeople and business managers: some are very close to engineers, and interested in how the building is engineered and constructed: some are excellent project managers and will ensure that budgets and schedules are kept: some are inspiring managers of people and will run an exciting and enjoyable office: some are brilliant at the design of details, the behavior of materials and the development of construction documents: and some are thoughtful and inventive designers. The large, well-run office will have a mix of the above in its staff. The small office must try and find a few people that combine the above roles. As the profession of architecture becomes more complex, specialization is becoming more common: even large firms cannot play all roles, and the small office must specialize in a limited type of design. The advent of CAD and other information systems has extended the range for the small practitioner, but these systems need large capital investments that produce their own forms of limitation.

6.11 Future Images

6.11.1 Beyond the International Style

The tenets of the International Style began to be seriously questioned in the mid-1970's, both in print by architectural critics and historians and in practice by architects beginning to bring new design approaches to the drawing board and to construction. This questioning finally bore fruit in an architectural style known broadly as "Post-modern". Although this term was criticized by critics and the architects who were seen to be designing in this style, the term became a useful mark of identity. In general, post-modernism meant:

- the revival of surface decoration on buildings
- a return to symmetry in overall form
- the use of classical forms, such as arches, decorative columns, pitched roofs, in nonstructural ways, and generally in simplified variations of the original elements.
- a revival of exterior color as an element, with a palette of characteristic colors (e.g. dark green, pink, Chinese red, bright yellow, buff etc)

Developments of post-modernism also involved both the revival of full, scholarly, classical revival as a style., and also very personal images by a few prominent architects in terms of scale and forms, which were derived from a variety of sources, such as Victorian engineering, ancient Egyptian architecture and non-Euclidean geometry.

In seismic terms, this change in stylistic acceptance was, if anything, beneficial. The return to classical forms and symmetry was helpful to the structure as a whole, and almost all of the decorative elements were nonstructural. Inspection of an early icon of post-modernism, the Portland office building designed by Michael Graves, (Figure 6-45). shows an extremely simple and ordinary structure. Indeed, the Portland building, which created a sensation when completed, has a form

that approximates our optimal structure: the sensation is all in the nonstructural surface treatments. Designed as an economical design/build project the building has recently undergone seismic retrofit unrelated to its configurational characteristics.

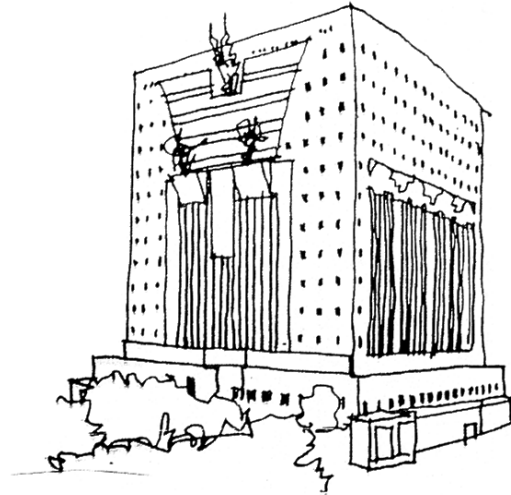


Figure 6-45. Office building, Portland, Oregon. Michael Graves, architect, 1979

It should be noted, however, that an interest in seismic design had no influence on the development of post-modernism - it is, and was a strictly aesthetic and cultural movement.

At the same time that post-modernism was making historical architectural style legitimate again, another style evolved in parallel: This style, originally christened "hi-tech" (the term has not stuck) returned to the celebration of engineering and new industrial techniques and materials as the stuff of architecture. This style developed primarily in Europe, notably in England and France, and was exemplified in a few seminal works, such as the Pompidou Center in Paris, the Lloyds building in London, and the Hong Kong and Shanghai bank in Hong Kong. These buildings proclaimed a new version of the functionalism of the thirties, updated to provide flexibility, adaptability and advanced servicing for an uncertain future, using exposed structure with beautiful castings as connections. In truth, these buildings are as

aesthetically and stylistically conceived as any post-modern or classical revival building.

The rise of post-modernism released architects from the strait-jacketed moralities of the International Style. As a result, at present a kind of aesthetic bedlam reigns, and several competing private styles co-exist, competing for clients - and finding them. The leading exponents of the new styles form an architectural jet-set, cruising the world dropping off their stylistic gems to clients and countries that can afford them.

The importance of well-publicized designs by fashionable architects is that they create new accepted styles. Architects are very responsive to form and design and once a form 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 became clear in the adoption of the metal and glass curtain for building exteriors. The first two highly publicized curtain walls were that of the United Nations building and the Lever Brothers building, both in New York city in the early 50's; by the mid 60's every town in America had its stock of blue-green glazed commercial buildings.

So, to predict the design vernacular of the future it is necessary to look at what is being done in high-style architecture, and in particular, to try and guess which forms seem to be catching the imagination of architects and starting to be reproduced at a more modest level. Amid the bedlam of design voices, three influential trends can be discerned..

6.11.2 Influential Trends

- **The bridge building:**

The bridge building form is that of twin high-rise buildings connected at the roof with horizontal occupied space that acts as a bridge. The concept is that of a single building. The prototypical form of this, that has seized architect's imaginations, is that of the Grand Arch of the Defense (Figure 6-46), in Paris, one

of the late President Mitterand's "grand projects". This is a single office building, some 34 stories tall, designed as a cubical arch, framing the end of the Defense development on the perimeter of Paris. The arch is in line with the main axis through Paris to the Louvre, on which lies the Arch De Triomphe. The horizontal bridge structure provides exhibition and meeting spaces.

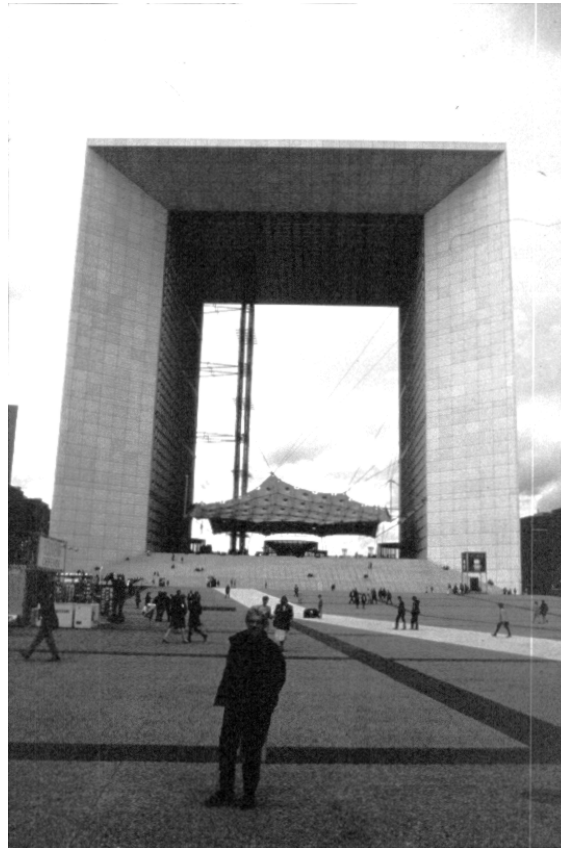


Figure 6-46. Grande Arche of the Defense, Paris, Johan Otto von Spreckelsen, architect

A similar form is that of the Umeda Sky Building (Figure 6-47) in Osaka, Japan. This building incorporates a mid-air garden, midair escalators and a mid-air bridge to connect the two parts of the building. The architect, Hiroshi Hara, sees this form as the beginning of an approach to a three-dimensional network to our congested cities. This building is in a fairly severe seismic zone and is carefully designed for earthquake resistance.



Figure 6-47. Umeda Sky building, Osaka, Japan, Hiroshi Hara, architect, 1988

The bridge or twin tower forms have immense drama and appeal, and so we can expect to see five story versions of them appearing in our shopping malls and suburban centers.

• The warped building:

A strong design trend is that of buildings that use warped forms, often combined with non vertical walls and irregular warped exterior surfaces. The most prominent exponent of these forms is the American architect Frank Gehry, who is now building these forms all over the world. His Guggenheim Museum in Bilbao, Spain, completed in 1997 is typical of his style, and has been hailed as a masterpiece by architectural critics world-wide (Figure 6-48). His tower for the Rapid Transport Headquarters

in Los Angeles, (Figure 6-49) shows his warped and non vertical forms applied to a skyscraper. Despite its flourishes, the building is essentially rectilinear with the warped elements achieved by nonstructural add-ons to the main structure.

• The Deconstructed Building

Deconstruction is a term applied to the work of a number of architects presently working around the world: the term is derived from the language and literary movement of the same name that originated in literary criticism. The principles of deconstruction were first formulated by the French philosopher and critic Jacques Derrida, in the early 1970's and have since revolutionized literary criticism and the study of language and meaning.

Because deconstructed buildings essentially ignore the limitations of constructability, few have yet been built. One of the architects most commonly associated with deconstruction is the Iraqi, Zaha Hadid, who works in London. Figure 6-50 shows her design for a normally prosaic building - a fire station completed in 1993 in Germany.

6.12 CONCLUSION

These examples of new trends in architecture have been selected because experience has shown the force of images created by architectural innovators, however strange they may at first appear. The architects illustrated are those -among many- who are having great influence in the schools of architecture and among younger professionals. Engineers may expect to be confronted by these kinds of configurations in the coming years.

Engineering rationality, and even buildability, appears to have little influence on these forms. There is controversy in the profession about this, and many critics view the new architecture as akin to theater set design, in which image is everything and its method of construction and longevity is irrelevant. Be that as it may, the zeitgeist is changing, and architects will perforce have to obey it.

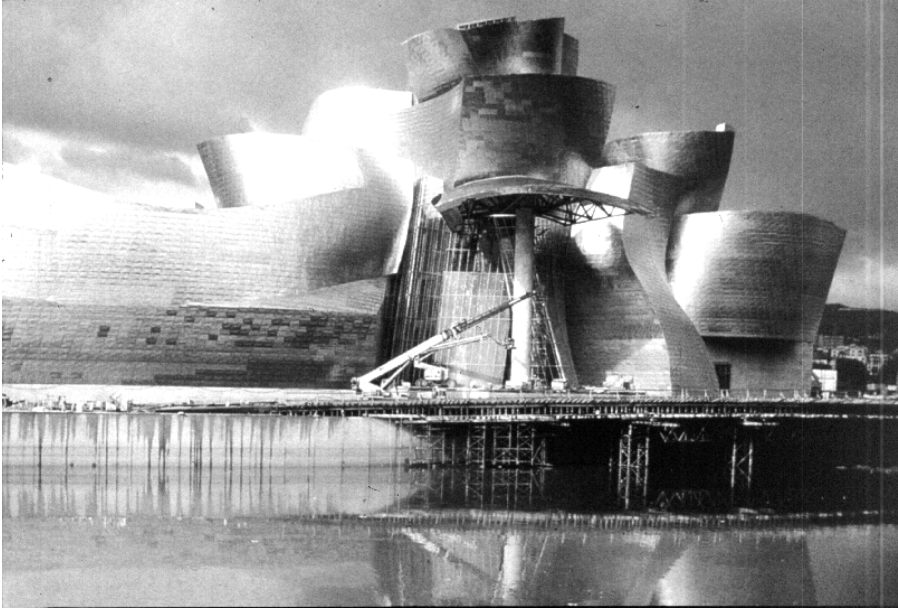


Figure 6-48. Guggenheim Museum, Bilbao, Spain, Frank Gehry, architect, 1996

Successful engineers will understand these imperatives, enjoy the experimentation that this work represents, and assist the architects in realizing their ambitions. 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.

Meanwhile, the residue of configuration problems left by the architecture/engineering of the 50's to 70's must be dealt with. Some will disappear as aging buildings are replaced: this should be encouraged, as it is the only guaranteed way of removing the earthquake threat. For other buildings, engineers must use their ingenuity and imagination to find affordable methods of retrofit. And there need be no recriminations: these problems are the joint product of architect/engineer interaction that, in its time, was fruitful: nature always has the last word in reminding us of our collective ignorance.

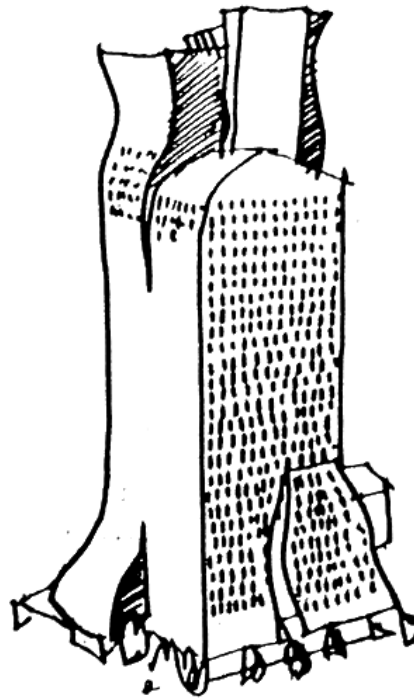


Figure 6-49. Rapid Transport District Headquarters, Los Angeles, Frank Gehry, architect, 1995

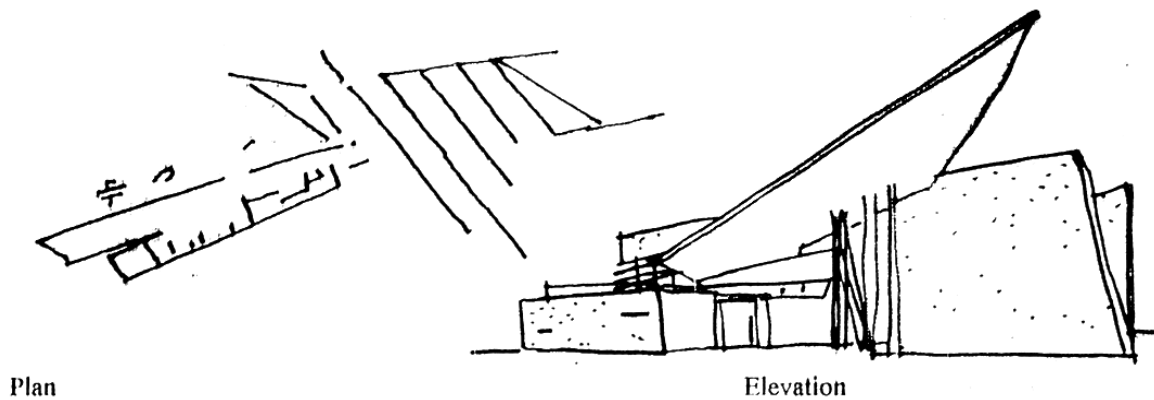


Figure 6-50. Fire Station, Vitra factory complex, Weil-am-Rhein, Germany Zaha Hadid, architect, 1995

Simple, economical buildings will continue to be built, and our optimal seismic design will continue to be viable. It may form the basis of performance based design which, if it is to be successful, will have to be free of the kinds of irregularities that make performance prediction difficult or impossible. We may expect design to develop in ways analogous to the poetry and prose of written communication. Most discourse is carried out in prose: the serviceable language of business and news reporting. At the level of literature, prose approaches an art form, in which the subtleties of language and human behavior are explored. Out in advance, often almost unintelligible, are the poets using words and language in new and unexpected ways: but over time they reveal insights in language so compelling that our speech and even our behavior is changed. Thus the language of Shakespeare shows up in the newspaper and even the office E-mail.

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