

ARCHITECTURAL SEISMIC DESIGN CONCEPTS

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CAMPUS HONORS COURSE

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ARCHITECTURAL SEISMIC DESIGN CONCEPTS

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PART I

BUILDING CONFIGURATION

Learning Objectives

- ❑ Illustrate examples of regular building configurations
- ❑ Explain how regular configurations provide seismic resistance
- ❑ Describe how irregular configurations become problematic during an earthquake
- ❑ Summarize how building codes address configuration issues
- ❑ Describe a soft first story design and how it can fail during an earthquake
- ❑ Cite some solutions to the soft story problem
- ❑ Discuss the problem of discontinuous shear wall design and how it can be resolved
- ❑ Describe how variations in perimeter strength and stiffness affect a building and possible solutions
- ❑ Illustrate re-entrant corners, the problems posed by them and possible solutions

Introduction

Statistics reveal that the performance of a building under ground motion is *greatly* influenced by its architectural form. The interaction of all the structural elements and the architectural components subjected to earthquake forces makes this happen. Certain specific architectural forms create very complicated structural responses which result in concentrating and dissipating earthquake forces in highly detrimental ways.

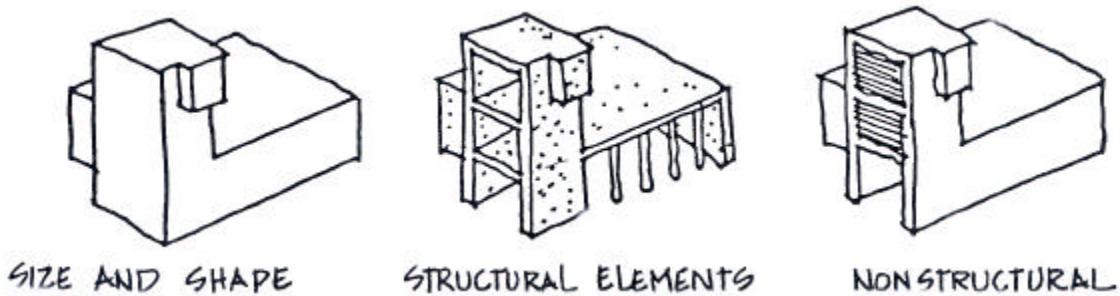
Seismic codes differentiate between regular and irregular configurations. It is the irregular configuration that has a negative influence on the effectiveness and efficiency of seismic design and building performance.

This course will review the architectural and structural features related to building configuration, and also the role of non-structural components in seismic design. Some design approaches to avoid or mitigate the above problems will also be dealt with.

What is Building Configuration?

The term *building configuration* refers to the architectural form of a building in seismic design. To be more specific, configuration can be defined as: *building size and shape, the size and location of structural elements that may affect structural performance*. The latter includes such elements as heavy nonstructural walls, staircases, exterior wall panels and heavy equipment items.

Building configuration primarily determines the way forces are *distributed* throughout the structure and also the relative magnitude of those forces. The physical features of a building that concern seismic design will be discussed in this course.



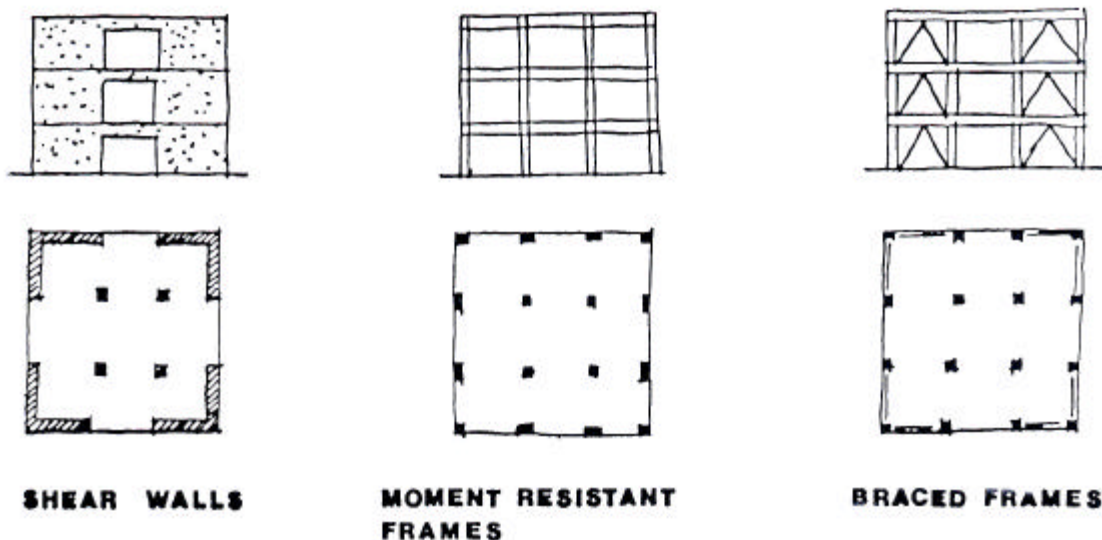
Configurations are mainly classified as **Regular** and **Irregular**.

Types of Configurations

Regular Configurations

Regular configurations make structures seismically optimal. They use the three main alternatives for lateral load resistance systems, i.e. shear walls, moment resistant (rigid) frames, braced frames that could still provide useful and common architectural forms. Following are some characteristics of these configurations that make them optimal, or desirable:

- *Equal Floor Heights, Symmetrical Plan*
- *Uniform Plan and Elevation*
- *Maximum Torsional Resistance*
- *Balanced Resistance*
- *Short Spans/ Redundancy*
- *Direct Load Paths*



Theoretically, circular plans have better configurations because of their complete symmetry, but they are structurally more complex and, not very useful in architectural planning and urban design terms. However, not all regular building forms, are equally effective as seismic configurations. The size and geometrical proportions of a building also affect its seismic response. Long span structures may have difficulty in responding as one unit to seismic vibration, resulting in additional longitudinal compressive-tensile stresses and horizontal displacements. Industrial or warehouse type buildings may be some examples. Different locations in the building may respond out of phase with one another, instead of as a single unit. This causes stress concentrations in the structure's horizontal diaphragms. Multiple shear walls or frames are added as a solution to reduce the span of the diaphragm, though this may present internal planning problems. Breaking up the building into smaller units, separated by seismic joints is a possible alternative. Though this may be an ideal solution seismically, it introduces difficult architectural detailing problems at the joints between building units.

Buildings that are extremely long though not wide in plan may develop large forces in shear walls of frames, and in the diaphragm. Addition of cross walls or frames, or subdividing the building is the solution. The long wings of Frank Lloyd Wright's Imperial Hotel in Tokyo, for example, were actually divided into a large number of separate small rectangular buildings that helped the structure survive the 1923 Tokyo earthquake (Arnold and Reitherman, 1982).

Problems in proportion of very slender buildings principally relate to the possibility of *overturning*. This more commonly relates to the proportions of resisting elements such as shear walls, while this could also apply to the form of the entire building.

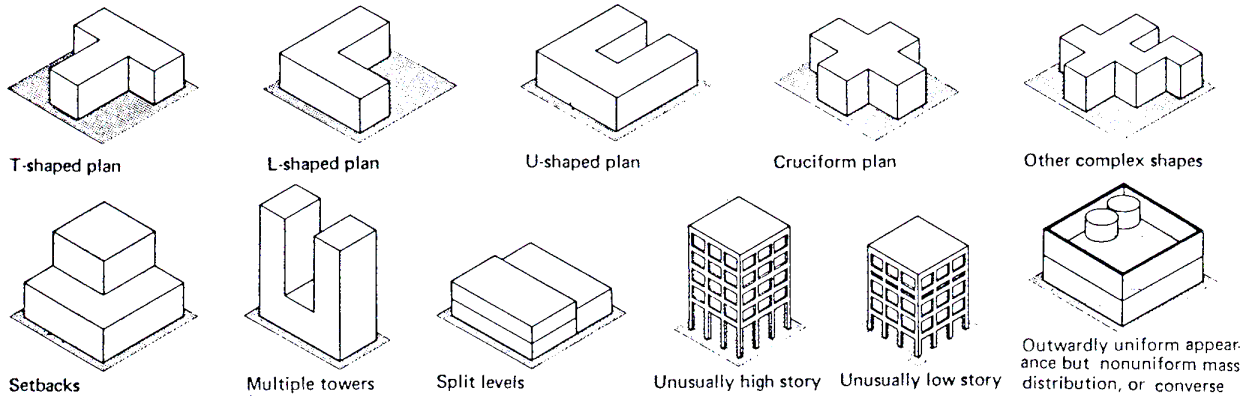
Irregular Configurations

Irregular configurations refer to structures that deviate from a simple regular, symmetrical form in plan and elevation that cause strength and stiffness irregularities. This deviation tends to create two basic kinds of problems: Torsion and Stress Concentration.

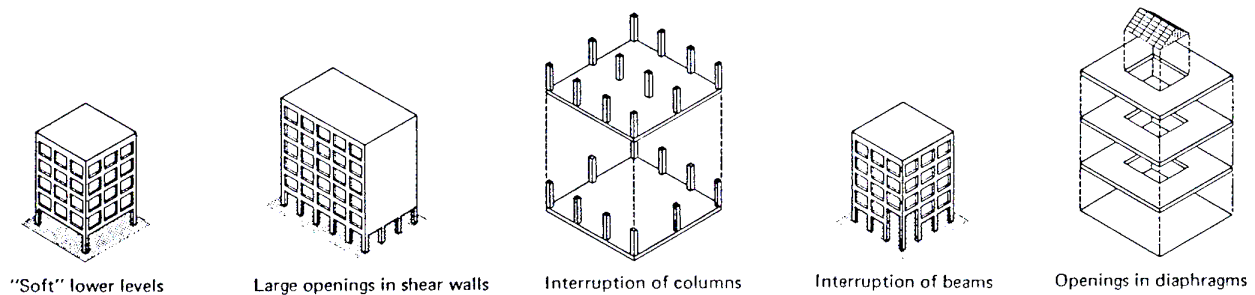
Configuration irregularities cannot always be discounted as the designer's negligence. Often, they may arise for sound planning or urban design considerations. For example, the re-entrant corner forms are very useful in achieving high-density housing solutions on small lots. The large floor spaces of offices or hotels require higher first stories and smaller rooms on upper floors. Understanding the seismic effect of configuration irregularity will enable necessary irregularity to be accommodated without significant detriment to seismic performance.

“IRREGULAR STRUCTURES OR FRAMING SYSTEMS” (SEAOC)

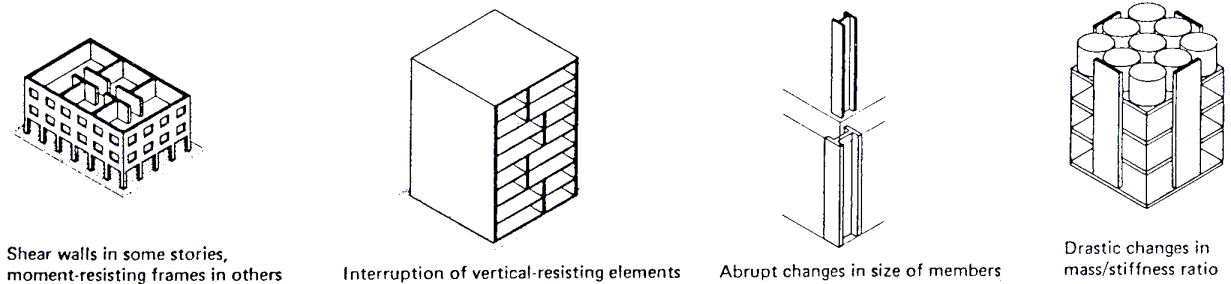
A. BUILDINGS WITH IRREGULAR CONFIGURATION



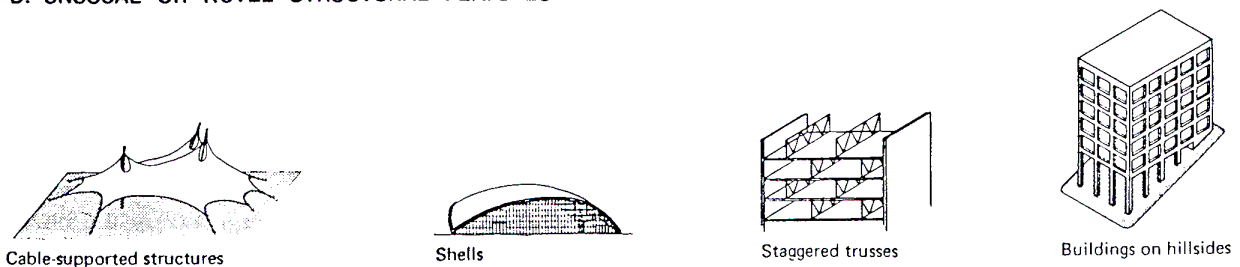
B. BUILDINGS WITH ABRUPT CHANGES IN LATERAL RESISTANCE



C. BUILDINGS WITH ABRUPT CHANGES IN LATERAL STIFFNESS



D. UNUSUAL OR NOVEL STRUCTURAL FEATURES



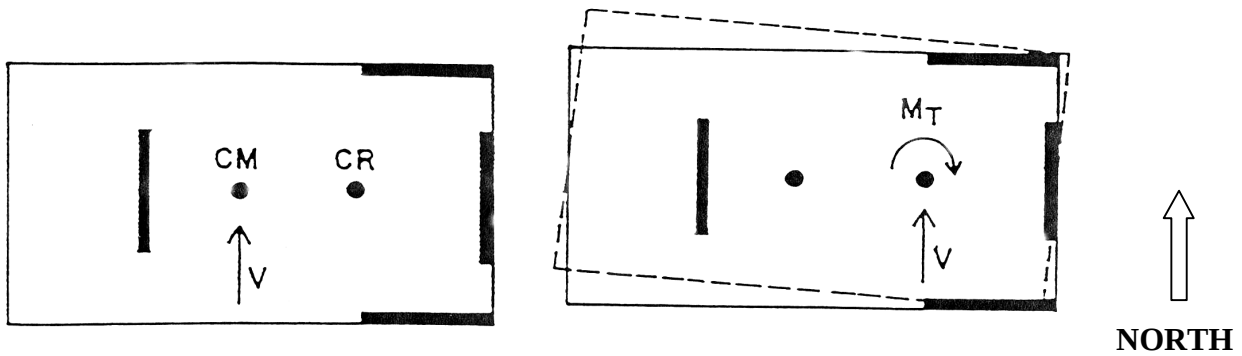
Irregular structures or framing systems

Some causes of horizontal irregularities are described below:

Torsional irregularity: Torsion usually happens when the center of mass and the center of rigidity of a structure with rigid diaphragm do not coincide. The distance between these two points is called eccentricity. Torsion problems are most characteristically coupled with plan irregularity or geometries, where the size and location of vertical elements produce eccentricity between the centers of mass and resistance, creating great uncertainty in analyzing the building's resistance. When an excessive proportion of the overall seismic force is concentrated at one or a few locations in the building, such as a particular set of beams or columns, stress concentrations occur. There will always be some buildings with unique plans with awkward locations of lateral load carrying elements that result in torsional irregularities. The name of the game is to minimize the torsional irregularity.

When perimeter strength and stiffness variations occur in buildings whose configuration is geometrically regular and symmetrical from an architectural standpoint, but nonetheless irregular structurally for seismic design purposes, the problem of torsion arises. If there is wide variation in strength and stiffness around the perimeter, the center of mass will not coincide with the center of resistance, and torsional forces will tend to cause the building to rotate around the center of resistance. Hence the nature of the perimeter design strongly influences a building's seismic behavior.

The first strategy is to design a frame structure of approximately equal strength and stiffness for the entire perimeter. A second strategy is to increase the stiffness of the open facades by adding shear walls at or near the open face. A third approach is to use very strong moment-resistant or braced frame at the open front, which approaches the solid wall in stiffness (AIA/ACSA, 1994).



Torsion in a building

Torsional Moments due to a N-S seismic force rotating about C.R. is:

$$M_t = V.e_x$$

Torsional Moments due to an E-W seismic force rotating about C.R. is:

$$M_t = V.e_y$$

Force due to direct shear,

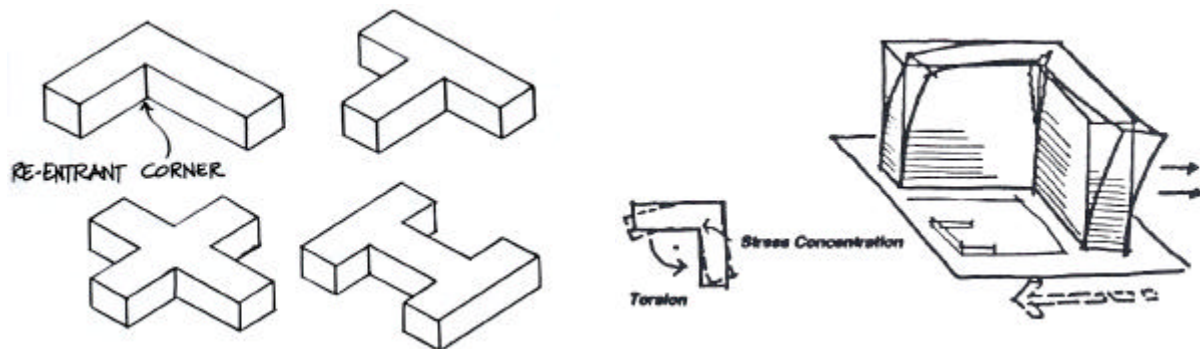
$$F_v = V \frac{R_y}{\sum R_y}$$

Force due to torsion,

$$M_t = T \frac{R \cdot d}{\sum R \cdot d^2}$$

where R is the relative rigidity of the shear walls or frames along the direction of the earthquake and d is the distance of the shear walls or frames from the C.R. of the building. The total force in a frame or wall in a given direction is $F_v + F_t$. A 5 % accidental eccentricity in addition to e_x and e_y is specified by the codes for calculating M_t .

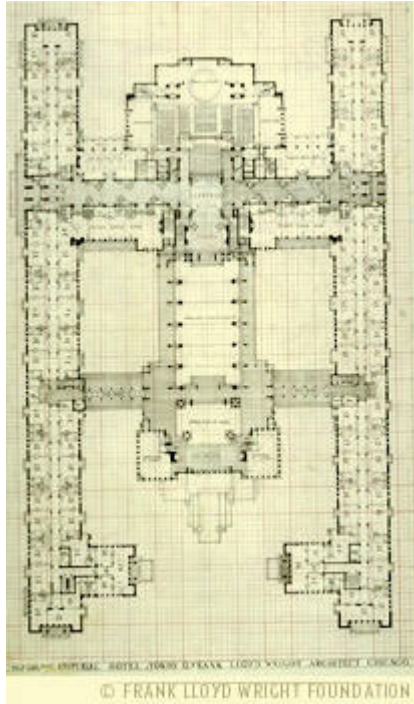
Re-entrant corners: The most useful and traditional set of building shapes, which enable large areas to be accommodated in relatively compact form, yet provide a percentage of perimeter rooms with access to air and light. The re-entrant corner is the common characteristic of building forms that, in plan, assume the shape of an L, T, H, etc., or a combination of these shapes.



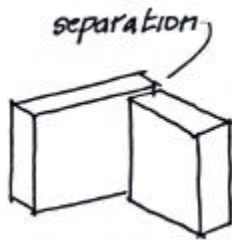
Re-entrant corners

There are two problems created by these shapes. First, this form causes **torsion**. The result is rotation or twisting, that will tend to distort the building in ways that will vary in nature and magnitude depending on the characteristics of the ground motion. Second, it produces variations of **rigidity**, and hence differential or out-of-phase motions between different portions of the building, resulting in stress concentration at the re-entrant corner.

There are two basic alternative approaches to solve the problem of the re-entrant corner forms: to separate the building structurally into simpler shapes, or to tie the building together more strongly. Frank Lloyd Wright adopted the former solution when he divided the Tokyo Imperial Hotel into a number of rectangular blocks.



Tokyo Imperial Hotel

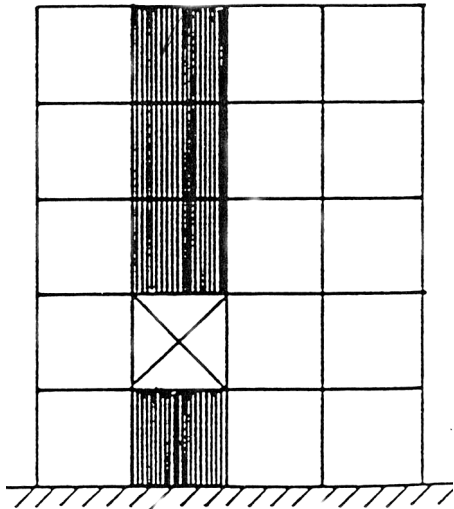


Some examples of vertical irregularity are described below:

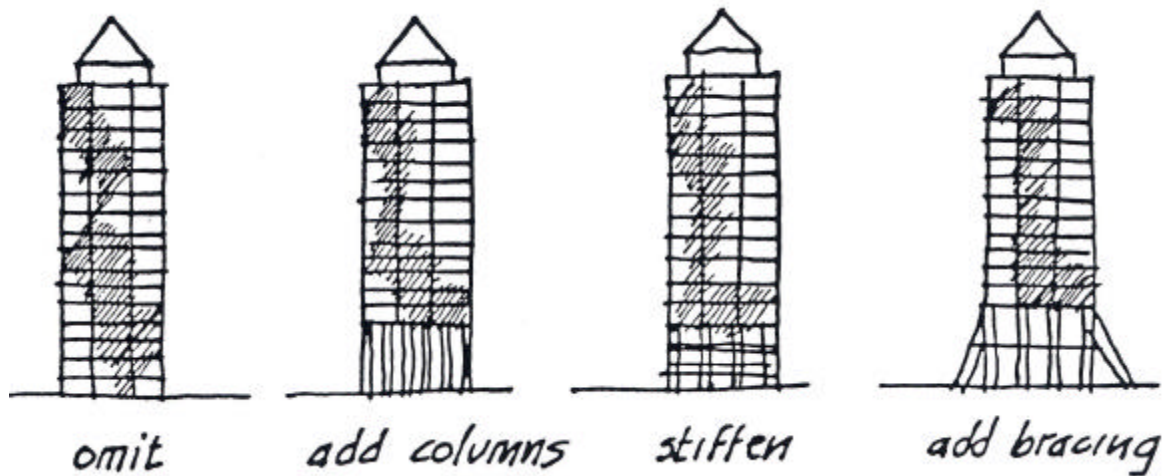
In-plane Discontinuity in Lateral Load Carrying Element: The lateral load carrying system shall be continuous from ground to roof, no exceptions.

Mass Irregularities and Vertical Configuration Irregularity: The building masses should be uniform along the full height of the structure. But in some cases this may not be possible, i.e. a tower atop a platform, where both conditions cannot be avoided. Still the lateral load carrying system shall encompass the full height of the building. Care should be taken in regard to the stiffness of the lateral load carrying elements at the base. They will be short and relatively stiff and tower lateral load elements flexible.

Weak Story: A weak story is one where there is significantly less strength at any one level than that of the level above it. It is a weak link in the building. This should not be employed in any case.

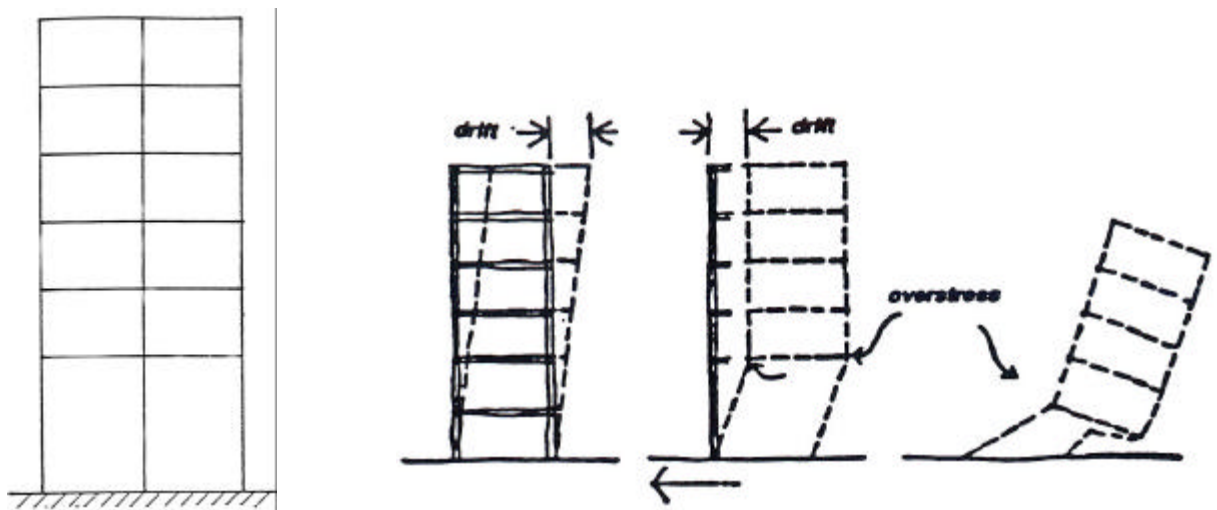


Weak Story



Potential Solutions for weak story

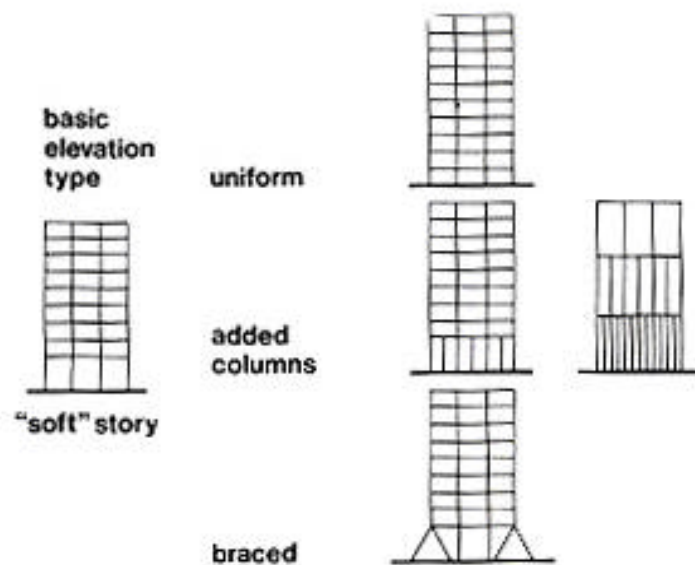
Soft Story: This is not the same as a weak story. Here, it is the stiffness and not the strength that is the issue. The most prominent of the set of configuration problems is caused by the significant reduction of stiffness in the soft story. This term has commonly been applied to buildings whose ground level story, while adequate in strength, is less stiff than those above. A story at any floor creates a problem, but since the forces are generally greatest towards the base of a building, a stiffness discontinuity between the first and second floors tends to result in the most serious condition.



Soft Story



Soft story problem in San Francisco earthquake Olive view hospital, San Fernando earthquake

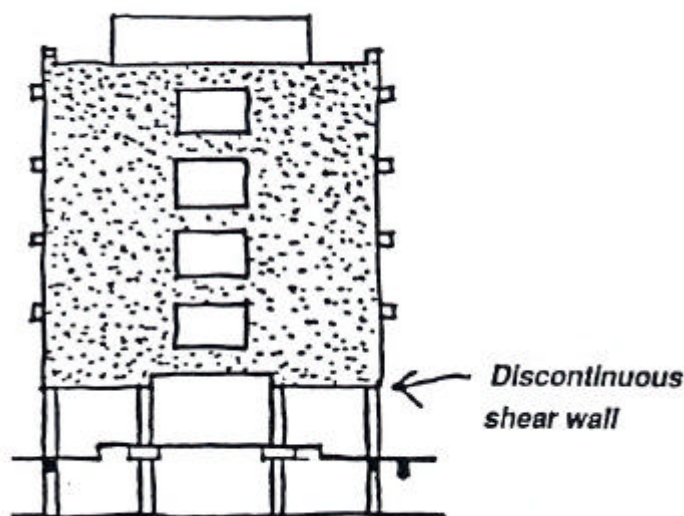


Potential solutions for soft story

Instead of a building's lateral deflection under seismic forces being distributed equally among the upper floors, it is accommodated almost entirely in the first floor. Tremendous distortion in the floor, and stress concentration at the second floor connections, can cause failure at this level, resulting in the collapse or partial collapse of the upper floors.

Discontinuous Shear Walls: Discontinuous shear wall condition represents a special, but common, case of the “soft” story problem. When shear walls form the main lateral resisting elements of the building, they may be required to resist very high lateral forces. If these walls do not line up in plan from one floor to the next, the forces cannot flow directly down through the walls from the roof to foundation, and the consequent indirect load path can result in serious overstressing at the points of discontinuity.

A discontinuity in vertical stiffness and strength leads to a concentration of stresses and ultimately to damage and collapse, and the story which must hold up the remaining stories in a building should be the last, rather than the first component to be sacrificed. The best solution to this problem is to eliminate the condition. This may however create architectural problems of planning, circulation or image. This then proves that the decision to use shear walls as lateral load-resistant elements was wrong from the inception of the design. On the contrary, if the decision is made to use shear walls, then their presence must be recognized from the beginning of schematic design, and their size and location must be the subject of careful architectural and engineering coordination.



Discontinuous shear wall

Configuration Irregularities and the Code

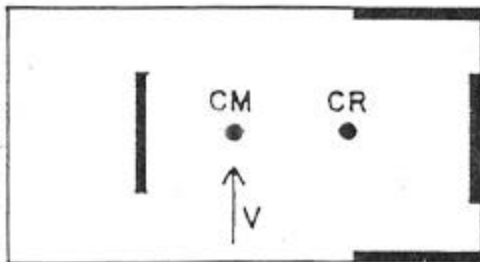
A number of assumptions must be made in order to establish seismic forces for the practical design purposes by the use of seismic codes. Primary of these is that the forces are analyzed in two directions, loads are analyzed independently and combined by adding, and structures are assumed to provide direct load paths and be regular in form (AIA/ACSA, 1994). For establishing earthquake forces the code procedures commonly in use are applicable to structures based on these simplifying assumptions. Until the 1973 edition of the Uniform Building Code the configuration problem was not dealt with in a specific clause at all, and until the 1988 edition of the code the problem was only covered by a general caveat. That is to say, the designer had to use his judgment and knowledge in assessing the magnitude and distribution of the code forces.

In essence, the seismic design problem has historically been too complex to be dealt with by simple quantitative code rules, and must be left to engineering judgment. However, starting with the 1988 UBC and the 1988 NEHRP Provisions, configuration irregularities are defined on a quantitative basis, and a more elaborate dynamic analysis is required where certain irregularities occur. The requirements that trigger modal analysis were complex and, in general, only applied to buildings over 5 stories or 65 feet in height, located in Zones 3 and 4 of UBC.

While the dynamic analysis is a step in the right direction, the problem is not totally alleviated. The 1990 Commentary to the SEAOC Lateral Force Requirements now includes an extensive discussion of the types of configuration irregularity, their effect and importance, and how they should be dealt with (Appendix ID5b, Irregularity and Setbacks). In some instances, clauses have been added to the code which deal directly with a problem. But, in general, the solutions are design and concept oriented and still rely on the engineer's understanding and experience (AIA, ACSA, 1994). These irregularities vary in importance as to their effect, and their influence also varies in degree, depending on which particular irregularity is present. Thus, while in an extreme form the re-entrant corner is a serious type of plan irregularity, in a lesser form it may have little significance. The determination of the point at which a given irregularity becomes serious used to be a matter of judgment, but the new codes now attempt to define the issue in a quantitative way.

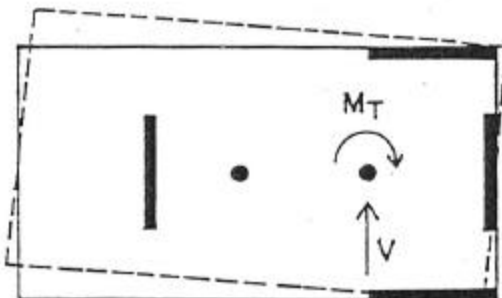
Plan Irregularity - Type And Description		Reference Section	Seismic Design Category Application
1 a	Torsional Irregularity – to be considered when diaphragms are not flexible.	5.5.6.4.3	D, E and F
	Torsional irregularity shall be considered to exist when the maximum <i>story</i> drift, computed including accidental torsion, at one end of the <i>structure</i> transverse to an axis is more than 1.2 times the average of the story drifts at the two ends of the <i>structure</i> .	5.3.5	C, D, E and F
1b	Extreme Torsional Irregularity - to be considered when diaphragms are not flexible Extreme torsional irregularity shall be considered to exist when the maximum <i>story</i> drift, computed including accidental torsion, at one end of the <i>structure</i> transverse to an axis is more than 1.4 times the average of the story drifts at the two ends of the <i>structure</i> .	5.2.6.4.3.	D
		5.3.5	C and D
		5.2.6.5.1	E and F
2	Re-entrant Corners Plan configurations of a structure and its lateral force-resisting system contain re-entrant corners, where both projections of a structure beyond a re-entrant corner are greater than 15 percent of the plan dimension of the structure in a given direction.	5.2.6.4.3	D, E and F
3	Diaphragm Discontinuity Diaphragms with abrupt discontinuities or variations in stiffness, including those having cut-out or open areas greater than 50 percent of the gross enclosed diaphragm area, or changes in effective diaphragm stiffness of more than 50 percent from one <i>story</i> to the next.	5.2.6.4.3	D, E and F
4	Out-Of-Plane Offsets Discontinuities in a lateral force resistance path, such as out-of-lane offsets of the vertical <i>elements</i> .	5.2.6.4.3	D, E and F
		5.2.6.2.10	B, C, D, E, or F
5	Nonparallel Systems The vertical lateral force-resisting elements are not parallel to or symmetric about the major orthogonal axes of the lateral force-resisting system.	5.2.6.3.1.	C, D, E, and F

PLAN STRUCTURAL IRREGULARITIES (NEHRP TABLE 5.2.3.2)



TORSIONAL IRREGULARITY

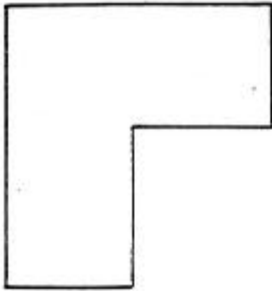
- WHEN DIAPHRAGM IS RIGID, TORSIONAL IRREGULARITY MAY EXIST WHEN C.M. AND C.R. DO NOT COINCIDE



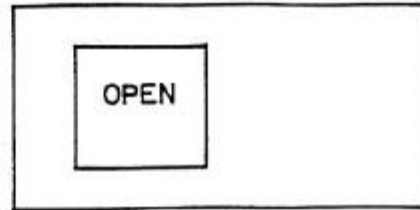
TORSION AFFECTS RELATIVE DISPLACEMENTS AND MAY INCREASE DEMAND ON SOME CONNECTIONS

- IF TORSIONAL IRREGULARITY EXISTS, NEHRP REQUIRES INCREASE IN DIAPHRAGM CONNECTION FORCES

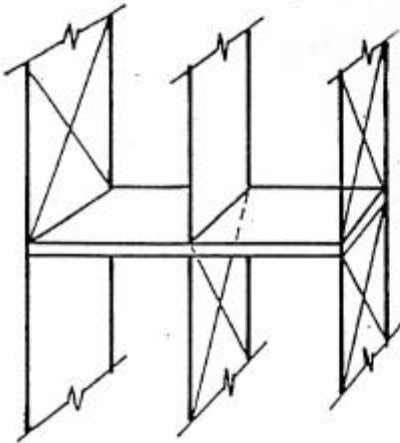
OTHER TYPES OF PLAN IRREGULARITIES



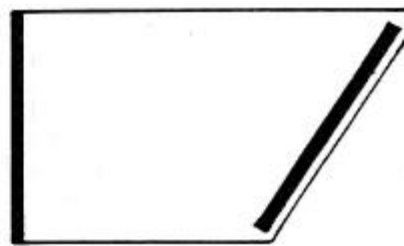
REENTRANT CORNERS



DIAPHRAGM DISCONTINUITY



OUT-OF PLANE OFFSETS

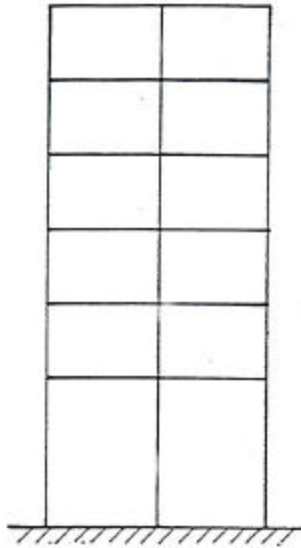


NON-PARALLEL SYST

Source: NEHRP 1997

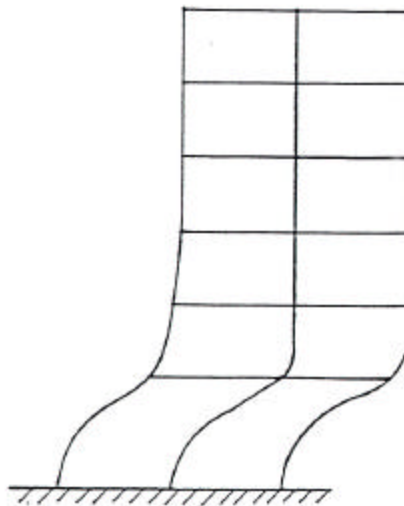
Vertical Irregularity - Type And Description		Reference Section	Seismic Design Category Application
1 a	Stiffness Irregularity - Soft Story A <i>soft story</i> is one in which the lateral stiffness is less than 70 percent of that in the <i>story</i> above or less than 80 percent of the average stiffness of the three stories above.	5.2.5.3.	D, E and F
1b	Stiffness Irregularity – Extreme Soft Story An extreme <i>soft story</i> is one in which the lateral stiffness is less than 60 percent of that in the <i>story</i> above or less than 70 percent of the average stiffness of the three stories above.	5.2.5.3. 5.2.6.5.1	D E and F
2	Weight (Mass) Irregularity Mass irregularity shall be considered to exist where the effective mass of any <i>story</i> is more than 150 percent of the effective mass of an adjacent <i>story</i> . A roof that is lighter than the floor below need not be considered.	5.2.5. 3	D, E and F
3	Vertical Geometric Irregularity Vertical geometric irregularity shall be considered to exist where the horizontal dimensions of the lateral force-resisting system in any <i>story</i> is more than 130 percent of that in an adjacent <i>story</i> .	5.2.5.3	D, E and F
4	In-Plane Discontinuity in Vertical Lateral Force Resisting Elements An in-plane offset of the lateral force-resisting <i>elements</i> greater than the length of those elements or a reduction in stiffness of the resisting <i>element</i> in the <i>story</i> below.	5.2.5.3 5.2.6.2.10	D, E and F
5	Discontinuity in Capacity – Weak Story A weak <i>story</i> is one in which the <i>story lateral strength</i> is less than 80 percent of that in the <i>story</i> above. The <i>story strength</i> is the total <i>strength</i> of all seismic – resisting <i>elements</i> sharing the <i>story</i> shear for the direction under consideration.	5.2.6.2.3 5.2.5.3 5.2.6.5.1	B, C, D, E, and F D, E and F E and F

VERTICAL STRUCTURAL IRREGULARITIES (NEHRP TABLE 5.2.3.3)



STIFFNESS IRREGULARITY (SOFT STORY)

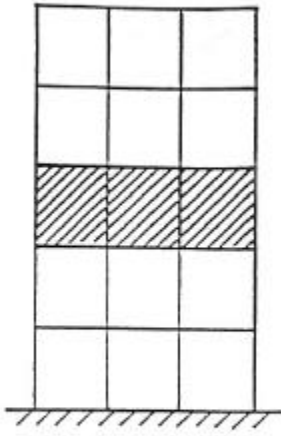
- LATERAL STIFFNESS LESS THAN 70% OF STORY ABOVE OR LESS THAN 80% OF AVG. STIFFNESS OF 3 STORIES ABOVE



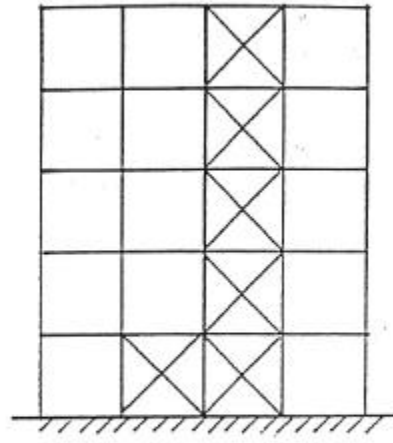
PRESENCE OF SOFT STORY AFFECTS MODE OF RESPONSE

- ELF PROCEDURE NOT PERMITTED FOR BUILDINGS WITH SOFT STORY IN PERFORMANCE CATEGORIES D, E & F

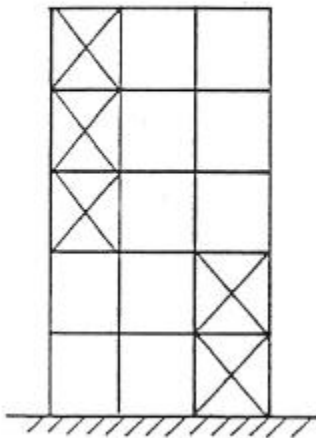
OTHER TYPES OF VERTICAL IRREGULARITY



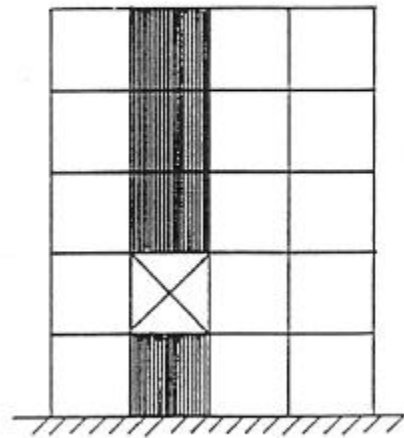
MASS CONCENTRATION



GEOMETRIC IRREGULARITY



IN-PLANE DISCONTINUITY



WEAK STORY

Non-Code Irregularities

All the eggs in one basket- The lateral force elements in any direction should not be located along one line in plan and then allowing the torsion effects to be resisted by the transverse elements. An example of this is a building with many shear walls all aligning along only one column line. The reason for not allowing this concept is that under severe seismic motion the diaphragms will yield and crack up. Also the collector lines will have substantial forces. Third, there is only one line of defense and probably no redundancy.

50 - 50 Rule- There shall be approximately 50 % of the concentric diagonal members in a braced frame sloping in each direction along the same brace line. A brace configuration that provides all the brace diagonals in one direction is to be avoided. The reason for this rule is that if all the diagonals were in the direction they all will buckle leaving nothing on this bracing line and the net result is a collapse.

Middle of the road rule- All seismic lateral system should never be located at one end of the bracing line or one end of the building. The collector or draglines will be long and have significant axial deformation.

Drag for tension only- All collector or drag lines in a concentric braced frame building should be checked for the tensile capacity of the braces neglecting the compression braces. The compression braces will buckle and the drag forces will redistribute to the tension members.

Historical Precedents

Most classical architectural styles took roots in seismic areas (Mesopotamia, China, Mediterranean, Indus Valley). It is, however, impossible to identify consciously understood and expressed seismic design principles that distinguish the architecture of these areas from the otherwise moderate or non-seismic regions. But the structural basis for design is undeniable. One can encapsulate much of the history of architecture until the late nineteenth century as a struggle to create suitable spaces under the constraint of materials that were only effective against compressive forces. With the advent of taller and more delicate structures, the designer developed a response to the nature of the lateral forces of the wind and buckling which created an analogy for seismic design as well. In historic structures, configuration is almost the only available tool of seismic design. Classical architectures provide great insights into configurational issues as regards seismic design. Santa Sophia and the Pagodas of the East are chosen for geographical and typological diversities.

Santa Sophia/ Hagia Sophia

From the perspective of the building configuration and seismic design, Santa Sophia is one of the most interesting buildings to analyze since at large it can be believed to be a skillful attempt to deal with the problem of lateral forces in a huge building. At Santa Sophia, for example – resistance to earthquakes has formed part of architectural history. It survived the latest devastating earthquake near Istanbul that knocked most of the buildings around. It is noteworthy that so many susceptible monuments have survived without the tensile materials of steel and reinforced concrete that strengthen and tie the joints of the structure together, and having been designed prior to the advent of all of the analytical and quantitative basics of earthquake-resistant design. The answers partially lie in the configuration, in the use of simple shapes that reduce the earthquake loads, and the insightful use of compressive materials in such a way that tensile, shear, and overturning forces are further reduced.

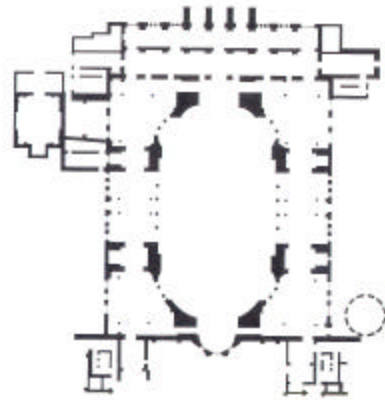
The building's configuration effectively handles the horizontal forces created by earth shaking. However, the simplicity, symmetry, and massing employed for dealing with vertical loads proved to be effective in dealing with both externally and internally induced horizontal forces. The lateral thrust problem induced by the large span shallow dome of Santa Sophia is

accommodated quite directly by the structure's configuration. Pendentives bring the dome's circular plan down to a square drum and convert the uniform outward thrust in all directions into forces at the corners. Huge buttresses take the thrust at the two sides, and half domes lean against the two ends. The volume and mass of the building spread out toward the base, efficiently distributing lateral and vertical resistance.



View of Santa Sophia

www.eugenet.com.tr/mastersj/encyclopedia-h.html



Plan of Santa Sophia



Analysis of lateral force resistant system of Santa Sophia

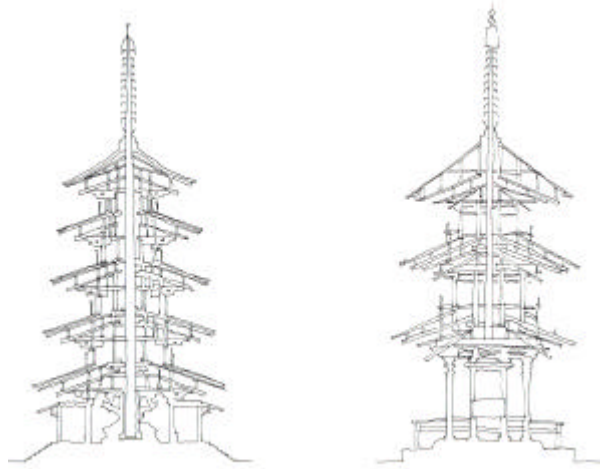
Pagodas

Historic Japanese design and construction have developed along lines quite different from those of the large masonry structures of the West. The typical structure consists of a wooden frame, with deep overhanging eaves to protect the wood structure from decay.

However, the wooden pagoda, generally part of the Japanese temple complex, has ever since been an exception for no instance of serious damage to these structures has been reported. This unusual resistance of the pagodas is based on the theory of their peculiarity in construction. The pagoda is constructed using a central column independent of the surrounding structural frames, suspended like a pendulum from the top of the pagoda. This eliminated the difference between the small shrinkage of the central column in its longitudinal direction and the large shrinkage of the surrounding girders and beams across their grains. However, there are many examples of pagodas in which the central column stands directly on the ground or is supported by a girder at the second floor. Therefore, one cannot conclude that the good earthquake performance of pagodas was entirely due to the pendulum-like central column.

Professor Tanabashi of Kyoto University summarized a set of reasons for the good performance of the pagoda in terms that closely resemble those of Glen Berg (Arnold and Reitherman, 1982). He suggested four features of the pagoda:

1. The natural period of the pagoda is very long (between 1 and 1.5 seconds) compared with other traditional structures, and generally considerably longer than the ground period.
2. Pagodas have sufficient strength to withstand considerable lateral forces.
3. Pagodas can suffer large deformations before failure.
4. Pagodas provide a large amount of structural damping.



Horyu-ji Temple at Nara and the Sammyo-ji Temple at Tokokawa-shi

An exceptional example of the combined role of architect and iconoclastic engineer is Frank Lloyd Wright for his design of the Imperial Hotel.

Conclusions

A good or bad configuration is primarily the architect's contribution to seismic performance. If the configuration is good the seismic design will be simple and economical and good performance is more likely to be assured. If the configuration is bad the seismic design will be expensive and good performance will be less than certain.

“This is not to say that all buildings should be symmetrical cubes. The architect has many agendas, of which meeting seismic requirements is but one. But understanding the problems caused by configuration irregularities will go a long way towards assuring feasible solutions, and early consultation between the architect and engineer should be directed toward creative compromise other than adversarial stubbornness” (AIA/ACSA, 1994).

A number of features contributing to seismic resistance are presented below.

1. Building (superstructure and non-structural components) should be light and avoid unnecessary masses.
2. Building and its superstructure should be simple, symmetric, and regular in plan and elevation to prevent significant torsional forces, avoiding large height-width ratio and large plan area.
3. Building and its superstructure should have a uniform and continuous distribution of mass, stiffness, strength and ductility, avoiding formation of soft stories.
4. Superstructure should have relatively shorter spans than non-seismic-resistant structure and avoid use of long cantilevers.
5. Superstructure should be detailed so that the inelastic deformations can be constrained (controlled) to develop in desired regions and according to a desirable hierarchy.
6. Superstructure should have the largest possible number of defense lines, that is, it should be composed of different tough structural subsystems which interact or are interconnected by very tough structural elements (structural fuses) whose inelastic behavior would permit the whole structure to find its way out from a critical stage of dynamic response.
7. Superstructure should be provided with balanced stiffness and strength between its members, connections and supports. Also, the stiffness and strength of the entire building should be compatible with the stiffness and strength of the soil foundation.

This list may be intimidating to an architect, who would pose the basic question: Does conscientious attention to the guidelines expressed here mean that the seismically economical and safe structure must be visually symmetrical, uniform, regular, repetitive, and bland? It could be argued to the contrary: if the precepts of good seismic design are applied with understanding and imagination, rather than with superficial adherence to rules, the prospects for design expression that have yet to be realized are brighter.

Key points

- ❑ Configuration is dependent upon:
 - 1) building size and shape in plan and elevation; and
 - 2) the nature, size, proportions and location of structural elements
- ❑ Configuration determines how earthquake forces are distributed in buildings.
- ❑ Seismically-optimum configurations are those with shear walls, moment-resistant frames, or braced frames.
- ❑ The seismic-response of regularly-configured buildings can be affected by size and proportion of structural elements.
- ❑ Irregular configurations are susceptible to torsion and stress concentration.
- ❑ Building codes are now more prescriptive, but often leave seismic design problems to the judgment of engineers.
- ❑ In soft first stories, earthquake forces are concentrated at or near the connections between the weak first floor and the stronger floors above.
- ❑ In buildings with discontinuous shear walls, earthquake forces cannot flow directly from the roof to the foundation, so stresses build up at weak points.
- ❑ Buildings with variations in perimeter strength and stiffness are susceptible to torsion, causing the building to rotate around the center of rigidity.
- ❑ Re-entrant corners are subject to both torsion and local stress concentration when different parts of the building move differentially.

PART II

NON-STRUCTURAL ELEMENTS

Learning Objectives

- ❑ List the types of safety hazards that non-structural components can present
- ❑ Describe the ways architectural components can cause damage (or be damaged) in an earthquake
- ❑ Describe the ways mechanical and electrical components can cause damage (or be damaged) in an earthquake
- ❑ Discuss the key causes of non-structural damage
- ❑ Describe some general ways to reduce non-structural damage
- ❑ Summarize the philosophy of seismic codes regarding non-structural damage
- ❑ Select examples of non-structural components and explain how each can be made seismically resistant

Introduction

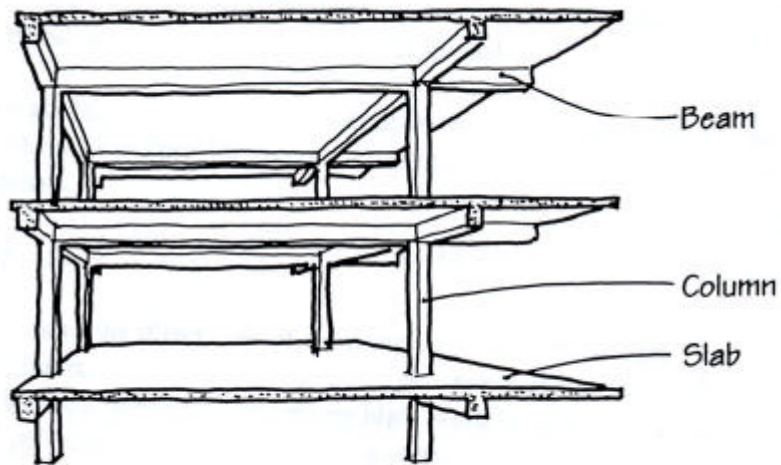
For both analysis and detailing, the effects of the non-structural partitions, infill walls, and stairs must be considered. The non-structural systems that are rigidly tied to the structural systems can have substantial influence on the magnitude and distribution of the earthquake forces, causing a shear wall like response with considerable higher lateral forces and overturning moments. Any element that is not strong enough to resist the force that it attracts will be damaged; therefore it should be isolated from the lateral force resisting system.

Non-Structural Elements in Seismic Design

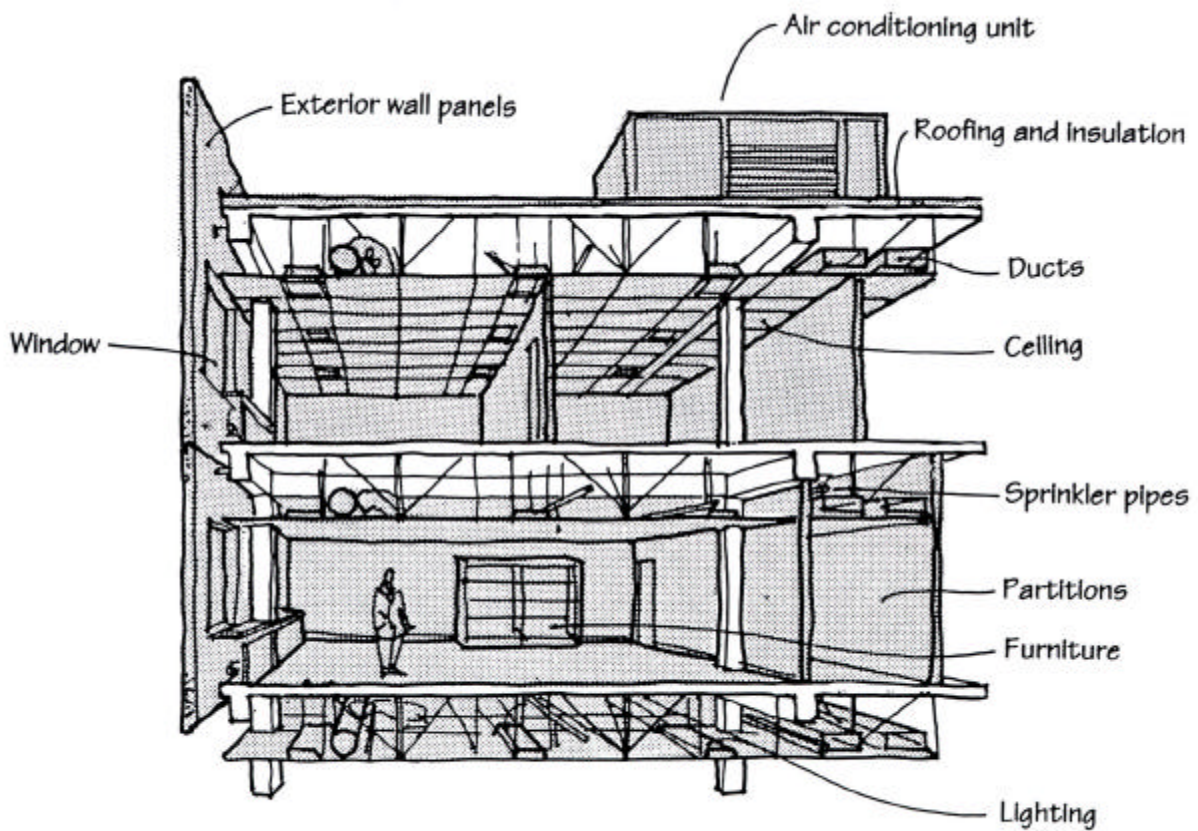
To the engineer, nonstructural components are those that are not part of the structural system of the building. For seismic design purposes, these are commonly classified as:

- Architectural components
 1. *Exterior Cladding*
 2. *Partitions*
 3. *Suspended Ceilings*
 4. *Appendages and Parapets*

5. *Canopies and Marquees*
 6. *Doors and Windows*
 7. *Chimneys and Stacks*
 8. *Stairs*
- Mechanical and electrical components
 1. *Mechanical Components*
 2. *Plumbing Components*
 3. *Elevators*
 4. *Electrical Components*
 5. *Communication Equipment*
 - Building contents and equipment
 1. *Furniture*
 2. *Computers*
 3. *Gadgets*
 4. *Artefacts*



STRUCTURE



NONSTRUCTURE (shaded)

Because of the tremendous rigidity of walls as compared to frames, a small portion of wall in the wrong place can drastically redistribute loads and change the structure's performance. If rigid enclosure or walls are not isolated from the structure by slip joints, they must be designed as integral parts of the structure. Their location then becomes a structural issue. Staircases, since they may form diagonal braces, are similarly quite rigid and quickly assume a large structural role, for good or ill, unless isolated from participating in lateral movements. Asymmetrical wall arrangements can overwhelm a symmetrical frame's attempt to respond to lateral forces in a relatively torsion-free manner.

However, nonstructural elements may also provide a degree of useful redundancy. A common example of beneficial, uncalculated seismic resistance, demonstrated in a number of earthquakes, is the ability of "nonstructural" wood-frame partitions to hold up an unreinforced masonry building after the exterior "load-bearing" walls have completely collapsed. In older apartment or hotel buildings, continuous wooden joists sometimes carried their loads by undesigned cantilever action after exterior walls fell. One of the clear virtues of normal wood-frame residential construction lies in the redundancy of load paths and the multiplicity of joints (Arnold and Reitherman, 1982)

Code requirement for seismic design are currently aimed primarily at life safety, which is interpreted in engineering terms as ensuring against structural collapse. However, damage to non-structural components may also cause casualties, even if the structure meets its design objectives. Perhaps of more significance is that non-structural damage is of much economic loss and its repair may leave the building unusable for weeks or months. Thus the problems of casualties, economic loss, and loss of building use must be alleviated by seismic design of the structure and the non-structural components and by the protection of the building contents.

While seismic design in general has made enormous strides in the last few decades, it is still true that, even in a well – designed and constructed building, freedom from earthquake damage cannot be guaranteed. This was proven again in 1994 Northridge, California quake, where non-structural damage costs ranged into the hundreds of millions of dollars. Even if the building

structure is undamaged and the occupants are safe and unharmed, substantial amounts of non-structural damage must be expected unless special steps are taken to eliminate it.

Concerns for Safety and Loss

Four types of safety hazards presented by non-structural components are:

- Direct hazard – the possibility of casualties because of broken glass, light fixtures, appendages, etc.,
- Loss of critical function – casualties caused by loss of power to hospitals or life support systems in bed panels, or functional loss to fire, police, health and emergency service facilities,
- Release of hazardous materials – casualties caused by release of toxic chemicals, drugs, or radioactive materials and,
- Fire caused by non- structural damage- breakage of gas lines, electrical disruption, etc.

Though these hazards have all caused loss of life and injuries in earthquakes, number of deaths and serious injuries has been rather low, suggesting more of random chance than a significant pattern of cause and effect. However, the possibility of heavy casualties, whether from a toxic spill, major glass breakage, or any other low probability damage, suggests that the life safety threat of non-structural components should not be discounted.

Economic loss- Nonstructural damage may be very expensive.

Functional loss- Nonstructural damage may cause serious post-earthquake disruption in essential services and productivity.

Life safety- Nonstructural damage may injure or kill people.

Structural interaction- Nonstructural elements may interact with structural components and may change the overall structural behavior, which can be beneficial or harmful to the structure.

The Causes of Nonstructural Damage

Generally, nonstructural damage is caused in two ways: *acceleration* or *displacement*.

In acceleration related damage, a nonstructural component is directly affected by ground motion transmitted by the main structure of the building and is subject to accelerations and consequent

inertial forces in a similar way to the building structure. In displacement related damage, there is movement or distortion in the structural elements that support or abut the elements.

Reducing Nonstructural Damage

Seismic codes and guidelines broadly define a group of non-structural components as life safety hazards and provide criteria for design requirements aimed at reducing hazard. Methods of reducing the damage to nonstructural components must be directed towards the probable modes of failure, whether through inertial forces or distortion in backing or abutting structures. For inertial forces, nonstructural components must be designed in a similar way to the building structure, using an analysis of forces to determine the loads on the component or its anchorage or bracing. To accommodate distortion, separation from back-up or abutting structures is necessary. Cladding must be designed to allow for movement of supporting frames, and heavy nonstructural walls must be detached from enclosing structure to allow for differential movement.

Mechanical, electrical, and plumbing distribution systems must be secured to the building structure— with allowance for differential movement where applicable – such as where systems cross a seismic separation joint.

The nonstructural damage problem is particularly difficult to deal with because the nonstructural components subject to seismic forces are not normally within the design scope of the structural engineer, whose responsibility is typically confined to the design of the building structure. In addition, nonstructural components – such as partition walls – are often added after the initial building design, and the original architect, or any architect at all, is often not involved. Finally, nonstructural equipment and furnishings are generally selected by those uninvolved in the building design. However, whenever an architect or engineer has the opportunity, he or she should advise the owners of the potential hazards that are posed by nonstructural elements and urge them to seek professional help to mitigate them.

Various design codes specify equivalent seismic force to be sustained by nonstructural elements. The equivalent static force to be applied to architectural, mechanical, and electrical components is obtained from the following equation (NEHRP 1997):

$$F_p = \frac{0.4 a_p S_{DS} W_p}{R_p / I_p} \left(1 + \frac{2 z}{h} \right)$$

$$0.3 S_{DS} I_p W_p = F_p = 1.6 S_{DS} I_p W_p$$

where

F_p = seismic design force centered at the component's center of gravity and distributed relative to component's mass distribution

S_{DS} = spectral acceleration, short period

a_p = component amplification factor that varies from 1.00 to 2.50

I_p = component importance factor that varies from 1.00 to 1.50

W_p = component operating weight

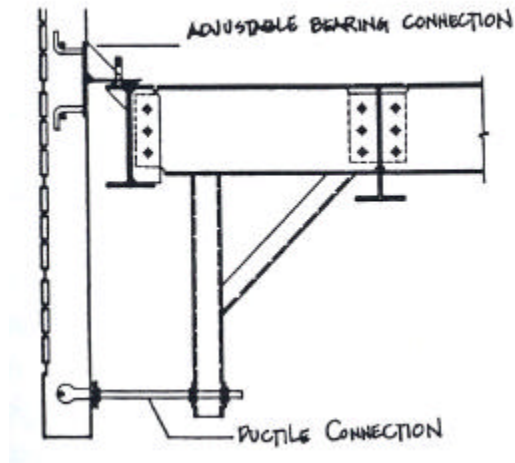
R_p = component response factor that varies from 1.0 to 5.0

z = height in structure of highest point of attachment of component (for stems at or below the base, z shall be taken as zero)

h = average roof height of structure relative to grade elevation

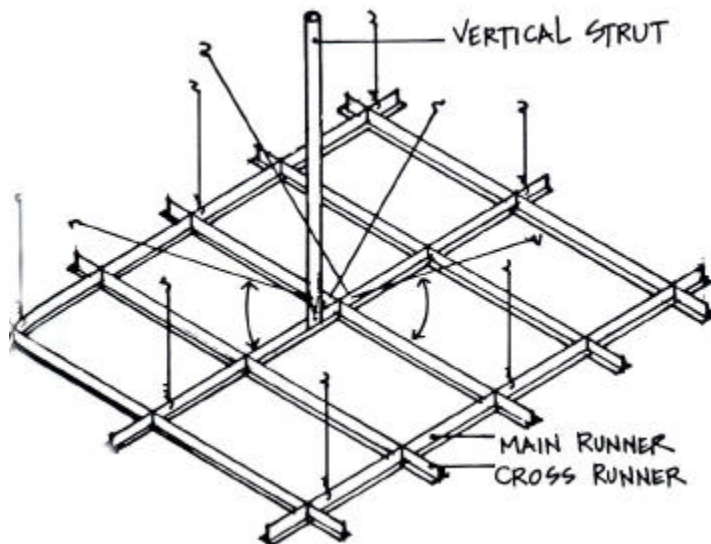
Design Strategies for Nonstructural Damage Reduction

1. Pre-cast Concrete Cladding



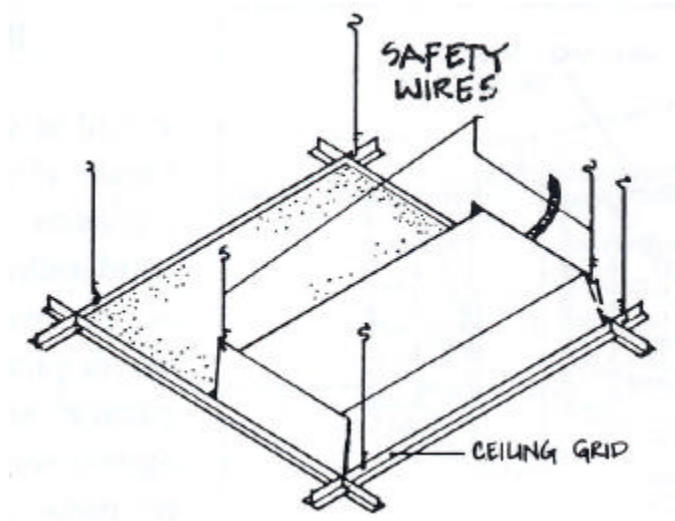
In the above typical “push-pull” connections, the top connection provides bearing and the bottom connection uses a steel rod that will bend under lateral load and not transmit racking forces to the panel.

2. Suspended Ceilings



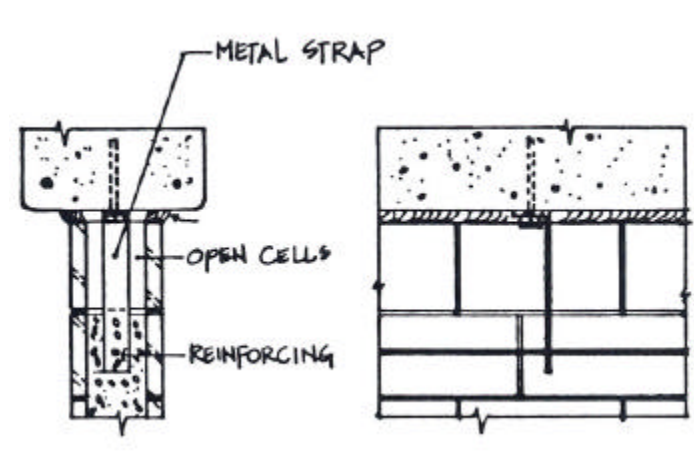
Diagonal bracing by wires or rigid members: spacing should not be greater than 12'-0" x 12'-0". The vertical strut is recommended for large ceiling areas in high seismic risk zones.

3. Light Fixtures



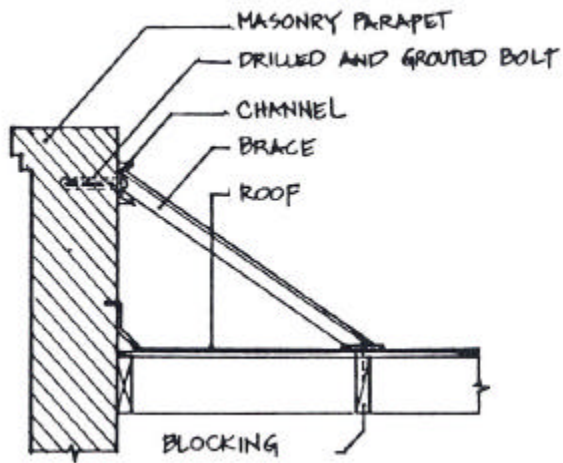
Heavy fluorescent light fixtures in suspended ceilings must be supported independently, so if the grid fails the fixture will remain. Suspended fixtures should be free to swing.

4. Heavy Partitions



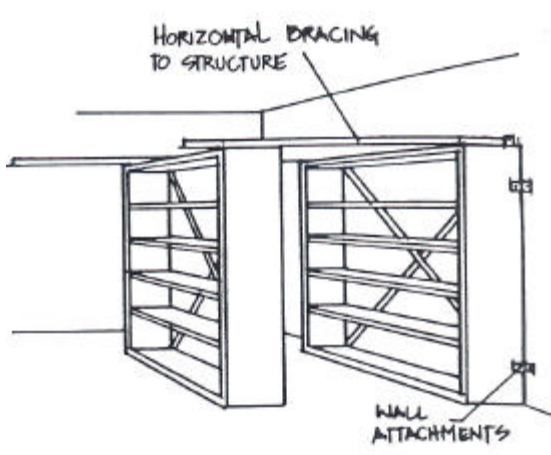
Heavy partitions should be separated from surrounding structure to avoid stiffening the structure and to avoid transmitting racking forces into the wall. The flexible steel strap resists out-of-plane forces but allows the structure to drift without imparting forces to the wall.

5. Parapet Bracing



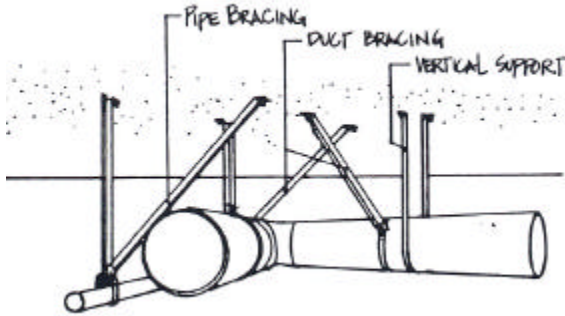
Heavy parapets should be braced back to the roof structure. The above figure shows bracing for an existing masonry parapet: the roof should also be tied to the wall (not shown).

6. Tall Shelving



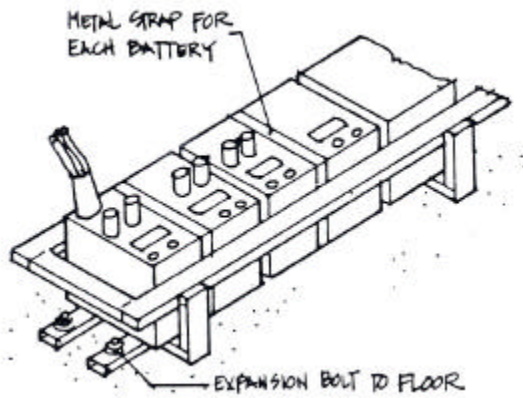
Tall shelves need longitudinal bracing and attachment to the floor. The top bracing should be attached to the building structure, and strong enough to resist buckling when the heavy shelves attempt to overturn.

7. Mechanical Ductwork and Piping



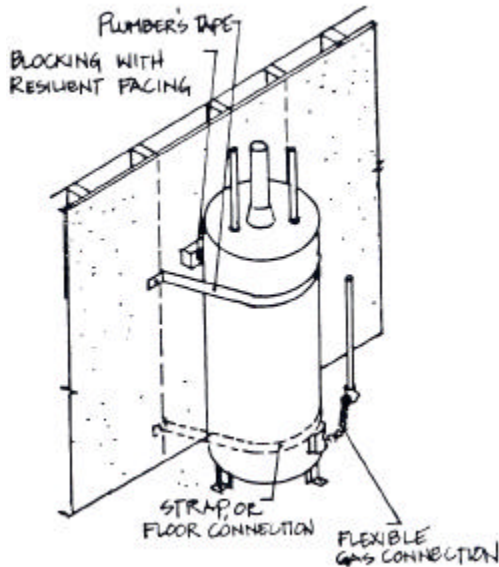
The sketch shows a typical bracing for sheet metal ducts over 28" in diameter. Vertical support can be by straps or a metal angle. Heavy piping also needs to be braced.

8. Emergency Power Battery Racks



Batteries for emergency power need positive restraint. The sketch shows a custom designed rack constructed from steel sections, to support and restrain batteries.

9. Gas Water Heaters



Domestic gas water heaters need restraint to prevent the heater tank from toppling and breaking the gas connection. The bottom restraint can be provided by an additional strap, or by securely bolting the base supports to the floor.

10. Desk-top Equipment



Light equipment, such as computer monitors, can be restrained with “velcro” type devices. These provide good lateral restraint but do not prevent easy relocation.

11. Hazardous Material Containers



Materials such as oxygen tanks need positive restraint. Dangerous or essential bottled supplies can be placed in enclosed shelves or restrained by spring loaded wires to provide easy accessibility.

Conclusions

The importance of non-structural components is also clear. The damage caused by them is life threatening, obstructive, and expensive. The design of these components with seismic provisions is necessary, as evident from the Northridge earthquake. If appropriate mitigation measures are taken into consideration, most of the damage due to non-structural elements and building components can be avoided at little or no extra cost when included in the original design of the building. The non-structural components should either be well separated so that they will not interact with the rest of the structure, or they should be integrated with the structure. On the latter case, it is desirable that the structure should have sufficient lateral stiffness to avoid significant damage under minor and moderate earthquake shaking, and toughness with stable hysteric behavior (that is, stability of strength, stiffness and deformability) under the repeated reversal of deformations which could be induced by severe earthquake ground motion. The stiffer the structure, the less sensitive it will be to the effects of the interacting non-structural components, and the tougher it is, the less sensitive it will be to effect of sudden failure of the interacting non-structural elements.

Key points

- ❑ Nonstructural components may cause injuries, even when structural components do not.
- ❑ Nonstructural components presents four types of hazard.
- ❑ Economic loss refers to the direct cost of repairing non-structural damage.
- ❑ Loss of building function is the result of damage to the systems that are necessary for the building to function (e.g. plumbing).
- ❑ Nonstructural components can compromise the structural response of a building, such as when heavy partitions are placed in locations that could create torsional effects.
- ❑ Architectural damage includes the collapse of exterior cladding, racking of partitions, fallen ceilings and exterior appendages, and loss of egress and access.
- ❑ Mechanical and electrical damage includes breaks at piping connections and joints, derailed elevators and snagged cables, loss of emergency power as a result of damaged electrical equipment, and loss of emergency services caused by communications failures.
- ❑ The contents of stiff structures typically suffer less damage than those in flexible buildings.
- ❑ Nonstructural damage is caused by direct transmission of ground motion through the structural elements (acceleration), and by movement or distortion of structural elements (displacement).
- ❑ To accommodate the effects of acceleration, nonstructural components must be seismically designed like structural components.
- ❑ To accommodate the effects of displacement, nonstructural components must be seismically isolated from abutting structures.
- ❑ Damage from nonstructural components cannot be completely eliminated.

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