INFLUENCE OF ARCHITECTURAL CONFIGURATION ON BUILDING SEISMIC PERFORMANCE

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
DISASTER MITIGATION AND MANAGEMENT

By

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MAY, 2014

CANDIDATE DECLARATION

I hereby declare that the work that is being presented in this dissertation, entitled "**INFLUENCE OF ARCHITECTURAL CONFIGURATION ON BUILDING SEISMIC PERFORMANCE**" is an authentic record of my work carried out during the period of July 2013 to May 2014, under the guidance of **D.K. PAUL**, Emeritus Fellow, Department of Earthquake Engineering, Indian Institute of Technology Roorkee.

Place: Roorkee
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CERTIFICATE

This is to certify that the above mentioned statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

The architect is often the only the professional with an overall view of all aspects of the design and construction. The architect serves the client, brings in the structural engineer and other engineering specialists. He works closely with the contractor and ideally, he orchestrates the project till end. That's why Architects are in a crucial position to influence the seismic safety of structures through their designs. In this context, Configuration is not mere shape or form of structure, but it comprises overall size and shape of building, as well as individual size and location of structural elements, and the nature of their joints. And it also includes size, location and nature of interaction of nonstructural elements that may affect structural performance. The nonstructural elements may include such as heavy nonstructural walls, staircases, hoardings and heavy equipment etc. Knowing these influential characteristics of buildings, an attempt has been made to understand configuration problems originated through design. Damage patterns observed in contemporary modern buildings, from recent earthquake reports assured relation between performance and configuration. Most commonly observed problems in our modern RC buildings are soft story, discontinuous load path, double height first stories and captive columns etc. These configuration irregularities can be avoid or at least minimized by architects easily in early design stages. For several reasons this potential is not always fully realized. In addition to that, Lack of collaboration between architects and other professionals related to structural design and construction is evident through the damaged buildings in many earthquakes. To overcome these problems, all professionals involved in design and construction process should know their own strengths, roles and responsibilities to ensure the safety of structure against earthquake. But in existing conditions, awareness and knowledge of Architects related to the importance of their Architectural design and corresponding final building configuration is low, which has significant effect on seismic performance. This is an attempt to compile configuration influences on seismic performance of buildings by pointing out problems and possible enhancements to make sure the buildings resist earthquake forces, thus ensuring life safety.

ACKNOWLEDGEMENT

The culmination of this dissertation on the "**INFLUENCE OF ARCHITECTURAL CONFIGURATION ON BUILDING SEISMIC PERFORMANCE**" has brought me to the final step to the completion of the **Master of Technology** in **Disaster Mitigation and Management**.

First of all, I would like to express my sincere gratitude, deepest respect heartiest thanks to my supervisor **D.K. PAUL**, Emeritus Fellow, Department of Earthquake Engineering, Indian Institute of Technology Roorkee, who provided me invaluable guidance and assistance in this dissertation work.

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Finally but not least, I want to express my gratitude to **the Almighty**, for giving me courage, strength, sound health & patience to carry out my work.

Place: Roorkee
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1 Introduction

Architectural configuration

When an earthquake hits a building, all the structural components and nonstructural components of it are subject to seismic effect which may influence one another in a complex manner. The effect may result, negligible damage to components and services with little economical loss, if they are earthquake resistant. In another case, the result may be in terms of casualties with the partially or totally collapse of buildings. To avoid or minimize these ill effects, all professionals involved in the design and construction process should acquaint with their own roles and responsibilities to ensure the safety of the structure against earthquake. But in existing conditions, awareness and knowledge of Architects related to the importance of their Architectural design which has a significant effect on seismic performance of the structure is low. So being architect knowing **seismic issues associated with configuration of structure** can yield good compatible designs which are functionally good and structurally strong. That is ensuring that building's elements produce adequate stiffness, strength, ductility and synchronization in the manner they are configured and envisioned.

The building is comprised of structural and nonstructural components. **Architectural configuration** is about how, **all components are arranged in three dimensional space** into different forms and shapes for the smooth function of building even with complex interactions among them.

Structural components are foundations, columns, beams and slabs, lintels, seismic belts, additional reinforcement in specified areas, projections, and staircases etc. And some of **the non-structural components taking part in defining** the building configuration are exterior, internal walls and partitions, water tanks, infill, openings and stairways etc. So non-structural components also have an influence on performance of structural members because they are imposing load and intact with other members. So earthquake resistant building configuration are those, which are designed and constructed with complex combination all type interactions of the components.

Problem identification and Need of study

Many Architects introduce different configurations in a building which may affect the building performance adversely. So being **Architect and Disaster mitigation manager** who is one of the professionals involved in this design and construction field should study and make an effort to reduce the impact of this unpredictable and unstoppable natural event turning into disaster.

Aim and Objective

The main aim is to contribute in building earthquake resilient society. And objective of this dissertation is to study the building **configuration influence on its seismic performance** and addressing the possible guidelines for enhancing their performance.

Scope and limitations

The scope of this dissertation is **emphasize the overall configuration plan**, mass and orientation of basic structural members considered in the initial stages of architectural design which influences the seismic performance of building during shaking. Computational or analytical techniques are not included in this study.

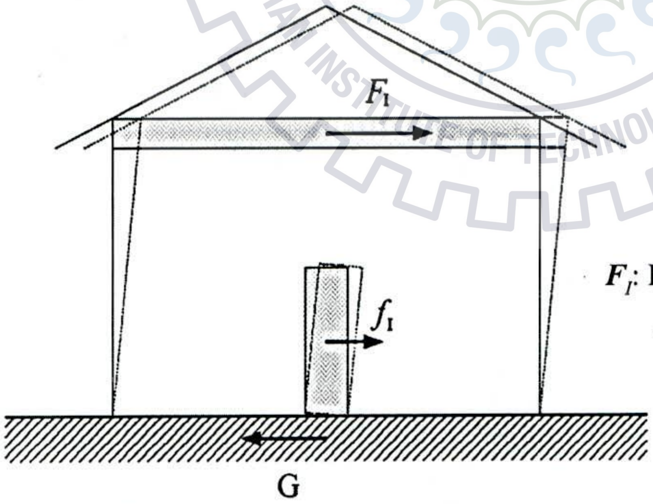
2 Literature Review

2.1 Earthquake characteristics and effects on buildings

2.1.1 Earthquake

Shaking or trembling motion of the earth's surface, because of tectonic plate movements and interactions along the fault line is called an earthquake. An earthquake strikes without warning at any time intensively.

Epicenter, fault, magnitude, intensity and seismic waves are the basic terms associated with earthquakes. Earthquakes are usually measured by their magnitude which is the quantitative amount of liberated energy measured on a scale called the Richter scale. It is expressed on a logarithmic scale of 1 to 10. It remains same irrespective of observation location. This is determined by analyzing seismic data obtained from seismometers kept in network to minimize uncertainties. Another parameter confused with magnitude is the intensity of an earthquake which is determined with the help of the Modified Mercalli Intensity (MMI) Scale which varies being influenced local site conditions. It is a qualitative quantity calculated from physical observations of the earthquake's impact at a desired location as it attenuates from the point of the earthquake source.



F_I: Inertia force actions on the building
f_I: Inertia force on the content
G: ground motion

Figure 2.1: Building response during earthquake

Source: Christopher Arnold, The Seismic Design Handbook

2.1.2 How earthquakes effect or damage structures?

The primary and immediate cause of damage to the building is the ground shaking. When earthquake force is exerted on a building (**Figure 2.1**) it develops a restoring force in the opposite direction due to inertia, if the building is designed to withstand that force or dissipate the energy (because of the force) by any means that effect may be reduced. In general Buildings can withstand vertical forces very well, while deficient against lateral forces which are exerted during earthquakes. These lateral forces are responsible for earthquake damage of buildings in case of major earthquakes.

Earthquake damage is different in different regions and also depends on many parameters, including earthquake ground motion characteristics (intensity, duration and frequency content of ground motion), soil characteristics (topography, geologic and soil conditions), building characteristics like **Building configuration**, Opening size, Stiffness distribution, ductility, strength of building, foundations, and quality of construction etc.

2.2 Effects of shaking

There are different direct and indirect effects, because of earthquakes. Landslides and liquefaction are induced or triggered indirect effects. But the most common and basic cause of earthquake damage is ground shaking which directly effects the buildings. Seismically induced shaking affects buildings in three primary ways, they are inertial forces, period and amplification, and torsion.

2.2.1 Inertial forces

In a building, forces are generated internally by the vibration of its mass during the ground shaking may or may not lead to damage. This force is the product of mass and acceleration. So **mass is an attribute** of the building, and at ground level, it is equivalent to the building weight. For a particular acceleration, even a small increase in this major attributes will attract more forces.

Another harmful feature of mass, in addition to its function in increasing the lateral loads is, making the vertical elements such as columns and walls to fail by buckling. I.e. when a member bends or moves out of plumb by the lateral forces the mass pushes down due to gravity. It exerts its force and burdens strained members further which is called as P-delta effect.

That's why, there is a real advantage when **lightweight construction** is used as a Seismic design approach to reduce inertial forces. Material selection plays major role in this step of Architectural design.

2.2.2 Period or frequency and Amplification

Every object has a natural or a fundamental frequency (Inverse of period) at which it vibrates even for a small push. One of the major characteristics of earthquake waves is their frequency. This frequency tells us whether waves are fast or slow and abrupt or rolling. The information is important in calculating the magnitude of seismic forces.

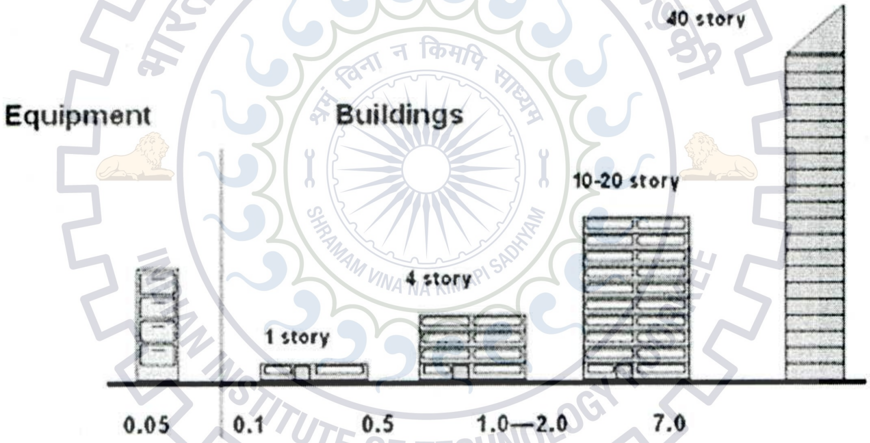


Figure 2.2: Natural periods of structures

Source: Architectural Design for Earthquake, Andrew Charleson,

It is impossible to vibrate anything, other than its natural period without dragging it to and fro. For example in a child swing, to be effective, shove must be approximately equal to the natural period of it. If correctly measured, we will realize that, even small push can set the swing going effectively.

Similar to above phenomenon, the ground motion during earthquake initiates a building to vibrate and to sway to and fro with its natural frequency. For further pushes, the vibrating structure starts resonating at some point, where the natural frequency of it matches with the frequency of ground motion frequency. This resonance can increase resultant forces of 4-5 times as acceleration increases.

The natural periods of structures (**Figure 2.2)** vary according to their height. A small equipment like as a filing cabinet may have 0.05s where it is 0.10 seconds for a single story building. A three story building may have 0.50 second as its natural period. Where periods of 1 to 2 seconds for a small building of 4 to 5 stories, and about 5 to 7 seconds for taller buildings between 10 and 20 stories.

Even though not accurate, building period equals the number of stories dividing by 10. It's just a thumb rule. As we learned calculating periods of structures based on height, still it is not sufficient alone. Though height is the most important factor in building, other factors like **building's geometric proportions**, stiffness and construction materials also affect the period. In addition, tall buildings undergo multiple modes of vibration, so the buildings sway to and fro in a very complex manner with super imposed modes.

Additional factors to be known are different types of ground and their respective periods (**Figure 2.3**). Structures undergo severe damage in soft ground sites because they amplify forces by lowering the frequency and producing longer periods. But hard grounds such as rock having

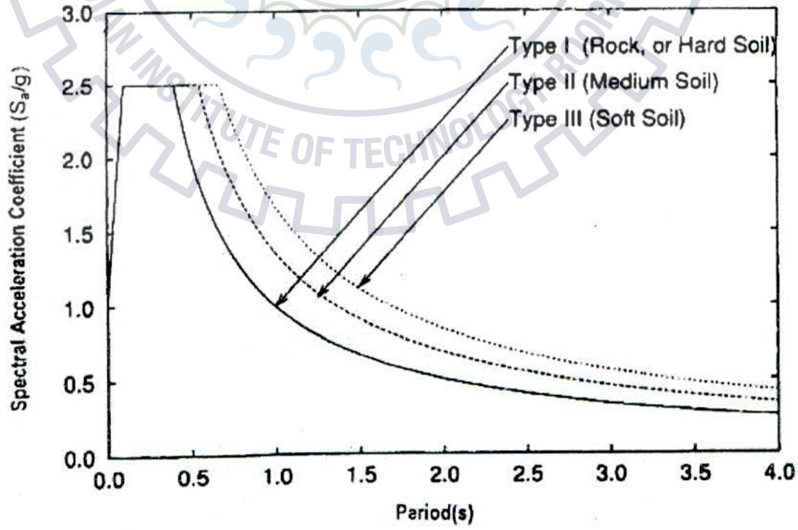


Figure 2.3: Site response spectra

Source: IS 1893 (Part 1) :2002

high frequency and short periods are less harmful to the structure. Many earthquakes made this clear in which building sinking or fall due to liquefaction had reported, example 2001 Bhuj (Gujarat) earthquake.

From the information collected about the nature of the ground, a relationship between periods at which building response probably maximum is developed. This is called **response spectrum** of that site which is characteristic and distinctive property of it.

On abscissa, response spectrum shows varying periods of corresponding accelerations on which are shown on the ordinate. That is useful in ensuring that building natural frequencies do not match with site's peak frequencies. These frequencies and resonance effect give an idea of how structural and nonstructural elements should be erected, inclined, leaned or laid in space and their joints to make them flexible, which may let their **frequencies no to match with the ground**.

2.2.3 Torsion

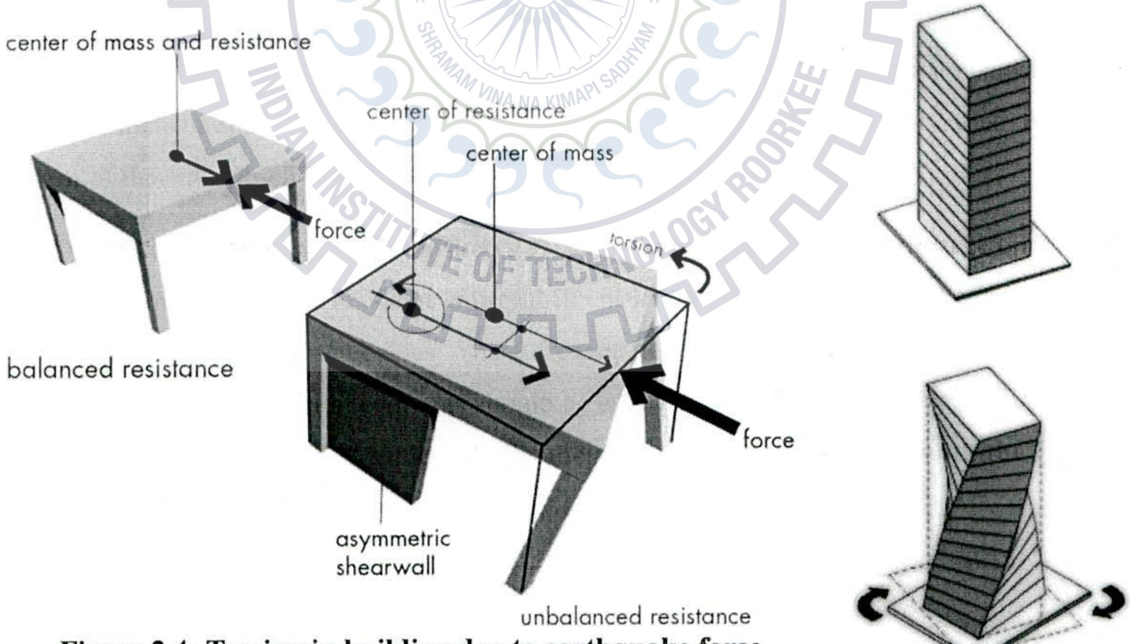


Figure 2.4: Torsion in building due to earthquake force

Source: Principles of Disaster Mitigation in Health Facilities

Object can be kept in equilibrium state with possible less amount of effort through only its center of gravity or center of mass. In a plan, center of mass and geometric center coincide if and only if mass is distributed properly or uniformly.

In plan where (**Figure 2.4**) distribution of mass is not uniform, the center of mass and geometric center do not coincide.

Uniformly distributed mass within a floor lets the lateral force to exert through the floor's center which is resultant of horizontal acceleration of its all particles. Dynamic balance can be maintained, if the resultant of the resistance force provided by frames and walls acts back, from this point.

An earthquake force is eccentric if the mass is uniformly distributed about the center of resistance and the force exerted is proportional to the amount of mass. In this instance the floor tends to rotate about the center of resistance and creates "torsion" a twisting action in plan, resulting a very aversion kind of stress concentration. In a building with evenly distributed mass in plan (symmetrical building with uniform floor plan, wall and column masses), ideally the earthquake resistant elements would be placed symmetrically in directions such that the structure exerts an equal and opposite stiffness that prevents rotation. The building codes make provision for a certain amount of torsion that is bound to be present in a structure.

2.3 Resisting the effects of ground motion

Three basic characteristics of buildings help in resisting and dissipating the effects of seismically induced motions are

- Damping
- Ductility
- Strength/stiffness

2.3.1 Damping

In response to earthquake force, dynamic behavior of the building can be modified by damping considerably. As discussed earlier in **2.2.2,** if building resonance phenomenon occurs, with the efficiency of a swing or a pendulum in response to ground motion, its acceleration should amplify and resulting seismic forces to increase significantly. Still, buildings are saved from resonance effect. Damping is character which doesn't allow building to resonate with the purity of a pendulum. That is why a building set into motion will return to initial state soon.

The rate of decay of a building or its damping is characterized by its design assumptions, "**connections of structural and nonstructural elements and construction materials"**. If damping is in effect, the general response remains the same, but the magnitude is greatly reduced.

2.3.2 Ductility

A well damped building, in an intense earthquake may experience much higher forces **than** calculated while designing by following the building codes. But accommodating members to resist maximum forces would result in a very **uneconomic** design, and the **size and placement of resisting elements** would pose planning and **architectural problems.** To achieve good ductility we need special, expensive input and so much care in detailing of joints.

The ability to fail after desired deformation is material's one of the properties called "ductility" which deals with this gap of calculated forces and possible actual forces. Steel being one major construction materials having this high ductility can undergo deformation and dissipate the energy to certain level assuring the life safety in economical or mass buildings.

Masonry laid with layers of bricks without reinforcement, which are brittle in nature and concrete which is inefficiently reinforced fail without or a little ductility. They deform minimum before they fail. But still, in some cases few buildings survived being encountered more than the forces estimated in their design. This shows that analysis of forces is not yet accurate. So few building can really survive at higher forces then the anticipated because of additive fictitious **strength from components like partitions** which are not considered in calculations.

2.3.3 Strength and Stiffness

Two primary characters of a structure are strength and stiffness. Although they come into picture as a part of structural design and analysis which is non-seismic, the difference between strength and stiffness is regarded to be a critical affair and its study in a highly developed form and used in structural engineering for understanding lateral forces applied to earthquake problems.

To ensure a structure, to take imposed loads without exceeding certain stress values, sufficient strength is necessary. Here stress values are internal forces developed within members by resisting the external force. Force per area is the measurement for this stress.

Measurement of stiffness is in terms of deflection of members like a roof, floor or wall structure, which bend due to loads. It is generally expressed as a fraction of length of the member or assembly.

IBC provides stress and deflection limits that are not to be exceeded for commonly used materials and assemblies to ensure sufficient strength and stiffness.

2.4 Types of damages

Types of damage are different in different types of buildings i.e.

2.4.1 Mud houses

Being traditional old type construction, mud houses are vernacular and economical. They are constructed by sundried bricks in mud mortar with help of low skilled labor. They are weak in shear, tension and compression and the joints easily separate during low level ground shaking leading to collapse.

2.4.2 Masonry Buildings

Unreinforced and reinforced

Because of large in plane rigidity causing low time periods of vibrations it attracts large seismic forces, so cracks are developed at corners and piers between the openings. The lack integrity is due to lack of through stone, bond between cross walls and diaphragm action at roof level. They cannot also take inertia forces from roof/floor if it is not properly tied to the walls. If it is reinforced with steel or wood with dressed masonry, the strength of these buildings is increased considerably.

2.4.3 RC frame building

RC frame buildings are having frame structure with masonry walls as infill which are laid with bricks in layers with cement mortar. But lack frame action between slabs, columns and beams in transmitting loads to the foundations of building may develop cracks and eventually collapse. Poor reinforcement, wrong calculations/assumptions in design members and lack of infill at irregular locations for Architectural aesthetics, soft stories and short columns magnify the damage. There are other types of buildings with different type of damage patterns. Steel and RC composite building are much stronger than earlier discussed buildings in all aspects with better ductility and fire resistant. Still these buildings have limitations because of high construction quality and high cost which are not suitable for mass housing for which we are looking in most of situations.

From above, we can conclude building that components/features contributing damage are poorly designed with unsymmetrical plan, shape, and form, flaws in building materials, unsupervised construction, and failure of nonstructural members inducing structural members to fail (water tanks). Even aging lead to deterioration of strength, which can be an eventual problem in any type building depending upon its maintenance.

2.5 Influence of architectural design and configuration

After observing the failure patterns and referring to the reports published, about major earthquake damages, we have learned about factors influencing the performance of structure. From them, by keen observation in to stages of building life, we can say that the critical design decision steps at early stages those which create the building configuration are so important in deciding their strength . Here configuration can be defined as the **three dimensional shape, building's overall size and corresponding complexities** into the structure driven by the. It becomes clear that one of the major and influential factors is Architectural configuration of structure.

As we know, the architect being a pivotal point by simultaneously serving the client, bringing in the structural designer and other construction related specialists and working closely with the contractor has more opportunity in involve in every step of project not just in design step.

The decisive position, to influence the seismic performance of structures is there for Architects from initial stages of project itself. Now by realizing that seismic configuration problems originated globally in adoption of the modern architectural styles like "International Style, Deconstructivism" in the twentieth, we try to conclude and give some architectural guidelines to avoid and corresponding structural problems.

3 Building Configuration and influence

3.1 Configuration

According to **FEMA-454**, kinds of unusual conditions and buildings are result from early architectural decisions that determine the configuration of the building. For these purposes, "**configuration can be defined as building size and shape, the size and location of structural elements, and the nature, size and location of nonstructural elements** that may affect structural performance". The nonstructural elements may include such elements as heavy nonstructural walls, staircases and exterior walls. The seismic significance of the building configuration is that it primarily determines both the way forces are distributed throughout the structure and also the relative magnitude of those forces. Seismic codes distinguish between regular and irregular configurations, and it is the latter that may have a detrimental influence on the effectiveness and cost of seismic engineering and on building seismic performance itself.

3.2 Influence

Experience in earthquakes has shown that the architectural form of a building has a major influence on its performance under ground motion. This influence is the result of the three dimensional interaction of all the structural systems and architectural components under earthquake forces. For certain architectural forms, the response of the building can become very complex, and the earthquake forces can be concentrated and distributed in undesirable ways. The term building configuration is used in seismic design to define the architectural form of a building. And coming to regular and irregular configurations it is necessary to know basic structural systems of contemporary structures.

3.3 The basic seismic structural systems

Buildings of contemporary architecture take loads in **vertical and horizontal planes through different structural systems.** The location of structural components like walls and columns is an outcome of the buildings structural system which is influenced by the architectural configuration. It also represents the type joints between them. Basic vertical and horizontal resisting system are shown in **Figure 3.1 and 3.2**

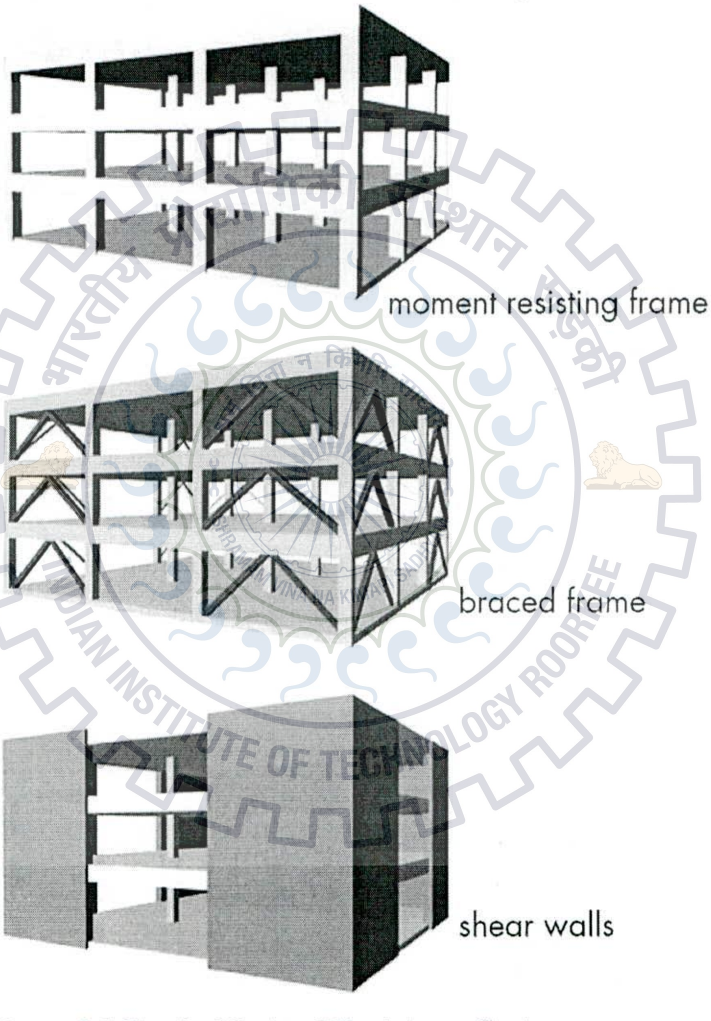


Figure 3.1 Vertical Lateral Resistance Systems

Source: FEMA 454-Designing for Earthquakes

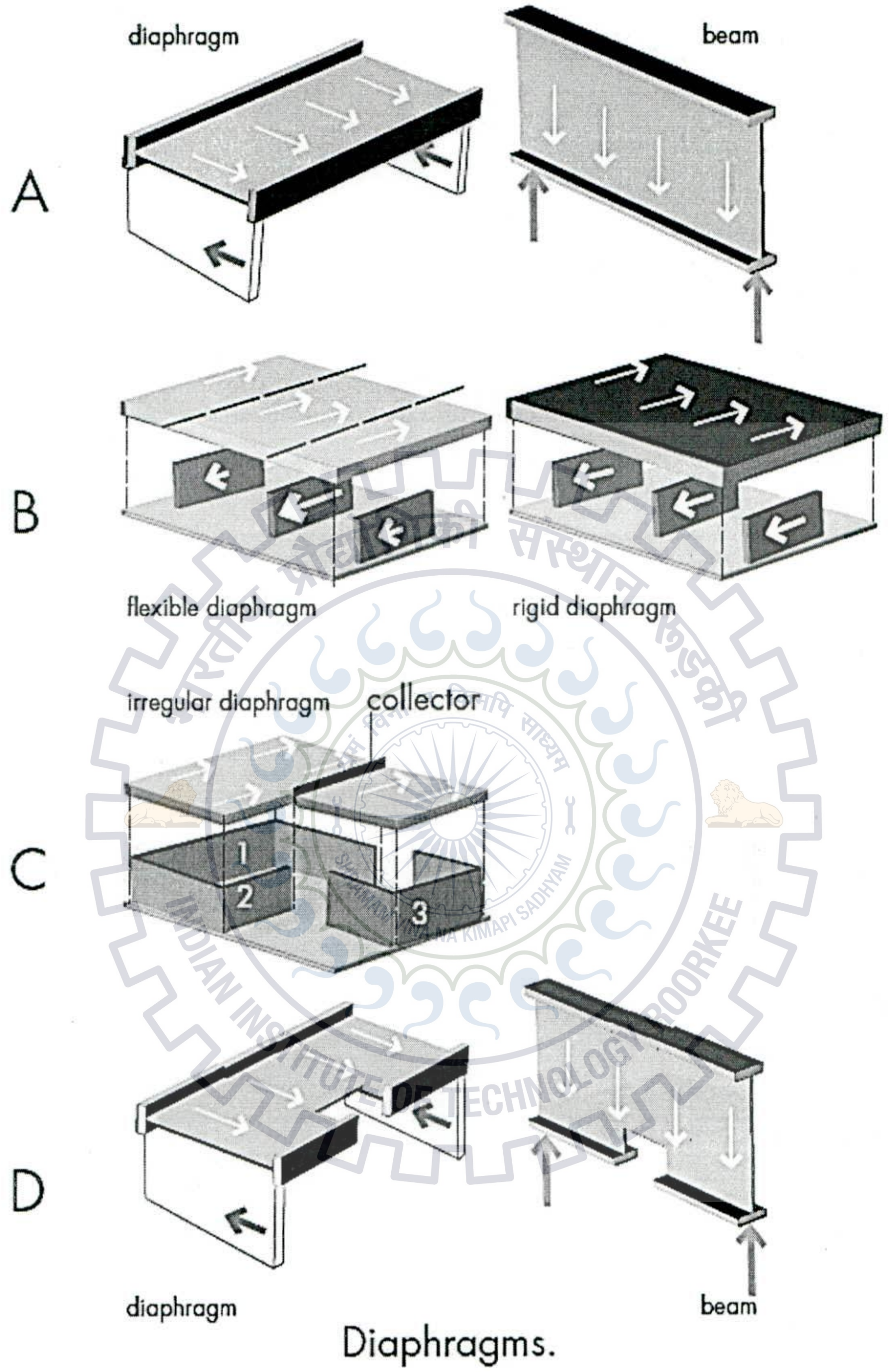
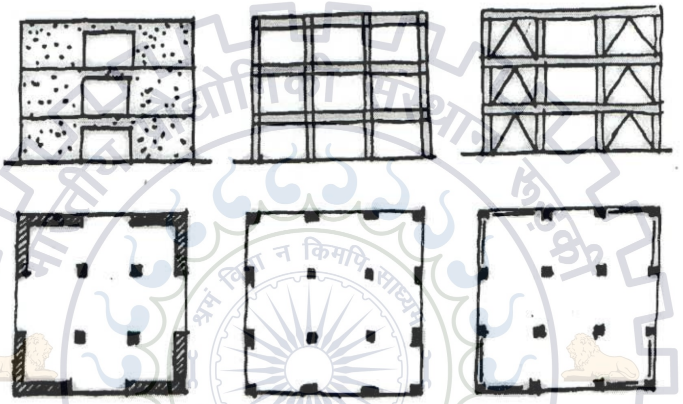


Figure 3.2 Diaphragms: Horizontal Resistance System

Source: FEMA 454-Designing for Earthquakes

3.4 Regular configurations

Regular configured buildings are optimized **architectural and structural Configurations**. The kind of regular (or uniform) configuration upon which we assume and estimate of code seismic forces is based is shown. These three diagrams (**Figure 3.3**) represent structures that are seismically optimal, which use the three main alternatives for lateral resistance systems, and which still provide a useful and common architectural form. The characteristics of these configurations are that make them optimal and desirable as shown. (The particular structure shown here is, a three story, three bay building).



Shear Wall Moment Resistant Frame Braced Frame

Figure 3.3: Regular and seismically optimal structures

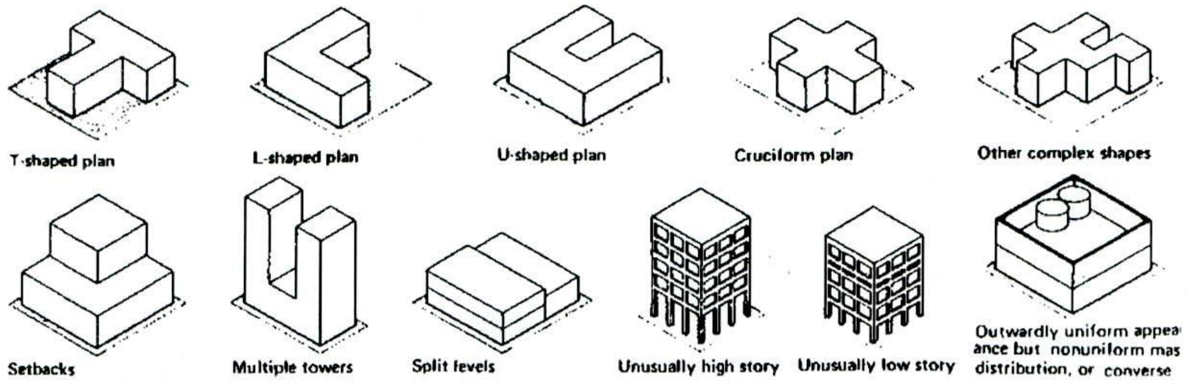
Source: Christopher Arnold, The Seismic Design Handbook

3.5 Irregular configurations

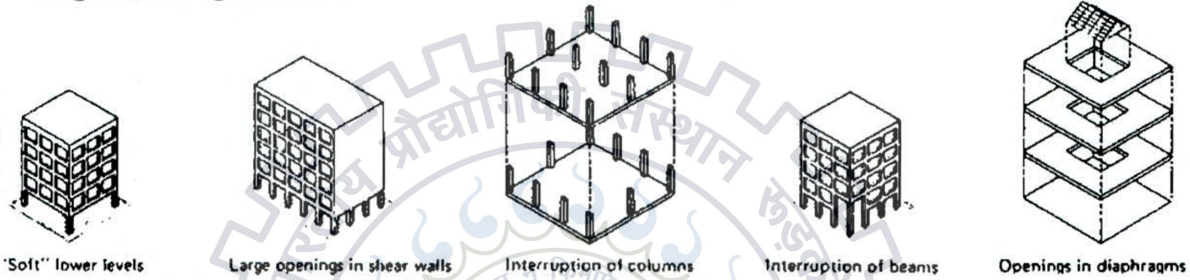
Irregular configurations (**Figure 3.4**) occur when the building deviates from a simple regular, symmetrical form (**Figure 3.3**) in plan and section as shown in regular configuration. This deviation tends to create two basic kinds of problems

- **Torsion**
- **Stress concentration**

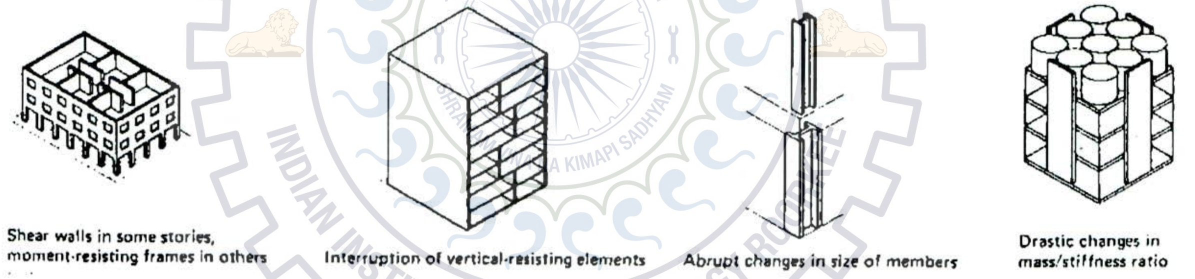
Torsional problems are most typically associated with plan irregularity or geometries, where the size and location of vertical elements produce eccentricity between the centers of mass and resistance. Torsional forces also create great uncertainty in analyzing the building's resistance.



Irregular configuration



Abrupt changes in lateral resistance



Abrupt changes in lateral stiffness

Unusual structural features

Figure 3.4: Irregular configurations

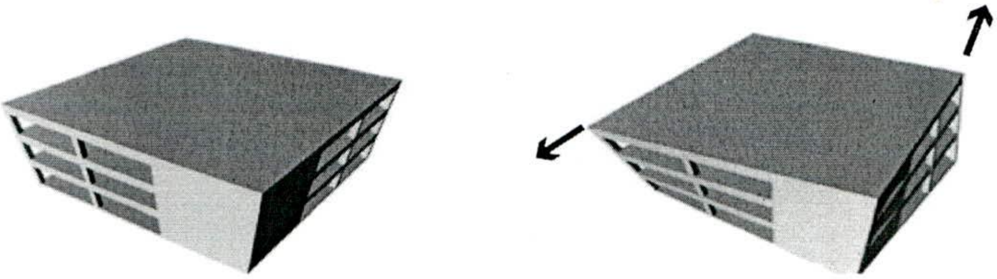
Source: Christopher Arnold. The Seismic Design Handbook

Stress concentrations occur when disproportionation of overall seismic force is concentrated at one or a few locations in the building, such as a particular set of columns or beams. Many building failures occur because of the lack of balanced resistance, which results in undue stress being placed on a member or members, with consequent overstress or failure. Torsional forces and stress **concentrations induced by configuration irregularities**, such as abrupt changes of strength or stiffness are the prime cause of such imbalances. Configuration irregularities often arise for sound planning or urban design reasons and are **not necessarily the result of the designer's intensions**. For example, the re-entrant corner forms are very useful in achieving high density housing solutions on small lots. High first stories may be necessary for buildings such as hotels or offices in which large first floor spaces require much higher ceilings than 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.

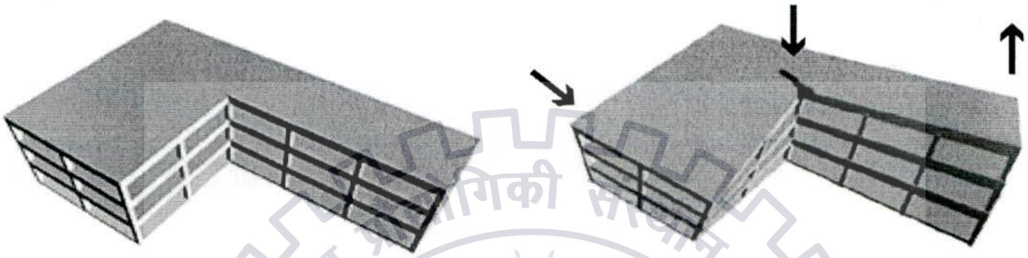
3.6 How much is configuration irregularity and its influence?

To establish seismic forces for practical design purposes by use of a seismic code, a number of assumptions must be made, typical of these assumptions are that the forces are analyzed in two directions, loads are analyzed independently and aggregated by simple addition, and structures are assumed to provide direct load paths and be regular inform. The code procedures commonly in use for establishing earthquake forces apply to structures based on these simplifying assumptions.

Likewise the quantifying the influence of these irregularities also need some assumptions. This quantity varies to different degrees depending upon the location and importance of the irregularity. So, it becomes obvious, why the re-entrant corner is a serious issue in an extreme form and not in a lesser form. The determination of the point at which a given irregularity becomes serious used to be a matter of judgment, but the new codes and computer simulations now help to define the issue in a quantitative way to some extent. Images here, show how deformation associated with every type of irregularity in plan (**Figure 3.5**) or Horizontal plane and Vertical plane (**Figure 3.6**)

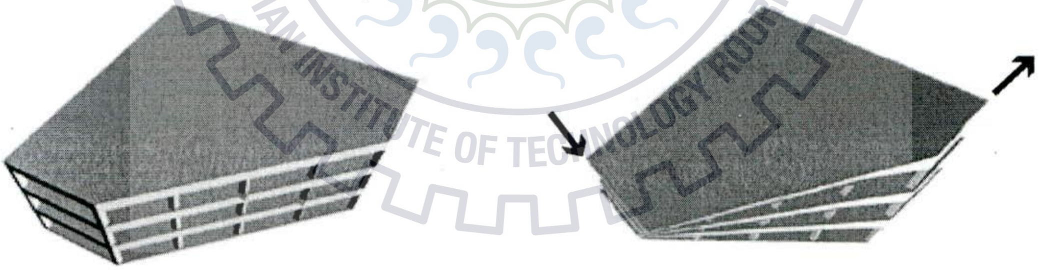


Torsional irregularity and unbalanced resistance

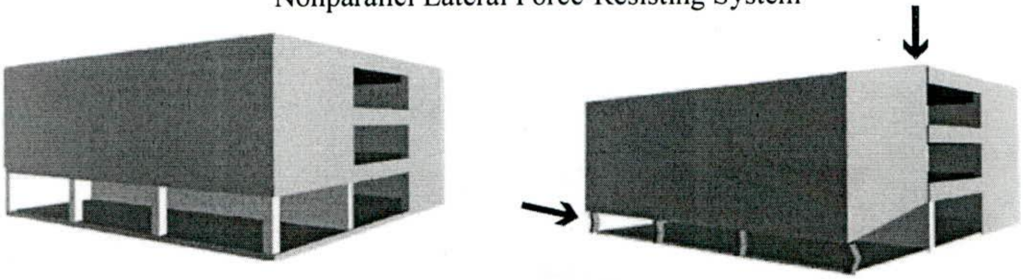


Re-entrant Corners

Diaphragm Eccentricity and Cutouts



Nonparallel Lateral Force-Resisting System



Out-of-Plane Offsets: Discontinuous Shear walls

Figure 3.5 Horizontal irregularity and damage patterns
Source: FEMA 454-Designing for Earthquakes

Soft Story: Stiffness Irregularity

Weight/Mass Irregularity

Vertical Geometric Irregularity

In-Plane Irregularity in Vertical Lateral Force System

Capacity Discontinuity. Weak Story

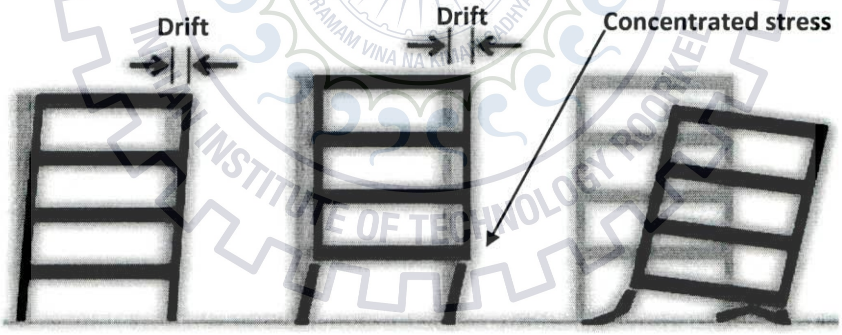
Figure 3.6 Vertical irregularity and damage patterns

Source: FEMA 454-Designing for Earthquakes

4 Common configuration problems

4.1 Soft Story

Generally if there is existence of a building floor that possess a significantly lower stiffness than the others is an irregularity called soft story. As per **ASCE 7-10**, "the irregularity of soft story said to be existed, if there is a story with the lateral stiffness less than 70% of that in the story above or less than 80% of the average stiffness of the three stories above. We can find soft **first story** as the most common type of soft story irregularities. It is mostly present in modern RC frame buildings when a large number of nonstructural rigid components, such as masonry walls, are attached to the columns of the upper floors of a RC frame structure while the first story is left empty of walls or with a reduced number of walls in comparison to the upper floors for parking and other architectural requirements. The rigid nonstructural components in upper floors can limit deformation of the columns to some extent, modifying the structural performance of the building to horizontal forces. In a regular building, the earthquake shear forces increase towards the first story. So in soft story buildings, the first story columns which have to take axial and shear load also, may fail when ground shakes **(Figure 4.1)**



Regular (With continuous load path, presence of walls in ground floor)

Soft story (Discontinuous load path, without walls in ground floor)

Collapse

Figure 4.1: Soft story failure mechanism

Source: FEMA 454-Designing for Earthquakes

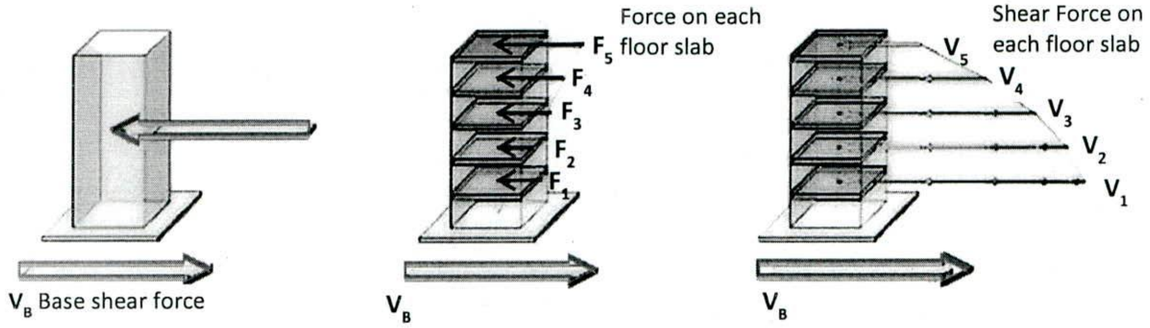
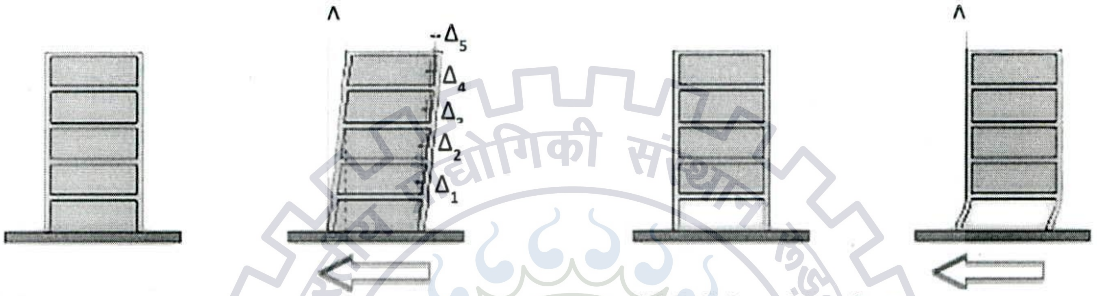


Figure 4.2a: Lateral forces and shear forces in a building when ground shakes



(a) Regular building (b) Building with soft story

Figure 4.2b: Distribution of total displacement generated by an earthquake force

Source: Structure and Architecture, Angus J. Macdonald

Above figure **(Figure 4.2a)** shows the total displacement and corresponding force (**F_n**) induced by an earthquake tend to distribute homogeneously in each floor throughout the height of the building. Deformation in each floor (**Δ_T**) would be similar. When a more flexible portion of the lower part of the building supports a rigid and more massive portion, the bulk of the energy will be absorbed by the lower significantly more flexible story while the small remainder of energy will be distributed amongst the relatively rigid upper stories, producing on the most flexible floor, larger relative displacement between the lower and the upper slab of the soft story and therefore, the columns of this floor will be subjected to large deformations**(Figure 4.2b)** and may lead building to collapse. The flexible portion present at lowest level, in the path of force transmission may create a critical situation during an earthquake, the stiffness discontinuity between the first and the above stories might cause significant structural damage or even total collapse of the building**(Figure 4.1)**. The structural elements are homogenously distributed throughout the building, but the apartments are located on the upper floors with many masonry walls, while the lowest floor is left totally or partially free of partitions for parking vehicles and for social areas that require wide spaces. In the case of double height first soft stories **(Figure 4.3)**, columns are very

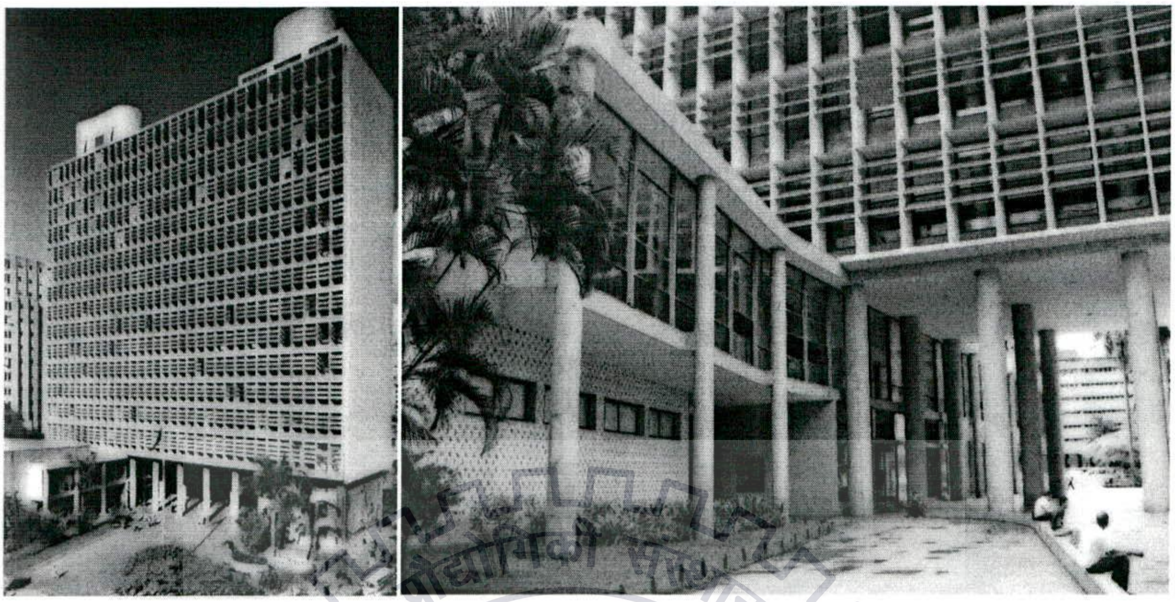


Figure 4.3: Double height first soft story (Ministry of Education, Rio de Janeiro)
Source: http://www.greekarchitects.gr/

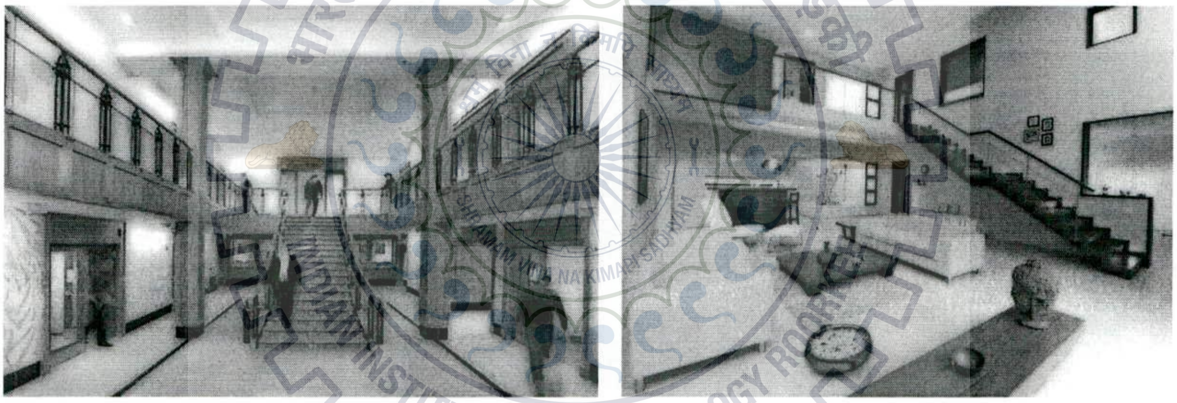


Figure 4.4: Interiors of double height first soft stories in modern buildings
Source: http://www.oikos.com/library/showcase/cambridge/index.html

flexible not only due to the total or partial absence of walls but as a result of their significantly greater height in relation with those from the upper floors. This configuration is one of the characteristic models of modern design for office buildings, hotels and hospitals, in which the access for general public has a great importance.

This type of configuration is also very common in modern mixed-use buildings, in which the urban code requires that the lower floors are of a greater height in order to accommodate shops with mezzanines for storage. As a variant of this configuration, we can find the use of columns of different heights in a corner of the building in order to give more importance to that space. Examples of modern buildings interiors with double height first soft story are shown (**Figure 4.4**).

Soft story may also exist at intermediate floors. It is a typical configuration of massive low cost housing programs which follow the patterns of the **"Unite d'habitation (Figure 4.5)"** in Marseilles of Marseille (1947-1952) by **Le Corbusier (LC)**. The concept which prevailed on the layout of this sort of isolated building was the self-sufficiency, as the residence features were included, communal facilities, such as, a library, nursery school, film club, recreational, businesses and others areas of which needed wide available spaces therefore an entire floor or a great section of it was left with no walls.

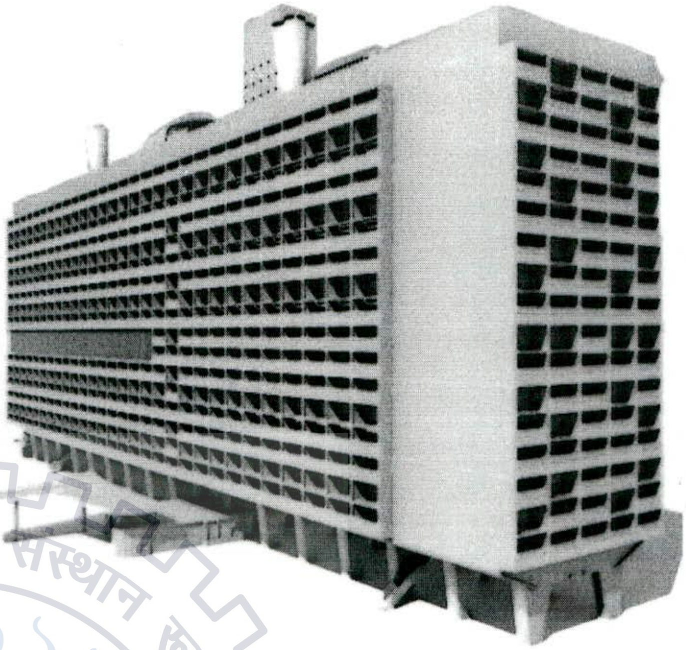


Figure 4.5: Unite d'habitation

Source: http://www.turbosquid.com/3d-models/3d-le-corbusier-habitation-marseille-model/733416

4.2 Weak Story

The existence of a building floor that possess a significantly lower lateral structural resistance than the immediate superior floor or the rest of the floors of the building is an irregularity of weak story. As per **ASCE 7-10**, "irregularity of weak story said to be existed, if the lateral strength of story is less than 80% of that in the story above. Here, the story lateral strength is the overall lateral strength contributed by every seismic resisting element sharing the story shear for the direction under consideration". Due to its inability to withstand the different types of loads (lateral, vertical and moments) produced by the ground motion the building's weakest part would suffer severe damages. Current seismic regulations like **NEHRP**, and recent versions of IBC, have included numeric values for the assessment of weak story.

Weak story configuration is often generated in hotel, hospital buildings and public buildings where people assemble, in which not only the first floor is designed less walls than the other floors, but generally, due to its importance, it also has a greater height than the rest of the floors. Weak story can be existed if there is elimination or weakening of seismic resistant components at the first floor or mixed systems: frames and structural walls, with wall interruption at the second floor or at intermediate floors. This irregularity can also be present at the first floor or at intermediate floors. There are numerous examples of many buildings presenting a combination of these types of irregularities, soft and weak story, making them seismically vulnerable.

4.3 Practice of Soft story and the weak stories in architecture

The **soft story** and the **weak story** are building irregularities which influence the stiffness and resistance of building. **"Open floor"** is the term is used in architecture for these irregularities. As number of advantages are provided by concept of modern architectural design, both aesthetical and functional, it has been practiced all around the world since the first half of the 20th Century. The mentioned phenomenon becomes obvious when the "ground floor" has no walls (**Figure 4.6**), while stiff non-structural walls are present in the upper floors, or when shear walls of upper stories do not continue to the foundations which interrupt the load path.

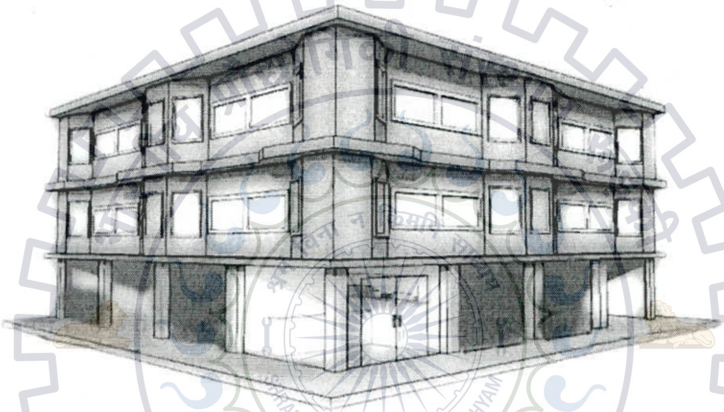


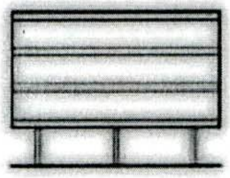
Figure 4.6: Building without walls in the ground floor

Source: http://www.cambridgema.gov/CDD/zoninganddevelopment/sustainablebldgs.aspx

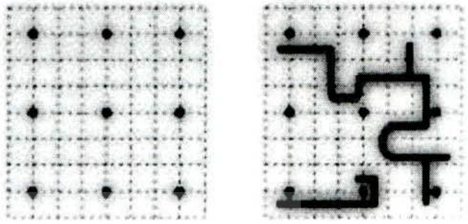
After through reading about evolution of modern structural designs from architectural perspective, It is apparent that, the roots of architectural configuration commonly used in present cities is mainly derived from the first three points of the **"Five points for a new architecture" (Figure 4.7)** by architect **Le Corbusier (LC)** in 1926, which defined the modern architecture.

1. **Pillars : Open first floor,**
2. **Free designing of the ground plan,**
3. **Free design of facade,**
4. **The horizontal window**
5. **Gardens at Roof**

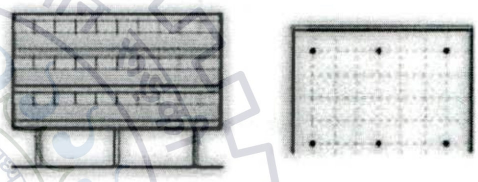
1. **Pillars/Open first floor,** those are the replacement of supporting walls by a grid of reinforced concrete columns that bears the load of the structure and raised above ground is the basis of the new aesthetics, easy surveillance and commuting purposes



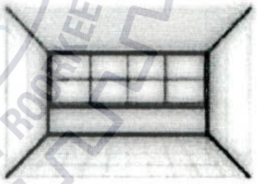
2. **Free designing of the ground plan**. The absence of supporting walls means that the house is unrestrained in its internal usage and partitions can be erected as per function



3. **Free design of facade**, by separating the exterior of the building form its structural function the facade becomes free and additional space will be created inside.



4. **The horizontal window**, " to be lit evenly or to have structural independence, A cut along its entire length of facade



5. **Roof gardens**, besides providing essential protection to the concrete roof emphasising that building should give back space, they can also be utilized for a domestic purpose.

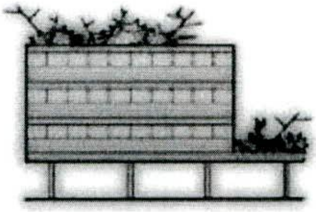


Figure 4.7: Five points for a new architecture

Source: Toward an Architecture bv Le Corbusier

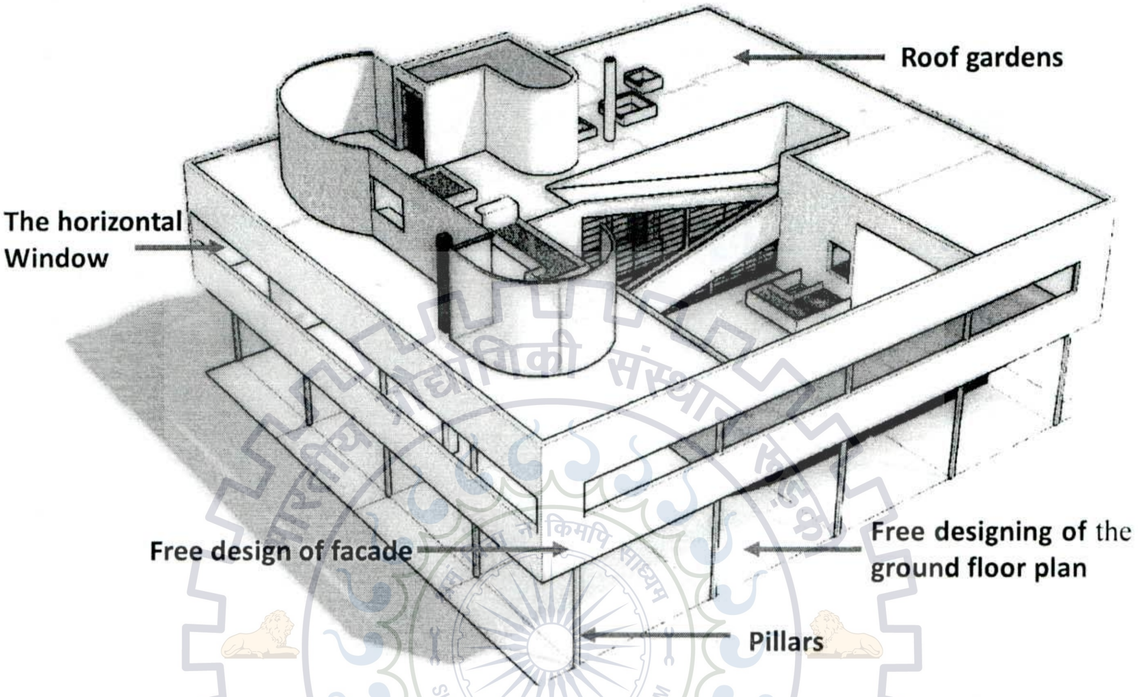


Figure 4.8: Villa Savoye, Based on his five points for new Architecture

Source: http://www.gratisprogramas.org/descargar/variedad-de-programas-mu/

4.3.1 Villa Savoye

Lying on the outskirts of Paris, France, Villa Savoye, built in 1931 is regarded to be one of the most functionally appropriate buildings according to International style of architecture. The villa was constructed according to Le Corbusier's five principles for the modernist architectural style. The inclusion of "pillars, functional roof spaces, open floor planning, long horizontal windows and free facades" defines the structure (**Figure 4.8**). The building occupies the center and increased the views with use of pillars and consequently this raised the house by one level. View and orientation of the sun finds special mention in its design. The structure exemplifies complex construction wrapped within simple design. Various practical problems engulfed the construction long after it was built. It was added to the French register of historical monuments in 1965.

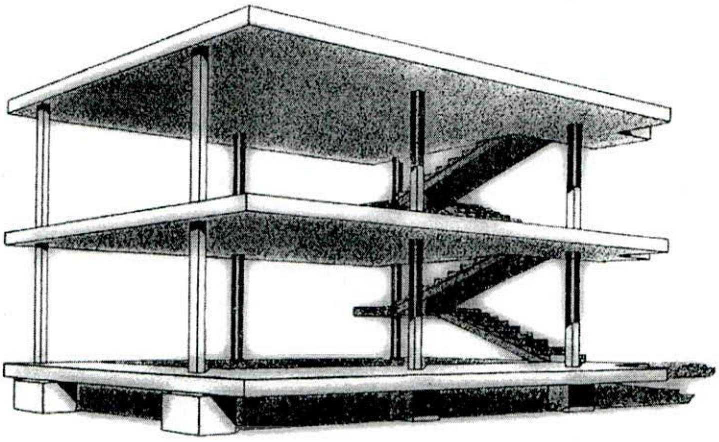


Figure 4.9: "Domino System" proposed by Le Corbusier for economic housing in France

http://thelyingtruthofarchitecture.wordpress.com/2010/05/07/the-duality-of-density

The modern and International style of architecture took so many turns in the hands of renowned architects like **Ludwig Mies van der Rohe**, **Le Corbusier**, **Walter Gropius, Frank Lloyd Wright, and Louis Sullivan.** They designed numerous different type buildings with clearly distinguished aesthetics and functional usage between traditional and modern architecture. These were possible due to the development of new construction technologies and innovative building materials and their combination, such as RC "frame structures"(RCFS) since the 20th Century. **RCFS** was construction technique which replaced the load-bearing structure consisted of continuous heavy walls with small openings.

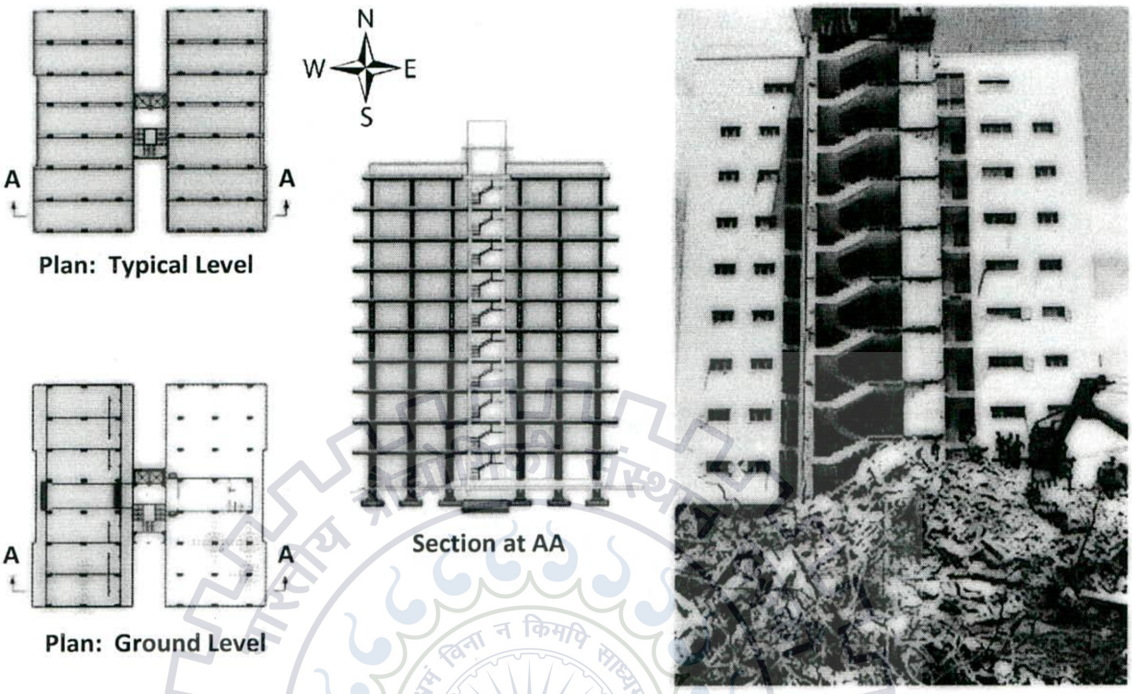
RCFS came into practice leaving behind the brick, mortar, stone and wood structural wall systems, that prevailed until early 20th Century. Development of the "Domino System" by **Le Corbusier** for economic housing was characterized by basic RCFS **(Figure 4.9),** with slender columns and flat slab that covered long spans between columns, without girders. This new structural system also allowed the use of a floor layout free of walls. Since interior partitions did not receive any load, this structural system gave the freedom for modifying the location of them allowing change the type of usage of building.

Most of our present **Urban Zoning Regulations**, consciously or unconsciously, encouraged the use of the open floor configurations, since, when the first story is free of walls then either builder or owner get benefited. Because, if this condition is present in the building, it is not reckonable as part of the allowed maximum built area, nor even for tax control, however, but it is countable for selling to the clients. But in seismic zones, from the beginning of the 20th Century this building configuration has been attributed as one important factor to the contribution to the seismic vulnerability in modern buildings. In all reports, published sooner or later every earthquake striking contemporary cities around the world, that evaluate the damage produced by earthquakes, the presence of "soft story" and "weak story" in damaged buildings is clearly mentioned, and it is also mentioned that it is closely linked to architectural decisions. These decisions usually are taken over, either from the initial steps of the design process, or as consequence of subsequent remodeling.

Even though results of these studies that established the link between the open floor architectural configuration and their effects produced by earthquakes on buildings, the impression of remedial actions have been restricted to the academic and professional field of structural engineering, while architects and urban planners are continuing to apply these modern pattern, not only for new architectural designs, but as a provision in **Urban Zoning Regulations**, not understanding the link between their decisions and the generation of seismic vulnerability that they produce in contemporary cities. Still In the 1970's, a few Architects from California took part in seismic engineer's effort in understating these problems and tried to implement the seismic codes of some special recommendations for their design and construction of buildings without compromising modern architectural configuration.

Few authors like **Guevara-Perez** (2009), **Arnold and Reitherman** (1982) mentioned that size and geometric form were not just enough parameters for defining the seismic vulnerability of a building. They emphasized the relationship between seismic performance and the **distribution of strength, stiffness and mass in the building**, the nature of size and location of structural and non-structural building components. But, it was not realized until an earthquake struck Mexico (1985), which made UBC (1988) edition to include for the first time, two tables defining some parameters to identify the "irregularity" in the configurations of plan (horizontal plane) and elevation (vertical plane). Since then in the majority of the international seismic provisions, the degree of irregularity in the configuration of a building is recognized as one of the most important factors that are established for defining the analysis procedure that should be used for the design of earthquake resistant buildings.

4.5 Examples of damaged buildings



Plan: Typical Level

Section at AA

Plan: Ground Level

Figure 4.10: "The Palace Corvin" with one of two towers collapsed

Source: http://anavelvor.fr/free-of-the-west-cb575-wing

4.5.1. In (1967 Caracas, Venezuela earthquake), "**The Palace Corvin**" an internationally known historic example of a building in which the evidence of the unfavourable conditions of soft first story was revealed. It consisted of an H-shaped first floor **(Figure 4.10)**. The two main bodies of the building housed residential apartments and were joined in the middle by the vertical circulation block. In the east wing, for parking purpose the first floor was left open, while in the west wing with shear walls were continued, following the upper floors. During earthquake, this east block collapsed. The portion of the building on the east side only collapsed completely while the part on the west side survived the earthquake without structural damage because of shear wall. Right side of **Figure 4.10** shows the remaining front part of the building and the elevator and staircase core.

The reasons behind the widely divergent behaviour of the two portions of the building may have different reasons contributed in failure, but lack of shear wall played major role.

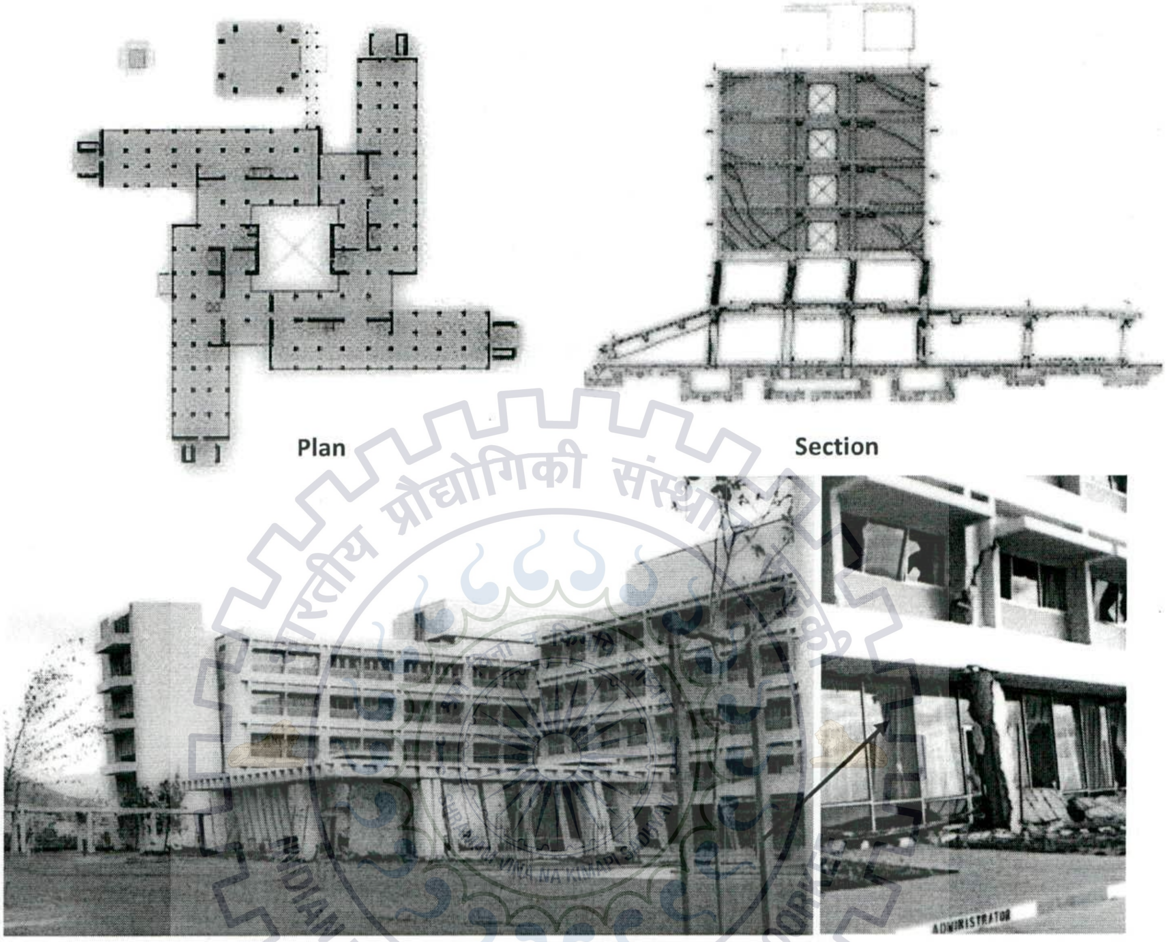


Figure 4.11: "Sylmar Olive View hospital" damaged in 1971 earthquake

Source: Online Archive , NISEE e-Library

4.5.2. The main building of the "**Sylmar Olive View hospital**" (1971 San Fernando, California earthquake) consisted of four bodies joined around a courtyard, as shown at the structural layout (**Figure 4.11**). Each body had six floors and a penthouse. Bertero (1978) report described its conditions as "The structural system has significant discontinuities. While the upper four stories consisted of shear walls combined with moment resisting space frames, the lower two stories had only a moment resisting space frame system. The floor system consisted primarily of a flat slab column system with drop panels at the columns. Tied and spirally reinforced concrete columns were used. The shape and reinforcement of these columns differed from story to story." This explains why that the large interstory drift in the main Treatment and Care Unit, which induced significant structural and non-structural damage. Consequently demolition of the building has taken place. This was only because of formation of a soft story at the first story level because on the lower floors there were columns, while there were reinforced concrete walls above the second floor level.

4.5.3. One more example is **"The Imperial County Services Building"** at Imperial Valley, California earthquake in the 1979. It consisted of six floors and a penthouse **(Figure 4.12).** After earthquake reports were examined, it was found that, Lateral resistance of this building was

West side Elevation Plan of Upper floors Perspective

East side Elevation Plan of Ground floor Section at AA

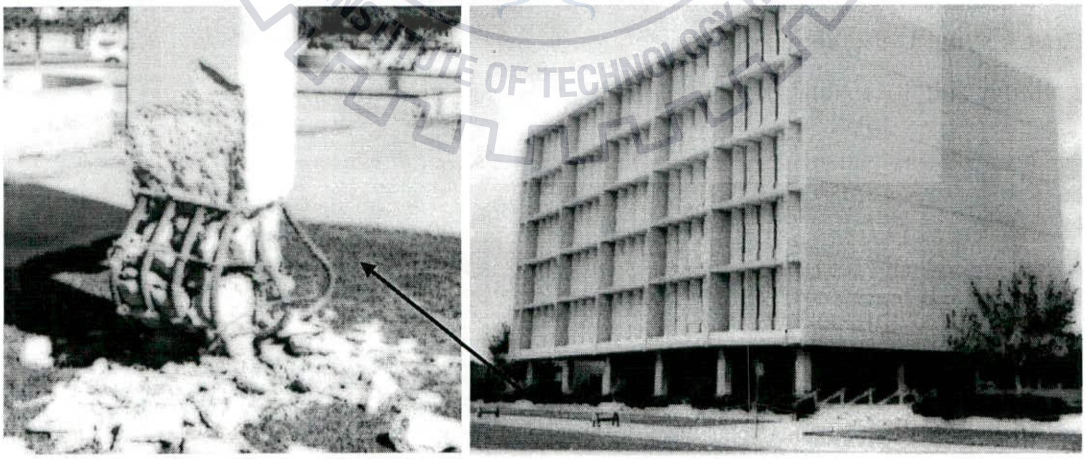
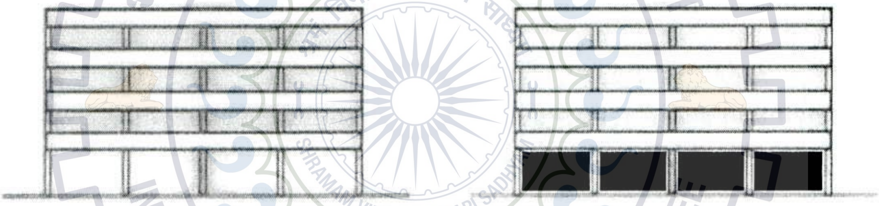


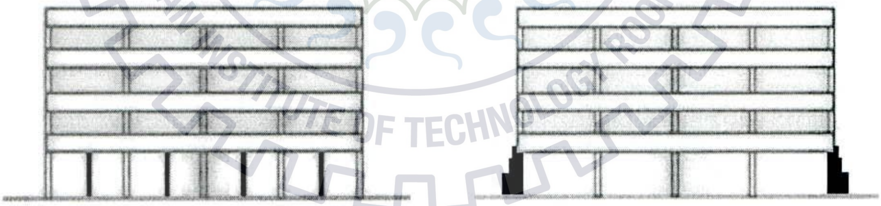
Figure 4.12: "The Imperial County Services Building" damaged in California earthquake, 1979

Source: www.nibs.org/resource/resmgr/BSSC/P-749_Chapter3 provided by moment resisting frame in the longitudinal direction (E-W) and shear walls used in transverse direction (N-S). The upper storey shear walls ran along the full width, while the ground level shear walls were smaller and ran in the transverse direction. The building responded as a soft storey in the E-W direction due to the use of spandrel panels. This led to severe damage to the first story columns, particularly those located at the east end. Arnold and Reitherman, (1982) explained, "this building suffered a major structural failure, resulting in column fracture and shortening by compression at one end (the east) of the building. Origin of this failure lies in the discontinuous shear wall at this end of the building". The building was brought down. The architectural difference between the east and west ends illustrates the failure that originated in the configuration. "The difference in location of the first floor shear walls was sufficient to create a major behavioral difference in response to rotational, or overturning, forces on the large end shear walls."

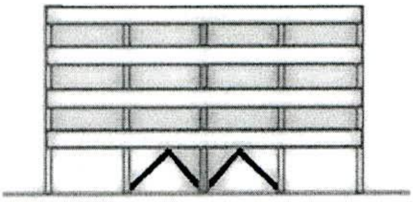
Enhancing the performance of soft story buildings



Soft story building **1 Addition of shear walls**



2 Addition of columns **4 Addition of external buttresses (Walls)**



3 Addition of bracing

Figure 4.13: Basic retrofitting strategies for soft story problems

Source: FEMA 454-Designing for Earthquakes

Economically speaking, adding columns, proper shear walls or bracing to the soft stories is regarded as the best way to retrofit a building **(Figure 4.13).** Making these small changes also can improve the performance building significantly.

4.6 Variations in Perimeter Strength and Stiffness

Buildings which are apparently having regular geometry and even symmetrical, may be irregular yet, when viewed from seismic design perspective. Here is an example which faces this problem.

The perimeter design of a building guides its seismic behavior. "If there is wide variation in strength and stiffness around the perimeter, the center of mass will not coincide with the center of resistance, and torsional forces will tend to cause the building to rotate around the center of resistance."

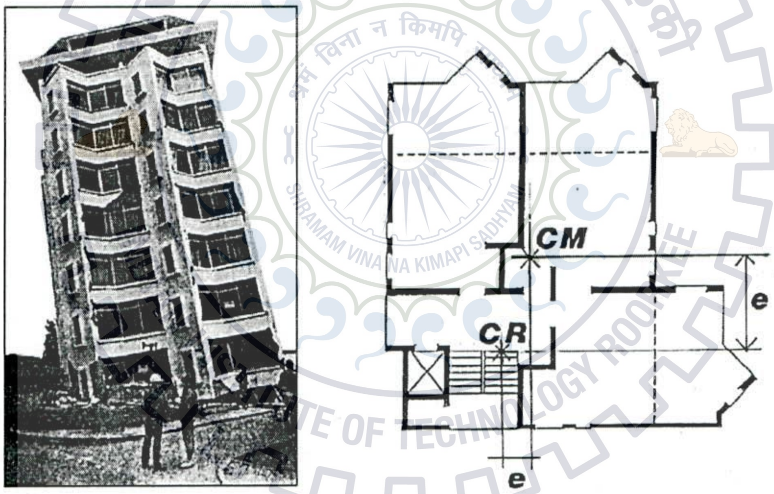


Figure 4.14 Earthquake effecting building, Right side, a typical floor plan showing the Eccentricity (e) along the two axes, because of different locations of Center of Mass (CM), Center of Resistance (CR); *Source: http://mitigation.eeri.org/*

Apartment house shown in **Figure 4.14** was in Vina del Mar, Chile, which was damaged in the earthquake of 1985. Being in ocean resort city, where open frontage for apartments facing towards beach is common, this building was no exception. This condominium was 7 story building having only 3 apartments per floor. And service areas with an elevator in opposite side of frontage and surrounded by reinforced concrete walls which expected to provide the seismic resistance.

During an earthquake, the building was subjected to rotation around its center of resistance. It was followed by a sharp tilt which resulted in a near collapse and subsequently demolished.

To facilitate the passage of vehicles, provision of a large doors, i.e. with an open front design is in widely practice, which is an excellent example of unbalanced perimeter situation. Generally Stores designed as a box with an open glazed front and three solid sides as showed in **Figure 4.15**

Torsional forces are a common consequence of a large imbalance in the perimeter strength and its stiffness.

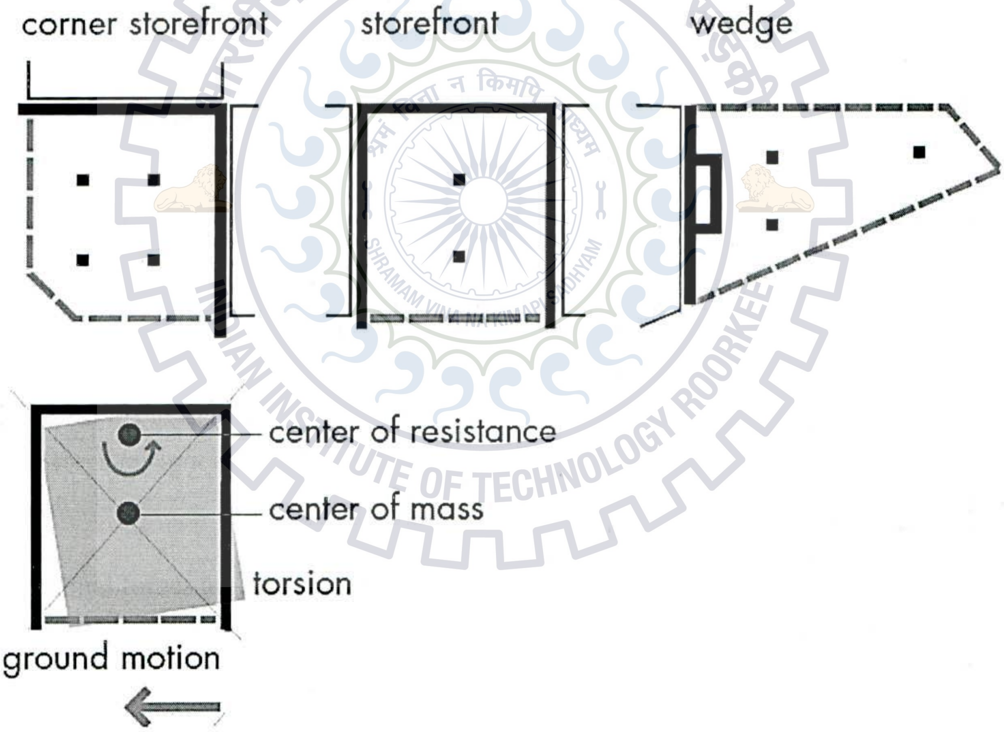


Figure 4.15 Unbalanced perimeter resistance: storefronts and "wedges"

Source: FEMA 454-Designing for Earthquakes

Enhancing the performance

The best way out is to balance the resistance around the perimeter by reducing the torsion. The cited illustration is of a store front. Few strategies those serve as alternatives have been shown in **Figure 4.16**

The frame structure of the perimeter should have equal strength and stiffness. Using lightweight cladding or avoiding heavy materials in the opaque portions, such as concrete or masonry, would not affect the seismic performance as shown in **Figure 4.16-A**

The second way out of this is to add relatively thick shear walls with lesser width near the open faces so that the stiffness increases, and resistance can be equalized provided by other walls as in **Figure 4.16-B**

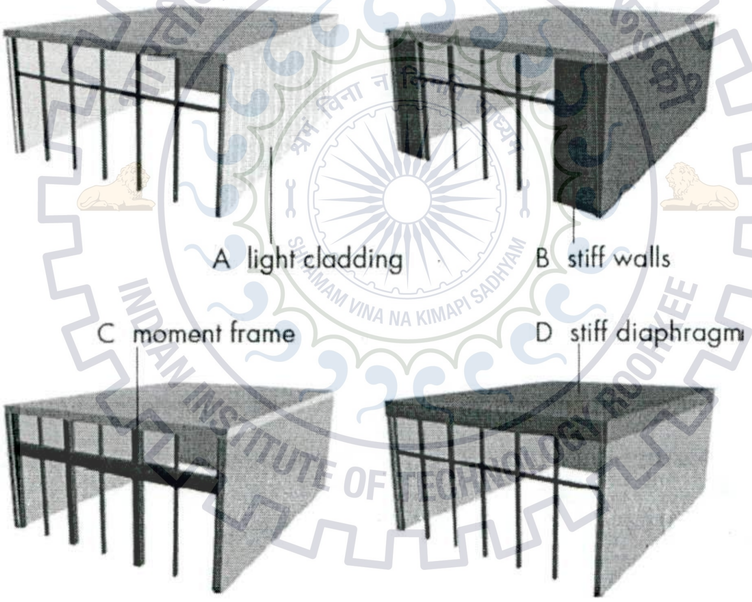


Figure 4.16 Solutions to store front type unbalanced perimeter resistance conditions

Source: FEMA 454-Designing for Earthquakes

The third solution is to employ a strong braced frame or moment resisting frame that resists the moment at the open front as solid walls do on other sides. The size of the façade and materials used for frame, would define the feasibility of this strategy. For wood frame structures, such as motels, small apartment buildings with ground floor garage areas or with small store fronts, this seems to be a good option. The illustration is in **Figure 4.16-C** and **Figure 4.16-D**

4.7 Re-entrant Corners

Buildings with the shapes of an L, T, H, etc., or a combination of these shapes generate re-entrant corners, which are common chrematistics of building forms as shown in **Figure 4.17**

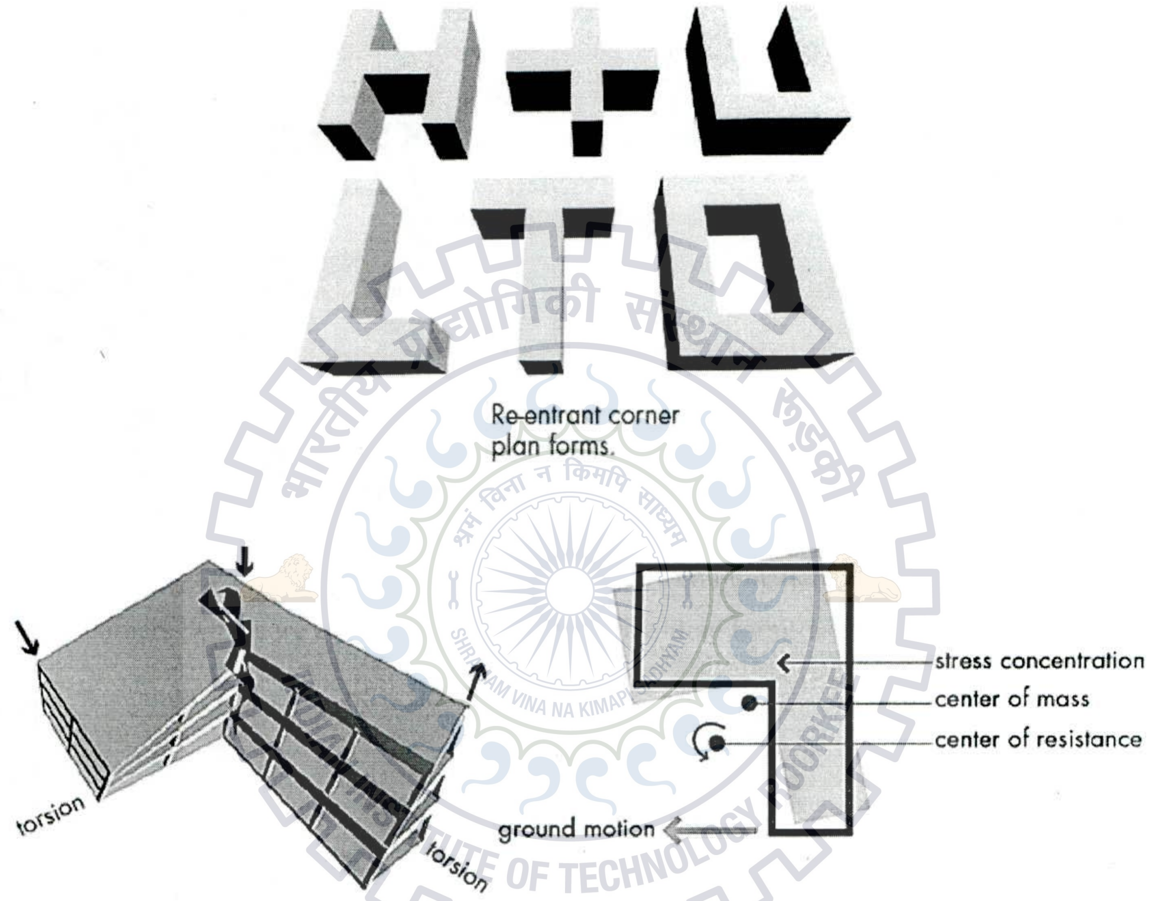


Figure 4.17 Re-entrant Corners forms

Source: FEMA 454-Designing for Earthquakes

Problems associated with these shapes

The first problem is the differential motions of different wings of the building that leads to stress concentration, particularly at the re-entrant corners. The second problem lies in the fact that the center of mass and rigidity can never coincide for all directions of earthquake and hence resulting in torsion. It is difficult to analyze and predict the resultant forces here. **Figure 4.17** shows the problem.

Severity of the problem and the magnitude of the forces depend on

- Ground motion characteristics
- Building mass
- Typologies of structural systems
- Aspect ratio of the wings and their lengths
- The height to depth ratio of the wings

Enhancing the performance

The best two solutions provided for re-entrant corners are either to separate the buildings into simpler shapes or to tie the various building elements into a structure that would provide a balanced resistance, as in **Figure 4.18**. However the second solution is applicable to smaller buildings.

Structurally separated entities should be able to resist vertical and lateral forces individually. And separated configuration should be balanced horizontal and vertical planes.

Separation joint must be designed only after consulting the maximum drift of the two units. When the structures lean toward each other simultaneously, that is regarded to be the most devious condition and thus "the sum of the dimension of the separation space must allow for the sum of the building deflections".

If separation joint is dispensed, several scenarios are created. Collectors at the intersection can transfer forces across the intersection area, but only if the design allows for these beam-like members to extend straight across without interruption. Continues walls of full-height are more effective. Stiffening elements should be placed at the free end of the wings to avoid where distortions usually takes place. "Splayed re-entrant corners are better than right angle re-entrant corners which lessens the stress concentration at the notch" like a member rounded or tapered is much better than other member notched abruptly.

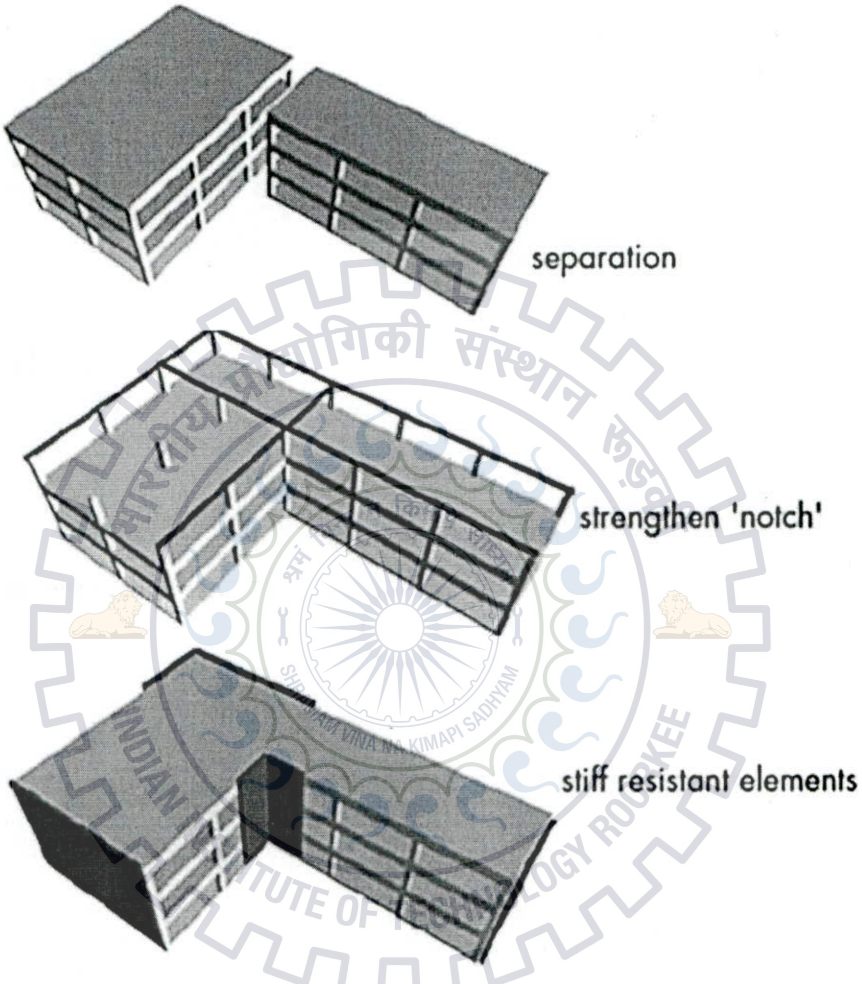


Figure 4.18 Solutions for the re-entrant-corner condition

Source: FEMA 454-Designing for Earthquakes

4.8 The captive column or a short column

The captive column or a short column (**Figure 4.19**) comes in picture in a structure when there is a need to provide openings with large horizontal windows for light and air circulation at more than eye level height. Presence of nonstructural elements, which confine partially leading to a **captive column by restricting its freedom to deform laterally** may happen intentionally or sometimes accidental modification to the original structural configuration.

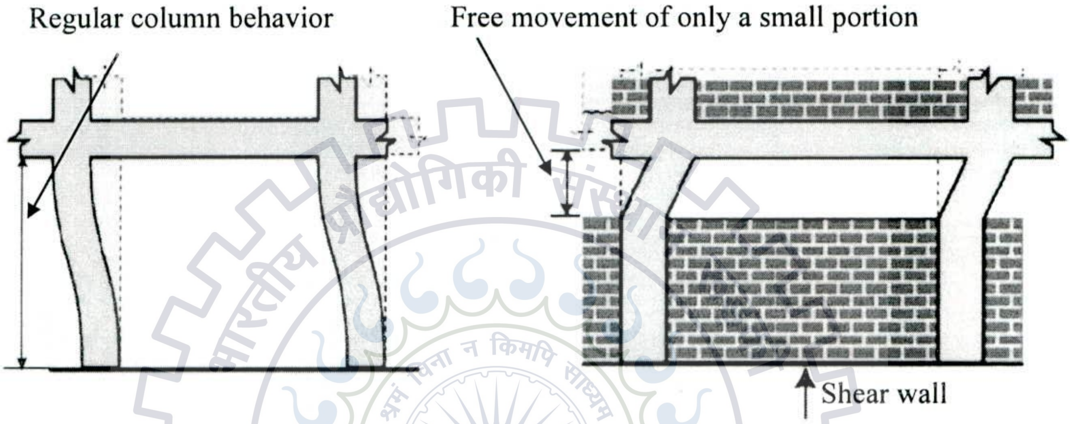


Figure 4.19 Restriction of lateral drift of column leading to captive effect

Source: Source: http://www.artidesign.no/strength-of-materials-and-structures-free

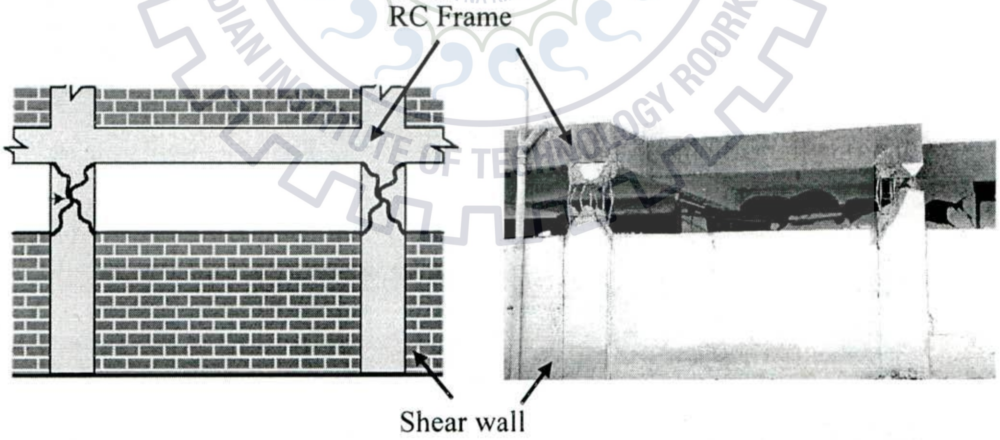


Figure 4.20 Typical captive column failure
http://earthquakespectra.org/loi/eqsa

These conditions originate in the architectural design of the building. Serious earthquake damage (**Figure 4.20**) can be done by these Captive column or a short column conditions.

Openings above the line of sight are used when there is a perceived need to provide lighting and ventilation while restricting visibility from one space to the other. This type of configuration is often found in storerooms, rest rooms, doctor's consulting rooms and school classrooms etc. It has been found that in this type of set up the nonstructural walls exceed the windowsills in height and as a result the windows are stretched across two consecutive columns to compensate opening area. Partially buried Basements are also have cut for lighting, and sometimes to accommodate exhaust fans leading to even more long cut at ground level creating this captive column effect. Other possible areas of this type problems are **open corridors in building complexes, buildings on sloping grounds (Figure 4.21). Sometimes** horizontal structural elements such as slabs, beams,

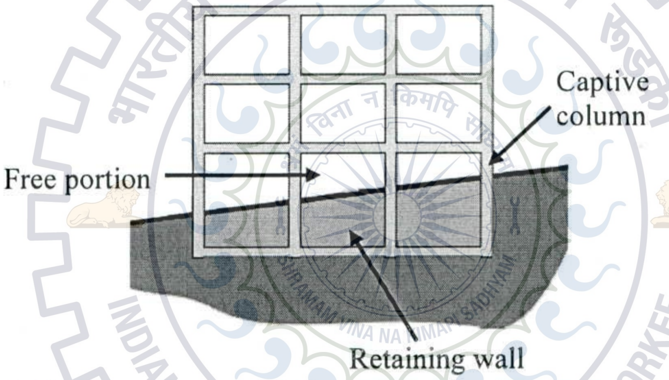


Figure 4.21 Captive column effect produced in structures on sloping ground
Source: Source: http://earthquakespectra.org/loi/eqsa

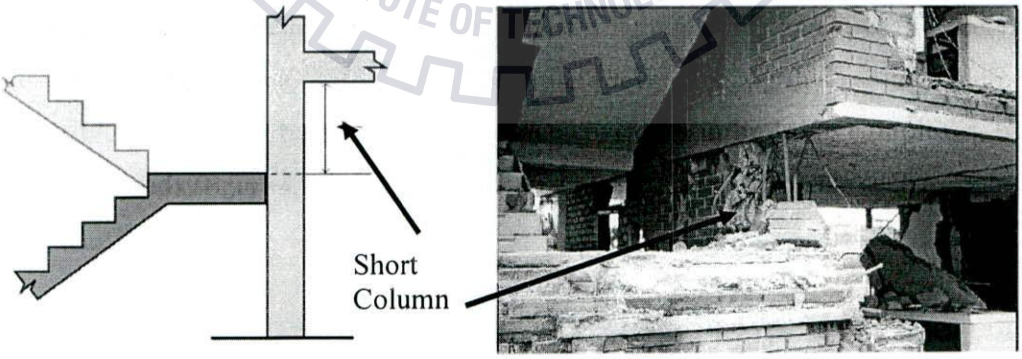


Figure 4.22 Staircase landing creating short column effect
Source: Source: http://earthquakespectra.org/loi/eqsa

and girders need to frame at different heights of the column which divides the column in two segments, thus producing the short column problem. Example of **Staircase landing creating short column effect is shown in Figure 4.22**

Enhancing the performance

Captive columns is avoidable the problem with little changes in design. Any type of nonstructural element that could hinder the free deformation capacity of a vertical structural element should be located in a different acting plane than the structural element, or must be separated from the structural element by appropriate joints. Adopting isolation option is also desirable, but we should ensure the out of plane lateral stability of the wall.

For split level buildings, in order to circumvent the short column effect, we can avoid locating a frame at the vertical plane where the transition between levels occurs. For buildings on slopes, special care should be exercised to locate the sloping retaining walls in such a way that no captive column effects are induced.

Where stiff nonstructural walls are still employed, these walls should be separated from the structure, and in no case can they be interrupted before reaching the full height of the adjoining columns. The study should be conducted carefully to use nonstructural components in order to avoid unintentional interaction with the structure of the building. The best way to address the influence of infill walls in masonry is either to them into consideration while designing or to allow for gaps between the columns.

5 Conclusions and recommendations

5.1 Conclusions

- Building with **irregularities damaged severely in past earthquakes** where their configuration played major role in attracting force.
- **It observed building performance is strongly connected to its configuration**. Reason found for **irregularities** is mainly architectural design. It is also observed mostly architects design building without intervention of structural engineers to produce astonishing forms to impress clients. Some other reasons might be there like budget of project, time consumption in regularly contacting or even ego between professionals. This is still in practice even in high seismic zones, resulted very vulnerable buildings with poor or irregular configurations.
- It is evident that, many distinct sections of the architectural design guidelines of different **modern concepts, promote the use of irregular configurations** like, curved shapes in plans, elevations, projections at higher levels without columns below, open floors at the first floor, double heights at entrance for grandness, by stimulating the common practice of projecting buildings with this bad configurations.
- Configuring buildings without any walls or architectural members is **trigged by modern requirements like camera surveillance** at low cost. Other reasons are, for ventilation, to delineate the parking at ground floor level, for party halls or other communal spaces or assembly spaces for functional purposes ignoring the structural vulnerability which is dominated by space requirement in cities. This arrangement is a royalty to the developer, designer, economical loophole to builder and finally aesthetically pleasing to client and it appears in almost every current contemporary mixed use buildings, shops and residences, located on arterial roads.
- And obligations in building bye laws is **easily trespassed in buildings to have an irregular configuration**. Lessons Learnt included in post-earthquake reports, regarding the influence of architectural features in buildings' seismic performance, such as open floor, hardly reach either architectural and city planning personnel's attention, or influence the decisions taken by city officials and politicians that continue including this configuration in the design.

5.2 General recommendations

- Most seismic codes those include special considerations for irregular **configurations are written in analytical terms** for engineers who are specialists in seismic design and **difficult to be understood by architects and urban planners**. For understanding the influence of architectural configurations on building seismic performance, conceptual knowledge on the effects of mass, stiffness and resistant distribution in buildings is necessary.
- It is to be noticed that contribution of a professional is not alone sufficient for reducing seismic vulnerability of contemporary cities to apply structural engineering oriented building codes in the design of building. The problem has to be solved **with a holistic approach where structural engineers, architects, urban planners, local authorities, builders and community participation**, not only in reducing existing vulnerability but avoiding the construction of future seismic risk. Improving the **collaboration and communication** between earthquake engineering disciplines (seismology, structural engineering, lifelines engineering and emergency response) architectural, urban planning and government authorities, which can greatly help in reducing the building seismic vulnerability.
- Coming to the solutions to existing configuration problems of buildings in high seismic zones, we can only retrofit where redesign is hardly possible.

Final words: Configuration problems originate in the schematic design of the building. A good or bad configuration is the architect's contribution to seismic performance of building. 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 desired. **This is not to say that all buildings should be symmetrical cubes. The architects may have many things to address, but meeting seismic requirements is should be his/her first priority.** The process of understanding and modifying the issues caused by configuration irregularities which likely to become problem, will go a long project towards assuring feasible solutions. Early consultation between the architect and engineer will result creative as well safe buildings, with little compromise rather than adversarial stubbornness.

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