Seismic Analysis and Design of Irregular Buildings

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Configuration

- Good structural configuration has implications for both safety and economy of the building.
- To quote Late Henry Degenkolb, the well-known earthquake engineer in California:

  If we have a poor configuration to start with, all the engineer can do is to provide band-aid – improve a basically poor solution as best as he can. Conversely, if we start off with a good configuration and a reasonable framing system, even a poor engineer can’t harm its ultimate performance too much.
Quote from NEHRP Commentary:

The major factors influencing the cost of complying with the provisions are:

1. The complexity of the shape and structural framing system for the building. (It is much easier to provide seismic resistance in a building with a simple shape and framing plan.)

2. The cost of the structural system (plus other items subject to special seismic design requirements) in relation to the total cost of the building. (In many buildings, the cost of providing the structural system may be only 25 percent of the total cost of the project.)

3. The stage in design at which the provision of seismic resistance is first considered. (The cost can be inflated greatly if no attention is given to seismic resistance until after the configuration of the building, the structural framing plan, and the materials of construction have already been chosen).
Irregularities

- Basic kinds
  - Of mass distribution
  - Of stiffness distribution
  - Of both

- In terms of
  - In plan
  - In elevation
  - In both
Problems with Irregularities

- In buildings with plan irregularity, load distribution to different vertical elements is complex.
  - Floor diaphragm plays an important role and needs to be modelled carefully.
  - A good 3-D analysis is needed.

- In buildings with vertical irregularity, load distribution with building height is different from that in codes.
  - Dynamic analysis is required.
Problems with Irregularities (contd...)

- In irregular building, there may be concentration of ductility demand in a few locations.
  - Special care needed in detailing.
  - Just dynamic analysis may not solve the problem.

- Dynamic analysis is not always sufficient for irregular buildings, and
  - Dynamic analysis is not always needed for irregularities.
### TABLE 5.2.3.2 Plan Structural Irregularities

<table>
<thead>
<tr>
<th>Irregularity Type and Description</th>
<th>Reference Section</th>
<th>Seismic Design Category Application</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1a</strong> Torsional Irregularity – to be considered when diaphragms are not flexible</td>
<td>5.2.6.4.2, 5.4.4</td>
<td>D, E, and F, C, D, E, and F</td>
</tr>
<tr>
<td>Torsional irregularity shall be considered to exist when the maximum story drift, computed including accidental torsion, at one end of the structure transverse to an axis is more than 1.2 times the average of the story drifts at the two ends of the structure.</td>
<td></td>
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<tr>
<td><strong>1b</strong> Extreme Torsional Irregularity -- to be considered when diaphragms are not flexible</td>
<td>5.2.6.4.2, 5.4.4</td>
<td>D, E, and F, C, D, E, and F</td>
</tr>
<tr>
<td>Extreme torsional irregularity shall be considered to exist when the maximum story drift, computed including accidental torsion, at one end of the structure transverse to an axis is more than 1.4 times the average of the story drifts at the two ends of the structure.</td>
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</tr>
<tr>
<td><strong>2</strong> Re-entrant Corners</td>
<td>5.2.6.4.2</td>
<td>D, E, and F</td>
</tr>
<tr>
<td>Plan configurations of a structure and its lateral-force-resisting system contain re-entrant corners where both projections of the structure beyond a re-entrant corner are greater than 15 percent of the plan dimension of the structure in the given direction.</td>
<td></td>
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</tr>
<tr>
<td><strong>3</strong> Diaphragm Discontinuity</td>
<td>5.2.6.4.2</td>
<td>D, E, and F</td>
</tr>
<tr>
<td>Diaphragms with abrupt discontinuities or variations in stiffness including those having cutout 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 story to the next.</td>
<td></td>
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<tr>
<td><strong>4</strong> Out-of-Plane Offsets</td>
<td>5.2.6.4.2, 5.2.6.2.10</td>
<td>D, E, and F, B, C, D, E, and F</td>
</tr>
<tr>
<td>Discontinuities in a lateral force resistance path such as out-of-plane offsets of the vertical elements.</td>
<td></td>
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</tr>
<tr>
<td><strong>5</strong> Nonparallel Systems</td>
<td>5.2.5.2</td>
<td>C, D, E, and F</td>
</tr>
<tr>
<td>The vertical lateral-force-resisting elements are not parallel to or symmetric about the major orthogonal axes of the lateral-force-resisting system.</td>
<td></td>
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</tr>
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<tr>
<td>1a  Stiffness Irregularity — Soft Story</td>
<td>5.2.5.1</td>
<td>D, E, and F</td>
</tr>
<tr>
<td>A soft <em>story</em> is one in which the lateral stiffness is less than 70 percent of that in the <em>story</em> above or less than 80 percent of the average stiffness of the three stories above.</td>
<td></td>
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</tr>
<tr>
<td>1b  Stiffness Irregularity—Extreme Soft Story</td>
<td>5.2.5.1  5.2.6.5.1</td>
<td>D, E, and F  E and F</td>
</tr>
<tr>
<td>An extreme soft story is one in which the lateral stiffness is less than 60 percent of that in the <em>story</em> above or less than 70 percent of the average stiffness of the three stories above.</td>
<td></td>
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</tr>
<tr>
<td>2  Weight (Mass) Irregularity</td>
<td>5.2.5.1</td>
<td>D, E, and F</td>
</tr>
<tr>
<td>Mass irregularity shall be considered to exist where the effective mass of any <em>story</em> is more than 150 percent of the effective mass of an adjacent <em>story</em>. A roof that is lighter than the floor below need not be considered.</td>
<td></td>
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<tr>
<td>3  Vertical Geometric Irregularity</td>
<td>5.2.5.1</td>
<td>D, E, and F</td>
</tr>
<tr>
<td>Vertical geometric irregularity shall be considered to exist where the horizontal dimension of the lateral-force-resisting system in any <em>story</em> is more than 130 percent of that in an adjacent <em>story</em>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4  In-Plane Discontinuity in Vertical Lateral-Force Resisting Elements</td>
<td>5.2.5.1  5.2.6.2.10</td>
<td>D, E, and F  B, C, D, E, and F  D, E, and F</td>
</tr>
<tr>
<td>An in-plane offset of the lateral-force-resisting elements greater than the length of those elements or a reduction in stiffness of the resisting element in the <em>story</em> below.</td>
<td></td>
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</tr>
<tr>
<td>5  Discontinuity in Capacity — Weak Story</td>
<td>5.2.6.2.3  5.2.6.5.1</td>
<td>B, C, D, E, and F  D, E, and F  E, and F</td>
</tr>
<tr>
<td>A weak <em>story</em> is one in which the <em>story</em> lateral <em>strength</em> is less than 80 percent of that in the <em>story</em> above. The <em>story strength</em> is the total <em>strength</em> of all seismic-resisting elements sharing the <em>story</em> shear for the direction under consideration.</td>
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</tbody>
</table>
Horizontal Distribution of Load

- Floor diaphragm plays an important role in seismic load distribution in a building.

- Consider a RC slab
  - For horizontal loads, it acts as a deep beam with depth equal to building width, and the beam width equal to slab thickness.
  - Being a very deep beam, it does not deform in its own plane, and it forces the frames/walls to fulfill the deformation compatibility of no in-plane deformation of floor.
  - This is **rigid floor diaphragm action**.
Concept of Floor Diaphragm Action

Fig. from Jain S K, "A Proposed Draft for IS:1893...Part II: Commentary and Examples," J. of Struct Engg, Vol. 22, No. 2, July 1995, pp 73-90
Lateral Load Distribution Due to Rigid Floor Diaphragm: Symmetric Case – No Torsion

- In symmetrical building and loading, the seismic forces are shared by different frames or walls in proportion to their own lateral stiffness.

Fig. from Jain S K, “A Proposed Draft for IS:1893...Part II: Commentary and Examples,” J. of Struct Engg, Vol. 22, No. 2, July 1995, pp 73-90
Analysis of Forces Induced by Twisting Moment (Rigid Floor Diaphragm)

- When building is not symmetrical, the floor undergoes rigid body translation and rotation.

Fig. from Jain S K, “A Proposed Draft for IS:1893...Part II: Commentary and Examples,” J. of Struct Engg, Vol. 22, No. 2, July 1995, pp 73-90
Rigid Diaphragm Action

- In-plane rigidity of floors is sometimes misunderstood to mean that
  - The beams are infinitely rigid, and
  - The columns are not free to rotate at their ends.
- Rotation of columns is governed by out-of-plane behaviour of slab and beams.

(a) In-plane floor deformation, (b) Out-of-plane floor deformation.

Fig. from Jain S K, “A Proposed Draft for IS:1893...Part II: Commentary and Examples,” J. of Struct Engg, Vol. 22, No. 2, July 1995, pp 73-90
Buildings without Diaphragm Action

- When the floor diaphragm does not exist, or when the diaphragm is extremely flexible as compared to the vertical elements
  - The load can be distributed to the vertical elements in proportion to the tributary mass
Flexible Floor Diaphragms

There are instances where floor is not rigid.

- “Not rigid” does not mean it is completely flexible!
  - Hence, buildings with flexible floors should be carefully analyzed considering in-plane floor flexibility.

- Note 1 of Cl. 7.7.2.2 gives the criterion on when the floor diaphragm is not to be treated as rigid.

Definition of Flexible Floor Diaphragm (Cl. 7.7.2.2)

In-plane flexibility of diaphragm to be considered when

\[ \Delta_2 > 1.5 \{0.5(\Delta_1 + \Delta_2)\} \]
One can actually model the floor slab in the computer analysis.

Alternatively, one can take the design force as envelop of (that is, the higher of) the two extreme assumptions, i.e.,

- Rigid diaphragm action
- No diaphragm action (load distribution in proportion to tributary mass)
Torsion

- Centre of Stiffness / Centre of Rigidity
  - If the building undergoes pure translation in the horizontal direction (that is, no rotation or twist or torsion about vertical axis), the point through which the resultant of the restoring forces acts.

- Static Eccentricity.
  - *Calculated distance* between the Centre of Mass and the Centre of Stiffness.

- Accidental eccentricity
  - The computation of eccentricity is approximate.
  - Change in use: moves centre of mass.
  - Rotational component of ground motion
Eccentricity

- Dynamic amplification
  - Under dynamic condition, the effect of eccentricity is higher than that under static eccentricity.

- Design eccentricity
  - Dynamic amplification on static eccentricity, plus
  - Accidental eccentricity
Design Eccentricity

- IS1893 provides design eccentricity as:

\[
e_{di} = \begin{cases} 
1.5e_{si} + 0.05b_i \\
e_{si} - 0.05b_i 
\end{cases}
\]

- Accidental eccentricity can be + or -. Hence, these equations are meant to be:

\[
e_{di} = 1.5e_{si} - 0.05b_i
\]

\[
e_{di} = e_{si} - 0.05b_i
\]
First Equation for Design Eccentricity (contd...)

Considering EQ in Y-Direction

Calculated locations of CM and CR

Location CM* to be used in analysis for first eqn.
Second Equation for Design Eccentricity (contd...)

Calculated locations of CM and CR

Location CM* to be used in analysis for second eqn.

Considering EQ in Y-Direction
CR for Multi-Storey Buildings

- It can be defined in two ways:
  - All Floor Centre of Rigidity, and
  - Single Floor Centre of Rigidity
Centre of rigidities are the set of points located one on each floor, through which application of lateral load profile would cause no rotation in any floor.

As per this definition, location of CR is dependent on building stiffness properties as well as on the applied lateral load profile.
All Floor Definition of CR

Figure 1: ‘All floor’ definition of center of rigidity

No rotation in any floor
Single Floor CR Definition

- Centre of rigidity of a floor is defined as the point on the floor such that application of lateral load passing through that point does not cause any rotation of that particular floor, while the other floors may rotate.
  - This definition is independent of applied lateral load.
Single Floor Definition of CR

Fig. Dhiman Basu

\[ j^{th} \text{ floor does not rotate} \]
\[ \text{(other floors may rotate)} \]
Choice of Definition

- Results somewhat different depending on the definition.
  - Difference is not substantial for most buildings.
  - Use any definition that you find convenient to use.

- For computer-aided analysis, the all-floor definition is more convenient.
To Locate CR

- The way we defined it, one needs to apply lateral loads at the CR.
  - But, we do not know CR in the first place.

- Notice the condition that the floor should not rotate.
  - Hence, we could apply the load at CM, and restrain the floor from rotation by providing rollers.
  - The resultant of the applied load and reactions at the rollers will pass through CR.
To Locate All-Floor CR

Central nodes of both ends of the diaphragm are constrained to ensure equal horizontal displacement.

(a) Lateral loads are applied at all floors of the constrained model.

(b) Free body diagram of a particular floor.

Resultant of column shears passes through the center of rigidity of the floor.

Fig. Dhiman Basu
To Locate Single-Floor CR

(a) Lateral load is applied at the constrained floor

(b) Free body diagram of a particular floor

Central nodes of both ends of the diaphragm are constrained to ensure equal horizontal displacement

Resultant of column shears passes through the center of rigidity of the floor

Fig. Dhiman Basu
Torsional Irregularity (contd...)

- Geometrically building may appear to be regular and symmetrical
  - But may be irregular due to distribution of mass/ stiffness.
- Better to distribute the lateral load resisting elements near the perimeter of the building rather than concentrate these near centre of the building.
Arrangement of shear walls and braced frames - not recommended. Note that the heavy lines indicate shear walls and/or braced frames.

Arrangement of shear walls and braced frames - recommended. Note that the heavy lines indicate shear walls and/or braced frames.
Torsional Irregularity (contd...)

- Code: torsional irregularity exists if the drift (lateral displacement) at one end of the building is more than 1.2 times the average of the drift at the two ends.

\[ \Delta_2 > 1.2 \left( \frac{\Delta_1 + \Delta_2}{2} \right) \]

Torsional irregularity when \( \Delta_2 > 1.2 \left( \frac{\Delta_1 + \Delta_2}{2} \right) \)
Re-entrant Corner

- When an otherwise regular building has a large re-entrant corner, wings of the building tend to vibrate in a manner different from that of the entire building.
- Building treated as irregular when offset dimension exceeds 15% of the total dimension.

Re-entrant corner when $A_1 > 0.15 \times L_1$ and $A_2 > 0.15 \times L_2$
Diaphragm Discontinuity

- Diaphragm discontinuity changes the lateral load distribution to different elements as compared to what it would be with rigid floor diaphragm.
- Also, it could induce torsional effects which may not be there if the floor diaphragm is rigid.
Discontinuity in Diaphragm Stiffness

Notice the words “mass resistance eccentricity” do not make sense.

Fig in Code

Fig in NEHRP

Vertical Components of Seismic Resisting System

Discontinuity in Diaphragm Stiffness
Out-of-Plane Offsets

- This is a very serious irregularity wherein there is an out-of-plane offset of the vertical element that carries the lateral loads.
- Such an offset imposes vertical and lateral load effects on horizontal elements, which are difficult to design for adequately.
Out-of-Plane Offsets (contd...)

Shear Wall

Out-of-Plane Offset in Shear Wall
Direction of Ground Motion

- During earthquake shaking, ground shakes in all possible directions.
  - Direction of resultant shaking changes from instant to instant.
- Basic requirement is that the structure should be able to withstand maximum ground motion occurring in any direction.
  - We already discussed that for most structures, main concern is for horizontal vibrations rather than vertical vibrations.
Direction of Ground Motion (Cl. 6.1.5) (contd...)

- One does not expect the peak ground acceleration to occur at the same instant in two perpendicular horizontal directions.
- Hence for design, maximum seismic force is not applied in the two horizontal directions simultaneously.
- If the walls or frames are oriented in two orthogonal (perpendicular) directions:
  - It is sufficient to consider ground motion in the two directions one at a time.
Building Plans with Orthogonal Systems
Building Plans with Non-Orthogonal Systems
Non-Parallel Systems

- Also called, Non-Orthogonal Systems
- When the lateral load resisting elements are NOT oriented along two perpendicular directions
- In such a case, design for X- and Y-direction loads acting separately will be unconservative for elements not oriented along X- and Y-directions.
Load Combinations for Orthogonal System

- Thus, an RC building with orthogonal system therefore needs to be designed for the following 13 load cases:
  - 1.5 (DL+LL)
  - 1.2 (DL+LL+ELx)  \( ELx = \text{Design EQ load in X-direction} \)
  - 1.2 (DL+LL-ELx)
  - 1.2 (DL+LL+ELy)  \( ELy = \text{Design EQ load in Y-direction} \)
  - 1.2 (DL+LL-ELy)
  - 1.5 (DL+ELx)
  - 1.5 (DL-ELx)
  - 1.5 (DL+ELy)
  - 1.5 (DL-ELy)
  - 0.9DL +1.5ELx
  - 0.9DL-1.5ELx
  - 0.9DL+1.5ELy
  - 0.9DL-1.5ELy
Non-Orthogonal Systems (Cl.6.3.2.2) (contd…)

- A lateral load resisting element (frame or wall) is most critical when loading is in direction of the element.
- It may be too tedious to apply lateral loads in each of the directions in which the elements are oriented.
- For such cases, the building may be designed for:
  - 100% design load in X-direction and 30% design load in Y-direction, acting simultaneously
  - 100% design load in Y-direction and 30% design load in X-direction, acting simultaneously
Note that directions of earthquake forces are reversible. Hence, all combinations of directions are to be considered.
Thus, EL now implies eight possibilities:

\[ (+E_{lx} + 0.3E_{ly}) \]
\[ (+E_{lx} - 0.3E_{ly}) \]
\[ -(E_{lx} + 0.3E_{ly}) \]
\[ -(E_{lx} - 0.3E_{ly}) \]
\[ +(0.3E_{lx} + E_{ly}) \]
\[ +(0.3E_{lx} - E_{ly}) \]
\[ -(0.3E_{lx} + E_{ly}) \]
\[ -(0.3E_{lx} - E_{ly}) \]
Non-Orthogonal Systems (Cl.6.3.2.2) (contd...)

- Therefore, one must consider 25 load cases:

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Load Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 (DL+LL)</td>
<td>1.5[DL+(ELx+0.3ELy)]</td>
</tr>
<tr>
<td>1.2[DL+LL+(ELx+0.3ELy)]</td>
<td>1.5[DL+(ELx-0.3ELy)]</td>
</tr>
<tr>
<td>1.2[DL+LL+(ELx-0.3ELy)]</td>
<td>1.5[DL-(ELx+0.3ELy)]</td>
</tr>
<tr>
<td>1.2[DL+LL-(ELx+0.3ELy)]</td>
<td>1.5[DL+(0.3ELx+Ely)]</td>
</tr>
<tr>
<td>1.2[DL+LL-(ELx-0.3ELy)]</td>
<td>1.5[DL+(0.3ELx-ELy)]</td>
</tr>
<tr>
<td>1.2[DL+LL+(0.3ELx+Ely)]</td>
<td>1.5[DL-(0.3ELx+Ely)]</td>
</tr>
<tr>
<td>1.2[DL+LL+(0.3ELx-ELy)]</td>
<td>1.5[DL-(0.3ELx-ELy)]</td>
</tr>
<tr>
<td>1.2[DL+LL-(0.3ELx+Ely)]</td>
<td>0.9DL+1.5(ELx+0.3ELy)]</td>
</tr>
<tr>
<td>1.2[DL+LL-(0.3ELx-ELy)]</td>
<td>0.9DL+1.5(ELx-0.3ELy)]</td>
</tr>
<tr>
<td>0.9DL-1.5(ELx+0.3ELy)]</td>
<td>0.9DL-1.5(ELx-0.3ELy)]</td>
</tr>
<tr>
<td>0.9DL+1.5(0.3ELx+Ely)]</td>
<td>0.9DL+1.5(0.3ELx-ELy)]</td>
</tr>
<tr>
<td>0.9DL-1.5(0.3ELx+Ely)]</td>
<td>0.9DL-1.5(0.3ELx-ELy)]</td>
</tr>
</tbody>
</table>
Non-Orthogonal Systems (Cl.6.3.2.2) (contd...)

- Note that the design lateral load for a building in the X-direction may be different from that in the Y-direction.
- Some codes use 40% in place of 30%.
In complex structures such as a nuclear reactor building, one may have very complex structural systems.

Need for considering earthquake motion in all three directions as per 100%+30% rule.

Now, EQ load means the following 24 combinations:

- \( \pm Elx \pm 0.3ELy \pm 0.3ELz \)
- \( \pm Ely \pm 0.3ELx \pm 0.3ELz \)
- \( \pm Elz \pm 0.3ELx \pm 0.3ELy \)

Hence, EL now means 24 combinations

A total of 73 load cases for RC structures!
Cl.6.3.4.2

In place of 100%+30% rule, one may take for design force resultants as per square root of sum of squares in the two (or, three) directions of ground motion

\[ EL = \sqrt{(EL_x)^2 + (EL_y)^2 + (EL_z)^2} \]
Most of the time, soft storey building is also the weak storey building.

In IS1893, distinction between soft storey and weak storey has not been made.

Soft/weak storey buildings are well-known for poor performance during earthquakes.

In Bhuj earthquake of 2001, most multistorey buildings that collapsed had soft ground storey.
Bldgs with Soft Storeys

Notice that the soft-storey is subject to severe deformation demands during seismic shaking.

Fig from Murty et al, 2002
IS1893 on Buildings with Soft Storeys

Choices:

- **Non-linear Pushover Analysis**
  - It is a very sophisticated approach.
  - Based on non-linear analysis.
  - No specifications in code for this approach.
  - Cannot be applied in routine design applications

- **Design soft-storey columns and beams for 2.5 times the design storey shear and moment**
  - I suggest not the beam between the infill storey and the soft storey

- **Else, provide additional shear walls to cover 1.5 times the design storey shear and moment**
Mass Irregularity

- Mass irregularity will be induced by the presence of a heavy mass on a floor, say a swimming pool.
- Note that the mass irregularity in IS1893 has been defined when weight of a floor exceeds twice the weight of the adjacent floor.
- NEHRP defines it when the weight exceeds 150% of that of the adjacent floor.
Mass and Stiffness Irregularity

- It is really the ratio of mass to stiffness of a storey that is important.
- Our code could provide a waiver from mass and stiffness irregularities if the ratio of mass to stiffness of two adjacent storeys is similar.
Vertical Geometric Irregularity

- Buildings with vertical offsets will fall in this category.
- Also, a building may have no apparent offset, but its lateral load carrying elements may have irregularity.
  - For instance, shear wall length may suddenly reduce.
- When building is such that larger dimension is above the smaller dimension, it acts as an inverted pyramid and is undesirable.