Earthquake Resistant Design

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Natural Disasters

Earthquake

Tornado, Cyclone

Floods

Fire
Loss of Human Life in Disasters

Loss of human life due to:
- Floods: 55%
- Earthquake: 30%
- Volcanos: 3%
- Other: 2%
- Hurricane: 10%
Effect of Earthquake

- **Primary Effects**
  - Ground Break, Fault formation

- **Secondary Effects**
  - Failure of R. C. & steel Structures
  - Failure of masonry Structures
  - Failure of railway, highway & bridges
  - Land slides, Liquefaction & site effects
  - Failure of geotechnical structures
  - Tsunami
Causes for Earthquake

- Tectonic earthquake
- Volcanic earthquake
- Rock fall or collapse of cavity
- Microseism
- Explosion (Controlled blast)
- Reservoir induced earthquake
- Mining induced earthquake
- Cultural Noise (Industry, Traffic etc.)
Classification of Earthquakes

Based on focal depth
Based on magnitude
Based on source
Period of Vibration

Building at Rest

Ground Accelerates to Left

Ground Accelerates to Right

Ground & Building at Rest
Repeated actions of earthquake results in loss of resistance to rocking effects.
Principal modes of Failure of Shear wall

- Sliding
- Rocking
- Bending
Failure of one of the shear walls in the building at the construction joints due to poor workmanship at the joints. And it was attributed to lack of adequate axial-flexural capacity.
Inertia due to earthquake

Figure 1: Effect of inertia in a building when shaken at its base

Figure 2: Inertia force and relative motion within a building

Figure 3: Principal directions of a building

Figure 4: Flow of seismic inertia forces through all structural components.
Earthquake effects on Buildings

Direction of forces on Building

Movement of building

U-D  EW  NS
Earthquake effects on Buildings

- **Vertical Acceleration** – Significant near epicenter
  (Adds to /Reduces the gravity forces, Large balconies)

- **Horizontal Acceleration** – produces sway
  (Effect of Inertia, distribution of lateral forces)

- **Effect of Resonance** - Excessive deflection
  (Natural frequency coincides with Earthquake frequency)

![Graph showing Ymax vs Weq/Wnat](image)
Modes of Vibration due to Earthquake Forces

(a) Section of building
(b) Transverse vibration
(c) Vertical vibration
(d) Longitudinal vibration
(e) Resultant inertia force on building
Effects of Earthquake on Stress Distribution

(a) Wall

(b) Before earthquake

(c) During earthquake

1 - Wall element,
2 - Vertical load from above the wall element
3 - Reaction from below
4 - Earthquake force

c - Compressive stress

t - Tensile stress
s - Shearing stress
Effects of Earthquakes on Stress distribution

Change in Stress

Change in Moment

Change in Load
Figure 1: Total horizontal earthquake force in a building increases downwards along its height.

Figure 2: Floor bends with the beam but moves all columns at that level together.

Figure 3: Infill walls move together with the columns under earthquake shaking.

Figure 4: Earthquake shaking reverses tension and compression in members – reinforcement is required on both faces of members.
Gravity resisting House Elements

- Roof Joists
- Walls
- Floor Beams
- Foundations
Horizontal Force resisting House Elements

Roof Diaphragm

Shear Wall

Floor Diaphragm

Foundation
Earthquake Resistant Design Concept

Level 1 Maximum Credible Earthquake (MCE)
500 Years Return Period
2 % Possibility of occurrence in 50 Yrs

Level 2 Design Basis Earthquake (DBE)
250 Years Return Period
10 % Possibility of occurrence in 50 Yrs
Earthquake Resistant Design Philosophy

Building

- should resist minor earthquakes (<DBE) with some non-structural damage
- should resist moderate earthquake (DBE) with some structural damage, but without failure
- can fail at most severe earthquake (MCE), but with sufficient warning.
SEISMIC ZONE MAP OF INDIA

F = m * a
a = Z * g
Z = Zone Factor
Architectural Aspects of Earthquake Resistant Construction
Regular and Irregular Configurations

- To perform well in an earthquake, a building should possess four main attributes:
  - Simple and regular configuration
  - Adequate lateral strength
  - Stiffness
  - Ductility

- Buildings having simple regular geometry and uniformly distributed mass and stiffness in plan as well as in elevation, suffer much less damage than buildings with irregular configurations.

- Buildings with plan irregularity suffer from torsional modes of vibration whose effects may not be adequately represented in the equivalent static seismic coefficient method.
IRREGULAR BUILDINGS

- Torsional Irregularity
- Plan Irregularity- Re-entrant Corners
- Out-of-Plane Offsets
- Stiffness Irregularity
- Mass Irregularity
- Vertical Geometry Irregularity
- Discontinuity in Capacity – Weak Storey
Guidelines for Planning

Geometry of buildings

Symmetric Plans

Symmetric Elevations
Guidelines for Planning

Geometry of buildings

Un-symmetrical Plans

Un-symmetrical Elevations
Guidelines for Planning

Desirable geometry of buildings

**Guidelines**

- **ELEVATIONS**
  - Length should be less than 3B
  - Height should be less than 4B

- **PLANS**
  - Width should be less than 0.25B
  - Separation should be at least 0.2B

- **ELEVATIONS**
  - Height should be less than 0.15B
  - Width should be less than 0.15B
Building Configuration... Plan Irregularities ...

✓ Re-entrant Corners

\[ \frac{A}{L} > 0.15 - 0.20 \]
Building Configuration... *Vertical Irregularities...*

✓ Vertical Geometric Irregularities

\[ \frac{A}{L} > 0.15 - 0.20 \]
Building Configuration...

- **Vertical Irregularities**
  - ✓ Stiffness Irregularity (Soft Storey)

\[
k_i < 0.7k_{i+1}
\]

\[
k_i < 0.8 \left( \frac{k_{i+1} + k_{i+2} + k_{i+3}}{3} \right)
\]
Mass Irregularity

\[ W_i > 2W_{i-1} \]
\[ W_i > 2W_{i+1} \]
Cantilevers and Projections

- Towers, Parapets, Stacks, Balconies (Small)
  - Design of these attachments
  - Design of their connections to main structure
- Design force
  - 5 times vertical seismic coefficient for horizontal projections
  - 5 times horizontal seismic coefficient for vertical projections
Guidelines for Planning

Arrangement of Columns

Good arrangement of columns

Poor arrangement of columns
Guidelines for Planning

Rotation about the axis

Building is strong about YY axis and weak about XX axis

Provide columns to make it strong about XX axis
Guidelines for Planning

Lateral load Resisting system

Provide cross Wall to increase stiffness

Clear spacing < 40 times thickness of wall

( L and B < 7 m )
Lateral force resistant systems

Simply supported System

Rigid Frame

Bracing system

Shear wall System
Lateral force resistant system - Braced System

Bracing system
Earthquake Resistant Construction – Bad Geometry

Figure 1: Buildings with one of their overall sizes much larger or much smaller than the other two, do not perform well during earthquakes.

Figure 2: Simple plan shape buildings do well during earthquakes.

Figure 3: Sudden deviations in load transfer path along the height lead to poor performance of buildings.

Figure 4: Pounding can occur between adjoining buildings due to horizontal vibrations of the two buildings.

(a) Setbacks
(b) Weak or Flexible Storey
(c) Slopify Ground
(d) Hanging or Floating Columns
(e) Discontinuing Structural Members

(a) Partial collapse of stone masonry walls during 1991 Uttarkashi (India) earthquake
(b) Collapse of reinforced concrete columns (and building) during 2001 Bhuj (India) earthquake

Figure 6: Importance of designing walls/columns for horizontal earthquake forces.
Torsion of unsymmetrical Plans

Center of lateral resistant /stiffness center

Resisting force

CG. Of Building mass

Applied force

Lateral bracing

Direction of Ground Motion
Earthquake Resistant construction

Proper

Improper

Earthquake Resistant construction
General Guidelines for Planning

Building and its Structure Should Have a Uniform and Continuous Distribution of Mass, Stiffness, Strength and Ductility
Structural Aspects of Earthquake Resistant Design
Structural Aspects

Soft storey Mechanism

- Basement
- First floor
- Second floor
- Third floor
- Shear wall
Figure 5: Avoiding open ground storey problem – continuity of walls in ground storey is preferred.

Figure 4: Open ground storey building – assumptions made in current design practice are not consistent with the actual structure.
Figure 1: Ground storeys of reinforced concrete buildings are left open to facilitate parking – this is common in urban areas in India.

(a) 1971 San Fernando Earthquake

(b) 2001 Bhuj Earthquake

Figure 3: Consequences of open ground storeys in RC frame buildings – severe damage to ground storey columns and building collapses.
Soft Storey Collapse
Soft Storey Collapse, Bhuj 2001
Large Span Cantilevers

Up/Down Acceleration
Large Span Cantilevers

Up/Down Acceleration
Avoid Resonance

Natural frequency & Its Importance
Tacoma Narrows bridge (1940)
Western Washington State, Pacific Northwest

Before Collapse
Wind provided an external periodic frequency that matched the natural frequency of 853 m long Suspension Bridge

After Collapse
Avoid Head Weight

SA-7, Head Weight, Bhuj 2001
Head Weight
Krishna
Apartments,
Airport Road,
Bhuj
Building Configuration... Vertical Irregularities...

✓ Mass Irregularity

Stiffness Irregularity

\[ W_i > 2W_{i-1} \]
\[ W_i > 2W_{i+1} \]
Stress concentration & change in the stiffness
Structural Aspects

Strong column and weak beams

Good – Failure in beams

Poor – Failure in Columns
Strong Column & Weak Beam Concept
Structural Aspects

Weak column and strong beams
Figure 1: Buildings with short columns – two explicit examples of common occurrences.

Figure 2: Short columns are stiffer and attract larger forces during earthquakes – this must be accounted for in design.

Figure 3: Short columns effect in RC buildings when partial height walls adjoin columns – the effect is implicit here because infill walls are often treated as non-structural elements.
Failure of Express highway in Kobe
Short column failure due to insufficient transverse reinforcement

Krishna Apartments, Airport Road, Bhuj
Crushing of corner column – Insufficient reinforcement:
Tera Nam Mandir, Bhuj
Structural aspects

Redundancy in Building

Simple Connection
One load path

Rigid Connection
Two load paths

Walls

Columns
No Pounding

Maintain a good distance between adjacent tall buildings to avoid collision during oscillation.
Whip Effect of Apartment Bhuj 2001
Figure 4: Earthquake-resistant detailing of staircase in masonry building — must be carefully designed and constructed.
No lateral load force transfer mechanism to the core
Punjal Apartments, Ahmedabad
Himagiri Apartment weak link
Failure of Pre cast components in a building due to inadequate connection
Loss of Support

Simple Supports
Structural aspects

Column Beam connection

Movement of supports due to horizontal force
Bad construction practice of casting the ground floor columns up to the bottom of the beam and leaving a gap
Shri Hari Niwas Building, Main Road, Bhuj
Weak joint
Bhuj 2001
Discontinuity of the longitudinal reinforcement Bombay Dying Market, Station Road, Bhuj
Neelima Park Apartments, Ahmedabad

Poor quality materials and workmanship
Perfect Apartment- no failure, Bhuj 2001
For you to conclude

- Does the earthquake kill people or the engineers/architects or buildings are responsible for it?
- Will a well engineered structure behave better?
- Is it necessary to build all structures at all locations to be earthquake proof to same degree?
- If so, what magnitude of earthquake should they counter?
Six main focus areas

1. Awareness and Preparedness
2. Response
3. Education, Training, Capacity-Building, Research & Development, and Documentation
4. Regulation and Enforcement
5. Earthquake-Resistant Construction of New Structures
6. Selective Seismic Retrofitting of Existing Critical and Lifeline Structures
Conclusions

- Earthquake risk arises mainly due to unsafe constructions. For meaningful earthquake risk mitigation, the country has to embark on two initiatives in a pre-decided time frame:
  - First to ensure that all new constructions must have earthquake resisting measures and
  - Second, the critically important existing buildings should be identified, assessed and retrofitted as found necessary.

- Establishment of techno-legal and techno-financial regimes.

- Capacity building of architects, engineers and masons.
Thank You