Seismic Evaluation of Reinforced Concrete Buildings: A Practical Approach

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Aim of Seismic Evaluation

- To assess the seismic capacity of earthquake vulnerable buildings or earthquake damaged buildings for the future use

- Degree of retrofitting required in seismically deficient structures

- To identify the weak links in the structure that could precipitate the structural or component failure
Seismic Evaluation Methodologies

Qualitative Methods

- Based on
  - Architectural & Structural Drawings
  - Past Performance of Similar Buildings
  - Visual Inspection Report
  - Non-destructive test results etc.

- Field Evaluation Method
- Rapid Visual Screening Method
- ATC-14 methodology etc
Analytical Methods

- Based on
  - Capacity and Ductility of buildings on the basis of available drawings

- Capacity/demand method
- Pushover analysis
- Nonlinear inelastic analysis
The proposed methodology is divided into three components:

Condition Assessment

- Data collection from architectural and structural drawings
- Performance characteristics of similar type of buildings in past earthquake
- Rapid evaluation of strength, drift, materials, structural components and details
Visual Inspection / Field Evaluation

- Based on observed distress and damage in structures
- Visual inspection is more useful for damaged structures however it may also be conducted for undamaged structure

Non-destructive Evaluation (NDE)

- Quick estimation of materials strength and extent of deterioration
- To establish causes remain out of reach possible from visual inspection and determination of reinforcement and its location
Data Collection/ Information Gathering

Building Data
- Architectural, structural & construction drawings
- Vulnerability parameters: number of storeys, year of built, total floor area, etc
- Specifications, soil reports, design calculations, seismicity of the site

Construction Data
- Identifications of gravity and lateral load resisting system
- Maintenance, addition, alteration, or modifications in structures
- Field surveys of the structure's existing condition
**Structural Data**

- Materials
- Structural concept: vertical & horizontal irregularities, torsional eccentricity, pounding, short column and others
- Detailing concept: ductile detailing, special confinement reinforcement
- Foundations and non-structural elements
Materials Concerns

- Low grade of concrete, Deterioration in concrete and reinforcement, High cement-sand ratio
- Corrosion in reinforcement, Use of recycled steel
- Spalling of concrete by the corrosion of embedded reinforcing bars
- Corrosion is related to insufficient concrete cover
- Poor concrete placement and porous concrete
Past Performance Data

**Structural Concerns**

- The relatively low stiffness of the frames - excessive inter-storey drifts - damage to Pounding - column distress - possibly local nonstructural items  Collapse
- Unsymmetrical buildings (U,T,L,V) in plan – torsional effects & concentration of damage at the junctures (i.e., re-entrant corners)
- Unsymmetrical buildings in elevation - abrupt change in lateral resistance; Vertical strength discontinuities - concentrate damage in the "soft" stories
- Short column
Detailing Concerns

- Large tie spacing in columns - lack of confinement of concrete core - shear failures.
- Insufficient column lengths - concrete to spell.
- Locations of inadequate splices - brittle shear failure.
- Insufficient column strength for full moment hinge capacity - brittle shear failure.
- Lack of continuous beam reinforcement - hinge formation during load reversals.
Inadequate reinforcing of beam-column joints or location of beam bar splices at columns - joint failures.

Improper bent-up of longitudinal reinforcing in beams as shear reinforcement - shear failure during load reversal.

Foundation dowels that are insufficient to develop the capacity of the column steel above local column.
Seismic Evaluation Data

Materials Evaluation

- Buildings height >3 stories – Min. grade concrete M20, desirable M 30 to M40 in particularly in columns of lower stories
- Maximum grade of steel should be $f_e$ 415 due to adequate ductility
- No significant deterioration in reinforcement,
- No evidence of corrosion or spelling of concrete

Structural Components

- Evaluation of columns shear strength and drift check for permissible limits
– Evaluation of plan irregularities – check for torsional forces and concentration of forces
– Evaluation of vertical irregularities – check for soft storey, mass or geometric discontinuities
– Evaluation of discontinuous load path – check for ground floor columns, projected cantilever beam and ductile detailing at beam-column joints
– Evaluation of beam–column joints – Check for strong column – weak beams
– Evaluation of pounding – check for drift control or building separation
– Evaluation of interaction b/w frame & infill – check for force distribution in frames and overstressing of frames
Structural Detailing

**Flexural Members**

- Limitation of sectional dimensions
- Limitation on min. and max. flexural reinforcement – at least two continuous at top and bottom of the members, Restriction of lap splices
- Development length requirements: for longitudinal bars
- Shear reinforcement requirements: stirrup and tie hooks, tie spacing, bar splices,

**Columns**

- Limitation of sectional dimensions
- Longitudinal reinforcement requirement
– Transverse reinforcement requirements: stirrup and tie hooks, Column tie spacing, Column bar splices, Special confining requirements

**Foundation**

– Column steel doweled into the foundation
– *Non-structural components*
– Cornices, parapet, and appendages are anchored
– Exterior cladding and veneer are well anchored

*Note: Structural detailing in the structural member should comply with IS: 13920: 1993*
Field Evaluation/Visual Inspection Method

Description

- Perform a walk through visual inspection to become familiar with the structure
- Gather background documents and information on the design, construction, maintenance, and operation of the structure
- Plan the complete investigation
Perform a detailed visual inspection and observed type of damage - Cracks, spells and delaminations, permanent lateral displacement, and buckling or fracture of reinforcement, estimating of drift.

Observed damage documented on sketches - interpreted to assess the behaviour during earthquake.

Perform any necessary sampling - basis for further testing.
 Equipments

– Optical magnification - allows a more detailed view of local areas of distress

– Stereomicroscope - that allow a three dimensional view of the surface. Investigator can estimate the elevation difference in surface features by calibrating the focus-adjustment screw

– Fiberscopes and bore scopes - allow inspection of regions that are inaccessible to the naked eye.

– Tape - to measure the dimension of structure, length of cracks

– Flashlight - to aid in lighting the area to be inspected, particularly in post earthquake evaluation, power failure
– Crack comparator - to measure the width of cracks at representative locations - two types - plastic cards and magnifying lens comparators

– Pencil - to draw the sketch of cracks

– Sketchpad - to prepare a representation of wall elevation, indicating the location of cracks, spelling, or other damage, records of significant features such as non-structural elements.

– Camera - for photographs or video tape of the observed cracking
Execution

- To identify the location of vertical structural elements - columns or walls
- To sketch the elevation with sufficient details - dimensions, openings, observed damage such as cracks, spelling, and exposed reinforcing bars, width of cracks
- To take photographs of cracks - use marker, paint or chalk to highlight the fine cracks or location of cracks in photographs
- Observation of the non-structural elements - inter-story displacement
Limitations

- Applicable for surface damage that can be visualised
- No identification of inner damage - health monitoring of building - change of frequency and mode shapes etc
Identification of Damages in Building Components

In Columns
Mode 1: Formation of plastic hinge at the base of ground level columns
Identification of Damages in Building Components

Mode 1: Formation of plastic hinge at the base of ground level columns
Mode 1: Mechanism

The column, when subjected to seismic motion its concrete begins to disintegrate and the load carried by the concrete shift to longitudinal reinforcement of the column. This additional load causes buckling of longitudinal reinforcement. As a result the column shortens and looses its ability to carry even the gravity load.
Mode 1....

Reasons:

- Insufficient confinement length and improper confinement in plastic hinge region due to smaller numbers of ties.

Design Consideration:

This type of damage is sensitive to the cyclic moments generated during the earthquake and axial load intensity. Consideration is to be paid on plastic hinge length or length of confinement.
In Columns
Mode 2: Shear or flexure shear failure inform of diagonal shear cracking in mid span of columns
Identification of Damages in Building Components

Mode 2:
Shear or flexure shear failure in form of diagonal shear cracking in mid span of columns
Mechanism:

In older reinforced concrete building frames, column failure was more frequent since the strength of beam in such construction was kept higher than that of the columns. This shear failure brings forth loss of axial load carrying capacity of the column. As the axial capacity diminishes, the gravity loads carried by the column transferred to neighboring elements results of massive internal redistribution of forces, which also amplified by dynamic effects resulting in spectacular collapse of building.
Mode 2....

Reason:

Wide spacing of transverse reinforcement

Design Consideration:

To improve understanding of column shear strength, as well as to understand how the gravity loads will be supported after a column fails in shear
In columns
Mode 3: Shear and splice failure of longitudinal reinforcement
Mode 3: Shear and splice failure of longitudinal reinforcement
Mechanism:

Splices of column longitudinal reinforcement in older buildings were commonly designed for compression only with relatively light transverse reinforcement enclosing the lap. For example, as per IS: 456 - 1978, a lap splice length of 20 or 24 longitudinal bar diameters with transverse reinforcement should be equal to the least column dimension or 16 longitudinal bar diameter. Under earthquake motion, the longitudinal reinforcement may be subjected to significant tensile stresses, which require lap lengths for tension substantially exceeding those for compression. As a result, slip occurs along the splice length with spalling of concrete.
Mode 3…..

Reason:

Deficient lap splice length of column longitudinal reinforcement with lightly spaced transverse reinforcement, particularly if the splices just above the floor slab particularly if the splices just above the floor slab, which is very common in older construction.

Design Consideration:

Existing information on splice behavior is very limited.
In columns

Mode 4: Shear failures in captive columns and short columns
Mode 4: Shear failures in captive columns and short columns
Mechanism:

A reduction in the clear height of captive or short columns increases the lateral stiffness. Therefore, these columns are subjected to larger shear force during the earthquake since the storey shear is distributed in proportion to lateral stiffness in the same floor. If these columns, reinforced with conventional longitudinal and transverse reinforcement, and subjected to relatively high axial loading, fail by splitting of concrete along their diagonals. If the axial loading level is low, the most probable mode of failure is by shear sliding along full depth cracks at the member ends. Moreover, in the case of captive column by adjoining non-structural walls, the confinement provided to the lower part of the column is so effective that usually damage is shifted to the short upper section of the column.
Mode 4……

Reason:

Large shear stresses, when the structure is subjected to lateral forces are not accounted for in the standard frame design procedure.

Design Consideration:

The best solution for captive column or short column is to avoid the problem otherwise use separation gap in between the non-structural elements and vertical structural element. In that later case appropriate measures should be taken to warrant the out-of-plane stability of the masonry.
In beams

Shear- flexure failure of beams
Identification of Damages in Building Components

Shear- flexure failure of beams
• **Mechanism:**

Two types of plastic hinges may form in the beams of multi-storeyed framed construction depending upon the span of beams. In case of short beams or where gravity load supported by the beam is low, plastic hinges are formed at the column ends and damage occur in the form of opening of a crack at the end of beam otherwise the formation of plastic hinges at and near end region of beam in the form of diagonal shear cracking.
Beam...

Reason:

lack of longitudinal compressive reinforcement, infrequent transverse reinforcement in plastic hinge zone, bad anchorage of the bottom reinforcement into the support or slip of the longitudinal beam reinforcement, bottom steel termination at face of column
Design Consideration:

- To ensure that the plastic hinges zones in beams have adequate ductility, the following considerations must be considered:
  - Lower and upper limits on the amount of longitudinal flexural tension steel
  - A limit on the ratio of the steel on one side of the beam to that on the other side
  - Minimum requirements for the spacing and size of stirrups to restrain buckling of the longitudinal reinforcement
Beam column joint
Diagonal compression or shear failure in interior beam column joint
Diagonal compression or shear failure in interior beam column joint
Interior beam column joint……

- **Mechanism:**

  Interior joint failure is dominated by the moment resisting capacity in a joint panel i.e. the bond transfer from the beam and column longitudinal bars to surrounding concrete in a joint or the flexural capacity at the beam critical section whichever is smaller. Generally, the joint core concrete fails by diagonal compression since the compressive stain with in a joint panel increase with the storey drift and exceeds the permissible range.
Interior beam column joint……

Reason:

Typical damage to beam columns joint due to inadequate beam rebar anchorage, lack of transverse tie in the joint.

Design Consideration:

Top and bottom steel pass continuously and restriction on bar diameter should not be exceeded one-twentieth of the column width.
Beam column joint

Shear failure in exterior beam column joint
Identification of Damages in Building Components Continue……..
Exterior beam column joint……

- **Mechanism:**

  Exterior beam column joints are subjected to high shear force which is resisted by panel truss action and diagonal strut action in joint panel rather than shear reinforcement in the joint

- **Reason:**

  Anchorage of flexural steel in beams at external column
Exterior beam column joint……

**Design Consideration:**

The provision on anchorage stub for the beam reinforcement improves the performance of external joints by preventing spalling of concrete cover on the outside face resulting in loss of flexural strength of the column. This increases diagonal strut action as well as reduces steel congestion as the beam bars can be anchored clear of the column bars. The anchorage of the beam bars by binding them into the column helps to sustain diagonal strut action.

Provision of additional reinforcement may another alternative to avoid the failure.
In Slabs
Identification of Damages in Building Components

Shear cracking in slabs
Slabs ……

- **Mechanism:**
  
  Under severe earthquakes, hinges are expected to develop against the column face, produces large tensile strain in the slab, which cause longitudinal reinforcement to yield.
Slabs ……

Reason:
Damage to slab is oftenly due to existing micro cracks which widen due to shaking differential settlement; sometimes due to punching shear in flat slab

Design Consideration:
- Use secondary reinforcement in the bottom of the slab
- Avoid the use of flat slab in high seismic zones, provided this done in conjunction with a stiff lateral load resisting system
Failure of Shear Walls

Diagonal tension-compression failure

Sliding shear failure
Identification of Damages in Building Components

Failure of Shear Walls

Flexure and compression

Flexural/ Diagonal tension
Identification of Damages in Building Components

Failure of Shear Walls

Flexure Shear cracks

Flexural/ Diagonal tension
Mechanism:

Shear walls are subjected to shear and flexural deformation depending upon the slenderness ratio. Therefore, the damage in shear walls may generally occur due to inadequate shear and flexure capacity of wall. Slender walls are governed by their flexural strength and cracking occurs in the form of yielding of main flexure reinforcement in the plastic hinge region, normally at the base of the wall. Squat walls are governed by their shear strength and failure takes place due to diagonal tension or diagonal compression in the form of inclined cracking. Coupling beams between shear walls or piers may also damage due to inadequate shear and flexure capacity. Sometimes damage occurs at the construction joints in the form of slippage and related drift.
Shear walls....

Reason:

- Flexural/ boundary compression failure - Inadequate transverse confining reinforcement to the main flexural reinforcement near the outer edge of wall and in boundary elements
- Flexure /Diagonal tension – inadequate horizontal shear reinforcement
- Sliding shear – absence of diagonal reinforcement across the potential sliding planes of the plastic hinge zone
Shear walls…..

Reason…..

- Coupling beams - inadequate stirrup reinforcement and no diagonal reinforcement
- Construction joint – Improper bonding between two surfaces

Design Consideration:

- The concrete shear walls must have boundary elements or columns thicker than walls, which will carry the vertical load after shear failure of wall.
Shear walls….

**Design Consideration**

- A Proper connection between wall vs. diaphragm as well as wall vs. foundation to complete the load path.
- Proper bonding at construction joint in the form of shear friction reinforcement.
- Provision of diagonal steel in the coupling beam.
In masonry Infills
Shear failure of masonry infill
Masonry Infills……

• **Mechanism:**

Frame with infill possesses much more lateral stiffness than the bare frame, and hence initially attracts most of the lateral force during an earthquake. Being brittle, the infill starts to disintegrate as soon as its strength is reached. Infills that were not adequately tied to the surrounding frames, sometimes dislodges by out-of-plane seismic excitations.
Reason:
Infill causes asymmetry of load application, resulting in increased torsional forces and changes in the distribution of shear forces between lateral load resisting system.

Design Consideration:
Two strategies are possible either complete separation between infill walls and frame by providing separation joint so that the two systems do not interact or complete anchoring between frame and infill to act as an integral unit. Horizontal and vertical reinforcement may also be used to improve the strength, stiffness, and deformability of masonry infill walls.
In Parapets
Mode: Shear failure of masonry infill
Parapets ……

- **Mechanism:**
  Parapet walls are acceleration sensitive in the out-of-plane direction; the result is that they may become disengaged and topple

- **Reason:**
  Not properly braced

- **Design Consideration:**
  Analyzed for acceleration forces and braced and connected with roof diaphragm
## Concrete Distress and Deterioration other than Earthquake

<table>
<thead>
<tr>
<th>Description</th>
<th>Typical Causes</th>
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</thead>
<tbody>
<tr>
<td>Cracking</td>
<td>Plastic shrinkage, Drying shrinkage, Restraint, Sub-grade support deficiencies, Vapour barrier, Expansion, Corrosion of reinforcing steel, Thermal loading, Overloading, Aggregate reaction,</td>
</tr>
<tr>
<td>Scaling</td>
<td>Inadequate air content, Finishing problems, Freeze-thaw cycling, Chemical de-icers</td>
</tr>
<tr>
<td>Spalling</td>
<td>Aggregate reaction, Corrosion, Freeze-thaw cycling, Construction problems: poor preparation of construction joints, early age loading</td>
</tr>
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<td>Description</td>
<td>Typical Causes</td>
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</tr>
<tr>
<td>Disintegration</td>
<td>Frozen concrete, Freeze-thaw cycling, Low strength, Chemical attack, Sulphate attack</td>
</tr>
<tr>
<td>Discoloration and straining</td>
<td>Different cement production, Different water-cement ratios, Corrosion, Aggregates, Use of calcium chloride, Curing, Finishing, Non-uniform absorption of forms</td>
</tr>
<tr>
<td>Honeycombing and surface voids</td>
<td>Poor placement, Poor consolidation, Congested reinforcement</td>
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</tbody>
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Visual inspection has the obvious limitation that only visible surface can be inspected. Internal defects go unnoticed and no quantitative information is obtained about the properties of the concrete. For these reasons, a visual inspection is usually supplemented by NDT methods. Other detailed testing is then conducted to determine the extent of deterioration and to establish causes.
NDT Tests for Condition Assessment of Structures

- Rebound hammer/ Swiss hammer
- Penetration Resistance Method – Windsor probe test
- Rebar locator/ convert meter
- Ultrasonic Pulse Velocity
- Impact Echo
- Spectral Analysis of Surface Waves (SASW)
- Penetrating Radar
The rebound hammer is the most widely used non-destructive device for quick surveys to assess the quality of concrete. In 1948, Ernest Schmidt, a Swiss engineer, developed a device for testing concrete based upon the rebound principal strength of in-place concrete; comparison of concrete strength in different locations and provides relative difference in strength only.

Limitations

- Not give a precise value of compressive strength, provide estimate strength for comparison.
Rebound Hammer/ Swiss Hammer continue.....

- Sensitive to the quality of concrete on the outer several; carbonation increases the rebound number
- More reproducible results from formed surface rather than finished surface; smooth hard-towelled surface giving higher values than a rough-textured surface.
- Surface moisture and roughness also affect the reading; a dry surface results in a higher rebound number
- Not take more than one reading at the same spot
Penetration resistance methods are used to determine the quality and compressive strength of in-situ concrete. It is based on the determination of the depth of penetration of probes (steel rods or pins) into concrete by means of powder-actuated driver. This provides a measure of the hardness or penetration resistance of the material that can be related to its strength.

Limitations
- Both probe penetration and rebound hammer test provide means of estimating the relative quality of concrete not absolute value of strength of concrete
• Probe penetration results are more meaningful than the results of rebound hammer
• Because of greater penetration in concrete, the probe test results are influenced to a lesser degree by surface moisture, texture, and carbonation effect
• Probe test may cause of minor cracking in concrete
It is used to determine quantity, location, size and condition of reinforcing steel in concrete. It is also used for verifying the drawing, and preparing as-built data if no previous information is available. These devices are based on interaction between the reinforcing bars and low frequency electromagnetic fields. Commercial covertmeters can be divided into two classes: those based on the principal of magnetic reluctance and those based on eddy currents.
Limitations

- Difficult to interpret - at heavy congestion of reinforcement or depth of reinforcement is too great
- Embedded metals sometimes affect the reading
- Used to detect the reinforcing bars closest to the face
Ultrasonic Pulse Velocity

It is used for determining the elastic constants (modulus of elasticity and Poisson’s ratio) and the density. By conducting tests at various points on a structure, lower quality concrete can be identified by its lower pulse velocity. Pulse-velocity measurements can detect the presence of voids or discontinuities within a wall; however, these measurements cannot determine the depth of the voids.

Limitations

- Moisture content: an increase in moisture content increases the pulse velocity;
• Presence of reinforcement oriented parallel to the pulse propagation direction- the pulse may propagate through the bars and result is an apparent pulse velocity that is higher than that propagating through concrete

• Presence of cracks and voids- these can increase the length of the travel path and result in a longer travel time
Impact Echo

Impact echo is a method for detecting discontinuities within the thickness of a wall. An impact-echo test system is composed of three components: an impact source, a receiving transducer, and a waveform analyzer or a portable computer with a data acquisition.

Limitations

- Accuracy of results highly dependent on the skill of the engineer and interpreting the results
- The size, type, sensitivity, and natural frequency of the transducer, ability of FFT analyzer also affect the results
- Mainly used for concrete structures
Spectral Analysis of Surface Waves (SASW)

To assess the thickness and elastic stiffness of material, size and location of discontinuities within the wall such as voids, large cracks, and delimitations of surface waves have used.

Limitations

- Interpretation of results is very complex
- Mainly used on slab and other horizontal surface, to determine the stiffness profiles of soil sites and of flexible and rigid pavement systems, measuring the changes in elastic properties of concrete slab
Penetrating Radar

- It is used to detect the location of reinforcing bars, cracks, voids or other material discontinuities, Verify thickness of concrete

Limitations

- Mainly used for detecting subsurface condition of slab-on-grade
- Not useful for detecting the small differences in materials
- Not useful for detecting the size of bars, closely spaced bars make difficult to detect features below the layer of reinforcing steel