Seismic Evaluation of Existing Buildings and Strengthening Techniques

Abstract

Occurrence of recent earthquakes in India and in different parts of the world and the resulting losses, especially human lives, has highlighted the structural inadequacy of buildings to carry seismic loads. There is an urgent need for assessment of existing buildings in terms of seismic resistance. In view of this, various organizations in the earthquake threatened countries have come up with documents, which serve as guidelines for the assessment of the strength, expected performance and safety of existing buildings as well as for carrying out the necessary strengthening required.

Can we identify those buildings that are likely to be damaged to an extent that would create unacceptable life-safety hazards for their occupants? Similarly, can we identify those buildings that, although they do not satisfy current design codes and standards, would be expected to perform satisfactorily in the next earthquake? These questions are faced daily by building owners, occupants, government officials and engineers. Consideration of the financial issues, such as the potential economic losses due to earthquake damage and the cost of the structural upgrading, complicates the problem further and makes decision making extremely difficult. Seismic evaluation of existing buildings in any region of seismicity constitutes a three-tiered process, viz. Screening Phase (Tier 1), Evaluation Phase (Tier 2) and Detailed Evaluation Phase (Tier 3).

This paper deals with the details of methodology of seismic evaluation; which is applied to a four storey Hospital Building to understand the concept of evaluation.

Keywords: Seismic Evaluation, Evaluation requirements, Checklists, Storey Shear, Storey Drift, Demand Capacity Ratio.

1. Introduction

Earthquake engineering has developed during the last eight decades at a steadily increasing rate. Although recent improvements in seismic design codes and standards have resulted in increased earthquake resistance for newer properly designed buildings, they have created a dilemma for older existing ones. There are many buildings that have primary structural systems, which do not meet the current seismic requirements. A large number of existing buildings in India are severely deficient against earthquake and might suffer extensive damage or even collapse if shaken by a severe ground motion. This has been highlighted in the past earthquakes. There are several reasons such as a lack of knowledge of seismic regulation to design the earthquake resistant building in the past, type of construction that is more vulnerable to earthquake forces, errors and omissions in the design and construction of buildings, buildings in which the earthquake resistance has been deteriorated due to factors such as decrease in the strength of construction material, fire damage, foundation settlement etc, upgrading of seismic zone after the design and construction of building, change in seismic regulations etc for existence of such buildings

2. Evaluation Requirements

2.1 Level of Investigation Required

Building evaluation involves many substantial difficulties. One is the matter of uncovering the structure since plans and calculations often are not available. The evaluation should be based on facts, as opposed to assumptions, to the greatest extent possible. If the results are sensitive to the assumptions, more detailed information should be obtained. Two of the more important factors in any evaluation are the material properties and strengths. While evaluating a building, the design professional should:

1. Look for an existing geo-technical report on site soil conditions;
2. Establish site and soil parameters;
3. Assemble building design data, including contract drawings, specifications, and calculations;
4. Look for other data, such as assessments of the building performance during past earthquakes;
5. Select and review the appropriate sets of evaluation statements.

2.2 Site Visits

Many of the Tier 1 Checklist items can be completed during the initial site visit. Subsequent assessment of the evaluation statements may indicate a need for more information about the building. Relevant building data, which shall be determined or confirmed during a site visit, includes the following:

1. General building description: Number of stories, year(s) of construction and dimensions
2. Structural system description: Framing, lateral force resisting system(s), floor and roof diaphragm construction, basement and foundation system
3. Non-structural element description: Non-structural elements that could affect seismic performance
4. Non-structural component connections: Anchorage conditions, location of connections or support
5. Building type(s), Site class, Building use
6. Special architectural features: Finishes, registered historic features
7. Adjacent building: Pounding concerns, falling hazards
8. Building condition: Dry-rot, fire, insect, corrosion, water, chemical, settlement, past-earthquake, wind, and other damage and related repairs, alterations and additions that could affect seismic performance.

2.3 Level of Performance

A desired level of performance shall be defined prior of conducting a seismic evaluation. Life Safety (LS) and Immediate Occupancy (IO) are the two performance levels.

The definition of Life Safety (LS) performance level contains two performance criteria that require judgment to be exercised by the owner and the building official. These are: (a) at least some margin against either partial or total structural collapse remains, or (b) injuries may occur, but the overall risk of life-threatening injury as a result of structural damage is expected to be low.

The definition of Immediate Occupancy (IO) performance level contains two performance criteria that require judgment to be exercised by the owner and the building official. These are: (a) after a design earthquake, the basic vertical and lateral force resisting systems retain nearly all of their pre-earthquake strength, and (b) very limited damage to both structural and nonstructural components is anticipated during the design earthquake that will require some minor repairs, but the critical parts of the building are habitable. In general, buildings classified as essential facilities categorized as fire or rescue and police stations, Hospitals, Designated other medical facilities having surgery or emergency treatment facilities, Designated emergency preparedness centers including the equipment therein, Emergency vehicle garages, Designated communication centers, Structures containing sufficient quantities of toxic or explosive substances deemed to be dangerous to the public if released, Other facilities may be deemed ‘essential’ by local jurisdiction should be evaluated to the Immediate Occupancy Performance Level.

2.4 Level of Seismicity

The level of seismicity of the building shall be defined as low, moderate or high in accordance with Table 1. Levels of seismicity are defined in terms of mapped response acceleration values and site amplification factors.

Table1: Levels of Seismicity Definitions

Level of Seismicity	S_{DS}	S_{D1}
Low	*<0.067g*	*<0.067g*
Moderate	*≥0.167g* *<0.500g*	*≥0.067g* *<0.200g*
High	*≥0.500g*	*≥0.200g*

Where, S_{DS} = Design short-period spectral response acceleration parameter

S_{D1} = Design spectral response acceleration parameter at a one-second period.

2.5 Quick Checks

Quick Checks shall be used to compute the strength and stiffness of building components.

1. Story Drift for Moment Frames:

Equation 1 shall be used to calculate the drift ratios of regular, multi-story, multi-bay moment frames with columns continuous above and below the story under consideration.

$$D_r = \left(\frac{k_b + k_c}{k_b k_c}\right)\left(\frac{h}{12E}\right)V_c \qquad \text{-------------------------} \quad (1)$$

Where, D_r = Drift ratio: Inter story displacement divided by story height

k_b = I/L for the representative beam,

k_c = I/h for the representative column

h = Story height (mm)

I = Moment of Inertia (mm^4)

L = Beam length from center to center of adjacent columns (mm)

E = Modulus of elasticity (N/mm^2)

V_c = Shear in the columns (N)

The column shear forces are calculated using the story shear forces.

2. Story shear:

The total design lateral force or design seismic base shear (V_B) along any principal direction shall be determined by the following expression as per Cl.7.5.3, IS1893 (Part 1):2000

$$V_B = A_h W \text{ ---} \quad (2)$$

Where, A_h = Design horizontal acceleration spectrum value as per IS1893 (Part 1):2000

W = Effective seismic weight of the building including the total dead load and applicable portions of other gravity loads.

3. *Story Shear Forces:*

The design lateral force calculated in accordance with equation 1.1 shall be distributed vertically in accordance with Cl.7.7.1, IS1893 (Part 1):2000

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{j=1}^{n} W_j h_j^2} \quad \text{---} \quad (3)$$

Where, Q_i = Design lateral force at floor *i*
W_i = Seismic weight of floor *I*
h_i = Height of floor *i* measured from base, and
n = Number of storeys in the building is the number of levels at which the masses are located.

For buildings with stiff or rigid diaphragms, the story shear forces shall be distributed to the lateral-force-resisting elements based on their relative rigidities.

4. *Shear Stress in Concrete Frame Columns*

The average shear stress, v_j^{avg} ,in the columns of concrete frames shall be computed in accordance with equation 2.

$$v_j^{avg} = \frac{1}{m}\left(\frac{n_c}{n_c - n_f}\right)\left(\frac{V_j}{A_c}\right) \quad \text{----------------------------} \quad (4)$$

Where, n_c = Total number of columns
n_f = Total number of frames in the direction of loading
A_c = Summation of the cross-sectional area of all columns in the story under consideration
V_j = Story shear computed in accordance with equation 1.2.
m =Component modification factor, *m* shall be taken equal to 2.0 for buildings being evaluated to the Life Safety Performance Level and equal to 1.3 for buildings being evaluated to the Immediate Occupancy Performance Level.

5. *Axial Stress Due to Overturning:*

The axial stress of columns in moment frames at the base subjected to overturning forces, p_{ot}, shall be calculated in accordance with equation 3.

$$p_{ot} = \frac{1}{m}\left(\frac{2}{3}\right)\left(\frac{Vh_n}{Ln_f}\right)\left(\frac{1}{A_{col}}\right) \quad \text{-----------------------------} \quad (5)$$

Where, n_f = Total number of frames in the direction of loading
V = Design lateral force as per eq.3.1.1.
h_n = Height (in mm) above the base to the roof level
L = Total length of frame (in mm)

m = Component modification factor, m shall be taken equal to 2.0 for buildings being evaluated to the Life Safety Performance Level and equal to 1.3 for buildings being evaluated to the Immediate Occupancy Performance Level.

A_{col} = Area of the end column of the frame.

3. Evaluation Process

The evaluation process consists of 3-Tiers as shown in Fig.1.

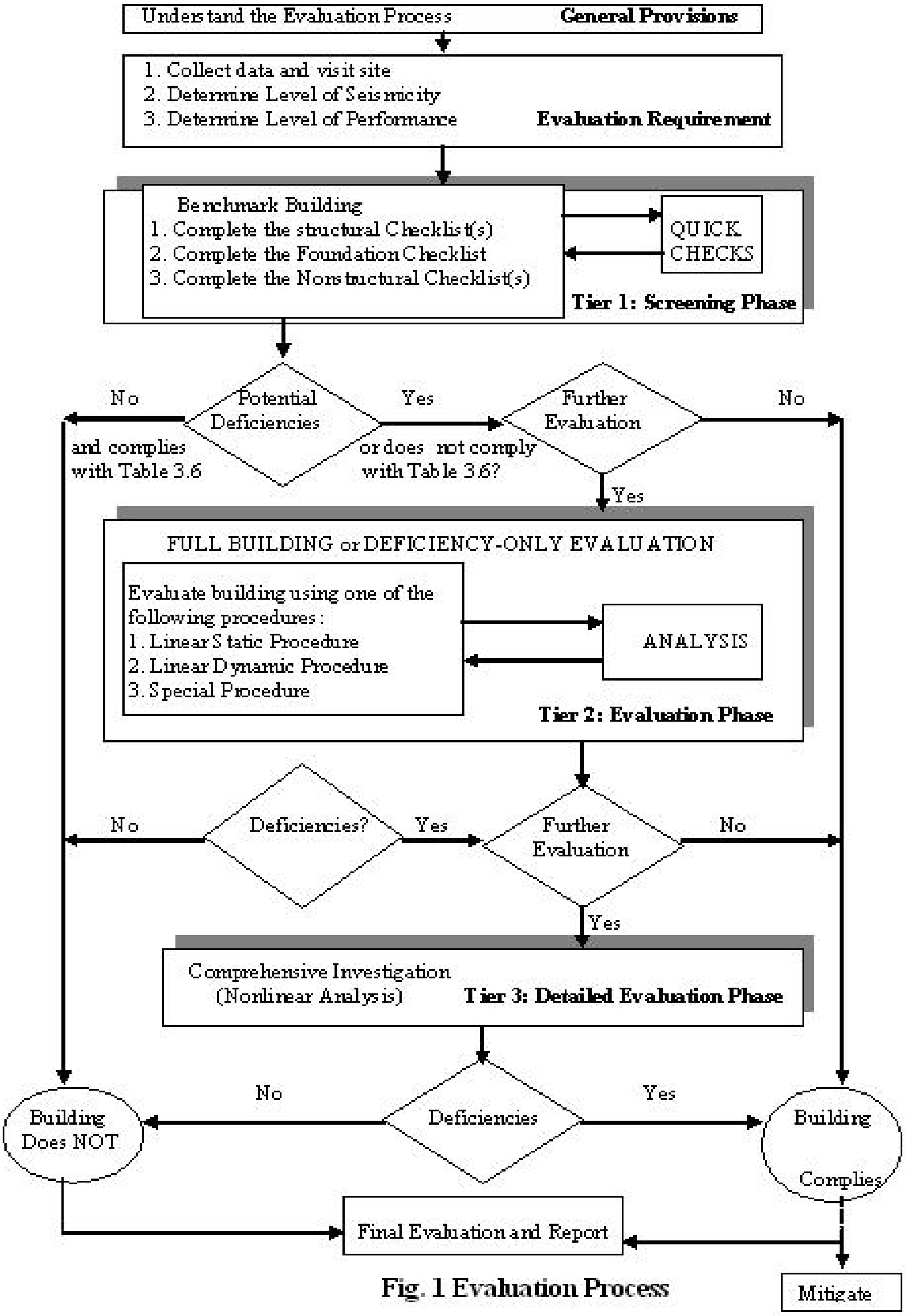

Fig. 1 Evaluation Process

3.1 Evaluation Phase (Tier 2)

A Tier 1 Evaluation shall be completed for all buildings prior to performing a Tier 2 Evaluation. A Full-Building Tier 2 Analysis and Evaluation of the adequacy of the lateral-force-resisting system shall be performed for the buildings designated as T2 in Table 2. A Tier 2 Evaluation shall include an analysis using one of the following linear methods: Linear Static Procedures, Linear Dynamic Procedures, or Special Procedures. The analysis shall address, at a minimum, all of the potential deficiencies identified in Tier 1.

The linear static procedure is applicable to all buildings unless a linear dynamic procedure or special procedure is required. The linear dynamic procedure shall be used for buildings taller than 100 feet, or buildings with mass, stiffness, or geometric irregularities

A Tier 3 Evaluation is required only for Buildings of type: Un- reinforced Masonry Bearing Walls, in moderate and high level of seismicity, for Immediate Occupancy Performance Level.

4. Case Study

This case study consists of a 4 story (G+3) R.C.C. Building located at Jaysingpur, Dist. Kolhapur, (India). The building is constructed in the year of 2000-01 and is used as a Hospital. It is founded on medium hard strata. It is not designed in accordance with IS 1893 (Part I):1984/2002. The 3- D model of the building is prepared using SAP 2000 software. The building is located in Seismic Zone II as per I.S.1893 (Part I):2002. Fig. 3 shows photograph of the study building and fig. 4 shows the 3-D view of the study building.

Fig.3: Photograph of the Study Building

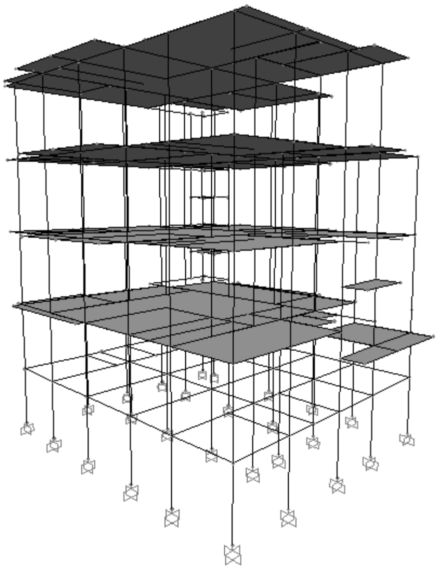

Fig. 4: 3-D Model of Building

4.1 Screening Phase (Tier 1 Evaluation)

We know that a Tier 1 Evaluation familiarizes the design professional with the building, its potential deficiencies and its potential behavior. As per Table 1, for Level of Seismicity-Low and Level of Performance is Immediate Occupancy (IO), the checklists shall be completed for Tier 1 Evaluation such as 1) Basic Structural Checklist, 2) Geologic Site Hazard and Foundation Checklist & 3) Basic Non Structural Checklist. Only non-compliant statements are presented here.

4.2 Basic Structural Checklist

a) Building System

C [✓ **NC**] **N/A** Soft Storey: The stiffness of the lateral-force-resisting system in any storey shall not be less than 70 percent of the lateral-force-resisting system stiffness in an adjacent storey above or below, or less than 80 percent of the average lateral-force-resisting system stiffness of the three stories above or below for Life Safety and Immediate Occupancy. This applies to the columns below first storey.

C [✓ **NC**] **N/A** Vertical Discontinuities: All vertical elements in the lateral-force-resisting system shall be continuous to the foundation. This applies to the Dummy Column provided for the Rear Staircase.

b) Geologic Site Hazard and Foundation Checklist: All Statements in this checklist are either compliant or not applicable.

c) Basic Non Structural Checklist

C [✓ **NC**] **N/A** ***Unreinforced Masonry:*** Un-reinforced masonry or hollow clay tile partitions shall be braced at spacing equal to or less than 10 feet in levels of low or moderate seismicity and 6 feet in levels of high seismicity.

C [✓ **NC**] **N/A** ***Multi-Storey Panels:*** For multi-storey panels attached at each floor level, panel connections shall be detailed to accommodate a storey drift ratio of 0.02. Panel connection detailing for a storey drift ratio of 0.01 is permitted where Table 3.2 requires the Basic Nonstructural Component Checklist only.

C [✓ **NC**] **N/A** ***Flexible Coupling:*** Fluid, gas and fire suppression piping shall have flexible couplings.

4.3 Vertical Distribution of Base Shear (Storey Shears)

As per Cl.7.7.1, IS1893, the design base shear VB = 392 KN (calculated as per procedure given in IS: 1893-2000) shall be distributed along the height of the building as per the following expression,

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{j=1}^{n} W_j h_j^2} \quad \text{-- (6)}$$

Table 2: Design Lateral Forces (Storey Shears)

Level	W_i *(kN)*	h_i *(kN)*	$W_i \times h_i^2$	$Q_{ix} = Q_{iy} = Q_i$ *(kN)*
Plinth Beam	*585*	*2.743*	*4401.57*	*1.282*
Mezzanine	*162*	*4.877*	*3853.19*	*1.122*
First Floor	*2058*	*5.944*	*72711.48*	*21.187*
Second Floor	*2827*	*9.449*	*252404.74*	*73.549*
Third Floor	*2811*	*12.954*	*471702.99*	*137.452*
Terrace	*1994*	*16.459*	*540171.97*	*157.404*
Total				*392 kN =* V_B

4.4 Quick Checks

Following quick checks are taken as part of Tier 1 Evaluation to study the compliance of Storey Drift, Shear Stress and Axial Stress in columns due to overturning-

1. Storey Drift:

Storey drift as calculated from equation 1 for study building = 3500 × 7.4181 × 10-3 mm = 25.96 mm. But Storey Drift Limitation in any storey, as per Cl.7.11.1, IS1893 is given by, Storey Drift < 0.004×storey height i.e. < 0.004 × 3500 (=14mm)

Thus, calculated storey drift is more than permissible storey drift for the study building. Therefore Storey Drift Check is Non-compliant.

2. Shear Stress

The average shear stress, v_j^{avg}, in the columns of concrete frames computed in accordance with equation 4 is 0.117 N/mm^2 < 2√fc'(= 2√15 = 7.74 N/mm2). Hence OK. Therefore Shear Stress Check is Compliant

3. Axial Stress due to overturning

The axial stress of columns in moment frames at the base subjected to overturning forces, p_{ot}, shall be calculated in accordance with equation 3 is P_{ot} = 1.114 N / mm^2 < 0.30 $f_c{}'$(=0.30×15=4.5 N/mm^2) Hence, axial stress check is compliant.

Studying the various non-compliant statements in Tier 1 and non-compliant quick checks, it is decided to carry out Tier 2 Evaluation.

4.5 Evaluation Phase (Tier 2 Evaluation)

Complete building Tier 2 Evaluation is achieved by making the structural model of the study building using SAP 2000 software. Later this model is analyzed and the provided sections are checked for their capacity to carry anticipated loads.

Following is the indication for the colour as per SAP:

Colour		**Demand Capacity Ratio**
Sky Blue	🟦	0.0 to 0.5
Green	🟩	0.5 to 0.7
Yellow	🟨	0.7 to 0.9
Dark Orange	🟧	to 1.0 **(Non -Compliant if >0.95)**
Red	🟥	> 1.0 **(Non -Compliant)**

The demand capacity ratios are particularly of significance to the columns and they are also indicated as Column P-M-M Interaction Ratios by SAP.

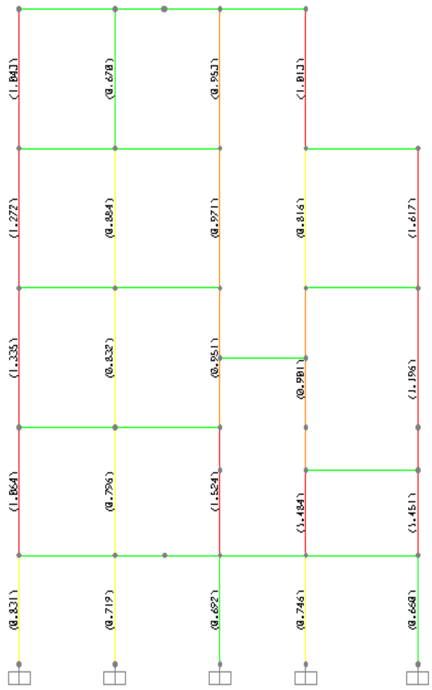

Fig.5. Column Demand Capacity Ratios in for a frame in XZ plane at Y=0m Y=0m

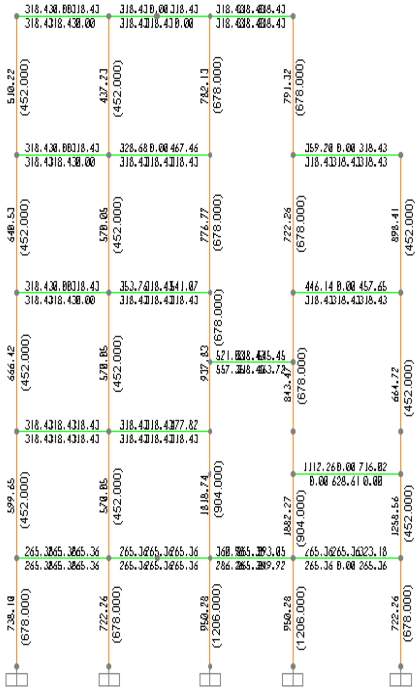

Fig.6. Required Column reinforcement mm^2 for a frame in XZ plane at Y=0m

(Fig. in bracket indicate provided Reinforcement)

5. Conclusions

1. As forecasted during the site visits, majority of the columns of the building frame are found deficient to carry the seismic loads. This is firstly because the building has not been designed to resist such lateral forces as per IS1893 and secondly because it has a stilt storey-the space below which is utilized for parking.
2. Dummy column in the rear staircase made that column and adjoining columns deficient. This is because they are required to transfer greater seismic loads to the foundation.
3. The multistory glass panel provided in the front staircase for elevation treatment can pose falling hazard during an earthquake.
4. The front staircase is up to third storey only. The rear staircase which goes up to the terrace is supported by cantilever beams and therefore it may pose more lateral displacement during an earthquake. This can cause collapse of masonry units on the flights. Escaping of the occupants living on fourth storey using this rear staircase can be dangerous or difficult.
5. No beam in the whole building is found deficient to resist the seismic load.
6. The plinth beams at the ground storey helped to reduce the effective lengths of columns thus giving lesser values of capacity ratios. In the absence of such plinth beams the capacity ratios go higher than 3 indicating a large amount of reinforcement requirement.
7. The deficiency in the columns of this study building to resist the anticipated seismic loads can be overcome by one of the following retrofitting/strengthening technique –
    a. Reinforced Concrete Jacketing to the columns on four sides
    b. Steel Plate Jacketing to the columns
    c. Fibre Reinforced Polymer Sheet Wrapping to the columns
    d. Adding Shear Walls on the peripheral frames of the study building
    e. Adding Steel Braces on the peripheral frames of the study building
8. By undertaking such evaluation of various important buildings such as hospitals, community buildings, business and institutional buildings etc., one can find its present seismic resistance. According to the results of such evaluation, proper strengthening technique can be adopted. This ensures proper functioning of the building in the event of an earthquake.

References

___ Evaluating The Seismic Resistance of Existing Buildings (1987), *ATC 14, Applied Technology Council,* California.

___ Seismic Evaluation and Retrofit of Concrete Buildings (1996), Vol. I and Vol. II, *ATC 40, Applied Technology Council,* California.

___ Guidelines for Structural Condition Assessment of Existing Buildings (2000), *ASCE/SEI 11-99, American Society of Civil Engineers*.

___ Seismic Evaluation of Existing Buildings (2003), *ASCE/SEI 31-03, American Society of Civil Engineers*.

Bhandari N. M. and Dwiwedi A. K. (2003), “Repair Materials and Techniques for Retrofitting”, ‘*Workshop on Retrofitting of Structures’*, IIT, Roorkee, pp 86-104.

Jain S. K., (2004) “Seismic Strengthening of Existing Reinforced Concrete Buildings”, *Indian Concrete Journal Compilation on Repair and Rehabilitation*, pp 45-51.

__ Repair and Seismic Strengthening of Buildings-Guidelines, *IS13935: 1993 (Reaffirmed 1998), Bureau of Indian Standards,* New Delhi, India.

Sengupta A.K., Badari Narayan V.T. and Asokan A. (2003), “Seismic Retrofit of Existing Multi-Storied Buildings In India- *An Overview of the Method and Strategies”, Workshop on Retrofitting of Structures*, IIT, Roorkee, pp 17-27.

Singh Yogendra and Paul D.K. (2005), “Retrofitting of RC Buildings”, *NPEEE Short Term Course on Seismic Evaluation and Retrofit*, IIT, Roorkee,

Rai Durgesh C. (2005), IITK-GSDMA Guidelines for Seismic Evaluation and Strengthening of Buildings, *Provision with Commentary and Explanatory Examples,* Indian Institute of Technology, Kanpur, 2005.

___ Criteria for Earthquake Resistant Design of Structures, Part I- *General Provisions and buildings (Fifth Revision), IS1893 (Part 1): 2002,* Bureau of Indian Standards, New Delhi, India.