Seismic Upgradation of Non-Ductile Reinforced Concrete Framed Building: A Case Study

Amit Srivastava*
Department of Civil and Environmental Engineering, The NorthCap University, Gurgaon – 122017, Haryana, India.
amitsrivastava@nucindia.edu

Abstract

Objectives: An existing multistory framed building structure analyzed for its performance under seismic environment and seismic upgradation of buildings is suggested based on the findings of methodological field investigation and structural analysis techniques. Methods/Statistical Analysis: The office building in question was studied and analyzed in three stages. In the first stage, reconnaissance (post-earthquake study) of the building that faced recent high magnitude Nepal earthquake (25th April, 2015 with a magnitude of 7.8), collection of as-built layout plan and section of reinforcement detailing of beams, slab and columns as well as additional available technical parameters were gathered like the sub-soil type, concrete mix used, etc., was done. In the second stage, with the help of as-built drawings, detailed structural analysis of the building was carried out using Response Reduction Method (IS 1883-Part 1) with the help of commercially available software ETAB. In the third and last stage, based on the outcome of structural analysis, the upgradation methods were suggested to mitigate structural inadequacy of the building. Findings: The analysis recommends installation of fluid viscous dampers in the frame of building, for example, inclined bracings with ends connected to columns at base and top with the beams. I addition to that few columns are also required to be retrofitted by increasing their size, the jacketing of columns. Application/Improvements: The study provides an insight to how to judge structural deficiency of buildings and provide knowledge of use of dampers to arrest seismic forces thereby enhancing the structure performance during a seismic activity.

Keywords: Damper, Frame Structure, Numerical Analysis, Seismic Retrofitting

1. Introduction

Old and non-engineered building face severe damages during an event like earthquake as experienced during Northridge and Chi-Chi earthquakes. It is noted that a high magnitude earthquake is not necessarily required to cause damage to such buildings. If damage occurs, common structural deficiencies are poor construction quality, excessively slender and flexible structural components, inadequate lateral support, under-designed structural elements, integration of brittle component, inadequate reinforcement and concrete cover, poor detailing, structural irregularity in plan and elevation, inadequate foundation system, etc. Hence, seismic evaluation and then retrofitting or seismic rehabilitation of the vulnerable buildings is one of the major activities of civil engineering profession as it has great social and political relevance. One of the most widely used methodology for seismic screening of building is developed by National Research Council (NRC) in which a parameter known as “Seismic Priority Index” is fixed numerically through two indices, namely, structural index and non-structural...
Seismic Upgradation of Non-Ductile Reinforced Concrete Framed Building: A Case Study

Seismic Upgradation of Non-Ductile Reinforced Concrete Framed Building: A Case Study

Traditional seismic retrofitting methods were based on the concept of either increasing the strength and stiffness or reducing the mass that were considered to be quite expensive. In the last decade, lots of research has been carried out to develop innovative techniques for the retrofitting of existing buildings that involve any one or combinations of techniques like stiffness reduction using base isolators, increase ductility using Fiber Reinforced Polymers (FRPs), damage control structures using dampers, using composite materials especially for masonry structures and active control using servo-activated device with the help of sensors and actuators which apply force opposite to the seismic forces. It should be noted that each building is unique in its own way and there is no standardized approach or guidelines applicable to all types of buildings and sometimes there is a possibility that the local building codes may be silent about certain aspects that requires special consideration and creativity in problem solving. Although, Federal Emergency Management Agency (FEM) discuss various aspects of seismic rehabilitation of existing building code yet there is no such thing like “cookbook approach”.

In the recent Nepal earthquake, as occurred on 25th April 2015, several buildings and other manmade structures in northern region faced tremendous shaking and showed different level of damages in the structures beyond the expectations. In the aftermath of the earthquake, several experts in their own capacity suggested revaluation of existing building under seismic environment and suggested retrofitting of existing structures. Use of dampers is one of the most widely used solution for the seismic rehabilitation of the existing structures due to its capacity to either eliminate or reduce plastic deformation and thereby reducing the chance of structural damage. Other options of improving performance of concrete used in the structural elements of framed structure are discussed elsewhere. The present paper deals with such one case in which seismic rehabilitation of one of the office buildings was carried out after rigorous analysis. Indian standard code of practice provide detailed guidelines for the assessment of seismic performance of existing building, strengthening of structural element to improve the performance of the structure and it has been followed to the extent possible for the evaluation and retrofitting purposes.

2. Objectives of the Present Study

In view of the recent high magnitude Nepal earthquake, the office building located in Delhi region, which was constructed in the year 2009-10, faced large shaking due to tremors. Visual inspections confirmed development of cracks at various critical locations in the building. Hence, it was desired to undertake detailed structural audit and carry out seismic upgradation of the office building. To accomplish the task, following objectives were defined:

- A detailed structural design evaluation based on post-earthquake investigations about the Office Building.
- To lay down the structural design assessment parameters based on which a detailed analysis to be undertaken.
- To suggest seismic upgradation of the building based on the outcome of the detailed structural analysis.
- Numerical analysis of the original and upgraded building and comparison of results to study the effect of up gradation of building.

3. Structural Description and Subsurface Information of the Building

The office building under review is a reinforced concrete framed building, which was constructed in the year 2008-2009 and became operational in the year 2009. It consists of G+3 floors with no basements and the third floor is partially constructed with part area being used as a terrace garden. The foundation system consists of isolated footings. There are 8 columns in North-South direction and 7 in East-West direction. There are a total of three stairwells and two lifts, one at the Eastern entrance and the second in the West. The center to center distance between columns varies between 8 to 10 meters. The floor is a Flat Slab with Drop Panels; there are no beams and no shear walls in the building. The building covers 81 meters × 50 meters in plan and the height of the building is 15 m.

Subsurface information was gathered through bore holes created around the building. As the building already existed, no bore hole could be located within the premises of the building. SPT data from the bore hole indicated that average N-value observed at 1.5 meter depth was 18 and at 3.0 meters depth was 26.
geotechnical analysis, SPT data was correlated to the bearing capacity of the subsoil and it was estimated that the net allowable bearing capacity for isolated footings can be considered in the range of 12-15 Ton/m² at 1 meter depth from Normal Ground Level (NGL) and 18-20 Ton/m² at 2 meters depth from NGL. The foundation design, as per Indian standard, has considered a soil bearing capacity of 21 Ton/m² at the founding level, which is at 2.0 m below NGL. There was no effect of Ground Water Table (GWT) observed. Hence, effect of GWT was completely ignored.

4. Design Parameters and Standards

In Table 1 indicates the Indian Standards issued by Bureau of Indian Standards that were used during the structural analysis of building frame and design for upgradation of building. In Table 2 shows the material properties and design parameters used for structural element of the building made up of concrete and steel. Other parameters included in the study are:

Thickness of floor finishes
- Ground Floor = 100mm
- All other Floors = 75mm
- Stairs = 50mm

Quantum of earth fill
- On partial roof of Second Floor = 600mm (terrace garden on third floor)

| Table 1. | Indian standards code of practice. |
|---------|----------------------------------|
| NBC 2005 | National Building Code of India |
| IS 875(Part 1)-1987 | Dead Loads - Unit Weight of Building Material and Stored Material |
| IS 875(Par 2)-1987 | Imposed Loads |
| IS: 1893-2002 | Criteria for earthquake resistant design of structures |
| IS: 456-2000 | Code of practice for plain and reinforced concrete |
| IS: 1904-1986 | Code of practice for design and construction of foundations in soils |
| IS: 13920: 1993 | Ductile Detailing of Reinforced Concrete Structures subject to Seismic Forces |
| IS:15988 - 2013 | Seismic evaluation and strengthening of existing reinforced concrete building-guidelines |

Table 2. Material properties and design parameters.

| The Grade of Concrete for Columns | M40 |
|----------------------------------|-----|
| Grade of Concrete for Slabs, Isolated footing, Slab – on – grade, plinth beam | M30 |
| Density of concrete | 2400 kg/m³ |
| Poison’s ratio of concrete | 0.2 |
| Coefficient of thermal expansion (ac) of concrete | 9.9x10^-6/°C |
| High yield strength deformed bars (fy) | 500 MPa |
| Density of steel | 7,850 kg/m³ |
| Young’s Modulus of steel | 2.05x105MPa |
| Poison’s ratio of steel | 0.30 |
| Coefficient of thermal expansion (as) of steel | 11.7x10^-6/°C |

5. Seismic Loading Parameters

The seismic load calculations were carried out in accordance with Indian standard and the following parameters provided in Table 3 were used. It is to be noted that the response reduction factor is taken as 3.0 as Table 3 of the code does not give an option for a flat slab building. Also this building does not have any shear wall and the confinement rules of Indian Standard have also not been followed. Hence, it is recommended that the response reduction factor for this building configuration should not be taken greater than 3. Further, in the analysis Dead Load (DL) and Live Load (LL) were considered as per Indian standards.

| Table 3. | Seismic loading parameters (IS 1893-2002). |
|----------|------------------------------------------|
| Parameter | Value |
| Seismic zone | IV |
| Peak Ground Acceleration | 0.24g |
| Importance Factor | 1.5 |
| Response Reduction Factor | R = 3 |
| Fundamental natural period | From modelling |
| Approximate Fundamental period | Ta calculated as per the clause. All exterior walls are masonry in fills. |
| Soil Type | Medium |
6. Seismic Evaluation of Building and Ductile Detailing Check

During recent high magnitude earthquake in Nepal, the office building faced structural distress at various locations. During site visits and inspection, it was noted that the shaking and resultant cracks in masonry/floor/staircase walls was more on the upper floors and when looking at the building plan are more prominent at the four corner locations in Figure 1.

Even though the epicenter of the earthquake was 1100 kilometers away, this Office Building did sway more than would be normally accepted. Hence, it became imperative to examine the existing structural system and compare with the compliance criteria as given in the seismic codes existing of date\cite{9,10}. Deficiencies, if any, were reported and remedial measures were then suggested. Structural system of the building was reviewed with respect to resistance to lateral load and compliance to ductile detailing and following observations were made:

- Reviewing the grade of concrete, it was noted that columns were M40 and in other structural elements, it were M30. The grade of steel was Fe500 (High Yield Strength Deformed bars). The development length/ lap length of bars used in M30 concrete is 39D and in M40 concrete is 32D. For beams, the development length is 50D. Concrete cover for beams, slabs, column and foundations are 25mm, 15mm, 40mm and 50mm, respectively, which was in conformity to Indian Standard\cite{11}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{cracks.png}
\caption{Site photographs of cracks.}
\end{figure}
• **Reviewing the ductile detailing of the column**, it was noted that there are a total 6 types of columns out of which 3 predominant types that are indicated as C1, C1A and C2. There are 10 Nos. C1 columns, 19 Nos. C1A and 25 Nos. C2 columns. All of the columns C1, C1A and C2 are deficient in ductile detailing as per the rules given in Indian standard\[10]. The vertical spacing of stirrups in the special confinement zone Lo is 150mm whereas clause 7.4.6 on page-10 of Indian standard\[10] states that it should not be more than 100mm. Hence, this causes a deficiency in ductile detailing and the ability of the columns to withstand the seismic forces. Also, out of the 28 longitudinal bars in columns C1 and C1A, 16 bars are not directly confined with stirrups, this detailing is not a good engineering practice especially when the building structural is having no shear walls and all of the horizontal forces are to be withstood by the columns alone.

• **Reviewing the Ductile detailing in perimeter Beams**, it was noted that the perimeter columns of Office Building are tied with beams of size 550mm x 530mm. All of these beams are having 5 bars each at the top and bottom. Also these bars are in two layers at the beam edges (top reinforcement) and central portion (bottom reinforcement). However, all beams are having only two-legged stirrups; the ductile detailing rules of Indian Standard\[10,14], clause (d) have not been complied with. This was a serious concern and reason for high stresses developed in a seismic event.

• **Reviewing structural system of the building**, it was noted that the building's foundation system consists of isolated footings and the structural system is columns and flat-slab floor, there are no shear walls what-so-ever. This structural system is not listed in Table 4, page-23 of Indian standard\[9], where the seismic code tabulates the various structural systems to be followed in different seismic zones along with the response reduction factor to be used.

In the international building codes the flat-slab structural system is specifically not-permitted in areas of high seismicity; the Indian code\[9] does not contain wordings, specifically, either banning or permitting this structural form. The code is silent on this aspect. It has explicitly spelt out that such structures shows poor performance during earthquakes. Subject Office building used the structural system which is highly prone to collapse in an earthquake, the drawings are too salient and do not cover this aspect.

• **Building envelope** was an issue. The Office Building is 81meters x 50 meters and does not contain any expansion gaps.

• **Mass and Vertical Geometric Irregularity** was also observed. The third floor of Office Building is not fully constructed and an area of approximately 36 meters x 34 meters is used as a terrace garden and has soil fill of 600mm. The approximate weight of the saturated earth-fill which is concentrated at the right-lower quadrant when viewing the building in plan is 1305 Tons. This causes a mass irregularity in the building as given in Table 5, page-18 of Indian

Table 4. Modal mass participation ratios for the first 12 modes.

| Mode | Period | UX  | UY  | RZ   | SumUX | SumUY | SumRZ |
|------|--------|-----|-----|------|-------|-------|-------|
| 1    | 0.778  | 77.33 | 0.027 | 2.820 | 77.33 | 0.0269 | 2.820 |
| 2    | 0.746  | 2.780 | 2.187 | 74.31 | 80.11 | 2.2135 | 77.13 |
| 3    | 0.709  | 0.014 | 77.07 | 2.298 | 80.13 | 79.280 | 79.43 |
| 4    | 0.229  | 8.974 | 0.025 | 0.036 | 89.10 | 79.305 | 79.47 |
| 5    | 0.227  | 0.072 | 0.867 | 8.613 | 89.17 | 80.171 | 88.08 |
| 6    | 0.212  | 0.009 | 8.370 | 0.665 | 89.18 | 88.540 | 88.74 |
| 7    | 0.145  | 0.010 | 0.547 | 0.443 | 89.19 | 89.087 | 89.18 |
| 8    | 0.140  | 1.597 | 0.066 | 0.894 | 90.79 | 89.152 | 90.08 |
| 9    | 0.134  | 1.530 | 0.527 | 0.735 | 92.31 | 89.680 | 90.81 |
| 10   | 0.123  | 0.104 | 2.239 | 1.510 | 92.42 | 91.920 | 92.32 |
| 11   | 0.097  | 0.004 | 0.245 | 0.117 | 92.43 | 92.163 | 92.44 |
| 12   | 0.092  | 1.574 | 0.362 | 1.217 | 93.99 | 92.526 | 93.66 |
The discontinuity in the building at the area of the terrace garden also causes vertical geometric irregularity as defined in Table 5, page-18 of Indian standard. The results of the analysis indicate that the building fails in ductile detailing and the displacement of the building is beyond the acceptable limit under the seismic load case. In the present form and state, the building does not meet even the minimum code level of earthquake protection of “Collapse Prevention”. Hence, seismic retrofitting of the building is essential.

Table 5. | Roof displacements using natural time period (clause 7.11.1 of IS-1893 (2002)).

| Story | Point No. | Load Case (Max) | UX | UY | Response Reduction | Total Disp. in mm | Max Allowed in MM | Percentage Exceeded |
|-------|-----------|-----------------|----|----|--------------------|-------------------|-------------------|---------------------|
| Roof  | 17        | UDCON17 MAX     | 32.2781 | 4.284 | 3 | 97.68 | 57.6 | 69.59 |
| Roof  | 18        | UDCON17 MAX     | 32.258 | 3.9438 | 3 | 97.49 | 57.6 | 69.26 |
| Roof  | 59        | UDCON17 MAX     | 32.1485 | 4.2702 | 3 | 97.29 | 57.6 | 68.91 |
| Roof  | 19        | UDCON17 MAX     | 32.2323 | 3.2906 | 3 | 97.20 | 57.6 | 68.75 |
| Roof  | 17        | UDCON19 MAX     | 32.0789 | 4.2964 | 3 | 97.10 | 57.6 | 68.57 |
| Roof  | 20        | UDCON17 MAX     | 32.2123 | 3.0307 | 3 | 97.06 | 57.6 | 68.51 |

Figure 2. Wire frame 3D model of the building.

Figure 3. Location of maximum roof displacement of the building.
On these grounds, a supplementary damping system has been designed for this building as its main lateral load resisting system. The seismic performance on the building with seismic dampers has been assessed using Time-History analysis using ETABs. The results of the analysis showed that the addition of dampers has reduced the story drift ratios and thus demand on reinforced concrete structural members significantly. A major portion of the earthquake energy is now being absorbed by the Fluid Viscous Damping Devices (FVDD), thus only a fraction of the seismic energy is now being transmitted to the structure. This also has reduced the stresses and floor accelerations in the building. There are total of 84 FVDDs in the perimeter frame of the building. The building envelope is 81 meters × 50 meters and contains Ground plus 3 floors. The addition of dampers has enhanced the seismic performance of the building structure to “Immediate Occupancy” for design level earthquake. Cracking is expected in the non-structural unreinforced masonry walls but to a much lesser extent as the FVDD limit the story drifts and floor accelerations.

8. “Immediate Occupancy” and “Collapse Prevention”

The draft ‘Indian Seismic Code IS-1893 – 2016’ released for public comments in February 2016 defines “Immediate Occupancy” and “Collapse Prevention” performance of buildings as follows;

8.1 ‘Immediate Occupancy’ Structural Performance Level

In this post-earthquake damage state, very limited structural damage has occurred. The basic vertical- and lateral-force-resisting systems of the building retain almost all of their pre-earthquake strength and stiffness. The risk of life-threatening injury as a result of structural damage is very low, and although some minor structural repairs might be appropriate, these repairs would generally not be required before re-occupancy.

8.2 ‘Life Safety’ Structural Performance Level

In this post-earthquake damage, a structure has damaged components but retains a margin against the onset of partial or total collapse. The damage has not resulted in large falling debris hazards, either inside or outside the building. Injuries might occur during the earthquake; however, the overall risk of life-threatening injury as a result of structural damage is expected to be low.

8.3 ‘Collapse Prevention’ Structural Performance Level

In this post-earthquake damage state, a structure has components damaged to an extent that it has no margin against collapse but it continues to support gravity loads. The building is on the verge of partial or total collapse. Substantial damage to the structure has occurred, potentially including significant degradation in the stiffness and strength of the lateral-force-resisting system and large permanent lateral deformation of the structure.

9. Structural Analysis of Building with FVDDs

To reduce demand on existing members, seismic dampers were included in the model. The viscous dampens were only added at the perimeter where reinforced concrete moment frames exist as shown in Figure 4. The seismic hazard at the site was based on the provisions of Indian Code. The unreduced 5% - damped acceleration response spectrum for the site is shown in Figure 5. Nonlinear time history analysis was conducted and three sets of ground motions were synthesized whose spectra closely matched the site spectrum as shown in the same in Figure 6.
10. Results of the Analysis and Discussion

The analysis was carried out with the objective that whether seismic dampers can be used to reduce the demand on structural members and to enhance the performance of the building to immediate occupancy for the design level earthquake. Nonlinear time history analysis was conducted and the maximum responses for the three pairs of ground motions were processed. The addition of dampers results in significant reduction in story drift ratios (defined as relative story displacement divided by the story height) as indicated in Table 6.

The addition of dampers also results in approximately 20-25% reduction in the seismic base shear of building; as provided in Table 7. Given the building weight of approximately 183,000 kN, The unreduced (R, Q=1) damped base shear is approximately 45% of the overall weight of the structure.

The overall reduction in responses is approximately 30-40% for displacement and 20-25% for base shears. A 30-40% reduction in response corresponds to an approximate effective damping ratio of 20%. The reduction in the responses is due to the significant energy dissipated by the seismic dampers. Such energy dissipation reduces the earthquake demand on and protects the existing concrete elements. In Figure 7, the red line shows the total seismic energy whereas the blue line shows the energy absorbed by the dampers. Thus, a majority of the energy is being absorbed by the dampers so as to keep the structural members protected. The properties of dampers, as suggested, are provided in the following Table 8. The damper driver brace, gusset plates, damper attachments, and details for the damper connection are presented in the following Figure 8.

Table 6. Storey drift ratio.

| Level  | Damped X | Damped Y |
|--------|----------|----------|
| Roof   | 0.33%    | 0.41%    |
| Third  | 0.53%    | 0.57%    |
| Second | 0.76%    | 0.79%    |
| First  | 0.86%    | 0.85%    |
| Ground | 0.74%    | 0.67%    |

Table 7. Computed base shear (without and with dampers).

| Base Shear Case | Direction X | Direction Y |
|----------------|-------------|-------------|
| Existing       | 103,200     | 104,700     |
| Damped         | 76,200      | 89,800      |

Table 8. Damper properties.

| Damper Numbers | 84         |
| Damping Coefficient, C | 770         |
| Alpha (velocity exponent) | 0.3         |
| Displacement     | 0.05       |
| Force Capacity   | 750        |
11. Conclusion

Seismic dampers were added to the building perimeter frames. Nonlinear response history analysis was conducted and showed significant reduction in the story drifts and base shear when the building was subjected to design level earthquakes. It is anticipated that the structure with added viscous dampers, will meet its enhanced performance objective of Immediate Occupancy (IO) at the design earthquake.

12. References

1. National Building Code of Canada by National Research Council of Canada (NRC), Ottawa: Ontario. NBCC, 1995
2. Huang Y, Wada A, Iwata M, Mahin SA, Connor JJ. Design of Damage Controlled Structures in Innovative Approaches to Earthquake Engineering. WIT Press, Ashurst, UK, 2001.
3. FEMA. Techniques for the Seismic Rehabilitation of Existing Buildings, 2006. Date accessed: 21/11/2016. Available at: https://www.fema.gov/media-library-data/20130726-1554-20490-7382/fema547.pdf.
4. Annadurai A, Ravichandran A. Flexural Behavior of Hybrid Fiber Reinforced High Strength Concrete, Indian Journal of Science and Technology. 2016 Jan; 9(1):1–5.
5. Priyadharshini E, Veerakumar R, Selvamani P, Kaveri S. An Experimental Study on Strengthening of Reinforced Concrete Beam using Glass Fiber Reinforced Polymer Composites, Indian Journal of Science and Technology. 2016 Jan; 9(2):1–4.
6. Hosseini M, Ashrafi HR, Beiranvand P, Ghanbari B. Nonlinear Analysis of Torsion in Reinforced Concrete Members after Developing Initial Crack, Indian Journal of Science and Technology. 2016 Feb; 9(7):1–17.
7. IS: 15988. Seismic Evaluation and Strengthening of Existing Reinforced Building – Guidelines, Bureau of Indian Standard, New Delhi, 2013.
8. IS: 1904. Code of Practice for Design and Construction of Foundations in Soils: General Requirements, Bureau of Indian Standard, New Delhi, 1986.
9. IS: 1893. Criteria for Earthquake Resistant Design of Structures, Part 1: General Provisions and Buildings (Fifth Revision), Bureau of Indian Standard, New Delhi, 2002.
10. IS: 875 – Part 1. Code of Practice for Design Loads (Other Than Earthquake) For Buildings and Structures. Part 1: Dead Loads, Bureau of Indian Standard, New Delhi, 1987.
11. IS: 875 – Part II. Code of Practice for Design Loads (Other Than Earthquake) for Buildings and Structures. Part 2: Imposed Loads, Bureau of Indian Standard, New Delhi, 1987.
12. IS: 13920. Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces, Bureau of Indian Standard, New Delhi, 1993.
13. IS: 456. Plain and Reinforced Concrete, Bureau of Indian standard, New Delhi, 2000.
14. SP 34. Handbook on Concrete Reinforcement and Detailing, Bureau of Indian Standard, New Delhi, 1987. Date accessed: 1/12/2016. Available at: https://law.resource.org/pub/in/bis/S03/is.sp.34.1987.pdf.