Effect of Design and Detailing Deficiencies on Seismic Performance and Vulnerability of Indian RC Frame Buildings

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SUMMARY:
The design, detailing and construction practices in India vary from “complete absence of seismic resistance provisions” to “the state-of-art practice”. However, most of the reinforced concrete (RC) buildings fall in the category of inadequately designed and detailed buildings which have one or more types of deficiencies. To determine the prevailing design, detailing and construction practices in India, a survey of multi-storey RC buildings in a model township within the national capital region is performed. Common irregularities and deficiencies in Indian construction and the major issues related to design and detailing of RC buildings are identified. Seismic performance and vulnerability of RC frame buildings with the most common design and detailing deficiencies are estimated. It is shown that buildings designed for gravity load alone have some overstrength and can withstand earthquakes of moderate intensity, provided these are detailed and constructed properly.

Keywords: Reinforced Concrete, Multistorey Buildings, Seismic Deficiencies, Vulnerability

1. INTRODUCTION

Due to rapid increase in demand of residential and commercial buildings in India, there is a steep increase in land prices, which is leading to compulsory usage of maximum land and giving birth to irregular shapes of multistorey buildings. Further, in Indian multi-storey buildings, parking is a major problem. Professional consultants/ architects find an easy solution for parking by providing open ground storey; however, the other storeys of these multistorey buildings are infilled with masonry panels. Other problems are typically the re-entrant corners to provide ventilation in these buildings, insufficient seismic gap between two building blocks and asymmetric distribution of mass, stiffness and strength creating torsion irregularity. Along with these configurational deficiencies, there are a lot of design, detailing and constructional deficiencies.

To have an overview of the prevailing design and construction practices in India, a survey of multistory buildings was conducted in the New Okhla Industrial Development Authority (NOIDA) Township in the national capital region (NCR). NOIDA is one of the fastest growing cities of the world and the largest existing planned industrial township of Asia. About 50 randomly selected multistoried RC frame buildings have been surveyed. The survey was based on visual inspection using a questionnaire. In some cases, access was available to structural drawings, but in most of the cases, structural configuration was plotted at site and typical member sizes were measured. It has been found that most of these building lacks and even voilets the basic seismic resistant provisions. It was found that the surveyed buildings do not have one but a combination of several deficiencies. Simplified Vulnerability Assessment (SVA) of buildings was conducted as per the procedure of FEMA-310 (1998). The observed deficiencies have been broadly classified into two groups, ‘Configurational’ deficiencies and ‘Design and Detailing’ deficiencies. The detail of common deficiencies observed during survey has been discussed in the paper. The seismic performance and vulnerability of RC buildings with the most common design and detailing deficiencies have been estimated.

2. COMMON CONFIGURATIONAL DEFICIENCIES OBSERVED AND THEIR IMPACT

These deficiencies arise due to improper planning of buildings. Mainly architects/consultants are responsible for this type of deficiencies. Following configurational deficiencies have been observed in multistorey buildings in NOIDA.

2.1. Plan Irregularities

To provide good natural light and ventilation and to have a good outside view from all the rooms, the architects develop very complex plan shapes with re-entrant corners, floor slab cut-outs, and asymmetry as shown in Fig. 2.1. These irregularities are acceptable to limited extent, but require special consideration in analysis and design, which is generally never made. In case of RC buildings, not only the plan should be of regular shape, the arrangement of lateral load resisting vertical elements should also be symmetric. During investigation of collapsed or severely damaged building, it has been observed the causes of damage are directly or indirectly related to the irregularities developed during architectural design (Tezcan et al. 2001). To quantify the plan irregularity of buildings, limits on re-entant corners and torsion irregularity has been considered.

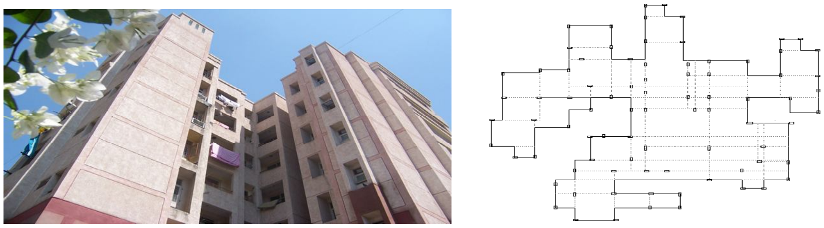


Figure 2.1. A typical elevation and plan of a multistory building in NOIDA

2.1.1. Re-entrant corners

Many buildings during survey were found to have irregular plans. Based on IS 1893 Part-1 (2002), buildings having projection less than 15% of its plan dimension has been considered safe, buildings having projection between 15% to 20% has been considered deficient and the buildings having projection more than 20% have been considered highly deficient. Expected building damage due to re-entrant cornerd can be seen from Fig. 2.2. Only 26% buildings were found to be safe for re-entrant corners, 30% buildings belong to the deficient category and 44% belongs to highly deficient category.

2.1.2. Torsion irregularity

Accurate calculation of torsion irregularity in a building is very difficult task, as it requires dimensions of structural members, such as columns and beams and non structural members such as masonry walls. An existing building in NOIDA with acute plan irregularity is shown in Fig. 2.3. To calculate torsion irregularity in surveyed buildings, formulae given by Otani (2000) have been used. Torsion irregularity has been determined only for ground floor, as the other floors are also generally similar, and access to the upper floors was not available. Since in most of the buildings, ground floor was open and no infill wall was present, only stiffness of columns and lift core shear wall has been considered. Calculation of center of mass and center of rigidity is based on conventional method. Accidental eccentricity of 5% of respective plan dimension has been added to actual eccentricity. Elastic radius of stiffness in longitudinal direction (r_{ex}) has been calculated based on following formula:

$$r_{ex} = \sqrt{\frac{\sum (K_x y^2) + \sum (K_y x^2)}{\sum K_y}} \tag{2.1}$$

Where K_x and K_y are stiffness of a column in longitudinal and transverse direction, and x and y are the distances of the column from longitudinal and transverse axis.

Similarly, elastic radius of stiffness in transverse direction (r_{ex}) has been calculated. Eccentricity ratio in each direction has been determined as ratio of total eccentricity to elastic radius of stiffness in corresponding direction.

Buildings are considered safe for torsion irregularity in a direction if the eccentricity ratio is less than 0.15, deficient if the eccentricity ratio is between 0.15 to 0.3 and highly deficient if eccentricity ratio is more than 0.3. As shown in Figs. 2.4 and 2.5, survey reveled that independently 57% buildings are safe in longitudinal direction and 65% buildings are safe in transverse direction. But while considering the torsion irregularity in both directions simultaneously, only 38% buildings are safe in both the directions. 17% buildings were found to be highly deficient in longitudinal direction but no building was found highly deficient in transverse direction.

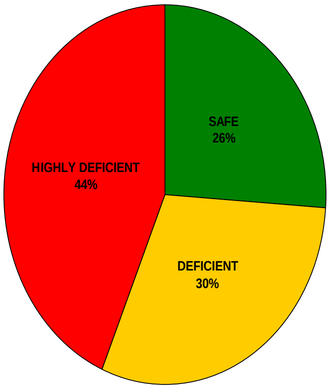


Figure 2.2. Expected building damage due to re-entrant corners

Figure 2.3. An existing building with acute plan irregularity

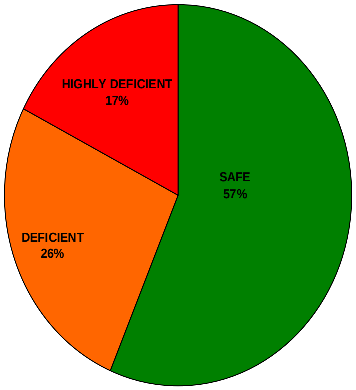


Figure 2.4. Torsion Irregularity (Longitudinal direction)

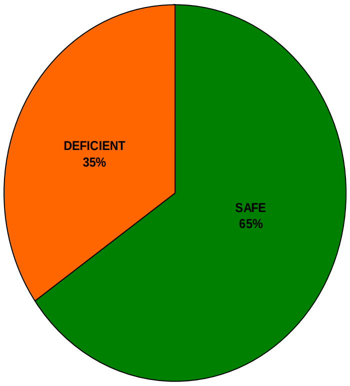


Figure 2.5. Torsion Irregularity (Transverse direction)

2.2. Elevation Irregularities

Architects quest for innovative elevations results in many vertical irregularities with drastically varying plans at different floors and connecting bridges between different buildings. Drastic changes in configuration along height results in concentration of stresses and hence irregularly distributed damage. It is very difficult to simulate behaviour of such buildings to predict their seismic performance, but one thing is certain about these buildings that their seismic performance is going to be hampered as compared to regular buildings.

2.2.1. Open ground story

The soft-weak open ground storey (OGS) buildings are not a country specific problem, but widespread through out the globe. Among all the buildings damaged /collapsed due to earthquake world over, the OGS buildings hold a major share. Severe damage and collapse of these kind of buildings has been observed in San Fernando earthquake (US), Dinar, Koaeli and Bingol earthquake (Turkey), Bam earthquake (Iran), Athens earthquake (Greece), Nigata chuestsu-Oki earthquake (Japan), Chi-Chi earthquake (Taiwan), Bhuj earthquake (India) and many more (Penelis 1997, Inel et al. 2008, Wallace 1999, Dogangun 2004, Sezen et al 2003., Naeim e. al 2000., MCEER 2000).

In India, the result of keeping open ground storey was observed during Bhuj earthquake. About 130 OGS buildings around epicenteral region as well as at a distance of few hundred kilometers collapsed.

In the buildings which did not collapse, the damage was confined mostly to OGS columns with nominal frame infill separation in the upper stories (EERI 2002).
From survey it was found that 95% buildings have soft ground storey, and in these buildings no shear wall other than lift core was found. Apparently, from dimensions of structural members and drawings of few building to which access was available, it was observed that codal provisions for designing ground storey columns for 2.5 times the normal base shear has not been followed. Interestingly these buildings have been constructed within last 4-5 years, after publication of recent revised seismic code in 2002.

2.2.2. Seismic pounding

Substantial damage to RC frame building has been observed during moderate to strong shaking of past earthquakes. In Mexico earthquake of 1985, out of 330 severely damaged buildings, pounding was present in about 132 buildings (Rosenbluth 1986). Widespread damage due to pounding was reported during 1989 Loma Prieta earthquake, post earthquake survey revealed 200 pounding occurrence involving more than 500 buildings (Kasai 1997). Pounding was observed in other earthquakes such as 1988 Sequenay earthquake in Canada, 1994 Northridge earthquake, 1995 Kobe earthquake and 1999 Kocaeli earthquake (Raheem 2006) and also at some locations in Bhuj earthquake (Mistry et al. 2001).

During survey, it has been found that in many buildings separation between different blocks are too small to accommodate drift during earthquake. It is expected that these buildings may suffer severe pounding damage during earthquake. According to FEMA 310, a distance of at least 4% of building height from adjacent structure should be maintained for life safety. In most of the surveyed buildings, adjacent blocks were separated by very small gaps, perhaps, considering only thermal expansion. In most of the buildings, different blocks were having matching floor levels, but in some cases height of blocks were different. The of drift ratio has been calculation as,

$$Drift\ \ Ratio = \left(\frac{\left(\frac{I}{L}\right)_{Col} + \left(\frac{I}{L}\right)_{Beam}}{\left(\frac{I}{L}\right)_{Col} X \left(\frac{I}{L}\right)_{Beam}} \right) \left(\frac{h}{12\,E}\right) V_{col} \qquad (2.2)$$

Where “h” is storey height, “I” is moment of inertia, “L” is center to center length of column, “E” is modulus of elasticity and “V_{col}” is shear in column.
This equation does not consider the effect of infill and shear walls. In the analysis, it is assumed that during strong shaking, infills will crack/collapse making the frame bare. From analysis, as shown in Fig. 2.6, it is found that 56% of surveyed building may get affected due to pounding.

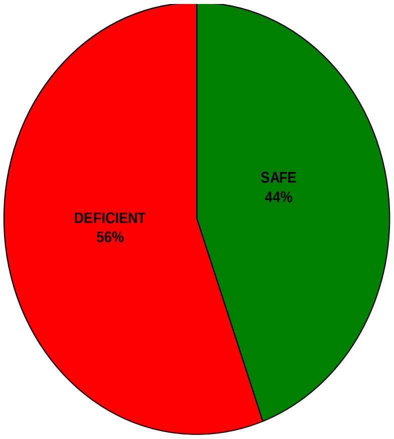


Figure 2.6. Expected Building damage due to seismic pounding

3. DESIGN AND DETAILING DEFICIENCIES

Mainly, structural engineers/designers are responsible for these kinds of deficiencies. The common deficiencies cropping up due to faulty design has been discussed in this section.

3.1. Frame Irregularities

The seismic performance of a frame building is based on the energy dissipation by flexural yielding of beams. Shear yielding of beams and yielding of columns is undesirable as it will result in brittle failure of the framing. A grid based framing configuration is necessary for this purpose. However, irregular framing, resulting in beam to beam connections is very common in Indian multistory residential buildings. It is not possible to ensure flexural yielding of beams in such cases and failures during past earthquakes have been reported. From the survey it was found that most of the buildings were having irregular frames, however, its impact on seismic performance has not been studied.

3.2. Inadequate lateral strength

Internationally, only the buildings which have been designed before enforcement of seismic codes fall in this category, but in case of India and other third world countries, many buildings are still being designed for gravity loads only, without any consideration for earthquake forces. During Bhuj earthquake, many buildings of this category collapsed. Similar behaviour has been observed during Kocaeli earthquake, Athens earthquake, and Dinar earthquake.

Based on FEMA 310, strength deficiency has been calculated for shear and overturning. Shear stress in ground storey column ($V_{average}$) for life safety has been checked by using following formula:

$$V_{average} = \frac{1}{2}\left(\frac{N_{tc}}{N_{tc} - N_f}\right)\left(\frac{V_B}{A_C}\right) \tag{3.1}$$

Where "N_{tc}" is total number of columns, "N_f" is total number of frames in the direction of loading, "V_B" is base shear considering response reduction factor as 1 and "A_c" is summation of the cross sectional area of all columns in ground storey.

Buildings having $V_{average}$ less than 0.15√fck have been considered to be safe, buildings having $V_{average}$ between 0.15√fck to 0.225√fck are considered deficient and building falls in highly deficient category if $V_{average}$ is more than 0.225√fck. As shown in Fig. 3.1, only 22% buildings were found to be safe for shear stress in ground storey columns, 39% were found deficient and another 39% were found to be highly deficient.

Safety against overturning has been calculated based on axial stress of columns subjected to overturning force. Following formula of FEMA 310 for life safety has been used to calculate safety against overturning:

$$P_{ot} = \frac{1}{3}\left(\frac{V_B\, h_t}{L\, N_f}\right) \tag{3.2}$$

Where "V_B" is base shear, "h_t" is total height of building from base to roof, "L" is total length of frame in the considered direction, and "N_f" is total number of frames in the direction of loading.

Buildings having P_{ot} less than 0.24fck have been considered safe whereas, between 0.24fck to 0.36fck have been considered deficient. If P_{ot} is more than 0.36fck, buildings fall in highly deficient category. From survey, it has been found that only 30% of buildings are safe against overturning, 44% buildings fall in deficient category and 26% buildings in highly deficient category (Fig. 3.2).

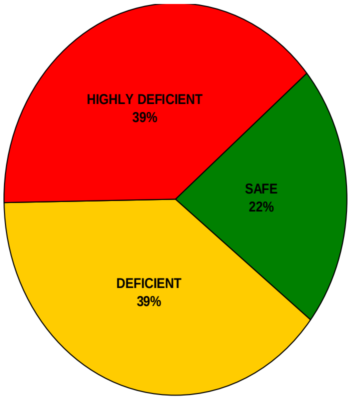


Figure 3.1. Expected building damage due to shear deficiency in ground storey columns

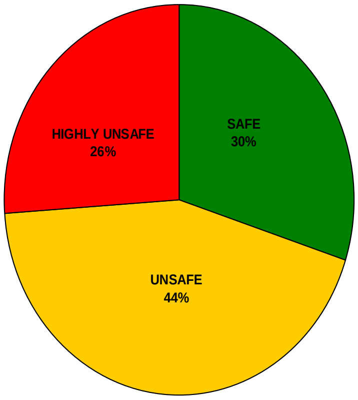


Figure 3.2. Expected Building damage due to overturning

3.3. Inadequate detailing

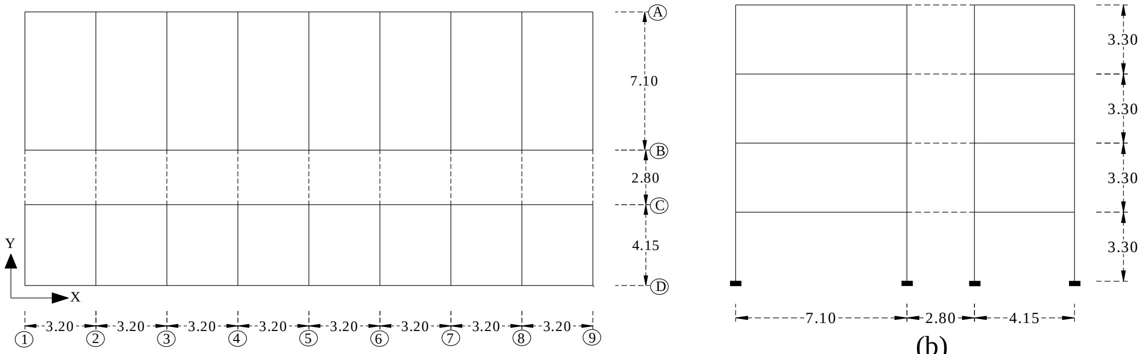
Inadequate detailing has been another important cause of failure of RC buildings, during past earthquakes. Common deficiencies, generally observed during survey are, inadequate anchorage at beam ends of exterior joints, inadequate shear and confining reinforcement in columns, faulty anchorage (90° hooks) of stirrups, inadequate shear reinforcement in shear walls, Inadequate detailing at slab-shear wall junction and inadequate confinement at splicing.
The compliance to detailing code in practice has been reviewed by observing the member dimensions in existing buildings and inspection of ongoing construction in new buildings. During the survey, improper spacing and anchorage (with 90° bend) of stirrups (Fig. 3.3) has been observed at many construction sites.

(a) (b)

Figure 3.3. Faulty reinforcement detailing practice, (a) 90° hooks, (b) Improper and inadequate confining stirrups in columns

4. EFFECT OF DESIGN DEFICIENCY ON SEISMIC PERFORMANCE AND VULNERABUILY

In the present study, behaviour of a four storey building with plan as shown in Fig. 4.1 and designed for gravity load only has been estimated and compared with the behaviour of the buildings designed for seismic hazard level corresponding to Zone V of IS:1893. The former have been referred to as 'GLD' buildings and the latter as 'ERD' buildings. The yield moment of the beams in the potential plastic hinge regions has been computed by section analysis using Mander's model for confined concrete (Mander et al., 1988). The member rotation capacity and performance acceptance criteria as per ASCE 41 have been used. Nonlinear Static Pushover (NSP) analysis has been used. Performance has been estimated using displacement modification method in terms of PGA which the building can sustain at Life Safety performance level (LS) and Collapse Prevention performance level (CP).



(a) (b)

Figure 4.1. (a) Plan of the building (b) Side elevation of four storey building

It has been observed that there is a significant difference in yield base shear and ultimate displacement capacity of GLD and ERD buildings. Yield base shear of GLD and ERD building in longitudinal direction was 650 kN and 2650 kN respectively, wheras in transverse direction 1050 kN and 2800 kN respectively, (Figs. 4.2 and 4.3). The yield base shear of ERD building is 4 times of the GLD building in longitudinal direction, while, in transverse direction the yield base shear of ERD building is only 2.6 of times the GLD building. It is generally expected that the GLD buildings will have a little resistance to the lateral load. However, in contrast to the general expectation, it was found that for a PGA of 0.24g the four storey building has ‘Life Safety’ performance and it performs without Collapse for PGA of 0.36g. This indicates that the four storey building designed even for the gravity load has sufficient overstrength to avoid collapse in MCE corresponding to the most severe seismic zone (Seismic Zone V with PGA for MCE = 0.36g). (It is to be noted that, the GLD building under consideration has been assumed to have conforming ductility provisions. It is a hypothetical case as the GLD buildings generally do not conform to the ductility provisions. In present study, this case has been considered to highlight the relative importance of strength and ductility deficiencies. As will be shown later, the GLD buildings with deficient detailing have poor performance even under moderate shaking.) In four storey building the base shear and overturning moment due to earthquake is relatively small and is taken care of by the available overstrength.

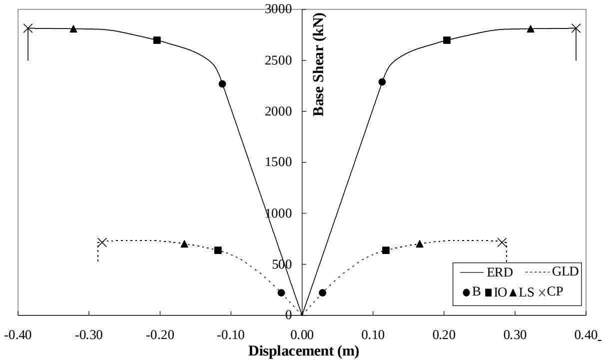


Figure 4.2. Capacity curves in longitudinal direction of the four storey building

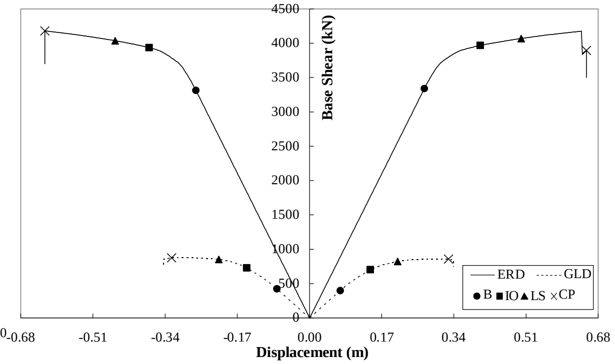


Figure 4.3. Capacity curves in transverse direction of the four storey building

The fragility of the building has also been determined in both the directions. Four damage states have been identified, but the fragility curves have been presented only for ‘Extensive’ and ‘Complete’ damage states. To develop the fragility curves, various Damage-State Beta’s have been taken from HAZUS-MH. The fragility curves for extensive damage are shown in Fig. 4.4. From the Figure it can be observed that, the fragility curves of four storey GLD and ERD buildings are close to each other indicating a lesser variation of damage at a given spectral displacement. Similar observations are also made for fragility curves for complete damage shown in Fig. 4.5.

5. EFFECT OF DETAILING DEFICIENCY ON SEISMIC PERFORMANCE AND VULNERABUILY

To estimate the effect of detailing on building performance, a four storey building has been designed for earthquake forces as per IS:1893 and three detailing cases have been considered. In first case the building has been made to satisfy strong column-weak beam (SCWB) criteria along with conforming detailing (C-SCWB) (similar to SMRF as per ACI 318). In the second case, the building has conforming detailing but no attempt has been made to make the columns stronger than beams. This design is equivalent to IMRF as per ACI 318. In the third case, the building has nonconforming detailing (OMRF). The hinge properties have been calculated and the rotational capacities for Conforming and Nonconforming detailing have been assigned as per ASCE 41.

The capacity curves for the buildings with three types of detailing are shown in Figs. 5.1 (a) and 5.1(b)

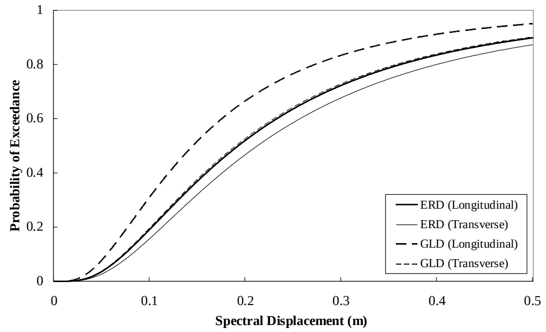


Figure 4.4. Fragility curves for extensive damage

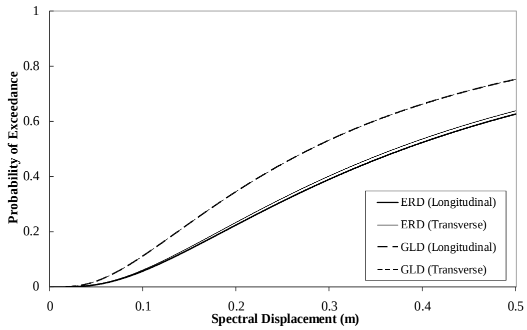
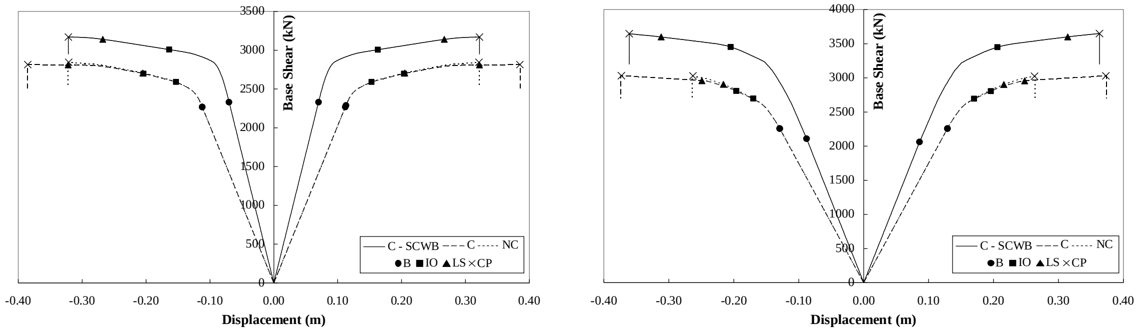


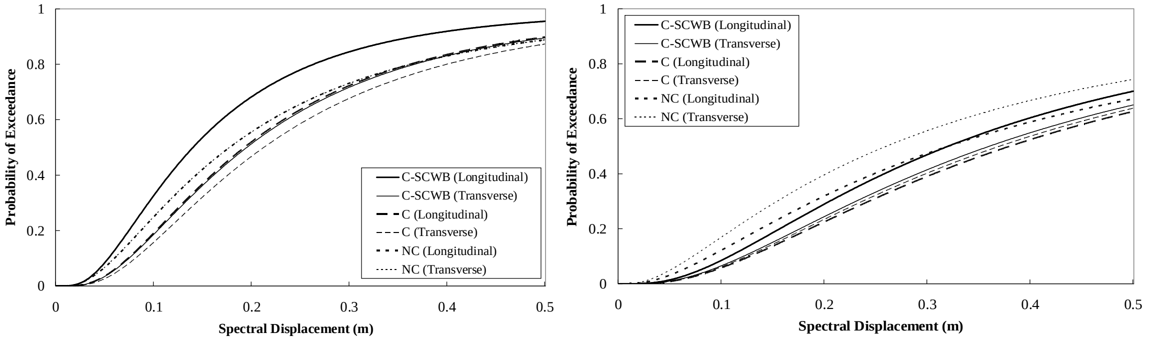
Figure 4.5. Fragility curves for complete damage

in longitudinal and transverse directions, respectively. It can be seen from capacity curves that the initial stiffness for C-SCWB building is higher than the other cases. This is because the sizes of few of the columns were increased to achieve strong column-weak beam behaviour. The fragility curves for three detailing types have been developed using Damage-State Beta's from HAZUS-MH. Fragility curves for extensive damage and complete damage are shown in Fig. 5.2 (a) and 5.2 (b), respectively.



(a) (b)

Figure 5.1. Capacity curves in (a) longitudinal (b) transverse direction of the four storey building designed for combined action of gravity and earthquake loads



(a) (b)

Figure 5.2. Fragility curves for (a) extensive (b) combined damage level designed for gravity and earthquake loads but with different ductility class

6. CONCLUSION

A survey of multistorey buildings in NOIDA, a model township in the National Capital Region, has been conducted to identify potential seismic deficiencies. As the access to building drawings and structural design details was not available, the observations are based on visual survey. A simplified vulnerability assessment has been conducted using the dimensions and plans measured during the visual inspection. Fragility functions have been obtained based on the general construction trends in India. Following are the major conclusions of the study:

1. Severe configurational deficiencies have been observed in the multistorey buildings in NOIDA. These include (i) Plan irregularities with excessive torsion and re-entrant corners, (ii) Irregular elevations with sharp variations in structural system along height and improper connection of different parts of buildings, (iii) Open ground storey for parking, (iv) Irregular framing system, (v) Inadequate separation between adjacent buildings or blocks of buildings.
2. Quest for ventilation and good outside view from each room has resulted in highly irregular planforms. Only 26% buildings were found to be safe for re-entrant corners, 30% buildings belong to the deficient category and 44% belong to highly deficient category.
3. Torsion in the surveyed multistorey buildings has been found to be another cause of concern. It has been observed that considering torsion independently in each direction, only 57% buildings are safe in longitudinal direction and 65% buildings are safe in transverse direction. Only 38% buildings are safe in both the directions. 26% and 35% buildings were found to be deficient in longitudinal and transverse directions, respectively. 17% buildings were found to be highly deficient in longitudinal direction.
4. Provision of parking space in multistorey buildings is the most important issue resulting in severe strength and stiffness irregularity. In 95% of the surveyed buildings, the ground storey was kept open for parking resulting in extreme soft and extreme weak ground storey. Performance of such buildings during past earthquakes has been particularly poor, resulting in collapse of ground storey. IS code has recommended design of such buildings for 2.5 times the design base shear for normal buildings. However, this provision is seldom followed. Architects quest for innovative elevations worsens the situation further, as in many cases taller (some times double storey height) columns are used for open ground storey.
5. Inadequate separation between adjacent blocks is another common deficiency observed in multistorey buildings in NOIDA. It is expected to result in severe damage due to seismic pounding. In the survey it is found that 56% of surveyed building may get affected due to pounding.
6. Irregular framing is the most serious cause on concern in NOIDA buildings. This configuration results in irregular placement of columns and beam to beam joints. The current code philosophy of earthquake resistant design is based on the assumption of adequate energy dissipation through flexural yielding of beams with intact columns. However, in such buildings, the failure mechanism are going to be quite unpredictable and therefore, the current codal guidelines are not applicable to such buildings.
7. Lack of adequate strength of structural system has been observed in the Simplified Vulnerability Assessment (SVA), as per FEMA-310. Only 22% buildings were found to be safe for shear stress in ground storey columns, 39% were found to be deficient and another 39% were found to be highly deficient. Further, it has been found that only 30% of buildings are safe against overturning, 44% buildings fall in deficient category and 26% buildings in highly deficient category for safety against overturning.
8. Under the combined effect of shear and overturning, it was found that only 21% buildings that are safe in shear are also safe in overturning. 17% of buildings are found to be highly unsafe in both shear and overturning.
9. The four storey GLD building has significant overstrength, as it shows Life Safety performance for MCE level earthquake in Zone IV (PGA = 0.24g) and can withstand MCE level earthquake in Zone V (PGA = 0.36g) without Collapse.
10. The building with strong column-weak beam design and conforming detailing has an increased stiffness due to increase in column sizes, but the ultimate displacement remains almost same as in case of building with conforming detailing without strong column-weak beam design. The building with nonconforming detailing has the same stiffness and strength as the building with conforming detailing but a reduced ultimate displacement capacity.
11. At given spectral displacement, the fragility curves in longitudinal direction of the building with conforming detailing and strong column-weak beam exhibit a higher damage probability as compared to the building without strong column-weak beam design. This shows the limitation of the

chosen criteria for defining damage state thresholds. On the other hand, the building with conforming detailing shows a clear improvement in damageability from the building with nonconforming detailing.

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