ESTIMATION OF CAPACITY CURVE PARAMETERS FOR INDIAN RC BUILDINGS WITH URM INFILLS

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SUMMARY:
Failure of Un-Reinforced Masonry infilled Reinforced Concrete frame buildings during Bhuj earthquake highlighted the need for vulnerability assessment of existing stock of such buildings in India. In order to get reliable estimation of capacity curve parameters, governed by local materials and construction practices, infilled RC frame buildings surveyed during a pilot survey in the National Capital Region, are classified depending on the number of storeys, roof/floor system, design force level, and detailing of reinforcement. Thereafter, parametric study is carried out considering all possible failure modes of infill panels and surrounding frame members. Infill panels are represented by concentric diagonal struts with stiffness as defined in ASCE-41 (2007) and strength obtained from the weakest failure mode. Non-linear static analysis is performed to obtain the capacity spectrum parameters. These parameters have been implemented in the spreadsheet-based seismic risk assessment tool 'SeisVARA'.

Keywords: URM infills, RC frame, Non-linear analysis, Capacity curve parameters, Model Building Types

1. INTRODUCTION

Un-Reinforced Masonry (URM) infilled Reinforced Concrete (RC) frame is the most popular structural system for modern multistory buildings in India, like many other countries of the world. The wide spread failure of such buildings and consequent extensive physical and social losses, particularly during the 2001 Bhuj earthquake, the first large earthquake in an urban area of India, highlighted the need for vulnerability assessment of the existing stock of such buildings in India. In order to develop effective policies for mitigation against future earthquakes, reliable estimation of capacity curve parameters is required. Estimation of capacity curve parameters for RC frame structure with URM infills in India is a challenging task. Most of these buildings are not designed for earthquake load at all. Sometimes earthquake forces are considered in analysis but construction and detailing do not comply with specifications of the standards. Further, Inadequate guidelines for design of such buildings have resulted in a huge stock of seismically deficient buildings throughout India.

With the view to develop analytical capacity curve parameters for reliable estimation of vulnerability functions for URM infilled RC frame buildings in India, a parametric study has been carried out for representative URM infilled Model Building Types (MBTs) selected from the database of a pilot survey in the National Capital Region of India (DEQ 2009), considering all parameters affecting seismic response of the structure. All possible failure modes of infill panels and surrounding frame members also have been considered for this purpose.

2. SELECTION OF REPRESENTATIVE BUILDINGS FOR PARAMETRIC STUDY

For reliable estimation of capacity curve parameters, the ideal way is to carry out nonlinear analysis of each and every building of the URM infilled RC building class and generate the statistical data to evaluate median and standard deviation to counter the uncertainty in capacity. Since it is numerically tedious and a time expensive way for dealing with large number of existing building stock, it is not practically feasible. To encompass the wide spectrum of Indian infilled RC frame buildings, a scheme has been adopted in the present study. According to the scheme, the infilled RC frame buildings surveyed during a pilot survey in the New Okhla Industrial Development Authority (NOIDA), a model township in the National Capital Region (NCR).(DEQ 2009), have been classified depending on the framing system, design seismic force levels, detailing of reinforcement and height of buildings. Existing URM infilled RC buildings are categorized in eight Model Building Types (MBTs) as shown in Table 2.1. In old construction and even in some of new constructions, appropriate seismic design forces levels have not been considered, therefore building designed for gravity loads only are also considered. Based on height, buildings are classified as low-rise for 1-3 stories, mid-rise from 4-7, and high-rise for buildings having eight or more stories. As far as detailing of reinforcements is concerned, buildings are classified either as detailing of reinforcement and execution not as per earthquake resistant guidelines or as detailed and executed as per earthquake resistant guidelines of relevant Indian Standards. The present study is limited to solid uniform infills only. It is well known (Asteris et al. 2011; Kaushik et al. 2006; EISeify et al. 2006) that presence of openings affects the stiffness and strength of infills, significantly and the same will be considered in future study.

Table 2.1. Description of Indian Model RC building types with URM infills

S. No.	Design and detailing description of Indian RC buildings with URM infills	Stories
1	Buildings designed for gravity loads as per relevant Indian Standards, without any consideration for earthquake forces as per provisions of BIS (1993); (BIS 2002)	1-3
2		4-7
3	Buildings in which earthquake forces considered in design as per provisions of BIS (2002)and detailing of reinforcement and execution are as per earthquake resistant guidelines of BIS (1993)for Ordinary Moment Resisting Frames (OMRF)	1-3
4		4-7
5		8+
6	Buildings designed, detailed and executed as per earthquake resistant guidelines of BIS (1993, 2002) for Special Moment Resisting Frames (SMRF)	1-3
7		4-7
8		8+

As NOIDA is a typical township representing the architectural, planning and construction features of housing stock of the country, and more specifically, representing multi-storey buildings of Urban India. The representative generic plan for the buildings considered in the study, as shown in Figure 2.1, is randomly selected from more than 50 multi-storey surveyed buildings. The considered plan is symmetric in both directions, but has significantly different redundancy in the two directions. Further, the spans of the beams in the two directions are also quite different, representing the characteristics of a wide range of real buildings in India.

A parametric study has been carried out on a set of multi-storey RC frame buildings with solid uniform infill panels, considering the generic building plan shown in Figure 2.1 for mid-rise and high-rise buildings. The thickness of solid infill panels are considered as 115*mm* and 230*mm* for interior and exterior partitions, respectively, as per the prevailing practice in India. As there are large number of existing buildings designed only for gravity loads even in high seismic zones (III, IV and V), the present study considers both the set of mid and high-rise buildings designed for gravity loads only, considering relevant Indian Standards BIS (2000), BIS (1987 (Part 1)) and BIS (1987 (Part 2)). The two sets of buildings have been assumed to be situated on hard soil in seismic zone IV (Effective Peak Ground Acceleration, EPGA = 0.24*g* for Maximum Considered Earthquake, MCE).

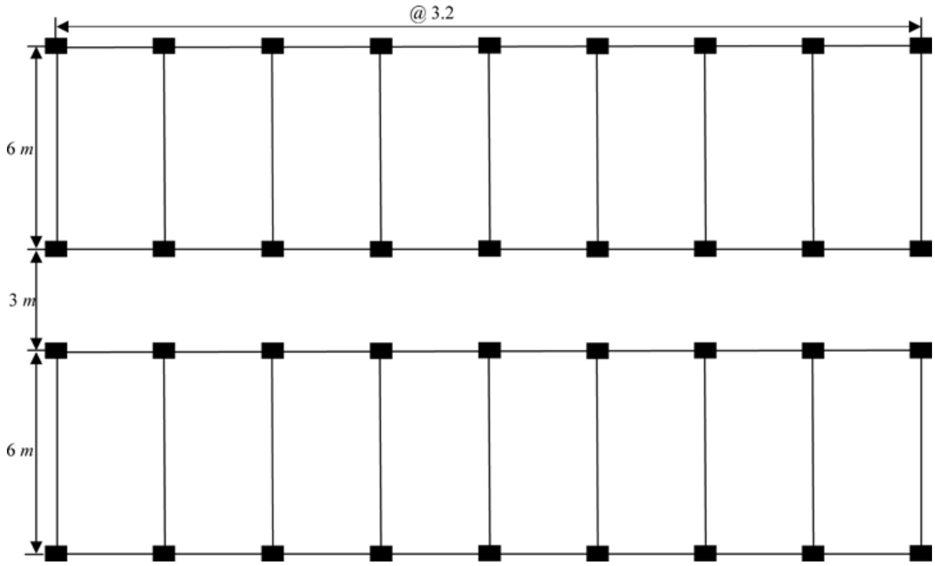


Figure 2.1. Plan of the generic buildings

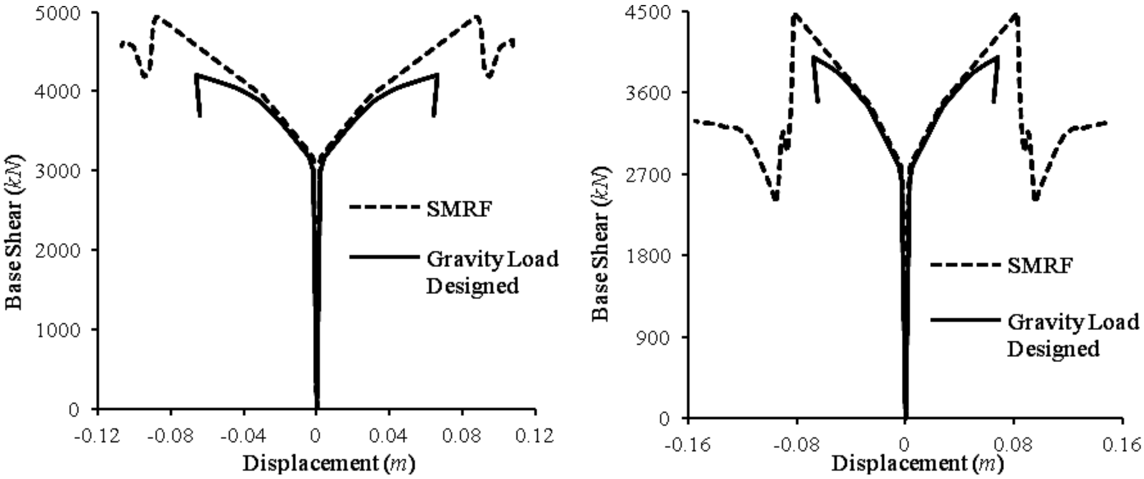
3. ANALYTICAL MODELING OF URM INFILLED RC FRAME BUILDINGS

Three dimensional space frame model of the buildings have been developed using structural analysis program SAP2000 Nonlinear (SAP2000 2010). Beams and columns have been modeled as 3D frame elements and an equivalent concentric diagonal compressive strut element has been used to simulate the infill panels. Traditionally, infill panels in framed buildings are provided after the frame is completed, at least for a few storeys. This sequential construction practice leads to improper contact between infill panels with the beam above; as a result no vertical load is transferred through infills. In order to simulate realistic behavior of infilled frame analytically, the effect of traditional Indian construction practice of infilled frame has been modeled in non-linear static pushover analysis. To simulate the effect of initial lack of fit between infield panel and beam above, 'gap' elements have been used. In presence of gap elements, the struts are active in compression only. Since the 'gap' element is active in nonlinear analysis only, the stiffness of the gap elements has been assigned in such a way that it will not affect the linear and nonlinear stiffness of the infilled frame.

In nonlinear analysis, in addition to the stiffness, strength of infill is also plays an important role to the overall performance of infilled frame under combined action of gravity and lateral loads. The strength properties of infills in different actions, including the nonlinear load-deformation curves, have also been modeled for each strut members. Strength of each strut member has been calculated based on the minimum strength considering all possible failure modes of infills observed in past earthquakes (compression failure, buckling and sliding shear failure of diagonal strut). The seismic performance of different buildings has been estimated using Nonlinear Static pushover analysis as per ASCE-41 (2007). Conforming, 'C' of transverse reinforcement has been considered for RC buildings with URM infills designed as SMRF to assign the plastic rotations for beams and columns as per ASCE-41 (2007). In analytical model, flexural (M) hinges have been assigned at both ends of beams, whereas axial force-moment interaction hinges (P-M-M) hinges have been assigned to columns. Axial plastic hinges have been assigned at mid-length of the equivalent diagonal struts simulating infills. The details of the analytical model of infilled frame can be found in Haldar and Singh (2012).

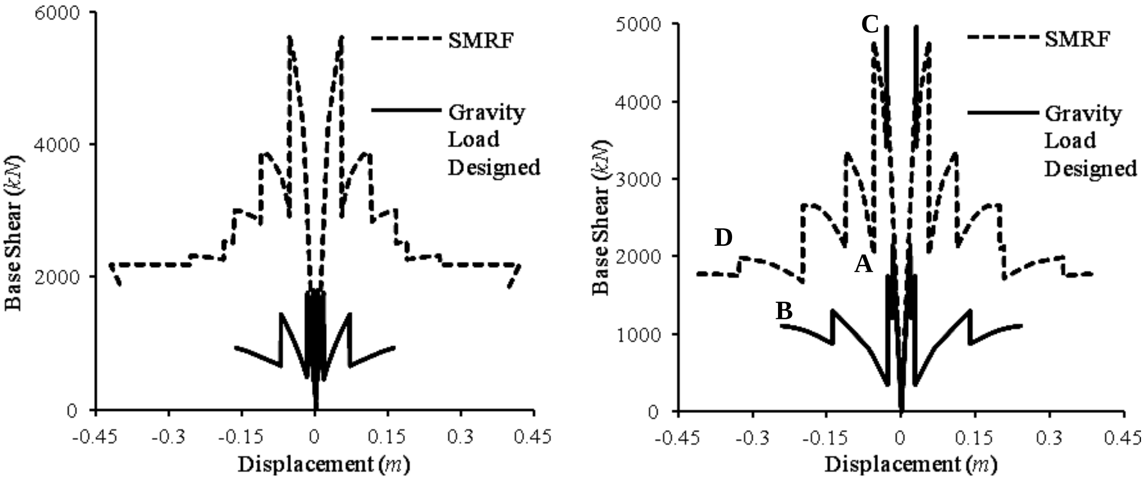
4. SEISMIC BEHAVIOUR AND CAPACITY CURVE PARAMETERS

Figure 4.1 and 4.2 show the comparison of capacity curves/pushover curves of mid-rise and high-rise uniformly infilled frames, respectively, designed for gravity loads only and as SMRF as per relevant Indian Standards. It can be observed from the Figure 4.1 that both gravity loads designed and SMRF mid-rise buildings yield at much lower lateral displacement with respect to the total lateral displacement, both in the longitudinal and transverse direction. This is because of failure of significant number of infills at very early stage. It can also be noted that there is little difference in yield strength of the two design levels because of the same member sizes in both the cases as strength is depended on the sizes of frame members and material strength. However, the ductility of SMRF building is larger than gravity loads designed buildings because of the ductile detailing of reinforcement.



(a) (b)

Figure 4.1. Comparison of capacity curves of mid-rise uniformly infilled RC frame buildings designed for gravity loads and as SMRF as per relevant Indian Standards in: (a) Longitudinal direction; (b) Transverse direction



(a) (b)

Figure 4.2. Comparison of capacity curve of high-rise uniformly infilled RC frame buildings designed for gravity loads and as SMRF as per relevant Indian Standards in: (a) Longitudinal direction; (b) Transverse direction

The effect of design level on the capacity curve is pronounced in case of high-rise buildings (Figure 4.2). Ultimate strength of SMRF building is 3.2 times higher and ultimate displacement is 2.6 times higher than gravity loads designed buildings.

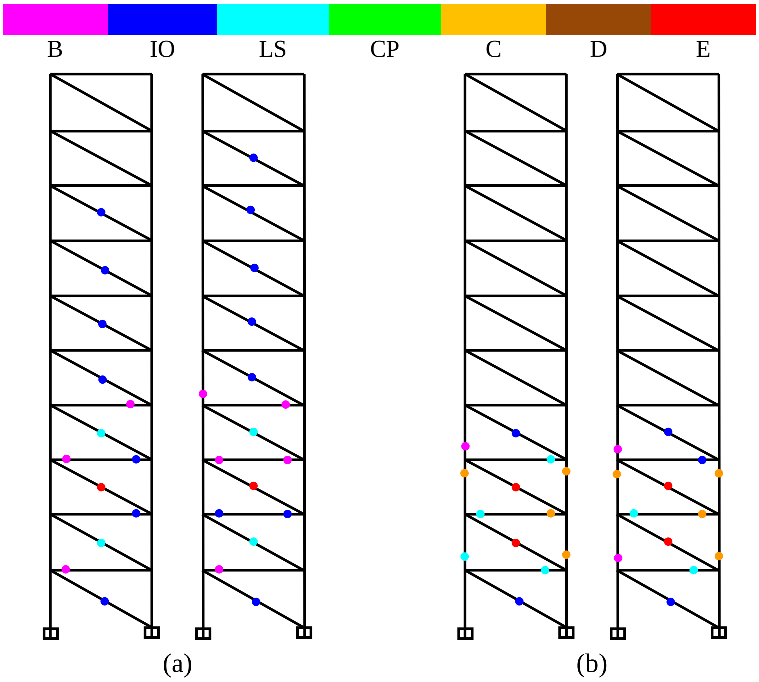


Figure 4.3. Hinge pattern of a typical frame in transverse direction of high-rise uniformly infilled RC frame buildings designed for gravity loads as per relevant Indian Standards at: (a) Peak; (b) Failure

Figure 4.3 shows the yield pattern of the infill panels and frame members of a typical frame in transverse direction of the high-rise gravity loads designed buildings under the combined action of gravity and lateral loading. Figure 4.3(a) shows the yield pattern at peak point marked as 'A' in Figure 4.2(b); and Figure 4.3(b) shows the yield pattern at failure marked as 'B' in Figure 4.2(b). Similarly, Figure 4.4(a) and (b) show the yield pattern of the infill panels in the high-rise buildings designed for earthquake loads at peak point marked as 'C' in Figure 4.2(a) and at failure marked 'B' in Figure 4.2(b), respectively. It can be observed from the Figure that all the infill panels except a very few and some of the beams at bottom storeys have yielded at point 'A' and crossed “Immediate Occupancy” (IO) performance level (ASCE-41 2007), whereas, in case of SMRF design, as shown in Figure 4.4 (a), no beam or column has yielded at peak point ('C'). Even after failure of a large number of infill panels, the RC frame members continue to resist lateral load until all columns of second storey in gravity load designed building (Figure 4.3(a)) have crossed “Collapse Prevention” (CP) performance level (ASCE-41 2007). Similar behavior is observed in case of SMRF designed buildings also, except that the yielding of columns occurred at much higher lateral displacement, due to relative increase in the size of frame members in case of buildings designed for earthquake forces. This observation is in agreement with the results of analytical and experimental studies reported by Kappos et al. (2006). The sharp saw-tooth pattern of capacity curves observed in Figure 4.2 is due to the sudden decrease in lateral strength with failure of a number of infill panels. The software used in the present study is not able to continue the analysis further after failure of a large number of infills. Therefore, to obtain the capacity curve after failure of infills, the failed infills were removed from the model and the revised model was re-analyzed.

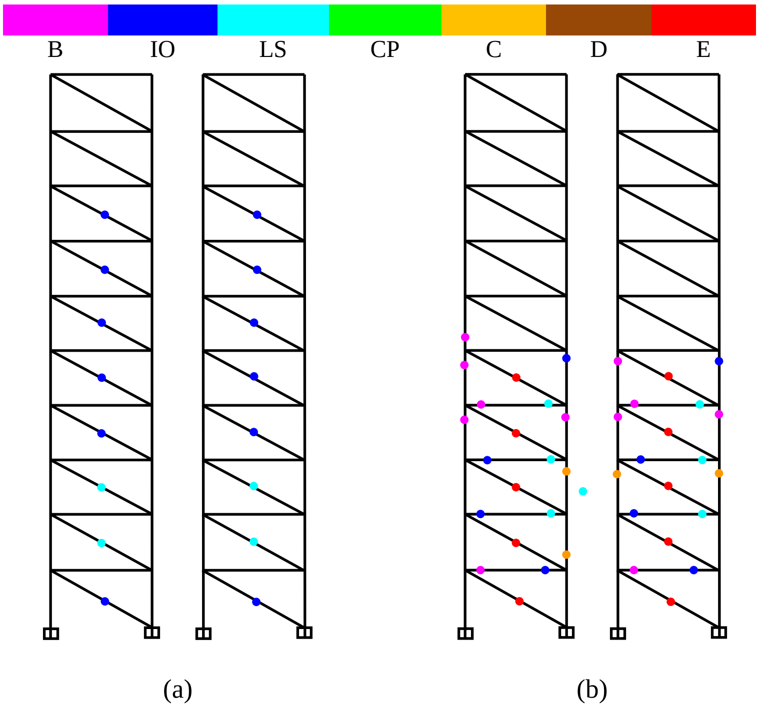


Figure 4.4. Hinge pattern of a typical frame in transverse direction of high-rise uniformly infilled RC frame buildings designed as SMRF as per relevant Indian Standards at: (a) Peak; (b) Failure

To obtain the capacity curve parameters the capacity curves/ pushover curves shown in Figure 4.1 and 4.2 have been idealized by bilinear curves using the ASCE-41 (2007) guidelines. In this procedure, the bilinear idealization is obtained by equating the area under the two curves and taking the effective stiffness as the secant stiffness at 60% of the idealized yield strength. The yield point is defined where a sizable number of members have yielded resulting in significant loss of stiffness of the whole structure. Similarly, ultimate point represents the point where the strength of the building degrades below 80% of the peak. The capacity spectrum parameters at yield (S_{ay}, S_{dy}) and ultimate (S_{au}, S_{du}) points are obtained analytically from the bi-linearization of capacity curves converted in to Acceleration Displacement Response Spectrum (ADRS) format as per ATC-40 (1996), using the following expressions,

$$S_a(g) = \frac{V}{W\alpha} \tag{4.1}$$

$$S_d = \frac{\Delta_{roof}}{\Gamma \phi_{roof}} \tag{4.2}$$

where, $$\alpha = \frac{\sum (w_i \phi_i)^2}{\sum w_i \sum w_i {\phi_i}^2} \tag{4.3}$$

$$\Gamma = \frac{\sum w_i \phi_i}{\sum w_i {\phi_i}^2} \tag{4.4}$$

V is the base shear representing the building lateral load resistance, W is the total weight of building, w_i is the lumped storey weight at i[th] floor levels, Δ_{roof} is the roof displacement, ϕ_i is the modal shape coefficient for i[th] floor, α is the modal mass coefficient (or fraction of the buildings weight effective in the pushover mode), and Γ is the modal participation factor for the pushover mode at the roof level of the building.

The capacity spectrum parameters for different classes of buildings as obtained by converted bi-linearized of capacity curves in to ADRS format, are summarized in Table 4.1.an It can be observed from Table 4.1 that the effect of variation in number of storeys is pronounced both in case of SMRF and gravity loads designed buildings. The spectral parameters of mid-rise SMRF and gravity loads designed buildings are quite closer because of the same member sizes in both the cases. This observation is in agreement with the observation made in the Figure 4.1.

Table 4.1. Capacity Spectrum Parameters of Indian Model RC building types with URM infills

S. No.	**Design Level**	**No. of Storey**	**Capacity Spectrum Parameters**			
			Yield Point		Ultimate Point	
			S_{dy} (mm)	S_{ay} (g)	S_{du} (mm)	S_{au} (g)
1	Buildings designed for gravity loads as per relevant Indian Standards, BIS (2000), BIS (1987 (Part 1)), BIS (1987 (Part 2)) without any consideration for earthquake forces as per provisions of BIS (1993, 2002)	Mid-Rise	1.8	0.370	41.8	0.470
2		High-Rise	1.6	0.056	4.3	0.073
3	Buildings designed, detailed and executed as per earthquake resistant guidelines of BIS (1993, 2002) for Special Moment Resisting Frames (SMRF)	Mid-Rise	2	0.4	62.3	0.5
4		High-Rise	16.9	0.190	40.3	0.228

The capacity spectrum parameters of the MBTs shown in Table 4.1 have been implemented in the Ms-Excel-based tools 'SeisVARA' (Seismic Vulnerability And Risk Assessment), developed as the extension of IVARA' (Seismic Vulnerability And Risk Assessment of Indian Housing) a seismic intensity based risk assessment tool for Indian housing (Haldar et al. 2010), to include capacity spectrum approach.

5. CONCLUSIONS

Based on prevailing Indian construction practices for urban multi-storey buildings, URM infilled RC frame buildings have been classified considering the primary features of vertical and horizontal framing systems and the number of storeys. Design level and reinforcement detailing has also been considered to differentiate the expected seismic performance of different MBTs. All possible failure modes of infill panels considering construction sequence of infills relative to frame also have been considered for this purpose. Capacity spectrum parameters at yield and ultimate points have been evaluated for the purpose of vulnerability assessment of and high-rise RC frames with URM infills designed for gravity loads alone, and as SMRF as per relevant Indian Standards. Developed capacity spectrum parameters have been implemented in the seismic risk assessment tool 'SeisVARA'.

REFERENCES

ASCE-41. (2007). *Seismic Rehabilitation of Existing Buildings (ASCE/SEI 41-06)*. Reston, Virginia: American Society of Civil Engineers

Asteris, P. G., D. J. Kakaletsis, C. Z. Chrysostomou, and E. E. Smyrou. (2011). Failure Modes of Infilled Frames. *Electronic Journal of Structural Engineering* **11** (**1**):11-20.

ATC-40. (1996). *Seismic Evaluation and Retrofit of Concrete Buildings (ATC-40, Vol. 1)*. Redwood City, California: Applied Technology Council.

BIS. (1987 (Part 1)). *IS: 875 (Part 1) Indian Standard Code of Practice for Design Loads (Other than Earthquake) for Buildings and Structures*, *Part 1: Dead Loads—Unit Weights of Building Materials and Stored Materials (Second Revision)*. New Delhi: Bureau of Indian Standards.

BIS. (1987 (Part 2)). *IS: 875 (Part 2) Indian Standard Code of Practice for Design Loads (Other than Earthquake) for Buildings and Structures*, *Part 2: Imposed Loads (Second Revision)*. New Delhi: Bureau of Indian Standards.

BIS. (1993). *IS: 13920 Ductile Detailing of Reinforced Concrete Structures Subjected to Seismic Forces – Code of Practice*. New Delhi: Bureau of Indian Standard.

BIS. (2000). *IS 456 Indian Standard Plain and Reinforced Concrete-Code of Practice (Fourth Revision)*. New Delhi: Bureau of Indian Standards.

BIS. (2002). *IS 1893 (Part 1) Indian Standard Criteria for Earthquake Resistant Design of Structures*, *Part 1: General Provisions and Buildings (Fifth Revision)*. New Delhi: Bureau of Indian Standards.

DEQ. 2009. Seismic Vulnerability of Multistorey Buildings in Noida. Roorkee, India: Department of Earthquake Engineering, Indian Institute of Technology Roorkee.

EISeify, M. O., M. M. EI-Attar, A. M. Ragab, and O. A. Hodhod. (2006). Modelling of Opening in Masonry Infill Panels in R.C. Frames, 2D Approach. *HBRC Journal* **2** (**1**):36-49.

Haldar, P., Y. Singh, D. H. Lang, and D. K. Paul. 2010. IVARA - A Tool for Seismic Vulnerability and Risk Assessment of Indian Housing. In *14th Symposium on Earthquake Engineering*. Department of Earthquake Engineering, IIT Roorkee,.

Haldar, Putul, and Yogendra Singh. (2012). Modelling of URM Infills and their Effect on Seismic Behaviour of RC Frame Buildings (Accepted). *The Open Construction and Building Technology Journal*, *Bentham Science Publishers*.

Kappos, A. J., G. Panagopoulos, C. Panagiotopoulos, and G. Penelis. (2006). A hybrid method for the vulnerability assessment of R/C and URM buildings. *Bulletin of Earthquake Engineering* **4** (**4**):391-413.

Kaushik, Hemant B., Durgesh C. Rai, and Sudhir K. Jain. (2006). Code Approaches to Seismic Design of Masonry-Infilled Reinforced Concrete Frames: A State-of-the-Art Review. *Earthquake Spectra* **22** (**4**):961–983.

CSI analysis reference manual for SAP2000 (2010). Computers and Structures Inc., Berkeley, California.