16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1034

Registration Code: S-W1463131717

TOWARDS AN APPROPRIATE SEISMIC VULNERABILITY ASSESSMENT MODEL IN INDIA

R. Bhasker [(1)], A. Menon [(2)]

[(1)] *PhD Student, Department of Civil Engineering, Indian Institute of Technology Madras, e-mail: rohanbhasker@gmail.com*
[(2)] *Assistant Professor, Department of Civil Engineering, Indian Institute of Technology Madras, e-mail: arunmenon@iitm.ac.in*

Abstract

Earthquakes have across history, led to heavy death tolls and monetary losses, forcing nations to deal with catastrophic repercussions. While the reasons behind these deaths and monetary losses can be attributed to a number of factors, a statistical analysis of the major cause of these fatalities worldwide, clearly points towards the collapse of buildings and other structures. The fact that the seismic hazard and exposure in a region cannot be controlled, suggests that any attempt to mitigate seismic risk should focus on minimizing the vulnerability of the building inventory. The Indian subcontinent, geographically spread over 3.287 million km^2 of landmass, is highly non-homogenous with respect to its seismogenic features. The seismic design code IS 1893-Part 1: 2002, that lays down the standards for seismic design of structures in India, recognizes four such seismic zones - Zone II, Zone III, Zone IV and Zone V, indicating regions with low, moderate, high and very high levels of seismic activity respectively.

Indian buildings exhibit significant heterogeneity with respect to their architectural and structural features. The performance of many building typologies in India during past earthquakes have not been satisfactory. From ill-conceived design and detailing to poor quality control and construction practices, a wide spectrum of factors hinder the desirable seismic behavior of buildings. Various classes of methods exist in literature for quantifying the vulnerability of structures. Although there have been many studies in the past to assess the seismic vulnerability of individual buildings in the country, it was not until 2013 that a technical document was released by the National Disaster Management Authority (NDMA) for the territorial scale assessment of Indian building stock. Out of the fifty four typologies that have been proposed for Indian buildings, many are combined together and represented using single vulnerability function. This paper briefly describes the seismological setting of India, and the performance of various building typologies in past earthquakes, with the view of emphasizing on the need for seismic vulnerability assessment. It further focuses on the state of the art methodologies for assessment and the development of appropriate vulnerability models in the Indian context. Important issues that need to be addressed by these models form the central theme of discussion in this paper.

Keywords: Seismic Vulnerability; Indian building stock; Building Typologies; Vulnerability model

1. Introduction

In spite of the significant advancements made in the area of science and technology over the past several decades, mitigating the potential aftermath of natural disasters still remains a challenge today. Natural disasters have across history, led to heavy death tolls and monetary losses, forcing nations to deal with catastrophic repercussions. Earthquakes are no exception to this statement, killing thousands and melting down economies in a matter of minutes. Such blows turn out to be disastrous, especially to developing nations, for which the economic losses translate to a significant share of their gross domestic product (GDP). The 25th April 2015 Nepal earthquake, for instance, resulted in an economic loss of $10 billion, which was about 52% of the country's GDP ($19.2 billion) for that year. The figures were even more alarming during the 2010 Haiti earthquake, which took 316000 lives and resulted in losses worth about $8 billion (more than 120% of that year's GDP for the country), leaving one of the poorest countries in the western hemisphere financially paralyzed. Even with global co-operation, recuperating from such calamities is a herculean task for any nation, particularly the economically backward ones.

While the reasons behind these deaths and monetary losses can be attributed to a number of factors, a statistical analysis of the major cause of these fatalities worldwide, clearly points towards the collapse of buildings and other structures. Post-earthquake data compiled by Coburn and Spence [1] indicate that over 70% of the fatalities during earthquakes are attributed to the low seismic resistance of structures. The term 'Seismic Risk' is used to indicate the expected losses that an element or group of elements is likely to experience under the action of earthquakes, over an indicated period of time in the future. Popular literature defines 'Seismic Risk' as the convolution of three important factors- Seismic Hazard, Seismic Vulnerability and Seismic Exposure. In a conceptual form:

$$\text{Risk} = \text{Hazard} * \text{Vulnerability} * \text{Exposure} \tag{1}$$

Seismic Hazard represents the probability of occurrence of an earthquake of a certain severity within an indicated period of time, in a given region. Earthquakes being natural phenomena; the hazard cannot be controlled, but merely quantified. The term Seismic Exposure represents the size of human population, infrastructure and economic activity under the threat of earthquakes. A metropolitan city would thus have more exposure compared to a rural area. The exposure is often dictated by other considerations such as employment opportunities, availability of resources for industry etc. and not by earthquakes. Seismic Vulnerability, on the other hand, represents the degree of loss or damage to a given element at risk, resulting from a given level of seismic hazard. Buildings vary in their vulnerability to earthquake ground motions. Vulnerability of a structure, which is a complex function of its geometrical and material properties, can be controlled through sound design and construction practices. Hence any attempt to mitigate risk should focus on minimizing the vulnerability of the building inventory.

India, a country with a long history of devastating earthquakes, represents a region highly diverse with respect to its seismic activity, exposure and building design features. However, a noteworthy fact about the country is that many of the regions of high hazard are also characterized by high population density, which in turn translates to high seismic exposure. The Nation's capital, New Delhi, for example, is located in a high seismic zone and has a population density of over 11297 people/ km^2. Information from the past building census also indicate that a significant share of the Indian building stock fall under the category of seismically vulnerable construction. Table 1 indicates the distribution of various types of households (by predominant wall material) within the country. A combination of high hazard, high exposure and high vulnerability of building stock could spell disaster for a region. With vulnerability being the only factor earthquake engineers can attempt to minimize, its assessment is on top of the list of priorities.

Table 1- Categories of Indian households (by predominant wall material) [2, 3]

Sl. No	Category of household (by predominant wall material)	Housing Census 2001			Housing Census 2011		
		Percentage			Percentage		
		Rural	Urban	Total	Rural	Urban	Total
1	Mud/ Unburnt brick	37.1	11.2	29.6	30.5	9.3	23.7
2	Stone	11.5	7.2	10.2	13.7	15	14.1
3	Burnt brick	35.3	68.7	44.9	40	63.5	47.5
4	Others	16.1	12.9	15.3	15.8	12.2	14.7
	Total	100	100	100	100	100	100

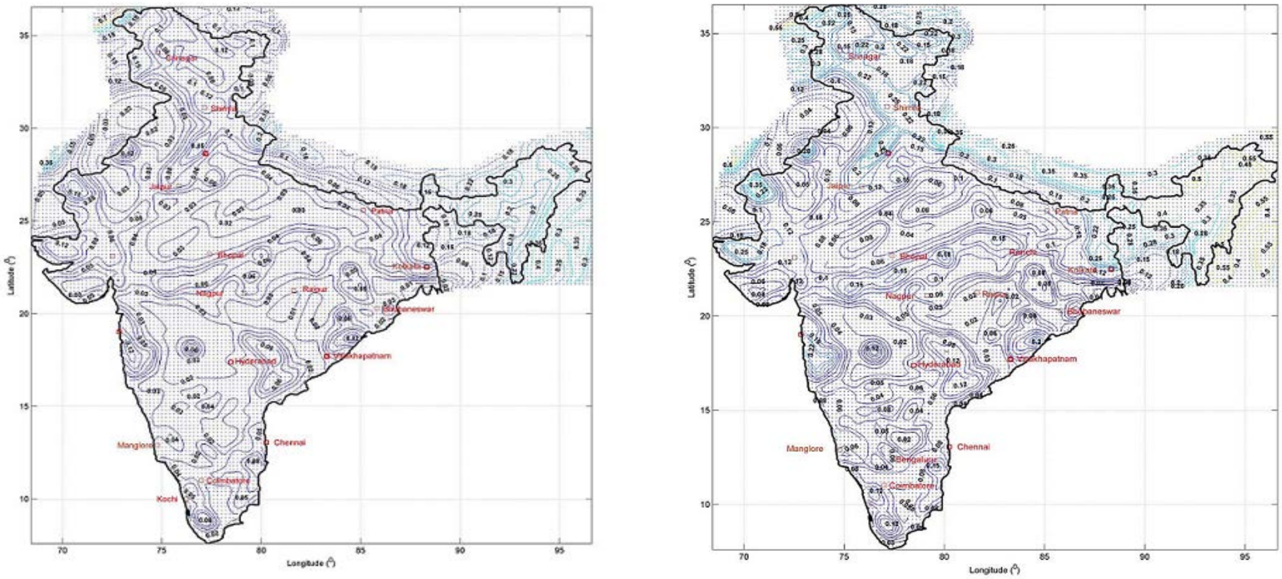
This paper briefly describes the seismological setting of India, and the performance of various building typologies in past earthquakes, with the view of emphasizing on the need for seismic vulnerability assessment. It further focuses on the state of the art methodologies for assessment and the development of appropriate vulnerability models in the Indian context. Important issues that need to be addressed by these models form the central theme of discussion in this paper.

2. Overview of the Seismological features of India

The Indian subcontinent, geographically spread over 3.287 million km^2 of landmass, is highly non-homogenous with respect to its seismogenic features. The Himalayan belt, located at the interface of the Indian plate and the Eurasian plate, has historically been the source of a multitude of major and great earthquakes. In a span of about 50 years, these regions have been subjected to four great earthquakes (magnitude > 8): The 1897 Assam (M 8.7) Earthquake; the 1905 Kangra (M 8.0) Earthquake; the 1934 Bihar–Nepal (M 8.3) Earthquake; and the 1950 Assam–Tibet (M 8.6) Earthquake. These regions are therefore characterized by high seismic hazard. On the other hand, the peninsular region of southern India has experienced fewer and less intense earthquakes over the years and hence, is deemed to pose low to moderate seismic hazard. Hence considerable variability exists in the level of ground shaking anticipated in different parts of the country. On the whole, it is estimated that more than 60% of the country is located in regions susceptible to earthquakes of intensity VII and above. Jain [4] gives a comprehensive list of some of the significant earthquakes in Indian history and their impact on the society in terms of casualties, deaths and the effects on structures and natural landscapes. Some of these earthquakes are listed in Table 2.

Table 2- Some Significant Earthquakes in Indian history [4]

Location of Epicenter	Year	Magnitude	Number of people killed	Location of Epicenter	Year	Magnitude	Number of people killed
Assam	1897	8.7	1500	Bihar-Nepal	1988	6.6	1000
Kangra	1905	8.0	19000	Uttarkashi	1991	6.4	768
Bihar-Nepal	1934	8.3	7253	Killari	1993	6.2	7928
Quetta	1935	7.7	35000	Jabalpur	1997	6.0	38
Makran Coast	1945	8.0	4000	Bhuj	2001	7.7	13805
Assam-Tibet	1950	8.6	3900	Sumatra	2004	9.4	250000
Anjar	1956	6.1	115	Kashmir	2005	7.6	87350
Koyna	1967	6.5	180	Sikkim	2011	6.9	78



(a) (b)

Fig. 1 PGA Contours with (a) 10% probability of exceedance in 50 years on A-Type Sites (b) 2% probability of exceedance in 50 years on A-Type Sites [6]

Recognizing the fact that different regions of the country are prone to different levels of seismic hazard, the Indian subcontinent is delineated into different seismic zones. The design code IS 1893-Part 1:2002 [5], that lays down the standards for seismic design of structures in India, recognizes four such seismic zones - Zone II, Zone III, Zone IV and Zone V, indicating regions with low, moderate, high and very high levels of seismic activity respectively. This approach of hazard estimation is rather subjective and deterministic since no recognition is given to the uncertainties underlying the earthquake hazard. The zoning is purely based on intensities observed during past earthquakes, without any scientific basis or probabilistic treatment. The fact that the Maximum Considered Earthquake (MCE) and the Design Basis Earthquake (DBE) stated in the code have no probabilistic basis, also renders the information from the above zone map incompatible for performance based design. Although there have been numerous studies carried out in the past to develop hazard maps for selected cities and regions, it was not until 2010 that a national level PSHA map (Fig. 1) was developed for India [6]. Such a map is very useful in translating typological vulnerability into typological risk and also in the framework of performance based structural design.

3. Performance of Indian building stock during earthquakes

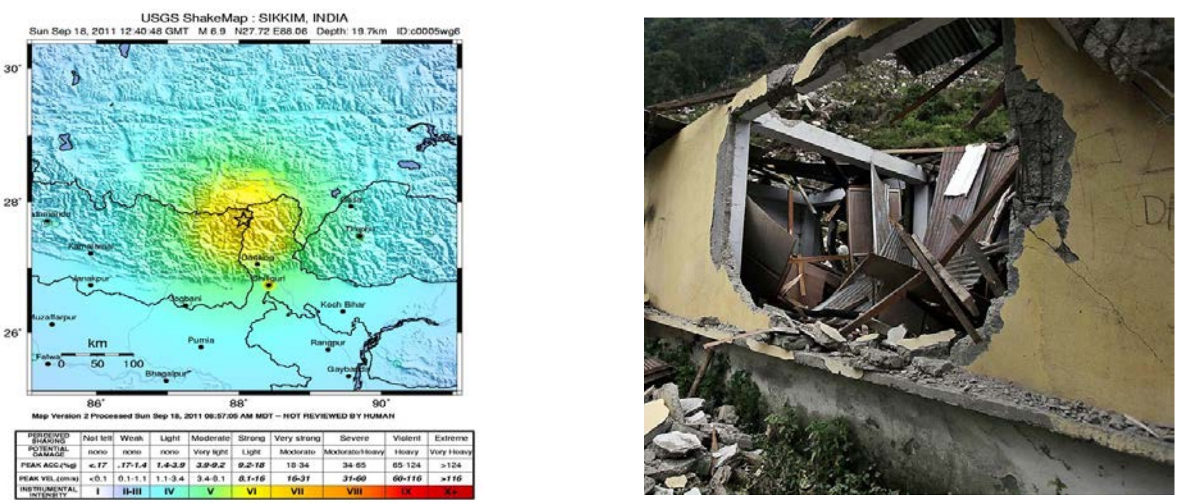
Indian buildings exhibit significant heterogeneity with respect to their architectural and structural features. A large number of structural typologies may be identified within the country, which exhibit unique response to the same seismic input. The performance of most of these typologies, however, have not been satisfactory during past earthquakes. A significant number of buildings or parts thereof have collapsed or undergone extensive damage even under moderate levels of shaking. Since reinforced concrete and masonry structures encompass the major share of the Indian building stock, sections 3.1 and 3.2 are devoted to discussing the performance of these classes of buildings during past earthquakes.

3.1 Performance of Reinforced Concrete Structures

The performance of several reinforced concrete buildings in the country have not been satisfactory during past earthquakes, with many of them undergoing damage much higher than what most PGA-Intensity or Magnitude-

Intensity relations would predict. For instance, a study [7] based on an earthquake catalogue compiled for southern India, has arrived at a magnitude-intensity relationship which predicts higher intensities for lower magnitude earthquakes compared to the Guttenberg-Richter M-I relationship [8]. This is clearly indicative of the higher vulnerability of Indian building stock relative to other parts of the world. Fig. 2(b) shows the out of plane collapse of a masonry infill wall in an RC building during the 2011 Sikkim earthquake. Such a building conforms to structure class C as per [9] and hence Grade 4 damage (destruction), such as that demonstrated in figure, is expected to occur only at MSK intensities of IX and above. However the maximum intensity on the isoseismal map [Fig. 2(a)] is only VI-VII. This clearly demonstrates poor seismic performance and could possibly be a result of deficient design.

It can also be observed that while the walls and roof collapsed, the RC frame remains intact. Damage studies on past earthquakes indicate that a large share of RC structures in India survive moderate earthquakes merely because of the fact that the infill masonry is of much lower quality and strength that a significant portion of the seismic energy is dissipated in the failure of the masonry and not the frame members. In other words, the low-strength masonry serves a purpose similar to a fuse in an electrical circuit and protects the load bearing members such as columns and beams from damage. On the contrary, if the infill was composed of high strength masonry, it would transfer the shear (which is higher than that in a bare frame building due to the increased stiffness) to the framing system and cause heavy damage to the members. [10] describes the effect of URM infills on the seismic vulnerability of Indian code designed RC frame buildings



(a) (b)

Fig. 2 (a) USGS Shake map of the 2011 Sikkim Earthquake [11] (b) out of plane collapse of masonry infill wall during the 2011 Sikkim Earthquake

In spite of seismic design standards coming into force in India from the 1960s, a significant portion of the buildings do not possess earthquake-resistant features. From ill-conceived design and detailing to poor quality control and construction practices, a wide spectrum of factors hinder the desirable seismic behavior of buildings. Some of the common causes for under-performance of Indian RC structures during past earthquakes may be summarized as follows:

<u>A. Issues pertaining to Structural Engineering Practice</u>

- ❖ Widespread construction of soft storey buildings, where the columns and beams of the soft storey are not designed for 2.5 times the storey shear and bending moment calculated under seismic loads. [Fig. 3(a)]
- ❖ Lack of understanding of torsional effects, stress concentrations etc. that may occur in buildings with poor seismic configuration (asymmetry in plan or elevation).
- ❖ Negligence of the possible effects of infill-frame interactions on seismic response.

B. Issues pertaining to Structural Design

- Provision of inadequate amount of shear reinforcement (non-conformity to the minimum spacing requirements of hoops) at the face of the beam-column joints and regions of potential flexural yielding.
- Largely spaced transverse reinforcement in columns leading to poor confinement of the concrete core and inadequate restraint to the buckling of longitudinal steel bars. [Fig. 3(b)]

C. Issues pertaining to Structural Detailing

- Provision of 90° hooks for lateral ties in lieu of 135° hooks, resulting in the opening of ties. [Fig. 3(c)]
- Non-compliance of ductile detailing requirements envisaged by IS 13920:1993 [12], including requirements on minimum top and bottom reinforcement in flexural members, minimum lap length, provision of hoops over the entire splice length etc.
- Large spacing of longitudinal reinforcement, resulting in increased crack-widths leading to the ingress of water and other chemicals which may deteriorate concrete and steel.

D. Issues pertaining to Quality control and Quality assurance

- Poor quality control and use of inferior materials for construction.
- Disparities between structural drawings and site execution.
- Provision of inadequate cover to the reinforcement (often due to uneven formwork), resulting in corrosion of steel under the prevailing tropical climate with high relative humidity and rains.

(a) (b) (c)

Figure 3 (a) Pancaking of an open storeyed residential building (b) Failure of RC column provided with large spacing of lateral ties [13] (c) Poor detailing of RC column with 90° hooks

3.2 Performance of Masonry Structures

Constituting about 85.4% of the Indian building stock [3], masonry structures represent one of the most vulnerable classes of buildings in the country. Overturned and diagonally cracked walls are hackneyed sights after every moderate to large earthquake (Fig. 4). However, most of these failures can be attributed to the fact that the masonry is unreinforced and do not possess the desirable ductile behavior. In other words, the vulnerability of a significant share of these buildings stems from non-compliance to IS 4326:1993 [14], which gives the guidelines for earthquake resistant masonry construction in India. The code recognizes four categories of masonry and wooden buildings – B, C, D, E based on their importance factor and seismic zone. Good seismic performance is ensured through standards on the quality of mortar, size of wall openings, seismic strengthening arrangements around openings, provision of bands, reinforcement detailing etc. for each building category. Buildings conforming to the above requirements have exhibited fairly good seismic behavior as opposed to their non-conforming counterparts. The IS 4326:1993 detailing for horizontal and vertical reinforcement in solid brick walls is cumbersome, labor intensive and almost never gets executed at a site leaving the URM structure vulnerable.

(a)

(b)

Fig. 4 (a) Out of plane collapse of upper storey masonry wall (b) In-plane cracking of masonry wall [15, 16]

Similar to RC buildings, the effect of conformity to codal requirements or the lack thereof must be reflected in the vulnerability model. Since nonlinear modeling of masonry is highly complicated and not feasible for territorial scale assessment, simple collapse mechanism based methods would be ideal for the analytical generation of motion-damage relationships.

4. Methodologies for Vulnerability Assessment

The term "Seismic Vulnerability" signifies the susceptibility of a structure to undergo damage when subjected to a specified level of ground shaking. In mathematical terms, seismic vulnerability represents the conditional probability that a structure reaches or exceeds various limit states under a given level of ground motion intensity. Seismic vulnerability of a particular building is a complex function of its geometric and structural characteristics. Such geometric features include building height, plan dimensions, elevation configurations etc. The structural characteristics that influence the vulnerability of a building include the nature of construction materials, mass, stiffness, quality control, strength, intrinsic ductility etc.

Vulnerability may be assessed at an individual building level or at a regional level. Individual building assessment permits more realistic structural modelling and refined characterization of material and geometric properties. Regional level assessment, however, involves collection, compilation and statistical processing of large amount of data pertaining to the inventory, which makes the whole process quite tedious. A limited knowledge of the buildings may be required, depending on the number of elements to be considered. It therefore becomes imperative to identify those set of building features and parameters that have the most serious implications on seismic response. The characteristics that are commonly captured in such studies include: architectural details, structural configuration, foundation details, building history, material properties etc.

Depending on the means by which the motion-damage relationship is established, a number of seismic vulnerability assessment methodologies have been recognized in literature (Fig. 5). A brief outline of these methods is presented in [17].

One of the earliest methods for vulnerability evaluation of structures, *the Expert-opinion method* relies on the proficiency of a panel of experts in drawing conclusions on the probable distribution of damage in various structural typologies under a given earthquake scenario. This method is suitable for regions of the world where little or no post-earthquake damage data from previous earthquakes are available. The method was first adopted for the regional seismic vulnerability assessment of California, USA by the Applied Technology Council [18]. The identified experts are asked to give their low, best and high estimates of damage factor for various typologies under various levels of ground shaking and to rate their confidence (on a scale of 0 to 10) in making the judgement. These ratings serve as weighing factors in computing the final damage profile. The response of the experts is subjected to statistical processing to arrive at the final conclusion. Depending on the mode of operation, two variants of the procedure is recognized: The Delphi method and The Consensus Method [19]. The expert opinion based method suffers from high subjectivity and is prone to bias. Though attempts can be made to minimize this subjectivity, it cannot be completely eliminated. Also, the ability of field experts in making estimates related to large magnitude seismic events is highly questionable as such events are associated with a larger return period and may not have been experienced by the experts. The method also requires a refined documentation of the building inventory.

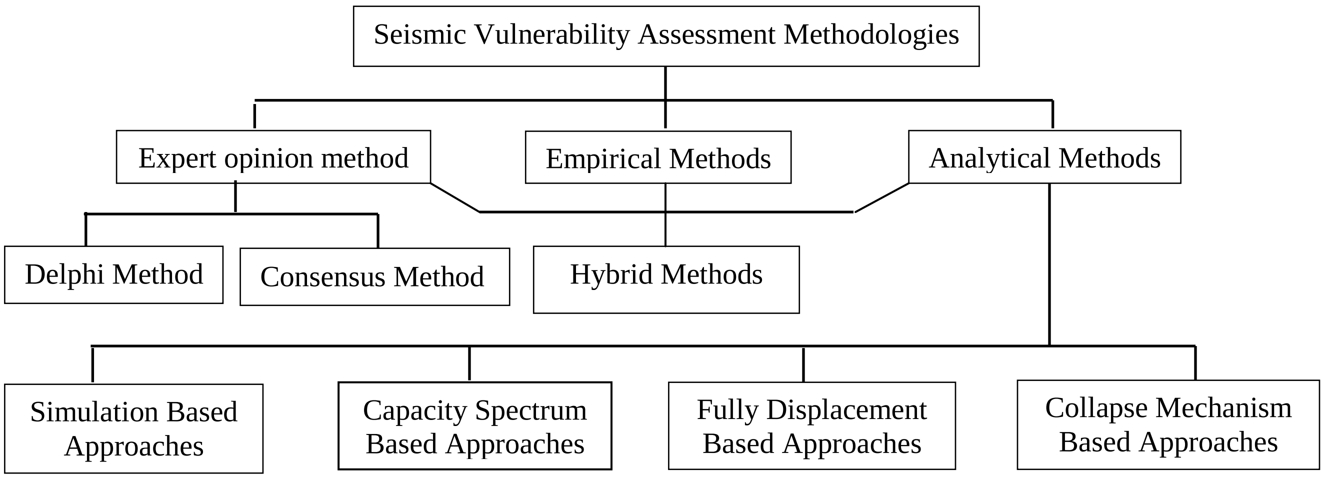


Fig. 5 Methodologies for Seismic Vulnerability Assessment

Empirical Fragility curves are derived from statistical elaboration of data collected through post-earthquake surveys. The main advantage of the method is that it is based on real observed data, which is the most realistic source of information, since they take into account all the characteristics of the building stock and of the ground motion. Such factors include soil structure interaction effects, site profile characteristics, source and path of the earthquake. However, due to the very same reason, these curves are highly specific to a seismotectonic, geotechnical and built environment. A large amount of data is in fact needed to obtain realistic vulnerability curves and to reduce the scatter in the results.

Analytical methods deal with nonlinear analysis of structures, probabilistic modelling of earthquakes and structural parameters, and generalizing results of a smaller area to a region or other cities. These methods are based on sound mathematical formulation. Different classes of such methods exist, such as Monte Carlo simulation based approach [20], Capacity-Spectrum based methods [21], Collapse-Mechanism based methods [22, 23], Fully displacement-based methods [24, 25, 26] etc. These methods are characterized by high computational demand, the level of which depends on the choice of analysis method, structural modelling etc. In case analytical techniques for vulnerability evaluation are adopted, the underlying uncertainties should be properly accounted for.

Hybrid or Semi-Analytical Methods are those which combine DPMs and fragility curves derived from the statistical analysis of post-earthquake data or expert-opinion with those derived analytically from a mathematical model of the building typology under consideration. Such techniques are ideal under the following circumstances

(i) Damage data related to certain ground motion intensity levels are scanty to derive statistically valid damage-motion relationship
(ii) Derivation of vulnerability functions for more recently emerged typologies for which relevant post-earthquake data is unavailable
(iii) Calibration of analytical models

These techniques significantly reduce the computational effort involved when compared to a purely analytical fragility curve. Kappos et al. [27] has proposed a hybrid methodology for the vulnerability assessment of RC buildings in Greece.

5. Seismic Vulnerability Studies in India

Although there have been many studies in the past to assess the seismic vulnerability of individual buildings in the country, it was in 2013 that technical documents were released by the National Disaster Management Authority (NDMA) for the territorial scale assessment of Indian building stock [19, 28, 29]. The set of documents, prepared by a project group comprising of earthquake engineering experts from IITs (Indian Institute of Technology) provides a rational framework for evaluating the vulnerability of various typologies of buildings.

Motion-damage relationships are established for a limited number of building typologies, grouping together structures which are expected to have similar seismic behaviour. An elaborate categorization of building classes is impractical as it would require the derivation of a larger number of vulnerability models. Broad categories, on the other hand, may group together buildings exhibiting completely different responses to seismic action, leading to an average model not representative of any typology. The type of vertical and lateral load bearing system forms the primary basis for such classification. Other factors that are crucial include number of storeys (or the height of building), period of construction, structural configuration, site planning, construction quality etc. However, most of the raw inventory data did not provide building-specific information and hence it was necessary to adopt a broad construction type classification based on the material used (Table 3.)

The typologies being defined, the MSK Intensity scale [9] was chosen as the ground motion descriptor and damage was described by means of an index called the damage factor, which is the ratio of repair cost and building replacement cost. The NDMA proposes the use of a vulnerability model of the form represented in Eq. (2), in order to estimate the extent of damage to a given building typology under a certain level of ground motion intensity (I).

$$\mathrm{Damage} = A + B * \Phi\left(\frac{\ln(I) - \mu}{\sigma}\right) \tag{2}$$

where A, B, μ and σ are regression coefficients and Φ is the cumulative distribution function for a standard normal variate. The vulnerability functions for non-engineered buildings (weak and strong) were developed based on information collected from post-earthquake damage surveys and analytical techniques. For masonry, reinforced concrete and steel structures, the functions have been synthesized from a combination of post-earthquake observations, expert opinion and analytical studies. These functions have been graphically represented in Fig. 6.

Out of the fifty four typologies that have been proposed for Indian buildings, many are combined together and represented using single vulnerability function. This has been done because the median seismic behavior of many building typologies is very similar to each other and they can be represented by a single curve. However, such coarse grouping of typologies is highly debatable. The median curves so defined may not be exactly representative of any of the typologies. Hence further research needs to be carried out in breaking down such clusters of typologies into numerous reasonably relatable groups. Also the document gives no indication of how the curves need to be modified for different building heights, irregularity in seismic configuration, slope of the ground etc. The deduction of such modification factors warrants further analytical studies on structural models and information from post-earthquake damage studies. The above model also fails to capture the effect of uncertainties in material strengths, geometrical parameters etc. on the seismic response. Issues discussed earlier such as the compliance to existing seismic design and detailing standards, quality control etc. also requires to be addressed. Synthesis of such refined vulnerability models will finally allow for convolution with seismic hazard to obtain an accurate representation of typological risk.

Table 3- List of proposed building typologies in India [28]

Material	Sub-Types	Load Resisting System
Masonry (M)	Rubble stone in mud/lime mortar or without mortar (A)	Stone Masonry Walls (ST)
	Massive stone masonry in lime/cement mortar (B)	
	Dressed stone masonry in lime/cement mortar (C)	
	Mud walls (D)	Earthen/Mud/Rammed Earthen Walls (EW)
	Mud walls with horizontal wood elements (E)	
	Adobe block walls (F)	
	Rammed earth construction (G)	
	Unreinforced brick masonry in mud/lime mortar (H)	Burnt clay brick/ block masonry walls (BW)
	Unreinforced brick masonry in mud mortar with vertical posts(I)	
	Unreinforced brick masonry in cement mortar (J)	
	Unreinforced brick masonry in cement mortar with RC floor/roof slabs (K)	
	Unreinforced brick masonry in cement mortar with lintel bands (L)	
	Confined brick/block masonry with concrete posts/tie columns and beams (M)	
	Unreinforced concrete block masonry in lime/cement mortar (N)	Concrete Block Masonry (CO)
	Reinforced concrete block masonry in lime/cement mortar (O)	
	With reinforced concrete (P)	Mixed Structure (MS)
	With composite steel (Q)	
	With timber, bamboo, others (R)	
Structural Concrete (C)	Designed for gravity loads only (A)	Moment Resisting Frame (MF)
	Designed with seismic features (B)	
	Frame with unreinforced masonry infill walls (C)	
	Flat slab structure (D)	
	Precast frame structure (E)	
	Frame with concrete shear walls (dual system) (F)	
	Open ground storey (G)	
	Walls cast in-situ (H)	Shear Wall Structure (SW)
	Precast wall panel structure (I)	
	With load bearing masonry (J)	Mixed Structure (MS)
	With composite steel (K)	
	With timber, bamboo or others (L)	
Steel (S)	With brick masonry partitions (A)	Moment Resisting Frame (MF)
	With cast in-situ concrete walls (B)	
	With lightweight partitions (C)	
	With various floor/ roof systems (D)	Braced Frame (BF)
	Single storey LM frame structure (E)	Light Metal Frame (LF)
	With load bearing masonry (F)	Mixed Structure (MS)
	With reinforced concrete (G)	
	With composite steel and concrete vertical members (H)	
	With Timber, Bamboo or others (I)	
Wooden Structures (W)	Thatch Roof (A)	Load bearing Timber Frame (TF)
	Post and beam frame (B)	
	Walls with bamboo/ red mesh and post (C)	
	Frame with masonry infill (D)	
	Frame with plywood/ gypsum board sheathing (E)	
	Frame with stud walls (F)	
	Dhajji-Diwari with lightweight sloping roof (G)	
	Dhajji-Diwari with heavy/stone sloping roof (H)	
	Thatra with timber plank partitions with lightweight sloping roof (I)	
	Thatra with timber plank partitions with heavy/stone sloping roof (J)	
	Thatra with Dhajji-Diwari partitions with lightweight sloping roof (K)	
	Thatra with Dhajji-Diwari partitions with heavy/stone sloping roof (L)	
	Kath-Kunni walls with stone packing with lightweight sloping roof (M)	
	Kath-Kunni walls with stone packing with heavy/stone sloping roof (N)	
Bamboo (B)	Thatch Roof (A)	Bamboo frames with Bamboo/ Ekra/ Straw partitions (BF)

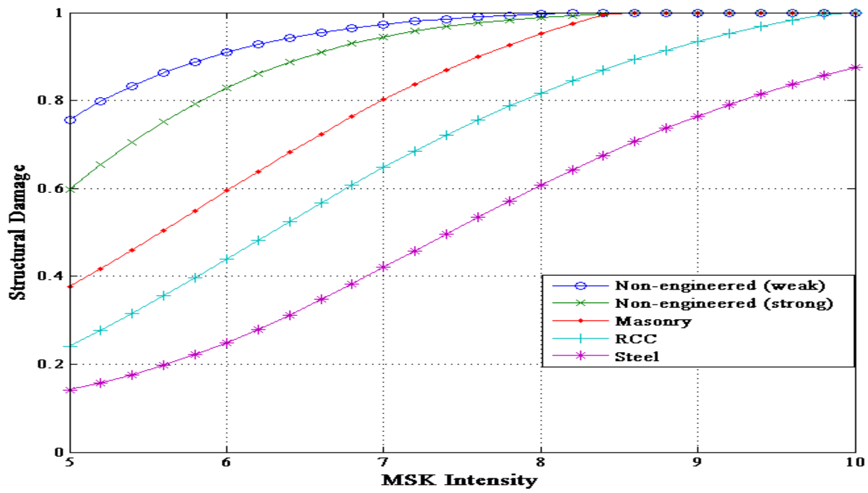


Fig. 6 Proposed Seismic Vulnerability curves for buildings in India [29]

6. Conclusion

Seismic Vulnerability Assessment, although a major area of research in the field of Earthquake Engineering for decades, still remains in a juvenile phase in India. The NDMA Vulnerability reports, though they serve as a starting point for assessment, still leaves a lot of issues unaddressed. Clusters of typologies need to be broken down into smaller ones and vulnerability functions defined for the same. Performance of buildings during the past earthquakes emphasize on the strong need for incorporating the effects of non-compliance to design and detailing standards, infill-frame interactions, quality control etc. into vulnerability models. Simplified methodologies that help modify the parent curves for various typologies need to be developed which account for the same. A national database with systematic uniform reporting of damage statistics needs to be developed to ensure realistic vulnerability assessment in India. Such data could further be used in the synthesis of hybrid models that provide a more accurate representation of the motion-damage relationship for various typologies.

7. References

[1] Coburn A, Spence R (2002): *Earthquake Protection*. John Wiley and Sons: Chichester, England.

[2] Houselisting and Housing Census Data (2001). Government of India, New Delhi.

[3] Houselisting and Housing Census Data (2011). Government of India, New Delhi.

[4] Jain SK (2016): Earthquake safety in India: achievements, challenges and opportunities. *Bulletin of Earthquake Engineering*, **14**: 1337–1436.

[5] IS 1893 (Part I): 2002. Criteria for Earthquake Resistant Design of Structures. Bureau of Indian Standards, New Delhi, India.

[6] National Disaster Management Agency (2010). Development of Probabilistic Hazard Map of India. NDMA Authority, Govt. of India, New Delhi.

[7] Corigiliano M, Lai CG, Menon A and Ornthammarath T (2012). Seismic Input at the archaeological site of Kancheepuram in South India. *Natural Hazards.*

[8] Gutenberg B, Richter CF (1956). Earthquake Magnitude, Intensity, Energy and Accelaration. *Bulletin of the Seismological Society of America*, **46**, 105-145.

[9] Medvedev SW, Sponheuer W, and Karnik V (1964). Seismic Intensity Scale Version MSK 1964.

[10] Haldar P, Singh Y, and Paul DK (2012). Effect of URM Infills on seismic vulnerability of Indian code designed RC frame buildings. *Earthquake Engineering and Engineering Vibration*, **11**(2), 233-241.

[11] U.S. Geological Survey (2011). *USGS ShakeMap : Sikkim, India*. United States Geological Survey, Virginia, United States.

[12] IS 13920 : 1993. Ductile detailing of Reinforced concrete structures subjected to seismic forces – Code of Practice. Bureau of Indian Standards, New Delhi, India.

[13] EERI (2001). Learning from Earthquakes: A field report on structural and geotechnical damages sustained during the 26 January 2001 M7.9 Bhuj Earthquake in Western India. Earthquake Engineering Research Institute, USA.

[14] IS 4326 : 1993. Earthquake Resistant Design and Construction of Buildings – Code of Practice. Bureau of Indian Standards, New Delhi, India.

[15] Rai DC and Murty CVR (2005). Preliminary report on the 2005 North Kasmir earthquake of October 8, 2005. Indian Institute of Technology Kanpur, India.

[16] Kaushik HB, Dasgupta K, Sahoo DR and Kharel G (2006). Reconnaissance Report: Sikkim Earthquake of 14 February 2006. National Information Center of Earthquake Engineering, IIT Kanpur, India.

[17] Calvi GM, Pinho R, Magenes G, Bommer JJ, Restrepo-Vélez LF, and Crowley H (2006): Development of seismic vulnerability assessment methodologies over the past 30 years. *ISET Journal of Earthquake Technology*, **43**(3), 75-104.

[18] ATC-13 (1985). Earthquake damage evaluation data for California. *Applied Technology Council* 1985, Redwood city, California, USA.

[19] National Disaster Management Authority (2013). Technical document on Seismic Vulnerability Assessment for Buildings. NDMA Authority, Govt. of India, New Delhi.

[20] Singhal A, Kiremidjian AS (1996): Method for probabilistic evaluation of seismic structural damage. *Journal of Structural Engineering,* **122**, 1459-1467.

[21] FEMA (1999): HAZUS 99 - *Earthquake loss estimation methodology: User's Manual*. Federal Emergency Management Agency, Washington DC.

[22] D'Ayala D, Speranza E (2002). An Integrated Procedure for the Assessment of Seismic Vulnerability of Historic Buildings. *Proc. 12th European Conference on Earthquake Engineering*, London, U.K., Paper No.561.

[23] Cosenza E, Manfredi G, Polese M and Verderame GM (2005). A multi-level Approach to the capacity Assessment of Existing RC buildings. *Journal of Earthquake Engineering*, **9**(1), 1-22.

[24] Calvi GM (1999). A displacement based approach for the vulnerability evaluation of classes of buildings. *Journal of Earthquake Engineering,* **3**(3), 431-446.

[25] Glaister S, Pinho, R. (2003). Development of a simplified deformation based method for seismic vulnerability assessment. *Journal of Earthquake Engineering* **7** (special issue 1), 107-140.

[26] Crowley H, Pinho R, and Bommer JJ (2004). A probabilistic displacement-based vulnerability assessment procedure for earthquake loss estimation. *Bulletin of Earthquake Engineering* **2**, 173-219.

[27] Kappos AJ, Stylianidis KC, and Pitilakis K (1998): Development of Seismic Risk scenarios based on a Hybrid method of Vulnerability assessment. *Natural Hazards,* **17**(2), 177-192.

[28] National Disaster Management Authority (2013). Technical document on Typology of buildings in India. NDMA Authority, Govt. of India, New Delhi.

[29] National Disaster Management Authority (2013). Technical document on Seismic Vulnerability Functions of BuildingTypologies. NDMA Authority, Govt. of India, New Delhi.