

Challenges of Low-to-Moderate Seismicity in India

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ABSTRACT: India is a vast country that is growing even faster. Particularly over the last decade, there has been a sudden spurt in the construction activity in the country, especially in the large low-to-moderate seismic regions of the country. But, no systems are in place to regulate these massive constructions to ensure seismic safety. This paper raises the challenges in the current practice and provides measures to overcome them. In particular, the paper argues for separate provisions for the design and construction of structures in low-to-moderate seismic regions.

KEYWORDS: Earthquake, India, seismic, safety, earthquake

1 INTRODUCTION

India has a two-pronged earthquake problem. There is severe seismic hazard along the Himalayan belt and the western margin of the country in the state of Gujarat, over a relatively smaller land area of about 27.3%, and low-to-moderate seismic hazard in the remaining large part of about 72.7% of land area [BMTPC, 2007]. A large number of large size earthquakes (including 4 Great earthquakes) have occurred in the area under severe seismic hazard, but the population in these areas is relatively lesser. On the other hand, few small size earthquakes have occurred in the area under low-to-moderate seismic hazard, but a large number of lives have been lost.

The country has a large population – about a sixth of the world’s population is in India. But, there is no critical mass of technical professionals (appropriately qualified and trained) to undertake the earthquake safety related technical and co-technical activities. The promulgation of the Disaster Management Act in 2005 and the formation of the National Disaster Management Authority is expected to lead to activities and initiatives that will eventually build the required critical mass of earthquake professionals. This paper presents an analysis of the issues involved and challenges the country is faced with on the various fronts to making India better prepared to face earthquakes with lesser loss of life and property, especially in the large land area with low-to-moderate seismic threat.

2 BASIC GEOGRAPHY AND TECTONIC FEATURES

India lies at the northwestern end of the Indo-Australian Plate, which encompasses India, Australia, a major portion of the Indian Ocean and other smaller countries [Bolt, 1999]. This plate is colliding against the huge Eurasian Plate (Figure 1) and going under the Eurasian Plate; this process of one tectonic plate getting under another is called subduction. A sea, Tethys, separated these plates before they collided. Part of the lithosphere, the Earth’s Crust, is covered by oceans and the rest by the continents. The former can undergo subduction at great depths when it converges against another plate, but the latter is buoyant and so tends to remain close to the surface. When continents converge, large amounts of shortening and thickening take place, like at the Himalayas and the Tibet.

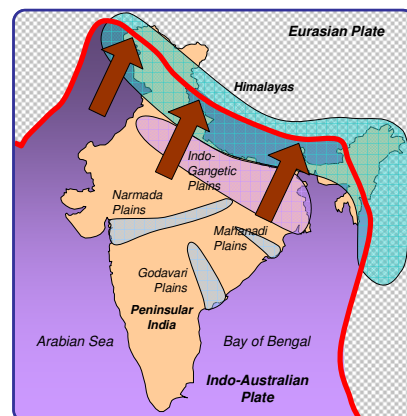


Figure 1. Geographical Layout and Tectonic Plate Boundaries at India [Murty, 2005]

Three chief tectonic sub-regions of India [GSI, 2000] are the mighty *Himalayas* along the north, the plains of the Ganges and other rivers, and the peninsula. The Himalayas consist primarily of sediments accumulated over long geological time in the Tethys. The Indo-Gangetic basin with deep alluvium is a great depression caused by the load of the Himalayas on the continent. The peninsular part of the country (i.e., low-to-moderate regions of the country) consists of ancient rocks deformed in the past Himalayan-like collisions. Erosion has exposed the roots of the old mountains and removed most of the topography. The rocks are very hard, but are softened by weathering near the surface. Before the Himalayan collision, several tens of millions of years ago, lava flowed across the central part of peninsular India leaving layers of basalt rock. Coastal areas like Kachchh show marine deposits testifying to submergence under the sea millions of years ago. Thus, understanding the seismotectonics of the peninsular region (i.e., low-to-moderate seismic region) of the country is a complex.

The seismotectonic atlas of the country [GSI, 2000] indicates few fault lines, but a large number of lineaments. This information is not readily usable in engineering applications owing to absence of slip rates at the faults and the size of potential maximum events at the faults. Also, there are no commonly understood mechanisms of macro-tectonics within the Indian plate (i.e., the low-to-moderate seismic region of the country) as agreed by the community of earth scientists, which leads to lack of confidence amongst the younger scientists to take to such investigations with conviction.

Time is opportune to take steps to (a) create a map of active and passive faults in the country, indicating the slip rates on them, and (b) develop and popularize macro-tectonic models for the low-to-moderate seismic regions of the country.

3 PAST EARTHQUAKES IN INDIA

3.1 Text and indenting

A formally collected and scientifically complete catalog is not available of earthquakes in India. Often, information on past earthquakes is gathered indirectly from historic renditions of the political history of the country or from religious scriptures [Iyengar, 2004]. Thus, most existing catalogs [e.g., Bapat et al, 1983] are incomplete from many points of view. A number of significant earthquakes occurred in and around India over the past century (Figure 2). Most earthquakes occurred along the high seismic region of the Himalayan plate boundary (i.e., inter-plate earthquakes), but a few have occurred in

the low-to-moderate seismic region of the peninsula also (i.e., intra-plate earthquakes).

Some of the damaging and recent earthquakes are listed in Table 1. Four Great earthquakes ($M > 8$) occurred in a span of 53 years from 1897 to 1950; the January 2001 Bhuj earthquake ($M 7.7$) is almost as large. Each of these caused disasters, but also allowed us to learn about earthquakes and to advance earthquake engineering. For instance, 1819 Cutch Earthquake produced an unprecedented ~3m high uplift of the ground over 100km (called Allah Bund). The 1897 Assam Earthquake caused severe damage up to 500km radial distances; the type of damage sustained led to improvements in the intensity scale from I-X to I-XII. Extensive liquefaction of the ground took place over a length of 300km (called the Slump Belt) during 1934 Bihar-Nepal earthquake in which many structures went afloat; liquefaction was brought to fore. Some of these events occurred in populated and urbanized areas and hence caused great damage. Many went unnoticed, as they occurred in relatively un-inhabited places. For these reasons, scientists showed lesser interest in areas with low-to-moderate seismicity.

Instrumented data also is scanty. Most of the strong motion arrays are in the severe seismic regions, and none in the low-to-moderate seismic regions; there are individual instruments scattered in the latter region, but not in arrays. Even the available data is neither compiled at a single reliable source, nor available easily. Even for recent events, e.g., 2004 Sumatra Earthquake and Tsunamis, strong ground motions are not available. Once again, an opportunity was lost to calibrate the ground motion with the performance of buildings and structures.

Steps should be taken immediately to (a) compile a scientifically complete catalog of past earthquakes in India, (b) make instrument recording reliable, and (c) maintain a centralized database of strong ground motions recorded from instruments.

4 SEISMIC ZONE MAPS

Four decades from 1962 also saw the development of the Indian seismic codes, and along with it the formal seismic zones and seismic zone maps. Varying geology at different locations in the country implies that the likelihood of damaging earthquakes taking place at different locations is different. The seismic zone map attempted to reflect these regions. The Indian Standards provided the first seismic zone map in 1962, which was later revised in 1966. The first seismic zone map [IS:1893, 1962] of Independent India had seven seismic zones, namely O, I, II, III, IV, V, and VI; O was considered non-seismic zone (Figure 3a).

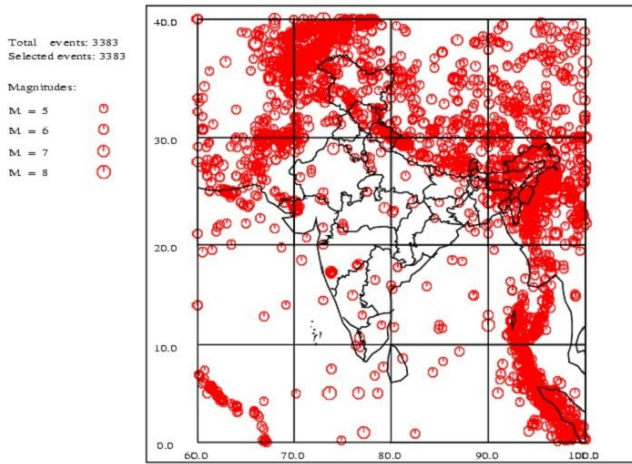


Figure 2. Epicenters of Past Earthquakes (1800-2001) of magnitude greater than 5.0 [IMD, 2008]

Table 1. Some Past Earthquakes in India [IMD, 2008; Bapat et al, 1983]

Date	Event	Time	Magnitude	Max Intensity	Deaths
16 June 1819	Cutch	11:00	8.3	VIII	1,500
12 June 1897	Assam	17:11	8.7	XII	1,500
8 February 1900	Coimbatore	03:11	6.0	X	Nil
4 April 1905	Kangra	06:20	8.6	X	19,000
15 January 1934	Bihar-Nepal	14:13	8.4	X	11,000
31 May 1935	Quetta	03:03	7.6	X	30,000
15 August 1950	Assam	19:31	8.5	X	1,530
21 July 1956	Anjar	21:02	7.0	IX	115
10 December 1967	Koyna	04:30	6.5	VIII	200
23 March 1970	Bharuch	20:56	5.4	VII	30
21 August 1968	Bihar-Nepal	04:39	6.6	IX	1,004
20 October 1991	Uttarkashi	02:53	6.6	IX	768
30 September 1993	Killari (Latur)	03:53	6.4	IX	7,928
22 May 1997	Jabalpur	04:22	6.0	VIII	38
29 March 1999	Chamoli	12:35	6.6	VIII	63
26 January 2001	Bhuj	08:46	7.7	X	13,805
26 December 2004	Sumatra	06:28	9.3	IX	10,749
10 October 2005	Kashmir	09:20	7.6	IX	~1,400

The seismic zone maps are revised from time to time (Figure 3) as more understanding is gained on the geology, the seismotectonics and the seismic activity in the country [Murty, 2005]. The second map [IS:1893, 1966] only moved the margins between these zones; the broad features were maintained (Figure 3b). Based on the levels of intensities sustained during damaging earthquakes in the interim period in regions considered to be low seismic areas (e.g., 1967 Koyna and 1969 Bhadrachalam Earthquakes), the 1984 version of the zone map [IS:1893, 1984] subdivided India into five zones – I, II, III, IV and V (Figure 3c), by merging area under erstwhile zone O to that of zone I, and of zone VI to that of zone V (Table 2). Also, significant changes occurred in the peninsular region along the western and eastern coastal margin, where these 1967 and 1969 earthquakes occurred. The maximum Modified Mercalli (MM) intensity of seismic shaking expected in the five zones I, II, III, IV and V were V or less, VI, VII, VIII, and IX and higher, respectively. Parts of Himalayan boundary in the north and northeast, and the Kachchh area in the west were classified as zone V.

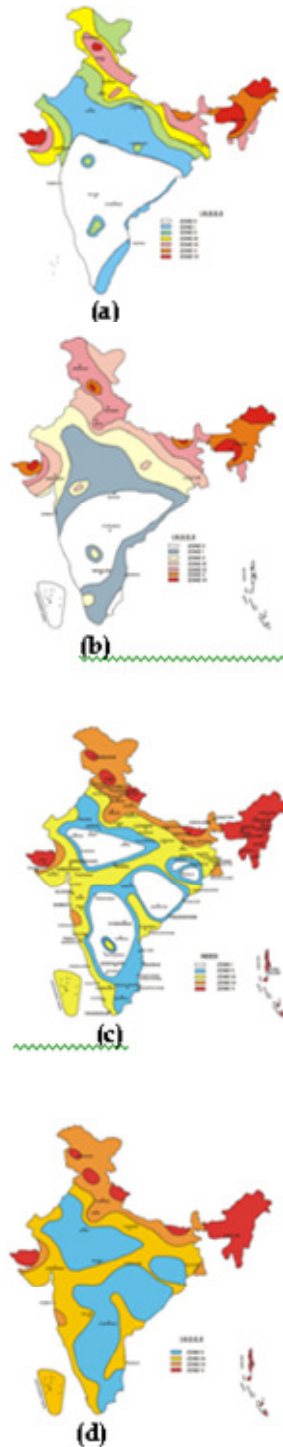


Figure 3. Indian Seismic zone maps since 1962: (a) 1962 edition, (b) 1966 edition, (c) 1984 version, and (d) 2002 edition (Redrawn based on IS:1893-1962, 1966, 1984 and 2002).

Public uproar following the 1993 Killari (Maharashtra, Central India) earthquake that occurred in the erstwhile seismic zone I, with about 8,000 fatalities, again raised questions on the validity of the seismic zone map in peninsular India. The 2001 Bhuj earthquake in the most severe seismic zone V of the country caused about 13,805 fatalities. These two events in particular pressured the Bureau of Indian Standards to revise the seismic zone map again in 2002 (Figure 3d); it now has only four seismic zones – II, III, IV and V [IS:1893, 2002].

Table 2. Indian Seismic zones reduced with each recent revision, owing to increased perception of seismic threat

Year of Release of Zone Maps			
1962	1966	1984	2002
0	0	I	II
I	I		
II	II	II	
III	III	III	
IV	IV	VI	
V	V	V	
VI	VI	V	

The areas falling in seismic zone I in the 1984 version of the map are merged with those of seismic zone II. Also, the seismic zone map in the peninsular region has been modified. Chennai now comes in seismic zone III as against in zone II in the 1970 version of the map. This 2002 seismic zone map is not the final word on the seismic hazard of the country, and hence there can be no sense of complacency in this regard.

The national Seismic Zone Map presents a large-scale view of the seismic zones in the country. Local variations in soil type and geology cannot be represented at that scale. Therefore, for important projects, such as a major dam or a nuclear power plant, the seismic hazard is evaluated specifically for that site. Also, for the purposes of urban planning, metropolitan areas are being microzoned to account for local variations in geology, local soil profile, etc.. On the one hand, a consistent material macro seismic zone map is not available, while on the other hand, detailed seismic micro-zonation studies are being undertaken for many cities of the nation. Field geology and paleo-seismology studies are too few especially in the low-to-moderate seismic zones, that there is little confidence in the available data. The number of qualified and trained technical hands is so few and the pace of urbanization is so rapid in the low-to-moderate seismic zones, that an urgent effort is required to revise the macro zones of the country. At least, the new constructions in these low-to-moderate seismic zones should be made consistent with the rationally considered prevalent seismic hazard. While in the long run, a probabilistic seismic zone map may be developed, for now a deterministically derived seismic zone map is necessary.

5 PALEOSEISMOLOGY IN LOW-TO-MODERATE SEISMIC REGIONS OF INDIA

Indian sub-continent is prone to earthquakes in the inter-plate as well as intra-plate regions. The areas that fall in severe seismic regions include the Himalayan belt in the north from Kashmir to Assam, Gu-

jarat in the west, and Andaman & Nicobar Islands in the southeast (Figure 4). The fault lines in these areas are capable in generating large magnitude earthquakes putting the neighbouring areas also to moderate ground shaking. But, on a large part of the remaining regions, information is not easily available on existing active and passive fault systems, thereby giving a false impression of low seismicity in that region. Surprise events (e.g., the 1993 Killari earthquake in the lowest seismic zone I) have resulted in heavy loss of life and property. Thus, seismic hazard assessment is of prime importance in India. It has been suggested that paleoseismic investigations are one of the best approaches to build understanding of the past historic earthquakes that remained unrecorded, in locating the areas having potential of producing large magnitude earthquakes, behaviors of individual active fault lines and slip rate along them, and recurrence interval of major earthquakes. This information is very vital in evaluating seismic hazard of any tectonically active region [McCalpin,1996]. However, very few studies have been carried out so far in India, specifically to identify the presence of active faults and to understand their potential to produce large magnitude earthquakes [e.g. Nakata, 1972; Yeats et al., 1992; Yeats et al. 1997; Seeber et al., 1996; Rajendran et al., 1998; Rajendran and Rajendran, 1999; Sukhija et al. 1999 a, b; Oatney et al. 2001; Kumar et al., 2001; Malik and Nakata, 2003; Malik et al., 2003; Malik and Mathew, 2005; Kumar et al., 2006; Malik et al., 2006; Rajendran et al., 2006; Rajendran et al., 2007]. Along with this, the historic data is not complete of earthquakes in India, hence making proper seismic hazard assessment even more challenging.

Paleoseismological information from the high seismic Himalayan regions has added to the existing data, and is of great importance for the moderate seismic region of the adjoining thickly populated Indo-Gangetic Plain which comprise thick alluvium that are highly vulnerable to hazard from liquefaction during strong seismic shaking. In the region of Kachchh, seismic events did not always result in surface rupture, indicating that large magnitude earthquakes are generated not only by active faults, but also by blind faults (Figure 5). This is also the situation in low-to-moderate seismic regions, which makes seismic hazard assessment in those regions most difficult and complex task.

The area of peninsular India where the rate of seismicity is very low as compare to that observed along the plate boundary. Inconsistency between the short term and long term geological manifestations of deformation on the surface because of very little neotectonic movement along the faults have resulted in poor understanding of intra-plate seismotectonics [Seeber et al., 1996]. The occurrence of 1993

(Mw6.1) event killing about 8,000 people was an example which suggested that the area which was considered to be the part of the “Stable Continental Regions” (SCR) is no more considered as stable. Therefore, such areas are extremely difficult to deal with in terms of seismic hazard assessment where no historic earthquake data as well as geological evidences are available.

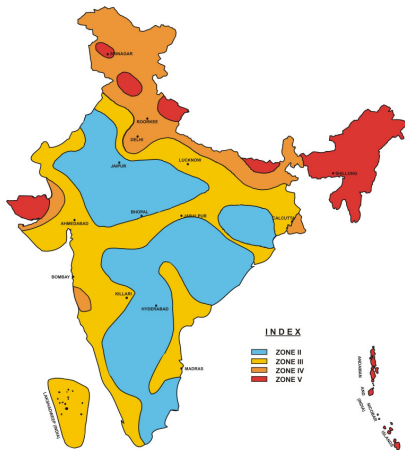


Figure 4. Current seismic zone map of India [Redrawn based on IS: 1893-2002]

Coordinated national research programme, including a strong component of paleoseismology, should be put in place urgently to develop better estimate the low-to-moderate seismicity in the country. Top-down research projects should be entrusted to active research groups with good track record, and bottom-up research proposals from younger scientists should be funded with appropriate accountability and peer review.

6 EARTHQUAKE ENGINEERING PRACTICE IN INDIA

The Indian earthquake history was well documented by the British. The 1897 Great Assam earthquake (M8.1) is a major event that led to an improvement of the Earthquake Intensity Scale – from I to X to I to XII, based on the widespread damages sustained by the built environment and extensive changes noticed in natural topography. The 1935 Baluchistan earthquake led to the first unofficial seismic zone map of undivided India, when a young engineer provided a zonation based on damages sustained by large earthquakes till then.

The 1930 Assam earthquake brought to fore the importance of soil liquefaction, while the 1905 Kangra earthquake showed that the un-reinforced masonry constructions can lead to large human fatalities. The recurrence of another large earthquake (1950 Great Assam earthquake) in the same tectonic region as the Great Assam earthquake of 1897, em-

phasized that India needs to reduce earthquake risk by improving its built environment.

In 1958, a young academic then, Professor Jai Krishna, of the University of Roorkee, on a short trip to North America learnt that indeed India could work towards reducing earthquake risk. On his return to India, he started the School of Research and Training in Earthquake Engineering (SRTEE) at the University of Roorkee in 1959. And the next two decades were spent in developing the earthquake engineering program – a post graduate program in Seismology, Soil Dynamics and Structural Dynamics, Shock Table (laboratory) facility, and earthquake recording instrumentation program. The SRTEE grew into the Department of Earthquake Engineering. In the late 1980s, the shake table was installed at the University of Roorkee. The faculty members at the University of Roorkee offered consultancy services to support the needs of large civil engineering projects of the country. But strangely enough from the 1960s through the 1980s earthquake engineering was not known to be on the list of activities of any other academic institute /university or of any organization of the country.

From 1988, the country has experienced nine earthquakes that resulted in loss of life and property. Awareness grew amongst the academics, practicing professionals, governments, and local population. In the last decade, a number of changes have taken place in the country. In 1999, the National Information Center of Earthquake Engineering (NICEE) was started at IIT Kanpur; this center gives away information on earthquake safety. In 2003, the National Programme on Earthquake Engineering Education (NPEEE) was initiated by the Ministry of Human Resource Development, Government of India; this is a program targeted towards training teachers on earthquake engineering. In 2005, the National Disaster Management Authority (NDMA) was formed to coordinate all matters related to disaster management, and the Disaster Management Act was passed in the Parliament of India, mandating the need to formally recognize disaster management in the plan process of the country. The NDMA released the

guidelines for management of earthquakes in July 2007. Work is underway to implement these guidelines in the various states.

Notwithstanding the above changes in the country, the practice has remained to be non-seismic. Earthquake resistant design was not taught at any college in India till 2003. Even after that only handful of colleges mandated the need to teach earthquake design concepts in the undergraduate programs of engineering and architecture. Hence, largely the practicing architects and engineers are ignorant of the correct practices of earthquake resistant design and construction. With over 60% of India un-

der the threat of moderate to severe seismic threat and no education at the technical colleges, the country continues to add brittle constructions in seismic areas. Moreover, there is no regulation in place to ensure that only such engineers are employed, who have the requisite education and experience to design and build earthquake resistant structures. Also, there is no mechanism in place to scrutinize the design submitted to the municipal offices by professional engineers for their compliance with the earthquake resistant design standards. With this plight in the high seismic regions, the challenge of making construction that can safely withstand seismic shaking in low seismic regions is a far cry.

In the severe seismic regions, the occasional occurrence of earthquakes does help sensitize the common man of the need to undertake steps to ensure earthquake safety in the built environment.

This opportunity is not available in low-to-moderate seismic regions. The rare occurrence of earthquakes in these regions develops complacency in the common man and prevents them from undertaking steps to protect themselves from the eventual reality of the earthquake shaking. Hence, an earthquake awareness program is required in low-to-moderate seismic regions to sensitize the various stakeholders of the importance of seismic design and construction.

Even though the country is huge and the population large, India needs to put a stop to non-formal practice of adding built-environment. As a step to improve the earthquake safety of the built environment, the Government of India should (a) enforce the regime of licensing of engineers, and (b) introduce the concept of peer review process for scrutiny of structural designs.



Figure 5. West wall view of trench excavated on the hanging wall of Allah Bund Fault (ABF) near Vigokot. The trench reveals occurrence of at least 3 events. The events have been inferred based on the formation of carter and its cross-cutting relationship

Human resource development should be given the highest priority. Implementing earthquake safety requires a large workforce that is trained in the subject. Formal training and private training, both should be made easily available. The Ministry of Human Resource Development should reinstate educational programmes, such as the National Programme on Earthquake Engineering Education, for sustained human resource development. In addition, another initiative should be put in place to encourage research on problems of national relevance. The areas of research should span all aspects of seismic hazard assessment, and earthquake resistant design and construction.

7 EARTHQUAKE-RESISTANT DESIGN FOR STRUCTURES IN LOW-TO-MODERATE SEISMIC REGIONS

7.1 Why Seismic Design is different from Design for Other Effects

Design for wind forces and for earthquake forces are distinctly different. The intuitive philosophy of structural design uses "force" as the basis, which is consistent in wind design wherein the building is subjected to a "pressure"-type loading on its exposed surface area. However, in earthquake design, the structure is subjected to random movement of the ground at the base of the structure (Figure 6). This motion at its base induces inertia forces in the structure that cause relative deformations in the structure, which

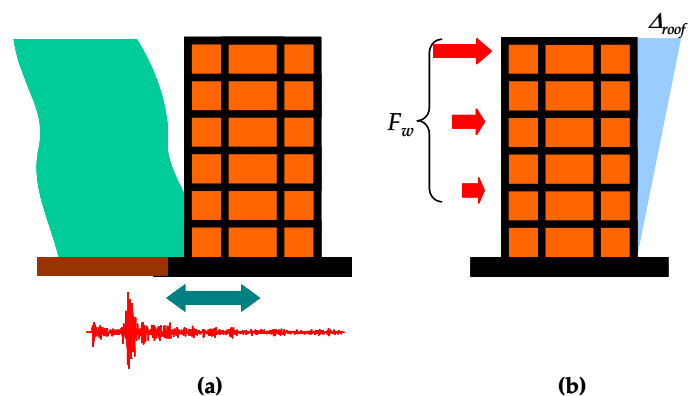


Figure 6. Difference in the design effects on a building during natural actions of earthquake and wind: (a) Earthquake Ground Motion at base, and (b) Wind Pressure on exposed area.

Further, wind force on the structure has a non-zero mean component superposed with a relatively small oscillating component (Figure 7). Thus, under wind forces, the structure may experience small fluctuations in the stress field, but reversal of stresses occurs only when the direction of wind reverses, which happens only over a large duration of time

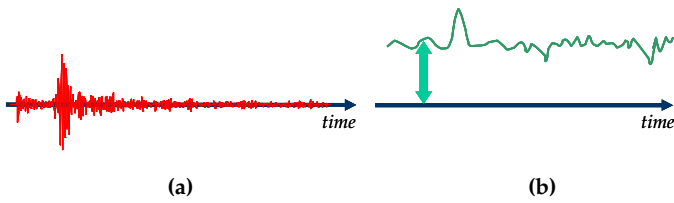


Figure 7. Nature of temporal variations of design actions of earthquake and wind: (a) Earthquake Ground Motion: zero mean, cyclic (b) Wind Pressure: non-zero mean, oscillatory.

On the other hand, the motion of the ground during the earthquake is cyclic about the neutral position of the structure. Thus, the stresses in the structure due to seismic actions undergo many complete reversals and that too over the small duration of earthquake.

Moreover, since the earthquake induces inertia forces, the mass of the structure being designed enters seismic design calculations. Normal civil engineering structures tend to be very massive, and designing them to behave elastically during earthquakes without damage may render the project economically unviable. On the contrary, it may be necessary for the structure to undergo damage and thereby dissipate the energy input to it during the earthquake. Therefore, as per the seismic design philosophy, (a) under strong shaking, structural damage is acceptable, but collapse is not, (b) under moderate shaking, repairable structural (and non-structural) damage is acceptable, and (c) under minor shaking, structural damage is not acceptable. Consequently, structures are designed only for a fraction of the force that they would experience if they were designed to remain elastic during the expected strong ground shaking (Figure 8), and thereby permitting damage (Figure 9). But, sufficient initial stiffness is ensured to avoid structural damage under minor shaking. Thus, seismic design balances reduced cost and acceptable damage, thereby making the project viable. This careful balance is arrived at based on extensive research and detailed post-earthquake damage assessment studies. A wealth of this information is translated into precise seismic design provisions. In contrast, structural damage is not acceptable under design wind forces.

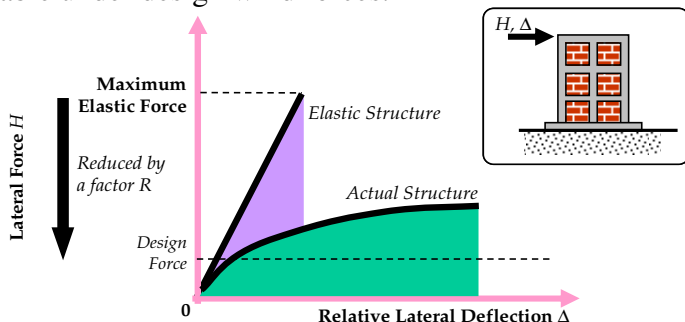


Figure 8. Basic strategy of earthquake design: Calculate maximum elastic forces and reduce by a factor to obtain design forces.

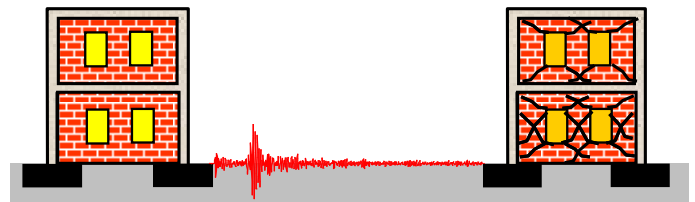


Figure 9. Damage during earthquakes: In normal structures, damage is acceptable. However, location and type of damage need to be carefully tuned through Capacity Design Concept.

7.2 Ductility

The design for only a fraction of the elastic level of seismic forces is possible only if the loading is displacement controlled (as imposed by earthquake shaking) and the structure, its components or the materials used in construction can stably withstand structural inelastic actions without collapse and undue loss of strength at deformation levels well beyond the elastic limit. This property is called *ductility* (Figure 10) and helps in absorbing input earthquake energy through hysteretic behavior. It is quantified as the ratio μ of *maximum deformation* Δ_{max} that can be sustained prior to failure (or significant loss of strength) to the *yield deformation* Δ_y .

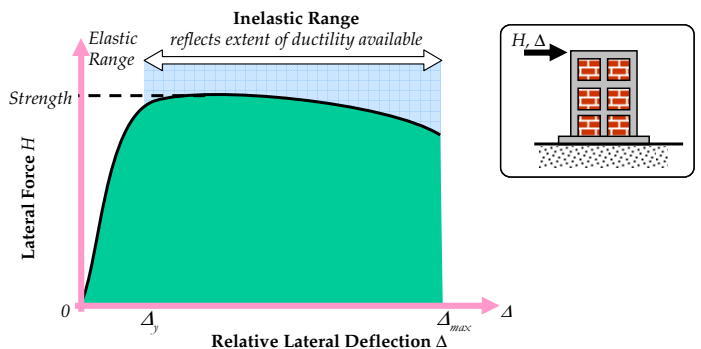


Figure 10. Ductility: Overall load-deformation relation of a structure with good inelastic range of behaviour following the initial elastic range.

Thus, a good ductile system exhibits enhanced inelastic deformation capacity without significant loss of strength capacity (Figure 11). This condition is the *plastic* condition of the structure.

Earthquake-resistant design of structures relies heavily on ductility in accommodating the imposed displacement loading on the structure. Overall ductility of a structure is realized through ductilities at different levels – these are structural or *global* ductility, *member* ductility, *section* ductility and *material* ductility. Good material ductility helps in achieving better section ductility, which, in turn, helps in achieving improved member or component ductility.

Good global ductility depends on good member, section and material ductility. Post-earthquake investigations of structures damaged during earthquakes and extensive laboratory tests on full-

scale specimen identified preferable methods of design and detailing that leads to improved ductility.

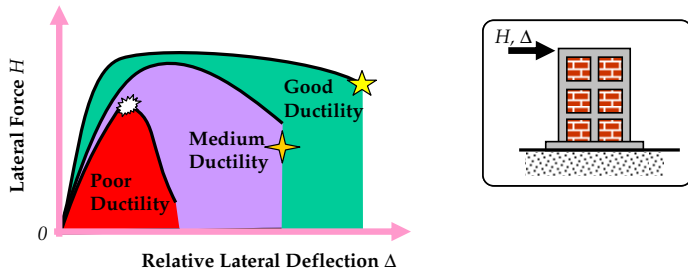


Figure 10. Ductility: overall load-deformation curves of three structures with varying ductility. Through seismic design, structures are designed and detailed to develop favorable failure mechanisms that possess specified lateral strength, reasonable stiffness and, above all, good post-yield deformability.

It is possible to design structures to possess a required lateral strength and initial stiffness by appropriately proportioning the size and material of the members, but achieving sufficient ductility through mobilization of plastic condition is more involved. For example in RC buildings, an overall *structural ductility* of only 2-5 may be possible (based on, say, roof displacement Δ), even when mild steel reinforcing bars (rebars) in RC beams have *material ductility* (i.e., ratio of ultimate strain and yield strain) as large as 150-170.

Ductility in buildings and structures can be achieved by (a) choosing a regular seismic structural configuration for the structure with adequate structural redundancy, (b) tuning damage to occur at pre-determined locations in members by capacity design concepts, and (c) ensuring that only a certain type of damage occurs (i.e., that with increased member ductility). The architect is responsible for achieving the first step and the second and third steps are the responsibility of the structural engineer, who must follow the requirements of the relevant codes in all regards. Performance-based Design

Under strong earthquake shaking, the structure undergoes nonlinear actions. As mentioned before, the earthquake imposes a displacement loading on the structure, i.e., the earthquake demands that the structure be capable of resisting a certain displacement loading underneath it. The more severe is the earthquake, the more is the relative displacement imposed in the structure (Figure 12). If the structure does not have that capacity to deform in the nonlinear range (i.e., it has poor ductility), the structure is expected to perform poorly during strong earthquakes.

The extent of these nonlinearities determines the level of damage incurred in the structure and its residual strength. While low levels of nonlinearities may not be manifested into visible signs, often high

levels of nonlinearities are visible. Thus, damage is classified in terms of users perceptions into three regions (Figure 13), namely (a) the structure *can be occupied* immediately after the earthquake, (b) the structure *does not pose threat to life and property*, but structural evaluation required before re-use of the structure, and (c) the structure *is in the pre-collapse stage*, it cannot be occupied after the earthquake and it cannot be re-used after this earthquake event. The boundaries between these regions are fuzzy; neither the user nor seismic behaviour subject experts can give sharp demarcation boundaries between these regions.

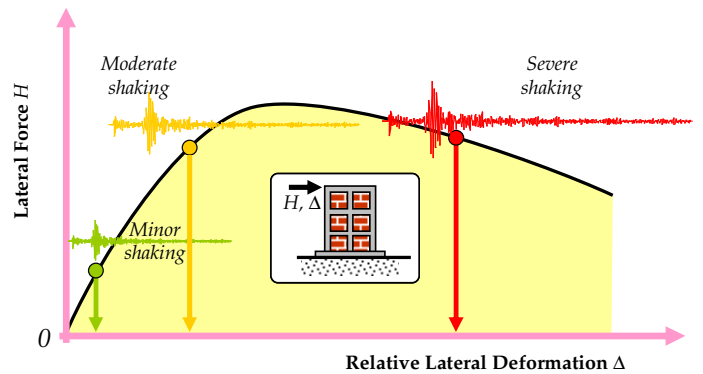


Figure 12. Levels of earthquake shaking: Stronger shaking pushes the structure into a larger displacement region on load-deformation relation of a structure.

But, given the visible damage in a structure, it is not easy even for experienced experimentalists to point out exactly the state of the structure on the load-deformation curve. In any case, the user is more interested in the direct losses (measured by the cost of retrofitting the structure to restore it to full capacity) incurred by each level of damage than in the level of nonlinearity.

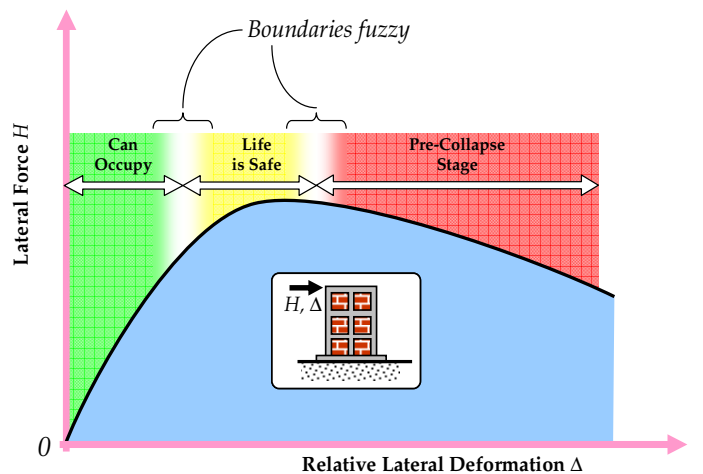


Figure 13. Performance regions: Overall load-deformation relation of a structure showing the various zones and their interpretation by users.

7.3 A Case for Displacement-Based Design

The current seismic codes assign a peak ground acceleration factor Z with each seismic zone. Thus, a typical designer associates this peak ground acceleration factor Z with force-based design – a total force demand is to be calculated, applied on the structure, elastic structural analysis performed, members designed for the stress resultants so obtained, elastic displacement demand verified to be within the permissible lateral inter-storey drift, and detailing done as per prescriptions of codes. The conflict arises when the designer is asked to guarantee certain *inelastic displacement ductility* in the overall structure that was just designed for a certain force level as per the zone. There appears to be a gap between the *steps involved* in the design process (that considers *elastic* behaviour) and the *end deliverable* of the design process (that reflects *inelastic* behaviour). Of course, the catch is in the ductile detailing prescribed by the seismic design codes – research has established that the ductile detailing makes members to develop certain ductility in them, and collectively the ductilities in these individual members result in certain displacement ductility in the whole structure.

Alternately, to make designers internalize the concept of ductility, it may be easier to bring the concept of displacement demand from the seismic zone map itself. Let each zone be assigned a certain *peak displacement demand* associated with the design ground motion in addition to the peak ground acceleration factor Z . This displacement demand is useful in designing the non-structural components, particularly ones whose design is governed by displacement demands. A few examples of such non-structural elements are: (a) brittle water and sewer pipes running along the height of buildings and structures, (b) safety of structural glazing under lateral deformation of buildings, and (c) electrical cables and gas pipes running from outside ground to inside the building that is swaying laterally by large displacements under strong ground motion.

Secondly, the near-field of an earthquake has long been recognized as a region in which conventional wisdom regarding earthquake resistance has been inadequate. Studies showed that the type and location of damage to buildings defied explanations presented by normal analyses. The reason for this is the presence of directivity and fling effects in the near field, which translate as strong and distinct pulses in the ground displacement and velocity records. These pulses are extremely damaging to buildings as they cause very high localized deformations. Moreover, conventional *force-based* equivalent static analysis often fails to take them into consideration.

Thirdly, a study of near-field data from the Northridge earthquake in 1994 described the implications of near-field characteristics of ground motion for structural design [Iwan, 1994]. A *drift spectrum* was proposed as a supplement to the response spectrum. It was argued that the response spectrum is useful as an indicator of the demand placed on a structure when the structural response is dominated by a single mode, and when the ground motion resembles a broad-band random process. It cannot account for the relative phasing of the modes of vibration while this factor is particularly important for pulse-like ground motion. The limitations of a response spectrum analysis can be understood by considering a tall structure excited at its base by a finite-duration constant-amplitude velocity pulse. The pulse will cause a traveling wave to propagate upward through the structure until it reaches the top and is reflected back. As more pulses begin to travel up and down the structure, the deformation gradually settles into a steady state dominated by one mode of the structure. However, the shape of the deformation wave during the first few cycles of reflection cannot be approximated by any single mode. Thus, it was concluded that the *force-based* response spectrum is a good indicator of maximum global amplitude of structural response, but does not accurately predict localized deformations.

7.4 Separate Provisions for Low-to-Moderate Seismic Regions

Low seismicity regions are faced with low probability of occurrence of earthquake events that can cause damage. But, when these events occur, losses are colossal because of poor performance of the structures. Notwithstanding this, design codes often do not mandate seismic design provisions (particularly those that build ductility into the structure) in low seismic regions. While this may be in order to ensure economy of constructions, it does not address the consequences when the rare earthquake event occurs. An alternative option is that all design provisions valid for high seismic regions may be applied in low seismic regions also, in particular the ductile detailing provisions. The design process may be kept same for both high and low seismic regions, with just the seismic zone factor Z being different.

The alternate option is conservative. Thus, the current practice (original option) needs to be reviewed for low seismic regions. When that rare event occurs in the low seismic regions, the design process must incorporate only such elements of the design process which will *guarantee no collapse* in the structure, even though it may have structural damage that is not repairable. This is not so straight-

forward a task to accomplish. In stiff structures, one may provide ductility, but that cannot be exploited because unless the structure swings and goes into inelastic range, the ductility capacity that is provided for use under inelastic conditions cannot be used. In flexible structures, again the ductility may not be usable, because most of the deformation is absorbed as elastic deformation and thereby leaving very little for inelastic actions. A comprehensive research program is required to develop such a design methodology.

8 CONCLUDING REMARKS

It is difficult to believe that in the largest democratic country of the world with over 1.1 billion population, there is a severe shortage of trained technical manpower to successfully conduct earthquake engineering practice. Over 60% of the country's land area is under the threat of moderate to high seismic activity. And, in the last 60 years of independence, India has added large vulnerability through its built environment even with four earthquakes of magnitude greater than 8.0 taking place during 1897-1950 and creating enough negative experiences.

But, there has been a significant change in the national scenario particularly in the last decade, and seismic hazard is being better understood by the stakeholders. During the last decade, a number of initiatives were undertaken in the country. Today, if the momentum of these initiatives is sustained through quality leadership and unflinching hard work, India may be well on the road to a strong earthquake engineering practice within another two decades. But, a prerequisite for this is that engineering design strategies need to be developed, particularly suited for low-to-moderate seismic regions. In particular, efforts are required towards (a) implementing an awareness campaign for all stakeholders especially in low-to-moderate seismic regions, (b) enforcing design codes by instituting a techno-legal regime, (c) providing education (teaching and research) in technical colleges and institutes along with schools, (d) continually developing and updating seismic design provisions towards improving earthquake safety, especially for the low-to-moderate seismic regions, and (e) understanding and estimating seismic activity across the country.

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