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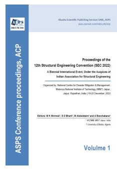

# Evaluation of Regional Demand Parameters for Design of Mid-high-rise Building Using Past Earthquake Records

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**Abstract**

Category of earthquake and distance from epicenter are the prime parameters that decide the demand on buildings for its engineering. As observed in past Bhuj earthquake of 2001 (7$M_w$), seventy buildings got severely damaged in Ahmedabad city which is located 250kms from the epicenter. Intensity index through observed damages fills the gap for the demand anticipations. Design of a building considering excitation frequency rather than just the zone factor is necessary to include effects of low frequency waves (e.g. *Mexico-city*). This paper shows the broad ways in which seismic demand can be obtained for performing PBD in Indian context. A mid-rise RC building is designed as per three standard code of practices (i.e. IS, ACI, EN) to provide seismic resistance. The anticipated demand levels are obtained using GMPEs (PEER), magnitude-intensity relations, micro-zonation study and NDMA hazard contours for 15 storey building in Ahmedabad. The highest capacity curve is for design using IS 1893 code and this building will survive earthquake having 0.22g PGA value. The magnitude-intensity-epicentral distance relation (*Gutenberg et al*, 1956) shows that the intensity of VII for Zone-III is not correct for Ahmedabad city and it shall be taken as VIII which is for Zone-IV (0.24g) as per zoning map of India. However, as per the micro-zonation study showing PGA of 0.18g for the city it can be said that building will survive the next earthquake of 7.0$M_w$ in Bhuj. The damage to non-structural elements is evident from the NLTHA using matched response spectrum obtained using Uttarkashi and Chamoli earthquake records (COSMOS). It is suggested to use intensity-based response spectrum for design of mid-high-rise buildings in Ahmedabad city. Moreover, a local directive based on social and technology resilience shall be developed to provide design basis based on loss (%)-multiple hazard (PGA) matrix using the matching relations found in this paper. Design provisions and loss reduction strategy can only lead to sustainable infrastructure in cities planning for vertical development.

*Keywords*: Performance-Based-Design, Site-specific-response, Earthquake Resistant Design, Time-History-Analysis, Seismic hazard

## 1. Introduction

India is a country having experienced earthquakes ranging from low magnitude to high magnitude since many years. The seismicity of country has been categorized in seismic prone zones through seismic hazard mapping and EPGA (effective time peak ground acceleration) values have been estimated to show the severity of a MCE (maximum considered earthquake) level earthquake. However, these EPGA values mentioned in IS1893 are not the true representative of the effect of a hazard on buildings. The demand to be estimated for a building which may be near to the fault or far away from the fault shall be representing the geological factors that change the mood of the seismic hazard towards that building. Estimation of demand is the most important factor for designing and evaluating the performance of a building as it is the necessary parameter towards estimation of risk. The risk on a building comprises of demand (hazard) and vulnerability (*Zhenming Wang*, 2009). The third parameter to estimate risk is the asset that is under the threat of earthquake (*Scawthorn et al*, 2006). Vulnerability can be social and technology based.

After the Bhuj earthquake in 2001, the study on the seismicity of Gujarat state became active as the region was not previously considered as seismically active region. Gujarat has earthquake hazards of each seismic zone represented by EPGA (zone-II to V). This earthquake made it clear to the engineers that multi-storey buildings located at 400km away from the epicentre can be damaged or razed (*Rastogi et al*, 2007). Ahmedabad city was largely affected as 130 buildings were either severely damaged or collapsed due to stronger demand. The region of Ahmedabad and Gandhinagar fall within the Cambay sedimentary basin and the soft sediments of Sabarmati river, which lead to amplification effects. The amplification levels obtained for Ahmedabad city through micro-tremor-based observations at hundred sites was 1.8-2 and is applicable for buildings having 0.4-0.8Hz frequency range (*Rastogi et al*, 2007).

The epicentral distance has significant effect on local seismic response for Kolkata city (*Mohanty et al*, 2013), based on which demand envelope is necessary for hazard estimation. This enables a structural engineer to understand the appropriate demand that needs to be taken for design of

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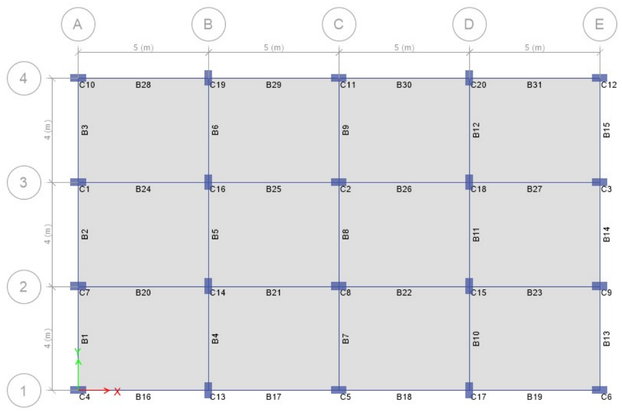



| | |
|---|---|
| Column (storey – size) | 1-3:700 ; 4-9:650 ; 10-14: 600 (IS Code)<br>1-3:900 ; 4-9:850 ; 10-14:800 (ACI Code)<br>1-3:1000 ; 4-9:900 ; 10-14:800 (EC8)<br>1-3:1000 ; 4-9:900 ; 10-14:800 (TSS-500) |
| Beam | 1-15: 500 (for all code design) |
| Slab | 120mm (rigid) |

Fig.1 Plan and section sizes of building (20m x 16m

a building in zones with amplification levels. This paper briefly covers the impact of epicentral distance and site amplification effects on design of a building through performance based seismic evaluation procedure for multiple seismic events.

## 2. Problem description

A regular 15 storey RC building is designed to suit the purpose of study. The building is SMRF type and it shall resist earthquake lateral forces by frame action to reduce the extent of problem for detailed investigation. The plan and section details of building are shown in Fig.1. The distance of the building to earthquake epicenter is considered as 250kms. The building is in seismic zone III (Ahmedabad city), designed using IS1893 (2016) and ductile detailing done as per IS13920 (2016). The time-period of building had to be set to have increased demand due to site amplification with reference to the seismic micro-zonation study done for Ahmedabad city. The designed building is put up for performance evaluation using pushover analysis and displacement coefficient method. Criteria for performance evaluation is the change in performance of building due to variation in demand parameter due to consideration of EPGA of code, seismic hazard map of NDMA for India and past earthquake records of India. Moreover, the performance of building designed with other potent seismic design codes with reference to distance from epicenter (DFE) criteria is to be evaluated.

## 3. Estimation of hazard for building

According to the seismic design code, Ahmedabad city is in zone-II having EPGA of 0.16g i.e. 156.96cm/sec$^2$ of acceleration will be experienced in this region during an earthquake in Bhuj. Based on the response spectrum of IS 1893 (2016), the value of ($Z.S_a/g$) for time-period of 1sec is found to be 0.22 which represent the coefficient of acceleration ($A_h$). However, this estimate is by deterministic approach and hence it does not exactly represent the seismicity of Ahmedabad city. The other method for better seismic hazard assessment is probabilistic approach. National Disaster Management Authority (NDMA) has developed PSHA hazard map for India having grid size of 0.2°x0.2°. According to this PSHA Map, Ahmedabad will be having the PGA values as per the return period specified for it (see Table1). Considering PSHA Contour map, the seismicity of 0.18g may be considered as the MCE level earthquake for the Ahmedabad city (refer Table-1). Considering the ground motion as 0.18g and 0.22g the response spectrum will change as the EPGA gets changed (see Fig. 3). Therefore, for 1sec ($T$) the value of $A_h$ changes to 0.25 and 0.3 (I=R=1) as compared to the value of 0.22 in case of EPGA of 0.16g. Considering this the value of seismic design force will increase by 1.14 times for 0.18g ground motion and 1.36 times for 0.22g ground motion. Hence, a multiplication factor of 1.25 can be assumed for seismic design force to include the PSHA results in code-based design of this building.

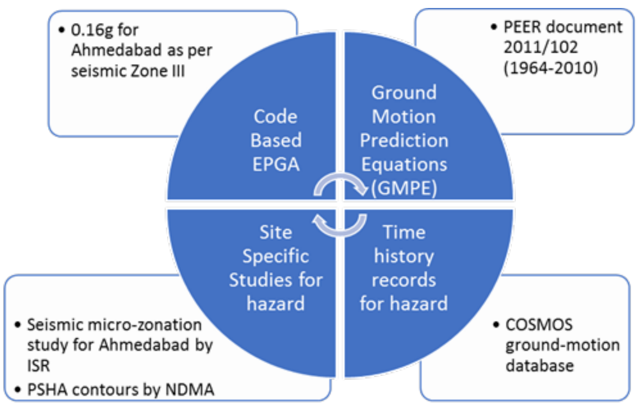



Fig. 2 Hazard estimation considered for 15-storey building

Table 1. PSHA (NDMA) results for Ahmedabad city

| Probability of exceedance | Return Period | PGA |
|---|---|---|
| 10% in 50yrs | 500yrs | 0.06g |
| 2% in 50yrs | 2500yrs | 0.12g |
| Strong earthquake | 5000yrs | 0.18g |
| Rare earthquake | 10,000yrs | 0.22g |

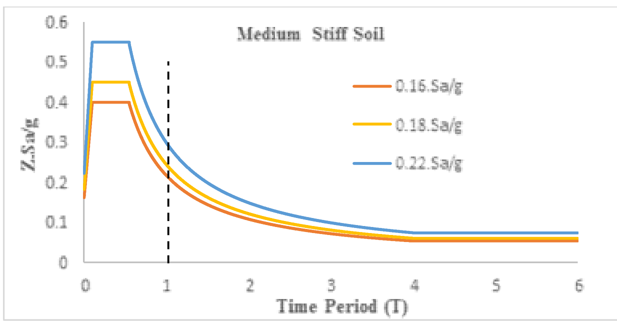



Fig. 3 Response spectrum for anticipated EPGAs

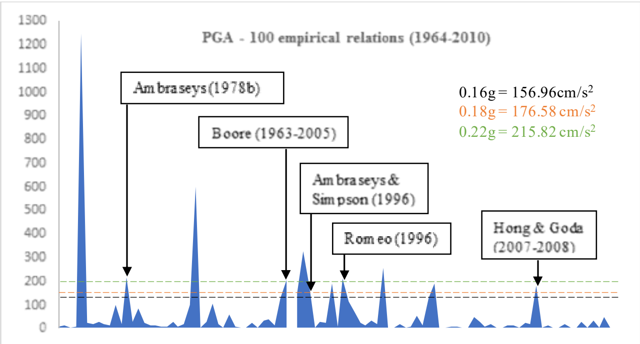



Fig. 4 Comparison of GMPEs to get distance-magnitude-acceleration (D-M-A) co-relation with estimate of seismic hazard for Ahmedabad

However, the seismic micro-zonation studies are the most accurate means for assessing the seismicity of a region. ISR had carried out seismic micro-zonation study for Ahmedabad city. Ahmedabad and Gandhinagar cities fall within the Cambay sedimentary basin with about 400 m thick Quaternary sediments. The alluvium mainly consists of alternate layers of fine to coarse grained sand, gravel and clay. The 2-5 times amplification at the frequency range of 0.4 - 0.8 Hz (i.e. 2.5s – 1.25s) that match with the fundamental frequency of 20 story buildings (*Rastogi et al*, 2007). The current building considered for seismic evaluation is having time-period of 1sec and 0.9sec which is quite rear to the frequency range specified above. Hence, the site amplification assumed for the building is taken to the value of twice the seismic acceleration considered for the building. This will require further increase in the seismic demand on building as the code-based design does not include the site amplification and nor the PSHA results. Therefore, a multiplication factor of 2.5 (= 1.25x2) is required for the seismic design force to accommodate the updated EPGA and site amplification studies for code-based design of building.

Additionally, there are more ways to estimate the seismic hazard for building based on the past earthquake records. One way of estimating the PGA values may be by using the empirical relationships developed by researchers (1964 – 2010) mentioned in PEER document (2011) for ground motion predictions. These empirical relationships are highly region specific and subject to error in results. However, they may be useful to judge the effect of real earthquakes on PGA with distance for different soil conditions and amplification factors. Out of 289 empirical relationships, 100 empirical relations were analyzed to understand the effect of magnitude (M), epicentral distance (D), soil condition (S) and fault type (F) on the seismic acceleration received at an epicentral distance of 250kms from the fault location i.e. Bhuj to Ahmedabad (refer Fig. 4). These relations are also useful in terms of estimation of seismic hazard for low to maximum magnitude earthquakes i.e. multi-level hazards with respect to magnitude of earthquake.

The magnitude of 7.0Mw is considered for the current study considering the Bhuj earthquake (2001). Based on the required seismic hazard index few of the empirical relationships matched the scenario for prediction of ground motion for Ahmedabad city (refer Fig. 4).

An integrated hazard map is developed by ISR-Gujarat through MASW study (*Dwivedi et al*, 2019) in which western-central part of Ahmedabad has the highest hazard due to presence of paleochannel (alluvium deposits due to Sabarmati River). It shows the sensitive regions in the city.

## 4. Performance Evaluation of Building

Performance evaluation of building using ASCE-41 guideline for displacement-based performance evaluation using target displacement is used for this building considering the basic behavior of building under lateral loading. The building elements are modeled with effective section properties i.e. 0.35I for beams and 0.7I for columns in ETABS software. The slab is rigid diaphragm in this study. The time-period for building design is 1sec in X-direction and 0.9sec in Y-direction based on the empirical formula of IS1893 code. For the time-period of 1sec when $T > Ts$ then $S_a = S_{X1}$ of the response spectrum. The spectral acceleration developed of this is 1.36.g/T i.e. 1.36g.

The effective time-period of the system is 1.2sec in X-direction and the target displacement obtained is 2.14m for Life Safety consideration (general spectrum). However, the response spectrum for zone factors (0.16, 0.18, 022) the value of $T_s$ will be (0.428, 0.48, 0.55) and the value of $S_a$ is (2.134, 2.40, 2.93). Accordingly, the estimate of target displacement ( $\delta_t$ ) will change with change in value of spectral acceleration ($S_a$) giving the values (312mm, 375mm, 500mm) respectively. Considering this scenario, the state of building elements will change, and more damage will be encountered in the building as the performance of building will be monitored for more displacement limit.

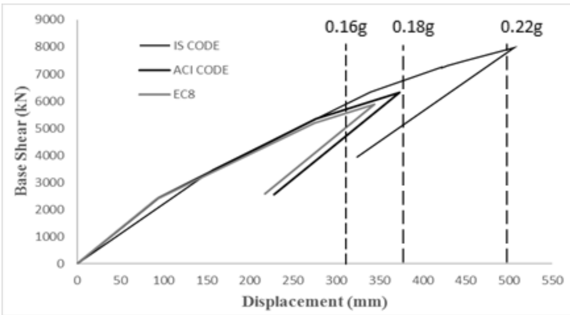



Fig. 5 Capacity curve for building for target displacements (ASCE-41)

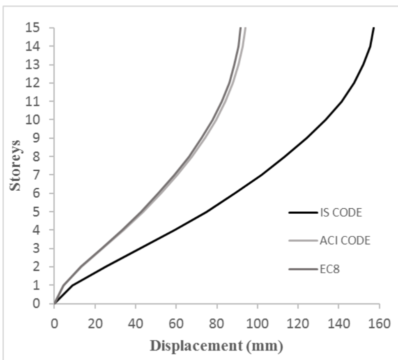
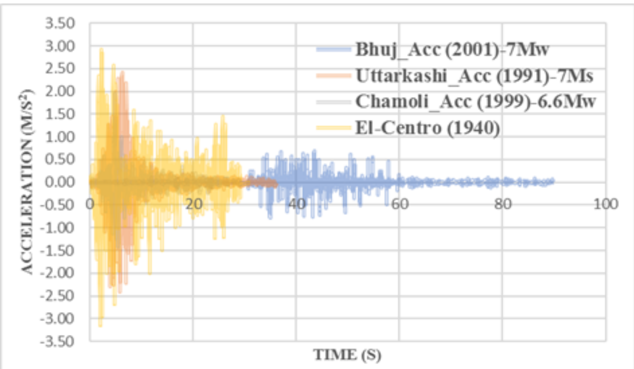



Fig. 6 Displacement in PUSHX direction for building

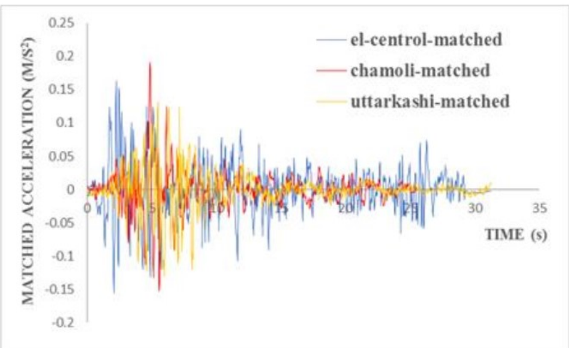
## 5. Overview of time histories for Indian earthquakes

The past earthquakes reveal the most about the hazard developed in a region and the associated damages of past can be counter-checked with the building designed for response spectrum of the code. The earthquakes that can be considered for this building are the Uttarkashi (1991), Chamoli (1999) and El-Centro (1940). The acceleration calculated as per GMPEs for 7.0Mw earthquake, the hazards as per IS Code, seismic micro-zonation studies and NDMA hazard contour can be used to monitor the range in which the time history can cause damage to the building. The effective peak ground acceleration obtained using the time history records of previous earthquakes is very general form of representing hazard. The response spectrum generated from it does not include the site effects in the code which gives wrong sense of safety to the design engineer. The geotechnical soil classification schemes were improved by considering site effects for engineering design practice (*Pitilakis et al*, 2004) against the response spectrum given in EC8. The study highlights the need to upgrade response spectrum as per the local site effects in the region. Seismic micro-zonation study of Ahmedabad shall be incorporated in design response spectrum to enable design engineer to estimate hazard and design accordingly. The use of matched response spectrum to simulate distance effects is shown.

The value of effective time-period is highest for El-Centro (1940) earthquake because of which it can be taken as a reference time history for most of the buildings. The time history plot shown in Fig.7 gives the idea about acceleration values, peak acceleration of Uttarkashi (1991),

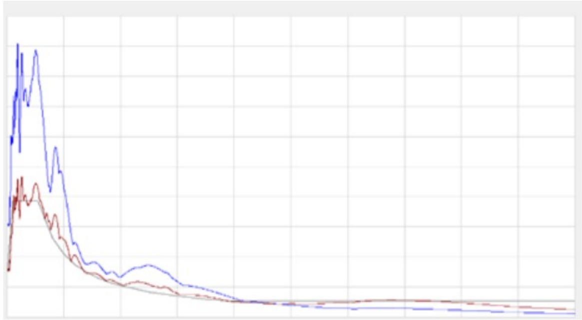



(a) Time history plot (COSMOS Database)

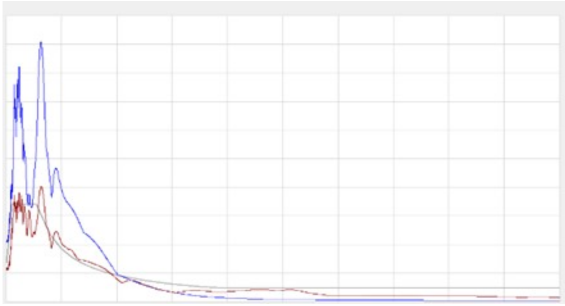


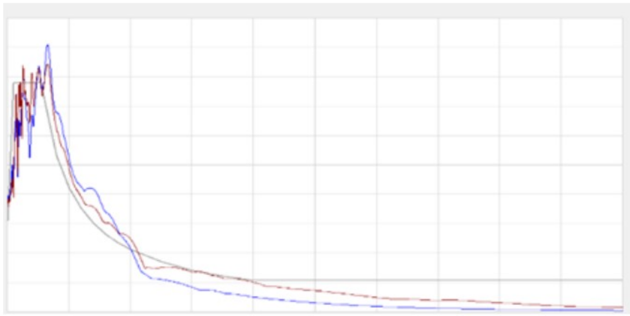

(b) Matched time history for three major earthquakes

Fig. 7 Comparison of time history plot with response spectrum for Zone-III earthquake



(a) spectrum matching for El-centro earthquake





(c) spectrum matching for Chamoli earthquake

Fig. 8 Comparison of response spectrum matching for NLTHA

Chamoli (1999) and El-Centro (1940) matching with zonal response spectrum. All three earthquakes have same magnitude range (6.5-7M). The duration of earthquake becomes important as the low frequency ranges will affect mid-high-rise buildings and cause non-structural damages as the earthquake energy content will be less to cause structural damages. Therefore, to quantify structural and non-structural damages in mid-high-rise buildings the intensity that can cause structural damage and one that can cause non-structural damage need justification (Fig.7(b)). The cost of repair of fire-fighting and plumbing pipelines for low magnitude earthquakes along with other non-structural damages will make the decision efficient for performance level to be achieved for low magnitude earthquakes.

## 6. Discussion of results

The building located in Ahmedabad city, designed as per three code of practice for seismic design and performance evaluation done using ASCE-41 procedure lead to following deductions:

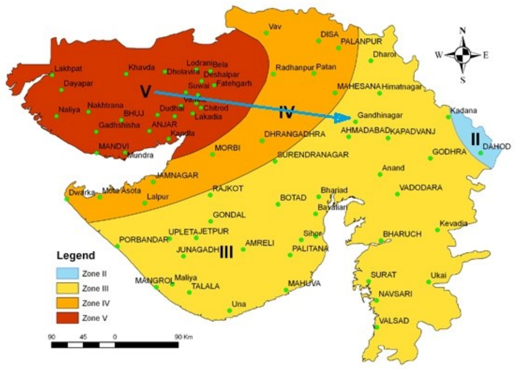
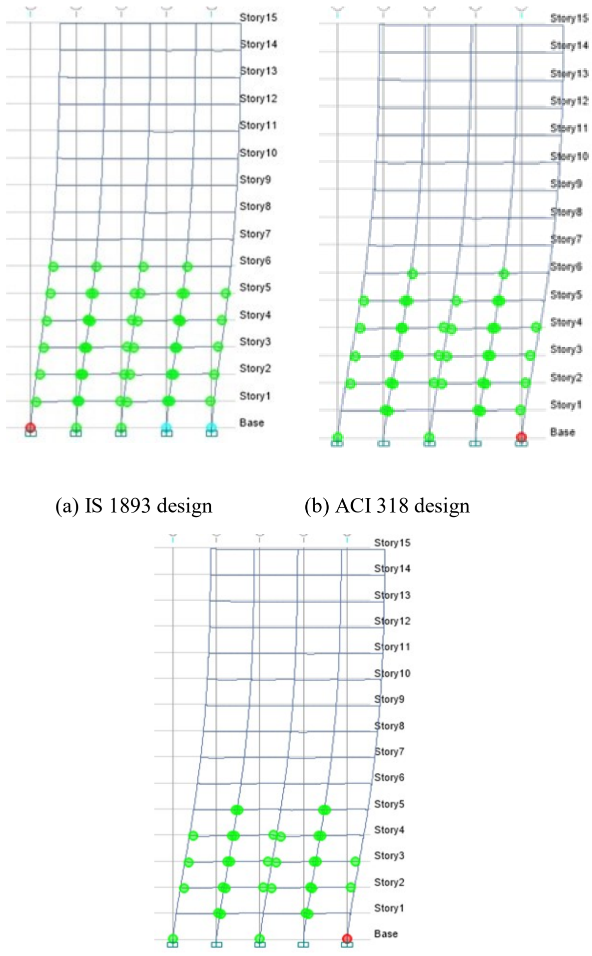



Table 2. Relations for I-Z-M-R

| I | IX | VIII | VII | VI | V |
|---|---|---|---|---|---|
| Z | 5 | 4 | 3 | 2 | 2 |
| M | 7 | 6.3 | 5.7 | 5 | 4.3 |
| R | 360 | 254 | 170 | 106 | 60 |

- The basic relation between earthquake magnitude (M), intensity (I) and seismic zoning (Z) done for Gujarat and India is reviewed for considering hazard for the epicentral distance (R). The relations suggested by *Gutenberg-Richter et al* (1956), are used to relate I-M to decide Z-R for design.
  It is observed that for epicentral distance of 250kms, the zone to be considered for design is Zone-IV. Also, an earthquake of magnitude 6.0M can cause VIII intensity shaking in Ahmedabad city (refer Table-2). However, the building was designed considering Zone-III which has VII intensity shaking as per seismic zoning criteria of the country. This gives the abrupt basis of considering only PGA as design basis rather than the intensity for estimating the demand on buildings for deciding its capacity to counteract the anticipated shaking.
- Seismic micro-zonation study for Ahmedabad gives hazard assessment (0.18g) and site amplification (1.8-2) to be taken for seismic design of building which is not considered while designing buildings with code-based response spectrum i.e. reduced base shear taken for routine design of building - 2.5 times less.
- GMPEs suggested by Ambraseys (1978) and Romeo (1996) gives seismic acceleration with respect to 7.0M earthquake at 250kms from Ahmedabad city close to NDMA study for 0.22g EPGA for extreme earthquake (refer Fig. 4).
- GMPEs suggested by Ambraseys & Simpson (1996) and Hong & Goda (2007) give EPGA close to seismic micro-zonation study done by ISR-Gujarat for Ahmedabad city (refer Fig. 4).
- The building designed as per IS 1893 (2016) performs well and has capacity to survive up-to 0.22g seismic hazard. While, the building designed as per ACI and EC can survive up-to 0.18g EPGA the performance of which is acceptable as per the micro-zonation study for Ahmedabad city (refer Fig. 5).
- The building was designed to have either the beam mechanism or the failure at column base. The building had same column base failure mode for all the three codes used for design (refer Fig. 9).

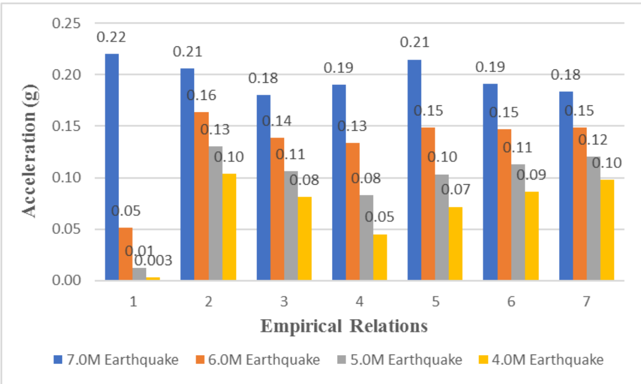



(a) IS 1893 design (b) ACI 318 design

(c) EC8 design

Fig. 9 Design outcome based on hinge formations in building

- It is found that, few of the empirical relations that match with the outcomes of EPGA suggested by IS 1893 and micro-zonation study can be used for obtaining the demand estimate for non-structural damages due to lower magnitude earthquakes (<7.0M). The distance from epicenter (DFE) parameter through distance-acceleration (DA) relations are mapped to justify the performance of building for multi-level earthquakes (refer Fig. 10).




**1** – Ambraseys (1978) ; **2** – Boore et al (1993;1997;2005)
**3** – Ambraseys & Simpson (1996) ; **4** – Free et al (1996)
**5** – Romeo (1996); **6** – Bommer (2003); **7** - Hong-Goda (2007;2008)

Fig. 10 Evaluation of matching GMPEs for estimating multi-level seismic demand

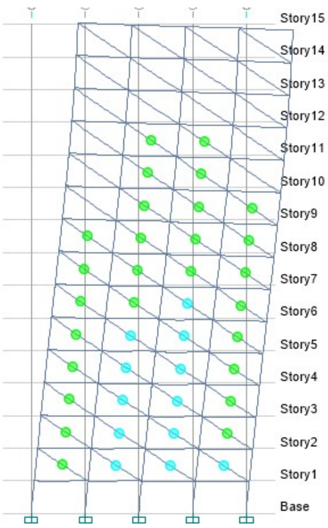
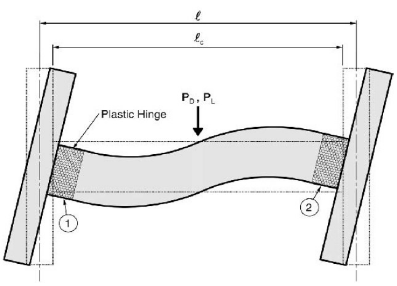


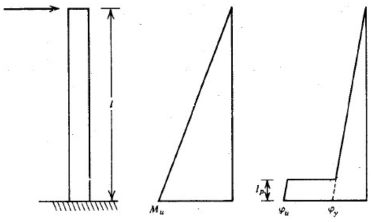

Fig. 11 Force dependent hinge formations for NLTHA (LS-PL) of single strut infill building model

- Nonlinear time history analysis (NLTH) was carried out to estimate the peak demand using matched time history feature of ETABS software. The time history plot for Chamoli earthquake matches with the response spectrum for Zone III region required for Ahmedabad city and minor matching was required. The force spectrum for three matched time history are compared for design base shear. Also, the force demand on non-structural elements were obtained and similar matching can be done to estimate design force for multiple hazards obtained using DFE relations (refer Fig. 10). This procedure for single strut masonry infill having 4MPa compressive strength and $550f_m'$ modulus of elasticity gives better confidence to estimate performance of force dependent components as per IS 1893 (refer Fig. 11).

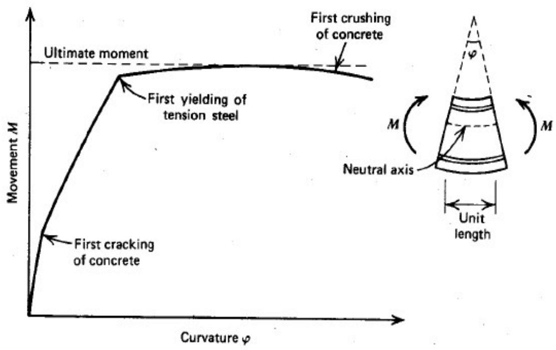
- Distribution of plasticity in the building was shown above, however, the extent of plasticity generated in the ground storey members where the stress is the highest is shown below (ref. Fig. 12).



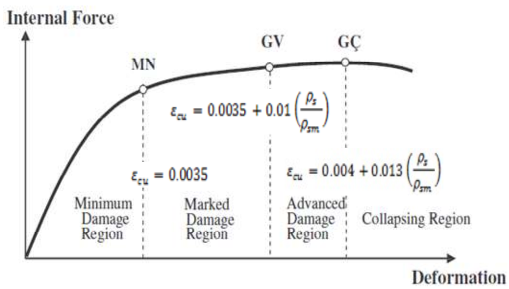

(a) double curvature in beams



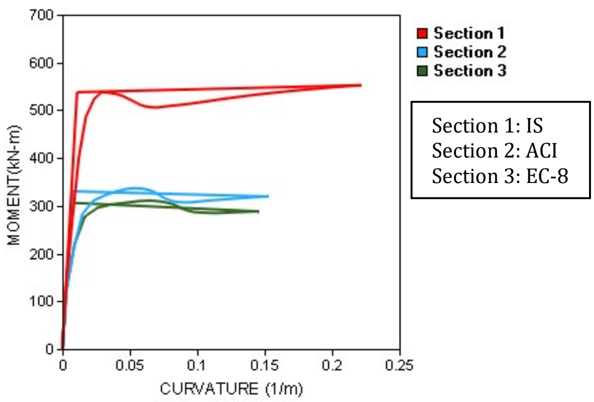
(b) plastic analysis of columns



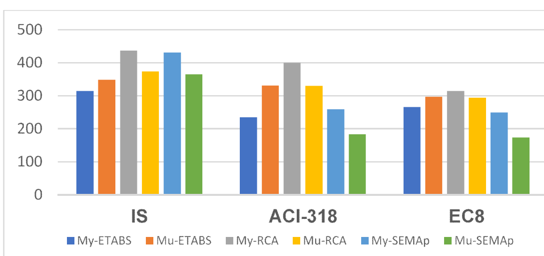

(c) moment curvature relationship



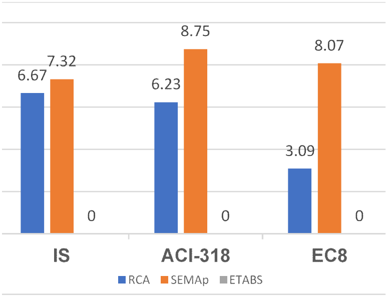

(d) moment vs strain relationship as per TEC07



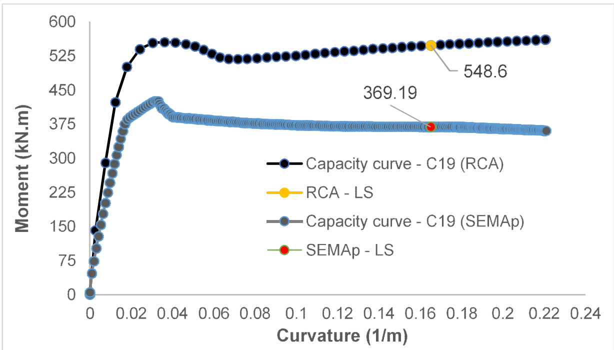

(e) moment-curvature of column C19



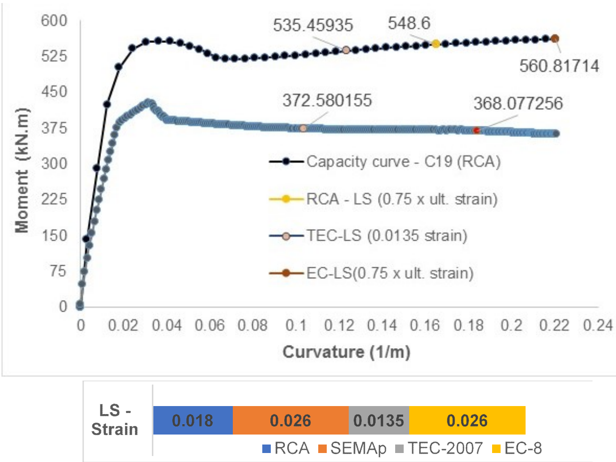

(f) comparison of moments for C19




(g) ductility ratio for C19




(h) LS threshold comparison for C19




(i) LS threshold comparison as per strain limits

Fig.12 Member performance comparison of column C19

Table 3. Model demand-loss (DL) limit criteria for DA relations (Zone V – II)

| Location from epicenter | PGA (g) | PO | Loss limit |
|---|---|---|---|
| 0 – 50kms | 0.4g | LS | 50% |
| 50 – 100kms | 0.3g | LS | 50% |
| **100 – 200kms** | **0.2g** | **LS** | **30%** |
| 200 – 400kms | 0.1g | LS | 20% |

## 7. Conclusion and critical remarks

The aim of the study was to evaluate the effect of seismic demand in the design of a mid-high-rise building using the PBD procedure. As the seismic micro-zonation study report (ISR) and PSHA (NDMA) results are available for Ahmedabad city, showing the anticipated demand for the building design. The DFA parameter were checked to match with the detailed reports using DA relations (GMPEs). The locations where seismic micro-zonation study is not carried out and estimates of demand for multiple-hazards are not available, this study can be used to execute Performance Based Design for multi-level-hazards obtained for 7M, 6M, 5M, 4M earthquakes generated at Bhuj fault zone i.e., 250-300kms away from the city (refer Fig. 10). The following are the outcomes of the study:

- The acceleration values obtained for each magnitude of earthquake using *Boore et al* (1993;1997;2005), *Romeo et al* (1996) and *Bommer et al* (2003) can be used to simulate the DFA condition for estimation of demand through design response spectrum. Moreover, the use of matched time history is a potent option to simulate the hazard for the structural and the non-structural performance levels.
- The non-linear static analysis method for the estimation of overall performance of a building at the structure level and element level suggests the Life Safety – Collapse prevention (LS-CP) criteria for building designed as per IS 1893 (2016). The performance of buildings designed as per ACI 318 and EC8 gives the same performance for 0.18g level of hazard. Hence, the building designed as per IS 1893 (2016) ensures better safety for mid-high-rise building having time-period of 1sec-0.9sec in X-Y directions.
- It is suggested to include the procedure to estimate the seismic demand for regions where amplification is anticipated in Indian Standard Code of practice for seismic design (IS 1893) to update the demand segment required for PBD procedure.
- Considering the impact of low-high magnitude (4-7M) events in loss estimate for mid-high-rise buildings, it is suggested to include mapping of multi-level-events for design of building through demand-loss (DL) envelope represented in form of decision matrix (refer Table-3). This will ascertain the minimum risk that can be used by local development authorities to give ground level design basis to developers and design engineers. The risk can be decided based on the community, demography and technology aspects of any particular region as India has vast differences in behavioral and engineering practices.

Critical remarks:

- Similar approach for old buildings through vulnerability assessment (both social and economic losses) can be referred in the article of *Zaalishvili et al* (2019) for Vladikavkaz city, Russia. The author suggested the use of MSK scale to estimate the seismic impact for loss assessments than the PGA values. However, the approach does not suggest the quantitative procedure to be adopted for design of new buildings with reduced seismic risk for mid-high-rise category.

- As the buildings go higher, performance matrix based on MMI and PGA both are necessary to obtain demand for design of buildings with reduced risk category based on community and technology resilience of a region.
- The city of Ahmedabad has experienced a major earthquake and hence the community resilience can be said to be upgraded towards recovering from the impacts of large earthquake. However, the demand parameter for its different regions as mentioned in micro-zonation study is not yet taken for the design of buildings as IS 1893 (2016) does not include the procedure to update response spectrum based on the amplification value.
- In absence of proper data, the relations developed by *Atkinson and Sonley* (2000) to obtain peak ground acceleration can be used as it gives good relation between PGA-MMI by magnitude and epicentral distance values. However, the relations are for California region and the more general study in this paper can be adopted to form the performance matrix for multi-level-hazards.
- This paper gives the approach that can be taken by a design engineer for moving towards sustainable infrastructure in the seismic prone regions by proper anticipation of hazard and reduction in vulnerability by reduced losses i.e. simulation of losses for multi-level seismic events. Also, more specific region-based response spectrum may be developed to update the response spectrum of IS 1893 (2016). The design of buildings with region-based response spectrum versus the performance evaluation procedure using updated demand spectrum will provide better engineering solution to buildings against earthquakes.

Though, the study cannot be said to have a generalized statement. But, for the considered building type complete envelope that need consideration for design to apply PBD procedure with better confidence of demand is explored. The local directives based on socio-economic and building type for seismic affected zones shall be the next step to reduce the seismic risk in cities aiming vertical development.

## Disclosures

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### Abbreviations

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|---|---|
| *PBD* | Peak Ground Acceleration |

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|---|---|
| *SMRF* | Special Moment Resisting Frame |
| *IS* | Indian Standards |
| *ACI* | American Concrete Institute |
| *EN* | European National |
| *GMPE* | Ground Motion Prediction Equations |
| *NDMA* | National Disaster Management Authority |
| *COSMOS* | Consortium of Organizations for Strong Motion Observation Systems |
| *MCE* | Maximum Considered Earthquake |
| *PEER* | Pacific Earthquake Engineering Research |
| *PSHA* | Probabilistic Seismic Hazard Assessment |
| *ETABS* | Extended Three Dimensional Analysis of Building System |
| *MMI* | Modified Mercalli Intensity |
| *DTE* | Distance To Epicenter |
| *DA* | Distance Acceleration |
| *MASW* | Multichannel Analysis of Surface Waves |