

Seismic Vulnerability Assessment of RC Building Stocks in Western Ahmedabad Using GIS-Integrated Capacity Spectrum-based Approach

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Abstract

Seismic risk in India's rapidly urbanizing corridors poses a significant threat to reinforced concrete (RC) building stocks in major cities like Ahmedabad and Surat. In this study, we integrate structural fragility analysis with ArcGIS-based spatial visualization to produce detailed, parcel-level vulnerability maps that can guide targeted disaster mitigation. Field-survey attributes—including building typology, age, occupancy, and height—were digitized and tagged in ArcGIS Pro, then combined with mean damage indices (DSm) derived from nonlinear static pushover analysis and Incremental Dynamic Analysis (IDA). Spatial statistics and cluster analysis were applied to identify high-risk hotspots across both urban centers. Results reveal that mid-rise RC frames in Ahmedabad's western zone exhibit mean damage indices up to 2.8 (moderate-severe), while similar buildings in Surat's western zone show indices around 2.4, indicating elevated collapse potential under Maximum Considered

Earthquake scenarios. Comparative modeling of IS code 1893 older (2002) versus revised (2016) version indicates up to 16% greater overstrength and reduced fragility in modernized designs. The resulting GIS maps and vulnerability clusters provide municipal authorities, urban planners, and policymakers with actionable insights for prioritizing seismic retrofitting and land-use planning. By visualizing risk at the parcel level, this approach fosters data-driven resource allocation and strengthens community resilience against future seismic events.

1. Introduction

India is acknowledged as a highly seismically active region globally, with urban centres becoming increasingly susceptible due to unregulated construction, deteriorating infrastructure, and rapid population growth. Ahmedabad, classified within Seismic Zone-III according to IS 1893 (Part 1): 2016, sustained significant structural damage during the 2001 Bhuj earthquake, despite the epicentre being more than 250 km distant. The

event revealed systemic shortcomings in structural design, construction quality, and seismic readiness within urban areas of Gujarat. Reinforced concrete (RC) buildings built before the implementation of contemporary ductile detailing provisions demonstrated significant failures attributed to soft-storey mechanisms and insufficient lateral resistance. The western zone of Ahmedabad, governed by the Ahmedabad Municipal Corporation (AMC) and the Ahmedabad Urban Development Authority (AUDA), has experienced considerable growth since the early 2000s. This area consists mainly of low- to mid-rise RC frame structures, many of which were built before the implementation of updated seismic regulations, including IS 1893:2002 and IS 13920:2016. The concentration of vulnerable building stock, along with rising population density and varied soil conditions, increases the seismic risk profile of the region. Observational studies reveal significant noncompliance with ductility and seismic detailing standards, even in constructions completed after 2002, which exacerbates the vulnerability of the built environment.

Seismic vulnerability assessment (SVA) is essential for urban risk mitigation, allowing planners, engineers, and policymakers to assess structural fragility under earthquake loading and pinpoint critical areas that need retrofitting or redevelopment (Gondaliya et al., 2025; Barbat et al., 2006). The Capacity Spectrum Method (CSM) is a robust and computationally efficient analytical tool for estimating structural performance under lateral seismic demand. The conversion of nonlinear pushover curves into spectral coordinates enables the identification of performance points, fragility thresholds, and anticipated damage states through CSM (Gondaliya et al., 2022; Barbat et al., 2010). The integration of Geographical Information Systems (GIS) has become essential for seismic risk modelling at the urban scale. Geographic Information Systems facilitate the spatial integration of structural attributes, soil classifications, and hazard data, thereby generating vulnerability maps and prioritizing interventions.

ArcGIS Pro functions as an effective platform for digitizing building footprints, organizing field-collected survey data, and visualizing fragility distributions within a specified region. This study combines CSM-based nonlinear analysis with ArcGIS spatial mapping to evaluate the seismic vulnerability of reinforced concrete building stocks in the western zone of Ahmedabad. The study employs detailed field surveys, representative structural modelling in SAP2000 (2023), and

fragility function calibration to identify high-risk clusters and assess the effectiveness of updated seismic codes. The results are anticipated to assist AMC and AUDA in executing proactive retrofit strategies, distributing emergency response resources, and developing zoning-based seismic resilience plans.

2. STUDY AREA AND BUILDING STOCK CHARACTERIZATION

2.1) Geographic and Urban Context

IS 1893 (Part 1): 2016 places Ahmedabad, India's fastest-growing city, in Seismic Zone-III. The city has rapidly urbanized westward along S.G. Highway, Prahladnagar, and Bodakdev in the past two decades, building residential, commercial, and institutional projects. The AMC and AUDA-governed Western Zone has the most new building, economic activity, and infrastructural investment in the city. The western zone has flat topography and medium-stiff alluvial soils with moderate seismic amplification potential. AMC infrastructure borehole data indicate soil profiles with varied depth to hard strata, which may worsen site-specific seismic sensitivity. Figure (1) shows the Thaltej, Vastrapur, Satellite, Bodakdev, and Jodhpur are in the region between 22.99°N and 23.05°N and 72.49°E and 72.56°E.



inventory of RC buildings. Using ArcGIS Pro and Bing Maps, building footprints were digitized and tagged with essential structural and occupancy attributes, including: (i) Year of construction, (ii) Number of stories, (iii) Structural system (RC-MI, RC-SW, RC-BF), (iv) Functional occupancy (residential, commercial, institutional), (v) Visible damage indicators (e.g., cracks, settlement). Survey teams composed of trained engineering students collected data from 476 buildings across 27 AMC wards. This sample covered approximately 15% of the total Western Zone stock and included 284 residential, 132 mixed-use, and 60 institutional/commercial buildings. GIS-enabled visualization facilitated thematic classification, zoning-level damage mapping, and cluster detection of high-risk zones. Preliminary analysis highlighted Vastrapur, Chandkheda, and Nigam Nagar as neighbourhoods with high concentrations of pre-code mid-rise buildings lacking lateral load-resisting systems.

3. METHODOLOGY

3.1) Capacity Spectrum Method (CSM)

The Capacity Spectrum Method (CSM) provides a performance-based analytical framework for evaluating the seismic demand-capacity relationship of buildings. In this study, nonlinear static pushover analysis (NSPA) was performed for selected RC archetypes, followed by transformation of the force-displacement curve into Acceleration-Displacement Response Spectrum (ADRS) format, as per the ATC-40 guidelines.

The CSM identifies the performance-point as the intersection of the capacity curve (from NSPA) and the demand curve (from IS 1893:2016 elastic response spectra for Zone-III). This intersection indicates the maximum expected displacement and acceleration the structure will endure under Maximum Considered Earthquake (MCE) conditions. Spectral acceleration (Sa) and spectral displacement (Sd) were computed using the following transformation for each control node:

$$\alpha_1 = \frac{[\sum_{i=1}^N (w_i \cdot \phi_{ip}^2) / g]^2}{[\sum_{i=1}^N (w_i / g)] [\sum_{i=1}^N (w_i \cdot \phi_{ip}^2) / g]} \text{ and } \alpha_2 = \sum_{i=1}^N \frac{\sum_{i=1}^N (w_i \cdot \phi_{ip}^2) / g}{[\sum_{i=1}^N (w_i \cdot \phi_{ip}^2) / g] \phi_{cp,p}}$$

where, V = Base shear, W = Seismic weight, α_1, α_2 = Modal participation factors, Δ_{cp} = Roof displacement at control point. The bilinear idealization of the capacity curve was

used to define yield and ultimate points, facilitating damage state classification.

3.2) Structural Modelling and Nonlinear Analysis

SAP2000 v23 (2023) was used to simulate Western Zone construction procedures in nine sample RC building models. These models were grouped by height (low, mid, high-rise) and design era (pre-2000, 2002-2016, post-2016). Key modelling assumptions: The structural modelling for the specified RC frames used $f_{ck} = 25$ MPa concrete compressive strength and $f_y = 415$ MPa steel yield strength. We applied a dead load of 2.0 kN/m² and a live load of 0.75 kN/m², following IS 875: Part I and II (1987) recommendations. Modelling a 150 mm slab as a rigid diaphragm ensured realistic in-plane floor stiffness and force distribution simulations. Fixed supports at the base of all columns ensured translation and rotation constraint for boundary conditions. According to IS 1893:2016 seismic zone categorization, the soil was medium-stiff. We used nonlinear hinge modelling to simulate seismic demand inelasticity. To model realistic frame performance under combined axial and lateral loads, beam members had M3 (flexural) hinges and column elements had P-M2-M3 (axial-biaxial flexural interaction) hinges. The hinge properties and acceptance criteria were developed according to ASCE 41-13 and FEMA 356, providing a rigorous foundation for nonlinear static pushover analysis and fragility estimate. First-mode triangular lateral load distribution was used for nonlinear static pushover. Each building model's base shear vs. roof displacement capacity curves were converted to ADRS format.

3.3) Fragility Function and Uncertainty Quantification

Fragility curves were constructed to express the conditional probability that a building will exceed a specific damage state (slight, moderate, severe, or complete) for a given spectral displacement demand. A lognormal cumulative distribution function was adopted:

$$p_k(S_d) = P[DS \geq DS_k | S_d] = \Phi \left[\frac{1}{\beta_k} \ln \left(\frac{S_d}{S_{d,ds}} \right) \right]$$

Where, S_d = Spectral displacement demand, $S_{d,ds}$ = Median displacement at damage state threshold, β_k = Logarithmic standard deviation (uncertainty factor), and Φ = Standard normal cumulative distribution function. The uncertainty factor (β) accounts for aleatory and epistemic sources of variability arising from material properties, geometric configuration, modelling assumptions, and ground motion characteristics.

As equation (3) demonstrated, a damage grade threshold is derived from the building structure's yield and ultimate spectral displacement.

$$S_{d,k} = \begin{cases} S_{d1} = 0.7D_y & \text{slight damage state} \\ S_{d2} = D_y & \text{moderate damage state} \\ S_{d3} = D_y + 0.25 ID_u - D_y K & \text{severe damage state} \\ S_{d4} = D_u & \text{complete damage state} \end{cases}$$

Where, D_y = yield spectral displacement, D_u = Ultimate spectral displacement.

To calibrate fragility functions, a binomial distribution was fitted to the empirical damage probability data, and a least-squares optimization was used to match the lognormal and binomial distributions. This approach also enabled the computation of the mean damage index (DS_m), which quantifies the expected severity of damage for each model.

3.4) Fragility Function and Uncertainty Quantification

A geospatially linked structural database was developed using ArcGIS Pro v3.0. Field survey data were digitized and tagged to building footprints using georeferenced base maps (AMC and Bing Maps). Each surveyed structure was characterized by attributes such as: Year of construction, Structural type (RC-MI, RC-SW, RC-BF), Occupancy type, Number of stories, Observed physical damage indicators. The collected data were integrated into thematic GIS layers representing: Building typology distribution, Damage state probability zones, Vulnerability cluster hotspots. Spatial cluster analysis and classification were performed to identify regions exhibiting high concentrations of seismically vulnerable structures. These maps serve as essential tools for urban planners and emergency response agencies.

4. RESULTS AND DISCUSSION

The outcomes of the seismic vulnerability assessment for RC buildings in the Western Zone of Ahmedabad were interpreted through four primary dimensions: structural capacity response obtained from nonlinear static pushover analysis, development of fragility curves including uncertainty quantification, spatial vulnerability distribution using GIS-based cluster mapping, and a comparative evaluation of design-era-based seismic performance. These components collectively provided a comprehensive, multi-scale understanding of regional seismic risk.

The nonlinear static pushover study of nine exemplary RC building archetypes by height (low-, mid-, and high- rise) and construction period (pre-2000, 2002-2016, and post-2016) produced detailed capacity spectra. The ADRS response curves showed unique lateral strength and deformation patterns. Low-rise buildings like LRC- Pre, LRC02, and LRC16 attained early yielding states with limited ductility, as shown in the Table [1] by their 18- 36 mm spectrum displacement capabilities and 1500-2000 kN base shear capacities. Mid-rise frames like MRC- Pre and MRC02 showed inelastic deformation with 350 mm ultimate displacements and 5500-6800 kN base shear capacities. High-rise buildings with shear walls, such as HRCS16 built after 2016, had greater lateral stiffness, with maximum base shear near 9000 kN and spectral displacement capacity over 650 mm, indicating improved ductility and energy dissipation. Compared to IS 1893:2016 spectral demand for seismic Zone-III (PGA = 0.16g), older buildings attained their performance points at lower displacement levels, making them more susceptible to early-stage seismic damage.

Lognormal distribution functions were used to construct fragility curves for all archetypes, including damage thresholds based on spectral displacement criteria and calibrated uncertainty values (β). These curves helped predict building damage states: minor, moderate, severe, and complete. MRC-Pre and LRC-Pre, older structures, had strong fragility gradients with 50% chance of serious damage at 116 mm and 133 mm spectrum displacements. All archetypes had uncertainty factors from 0.43 to 0.93. Buildings built after 2016 (e.g., HRCS16) showed increased design consistency, smaller uncertainty bands (β)= 0.35-0.61), and lower fragility due to compliance with IS 1893:2016 and IS 13920:2016. The mean damage index (DS_m) confirmed these findings. Pre- 2000 frames with DS_m values above 2.5 were more likely to sustain severe to total damage under maximum calculated earthquake (MCE) scenarios. Post-2016 buildings have DS_m values below 1.75, indicating greater seismic resistance.

Integrating fragility data, capacity spectra, and DS_m values with spatially mapped Western Zone building inventory in ArcGIS Pro (2025) helped assess seismic risk distribution. The thematic layers identified many vulnerability clusters. High-risk sites including Chandkheda, Nigam Nagar, and Vastrapur had older mid-rise RC frames without shear walls and DS_m values over 2.5. The majority of these structures

Table 1: Probability of occurrence of selected RC frame building for seismic hazard scenarios zone-III.

Model ID	Probability of Occurrence					DS _m
	No-damage	Slight	Moderate	Severe	Complete	
LRC-Pre	0.00	0.04	0.18	0.48	0.30	3.10
MRC-Pre	0.01	0.08	0.34	0.37	0.20	2.70
HRCS-Pre	0.15	0.34	0.38	0.10	0.03	2.05
LRC02	0.02	0.12	0.32	0.40	0.14	2.50
MRC02	0.03	0.16	0.36	0.34	0.11	2.35
HRCS02	0.20	0.40	0.30	0.08	0.02	1.85
LRC16	0.10	0.28	0.36	0.20	0.06	1.95
MRC16	0.15	0.33	0.34	0.15	0.03	1.75
HRCS16	0.36	0.44	0.17	0.03	0.00	1.25

were built before the 2002 seismic code modification. Satellite and Jodhpur had heterogeneous building portfolios, including pre- and post- 2002 constructions, indicating partial compliance and intermediate fragility. Post-2016 RC frames with shear walls and ductile details were found in low-risk zones like Prahladnagar and Thaltej, lowering vulnerability scores. This seismic risk distribution helps the AMC and AUDA prioritize retrofitting and enforce policy.

RC frames constructed under IS 1893:2002 performed better under earthquake loading than those modelled by IS 1893:2016. Post-2016 models like HRCS16 showed 30-40% improvements in base shear capacity and damage start delay due to material behaviour modelling and ductile details. Models with 20-25% lower uncertainty (β values) increased deterministic fragility forecasts. In particular, none of the post-2016 models exceeded FEMA P-695's 10% collapse probability threshold under MCE-level ground motion. Two out of three pre-2000 buildings exceeded this threshold, emphasizing the necessity to upgrade mid-rise RC frames built before contemporary seismic norms.

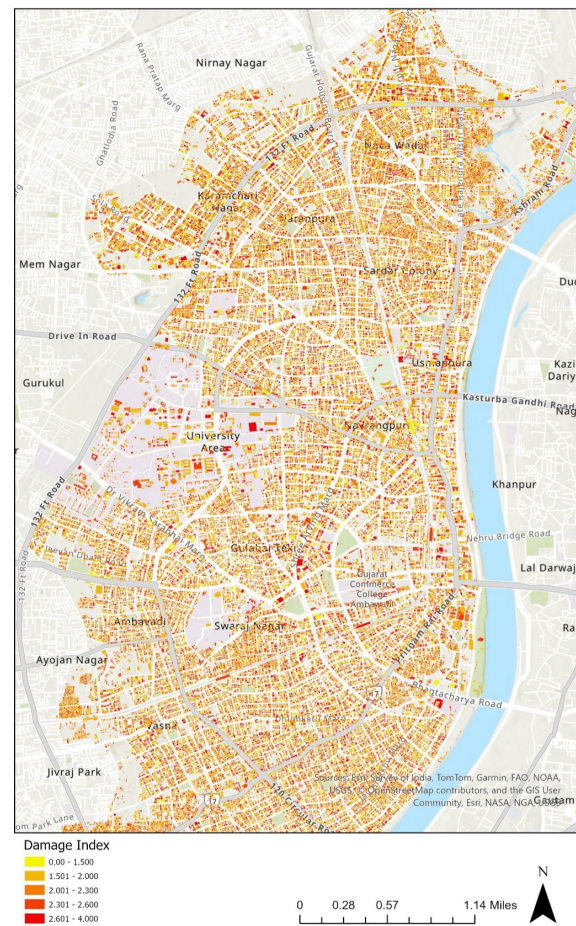


Figure 2: GIS-based Damage Index of the West Zone in the Ahmedabad City

Conclusion

This study presents an integrated framework for SVA of RC building stocks in Western Ahmedabad using nonlinear pushover analysis, CSM, and GIS-based spatial mapping. The findings emphasize the structural fragility of pre-code buildings and offer valuable insights for municipal risk mitigation strategies. Nonlinear analysis of sample RC building typologies showed that pre-2002 mid-rise RC moment-resisting frames have poorer lateral strength and ductility than post-2016 shear wall constructions. The fragility curves were derived from performance points and damage state thresholds identified by CSM. Former buildings, especially mid-rise frames with soft-storey layouts and poor seismic details, have high fragility and damage indices. GIS-enabled spatial mapping of building typologies, fragility characteristics, and damage indices identified Western Zone high-risk zones. Chandkheda, Nigam Nagar, and sections of Vastrapur were significant clusters of seismically sensitive buildings. Retrofit prioritizing, regulatory enforcement, and emergency readiness must begin in these regions.

The design code comparison showed IS 1893:2016 and IS 13920:2016's performance advantages. Post-2016 buildings had better lateral strength, lower spectrum displacement demands, and narrower fragility estimation uncertainty bounds. These findings support urban India's requirement for code-compliant design and enforcement. A scalable structural simulation, fragility modelling, and geospatial analytics tool is presented in this study. It helps local governments, urban planners, and emergency responders create seismic resilience in rapidly urbanizing Indian cities.

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