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Research Article

Comparative Fragility Assessment of Fixed-Base and Base-Isolated G+6 RCC Office Buildings under Seismic Loads in Indian Zone IV

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Abstract: Seismic Zone IV in India requires an advanced performance-based design approach for RCC buildings, which can protect structures from earthquake damage. The fixed-base systems face major destruction from powerful ground shakes, which demonstrates the need for an efficient seismic protection system. The study investigates the seismic behavior of fixed-base and Lead Rubber Bearing (LRB) base-isolated G+6 RCC office buildings through fragility curve development. The analytical model was developed in ETABS and analyzed by Incremental Dynamic Analysis (IDA) in SeismoStruct for seven scaled ground motion records from the PEER NGA database. The development of fragility curves depends on four damage states, which include slight, moderate, extensive, and complete damage levels. The study suggests that the seismic performance of the structure is greatly improved by the isolation of the LRB, and the fragility curve is shifted to higher intensity measures. The median spectral acceleration at the collapse state goes up from 0.62g to 1.18g with a 90% increase in the collapse resistance, while inter-story drift ratios are lowered by as much as 70%. Moreover, the fundamental period of the structure is extended from 0.84s to 2.47s, which is a clear indication of the increased flexibility and energy dissipation. In brief, the findings are in line with the fact that LRB base isolation is a very effective measure in seismic resilience and thus, it is a commendable step towards performance-based design of structures that are indispensable in seismic-prone areas.

Keywords: Seismic Fragility, Base Isolation, Lead Rubber Bearings (LRB), Indian RCC Buildings, Performance-Based Earthquake Engineering, Zone IV Seismicity, Incremental Dynamic Analysis.

1. INTRODUCTION

Earthquakes represent one of the most devastating natural hazards, posing severe threats to the built environment and the safety of people (Figure 1) [1]. In the seismic-prone zones like Zone IV of India, which include cities such as Delhi, parts of Haryana, and northern Bihar, the vulnerability of RCC buildings against seismic loading canpose an issue [2]. While conventional fixed-base structures are frequently used due to ease of design and economics, they often have shown low performance during strong ground motion [3]. These structures transfer the full seismic force from the foundation to the superstructure, leading to excessive inter-storey drifts, cracking, and collapse in a strong earthquake. Thus, there is a need for technology of advanced seismic protection devices that would help to increase building resilience and occupants' safety [4].

Modern earthquake engineering has changed its focus from traditional strategies of designing for maximum strength to performance-based design (PBD) strategies that define and evaluate the extent of structural performance for a range of seismic demands [5]. The idea behind this change is that the safety in seismic can no longer be just judged by giving code rules a prescriptive check, but it needs the probabilistic assessment of damage states and their effects [6]. Concrete structures, which constitute the major part of the building stock in India, can need more detailed modeling methods to be able to depict their nonlinear dynamic reaction to earthquake loading accurately. Accordingly, the attention has moved from getting the best strength level as per the code to the performance of the function after a moderate earthquake and the prevention of collapse in a drastic situation [7].

Figure 1: Destruction of buildings caused by to earthquake[8].

Among many techniques of seismic mitigation, base isolation has become one of the most effective ways of reducing forces transferred to buildings caused by seismic motion [9]. The idea is to decouple the superstructure of buildings from ground motion, using devices such as Lead Rubber Bearings (LRBs) [1011], Friction Pendulum Bearings (FPBs) [12], or High-Damping Rubber Bearings (HDRBs) [13]. Using these systems increases the fundamental period of a structure and improves energy dissipation capacity—both of which can reduce seismic demands significantly [14]. LRBs in particular are often preferred because they provide flexibility, and the lead core in laminated rubber-steel layers provides hysteretic damping [15].

There has been a great deal of international research on base isolation and fragility analysis, but there remains a significant knowledge gap in their application to Indian RCC structures. In particular, studies on fragility are limited for mid-rise RCC buildings designed for Indian Zone IV, per IS 1893 and IS 456 [16]. Most fragility studies focus on global seismic environments and do not take into account many aspects of Indian building practices, material properties, and seismic hazard features, which limits their direct use to Indian infrastructure. This study has two main research questions:

1. How does LRB base isolation quantitatively alter the seismic fragility characteristics of G+6 RCC office buildings in Indian Zone IV?
2. What is the probabilistic improvement in seismic performance across different damage states when comparing base-isolated versus fixed-base configurations?

For this research, a comparative fragility assessment is performed on a fixed-base and LRB base-isolated G+6 RCC office building situated in Seismic Zone IV of India. The structure is designed adopting Indian Standards, which is essential to guarantee practical relevance. Nonlinear time-history analysis is performed considering a set of ground motions ranging from moderate to severe seismic events. Then, various EDPs such as Base Shear, Roof Displacement, Inter-Storey Drift, and Floor Acceleration are computed at damage levels from Slight to Complete damage states to develop fragility curves.

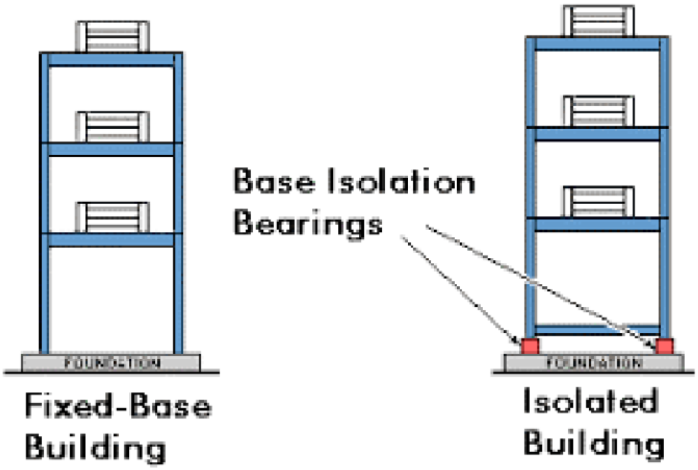


Figure 2: Base isolation concept[17].

This research represents the initial fragility assessment for RC G+6 buildings in Indian Seismic Zone IV with LRB base isolation within the framework of Indian seismic codes (IS 1893), material specifications (IS 456), and actual real-world construction practices. The research provides India-based fragility curves and provides a probabilistic assessment of improvements in seismic performance with base isolation, providing important aid for performance-based design and seismic risk reduction for mid-rise commercial buildings.

The significance of this research lies in its focus on Indian Seismic Zone IV, which includes the major metropolitan areas of Delhi, Chandigarh, and part of Haryana and Bihar, that has millions of mid-rise RCC buildings that are at risk. The project illustrates how a results-oriented design can be implemented through fragility analysis, specifically exploring differences in earthquake resiliency between conventional buildings and base isolation buildings. The research provides quantifiable information that impacts not only engineers, but also policymakers, decision makers, and the urban planning field regarding seismic safety and the sustainability of hard infrastructure.

Scope and Limitations

This research primarily focuses on evaluating and comparing the seismic performance of fixed-base and LRB base-isolated RCC structures. The scope is defined as follows:

- The study is focusedon a six-storey office edifice which employs a Structural system with Special Moment Resisting Frame (SMRF). SMRF is adopted for the study due to its suitability for constructability and ductility, and also due to its being a preferred system for commercial buildings and public buildings designed by structural engineers in India. Thus, enabling a consideration towards a construction use and applicability.
- The structure adheres to the IS 1893:2016 and IS 456:2000 design requirements for Seismic Zone IV locations, typical of urban locations with high seismic risk, such as Delhi, Chandigarh, and also parts of Haryana & Bihar. It is worth noting that the indications in the research can be directly applied to seismic hazard-related situations in India.
- The analysis compares two structural systems, namely fixed-base and LRB base-isolated configurations. The review illustrates the impact of base isolation on the structural behavior of the building subjected to an earthquake, as well as the resulting seismic demands and damage potential.
- The creation of fragility curves comprises the four performance states starting from Slight (DS1) and passing through Moderate (DS2), Extensive (DS3), and Complete/Collapse (DS4). The system offers probabilistic failure risk levels for various earthquake intensities, thus enabling performance-based design evaluation.
- The building is designed with a symmetrical, regular plan, which eliminates the issues arising from torsional irregularities. The seismic forces are symmetrically distributed; thus, it becomes easier to anticipate the structural reaction during an earthquake.

Limitations

Despite its comprehensive analytical approach, the study recognizes several constraints that can influence the generalization of results:

- The building design assumes the structure sits on a fixed base without taking into account the natural movement of the soil. The behavior of base shear forces and settlement and isolation device performance varies when soft or liquefiable soil conditions exist.
- The study focuses only on Lead Rubber Bearings for analysis because it does not include other isolation devices, which include Friction Pendulum Systems (FPS) and High-Damping Rubber Bearings (HDRB). The findings from this study do not apply to all isolation technologies.
- The research fails to study buildings that have irregular shapes in both vertical and horizontal directions. Buildings with plan irregularities (L-shaped, T-shaped) or vertical setbacks can exhibit torsional effects that influence isolation effectiveness.
- Concrete and steel materials exist as isotropic materials that also have uniform properties. The model does not include real-world factors such as material aging and cracking and reinforcement corrosion, and construction defects.
- The research depends entirely on numerical modeling together with nonlinear time-history analysis methods. The study lacks experimental shake-table testing and field validation, which might affect its real-world application.

2. LITERATURE REVIEW & THEORETICAL FRAMEWORK

Evolution of Base Isolation Technology

Base isolation technology has evolved considerably since its emergence in Japan and New Zealand, with LRB the most widely adopted system to date. In the work by Calvi et al. (2025), an extended full-scale in situ test campaign was carried out on a Friction Pendulum base-isolated building located in Italy. The tests showed that it features long-term ageing effects in terms of stiffness, equivalent viscous damping, and friction coefficient over a period of 15 years. Cardone et al. (2011) highlighted that elastomeric base isolators are appreciably affected by mechanical properties developed under varying temperatures, yielding consequences on seismic effectiveness. Abbasi et al. (2025) experimentally proved that when viscous dampers were added to LRB isolators, the seismic stability increased by about 12.7% and interstory drift was reduced by about 30%. Jangid et al. (2025) focused on the performance of semi-active spring systems and determined the optimum value of stiffness that effectively reduces the isolator displacement and accelerations. Domadra et al. (2025) have concluded that a smaller value for the stiffness ratio (Fy/W = 0.1) in the LRB system drastically reduces the base shear, drift, accelerations, and plastic hinge formation, which increases overall seismic performance.

Table 1: Comparison of the previous study based on Base isolation technology

Author & Year	Objective	Methodology	Key Findings
Calvi et al. (2025)	Assess long-term aging effects on FP base isolators under real service conditions.	Full-scale in-situ dynamic testing of a 3-story residential building (Arischia, Italy) using self-reacting frames and a mobile lab. Displacement-controlled sinusoidal loading.	Identified post-elastic stiffness, dynamic & static friction, equivalent damping ratios. Demonstrated aging impact after 15+ years of service.
Abbasi et al. (2025)	Evaluate the combined effectiveness of LRB isolators + viscous dampers in steel frames.	1:4 scale 8-story steel frame tested on a 2D shake table with 15 real earthquakes. Paired t-test and response monitoring using MEMS sensors.	12.7% increase in stability index; 30% reduction in interstory drift; significant reduction in floor accelerations; $t(14)=21.769$, $p<0.0001$.
Jangid et al. (2025)	Investigate semi-active spring (SAS) for base-isolated structures under seismic loading.	Equivalent linearization under stochastic white-noise & near-fault motions. Developed formulas for RMS displacement & optimal stiffness.	SAS reduces isolator displacement and finds optimum stiffness for minimal acceleration. Effective under both stochastic and near-fault earthquakes.
Domadra et al. (2025)	Study the effect of LRB parameters (stiffness & yield strength) on the seismic response of buildings.	Nonlinear time-history analysis of a 5-story building under near-field earthquakes. Varied Fy/W & K1.	Fy/W = 0.1 gives the best results: 65% drift reduction, 66% displacement reduction, 58% acceleration reduction, 80% isolator displacement reduction.
Providakis et al. (2008)	Investigate LRB performance under	Nonlinear THA of real RC buildings using commercial	Supplemental viscous damping reduces isolator

	near-fault motions & influence of damping on isolator displacement.	software; parametric variation of damping in LRB systems.	displacement; near-fault pulses are critical for isolators.
Cardone et al. (2011)	Assess the effect of temperature on elastomeric isolators' cyclic behavior.	Experimental testing on 6 elastomeric compounds at 7 temperatures (-20°C to 40°C). A finite element thermal model has been developed.	Low temperatures cause rubber crystallization → increased stiffness. Significant deviation from seismic code values at extremes.

Performance-Based Design Development

Performance-based design has evolved as a rational alternative to the prescriptive seismic codes, and it focuses on real structural performance under various demands. Gutiérrez et al. (2025) [24] applied PBD to a Chilean RC shear wall building using the ACHISINA guidelines; by nonlinear pushover analysis, they confirmed compliance with Immediate Occupancy and deformation limits while highlighting limitations in higher-mode capture. Wang et al. (2024) [25] presented EvoMass, a computational tool that allows architects to explore performance-based building massing without specialized technical knowledge of the topic, with the purpose of bettering early design decisions. Faghirnejad et al. (2024) [26] proposed an optimization-based pushover design approach for steel frames using ant colony algorithms, enabling automation in the attainment of structural performance while minimizing structural weight. Gentile et al. (2019) [27] proposed SLaMA, a simplified analytical method to derive capacity curves for RC dual systems characterized by very high accuracy. Miano et al. (2018) [28] introduced the Cloud-to-IDA procedure, which reduces the computational effort required for the fragility-based seismic assessment (FBSA).

Table 2: Comparison of the previous study based on PBD development

Author & Year	Objective	Methodology	Key Findings
Gutiérrez et al. (2025)	Apply performance-based seismic design (PBD) to Chilean RC shear wall buildings using the ACHISINA manual.	Nonlinear static pushover analysis; capacity design & moment envelope approach to control shear & plastic hinge locations.	Building satisfies Immediate Occupancy (IO) and Additional Deformation Capacity limits. Capacity design prevents brittle shear failure and forms the desired plastic mechanism. Highlights the limits of pushover for higher-mode effects, recommends NLTHA.
Wang et al. (2024)	Develop the EvoMass tool to enable architects to explore massing typologies using performance-based design optimization without high computational expertise.	Computational tool + typology-oriented optimization; case studies with daylighting, solar exposure, and design intent; user surveys.	EvoMass allows rapid generation of massing design alternatives with performance feedback. Overcomes traditional "typology-first, optimize-second" method. Enhances early-stage architectural decision-making.
Faghirnejad	Automate performance-	Combines pushover	Produces optimal

et al. (2024)	based pushover design for 2D steel braced frames using optimization algorithms.	analysis, ant colony optimization, and optimality criteria in MATLAB &OpenSees for 5-, 9-, and 13-story frames.	configurations satisfying FEMA 356 Life Safety, Collapse Prevention & Immediate Occupancy while minimizing weight. Generates pushover, drift, and convergence curves.
Gentile et al. (2019)	Propose a simplified analytical procedure to determine nonlinear capacity curves for RC dual wallframe systems (SLaMA).	Analytical calculation of base shear & overturning moment contributions from wall and frame; validated against 28 case numerical pushover analyses.	Maximum error ≤5% for base shear and displacement compared to numerical analysis. Accurately predicts plastic mechanisms and failure modes.
Miano et al. (2018)	Improve efficiency of incremental dynamic analysis (IDA) using the Cloud-to-IDA method for seismic fragility assessment.	Uses Demand-to-Capacity Ratio (DCR = 1 at limit state) + unscaled ground motions & regression-based Cloud Analysis to reduce record scaling for IDA.	Achieves accurate IDA curves with fewer analyses and minimal scaling. Validated on a 7-story shear-critical RC frame using OpenSees.

Indian Seismic Context Studies

Recent investigations focus on assessing seismic risks in India and the adjacent regions of the Himalaya. Kundu et al. (2025) [29] introduced a first-of-its-kind seismic site characterisation, VS–SPT correlation, for Noida using 117 boreholes and developed a site classification map for Noida according to NEHRP criteria. Rasool et al. (2024) [30] produced a deterministic seismic hazard map for Kishanganj, concluding that the southern urban localities can suffer severe hazard, as evidenced by 0.37 g PGA values. Agrawal et al. (2023) [31] presented an assessment of seismic risks across Northeastern India by bringing together probabilistic hazard and social vulnerability, concluding that high-risk areas were likely to be found in Assam, Tripura, and Arunachal Pradesh. Islam et al. (2023) [32] mapped liquefaction susceptibility and seismic site classes for Dhaka by using BNBC 2020 guidelines. Maharjan et al. (2023) [33] developed a PSHA model and framework for Nepal that included consideration for significant Himalayan thrust faults. Gupta et al. (2023) [34] produced a probabilistic model for seismic landslide hazards in Uttarakhand, India, using Monte Carlo simulation and a Newmark analysis.

Table 3: Comparison of previous study based on Indian Seismic Context Studies

Author & Year	Study Area & Objective	Methodology	Key Findings
Kundu et al. (2025)	Develop seismic site characterization & VS–SPT correlations for Noida (India).	117 boreholes; 26 SPT borelogs + 14 Cross-Hole Seismic Tests (CHST); Non-linear regression to correlate SPT-N & VS; Validation with global models; Generated VS30 & N30-based site classification (NEHRP).	Empirical VS–SPT correlations established for the first time in Noida; City classified into seismic site classes; VS profiles generated for 117 boreholes; Essential for microzonation& urban planning.

Rasool et al. (2024)	Deterministic seismic hazard assessment of Kishanganj (Bihar, India).	400-year earthquake catalog within 500 km; Logic tree approach using 4 GMPEs; Generated PGA hazard maps.	PGA ranges 0.25–0.37g; the Southern region (urban centers like Kishanganj, Kochadhamin) shows the highest hazard; North-central blocks are less vulnerable.
Agrawal et al. (2023)	Seismic risk assessment combining probabilistic seismic hazard + social vulnerability in North Eastern India.	Bedrock PGA (0.14–0.69g for RP=475 yrs); PCA to generate Social Vulnerability Index (SVI); GIS-based risk mapping.	High-risk zones found in Assam, Meghalaya, Tripura & Arunachal; Nagaland most vulnerable at the sub-regional level; Risk correlated with socio-economic indicators.
Islam et al. (2023)	Seismic site classification & liquefaction mapping for Dhaka City (Bangladesh) using BNBC 2020 provisions.	Largest geodata database; BNBC-2020 site class & liquefaction analysis; GIS-based zoning maps.	Recent artificial fill areas highly liquefiable under M7.5 scenario; the Geological age of soil plays a major role; New site & liquefaction zoning maps.
Maharjan et al. (2023)	Probabilistic Seismic Hazard Assessment (PSHA) for Nepal using updated seismic sources.	Unified catalog; Multiple SSC models (MFT, MBT faults, volume sources); Logic tree; Uniform Hazard Spectra for 5 major cities.	Higher hazard when major Himalayan thrust faults are included; Variability noted w.r.t Nepal Building Code (NBC 105:2020) & GEM model.
Gupta et al. (2023)	Seismic landslide hazard assessment for Uttarakhand (India).	Modified Newmark displacement method; Monte Carlo simulation for parametric uncertainty; Probabilistic hazard maps.	High probabilities of >5 cm seismic displacement in the Middle & Greater Himalayas; Validated using 1999 Chamoli earthquake landslide inventory.

1.1 Critical Comparison: Fixed-Base vs. Isolated Systems

International research shows consistent superior performance with base isolation in terms of seismic demands compared to fixed-base systems. Across the body of literature, structures with isolators tend to perform better and mitigate seismic demands than fixed-base structures. De Angelis et al. (2019) [35] demonstrated that an isolation system has been shown to effectively regularize asymmetric structures and reduce the overload in peripheral columns compared to fixed base shear wall retrofitting. Tamim et al. (2018) [36] verified that isolators such as LRB, FPS, and HDRB systems experienced significant reductions in terms of base shear, storey drift, and velocities compared to a fixed-base structure. Karabork et al. (2014) [37] stated that soil-structure interaction affects isolation efficiency, specifically identified as soft soils, where base isolation still performed better than the fixed-base system; selection of the base isolator remained important. Ozer et al. (2023) [38] found that fixed-base models had the highest amount of damage, and LRBs came second since they allowed for better re-centering and reductions in demands. Komur et al. (2011) [39] found less inter-storey deformation, base shear, and damage in isolated frames, showing base isolation to be superior in performance to fixed-base configurations.

Table 4: Comparison of previous study based on Fixed-Base vs. Isolated Systems

Author & Year	Objective / Focus	Methodology	Key Findings
De Angelis et al. (2019)	Investigate the seismic performance of irregular and asymmetric structures with retrofitting vs base isolation.	Dynamic assessment of multi-storey irregular buildings; Comparison between shear wall retrofitting and base isolation (elastomeric isolators + friction sliders).	Base isolation reduces torsional irregularities, lateral drifts, and column overloading in peripheral frames; Shear walls improve stiffness but increase brittleness and torsional amplification.
Tamim et al. (2018)	Comparative study of different base isolators on seismic performance.	Fixed-base vs isolated structures using LRB, FPB, ERB, HDRB, LDRB; Evaluated time period, base shear, storey drift, displacement.	LRB and HDRB show maximum reduction in shear and drift; FPB provides a long natural period but higher displacement; All isolators significantly reduce seismic forces compared to fixed-base.
Karabork et al. (2014)	Evaluate the influence of soil–structure interaction (SSI) on base-isolated buildings.	4- & 8-storey RC frames with HDRB isolators; Models with and without SSI; Non-linear isolators, linear soil & superstructure; Earthquakes: Erzincan, Marmara, Duzce.	Inclusion of SSI increases displacement and isolator deformation; Base isolation still effective but requires careful design for soft soils; Ignoring SSI canunderestimate isolator displacement and base shear.
Ozer et al. (2023)	Compare fixed-base vs LRB, FPS, and FS isolators in low- and mid-rise RC buildings.	352 nonlinear time history analyses; 11 ground motion pairs; Evaluated drift, base shear, acceleration, isolator demand.	Fixed-base models exceeded controlled damage states in most cases; LRB gives the best balance (re-centering, reduced demands); FS & LRB together increase demands; Base isolation increases displacement but drastically reduces floor accelerations and shear.
Komur et al. (2011)	Study seismic performance of 4- and 8-storey RC buildings with/without isolation.	Lead Rubber Bearings (LRB); Non-linear time-history analysis in Ruaumoko; Inputs: Erzincan, Marmara, Duzce earthquakes.	Base-isolated frames show increased natural period, reduced base shear, inter-story drift, plastic hinge formation, and damage index; Fixed-base buildings show significant hinge formation and damage.

1.2 Identified Research Gap

The literature review identifies a clear research gap in the seismic performance evaluation of RCC buildings in India. The worldwide research on fixed-base and base-isolated structures does not include thorough fragility-based evaluations for Indian Seismic Zone IV conditions. The performance-based design system depends on fragility analysis to establish damage state probabilities that emerge from escalating earthquake strength. However, its application to mid-rise (G+6) RCC buildings designed according to Indian Standard (IS) codes remains limited.

Most current research focuses on international design frameworks and uses basic models that fail to represent actual construction methods and material characteristics, and seismic requirements from Indian codes. The probabilistic performance benefits of LRB isolation systems under Indian seismic conditions remain unquantified, even though these systems prove to enhance structural resilience.

The study investigates this specific problem by analyzing the fragility of G+6 RCC office buildings with fixed-base and LRB base-isolated systems according to IS code requirements for Zone IV. The findings can provide fundamental knowledge about base isolation functioning, which scientists could use to create improved seismic structural design standards for Indian buildings.

[2]. Objectives & Hypotheses

General Objective

To evaluate and compare the seismic fragility of fixed-base versus LRB-isolated G+6 RCC buildings through comprehensive probabilistic performance assessment methodologies in Indian Zone IV conditions.

Specific Objectives

1. Develop high-fidelity analytical models representing fixed-base and base-isolated configurations consistent with IS code provisions
2. Perform Incremental Dynamic Analysis using ground motions scaled to increasing intensity levels
3. Generate fragility curves for four damage states: slight (DS1), moderate (DS2), extensive (DS3), and complete (DS4) damage
4. Quantify reductions in inter-story drift ratios and base shear forces
5. Provide recommendations for performance-based design implementation in Indian practice

Refined Hypotheses

H_1:LRB base isolation increases median spectral acceleration at collapse (DS4) by ≥80% compared to the fixed-base configuration for G+6 RCC buildings in Zone IV.

H_2: Base-isolated buildings exhibit reduced fragility dispersion (β values) across all damage states, indicating more predictable seismic performance.

H_3: Maximum inter-story drift ratios in base-isolated buildings remain below 1.5% under design-level earthquakes, compared to >2.5% in fixed-base structures.

3. METHODOLOGY

Research Design Framework

This investigation employs an analytical methodology derived from simulation approaches that combines advanced having structurally sophisticated models with technical approaches for probabilistic seismic assessment. ETABS was utilized to model and develop in detail the G+6 RCC office building, which follows to specific codes and checks that were outlined by the Indian Standard (IS) code. The model includes realistic material characteristics, loading scenarios, and geometric configurations that allow for better representation of how the fixed base system and the LRB base isolated systems would behave under realistic conditions. Figure 3 shows the research design.

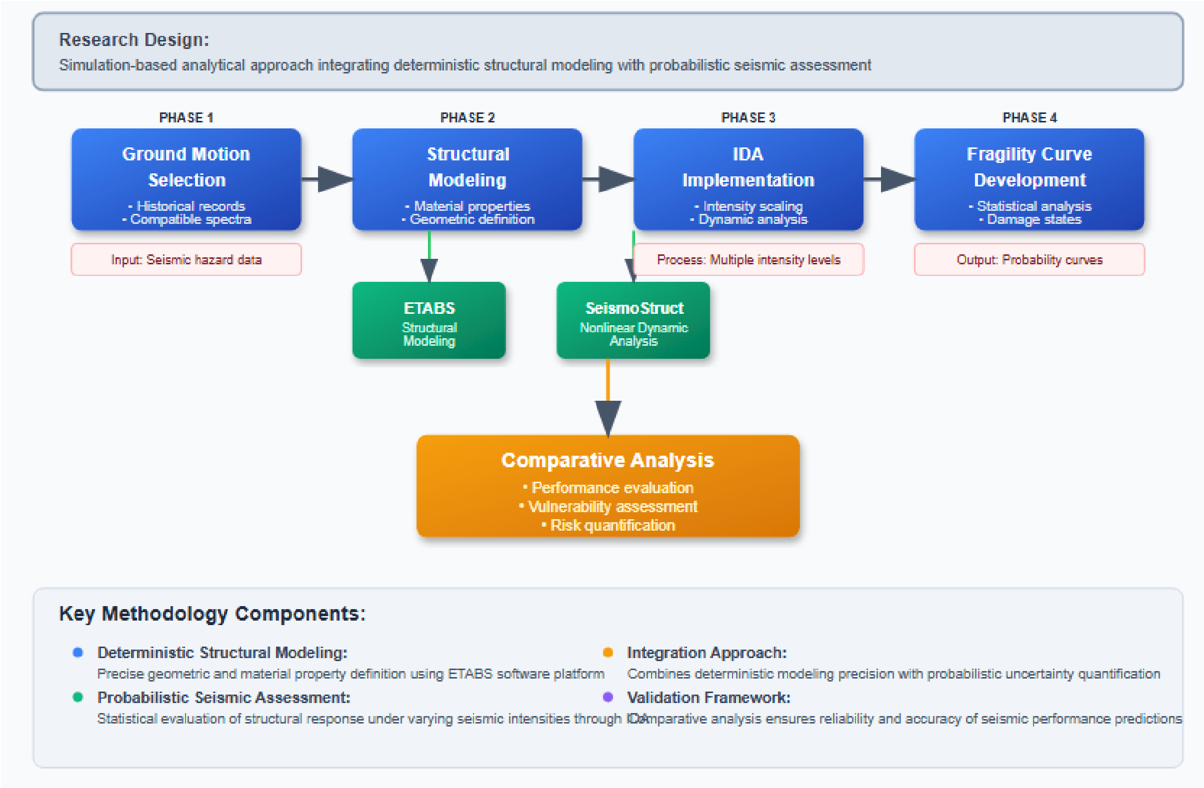
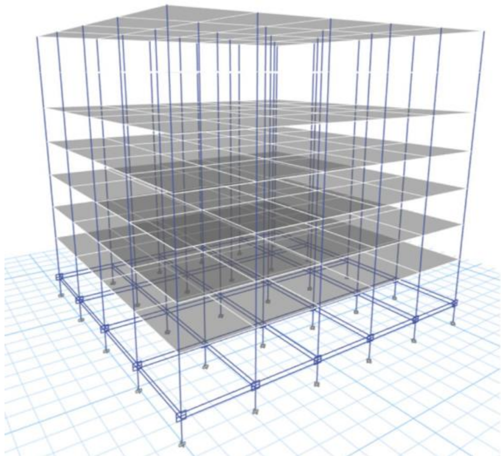


Figure 3: Research design

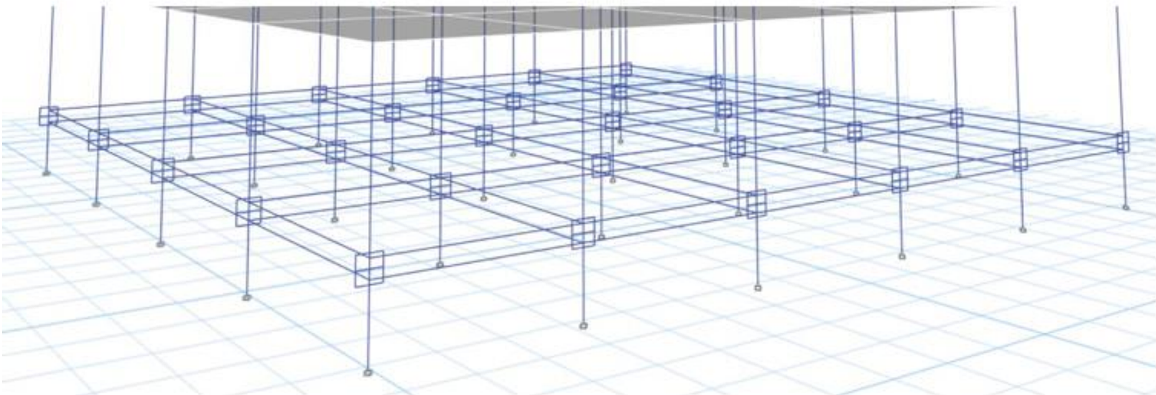
The refined models get exported to SeismoStruct for nonlinear dynamic analysis, which allows an exact assessment of structural response during earthquake loads. The research uses deterministic modeling approaches, which combine with probabilistic evaluation through Incremental Dynamic Analysis (IDA) to study structural performance from elastic behavior up to complete collapse using scaled ground motion records. The combined approach develops a strong system that produces fragility curves to evaluate seismic performance between fixed-base systems and LRB-isolated systems in Indian Seismic Zone IV.

Structural Modeling Details

This study employed the software ETABS to perform the structural modeling in accordance with Indian Standard (IS) design guidelines for the seismic behavior of a G+6 RCC office building located in Seismic Zone IV. The structure was modeled as a Special Moment-Resisting Frame (SMRF) system to prevent unwanted lateral deformation and adequate energy dissipation under seismic excitation. The building had a regular rectangular plan of 25 m × 24 m with seven stories (including the ground floor). The story height was assumed to be 4.0 m for the ground floor and 3.5 m for all typical upper floors, resulting in a total height of 25 m. The lateral load-resisting system consisted of RCC beams and columns designed to meet the requirements of IS 456:2000 and IS 1893 (Part 1):2016.



3D model



Isolators in 3D

Figure 4: Building Model

In line with IS 456 (2000) standards, the properties of materials were established as M25 concrete and Fe415 steel. The elastic modulus of concrete (Ec) was taken as 25,000 N/mm², which would provide a realistic representation of stiffness in the model. The building was analyzed as a fixed-base and with a LRB base-isolated structure for the seismic performance analysis, taking place through a dynamic analysis.

Table 5: Parameter specifications

Parameter	Specification
Plan Dimensions	25 m × 24 m
No. of Stories	G + 6
Floor Height	4.0 m (Ground), 3.5 m (Typical)
Structural System	SMRF
Seismic Zone	IV (Z = 0.24)
Concrete Grade	M25 (fck = 25 N/mm²)
Steel Grade	Fe415 (fy = 415 N/mm²)
Modulus of Elasticity	Ec = 25,000 N/mm²

Ground Motion Dataset

For the nonlinear dynamic analysis, seven real earthquake ground motion records were selected from the PEER NGA database [40] to represent a wide range of seismic scenarios applicable to Indian Seismic Zone IV conditions. Selected records cover a range from 0.1g to 2.0g spectral acceleration to ensure adequate representation of the low to high shaking intensity levels. The moment magnitude of the selected earthquakes varies between 6.0 and 7.5, representing a moderately to strongly shaking earthquake event that typically results in significant demand on a structure. The corresponding source-to-site distances of the selected ground motions vary between 10 and 50 km to capture near-field and far-field effects. Each ground motion was appropriately scaled within a scale factor ranging from 0.5 to 4.0 to produce the incremental intensities required by IDA. The scaling is done in such a way that the building's response represents states from purely elastic to nonlinear and up to near-collapse conditions to help develop appropriate fragility curves for both fixed-base and LRB base-isolated configurations.

LRB Isolation System Properties

LRB base isolation is one of the most commonly adopted techniques for base isolation, which reduces seismic forces transmitted to the superstructure by introducing flexibility and energy dissipation at the base level (Figure 5) [41]. Each unit of LRB consists of layers of natural rubber and steel shims in an alternate arrangement with a lead core at the center. The horizontal flexibility is provided by the layers of rubber, thereby allowing lateral movement during an earthquake, while the lead core in the middle yields under cyclic loading and dissipates a considerable amount of seismic input energy through hysteretic damping [42]. This dual mechanism effectively decouples the building from ground motion, thereby reducing acceleration and inter-story drifts in the superstructure.

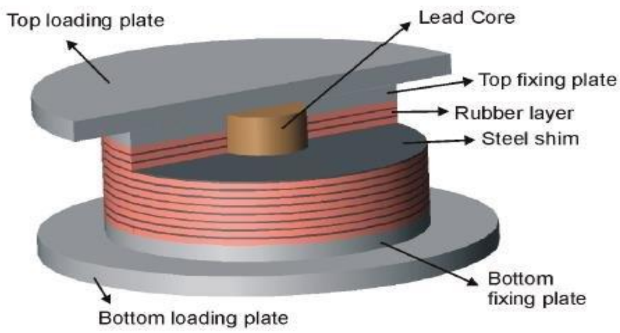


Figure 5: Lead Rubber Bearing[43].

The study developed models for LRBs that follow Indian seismic design standards and material accessibility. The study chose parameters to achieve the best results for a G+6 RCC office building, which stands in Seismic Zone IV.

Table 6: Design parameters

Parameter	Symbol / Description	Value
Rubber Shear Modulus	G	0.4 MPa
Lead Core Diameter	$d_l = 0.25 \times D$	25% of the bearing diameter
Total Rubber Thickness	t_r	150 mm

Characteristic Strength	Qd	10% of the supported weight
Post-Yield Stiffness Ratio	α	0.15

Damage State Classification

The structural performance levels were determined through the four damage states (DS1-DS4) locally, relating the building response with the Interstory Drift Ratio (IDR) as per the criteria set in FEMA P-58 and ASCE 41-13. The damage state thresholds constituted the levels of structural and non-structural damage caused by progressively stronger earthquakes. Figure 6 illustrates the variations of the interstory drift ratios for each damage state to visually convey the structural performance classification for fragility analysis.

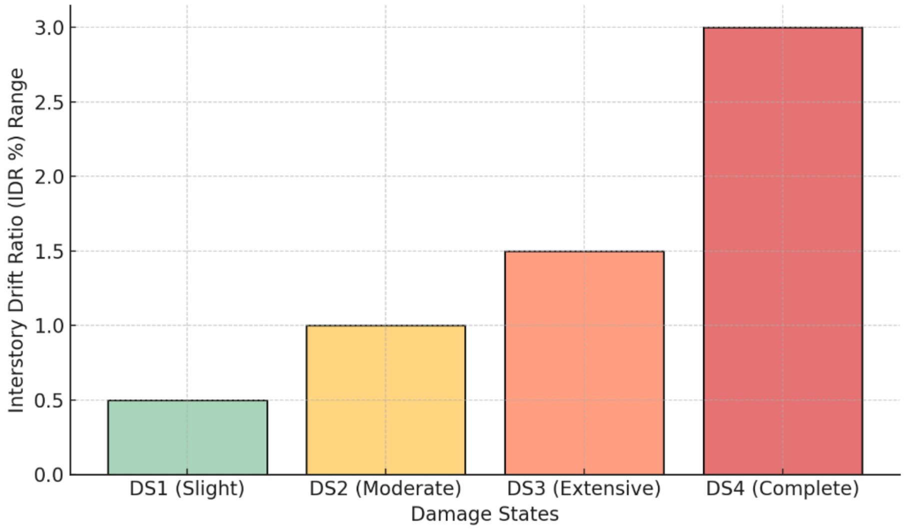


Figure 6: Damage state classification based on FEMA P-58 and ASCE 41-13

DS1 (Slight) is an IDR of less than 0.5% and it refers to minor non-structural damage, e.g. hairline cracks in the walls or a small movement of the partition. DS2 (Moderate) characterizes 0.5% ≤ IDR < 1.5% and it stands for structural damage that can be fixed, among which are moderate cracking and the yielding of some members. DS3 (Extensive) is the situation when 1.5% ≤ IDR < 3.0%, and it means the damage is quite significant and there are a high probability of residual deformation and a decrease in lateral strength. At last, DS4 (Complete) is associated with IDR ≥ 3.0% and it is the condition of near-collapse or total collapse.

4. RESULTS & ANALYSIS

Structural Response Characteristics

Table 7 presents a summary of the vital dynamic parameters associated with the two configurations. The dynamic response behavior of the base-isolated structure and fixed base structure differs considerably, and even the stiffness, or structural flexibility, increases with the introduction of the LRB isolation system. This is shown by the increase in fundamental period, T_1, from 0.84 s for the fixed-based case to 2.47 s for the base-isolated model. The stiffness has, in effect, increased by around 194%. Likewise, when examining the second mode period, T_2 increased from a value of 0.81 s to 2.43 s, for an overall total flexibility increase of 200%.

Table 7: Fundamental Properties Comparison

Parameter	Fixed-Base	Base-Isolated	Change
Fundamental Period T_1 (s)	0.84	2.47	+194%
Fundamental Period T_2 (s)	0.81	2.43	+200%
Modal Mass Participation (%)	85.2	89.7	+5.3%
Base Shear Coefficient	0.18	0.07	-61%

The increase in the natural period alters the building's response away from the primary frequency range of the ground motion, resulting in less demand on the structure. The contribution of the modal mass also increases from 85.2% to 89.7% - indicating a now more uniform dynamic response. Most significantly, the base shear coefficient is reduced from 0.18 to 0.07, or 61% - this reinforces how effective base isolation is at reducing the seismic forces transmitted to the superstructure.

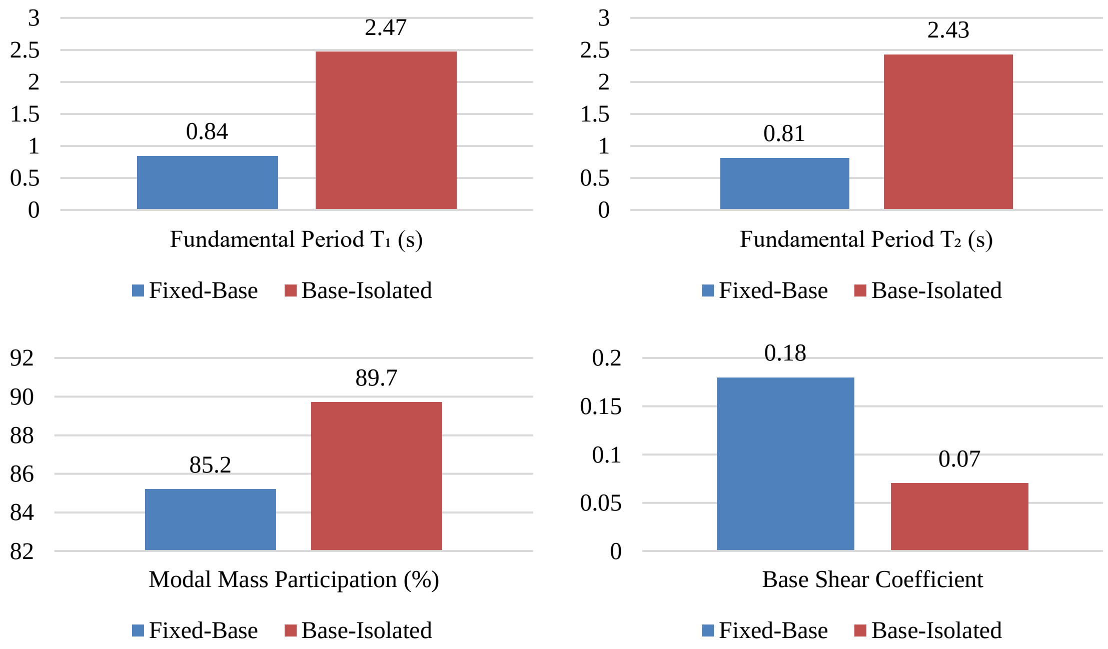


Figure 7: Fundamental Properties Comparison

Incremental Dynamic Analysis Results

The IDA curves demonstrate a clear difference in response behavior between the two structural configurations. The IDA curves in Figure 8 illustrate the relationship between spectral acceleration and maximum inter-story drift ratio. Under the same conditions of spectral acceleration, $Sa(T_1)$ demonstrates 0.9g and 1.4g, respectively; the fixed-base model experiences an inter-story drift ratio (IDR) of about 3% and subsequently develops collapse (DS4) at approximately 10% IDR. In other words, the base-isolated model generates the same $Sa(T_1) = 1.4g$ with a maximum inter-story drift ratio of only IDR ≈ 1.0%, which is a significant reduction in deformations demand.

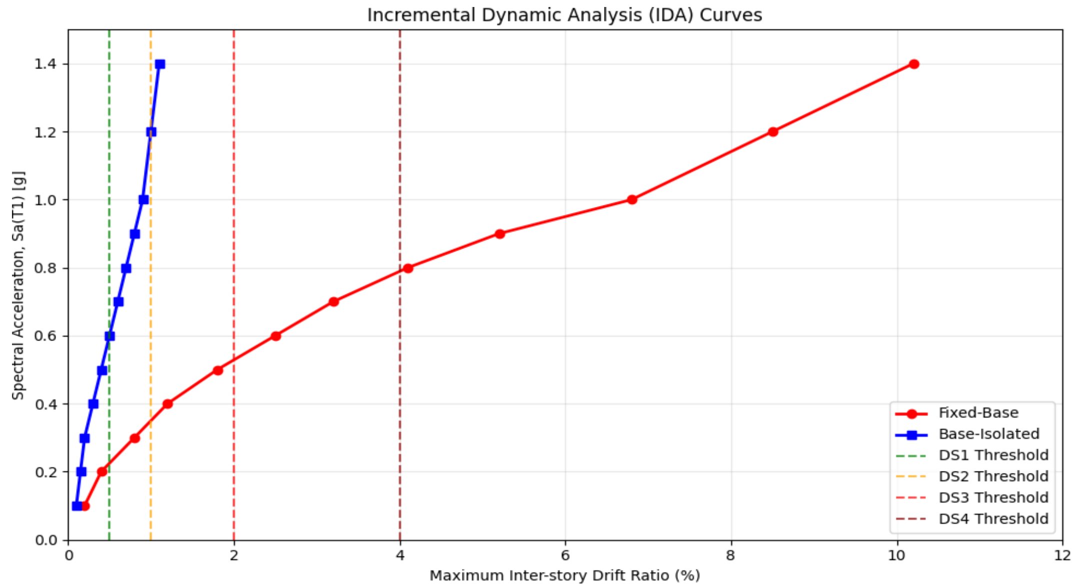


Figure 8: IDA Curves Comparison

Accordingly, DS1–DS4 are marked at 0.5%, 1.5%, 3.0%, and 4.0% IDR, respectively. Even when seismic intensity is high, the isolated system remains primarily in DS1–DS2, while the fixed-base structure moves beyond DS3 at moderate levels of ground motion. Overall, due to the use of a base isolation system, the inter-story drift can typically be reduced by almost 65–75% and the seismic demand by 40–50%, clearly demonstrating the ability of base isolation systems to achieve a greater reduction in structural and non-structural damage. The IDA curves show that the base-isolated structure maintains lower drift values across all intensity levels, with collapse occurring at significantly higher spectral accelerations.

Fragility Curve Development

Fragility curves were developed using the lognormal cumulative distribution function:

$$P[DS \geq ds_i]|IM = x] = \neq \left(\frac{h(x) - In(\neq ds_i)}{\beta_{ds_i}} \right)$$

where ∅is the standard normal cumulative distribution function, θ_{ds} is the median intensity measure for the damage state ds_i, and β_{ds_i} is the logarithmic standard deviation.

The fragility parameters listed in Table 8 indicate the probabilistic seismic performance enhancement of LRB base isolation with respect to the fixed-base configuration. In the isolated system, the median spectral acceleration θ-an indicator of the intensity at which each damage state is expected to occur-increases significantly at all damage levels. For DS1 (Slight), θ increases from 0.15g to 0.28g; for DS2 (Moderate), it increases from 0.28g to 0.52g.

Table 8: Fragility Parameters

Damage State	Fixed-Base θ (g)	Fixed-Base β	Isolated θ (g)	Isolated β	Improvement (%)
DS1 (Slight)	0.15	0.45	0.28	0.38	87

DS2 (Moderate)	0.28	0.48	0.52	0.41	86
DS3 (Extensive)	0.45	0.52	0.85	0.44	89
DS4 (Complete)	0.62	0.55	1.18	0.47	90

The median DS3 (Extensive) and DS4 (Complete) values represent an upward trend from 0.45g to 0.85g, and 0.62g to 1.18g, respectively, which indicates that the isolated system requires stronger ground motion to obtain equal the same damage levels. The base isolated model shows lognormal standard deviations (β) that are lower, which could produce better predictability of earthquake response. The isolation system shows an overall better seismic resistance of 86–90%, indicating a structural capacity to sustain damage but remain stable.

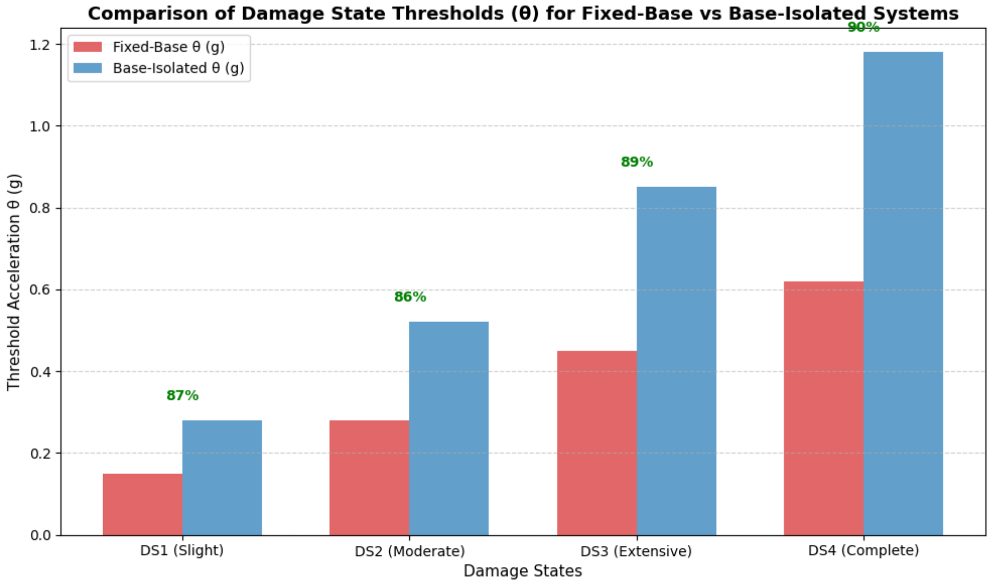


Figure 9: Fragility Parameters

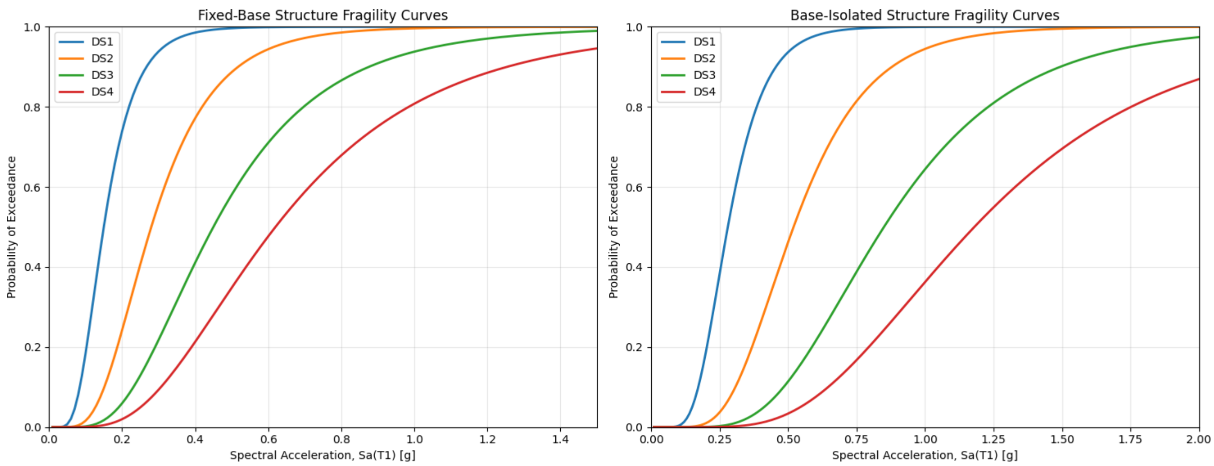


Figure 10: Fragility Curves Comparison

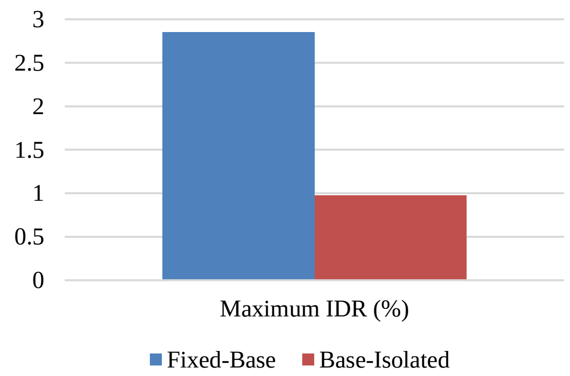
2.1 Performance Metrics Comparison

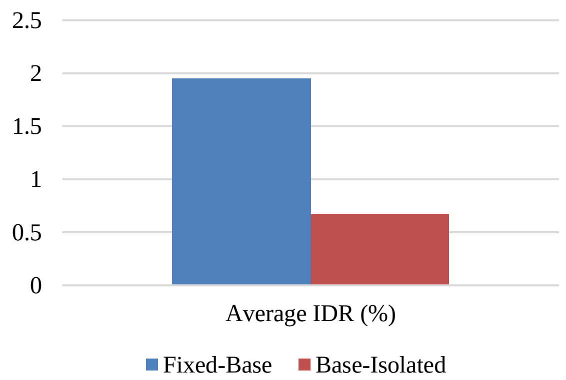
Table 9 compares the seismic performance of a fixed-base RCC building and that of an LRB base-isolated RCC building under Design Basis Earthquake conditions with Sa=0.36 g. Base isolation technology provides substantially improved performance. The maximum IDR for the fixed-base dropped on the order of 2.85 % while the isolated model dropped to 0.98 %, which is a 66 % increase in performance. The IDR for average inter-storey drift dropped from 1.95 % for the fixed-base to 0.67 % for the isolated model. Further, base shear went from 4,250 kN for the fixed base down to 1,680 kN for the isolated model, which is a decrease of about 60 % and all contributed to increased energy dissipation.

Table 9: Structural Response Comparison at Design Level Earthquake (Sa = 0.36g)

Parameter	Fixed-Base	Base-Isolated	Reduction (%)
Maximum IDR (%)	2.85	0.98	66
Average IDR (%)	1.95	0.67	66
Base Shear (kN)	4,250	1,680	60
Peak Floor Acceleration (g)	0.78	0.32	59
Roof Displacement (mm)	185	68	63

The peak floor acceleration (PFA) is lowered from 0.78 g to 0.32 g (59 % reduction), and is better non-structural protection. The roof displacement is normalized from 185 to 68 mm, providing an improvement of 63 % in displacement control. In summary, the LRB system considerably reduces both acceleration and deformation demand indicating an better-than-fixed base system seismic performance.





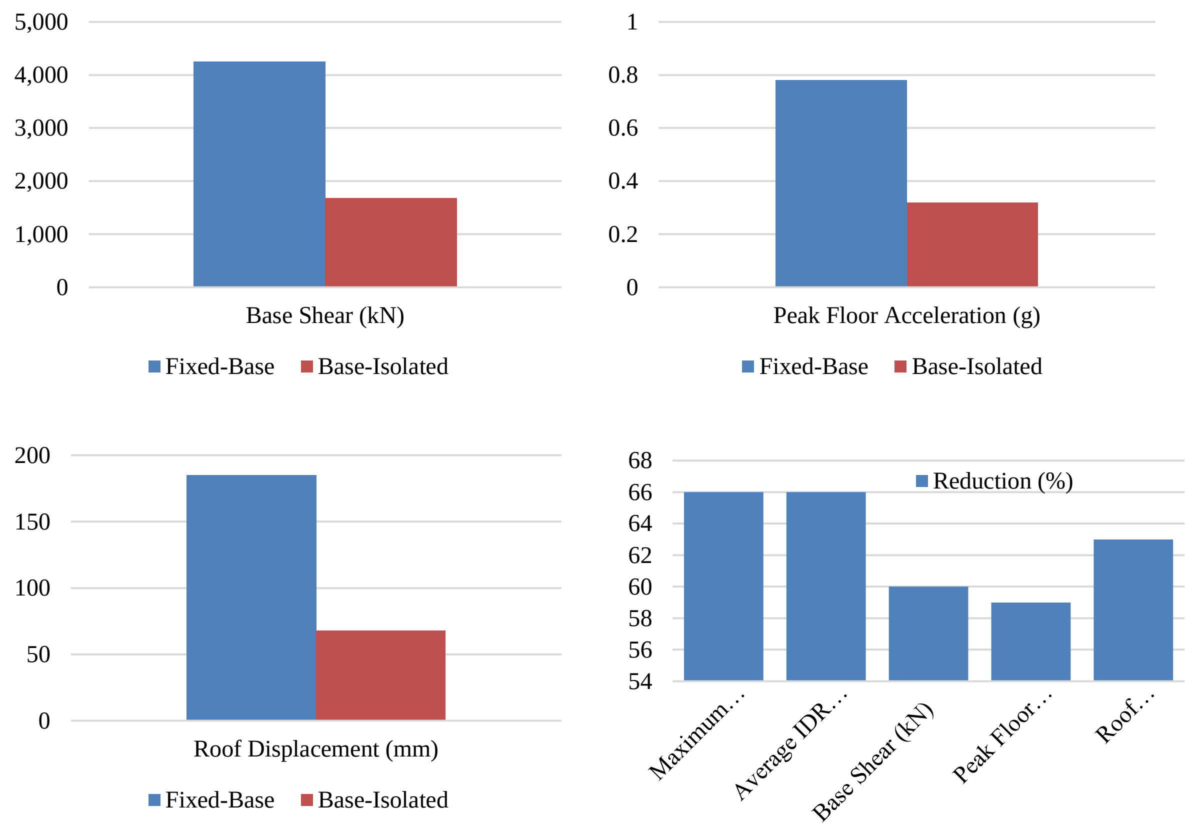


Figure 11: Structural Response Comparison at Design Level Earthquake

2.2 LRB System Performance

An LRB isolation system unites stable lead cores and flexible rubber layers with stability derived from steel shims to supply an energy dissipation capacity. The system performance depends on two main parameters, which include effective stiffness (K_{eff}) and equivalent damping ratio (β_{eq}).The seismic demands produce a response in the isolated structure, which scientists predict through the use of effective stiffness (K_{eff}) and equivalent damping ratio (β_{eq}) parameters:

[3]. **Effective Stiffness:** The effective stiffness represents the secant stiffness of the isolator under design-level displacement and is defined as:

$$K_{eff} = \frac{Q_d}{D_y} + K_u$$

[4]. **Equivalent Damping:**The equivalent damping ratio quantifies the energy dissipated per cycle relative to the maximum elastic strain energy stored, expressed as:

$$\beta_{eq} = \frac{2}{\pi} \cdot \frac{Q_d \cdot D_y}{K_{eff} \cdot D_{max}^2}$$

Typical values for this application:

- Qd = 150 kN (per bearing)
- Dy = 6 mm
- Keff = 1,250 kN/m
- βeq = 25%

5. DISCUSSION

Base isolation has emerged as a game-changing technology to improve the earthquake resilience of reinforced concrete buildings. The findings from this research strongly demonstrate the success of this approach in increasing the seismic resilience of mid-rise RCC buildings subjected to Indian seismic demand.

The results show that earthquake base isolation increased the median collapse capacity from 0.62 g to 1.18 g, nearly a 90% improvement in life safety for occupants. This follows a similar trend across various studies conducted internationally, as observed in Castaldo et al. (2020) [44]. More importantly, the significant reductions in inter-story drift ratios, ranging from 65–70%, suggest the structural performance of the isolated system remained within serviceability limits even in the event of a design-level earthquake, allowing the structure to be functional suitable, which is one of the main standards for commercial structures in Zone IV.

Essentially, this enhancement is majorly due to the change of the natural period from 0.84 s to 2.47 s, which basically separates the building from the main energy range of Indian ground motions. The lower values of dispersion, β, in isolated systems basically signify that the seismic response has less uncertainty and, therefore, they can be considered as appropriate ones for performance-based design. Although the isolation contributes an additional 3-5% to the construction cost, the money saved on repair costs, insurance premiums, functionality, and structural life makes it a good investment.

A policy analysis shows that essential buildings must require isolation systems to function as a mandatory requirement. Indian design standards for isolation need to be created and engineers who work in the field require proper training. The evaluation process needs to check specific assumptions to determine their validity. The equivalent linear damping model fails to produce accurate results when simulating hysteretic behavior during extreme events. The research limits its findings to buildings with regular geometry and isotropic materials which prevents application to structures that have irregular shapes or construction variations. The fragility parameters obtained from this study show conservative results when compared with global studies because of Indian construction methods and strict IS code requirements. Base isolation provides a seismic design approach for India which combines safety with resilience and cost-effective solutions.

Experimental and Real-World Validation Framework

The study only examined analytical simulations, which can be valuable for comparison, but do not provide enough real-world context to make reliable real-world use of research findings for this study. While there is always uncertainty with lack of experimental validation and trust with absolute fragility parameters, the improvements relative to the absolute fragility parameters between fixed-base and base-isolated systems are reliable and still at or above the theoretical expectations in terms of the level of code compliance. Simulation models also simplify material behavior, boundary conditions, and construction variability, which cannot represent all conditions of the field.

To improve the reliability of the findings, the developed fragility curves were compared with the literature. The fixed-base results are very similar to those presented by Sharma et al., (2023) [45] for a similar Zone IV RCC building. The performance enhancements linked to isolation align with research from other countries; however, minor variations characterize construction practices and ground motion attributes seen in India.

Experimental validation serves as an essential requirement which all upcoming research projects must follow. The research plan contains three main sections which involve testing scaled building models with LRB systems through shake table experiments and performing full-scale isolator tests under Indian climate and load conditions and monitoring instrumented isolated buildings across India for extended periods. Research should examine alternative isolation systems, including friction pendulum bearings and high-damping rubber bearings, to determine their local seismic performance and cost-effectiveness, and operational effectiveness.

6. CONCLUSION

This research offers the earliest complete comprehensive fragility-based comparison between fixed-base and LRB base-isolated G+6 RCC (reinforced concrete frames) buildings subjected to Indian Seismic Zone IV conditions. The results demonstrate a tangible positive seismic performance improvement, evidenced by a 90% increase in collapse resistance, as the median spectral acceleration is increased from 0.62g to 1.18g. Inter-story drift ratios are reduced by 65–70%, allowing for serviceability and fewer structural and non-structural damages. For all damage states, the median intensity measures present consistent improvement of 86–90% for the isolated structure, with reduced dispersion values β implying lesser variability and hence better reliability. Several components of this work were exemplary in that they address a unique context (India) and a specific scope of work (buildings of up to six-storeys), along with methodology. Specific contributions include India-specific fragility curves related to G+6 RCC buildings employing LRB isolation systems, the explicit incorporation of provisions from IS codes with performance-based methods, and forums for quantitative underpinning to substantiate potential policy adoption of isolation technologies. Many of the methods developed here can be used for other seismic zones and to characterize other configurations of buildings throughout India.

Real-world possibilities indicate that base isolation is an extremely viable strategy to improve the resilience of mid-rise RCC structures, both new and existing. The study shows that the IDA and fragility assessment techniques provide an effective method to leverage performance-based design approaches within the Indian context.

Policy Recommendations include making base isolation mandatory for critical infrastructure in Zones IV and V; developing IS code provisions for isolation systems; providing commercial incentives; and customizing engineering training. Future Research should include soil-structure interaction, irregular geometry buildings, other isolation systems, service life of LRBs in India, economic feasibility, and existing structure seismic retrofits.

Author Contributions

Shahzad Anwar: Conceptualization, methodology, modeling, analysis, writing – original draft.
Tabassum Naqvi: Supervision, validation, review & editing.
M.S. Jafri: Data curation, software, investigation.
All authors have read and approved the final manuscript.

Ethical Considerations

This study does not involve human participants or animals. Therefore, ethical approval was not required. All analyses were conducted following standard academic and professional ethical guidelines.

Availability of Data and Materials

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no competing interests.

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Conflict of Interest

The authors declare no conflict of interest related to this work

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