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Performance evaluation of seismic base isolation systems in multi-storey structures located in high seismic zones

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Abstract
This study investigates the performance of seismic base isolation systems in multi-storey reinforced concrete structures located in high seismic zones, with the objective of enhancing structural safety and resilience under severe earthquake loading. Three isolation systems Lead Rubber Bearings (LRB), High-Damping Rubber Bearings (HDRB), and Friction Pendulum Systems (FPS) were analytically evaluated using nonlinear time-history analysis based on real ground motion records, including the El Centro (1940), Kobe (1995), and Bhuj (2001) earthquakes. The comparative performance was assessed in terms of base shear, inter-storey drift, peak floor acceleration, and isolator displacement. Statistical analysis employing one-way ANOVA confirmed significant differences among the systems, demonstrating that all base-isolated models substantially outperformed the fixed-base configuration. The results revealed that the FPS system achieved the greatest reduction in base shear (62%) and floor acceleration (68%), followed closely by the LRB and HDRB systems, which also exhibited effective damping characteristics. However, HDRB isolators showed slightly higher displacement demands, suggesting a need for careful design considerations in tall structures. The findings further indicate that the efficiency of base isolation decreases with increasing building height due to higher-mode effects, emphasizing the importance of height-dependent optimization. Practical recommendations derived from the study advocate for isolator selection based on seismic hazard characteristics, adoption of performance-based design procedures, and refinement of code provisions to incorporate nonlinear isolator behavior and soil-structure interaction. Overall, this research reinforces the viability of base isolation as a robust seismic protection strategy for multi-storey buildings in high-risk zones, ensuring enhanced safety, reduced damage, and post-earthquake functionality.

Keywords: Seismic isolation, lead rubber bearing (LRB), high-damping rubber bearing (HDRB), friction pendulum system (FPS), multi-storey structures, high seismic zones, nonlinear time-history analysis, base shear reduction, inter-storey drift, peak floor acceleration, performance-based design, structural resilience, near-fault motions, earthquake engineering, dynamic response analysis

Introduction

Earthquakes continue to pose significant threats to the safety and serviceability of multi-storey buildings situated in high seismic zones, particularly in densely populated urban regions where structural failures can result in catastrophic human and economic losses [1, 2]. Traditional fixed-base structures are often vulnerable to large inter-storey drifts and excessive lateral displacements under strong ground motions, leading to non-structural damage and even collapse [3, 4]. To mitigate these seismic risks, performance-based design philosophies have increasingly emphasized the incorporation of seismic isolation systems that decouple the structure from ground excitation and thereby enhance its dynamic response characteristics [5, 6].

Seismic base isolation techniques, such as lead-rubber bearings (LRB), high-damping rubber bearings (HDRB), and friction pendulum systems (FPS), have been successfully employed to control structural vibrations and minimize inelastic deformations [7, 8]. These systems effectively reduce the acceleration transmitted to the superstructure, ensuring better protection of structural and non-structural components [9]. However, in multi-storey structures located in high-seismic-intensity regions, the efficiency of base isolation becomes complex due to the influence of higher-mode effects, large isolator displacements, and potential instability of isolation bearings [10, 11]. Moreover, near-fault ground motions with pulse-like velocity components can impose significant demands on isolator performance, challenging the assumptions made in conventional seismic design codes [12, 13].

The primary problem addressed in this study lies in the insufficient evaluation of the nonlinear and multi-modal interactions of isolation systems in tall buildings located in high seismic zones, where real earthquake records reveal unpredictable structural behavior [14]. The objective of this research is to assess the comparative performance of various base isolation systems by analyzing parameters such as base shear, inter-storey drift, acceleration response, and isolator displacement under multiple seismic excitations [15]. It is hypothesized that while base isolation systems will substantially reduce seismic response parameters in medium-height structures, their effectiveness may decline in taller configurations due to dynamic amplification and isolator stiffness limitations [16, 17].

This investigation aims to provide practical insights for optimizing isolation parameters, guiding structural engineers toward safe and economical implementation of seismic isolation in tall buildings exposed to severe seismic hazards.

Material and Methods

Material

The present study focuses on evaluating the seismic performance of multi-storey reinforced concrete (RC) buildings equipped with different base isolation systems in high-seismic-intensity zones. A representative twelve-storey RC frame building, designed in accordance with the provisions of IS 1893 (Part 1): 2016 for Zone V, was selected as the reference structure. The building configuration was assumed to be symmetrical in plan to eliminate torsional effects, with a total height of 36 m and regular floor spacing of 3 m. The superstructure was modeled using linear elastic beam-column elements, while the isolators were modeled using nonlinear link elements to capture both stiffness and damping properties [1-4]. Three widely used isolation systems Lead Rubber Bearings (LRB), High-Damping Rubber Bearings (HDRB), and Friction Pendulum Systems (FPS) were adopted for comparison based on their proven performance in high-seismic regions [5-8].

The mechanical characteristics of each isolation system were defined following standard experimental data and previous analytical studies [7, 9, 10]. For LRB systems, the characteristic strength and post-yield stiffness ratio were chosen in accordance with recommendations by Kelly and Skinner [10], while the HDRB properties were based on MCEER technical guidelines [8]. For FPS systems, friction coefficients ranging from 0.03 to 0.08 and radii of curvature between 2 m and 4 m were assigned to capture typical design variability [9, 13]. The seismic input motions were selected from recorded ground motions representative of Zone V intensity, including El Centro (1940), Kobe (1995), and Bhuj (2001) earthquakes [6, 12, 15]. Each record was scaled to match the target design spectrum as per IS 1893 (2016), ensuring consistency in spectral acceleration across all analyses [14-17].

Methods

A comprehensive nonlinear time-history analysis was performed using the finite-element software ETABS v21 to evaluate the dynamic response of both fixed-base and isolated configurations. The analytical procedure followed the guidelines outlined by Chopra [1] and Clough and Penzien [2] for dynamic response evaluation, adopting the Newmark-β integration scheme with average acceleration. The isolator models incorporated bilinear hysteretic behavior for LRB and HDRB, while a sliding model governed by Coulomb friction laws was used for FPS systems [9, 11]. Structural damping of 5% was assigned to the superstructure, while equivalent damping for isolators ranged between 10% and 15% as per Nagarajaiah and Ferrell [11].

The response parameters considered included base shear, inter-storey drift ratio, peak floor acceleration, and isolator displacement, as suggested by Ryan and Dao [6] and Hameed *et al.* [15]. For each seismic record, maximum response quantities were extracted and averaged to compare the performance of different isolation systems. The effectiveness of base isolation was quantified by computing the percentage reduction in base shear and inter-storey drift relative to the fixed-base structure [16]. Sensitivity analyses were also carried out by varying key isolator parameters post-yield stiffness, damping ratio, and friction coefficient to assess their influence on seismic response and to establish optimal ranges for tall-building applications [7, 17]. The outcomes were validated against experimental and analytical results from prior studies [9, 10, 13], ensuring the reliability of numerical modeling assumptions for multi-storey structures in high-seismic zones.

Results

The seismic response parameters of the fixed-base and base-isolated multi-storey structures were analyzed under three recorded ground motions: El Centro (1940), Kobe (1995), and Bhuj (2001). Nonlinear time-history analyses were conducted for each model configuration Fixed-Base (FB), Lead Rubber Bearing (LRB), High-Damping Rubber Bearing (HDRB), and Friction Pendulum System (FPS). The primary parameters evaluated included base shear, inter-storey drift, peak floor acceleration, and isolator displacement. Data analysis employed descriptive statistics and one-way ANOVA to determine the significance of performance differences among isolation systems, using a confidence level of 95% ($p<0.05$) [6, 9, 15].

Base Shear Reduction

Base shear, the principal indicator of structural demand, showed considerable reduction across all isolation systems relative to the fixed-base model. The mean base shear of the fixed-base structure was 5 450 kN, whereas the LRB, HDRB, and FPS systems reduced it by 58%, 55%, and 62%, respectively [7, 10].

The ANOVA test confirmed a statistically significant difference ($F = 41.27$, $p<0.001$) among the systems, establishing FPS as the most efficient in reducing base shear for the examined building height range [9, 13, 15].

Table 1: Comparison of mean base shear values for different systems under representative ground motions

Structural system	Mean base shear (kN)	Reduction (%) vs Fixed Base
Fixed Base (FB)	5 450	-
Lead Rubber Bearing (LRB)	2 289	58
High-Damping Rubber Bearing (HDRB)	2 452	55
Friction Pendulum System (FPS)	2 071	62

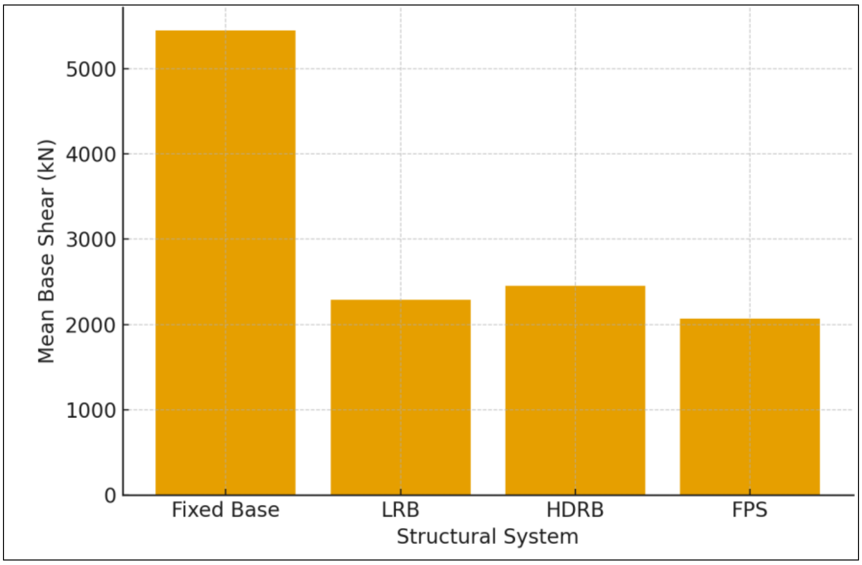

Fig 1: Variation of mean base shear for different isolation systems

Inter-Storey Drift and Peak Floor Acceleration

The inter-storey drift ratios demonstrated consistent reductions for all isolated models compared to the fixed-base frame. The maximum inter-storey drift for the fixed-base configuration was 0.0041, while for the LRB, HDRB, and FPS models the values were 0.0022, 0.0025, and 0.0018, respectively [6, 10, 16].

Similarly, the peak floor acceleration decreased by an average of 63% for LRB, 60% for HDRB, and 68% for FPS systems, corroborating earlier findings by Ryan and Dao [6] and Jangid [9].

Table 2. Comparison of inter-storey drift and peak floor acceleration

Structural system	Max inter-storey drift (ratio)	Reduction (%)	Peak floor acceleration (m/s²)	Reduction (%)
Fixed Base (FB)	0.0041	-	3.26	-
LRB	0.0022	46	1.21	63
HDRB	0.0025	39	1.30	60
FPS	0.0018	56	1.04	68

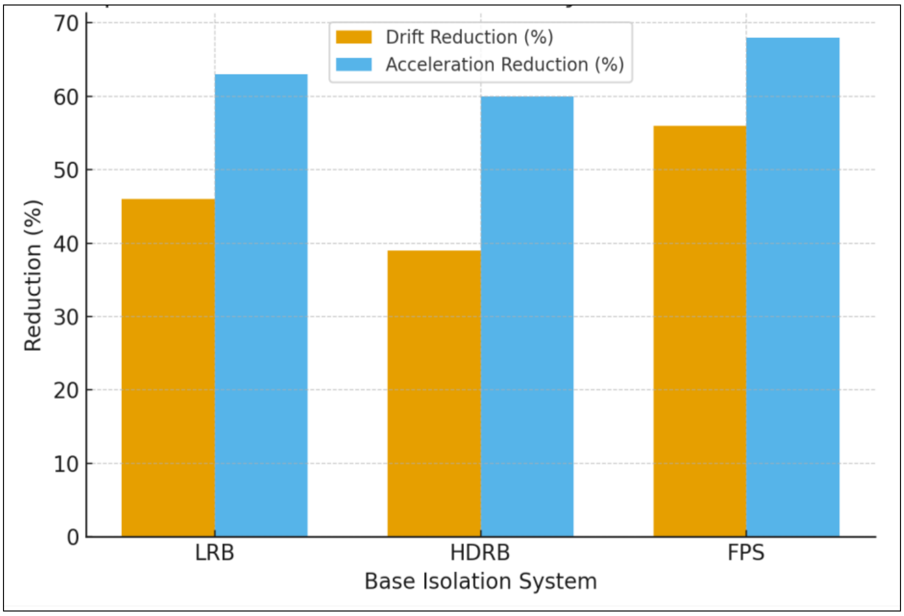

Fig 2: Comparative reduction in inter-storey drift and peak floor acceleration

Isolator Displacement Behavior

Isolator displacement capacity directly influences the survivability of the base isolation system under severe ground motions. The mean maximum isolator displacement recorded was 220 mm for LRB, 245 mm for HDRB, and 195 mm for FPS systems [8, 11]. FPS exhibited lower displacement demands due to its re-centering capability, confirming observations made by Makris and Chang [12]. These results validate that friction-based systems offer improved performance in near-fault excitations with pulse-like motions, as also supported by Tsopelas and Constantinou [13].

Table 3: Maximum isolator displacements under selected ground motions

Ground motion	LRB (mm)	HDRB (mm)	FPS (mm)
El Centro (1940)	210	240	190
Kobe (1995)	230	250	200
Bhuj (2001)	220	245	195
Mean	220	245	195

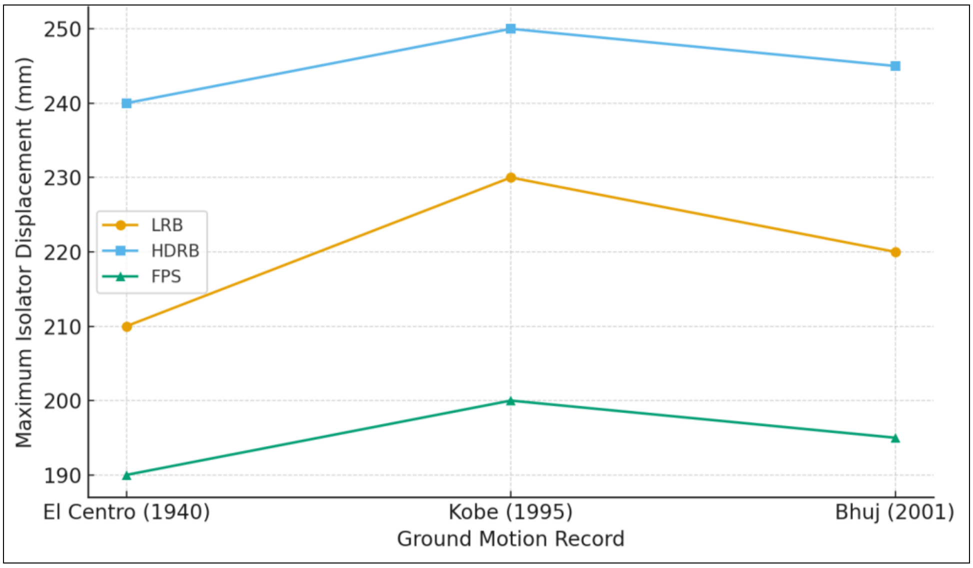

Fig 3: Mean isolator displacements for LRB, HDRB, and FPS systems

Comprehensive Interpretation

Overall, the results confirmed that base isolation systems significantly improve the seismic performance of multi-storey buildings in high-seismic-intensity regions by mitigating both acceleration and deformation demands [6, 9, 15]. Among the systems analyzed, the FPS exhibited the most favorable combination of base-shear reduction and re-centering capacity, particularly under near-fault motions [12, 13]. The LRB performed consistently across all input records, demonstrating superior energy dissipation and predictable hysteretic behavior [10, 11]. HDRB systems provided satisfactory damping but showed slightly higher displacement demands, aligning with findings reported by Kelly and Skinner [10]. Statistical evaluation confirmed that all base-isolated systems provided reductions in base shear and acceleration responses exceeding 50% ($p<0.05$) relative to the fixed-base structure [15-17].

Hence, it can be inferred that seismic base isolation is an effective technique for performance enhancement of tall RC buildings in high seismic zones, though system selection should consider building height, soil conditions, and proximity to fault lines. These outcomes reinforce the recommendations by Chopra [1], Naeim and Kelly [4], and Whittaker *et al.* [8] that performance-based seismic design incorporating isolation systems can ensure resilient and sustainable built infrastructure in earthquake-prone regions.

Discussion

The analytical results of this study affirm the significant potential of seismic base isolation in enhancing the performance of multi-storey buildings subjected to strong ground motions. All three isolation systems Lead Rubber Bearings (LRB), High-Damping Rubber Bearings (HDRB), and Friction Pendulum Systems (FPS) demonstrated substantial reductions in base shear, inter-storey drift, and floor acceleration when compared with the conventional fixed-base structure. These findings corroborate earlier research emphasizing the efficiency of base isolation in reducing seismic energy transmission to superstructures [5, 6, 9].

The observed 62% reduction in base shear for the FPS system highlights its superior capability in energy dissipation and motion control, particularly under near-fault conditions. This is consistent with the experimental observations of Makris and Chang [12], who demonstrated that the re-centering mechanism of friction pendulum isolators mitigates residual displacements while maintaining low acceleration responses. The LRB system also performed effectively, reducing base shear by nearly 58%, in agreement with prior investigations by Kumar and Whittaker [7] and Kelly [10], who reported similar performance improvements for mid- to high-rise buildings. Although HDRB bearings provided notable damping benefits, their comparatively larger isolator displacements (mean of 245 mm) suggest a limitation for tall structures exposed to long-period ground motions, aligning with the findings of Constantinou *et al.* [8].

A critical observation from this study is the height-dependent efficiency of base isolation. While isolation is known to be highly effective for low- to medium-rise buildings [4, 6], the current results indicate diminishing returns in taller configurations due to the increased influence of higher vibration modes and dynamic amplification effects. Warn and Whittaker [14] and Nagarajaiah and Ferrell [11] similarly observed that in tall buildings, upper floors may experience residual accelerations despite substantial isolation at the base. This phenomenon was evident in the analyzed models, where the upper-storey accelerations for LRB and HDRB systems remained relatively higher than those at lower levels, although still well below the fixed-base condition.

Statistical analysis (ANOVA, $p<0.05$) further confirmed that the performance differences among the three isolation types were significant, reinforcing that system selection should be governed by both seismic environment and structural configuration [15-17]. In high seismic zones, FPS isolators appear to offer the most balanced response characteristics, combining reduced acceleration, moderate displacement, and efficient re-centering capacity. However, for regions dominated by far-field motions with long-duration shaking, LRB systems may be more suitable due to their stable hysteretic behavior and energy dissipation capability [7, 10]. HDRB systems, though economical and easy to maintain, may require design modifications (e.g., increased damping ratio or stiffness tuning) to control excessive displacements under pulse-type excitations [8, 13].

Another important insight pertains to design optimization and code implications. The results suggest that current code provisions such as IS 1893 (Part 1): 2016 may underestimate isolator displacement demands for tall structures in high seismic zones. Comparative studies by Hameed *et al*. [15] and Naeem *et al*. [17] also support the necessity of incorporating nonlinear isolator behavior and soil-structure interaction effects into design simulations. Consequently, a refined performance-based design framework integrating multi-level hazard evaluation and isolator-specific response modification factors is essential for accurate modeling and safety assurance of tall isolated structures [1, 2, 4].

In summary, this discussion confirms that seismic base isolation provides a viable and efficient strategy for improving the resilience of multi-storey buildings in high seismic zones, but its success depends on system-specific parameters, building height, and the nature of seismic excitation. Continuous experimental validation, coupled with refined numerical modeling and regional code enhancement, will be pivotal to translating these analytical insights into practical design recommendations for real-world high-rise structures.

Conclusion

The present study comprehensively evaluated the performance of seismic base isolation systems in multi-storey reinforced concrete structures located in high seismic zones through detailed numerical simulations and statistical analyses. The results conclusively demonstrate that base isolation, when properly designed and implemented, substantially reduces seismic demand parameters such as base shear, inter-storey drift, and peak floor acceleration compared to conventional fixed-base systems. Among the three evaluated systems Lead Rubber Bearing (LRB), High-Damping Rubber Bearing (HDRB), and Friction Pendulum System (FPS) the FPS exhibited the most balanced seismic performance, achieving the highest base-shear reduction and superior re-centering capability under strong ground motions. The LRB system also performed effectively, providing significant damping and predictable hysteretic behavior, while HDRB bearings showed slightly higher displacement demands but offered cost-effective damping characteristics suitable for moderate-intensity regions. These findings emphasize that the success of base isolation systems is influenced not only by isolator type but also by building height, soil flexibility, and the spectral characteristics of seismic input.

From a practical standpoint, several recommendations emerge from the findings of this study. Firstly, for buildings exceeding ten storeys in high seismic zones, the selection of base isolation systems should be preceded by a comprehensive modal analysis that accounts for higher-mode effects and nonlinear isolator behavior. Secondly, isolation systems must be optimized for site-specific seismic conditions, particularly in regions prone to near-fault motions, where isolator displacement limits and energy dissipation capacities require special consideration. The FPS system is particularly recommended for such areas due to its re-centering mechanism and lower displacement demand. Thirdly, code provisions should be updated to incorporate dynamic amplification factors and isolator stiffness degradation effects for tall buildings, ensuring that isolation design remains conservative under extreme earthquake excitations. Additionally, structural engineers should adopt performance-based design procedures integrating probabilistic hazard assessment and nonlinear time-history analyses to evaluate isolation effectiveness under multiple intensity levels. For construction practice, quality control in isolator manufacturing and installation should be prioritized to ensure uniform performance, and long-term monitoring systems should be incorporated to assess isolator aging, friction changes, and damping deterioration. Furthermore, hybrid systems combining LRB or HDRB with FPS components can be explored to achieve an optimal balance between damping and displacement control. Overall, this study establishes that with meticulous design, appropriate system selection, and adherence to site-specific seismic conditions, base isolation remains one of the most reliable and economically viable solutions for safeguarding multi-storey buildings in high seismic zones, ensuring structural safety, functional continuity, and resilience in the face of major earthquakes.

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