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Original Research

Seismic response comparison of an RC frame structure with fixed base and lead rubber bearing isolation

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Abstract: In earthquake-prone regions, ensuring structural resilience is crucial, particularly for essential buildings such as hospitals, schools, and commercial complexes. This study investigates the seismic performance of a G+12 story reinforced concrete (RC) building using ETABS 2022 and evaluates the effects of base isolation with Lead Rubber Bearings (LRBs). The model was analysed in both fixed-base and base-isolated configurations under seismic loading, to assess key parameters, including inter-story drift, story displacement, shear, stiffness, and natural periods. The results indicated significant improvements in the base-isolated model, with inter-story drifts reduced by up to 68% in the X direction and 69% in the Y direction, demonstrating a marked reduction in lateral deformations. Although absolute story displacements increased, this was due to the flexibility incorporated into the isolation system, which enabled the isolators to absorb and dissipate seismic energy, thereby reducing forces on the superstructure. Furthermore, story shear was reduced by 29–31% across all stories, and story stiffness was enhanced by up to 318% at lower stories, contributing to improved structural stability. The natural periods of the building's vibration modes increased, with the fundamental period lengthening by 45.5%. This shifted the building's response away from the predominant seismic frequencies and reduced seismic acceleration demands. However, the study assumes ideal behavior of the LRBs without accounting for potential long-term degradation. Despite increased displacements, the reduction in base shear and drift indicates significant cost savings in repairs and maintenance, providing insights into the cost-effectiveness and benefits of base isolation in earthquake-prone areas.

Keywords: Structural resilience, Base isolation, Lead Rubber Bearings (LRBs), Seismic performance, Base shear

Introduction

In earthquake-prone regions, structural resilience is of paramount importance, especially for essential buildings such as hospitals, apartments, educational institutions, and commercial complexes. Earthquakes generate lateral forces and dynamic effects that can cause catastrophic failures if structures are not properly designed. To mitigate these risks, base isolation systems have emerged as one of the most effective passive seismic protection strategies [1, 2].

Base isolation decouples the superstructure from ground

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motion, effectively shifting the building's fundamental period away from the predominant frequency of seismic waves. This reduces the transmitted seismic forces, thereby minimizing structural deformation and non-structural damage [3, 4]. The principle is primarily implemented by inserting flexible isolation devices—such as Lead Rubber Bearings (LRBs) and High Damping Rubber Bearings (HDRBs)—between the foundation and the superstructure. These bearings provide horizontal flexibility and vertical rigidity, making them highly suitable for seismic applications [5, 6].

India, situated in several active seismic zones, has experienced major earthquakes in recent decades, highlighting the need for robust seismic design. The Indian Standard IS 1893 (Part 1): 2016 specifies criteria for earthquake-resistant design, while IS 875 Parts 1 and 2 provide load considerations for dead and imposed loads, respectively [7-9]. However, despite advancements in codes, the adoption of modern isolation systems remains limited, primarily due to cost implications and lack of design awareness. Numerous studies have highlighted the effectiveness of base isolation in improving building performance. Jain and Thakkar [10] demonstrated its viability in flexible structures. Rai and Mishra [11] conducted a comprehensive review of isolation applications in Eastern Uttar Pradesh, emphasizing the potential reduction in structural damage. Symans et al. [12], through analytical studies, confirmed the efficiency of LRBs in dissipating energy and controlling inter-story drift. Recent developments have also focused on smart and adaptive isolation systems that integrate with early warning mechanisms [13]. Moreover, new innovations in seismic isolation have been introduced, with studies on adaptive and magneto-rheological elastomer-based isolators showing promise for further enhancing seismic resilience [14].

LRBs are widely adopted because they combine energy dissipation through the lead core with flexibility provided by rubber layers. They have been shown to significantly reduce base shear and structural accelerations [15]. On the other hand, HDRBs offer high damping and are particularly suitable for buildings in regions with soft soil conditions, owing to their improved energy dissipation at larger shear strains [16, 17]. In addition to LRB and HDRB, recent studies have investigated the integration of magnetorheological (MR) elastomers for seismic isolation, demonstrating that these materials can optimize the performance of isolation systems under dynamic loads [18]. Further research combining LRBs with other damping systems has also produced promising results in reducing overall structural response to seismic activity [19, 20]. Recent advances in smart seismic isolation systems have led to the integration of adaptive control mechanisms, which use real-time data to adjust the behaviour of base isolators during seismic events. This enables more effective responses to earthquakes, particularly in minimizing damage and optimizing energy dissipation [21, 22]. Adaptive systems, often combined with early warning systems, represent the next generation of seismic isolation technology [23]. India's seismic infrastructure needs are further emphasized by the growing urbanization in high-risk regions. The application of base isolation is still in its infancy, with few successful large-scale implementations. However, recent pilot projects have demonstrated significant improvements in seismic resilience, underscoring the need for further research into the design, cost, and long-term viability of these systems [24, 25].

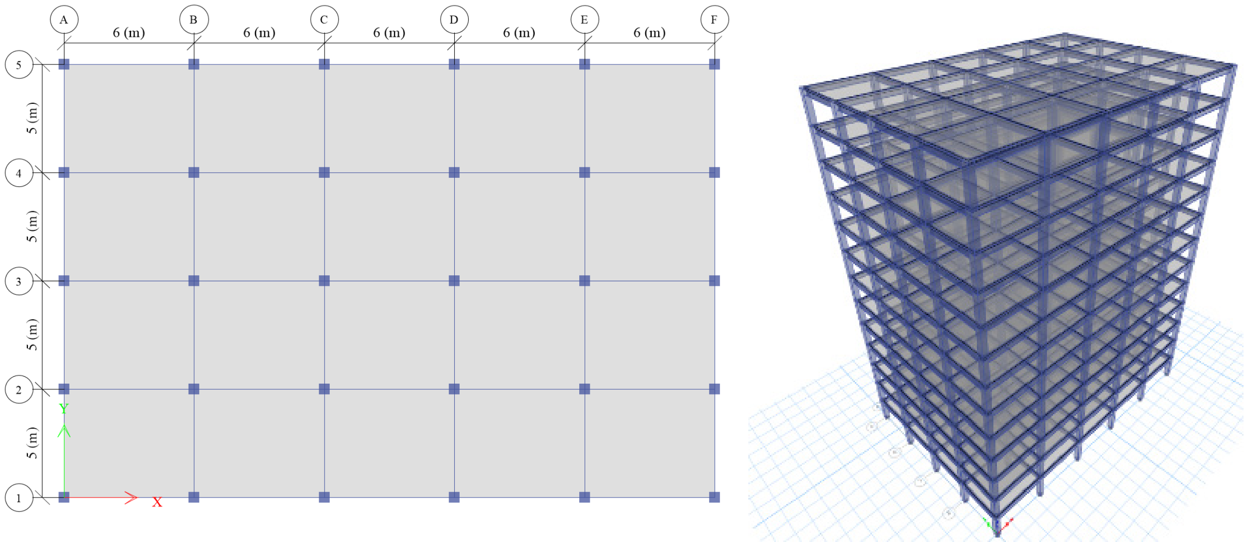
This study evaluates the seismic performance of a mid-rise reinforced concrete (RC) residential structure using ETABS 2022, comparing fixed-base and isolated-base conditions with LRBs. The analysis adheres to Indian standards (IS 1893:2016 and IS 875) and aims to demonstrate how base isolation influences dynamic behaviour, including natural period elongation, reduction in base shear, and story drift minimization.

Methodology

Structure design

To evaluate the seismic behavior of a G+12 Special Moment Resisting Frame (SMRF) reinforced concrete (RC) building, a detailed finite element model was developed using ETABS 2022 in accordance with IS 800:2007 and IS 456:2000 [27, 28]. Structural components were represented by appropriate element types: beams and columns were modelled as nonlinear frame elements with plastic hinges assigned at potential yield regions to capture flexural and axial inelastic responses; slabs were modeled using shell elements that account for both membrane and bending actions. The base isolation system, consisting of LRBs, was modelled using nonlinear link elements with bilinear hysteretic properties to simulate their actual behavior under lateral seismic loading, including stiffness degradation and energy dissipation capacity. Two configurations were analyzed: a fixed-base model and a base-isolated model. For the isolated model, LRBs were inserted between the foundation and the superstructure, enabling lateral flexibility while preserving vertical load-bearing capacity. Boundary conditions were applied by restraining all translational degrees of freedom at the base for the fixed-base model, while allowing horizontal movement in the isolated configuration. A mesh sensitivity study was performed, comparing coarse, medium, and fine mesh resolutions. A medium mesh with approximately 1-meter element size provided accurate and computationally efficient results, with less than 5% variation observed in base shear and inter-story drift compared to the fine mesh.

To assess the nonlinear seismic performance, time-history analysis was carried out using the 2007 Chuetsu-Oki earthquake ground motion. Modal properties were extracted using Ritz vectors, and Rayleigh damping of 5% was applied to the first two modes. Load definitions were based on IS 875 and IS 1893 standards: dead loads included self-weight, finishes, and partition walls; live loads were taken as 3.0 kN/m² for residential use; snow loads were neglected due to local climatic conditions; and the seismic mass included full dead load plus 25% of the live load. The overall geometry and structural configuration of the building are illustrated in Figure 1, and key modeling and design parameters are presented in Table 1. This comprehensive nonlinear modeling approach ensures accurate simulation of both superstructure and isolation system responses under strong ground motion. The acceleration time histories used in the analysis are illustrated in Figure 2, showing the scaled input ground motion from the 2007 Chuetsu-Oki Earthquake.



(a) Floor plane (b) 3D Model

Figure 1. View of G+13 RCC structure

Table 1. Model details

SI NO	Particulars Particulars	Description
1	Type of Frame	SMRF
2	No of Storey's	G+13
3	Height of Storey's	3 m
4	Height of Building	39 m
5	Slab Thickness	200 mm
6	Size of Column	(500*500) mm
7	Size of Beam	(300*500) mm
8	Concrete Grade	M30
9	Steel Grade	Fe 345
10	Specific Weight of RCC	24kN/m3
11	Type of Soil	Soft soil
12	Response Spectra	UBC 97
13	Response Reduction Factor(R)	5
14	Importance Factor(I)	1

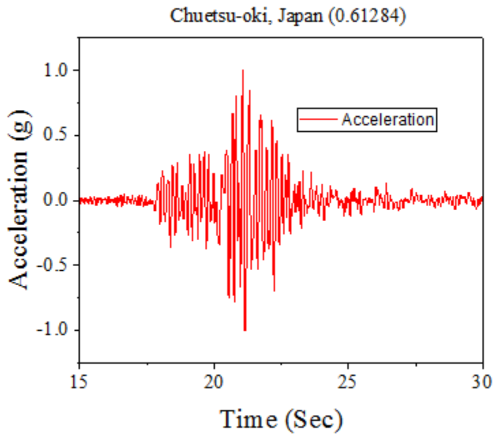


Figure 2. Acceleration time histories of the 2007 Chuetsu-Oki Earthquake

Analytical modeling and design of LRBs

LRBs are widely used in seismic base isolation systems because they provide lateral flexibility, support vertical loads, and dissipate energy through hysteretic behavior. This section presents the analytical derivation of key LRB parameters used in the finite element model. The derivations follow the analytical formulations proposed by Zorić et al. [28], which describe the post-yield behavior of LRBs, and are supplemented with additional parameters calculated from manufacturer data and design guidelines provided in [29], based on the target dynamic properties of the isolated structure. Using formulas (1) - (6), the key dynamic parameters of the isolation system were computed:

$$A_r=(D^2-d^2)\pi/4 \quad (1)$$

$$K_y=1.1G.A_r/H \quad (2)$$

$$A_l=d^2\pi/4 \quad (3)$$

$$Q_y=0.577f_yA_l \quad (4)$$

$$K_{eff}=(Q_y+K_y\cdot\Delta_d)/\Delta_d \quad (5)$$

$$\xi_{eq}=Q_y/\pi\cdot K_{eff}\cdot\Delta_d \quad (6)$$

Simply copy and paste these into your Word document. If you need them as proper equations, you can use Word's equation editor (Alt + =) and type them in using the symbols provided.

Where Ar: cross-sectional area of the rubber, D: Outer diameter, d: Lead core diameter, K_γ: Post-Elastic Stiffness, G: rubber shear modulus, A_l: Lead Core Area, Q_γ: Yield Force, K_{eff}: Effective Stiffness, ξ_{eq}: Equivalent Viscous Damping Ratio, Δ_d: design displacement

LRBs offer an efficient seismic isolation solution by combining vertical support, lateral flexibility, and energy dissipation, as shown in Figure 3. Table 2 summarizes their key geometric and mechanical properties used in the seismic model.

Result obtained from etab software

Story drift

Figure 4 presents the maximum inter-story drifts for fixed-base and base-isolated buildings in the X and Y directions, respectively. A detailed comparison reveals the enhanced seismic performance of the base-isolated structure, which significantly reduces inter-story drifts across the building's height. In both directions, the base-isolated structure exhibits slightly higher drift values at the lower levels (Stories 1 and 2). This can be attributed to the added flexibility introduced by the isolation system at the base. However, from Story 3 onward, a noticeable reduction in drift is observed in the isolated model compared to the fixed base model. In the X direction (Figure 4-a), the drift at Story 6 is reduced by approximately 31%, while at the topmost story (Story 13), the reduction reaches about 68%. Similarly, in the Y direction (Figure 4 3-b), the drift at Story 6 is reduced by 30%, and at Story 13, the reduction is around 69%. These reductions highlight the efficiency of base isolation in minimizing lateral deformations and preventing excessive sway, especially in the upper stories where seismic amplification is typically more pronounced. Overall, the comparison confirms that the use of Lead Rubber Bearings (LRBs) significantly enhances the building's dynamic performance. The isolated system shifts the natural period of the structure and dissipates seismic energy, which leads to improved control over inter-story drifts, ensuring compliance with seismic code requirements.

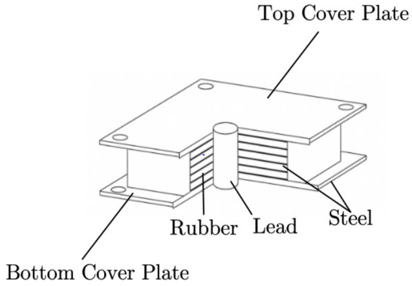


Figure 3. Lead rubber bearing

Table 2. Summary of LRB parameters in E-tabs

Parameter	Values
Total diameter	300 mm
Lead core diameter	120 mm
Number of rubber layers	12
Rubber layer thickness	10 mm
Shim thickness	3 mm
Cross-sectional area of the rubber annulus	0.0628m^2
Post-Elastic Stiffness	230.48 kN/m
Lead Core Area	0.0113m^2
U2 & U3 Yield Strength	65.28 kN
Effective Stiffness U2 & U3	3405.28 kN/m
For U1 Effective Stiffness	3405280 kN/m
Rotational Inertia	0.08877 kN/m
For U2 & U3 Effective Damping	0.05
For U2 & U3 Stiffness	230.48 kN/m
For U2 & U3 Distance From End J	0.001884m

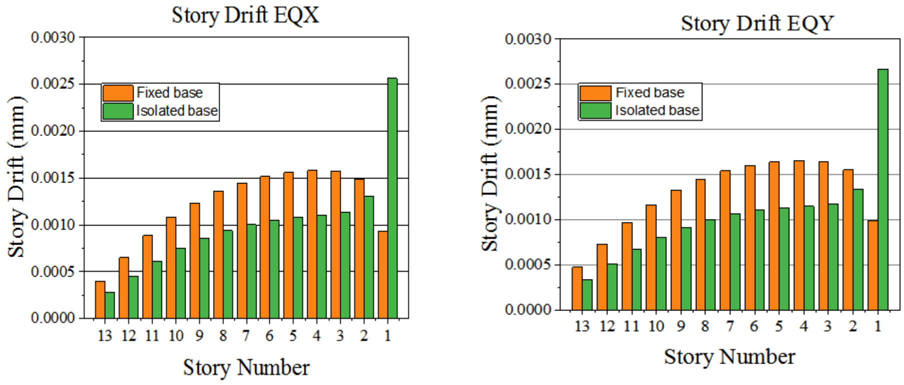


Figure 4. Comparison of inter-story drift in X-Y directions for fixed and base-isolated models

Story displacement

Figure 5 presents a comparison of story-wise displacement between fixed-base and base-isolated buildings in the X and Y directions, respectively. A detailed evaluation shows that the base-isolated structure experiences a significant increase in displacement across all floors, particularly due to the increased flexibility and period elongation introduced by the isolation layer. Unlike inter-story drift, which generally decreases in base-isolated systems, the absolute story displacements tend to increase. This occur because the entire structure moves more uniformly and slowly in response to ground motion—an intentional design feature that reduces internal force demands. In the X direction (Figure 5-a), displacement at the ground floor (Story 1) increases from 2.808 mm in the fixed base to 22.378 mm in the isolated base, reflecting the shift of deformation from the upper levels to the isolation interface. The upper stories also show consistent increases, with displacement at Story 13 rising by 14.47%, and intermediate stories, such as Story 10 and Story 6, exhibiting increases of 20.95% and 17.73%, respectively. In the Y direction (Figure 5-b), a similar trend is observed. The isolated base building demonstrates displacement increases of 14.91% at the top (Story 13) and up to 22.97% at mid-levels like Story 6, compared to the fixed base. These increases are expected and desirable, as base isolation is designed to shift the deformation demand away from the superstructure and into the isolators, which absorb and dissipate seismic energy. As a result, although story displacements increase, the overall seismic forces transmitted to the superstructure are reduced, enhancing structural safety and preventing damage. This confirms the effectiveness of Lead Rubber Bearings (LRBs) in improving seismic performance, particularly by reducing acceleration and inter-story drift while allowing controlled displacements at the base.

Story shear

Figure 6 presents a comparison of story shear forces between fixed-base and base-isolated buildings in the X and Y directions, respectively. The results clearly demonstrate a significant reduction in base shear due to the use of isolation systems. In both directions, the base-isolated model consistently shows lower shear forces across all floors, confirming its effectiveness in decoupling the structure from ground motion and dissipating seismic energy at the isolation level. In the X direction (Figure 6-a), the story shear at the 12th floor decreases from 810.15 kN in the fixed base model to 557.12 kN in the base-isolated model, representing a reduction of approximately 31.2%. This trend continues throughout the height of the structure, with reductions of around 30% at Stories 10, 9, and 6, and similar values near the base. The reduction in shear forces implies a significant decrease in the seismic demand on structural members. Similarly, in the Y direction (Figure 6-b), the story shear at the 12th floor decreases from 829.53 kN to 565.03 kN, showing a 31.8% reduction. Across other stories, the reductions range from approximately 30% to 31.2%, particularly notable at Stories 11, 9, and 6. These consistent reductions in both directions demonstrate the isolation system's ability to effectively reduce lateral forces, thereby protecting structural integrity and reducing the potential for damage during seismic events. Overall, the base-isolated system—whether using LRBs—significantly minimizes the shear demand throughout the structure. This enhances seismic safety, reduces design forces on vertical elements, and supports better performance under strong ground motion.

Story stiffness analysis

Figure 7 illustrates the comparison of story stiffness values between fixed-base and base-isolated buildings in the X and Y directions, respectively. Unlike displacements and drifts, where base-isolated models show increased flexibility, the analysis of stiffness reveals a counterintuitive but important result: the apparent lateral stiffness per story is significantly higher in the base-isolated model, particularly at lower and mid-level stories. This is a result of the isolation system's ability to reduce deformation demands on the superstructure, allowing the upper structure to behave more linearly and retain higher stiffness. In the X direction (Figure 7-a), the story stiffness at Story 12 increased from approximately 439,707 kN/m in the fixed base model to 433,244 kN/m in the isolated base model—an increase of about 21.5%. Similar trends are observed throughout the structure, with mid-level stories such as Story 10 and Story 6 showing increases of 19.5% and 18.3%, respectively. The effect becomes most prominent at Story 1, where the stiffness increases by over 318%, highlighting how the isolation layer shifts deformation away from the structural frame and concentrates it at the base. In the Y direction (Figure 7-b), the stiffness at Story 12 also rises from about 430,290 kN/m to 419,357 kN/m, marking an increase of 17.8%. Other stories show similar enhancements, with average increases between 17% to 18% across mid and upper levels. Again, the most substantial increase appears at Story 1, where stiffness improves by over 308%, consistent with the effects observed in the X direction. These findings reinforce that while base-isolated buildings allow greater total movement, they simultaneously enhance the relative stiffness of each story due to lower internal force demands and reduced inelastic behavior. This results in a more resilient superstructure, capable of withstanding seismic events with reduced damage potential, especially when LRBs are utilized.

Mode period

Figure 8 presents a comparison of the natural periods of the first twelve vibration modes for both fixed-base and base-isolated models. A consistent increase in modal periods is observed in the base-isolated structure across all modes, reflecting the effect of incorporating isolation devices such as Lead Rubber Bearings (LRBs). This increase in period, often referred to as period elongation, is a direct consequence of the added flexibility at the base level, significantly altering the dynamic characteristics of the structure. The fundamental mode period of the fixed-base model is 1.61 seconds, while the base-isolated model exhibits a significantly longer period of 2.341 seconds, corresponding to an approximate increase of 45.5%. Similar trends are observed in the second and third modes, with increases of 46.7% and 46.2%, respectively. Even in higher modes, such as the sixth mode, the period increases from 0.461 seconds in the fixed-base structure to 0.603 seconds in the isolated model, representing a 30.8% increase. This systematic elongation of modal periods across all modes indicates a shift in the structural response spectrum. Period elongation plays a critical role in seismic performance enhancement. By shifting the natural period of the structure away from the predominant frequency content of earthquake ground motions, the seismic acceleration demands are significantly reduced. As a result, the base-isolated structure is subjected to lower dynamic forces, which leads to decreased inter-story drifts and base shear forces, as previously discussed. Furthermore, the isolators contribute to energy dissipation, minimizing the transmission of seismic energy into the superstructure and reducing the likelihood of structural and non-structural damage. Overall, the observed increase in modal periods for the base-isolated model confirms the effectiveness of base isolation in modifying the dynamic response characteristics of the structure. This shift toward longer periods enhances seismic resilience and aligns with design objectives for performance-based seismic engineering.

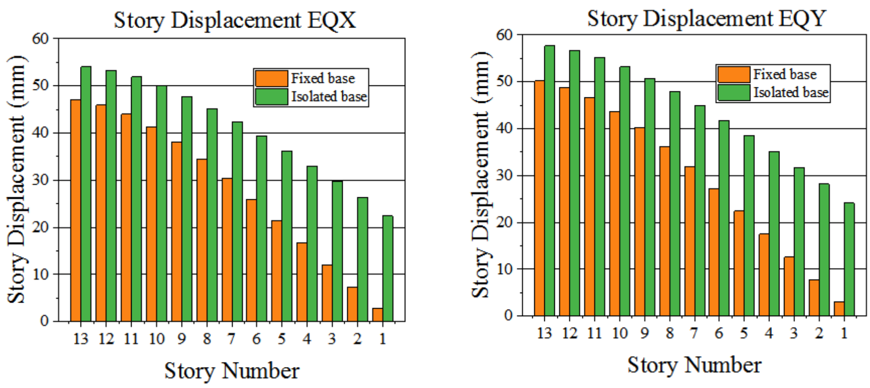


Figure 5. Story displacement profile in X-Y directions under earthquake excitation

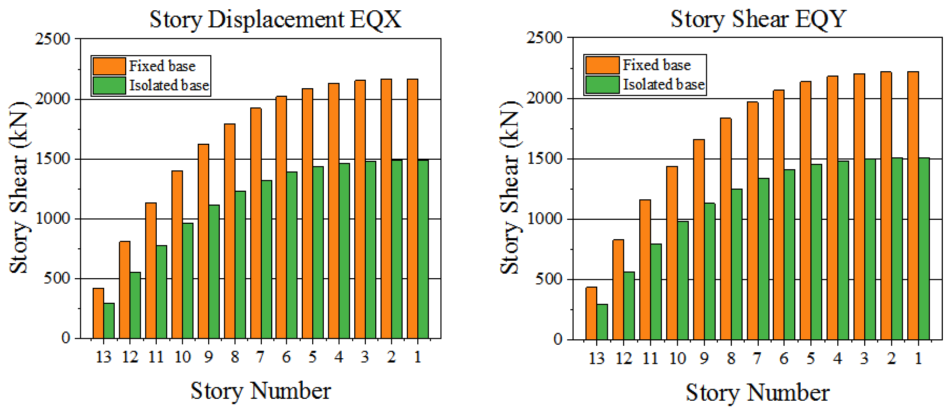


Figure 6. Variation of lateral shear along building height (X-Y Directions)

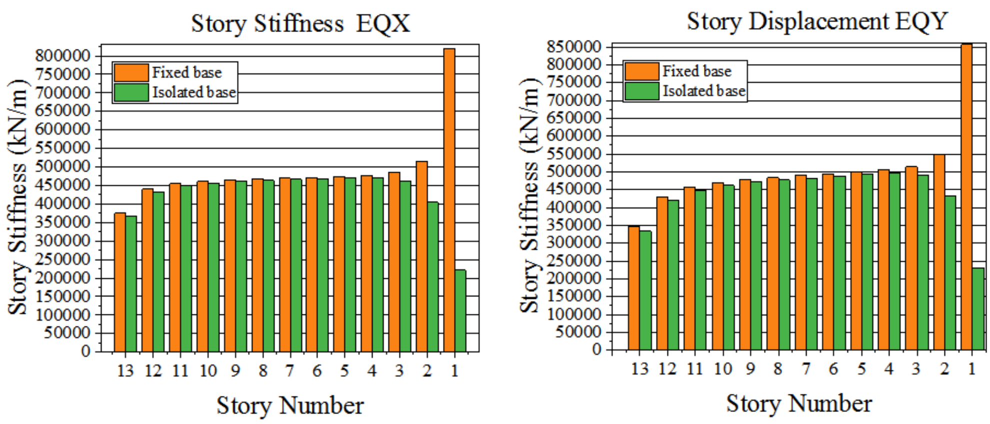


Figure 7. Story stiffness profile in X-Y directions – Fixed base vs. Base-isolated building

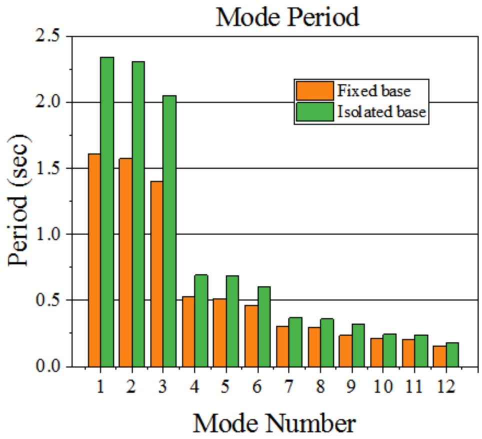


Figure 8. Natural periods for fixed and base-isolated models (First 12 modes)

Conclusion

This study has demonstrated the effectiveness of base isolation, particularly with Lead Rubber Bearings (LRBs), in improving the seismic performance of multi-story buildings. A comparative analysis between fixed-base and base-isolated models under seismic loading revealed several key findings:

- Inter-story drifts were significantly reduced in base-isolated structures, particularly from mid to upper stories, with reductions of up to 68% in the X direction and 69% in the Y direction, enhancing stability and minimizing damage during seismic events.
- Absolute story displacements increased due to the flexibility of the base, but these shifts are intentional and beneficial. The isolators absorb and dissipate seismic energy, reducing force demands on the superstructure, while ensuring controlled movement.
- Story shear forces showed a significant reduction of approximately 29–31% across all floors, indicating lower seismic demand and improved structural integrity in the isolated model.
- Story stiffness was notably higher in base-isolated structures, especially at lower and mid-level stories, with increases up to 318% at Story 1. The isolation system effectively shifted deformation away from the superstructure, allowing for more linear behavior of the upper structure.
- The natural periods of all vibration modes increased in the base-isolated model, with the fundamental period increasing by 45.5%. This period elongation reduces seismic acceleration demands by shifting the structure's natural frequency away from the predominant frequency content of earthquake ground motions.

Overall, the implementation of base isolation enhances seismic resilience by reducing drift, shear, and acceleration demands, while improving energy dissipation and period elongation. These results validate the use of LRBs as an effective seismic mitigation strategy and support their application in performance-based seismic design.

Authors' contributions

Moneef Mohamed Elobaid Musa: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Writing—Original Draft Preparation; Muhammad Usama Aslam: Conceptualization, Methodology, Software, Formal Analysis, Investigation; Mohammed Elhassan Omer Elhassan: Validation, Formal Analysis, Resources, Writing—Review & Editing; Musaab Suliman: Data Curation, Visualization, Writing—Review & Editing; Muhammad Usman Siddiq: Supervision, Project Administration, Writing—Review & Editing. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request

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