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REVIEW

# Seismic response of base-isolated buildings: exploring isolator properties

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## Abstract

This paper examines the impact of LRB and FPS-bearing isolator properties on the seismic behaviour of base-isolated buildings. A systematic analysis of various factors crucial to the performance of these base isolation systems was conducted. The seismic behaviour is critically reviewed, comparing and contrasting the seismic effects of LRBs and FPBs on the general characteristics of structural responses to earthquakes under dynamic loading. The main factors discussed include the coefficient of friction, radius of curvature, diameter of the lead core, and characteristics of the hysteretic behaviour. A comprehensive review of the available literature reveals that distinct groups of elements play vital roles in the seismic response of buildings equipped with lead rubber bearings (LRBs) and friction pendulum systems (FPSs), as discussed for isolated buildings (IBs). For LRB-isolated buildings, the key parameters include efficient damping, lead core diameter, and initial stiffness to post-yield stiffness ratio. Conversely, for FPS-isolated structures, parameters such as the friction coefficient, radius of curvature, and effective damping are closely associated with the seismic response. Based on an extensive literature review, it can be concluded that highly influential factors in determining the overall behaviour and performance of IB structures include the friction coefficient, radius of curvature in the FPS, initial stiffness, and ratio of pre- to post-yield stiffness in the LRB. This paper serves as a key resource for researchers, engineers, and practitioners engaged in seismic design and retrofitting activities, offering insight into the challenges associated with achieving optimal behaviour in base-isolated structures.

**Keywords** Base isolator · Earthquake control · Friction · Coefficient · Stiffness

## Introduction

An earthquake control system refers to a comprehensive set of measures and technologies designed to minimise the impact of earthquakes on structures and infrastructure. These systems typically incorporate various strategies such as base isolation, damping systems (Kaveh et al., 2020), and structural reinforcement, to enhance the resilience of buildings and infrastructure against seismic forces. Additionally, advanced monitoring and early warning systems play a crucial role in detecting seismic activity and alerting populations to take appropriate safety measures. By integrating these components, earthquake control systems aim to reduce casualties, mitigate property damage, and ensure the overall safety and stability of communities in earthquake-prone regions (Kaveh et al., 2015).

Base isolation represents one of the significant advancements in seismic engineering, providing a proven technique for mitigating the destructive effects of seismic loads on structures (Bao & Becker, 2018; Han & Marin-Artieda, 2015). During earthquakes, base-isolated structures separate themselves from ground motion through specialized isolation systems, thereby mitigating the effects of seismic activity. This decoupling process is crucial because it significantly diminishes the transmission of seismic forces to the main structure, thereby reducing potential harm and enhancing overall safety (Mokha et al. 1991; Yang et al. 2010). The significance of base isolation extends beyond making buildings less vulnerable; it also protects critical infrastructure, lowers repair costs, and expedites post-earthquake recovery efforts. The isolators effectively absorb and dissipate seismic forces, preventing their transfer to the structure above (Bao & Becker, 2019; Mazza & Mazza, 2016). This controlled movement serves not only to reduce structural distortion

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but also to restrict the acceleration and displacement of the structure, ensuring a safer and more predictable reaction. The characteristics of a seismic base isolation system are as follows:

- *Decoupling from Ground Motion* With base isolation, the structure is isolated from ground movement by the installation of flexible bearings or isolators between the foundation and superstructure. This makes the seismic forces less likely to be transmitted into the building.
- *Horizontal Movement Capability* Base isolators should be designed to allow horizontal movement of the structure during an earthquake. This so-called movement is critical for reducing seismic energy and preventing the transfer of large lateral forces to buildings.
- *Vertical Load Support* Base isolators are engineered to permit movement only in a horizontal direction while still furnishing vital support for vertical loads. This ensures that the building maintains its strength and stability.
- *Energy Dissipation* Base isolators encompass energy-absorbing mechanisms, such as sliding bearings or damping devices, which absorb and dissipate seismic energy during earthquakes. This plays a crucial role in mitigating excessive structural distortions during seismic events.

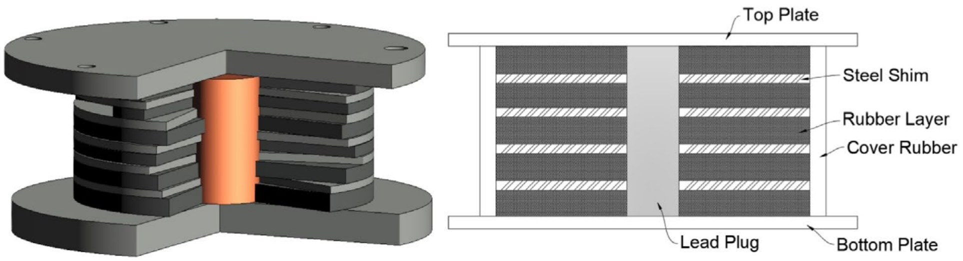
The behaviour of a building on base- isolation subjected to seismic shocks stands in stark contrast to that of a fixed-base building, highlighting the efficacy of seismic isolation technology. A fixed-base building experiences direct seismic stresses, resulting in swaying and significant lateral displacement (Behzad Talaeitaba et al., 2021). This often results in increased structural stress, potential injuries and compromised safety for anyone inside. Alternatively, when an earthquake is applied to a base-isolated building that has been equipped with specialized isolation accessories, such devices allow the building to make controlled sideways movements (Fakih et al., 2021; Sahoo, 2018) but at lower levels. Seismic base isolators have made great strides over the years and ushered in a new age of innovation concerning the mitigation of earthquake-based impacts on building structures (Al-Kutti & Islam, 2019; Haque et al., 2013; Palazzo et al., 2014). The modern designs of isolators are undergoing significant evolution, transitioning into more sophisticated systems. These modern systems now incorporate technologies such as lead rubber bearings (LRBs) or friction pendulum bearings (FPBs), resulting in enhanced capabilities. Furthermore, advancements in materials science and engineering have led to isolators with superior performance and durability, ensuring their long-term effectiveness. Recent studies have predominantly concentrated on adaptive isolators such as Variable (VFPS), Double (DFPS), Triple (TFPS), and Quintuple (QFPS) friction pendulum systems. Additionally, there has been research into intelligent isolators and other systems designed to effectively control earthquake forces (Fahimi Farzam & Kaveh, 2020; Kaveh & Ardebili, 2021). The findings from these studies enable the development of resilient structures capable of withstanding various levels of seismic wave activity, marking significant progress in enhancing the security and sustainability of buildings in earthquake-prone areas.

This review explores various aspects concerning the intrinsic properties of LRB and FPS devices, which have demonstrated promising earthquake control techniques by minimizing seismic forces transmitted from the ground to the superstructure through these devices.

## Lead Rubber Bearing (LRB)

Base isolation, as a method of protecting buildings from seismic forces, became popular during the 1960s and 1970s after its adoption. This is a clear historical trace of the origins of lead rubber bearings again in the mid-20 mid-twentieth century. The first seismic isolators used a system consisting of a rubber lamination with steel bearings (Chang, 2002). The use of lead as a damping material has greatly increased the energy dissipation capacity of these devices. The first application of lead rubber bearings in large buildings occurred in the late 1970s and early 1980s, especially in Japan. Since then, the technology has evolved with constant research and advancements in materials and design, making lead rubber bearings a vital component of earthquake-resistant engineering. Their application has been widespread on an international level, with the main focus on improving the seismic performance of critical infrastructure components such as bridges, buildings and industrial plants.

The dispersion of seismic energy has garnered significant attention for lead rubber bearings (LRBs) in the field of structural engineering. This characteristic renders LRBs highly effective at safeguarding structures by mitigating the adverse effects of earthquakes. LRBs are developed from the fundamental principle of utilizing a lead core encased in rubber as a damping material. In comparison to high damping rubber bearings (HDRBs), the damping of rubber in LRBs is not as critical, allowing for the use of standard rubber. LRB devices consist of alternating layers of rubber and steel, with a lead core at the center, as depicted in Fig. 1. This arrangement enables LRBs to exhibit both axial and transverse displacements while attenuating the transfer of seismic energy to the superstructure. However, the effectiveness of LRBs relies on numerous parameters, including the properties of the lead core (Das et al., 2014) and rubber stiffness.



(a) (b)

**Fig. 1** Lead rubber bearing **a** 3D view; **b** sectional view

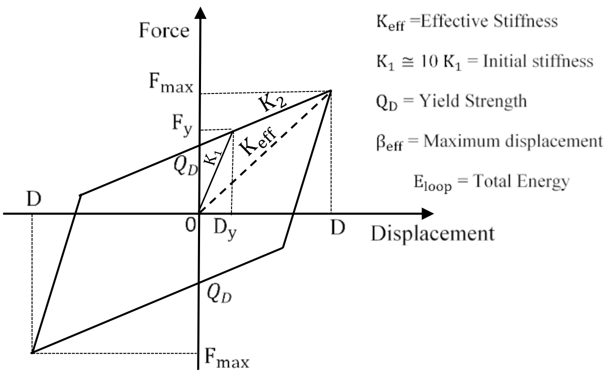


**Fig. 2** Hysteretic Behavior of Lead Rubber Bearings

The area of the lead core $A_{lead}$ is computed based on the characteristic strength $Q_D$ and the yield stress $\sigma_y$.

$$A_{lead} = \frac{Q_D}{\sigma_y} \tag{1}$$

The diameter $d_{lead}$ is easily found in the area.

$$d_{lead} = \left(\frac{4A_{lead}}{\pi}\right)^{1/2} \tag{2}$$

Figure 2 illustrates the bilinear hysteretic loop of the LRB indicating specific points influencing its characteristics.

Hysteretic behaviour is characterized by:

The effective stiffness $K_{eff}$

$$K_{eff} = \frac{W}{g}\left(\frac{2\pi}{T_D}\right)^2 \tag{3}$$

where W is the total vertical load on the isolator, g is the acceleration due to gravity in (m/s$^2$) and $T_D$ is the target design period which may be assumed from the start of the design step.

The energy stored in one cycle or loop $E_{loop}$

$$E_{loop} = 4\left(\mathrm{D}F_y - \mathrm{F}D_y\right) = 2\pi\beta_{eff}K_{eff}D^2 \tag{4}$$

With D, the displacement evaluated in equation-9 but should not be greater than $D_M$ in Eq. 10; $F_y$ is the yielding force expressed in KN and is calculated from Eq. 7 and $D_y$ is the corresponding displacement at yielding as shown in Fig. 2 and is accessed in Eq. 14. At the beginning of the design effective damping is assumed or calculated from equation Eq -13.

Yielding Strength $Q_D$ (KN)

$$Q_D = \frac{E_{loop}}{4(D - D_y)} \tag{5}$$

The post-yield stiffness $K_2$ (KN/m)

$$K_2 = K_{eff} - \frac{Q_D}{D} \tag{6}$$

The yielding force $F_y$ (KN)

$$F_y = K_1 D_y \tag{7}$$

where $K_1$ is the initial stiffness of the base isolator and can be taken to be nearly 10 times the post-yield stiffness.

Effective damping $\beta_{eff}$

$$\beta_{eff} = \frac{E_{loop}}{2\pi K_{eff} D^2} \tag{8}$$

According to ASCE-7 (2002) the design of the LRB starts by finding the minimum design displacement $D_D$ for the DBE level and the maximum design displacement $D_M$ for the MCE level earthquake computed with the relation.

$$D_D = \frac{gS_{D_1}T_D}{4\pi^2 B_D} \tag{9}$$

$$D_M = \frac{gS_{M_1}T_M}{4\pi^2 B_M} \tag{10}$$

where $S_{D_1}$ and $S_{M_1}$ are acceleration coefficients related to the site condition;$T_D$ and $T_M$ are the minimum and maximum periods $B_D$, respectively; and $B_M$ are the damping modification factors respectively at the design base earthquake (DBE) and maximum considered earthquake level (MCE), respectively.

$D_M = 1.5D_D$ was considered by Behzad Talaeitaba et al., (2021) as recommended by ASCE-7 (2002), while $D_M = 2D_D$ was used by Reddy et al., (2019).

The damping modification factor ($B_D$) is directly taken from the code or calculated from Eq. 11 if the effective damping $\beta_{eff}$ is known.

$$B_D = \frac{1}{\left(\frac{0.1}{0.05+\beta_{eff}}\right)^{1/2}} \tag{11}$$

According to AASHTO (2010), the modification factor is noted as $B_L$ and is expressed as:

$$B_L = \left(\frac{B_{eff}}{0.05}\right)^{0.3} \le 1.7 \tag{12}$$

The LRB yield strength $F_y$ and yield displacement $D_y$ are expressed as:

$$F_y = Q + K_2 D_y \tag{13}$$

$$D_y = \frac{Q}{K_1 - K_2} \tag{14}$$

According to ASCE FEMA-356 (2000), the rubber bearing elastic pre- to post-yield stiffness ratio $K_1/K_2$ ranges from 6.5 to 10. The total thickness of the rubber layer $T_r$ is:

$$T_r = \frac{D_D}{\gamma} \tag{15}$$

where $\gamma$ is 100% of the shear stiffness. The area of the rubber bearing ($A_{LRB}$) is computed as:

$$A_{LRB} = \frac{K_{eff} T_r}{G} \tag{16}$$

With G, the shear modulus is taken as approximately 0.7 MPa and its diameter to be calculated from the area.

$$n = \frac{T_r}{t} \tag{17}$$

$$t = \frac{d_{LRB}}{4S} \tag{18}$$

where n is the number of rubber layers; $d_{LRB}$ is the diameter of the LRB; t is the thickness of one layer of the rubber; and S is the shape factor calculated from:

$$S = \frac{d_{LRB}^2 - d_{lead}^2}{4td_{LRB}} \tag{19}$$

The horizontal stiffness $K_H$ and the vertical stiffness $K_V$ of the isolator are:

$$K_H = \frac{A_{LRB}}{t_r} G \tag{20}$$

$$K_V = \frac{A_{LRB}}{t_r} E_c \tag{21}$$

With $E_c$ the compression modulus, is expressed as:

$$E_c = E\left(1 + KS^2\right) \tag{22}$$

E is the Young's modulus of elasticity.

## Friction pendulum bearings (FPBs)

Friction pendulum bearings (FPBs) offer a new approach to seismic isolation by relying on the frictional energy dissipation principle, which is generated naturally. Friction pendulum bearings (FPBs) consist of a moveable concave surface (Cardone et al., 2015) supporting the structure to allow rotational motion and provide friction resistance, as illustrated in Fig. 3. The articulated slider moves on the concave plate, generating friction. This friction helps reduce the seismic forces that travel through the device to the superstructure.

The behaviour of the system during an earthquake is directly influenced by many variables such as the friction coefficient (Castaldo & Tubaldi, 2015), sliding surface curvature (Cardone et al., 2015), and the vertical and rotational stiffness of the bearing.

The free-body diagram of the FPS isolator is presented in Fig. 4 where $F_n$ is the normal reaction force towards the radius R of the pendulum; $F_f$ is the friction force due to the displacement D of the system and $F_o$ the restoring force; W is the vertical weight on the isolator; $\theta$ is the angle between the initial position of the device and in motion. The equation of equilibrium due to the applied load W is expressed as:

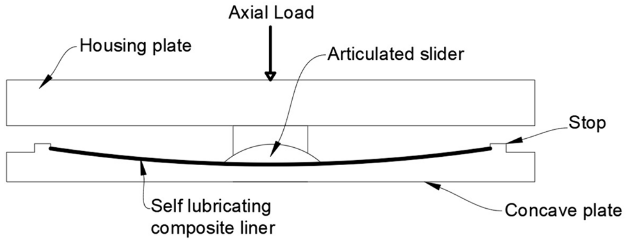


**Fig. 3** Section view of friction pendulum system

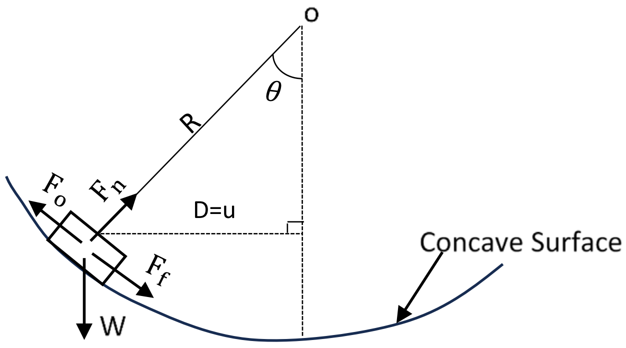


**Fig. 4** Free body diagram of the friction pendulum system

$$Sin\theta = \frac{D}{R} \tag{23}$$

$$F_o - F_f - WSin\theta = 0 \tag{24}$$

By summing up the various forces subjected to FPS, as illustrated in Fig. 4 along the horizontal direction through the projection of the restoring force $F_o$ is:

$$F_o = \mu Wsign(\dot{u}) + \frac{W}{R}u \tag{25}$$

where $\mu$ is the frictional coefficient usually in the range of 0.05 to 0.15 by Jangid (2005) and from 0.02 to 0.12 by Dolce et al. (2005); W is the total vertical weight in KN under the column to be considered, R is the radius of the concave surface in m and $u$ is the displacement of the isolator at time t and $\dot{u}$ is its velocity in m/s.

The friction coefficient of 0.05 to 0.15 was investigated (Castaldo & Tubaldi, 2015) through a twenty-four-shear type story building, and it was found that the higher the coefficient of friction, is greater the energy dissipation. This coefficient was critical at 0.08. Although there are various expressions used to estimate the friction coefficient, the most widely accepted state that it is dependent on velocity (Constantinou et al., 1990):

$$\mu = \mu_{fast} - (\mu_{fast} - \mu_{slow})e^{-rv} \tag{26}$$

The dynamic friction coefficient decreases with increasing contact pressure between the steel and the Teflon-coated surface (Mokha et al., 1990).

The ratio $\frac{\mu_{fast}}{\mu_{slow}}$ was experimentally found to range from 2 to 3.2 (Cardone et al., 2015). For simplicity, many researchers considered the ratio $\frac{\mu_{fast}}{\mu_{slow}}$ =2.5 (Nguyen & Dao, 2021; Vibhute et al., 2022a, 2022b) and the rate parameter r as:

$$r = \frac{1}{v_{ref}} \ln \frac{\mu_{fast} - \mu_{slow}}{\mu_{fast} - \mu_{ref}} \tag{27}$$

where $v_{ref}$ = referencevelocity and $\mu_{ref}$ = referencefrictioncoefficienttakenas 80%$\mu_{fast}$. Through the simulation of four shear-type structures akin to those in the Kobe earthquake, it was discovered that the base shear increases with increasing friction coefficient (Rabiei & Khoshnoudian, 2011).

The hysteretic behaviour of a constant friction coefficient of FPS is shown in Fig. 5.

According to ASCE FEMA-356 (Asce, 2000) the elastic stiffness of the sliding bearing is assumed to be 100 times the post-yield stiffness which was also advised by Konstantinidis et al., (2010).

A properly calibrated FPS base isolation system holds the promise of significantly enhancing a structure's resilience against seismic events. This is achieved through efficient dispersal of seismic energy and minimization of lateral displacements, facilitated in part by its exceptional recentering capability. The energy E dissipated per cycle is:

$$E = 4\mu Wu \tag{28}$$

The summation of each area of the hysteretic loop constitutes the total energy dissipated energy.

With a given target design period $T_d$ the radius of the concave surface $R$ is expressed as:

$$R = g\left(\frac{T_d}{2\pi}\right)^2 \tag{29}$$

The acceleration due to gravity in m/s$^2$ is g.

A study on the effect of the radius of curvature on the uplift of the isolator during seismic events was investigated by Mazza and Mazza (2016) on irregularly reinforced concrete buildings. During the study, it was noted that increasing

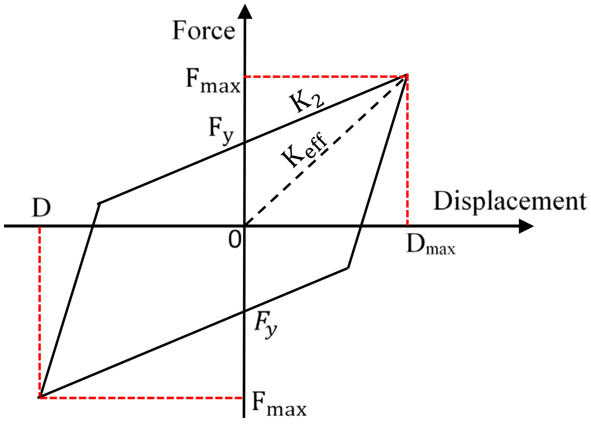


**Fig. 5** Hysteretic Behavior of the Friction Pendulum System

the radius of curvature of the FPS significantly reduces the potential for uplift, although it may increase within certain intervals for the aforementioned reasons.

As stated by Rabiei and Khoshnoudian (2011), an increase in the time period increases the base shear error and decreases the acceleration error. The greater the isolation period is, the greater the radius of the concave surface needed. Aashto (2000) recommends adjusting the isolation period to not exceed 6 s and ensuring that the product of post-yield stiffness ($K_2$) and displacement (D) is greater than 0.025 W. The effective stiffness $K_{eff}$ and effective damping $\beta_{eff}$ of the FPS-isolated building are computed from Eqs. 30 and 31:

$$K_{eff} = \frac{W}{R} + \frac{\mu W}{D} \tag{30}$$

$$\beta_{eff} = \frac{2}{\pi}\left(\frac{\mu}{\frac{D}{R} - \mu}\right) \tag{31}$$

The damping increases with increasing acceleration (Tajammolian et al., 2014).

To assess the yielding strength (Q) the equation below is generally employed:

$$Q = \mu W \tag{32}$$

## Review of the literature on LRB

During the past two decades, the properties and factors influencing the response of isolated buildings to lead rubber bearing have been investigated. The research conducted by some of these authors is outlined below:

Haque et al. (2013) investigated the eight-story seismic behaviour of educational buildings that use base isolation systems by focusing on the influence of different properties of lead rubber bearings (LRBs). This research focused on three important parameters of the LRB (lead rubber bearing) system: the initial stiffness (K1), yield strength ratio (Fy/W), and post to-preyield stiffness ratio (K2/K1). The analysis focused on three distinct seismic ground motions, evaluating the parameters of base shear, roof acceleration, and bearing displacement. Based on these observations, the reduction in the structural response is more significantly influenced by the yield strength and the ratio of post-to- preyield stiffness, as opposed to the initial stiffness. The study advised the use of a post to-pre yield stiffness ratio (K2/K1) ranging from 0.05 to 0.1 and a lower yield strength (Fy/W).

Das et al. (2014) optimized an LRB isolated building to resist seismic events. This study used stochastic analysis approaches to improve the performance of isolators while limiting displacements. The authors investigated the use of a multii-story shear type lead rubber bearing (LRB) system, specifically by comparing constrained and unconstrained optimization approaches. The results showed that using constrained optimization, which restricts isolator displacement, consistently yields higher yield strength values. The aforementioned approach successfully decreased isolator displacement while preserving the effectiveness of vibration isolation, thereby underlining its importance in the field of seismic design.

Han and Marin-Artieda (2015) researched seismic isolation techniques intended to safeguard critical equipment and components within tall buildings, such as lead-rubber isolated platforms. The process involved conducting experimental evaluations subjected to horizontal and vertical earthquake impacts. The introduction of lead rods aimed to enhance the damping platform's response ratio while increasing energy dissipation through a lead core. The findings demonstrated the effectiveness of isolating the platform, reducing input accelerations on the equipment due to roof movements. The displacements induced by the earthquake simulator significantly overestimate those on the isolated equipment, resulting in displacement levels deemed acceptable for seismic protection.

Islam and Al-Kutti (2018) focused on the performance of base isolation devices, particularly lead rubber bearings (LRBs), in reducing the vulnerability of buildings subjected to strong earthquake effects. The researchers presented a simulation of sixteen model buildings, each with one of the twelve types of LRB isolators on its surface. A comparison was then made between these buildings and fixed-base (FB) stereotypes. The results showed substantial reductions in lateral forces, displacement, inertia, and floor acceleration due to the installation of the LRB. In particular, the base shear significantly decreased from 12 to 40%.

Bhandari et al. (2018) validated the accuracy of the CSM (capacity spectrum method) in predicting seismic demands for lead rubber base-isolated frames against nonlinear time history analysis (NTHA) across different performance points.The research included several types of base isolators, i.e., stiff, medium and hard, which were used in two different reinforced concrete building types. The authors concluded that the CSM (capillary spectrum method) provides stable results up to a certain plasticity parameter, which is equal to the ensured earthquake intensity value for appropriate parameters reflecting the system's reaction. The same is true for their level of dependability, as they decline beyond that point.

Basshofi Habieb et al. (2019) analysed the performance of lead rubber bearings (LRBs), which are often used to mitigate seismic forces for mid- and high-rise buildings. The approach used in 3D finite element FE modelling focused on important features such as the plasticity observed in the lead core and rubber material hyper elasticity with viscous behaviour. The characteristics of rubber properties, such as hyper elasticity and damping, were identified using experimental data derived from laboratory tests. To evaluate the consistency in shear behavior between the model under assessment and an analytical model of lead rubber bearing (LRB) isolators, a comparison was conducted with results obtained from the finite element (FE) model. The findings demonstrated that incorporating the Abaqus User-Element (UEL) significantly reduced computational resources and facilitated accurate estimations of LRB performance.

Al-Kutti and Islam (2019) investigated seismic hazards in earthquake-prone areas and assessed the potential effectiveness of lead rubber bearing (LRB) devices as base isolation methods for mitigating structural damage in buildings. This study involved analysing16 building structures and comparing various LRB systems with FBs. Both static and dynamic methods were employed in the study, demonstrating that LRB isolators can effectively reduce story accelerations, story inertia, and base shear. The findings indicate that LRB isolators can achieve a significant reduction in base shear, up to 20%, surpassing the capabilities of FB technology, which typically achieves reductions between 10 and 20%. Additionally, LRB systems induced lateral displacement in the superstructure by enhancing flexibility. The most favourable outcomes were observed when the LRB systems exhibited lower characteristic strengths and longer isolation periods.

Fakih et al. (2021) studied the seismic performance of a 48-story reinforced concrete skyscraper built in an asymmetric shape in the Beirut. The authors compared the effectiveness of a rigid foundation configuration to that of an isolated base system employing lead rubber bearing (LRB) isolators. Nonlinear analysis and actual earthquake acceleration data from engineering modelling software were used to assess the impact of the LRB isolators. The results show significant improvements: the isolated structure demonstrated a 300% increase in the horizontal base shear capacity (HB), a 46.5% decrease in the lateral displacement at the roof level, and an 84.6% reduction in the spectral displacement at the roof. Furthermore, the dissipated energy on the top floor decreased by 55.24%, with the isolated base shear force dropping from 8368 to 1169 tonnes.

Marquez et al. (2021) analysed the functions of lead rubber bearings (LRBs) as part of seismic isolation systems, for construction and buildings. LRBs were used to minimize the impacts of horizontal earthquake-induced ground shaking by concentrating displacements in the bearings and reducing deformations in the structure. This study addressed the challenge of potential failure arising from heightened seismic loads on isolators or bounding on moat walls. To address this issue, researchers have developed a parallel nonlinear model incorporating lead core heating, reactant strain hardening, and unloading effects. This model guaranteed the resilience of LRBs against high strains. This research aimed to forecast isolator displacement and assess the possibility of surpassing the limit state. Additionally, the results highlighted the significance of numerical time history analyses in sensitively selecting models for LRBs.

Behzad Talaeitaba et al. (2021) used LRB base isolators as a means to mitigate seismic stresses on buildings. This study included the development of mathematical models for these isolators, hysteresis analysis, and evaluation of their effectiveness in simulating earthquake scenarios for steel and concrete structures ranging from 3 to 6 stories in height. Key findings indicate that the RRB (Rolling Rubber Bearings) offered superior initial stiffness, better load-carrying capacity, significantly greater energy dissipation (43% greater than that of the LRB), and notable damping characteristics (44–50% greater than that of the LRB across all measured frequencies).The implementation of RRB substantially reduced the acceleration levels (from 42.16% to 57.16%), shear force coefficients (from 37.93% to 56.83%), and drift values (35.33% to 59.66%) within the structures. Additionally, RRB exhibited a lower weight than LRB but also demonstrated a 23% decrease in effectiveness compared to that of LRB.

Hu et al. (2023) Focusing on improving the seismic design of base-isolated building structures, particularly those utilizing lead rubber bearings (LRBs), the author identified deficiencies in China's current seismic design code. This code separates the design of the isolation system and the superstructure, thereby preventing the simultaneous consideration of crucial parameters such as horizontal isolating coefficients and horizontal deformation of the isolation system. In response to these shortcomings, the authors proposed an efficient seismic design process for LRB base-isolated structures, presenting a mathematical formulation of key parameters involved in the process. By considering a specific yield strength ratio, the study determined the minimum horizontal seismic isolation coefficient through parameter analysis.

Figures 6 and 7 illustrate the maximum inter-storey drift and maximum base shear of the fixed-base and lead rubber bearing (LRB) isolated buildings, respectively. The reduction in the maximum inter-story drift and maximum base shear of LRB-isolated buildings compared to those of fixed-base buildings across various studies (Behzad Talaeitaba et al., 2021; Deringöl & Güneyisi, 2020; Hadian et al., 2013; Islam & Al-Kutti, 2018; Kazeminezhad et al., 2020; Pokhrel et al., 2016) demonstrates the efficacy of the LRB in mitigating seismic damage in earthquake-prone regions, as depicted in Figs. 6 and 7. This significant improvement can be attributed to damping phenomena facilitated by the LRB setup, resulting in energy dissipation during the transfer of seismic energy from the ground or foundation systems to the

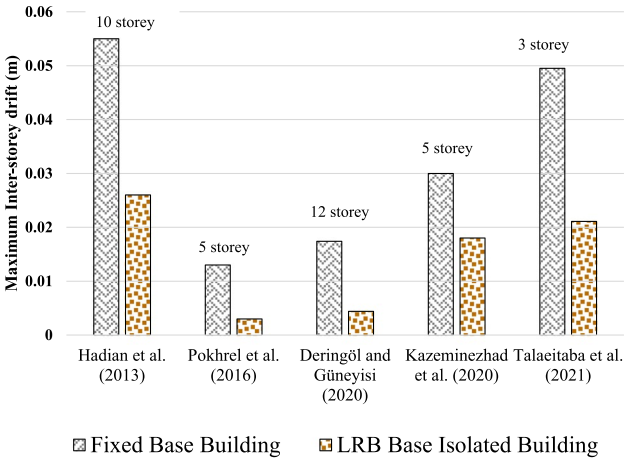


**Fig. 6** Comparative Maximum Inter-storey Drift of an LRB Isolated building with a Fixed Base Building

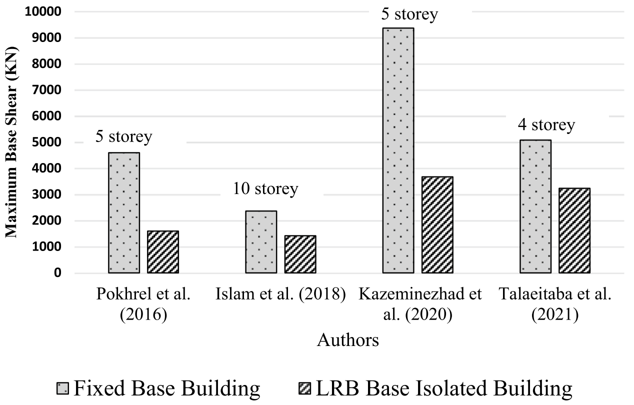


**Fig. 7** Comparison of the Maximum Base Shears of the LRB Isolated Building and the Fixed Base Building

superstructure. As shown in Fig. 6., the buildings with 3 stories according to Behzad Talaeitaba et al. (2021) exhibited the highest maximum inter-storey drift among the 3-storey buildings, compared to the 10-, 5-, and 12-storey structures. This discrepancy may stem from various factors, such as structural stiffness, building configuration, and the magnitude of seismic forces. Similarly, Kazeminezhad et al. (2020) noted the highest maximum base shear in their 5-story building, reflecting similar influences. Overall, differences in the performances of the LRB-isolated buildings can be attributed to variations in the LRB device properties.

## Review of the literature on FPS

Briseghella et al. (2013) reviewed the effectiveness of the Friction Pendulum System (FPS) as a technique that could be employed to increase this seismic capability in post existing structures under base isolation. The authors discussed and described three specific mechanical models of FPS (friction pendulum system) bearings and noted their impact on a building that became defective after the Italian earthquake that occurred in 2009 when it was hit by a L'Aquila quake. The objective is based on many attributes with a detailed description of the story shear, inter-storey drift, effective stiffness and energy dissipation. These analyses within the scope of life-safety and the ultimate limit state included response spectral analysis, linear dynamic analyses, and nonlinear dynamic analysis. From the results, it was shown that utilizing base isolation with FPS in turn causes a considerable drop in shear pressure and inter-story drift.

Palazzo et al. (2014) assessed the seismic reliability of base-isolated structures utilizing friction pendulum systems (FPSs) as seismic protection measures. This investigation considered the properties of FPS isolators, such as the coefficient of friction, and the dynamic characteristics of earthquakes. Seismic reliability was determined through comparative analyses of probability density and cumulative distribution functions, which were dynamically established by extensively studying influencing factors and considering limit state thresholds. This research focused on a conventional base-isolated structure intended for construction in L'Aquila, Italy, with an expected lifespan of 50 years. The study results indicated that the safety regulations outlined in NTC08 were largely met, particularly in the superstructure and substructure of the examined building. However, minor deviations from the guidelines outlined in FEMA 274 were observed at various levels.

Cardone et al. (2015) assessed the seismic capabilities of friction pendulum systems (FPSs) by performing a broad parametric analysis. The visco-plastic model of Constantinou et al. (1990) was used to assess the dynamic characteristics of the isolation system. This model includes the dependence of the changing friction coefficient on the sliding velocity and pressure of interaction. In addition, more than three hundred natural seismic ground motions recorded from various earthquakes were used to assess the seismic intensity, frequency, magnitude, epicentral distance and soil properties. A residual displacement response function was obtained via regression analysis to determine the correlation between the two parameters that govern FPS responsiveness. The findings indicated that the key factor that governs the restoring capacity of FPSs is the greatest seismic displacement -to -maximum static residual displacement ratio.

Pokhrel et al. (2016) compared the performance of two different seismic isolation systems, namely, a lead rubber bearing and a friction pendulum bearing, and their efficiency and adaptability in a five-story reinforced concrete structure subjected to four standardized earthquakes. This study employed the Bouc-Wen model to undertake a detailed design and nonlinear time history analysis. The results showed that both of the isolation systems lead to a basic period of structures and an increase in spectral acceleration. As a result, this caused a significant improvement in building efficiency. The greatest declines in the base elastic shear deformation and inter-storey drift were recorded for the lead rubber bearing, which outperformed the friction pendulum bearing for most tests of the benchmark earthquake.

Mazza and Mazza (2016) conducted a nonlinear seismic analysis on a collection of twelve FBS buildings equipped with friction pendulum (FP) devices, that were exposed to near-fault ground motions. During the study, the researchers examined varying the radius of curvature of the FP bearings and changing the shear-out friction coefficients. The study revealed that torsional strains were more prominent in unscaled earthquakes with significant horizontal components. Conversely, residual displacements were observed in structures with isolated bases subjected to unscaled earthquakes with strong vertical components. Furthermore, torsional and residual effects were roughly equivalent across different models involving various isolator types. Reducing the radius of curvature of the FP bearings resulted in a reduction in the residual displacement.

Mazza and Sisinno (2017) studied the behaviour of FP bearings while forgetting other state-of-the-art sliding bearings. This research addressed the spatial nature of the friction coefficient occurring in an FP system, which is dictated by the bearing sliding velocity. Additionally, it was observed that the frictional stress and restoring stiffness during sliding are directly related to the axial load. In this research, a six-story structure with an L-shaped structure and various setbacks was assessed via qualitative analysis of the behaviour of a reinforced concrete structure under earthquake action occurring near a fault rupture. These structures were created for FP systems with different friction coefficients and fast dynamic friction coefficients. The torsional effects were more apparent for earthquakes with high horizontal components, but residual displacement was observed in those with large vertical subsystems.

Bao and Becker (2018) analysed the nonelastic responses of friction pendulum-based isolation superstructures under impulsive loads, focusing primarily on how structural stiffness affects such responses. A two-degree-of-freedom simple model with the Bouc-Wen model was used to describe the nonlinearity of the dynamics in both the superstructure and isolation bearings. A nonlinear Hertz spring is used with a damper to model the impact force. The primary findings indicate that the stiffness of the superstructure significantly influences its response to transient impact pressures. In superstructures composed of stiffer materials, there is a notable escalation in the requirement for ductility to withstand impacts. Conversely, in more flexible superstructure categories, this escalation is comparatively less pronounced.

Ren et al. (2019) conducted an extensive investigation on a large-scale prototype of Friction Pendulum Bearings (FPBs) used in shaking table tests to analyse seismic behavior. This investigation aimed to establish scaling rules for FPBs, determine the physical parameters of models, and suggest an alternative technique for distributing scaled FPBs if the model has fewer FPB emulations than the prototype. The objective of this technique was to closely replicate the global seismic response of the prototype isolation layer and the maximum force experienced by any FPB in the model. Based on the findings presented in the study, it was concluded that the proposed equivalent technique accurately captures the most extreme loading conditions and yields results that broadly correlate with measurements obtained from the full-scale prototype.

Vibhute et al., (2022a, 2022b) studied the earthquake behaviour of a ten-story building structure with Friction Pendulum System (FPS) and Lead Rubber Bearing (LRB) isolation systems. This analysis aimed to assess the behaviour of structures subjected to numerous earthquake responses representing both far-field and near-field earthquakes that have diverse properties. In this study, seismic responses such as base shear, peak top story displacement, absolute acceleration isolator displacement and the number of plastic hinges produced, were measured to evaluate the effectiveness of FPSs and LRBs. The research findings reveal that the FPS has better recentring characteristics than the LRB in the case of a low friction coefficient (μslow) and high earthquake intensity (PGA).

Vibhute et al., (2022a) studied the friction coefficient of FRP and FPS (friction pendulum system) isolated structures. The fast friction coefficient was investigated because it minimizes important engineering demand parameters (EDPs). The optimal coefficient was analysed using two various approaches to the problem allowing for safety gaps. A 10-well building frame foundation separated by an FPS was adopted as a demonstration in the study, and it was observed when either far-field or near-field earthquakes were applied. The study's findings revealed that, in contrast to other methods of reducing earthquake-induced damage that exhibited varying degrees between low and medium levels in terms of changes in friction coefficients, the reduction achieved through the formation of plastic hinges demonstrated significantly greater sensitivity.

Ras and Hamdaoui (2023) analysed the dynamic response of metallic buildings installed with a friction pendulum system (FPS) to mitigate earthquake damage. They performed 3D numerical modelling along with fast nonlinear time history analysis using ten seismic signals. The results showed that the FPS damper effectively dissipated the response of steel frames subjected to different earthquake ground motions without reinforcing them with steel. In general, the study underscored the ability of FPSs to minimize structural responses during severe conditions, highlighting their durability and stability compared to those of other dampers.

Figures 8 and 9 show the comparative maximum inter-story drift and maximum base shear respectively, of fixed-base conventional RCC buildings and friction pendulum-bearing base-isolated buildings from various studies (Mokha et al., 1991; Briseghella et al., 2013; Garevski & Jovanovic, 2008; Pokhrel et al., 2016; Zhao et al., 2019). Both Figs. (8 and 9) depict a considerable reduction in both the maximum inter-story drift and the maximum acceleration induced in the superstructure for the FPS-isolated building. This scenario arises from energy dissipation through damping and the recentering capabilities of the isolating device. The variation in response observed across different research studies in Figs. 8 and 9 stems from discrepancies in the stiffness, number of stories, height, and magnitude of the horizontal forces applied to these buildings. The diminished response of the FPS isolated structure underscores the effectiveness of this device in mitigating seismic forces.

## Comparative Analysis of LRBs and FPBs

The selection between the two options, the LRB and FPB, hinges on structural requirements (Shiravand et al., 2022). LRBs are more suitable for structures demanding a high level of stiffness, whereas the FPB is favoured for its convenience and adaptability, rendering it a highly sought-after choice for various applications. Several researchers (Cross et al., 2019; Esra Ozer and Bayram Tanik, 2023) have focused on studying both isolators to determine the superiority of one over the other regarding their seismic resistance characteristics and operational modes under shake table methods. These investigations are tailored according to the available range of floor plans. In an extensive study, Ozer et al. (2022) noted that the columns of an LRB base-isolated building are weaker to torsion than those of FPS building types. This weakness can be exacerbated by fatigue failure induced by seismic activity at its epicenter, resulting in a loss of added advantage, depending on column directionality. The following year, Ozer et al. (2023) highlighted that the LRB is ideal for middle- to low-rise buildings, especially those structures without recentring issues.

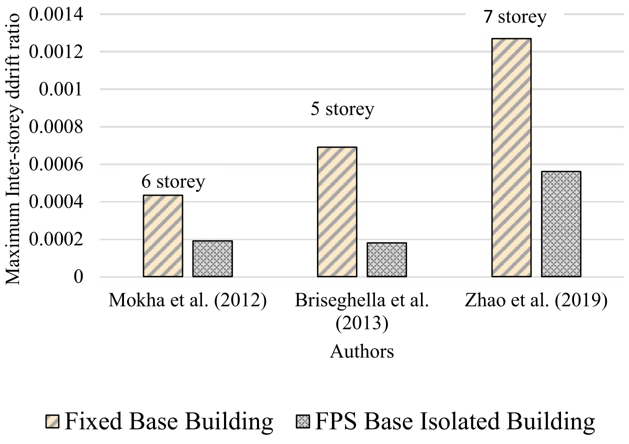


**Fig. 8** Efficiency of FPS in reducing Inter-storey drift

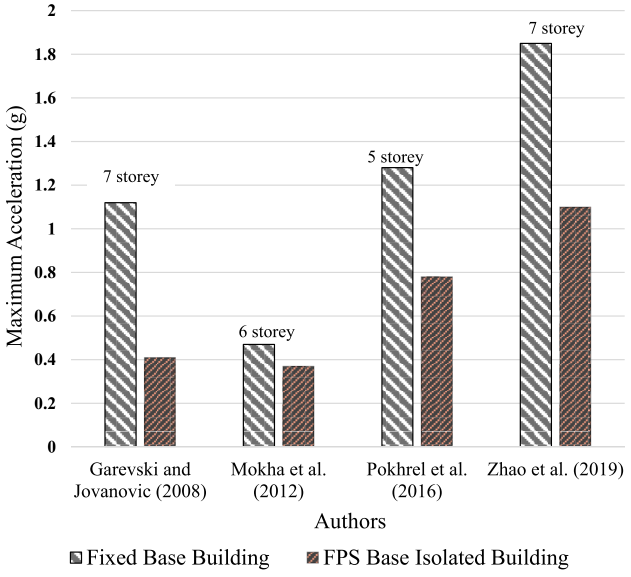


**Fig. 9** Efficiency of FPS in reducing acceleration

To determine the superior performance of the isolator between the LRB and FPS, Figs. 10 and 11 compare the responses of the LRB and FPS isolated buildings in terms of the maximum inter-storey drift and base shear across various research papers (Cross et al., 2019; Mishra, 2020; Vibhute et al., 2022a, 2022b). Observations from Figs. 10 and 11 indicate that buildings isolated with FPS (friction pendulum system) exhibit reduced maximum inter-storey drift and base shear compared to those isolated with LRB (lead rubber bearing). This disparity in performance can be attributed to the superior and inherent recentering abilities of FPSs over LRBs. The variations in performance across different stories, as discussed by the authors, stem from differences in the seismic forces applied to the structure, the rigidity of the structural systems employed, and the height of the stories considered.

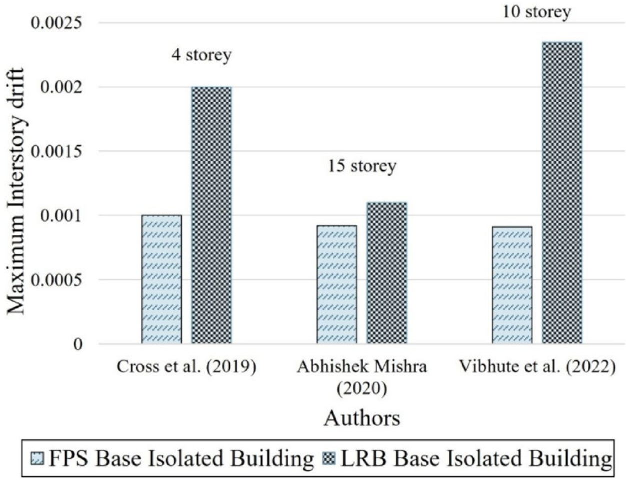


**Fig. 10** Comparative maximum inter-storey drift of the LRB and FPS base-isolated buildings

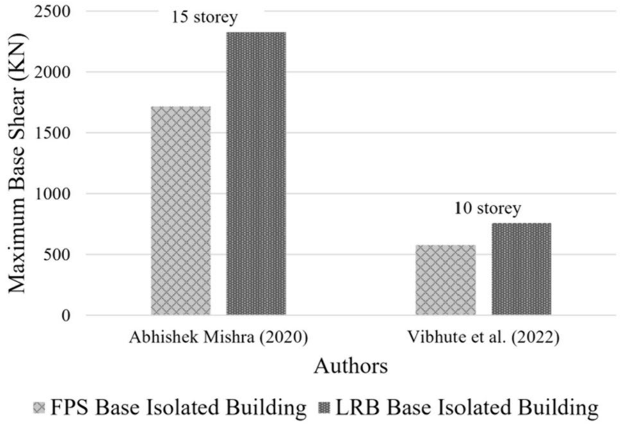


**Fig. 11** Comparative base shear of the LRB and FPS base-isolated buildings

## Challenges and considerations in LRB and FPB isolated buildings

In LRBs, a common challenge is safeguarding rubber against degradation over time, which can result from various factors such as environmental conditions or fatigue. Optimization campaigns must also consider material selection, aging effects, and the entire life cycle. Furthermore, verifying that the stiffness and damping characteristics of LRBs align with structural requirements can be a complex task.

For FPBs, the primary focus lies in optimizing the sliding interface. The energy dissipation capacity and performance significantly depend on the selection of materials for the sliding surfaces and their properties. Thus, it is crucial to appropriately design a restoring force mechanism to return the bearing to its original position after an earthquake. Considerations also extend to the ease of FPB design, durability, and adaptability to different structural configurations.

Both LRBs and FPBs must account for site-specific seismic hazards and structural demands. Balancing stiffness, damping, and energy dissipation characteristics, along with addressing durability and maintenance requirements, presents a significant challenge. Comprehensive analyses and testing are essential to ensure that these isolation systems deliver the desired seismic performance while effectively addressing the unique challenges associated with each type of bearing.

## Conclusions

The overall findings imply that careful selection and improvement of the base isolation method, which in this case is lead rubber bearing (LRB) system or friction pendulum systems, play a significant role in enhancing the seismic performance of different building types. The above studies highlight the importance of considering parameters such as yield strength points, post-to-preyield stiffness ratios, friction coefficient, radius of curvature, time period and hysteretic behavior when introducing an isolator for performance. This review also highlights the need for further study and reflection on different ground vibrations as well as structural scenarios to improve design concepts for best practices in terms of seismic provision. After conducting a comprehensive review of the aforementioned research, the following conclusions can be drawn:

- The lead rubber bearing reduces the inter-storey displacement through energy dissipation offered by the lead plug; hence, the greater its diameter is, the more energy is dissipated, which is the same as in the case of base shear.
- The higher the friction coefficient higher the heat release which results in turn leads to high energy dissipation.
- The higher the friction coefficient is, the greater the heat release, which results in high energy dissipation.
- The Fy/W and K1/K2 ratios influence the response of isolated buildings.
- The incorporation of the LRB and FPS reduces ground motion acceleration in the structure due to energy loss through recentring, rubber elasticity and friction.
- Base isolation is economically most suited for important buildings such as hospitals, educational halls, and nuclear power stations, to protect expensive equipment in seismically prone regions.
- Although the LRB and FPS effectively control earthquake inputs into buildings, there are more advanced adaptative isolators that employ the same concept of base

isolation systems but have improved performance under earthquakes.

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## Declarations

**Conflict of interest** The corresponding author, representing all co-authors, affirms that there are no conflicts of interest to disclose.

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