CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Base isolation systems are a resilient, efficient, and practical approach to safeguard structures and non-structural components against seismic risks. Various isolation techniques have efficiently diminished the dynamic behaviour during low to moderate earthquakes and restrained displacement during more severe seismic events.

This chapter provides a comprehensive literature survey on various seismic base isolation devices, presenting an in-depth review of existing studies and advancements in the field. It examines the characteristics, performance, and applications of different isolation systems, highlighting key findings from past research. Through this analysis, the chapter identifies research gaps that have yet to be addressed, ultimately leading to the formulation of specific objectives for the current study. These objectives are designed to bridge the identified gaps and contribute to the further development and optimization of seismic isolation technology.

Base isolation stands out as a crucial advanced strategy for safeguarding structures against the impact of strong ground motion. Seismic isolation problems have undergone extensive study, resulting in three primary solution categories: active, semi-active, and passive techniques. While active systems offer superior seismic control, their complexity, expense, and dependency on sensing, feedback, and external power make them more challenging. In contrast, passive techniques are promising due to their simplicity, consistency, robustness, and cost-effectiveness.

2.2 Types of Seismic Base Isolation Techniques

Various commonly used seismic response control techniques are illustrated schematically in Figure 2.1, and different types are described below.

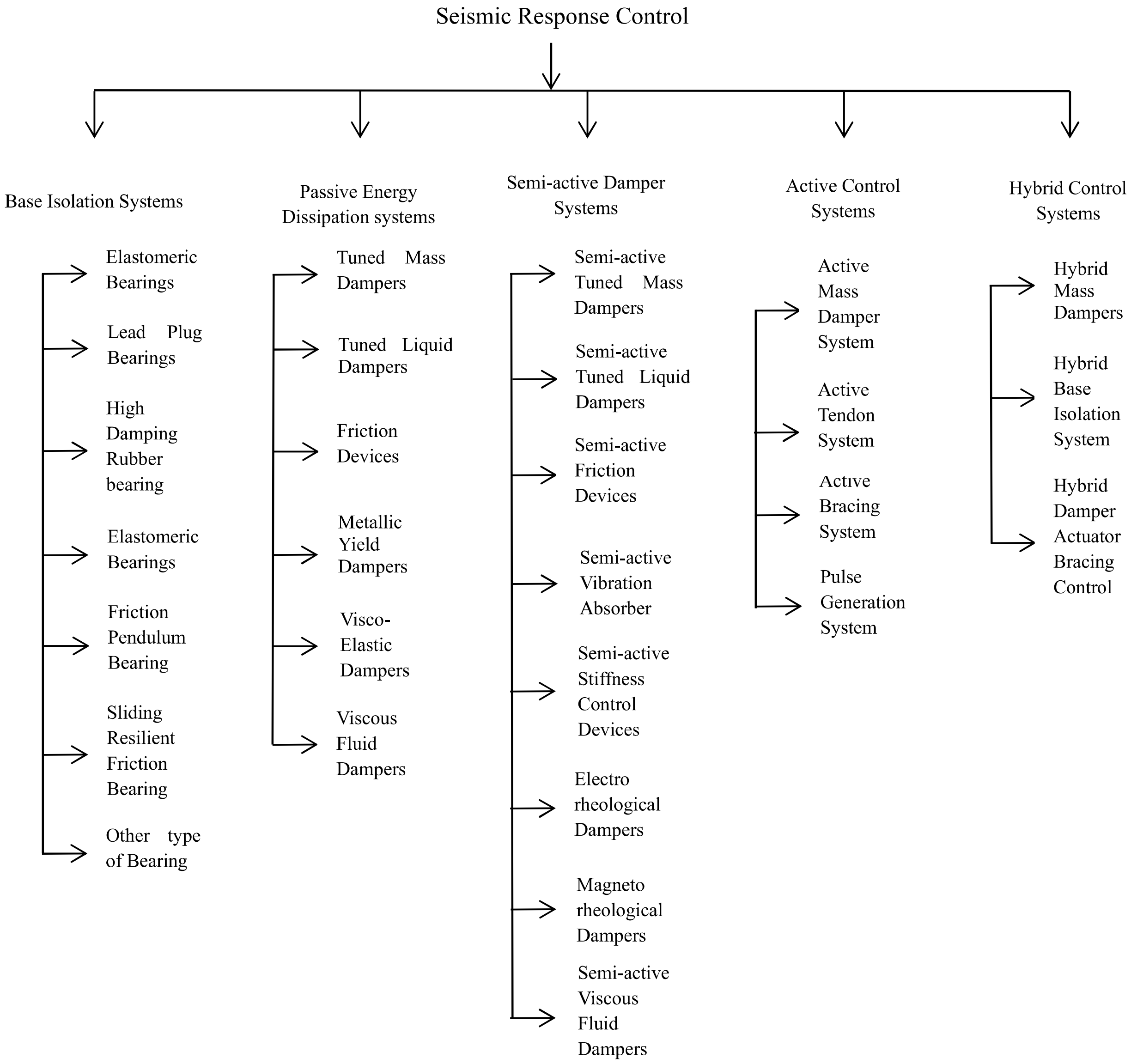


Figure 2.1 shows the seismic response control devices used to reduce the seismic motion

2.2.1 Friction Pendulum System (FPS)

In 1909, Mario Viscardini introduced a friction-based isolation device in response to the Messina earthquake. Literature [37] suggests that FPS, proposed in 1909 by Dr. Calanterients, initially involved pure sliding. He designed to address shortcomings in friction isolators, it applied a talc layer for isolation to mitigate acceleration response. The seismic properties of the isolation system are presented by the effective period of vibration T_{eff} and stiffness K_{eff}, and the effective damping ξ_{eff}. For the FPS isolator, if equivalent radius R and friction coefficient μ is considered, then,

$$T_{eff} = 2\pi\sqrt{\frac{N}{K_{eff} \cdot g}} = 2\pi\sqrt{\frac{1}{1+\frac{\mu . R}{A}}\frac{R}{g}} \tag{2.1}$$

$$K_{eff} = (1 + \frac{\mu . R}{A}).\frac{N}{R} \tag{2.2}$$

$$\xi_{eff} = \frac{2}{\pi}\frac{\mu}{\mu+\frac{A}{R}} \tag{2.3}$$

where, N represents the isolator subjected to vertical load, A is displacement amplitude, and g is gravity acceleration. To ensure the durability of pad material, various self-lubricant was introduced e.g., Ultra High Molecular Weight PolyEthylene (UHMWPE), filled PolyTetraFluroEthylene (PTFE), and other thermoplastics have been suggested as a bearing material [20][38]. Lubricants play a crucial role in enhancing the isolators' ability to withstand significant movements and high velocities without degradation. Past studies predominantly relied on Coulomb's law of friction, assuming equal dynamic and static coefficients. However, experimental results do not support this assumption [39].

To handle substantially larger displacements, the use of larger Friction Pendulum Bearing becomes essential, potentially raising construction expenditures. To address this, derivatives of FPS with multiple spherical components were devised to minimize bearing size. One such system, featuring doubled concave spherical surfaces, is referred to as the multiple-FPS [40]. Fenz and Constantinou conducted an in-depth examination of the double concave friction pendulum (DCFP) bearing. The DCFP bearing comprises two steel surfaces with concave faces, where the lower and upper surfaces may feature uneven radii of curvature. Additionally, the friction coefficient on the contact surface may vary between the two surfaces [41]. Castaldo and Alfano [42] introduced design correlations focused on seismic reliability. These correlations address response factors and displacement demands for structures exhibiting both softening and hardening features and inserted with DCFP bearings. The study explored the restoring capacity of the DCFP system. Three distinct types of surface lubrication were considered to modify the coefficient of friction (μ): (a) Low Friction, employing silicon lubricants on the surface; (b) Medium Friction, cleaning the surface through lubrication; (c) High Friction, maintaining the surface without lubricants [43]. The restoration capacity of FPS was assessed through theoretical investigations using bilinear hysteretic models and single degree of freedom systems [44]. Kim and Yun [45] and Ozbulut and Hurlebaus [46] conducted a sensitivity analysis to determine key parameters, including the natural vibration period, yielding displacement, and friction coefficient, for the precise design of the super-plastic friction isolator in bridges. Despite its entirely passive nature, the TFPB showcases adaptive stiffness and adaptive damping [47]. Fenz [48] and Becker [49] have performed analytical and experimental investigation of the bi-directional response of the triple FPS. Harvey and Kelly [26] conducted a comprehensive literature review on the historical evolution and future prospects of the rolling isolation system (RIS). The primary goal of RIS is to minimize displacement demand on the isolator during intense ground motion, thereby enhancing the displacement capacity of the base isolation system. Another type of bearing is proposed, the quintuple friction pendulum isolator, a type of multi-spherical derivative with six sliding surfaces, allows separate optimization for various performance objectives. However, its complex mechanisms hinder practical engineering applications, leading to the exploration of alternatives to traditional FPS [50]. Calvi introduced a variation of VFPB utilizing materials with distinct frictional characteristics [51]. Analytical and experimental studies investigate a novel Variable Friction Pendulum Bearing (VFPB) designed to exhibit different hysteretic properties for varying displacement amplitudes. An efficient analytical model, verified against experimental data, is proposed [52]. VFPB offers predictable and controllable variations in stiffness and damping at manageable displacements. Bibi [53] revealed three failure types—horizontal and diagonal cracking, slippage, and spalling of the isolation layer.

2.2.2 Electricite-de-France BI System

The EDF isolator is composed of neoprene pad laminates enclosed by a lead-bronze plate, which makes frictional contact with a steel plate securely attached to the base-raft of the structure [54]. The construction of this isolation system adhered to the standards set by "Electricite de France," specifically designed for nuclear reactors located in regions susceptible to strong ground motions [55]. The friction plate and the elastomeric bearing are provided in series for such an isolator.

2.2.3 Resilient-Friction BI System

In 1984, Mostaghel introduced this isolation system, which incorporates concentric layers of flat Teflon-coated plates surrounding a central rubber core. These layers make frictional contact and play a role in dissipating energy in R-FBI [56][57]. This system synergizes the constructive influence of friction-based damping with the flexibility of rubber, employing a flat slider to shift the structure's fundamental vibration frequency beyond that of ground motion waves. The rubber core functions as a re-centering mechanism for the base-isolated structure. The concurrent operation of friction, damping, and restoring force defines the characteristics of RF-B isolation.

2.2.4 Sliding Resilient-Friction (SR-F) BI System

Researchers propose using friction-based BI systems, leveraging friction for energy dissipation. Passive BI is the most cost-effective and secure choice, requiring no external energy source or routine maintenance. This strategy introduces sliding interfaces, allowing relative motion between the superstructure and foundation. It is applicable to both new constructions and retrofitting. Recent base isolation research focuses on incorporating cost-effective and efficient frictional components to diminish structural response and augment damping capability. Su *et al* [58] introduced an BI system, termed the Sliding Resilient-Friction (SR-F) base isolation system, which combines the features of two EDF-base isolators and the R-FBI base system. The researchers investigated acceleration and displacement response spectra under various earthquake intensities. This system proves highly efficient in diminishing building deflection and peak acceleration response without causing significant displacement. The isolator exhibits equivalent capabilities for energy dissipation and horizontal flexibility as those found in both EDF and R-FBI. In the SR-F BI system, concentric layers of Teflon-coated plates are situated atop a laminated rubber bearing or a rubber core. They used the famous El Centro Earthquake, Pacoima Dam Earthquake, and Mexico City Earthquake for their studies. Su *et al* [58] compared the SR-F isolation system with other isolation systems. Peng *et al* [59] proposed a sliding hydro-magnetic bearing, which is a kind of low-friction isolator.

2.2.5 Elastomeric Bearings

Elastomeric isolators are constructed using rubber sheets vulcanised with reinforcement sheets, typically made of steel or fibers, to constrain transverse expansion. These isolators are further categorized into low damping elastomers, high damping elastomers, and lead rubber bearings. Elastomeric bearings are isolators comprised of a loading plate, fixing plate, alternate layers of rubber layer, and steel shim. At the same time, LRB consists of a loading plate, a fixing plate, an alternate layer of rubber layer, a steel layer, and a lead core inserted at the center [60]. The critical damping typically falls within the ranges of 2% to 3% for the LRB, 10% to 20% for HDRB, and 15% to 35% for the LDRB. These values are calculated at 100% of their shear strain capacity. Rubber is an essential component in base isolators, influencing system behavior, especially under lateral loads. Selection depends on successful testing, with shear modulus typically ranging from 0.4 to 1 MPa [28]. External damping devices, such as yielding steel elements, plates, or dampers, are typically used in concurrence with natural rubber bearings to control excessive displacements. HDRB are achieved by adding carbon black and other fillers during the mixing process [37].

It is the most extensively investigated and applicable base isolation system. Kelly discusses the analysis of the dynamic response of the LRB isolation system, which is widely used [61]. The parameter within the isolation system, influencing the building's behavior, has been thoroughly examined. It has been noted in the literature that a lead core may not be essential in the bearing if the displacement demands in horizontal directions are minimal [62]. A numerical and experimental examination was also conducted to predict the strength degradation in LRB under ground motion. The proposed model was capable enough to predict the instant effect of temperature on the lead core and its sudden impact on the strength of LRB [63]. The sensitivity analysis is conducted on a square lead-rubber bearings to determine the mechanical properties. Results showed that the lead core radius had the most significant impact on the isolators quality, while the amount of rubber material had the least influence [64]. Another analysis conducted by Yang, examined the decline in vertical rigidity of laminated rubber isolators when subjected to lateral shear forces. The study discovered that the relationship between vertical stiffness is governed by the ratio of lateral deformation to the inertia radius, and it is not influenced by factors such as section shape, loading direction (tension or compression), and isolator size [65]. The seismic performance of a G+7, symmetrical residential building has been extensively investigated to understand the effects of seismic isolation with LRB [66]. Lee *et al* [67] designed LRB specifically for nuclear power plants. To estimate the critical load capacity for both elastomeric bearing and lead rubber bearing, they employed the overlapping area method. Arguc [68] studied the effect of Lead Core Heating on the superstructure response of buildings under cyclic loading. Fu *et al* [69] conducted numerical modeling and shake table tests on a BI system incorporating a magnetorheological damper and elastomeric rubber bearing.

Das et al. [70] studied the performance of fiber-reinforced elastomeric base isolators under cyclic loading conditions. Polymer bearings experimental study has been performed by Falborski [71]. The rolling seal-type air spring and laminated rubber bearing for three-dimensional base isolation were developed [72]. A 1/10 scale model of the 3D seismic isolation device is constructed to validate its performance under horizontal and vertical dynamic loads. Furthermore, a pressure resistance test for the air spring is executed through monotonic pressurization. Islam investigated the response of the seismic isolation system in multi-story buildings deeply. He found that HDRB is better than LRB in the instances of isolator base shear and displacement [73]. The analytical micro-modeling of LRB by using a finite element micro-model has been done [74]. Neethu and Das [75] examined the response of soil-structure interaction on bridges deeply by inserting elastomeric bearings to cater to the effect of strong ground motion. Iizuka [76] has developed a model to determine the deformation response of the laminated rubber bearing. The structure of this model reflected that of the Koh-Kelly model, with an expansion of the formulation to include non-linear springs and finite deformation. Force-Displacement curve from cyclic loading by numerical modeling was done by [77]. They compared the response of strain energy function's coefficients for the rubber material. Karimi and Khordachi [78] studied the behavior of LRB and laminated rubber bearing under different strong ground motions, i.e., El Centro (1940), Northridge (1994), and Kobe (1995). They performed the 3-D analysis on ABAQUS software. Maureira *et al* [79] developed a model predicting the non-linear mechanical performance of elastomeric bearings, as depicted in the schematic diagram Figure 2.2 and Figure 2.3 illustrate shear force-horizontal displacement, and vertical force-vertical deformation responses of the low-damping LRB, respectively. The vertical force vs deformation curve exhibits highly non-linear behavior in tension, attributed to softening or stiffness loss. The mathematical model was used in the program OpenSees software for the computation of the response of elastomeric bearings [80].

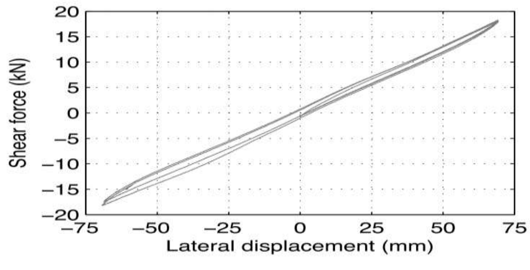


Figure 2.2 Lateral displacement vs shear force [36]

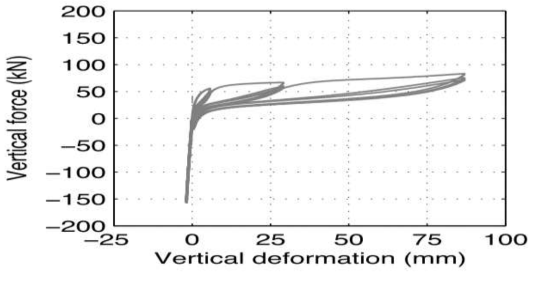


Figure 2.3 Vertical deformation vs vertical force [36]

2.2.6 Sliding BI Systems

The technique of sliding layers, initially incorporating a sand layer for masonry buildings, was introduced in the 1970s. The system experienced theoretical advancements and numerous analyses during the same decade. Crandall [81] examined the uniaxial and biaxial response of the sliding BI system; the response of the sliding BI building was investigated by Calvi and Calvi [15], Calvi [51], and Calvi and Ruggiero [82] have investigated the sliding mechanism is efficient in the sense that it can handle a varied array of frequency input from strong ground motion. Because the frictional force is proportional to the structures mass, the sliding support's Centre of mass and resistance coincide, reducing the torsional effects that occur due to asymmetric structure. Sachdeva *et al* [83] have evaluated experimentally the dynamic control response of the flat sliding bearing base isolation system. Quaglini *et al* [84] have been done on the correlation of temperature and friction coefficient at the interface of a sliding isolator. The analysis of experimental and numerical analysis of the sliding BI system for the bridge span model having single FP bearings was performed. It used $^{1}/_{4}$ scale for modelling. It also used vertical motion effects in test and analysis, including three stages of friction coefficient (4%, 6%, and 9%) and two types of axial loads [85]. A special smart restorable sliding BI system is proposed [86]. Comprising steel-PTFE flat sliding bearings and a memory alloy of super elastic shape wire, this BI system was utilized for a 1:4 scale model in a shaking table analysis. The non-linear time history results obtained through numerical analysis aligned with the shaking table test results. The conclusion drawn was that the smart restorable sliding BI system exhibits superior performance compared to commonly used isolators such as FPS and HDRB. **Figure with reference of Base Isolation System**

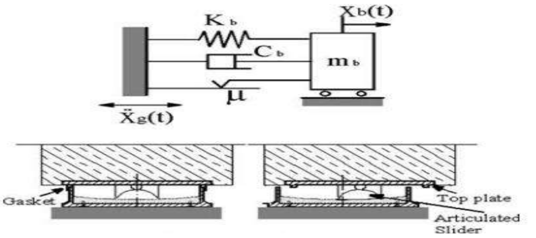


Figure 2.4 Friction Pendulum System [19]

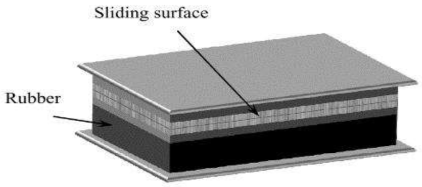


Figure 2.5 Electricite-de-France System [55]

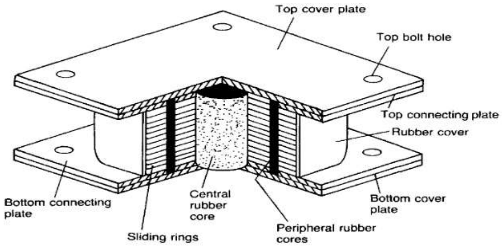


Figure 2.6 Resilient-Friction Base Isolation System [54]

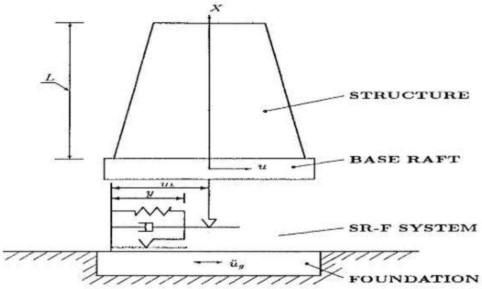


Figure 2.7 Sliding Resilient-Friction BI System [58]

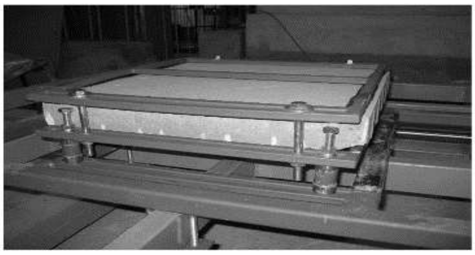


Figure 2.8 Elastomeric Polymer Bearings [71]

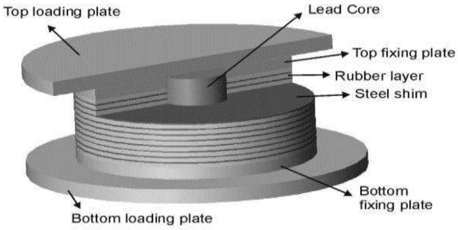


Figure 2.9 Lead Rubber Bearing [72]

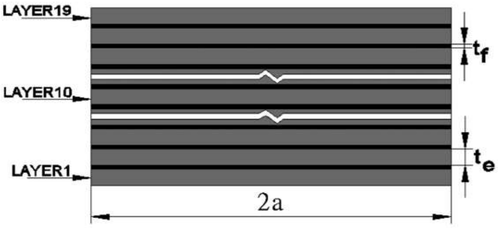


Figure 2.10 Fibre Reinforced Elastomeric Isolator [70]

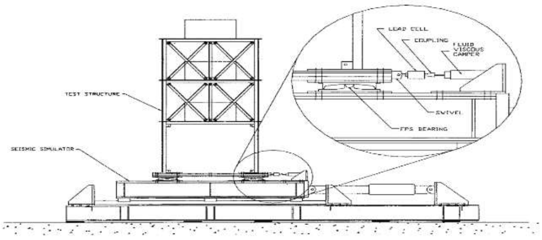


Figure 2.11 Sliding Base Isolation Systems [100]

2.3 Scaling and Modeling

Scaling is crucial for obtaining a realistic understanding of prototype structures. It offers an effective means to study the dynamic behavior of complex structures, considering accuracy, cost-effectiveness, and practicality in experiments. Researchers frequently conduct shaking table tests on scaled models of buildings equipped with lead rubber bearings to evaluate prototype performances [87][88][89]. The shaking table experiment yields insights into (a) seismic force distribution along the building height, (b) assessing full seismic capacity through failure patterns and damage mechanisms, (c) identifying the weakest points in buildings, and (d) validating new seismic models for the structural system.

Generally, most isolation models are scaled down for testing on shaking tables. Previous experiments have revealed a notable disparity in the response between the reduced-size bearing and its larger counterpart, particularly in terms of strength. This discrepancy is attributed to the heating of the lead core. The larger bearing exhibits greater susceptibility to lead core heating during repeated lateral cyclic motion, resulting in subsequent degradation in strength [18]. Mathematical expressions and equations are also introduced to forecast the heat generation in the lead core and the subsequent decline in strength [90]. Comparable outcomes are achieved in sliding bearings, attributed to frictional heating. The reduced-size bearing is modeled using the principle of dynamic similarity, which is extended to both superstructure and base isolation systems.For LRB, this similitude must include the consequence of heating the lead core [18]. The published paper [91] introduced a theoretical framework for forecasting the decline in yield stress and the dissipation of energy due to heat in the lead core as cyclic motion increases. The theory's predictions were validated through experimental verification [92]. A finite element model was developed in ABAQUS, considering element type as a 'four-noded heat transfer element' DCAX4 to analyze the heating response LRB. The interested reader can refer to those published papers for detailed theory and experimental verification of results. The scaling of lead rubber bearing was considered 3-4 times reduced-sized specimen for investigation [63]. They proposed a model that considered the rise in temperature in the lead core due to the repeated cyclic motion of LRB, which is dictated by the subsequent set of equations:

$$\frac{dT_L}{dt} = \frac{\sigma_{YL_0} \exp\left(-E_2 T_L\right) \cdot v(t)}{\rho_L c_L h_L} - \frac{k_s T_L}{a \cdot \rho_L c_L h_L} \left(\frac{1}{F} + 1.274 \cdot \left(\frac{t_s}{a} \right) \cdot (\bar{t})^{-1/3} \right) \tag{2.4}$$

$$F = \left\{ \begin{matrix} 2 \cdot \left(\frac{\bar{t}}{\pi}\right)^{\frac{1}{2}} - \frac{\bar{t}}{\pi} \cdot \left[2 - \left(\frac{\bar{t}}{4}\right) - \left(\frac{\bar{t}}{\pi}\right)^{2} - \frac{15}{4}\left(\frac{\bar{t}}{\pi}\right)^{3}\right], \bar{t} < 0.6 \\ \frac{8}{3\pi} - \frac{1}{2(\pi \cdot \bar{t})^{\frac{1}{2}}} \cdot \left[1 - \frac{1}{3 \cdot (4\bar{t})} + \frac{1}{6 \cdot (4\bar{t})^{2}} - \frac{1}{12 \cdot (4\bar{t})^{3}}\right], \bar{t} \geq 0.6 \end{matrix} \right\} \tag{2.5}$$

$$\bar{t} = \frac{\alpha_s t}{a^2} \tag{2.6}$$

where, T_L lead core temperature rise at time t, Parameter $\bar{t}$ is referred to as the 'dimensionless time'. In eq. (2.4)–(2.6), $\sigma_{YL_{0,}}$ initial effective yield stress of lead, ρ_L is the density of lead, c_L is the specific heat of lead, a is the radius of the lead core, $k_{s,}$ thermal conductivity of steel, α_s is the thermal diffusivity of steel, t_s is the total thickness of the shim plates, h_L is the height of the lead core, and E_2 related the effective yield stress of lead to its temperature. Here, E_2 is empirically derived from lead testing samples [93]. Equation (1) is an ordinary differential equation with input being the absolute value of the instantaneous resultant velocity of the top of the bearing with respect to its bottom.

Later on, in Japan, a comprehensive shake table test was undertaken to assess authentic seismic damage. Earlier, the single-story shake table experiment was performed using a sliding isolation system [94]. The response of multi-story building models using a shake table experiment inserted with sliding elastomeric bearing was performed [95] and with friction pendulum bearing [38]. Astroza *et al* [96] performed experiments on a full-scale five-story RC building using the NEES-UCSD shake table. The objective of the study is to scrutinize the structural response, non-structural elements, and their dynamic interplay under various ground motions. The researchers examined building specimens with both fixed and isolated bases under various conditions, including forced vibration, impact-free vibration, and ambient vibration. A comparison was made between the results obtained from the SEAONC Tentative

Code of 1986 and the shake table results. The analysis in this paper incorporated eight distinct ground motion records [95]. The three-story reinforced concrete masonry structure was scaled by one-quarter [97]. It used a rubber elastomeric bearing isolator to reduce the response of lateral force in areas of high seismicity. Wu and Samali [98] performed a shake table analysis to validate the numerical results of the 5-story steel frame structure inbuilt with laminated rubber bearings. They used a 3m×3m shake table having a maximum acceleration of ±0.9g, loads up to 10 tonnes, and maximum stroke of ±100mm. The input waveform frequency ranges from 0.1 to 50 Hz. The time axes for waveforms were scaled to one-third of the original. The modelling of 30-story high-rise building was done in China in 2007 [99]. The shake table used for dynamic response is 4m×4m, having a maximum payload of 250KN. The frequency ranges between 0.1Hz to 50 Hz. In vertical, longitudinal, and transverse directions, the maximum accelerations are 0.7g, 1.2g, and 0.8g, respectively. Madden *et al* [100] and Patrick *et al* [101] examined the implementation of the adaptable base isolation system in a scale-model building structure in a laboratory experiment. They extracted dynamic properties by floor acceleration under white noise excitation by the frequency response of autoregressive with the exogenous term (ARX) method and frequency response function (FRF) curve-fitting method [102]. The three-dimensional shake table testing of the base isolation system took place at E-defense, located in the Hyogo Earthquake Engineering Research Centre in Japan. The E-Defense shaking table boasts a platform measuring 15m×20m with the capacity to support up to 12,000 metric tons, making it suitable for testing small to full-scale buildings. It has the capability to generate horizontal accelerations surpassing 0.9g and vertical accelerations of up to 1.5g at maximum payloads [103]. A five-story steel frame structure underwent shaking tests at E-Defense. The structure, inclusive of non-structural elements (such as ceilings, piping, interior walls, and concrete panels), was subjected to shaking both with and without Triple Friction Pendulum Isolators (TFPS). The current shaking table experiment on a full-scale isolated structure at E-defense has provided significant insights into the performance of lead rubber bearings and the genuine response of the superstructure, considering factors like base shear, floor acceleration, maximum story drift, and more. The evaluation also encompasses the validation of diverse sliding bearings [104]. Sliding Implant-Magnetic Bearings [59] and hydro-magnetic bearings [105] was performed on a shaking table test in the office building in Taipei. The structure model used is of the quarter length scale of six-floor and two-span MRF (Moment Resisting Frame) structure. The seismic analysis of the steel pellet rack on the shaking table was done in the FIP MEC laboratory, in Italy [103]. It consists of a 2m×2m seismic motion simulator having a maximum stroke ± 200mm and a velocity of 400 mm/s. The motion of the table platform is controlled by FlexTest 60 controller hardware. Scaling is an essential tool to sustain the dynamic similarity between the full-scale structure and corresponding models.

2.4 Numerical Simulation and techniques

Researchers and academicians have used software, e.g., ABAQUS, SAP2000, LS-DYNA, OpenSees, MATLAB, etc., to study the responses of the structure [65]. For instance, Khan [19] performed a comparative study of three passive base isolators—HDRB, LDRB, and LCRB is done. To achieve this goal, a state-space approach in MATLAB is employed, an 8-story structure is analyzed, focusing on parameters like peak global drift, inter-story drift, and acceleration transmissibility. Seismic isolation devices exhibit nonlinear responses, emphasizing high stiffness for minor horizontal loads and substantial energy dissipation during loading and unloading [106]. In base-isolated buildings, the dynamic, nonlinear behavior is concentrated in the isolation bearings. Designs prioritize stable isolation systems and elastic superstructures for seismic resilience. Currently used methods for analyzing inelastic superstructure behavior: are non-linear dynamic analysis (NLTHA) and non-linear static analysis (NLSA) [107]. The numerical methods provide a pivot in analyzing the building inserted with BI technology. Numerous non-linear dynamic analyses scale accelerograms to various intensity levels. Incremental Dynamic Analysis (IDA) and Multiple-Stripe Dynamic Analysis (MSDA) are commonly used for seismic performance evaluation in earthquake engineering. MSDA, particularly, assesses structures at multiple performance levels by analyzing records scaled to different Peak Ground Acceleration values [108]. These methods address both the demand and capacity of a building, making them convenient for investigating and simulating base isolation systems. It is used to develop a fragility curve. The approach involves scaling the earthquake motion until the evaluation of the structure failure.

2.5 Comparison between Isolated Base and Fixed Base

The literature consistently supports these findings, with numerical results aligning well with experimental verification. This section discusses the advantages of seismic isolation devices in mitigating earthquake effects compared to traditional structures. Ryan *et al* [109] applied various approaches to conduct a comparative analysis of isolated bases and fixed bases, aiming to systematically present the findings of a comprehensive analysis that contrasts the performance of buildings with BI and those with fixed bases, following the SEAOC recommendations from 1990. The comparison involved several base isolated systems and fixed bases, as documented in various literature sources [56]. The behaviour of the BI structure was compared with that of the flexible and rigid superstructure by using time-history [110]. To evaluate the responses, an examination was conducted on an elastomeric bearing and a sliding BI system. The study incorporated several assumptions, such as assuming the force-displacement response of the building to be linear, considering each floor story of the building to be rigid, restricting tilting or overturning, and assuming the friction coefficient for the sliding isolator to be independent of relative velocity at the interface. The analysis led to the conclusion that the flexibility of the superstructure cannot be disregarded when calculating the response in floor acceleration analysis. Shaaban and Ahmed [111] have done a modal analysis of two buildings i.e., isolated base and fixed base, using non-linear time history analysis. The drift demands of 3-story inelastic BI building and fixed base structure at $(T_b = 2s, \xi_b = 0.1)$ shows that median drift ratio was reduced approximately for BI structures by 0.05-0.07 times as of fixed-base buildings at top story [112]. As the structure is getting taller, this reduction is smaller. They concluded that the damping ratio and natural period for BI buildings, estimated by complex-mode and real-mode Eigen values, are approximately the same. They used the National Building Code of Canada 2010 to check lateral and inter-story drift. Dao *et al* [113] developed a three-dimensional model using OpenSees software to assess the building's response with a triple friction pendulum on a shake table. Additionally, the author contrasted this response with the fixed base result. Despite incorporating the non-linear behavior of concrete and steel in the analysis, both computational and experimental findings indicate that the non-linear response of the structure within a BI system is minimal. It was observed that the base isolation system is three-fold stronger than the corresponding fixed-base system [114]. It is evident from Figure 2.12 that an increase in the time period and damping of the structure leads to a significant decrease in the structure’s response to ground motion. Figure 2.13 illustrates a comparison between the acceleration responses of a fixed base conventional structure and a base-isolated structure in relation to time period and frequency, respectively [115]. The analysis of the literature revealed that a building constructed in a high seismic zone, equipped with seismic BI, can withstand a PGA of 0.7g. In contrast, a fixed base building in a low seismic hazard area with the same site conditions has a PGA of 0.15g [116]. The present section defines the benefits of seismic BI device in reducing the response of the earthquakes over conventional structures.

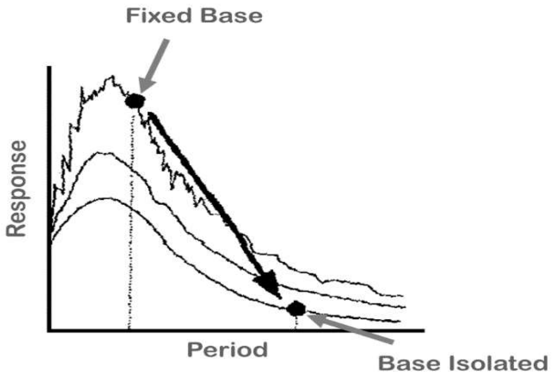


Figure 2.12 Response vs Time Period for conventional fixed base and base isolated structures.

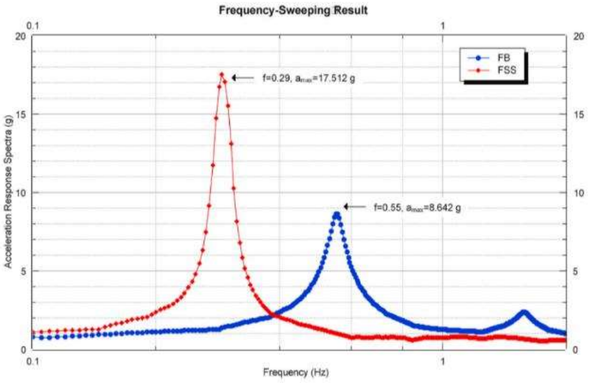


Figure 2.13 Acceleration response vs frequency sweeping with FB and FSS structures [115].

The limitations of the low-stiffness vertical isolation system were suggested [117]. The dead load of isolation buildings may lead to early settlement, and significant isolation drift can occur during intense ground motion or with numerous low-frequency components. These challenges may arise in the construction of vertical base-isolated structures. Additionally, the BI system is ineffective under very small seismic excitation, resembling a conventional fixed base structure. Figure 2.14 illustrates the limitations of BI structures, highlighting vulnerability when adjacent to multi-story buildings with water tanks and unreinforced structures.

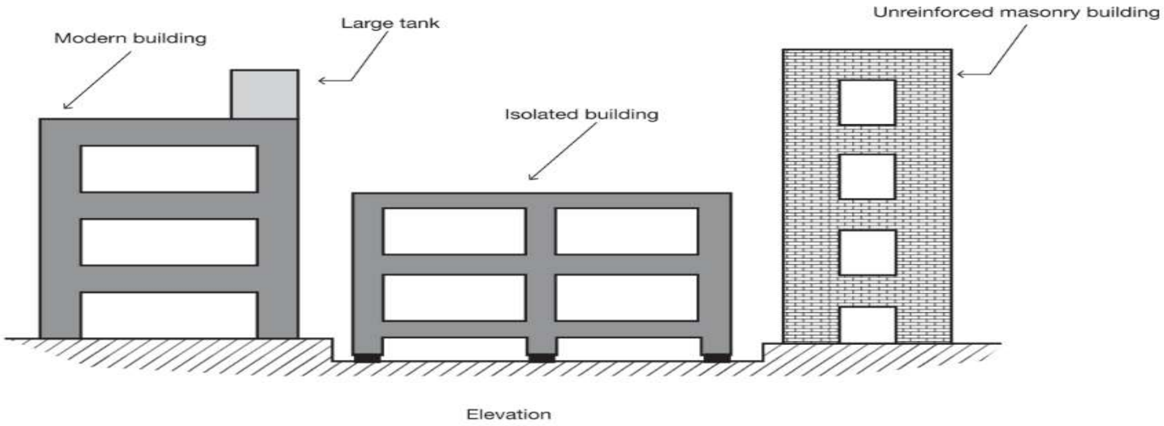


Figure 2.14 Limitation of Isolated building [117]

2.6 Application of Base Isolation System

2.6.1 Retrofitting and Rehabilitation of historical buildings

The BI system is widely used in the retrofitting and rehabilitation of existing monuments and buildings, preserving their cultural relics and aesthetics. Conventional retrofitting materials and methods, such as concrete jacketing, steel casing, RC shear walls, steel braces, etc., do not effectively respond to strong ground motion. Modern methods, including energy dissipation, carbon fiber-reinforced polymers, and Seismic Base Isolation, demonstrate better responses against seismic excitation effects. The carbon fiber-reinforced polymer (CFRP) is utilized in seismic retrofitting with the BI technique, adhering to the standards of new Italian instructions [118]. This combination of CFRP and BI is employed to retrofit the original existing building, significantly reducing the seismic response of the superstructure. Elastomeric and sliding bearings prove effective in retrofitting various structures such as buildings, bridges, tanks, and monuments [119]. A novel seismic retrofitting method has been proposed, aiming to preserve the originality of existing structures while markedly reducing dynamic responses [120]. The examination of the retrofitting endeavors undertaken on the Ninth Circuit building in the United States, significantly impacted by the Loma Prieta earthquake in 1989, has been thoroughly investigated by Mokha *et al* [121]. The study advocates for the comprehensive testing of full-sized isolators to anticipate real-world behaviors and validate the foundational assumptions of the design. In the rehabilitation efforts for the damaged structure, the Federal Emergency Management Agency (FEMA) 356 and EC8 guidelines are implemented. The evaluation of the non-linear seismic behaviour of masonry infills, retrofitted with an isolation system and fixed base, relies on near-fault ground motion data. The structures performance in a high-risk seismic zone [39] is analyzed using the Italian Code, focusing on a six-story building with masonry infills considered as non-structural components distributed at the corners of the perimeter frames. The retrofitting procedure for seismic-isolated historical buildings is illustrated in Figure 2.15 [122].

2.6.2 Effect of liquid retaining structure on Isolator

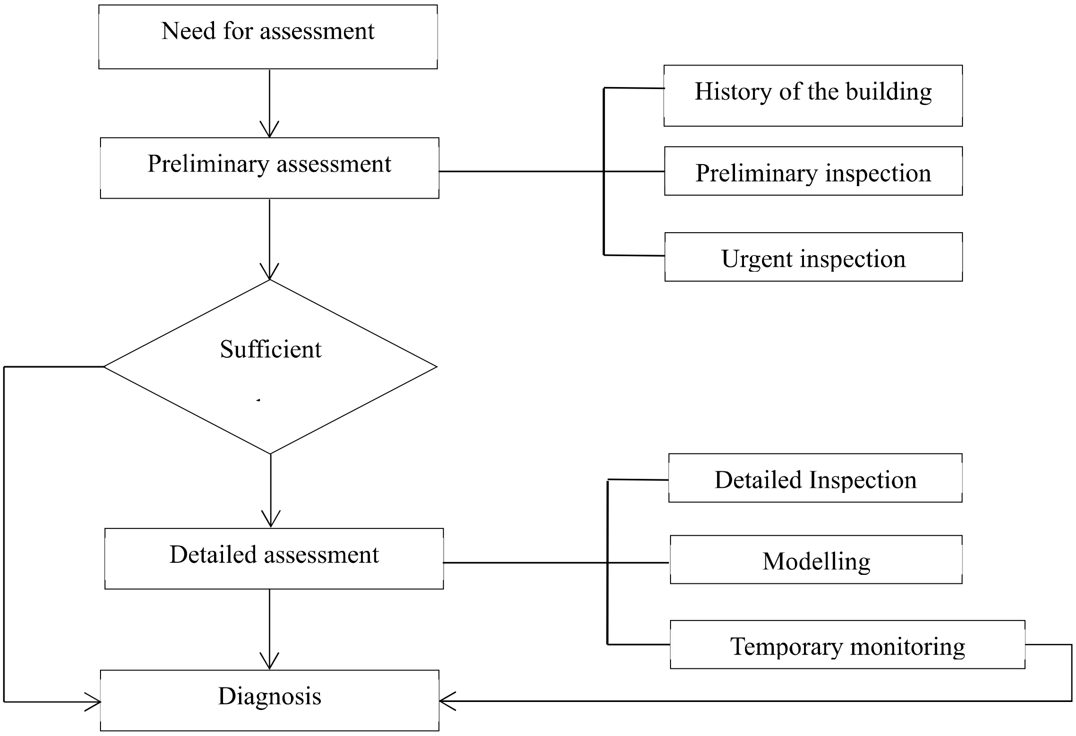


Figure 2.15 Approach to rehabilitation of the historical building [122]

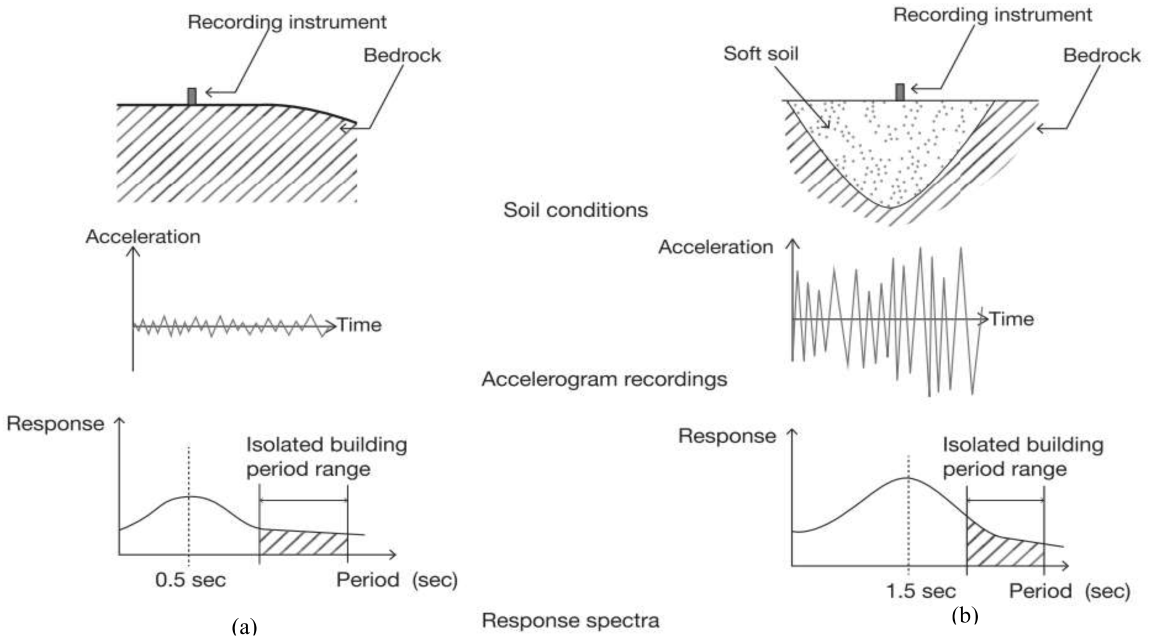
The BI system has wide applications, including historical monuments, buildings, bridges, elevated water storage tanks, etc. The water tanks exhibit dynamic behaviour during the ground motions. They are subjected to hydrodynamic pressure and inertial loads [123]. EPS has presented a large-scale BI storage tank (Available online: www. earthquakeprotection.com., 2019) [124]. The performance of an FE elevated liquid tank is performed [125]. This paper examined the performance of elevated tanks by both modal analysis and time history methods. This analysis considered the effects of sloshing (convective components) and tank wall (impulsive components) flexibility. The seismic behavior of the ground-supported BI liquid storage tank, considering the effects of SSI, is deeply investigated by Hwan *et al* [126]. This paper considered a homogenous half-space spring dashpot model with frequency-independent components. The half space was investigated by coupling methods that included FEM (Finite Elements Methods) for structure and BEM (Boundary Elements Methods) for liquid components. The ground motion response of the cylindrical liquid storage tank on an elastic homogenous soil medium is examined. The study concluded that the SSI effects reduce the lateral, impulsive, and rotational frequencies, and soil stiffness has no considerable effect on the convective components of the tank, as soil stiffness diminishes the maximum displacement of the impulsive mass, base shear, and overturning moment decreases [127].

2.6.3 Effect of Soil-Structure Interaction

The impact of Soil-Structure Interaction (SSI) on the seismic response of elevated liquid storage was investigated [128]. The dynamic response of the underground liquid storage tank under SSI-induced ground motions was studied as well [129]. This analysis considered two types of steel liquid tanks: broad and slender, with aspect ratios (height to radius) of 0.6 and

1.85, respectively. Often, the effect of SSI is overlooked in isolator design, assuming a rigid base [130]. However, neglecting SSI leads to inaccuracies in evaluating structural responses. SSI can be defined as the reciprocal influence between soil motion and structural motion. The study presents the seismic response performance of bridges equipped with elastomeric bearings, considering the impact of SSI [75].

In 1978, the equivalent linearization method was used (Bielak, 1978) [131] to analyze the harmonic response of bilinear hysteretic structures supported on a visco-elastic half-space. If soil flexibility is disregarded and the BI system is assumed to be linear, results are derived [132]. Bielak's model was expanded [133] to explore the effect of SSI on the non-linear dynamic behavior of the BI system for simple elastic structures. The conclusion was that, in the absence of SSI effects and in undamped cases, a harmonic motion occurs beyond the steady-state response of the isolator, rendering the superstructure unbounded. Furthermore, the study determined that considering the BI system as rigid aligns with the results of [134] for the elastic 1-DoF system. If the superstructure is treated as rigid, the results of are applicable [131]. Veletsos and Tang [135] found that SSI significantly diminishes the response of impulsive components but has an insignificant effect on convective components. However, recent studies suggest that for intense ground motion, non-linear effects (e.g., gapping, uplift, and sliding) are common near the soil-structure boundary [136]. The SSI effect is categorized into Kinematic Interaction and Inertial Interaction. While kinematic interaction remains part of ongoing research, inertial interactions have been explored [137]. Soft soil, compared to rock, resonates, intensifying shaking and increasing the natural period at peak response, bringing it closer to the natural periods of vibration of isolated buildings. Figure 2.16 illustrates the response of soft soil and rock [138]. Han and Marin [139] employed an iterative approach for the numerical simulation of BI systems used in nuclear power plants, considering the mutual effect of SSI. The authors accounted for the material non-linearity of the isolator. The SSI analysis response demonstrated a significant reduction in the horizontal movement of isolated nuclear power plants. Linear equivalent SSI analysis [140] and non-linear SSI analysis of isolated nuclear structures with rigid basemats were conducted [141]. The reference paper considered ASCE 4-16 for non-linear analysis, following a multi-step procedure that combines equivalent linear methods and time-domain techniques, incorporating both SSI effects and the non-linear behavior of the isolation device.



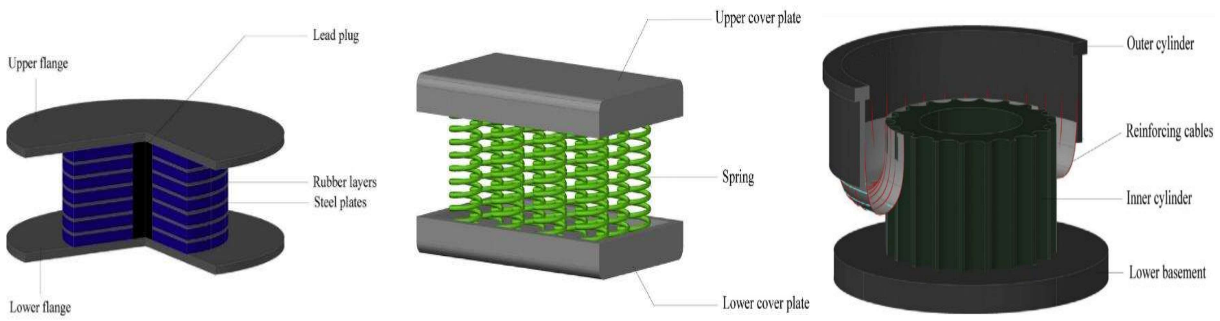
(a) (b)

Figure 2.16 The effects of soft soil on earthquake shaking at (a) rock site and at (b) a soft soil site [138]

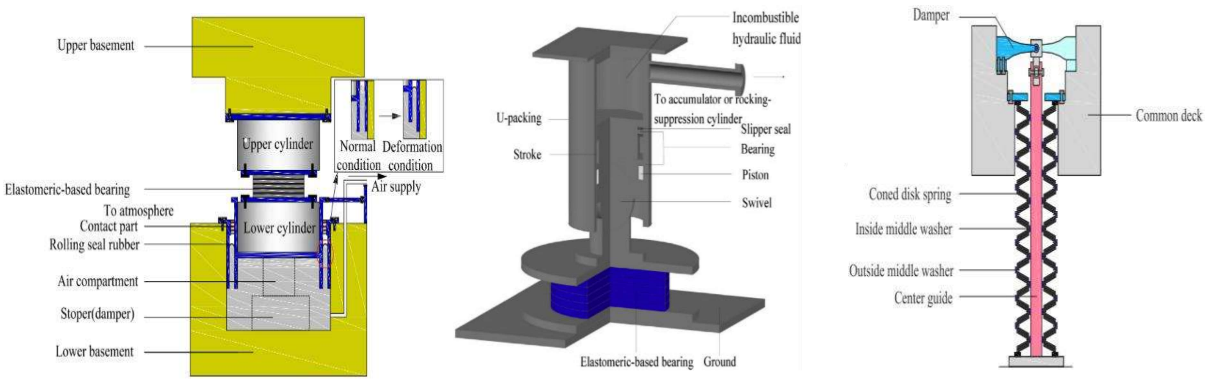
2.6.4 3-D Base Isolator

Researchers increasingly favor 3-D isolation systems for critical structures due to their recognized feasibility, economic viability, and performance benefits in both horizontal and vertical isolation. This technology allows for a larger design margin without altering standardized designs. While conventional base isolation effectively reduces horizontal building responses, it does not address the direct transmission of vertical seismic components to the superstructure. This has led researchers to focus on three-dimensional base isolation systems and vertical ground motion components. In 1986, the Kajima Corporation initiated early efforts to develop a three-dimensional laminated rubber-bearing seismic isolation system for constructing a two-story RC structure in Japan [142]. This approach was later explored in the U.S. nuclear industry. Beyond modifications to design parameters, new 3-D systems were introduced. The GERB system, featuring helical springs flexible in both horizontal and vertical directions, was designed to prevent excessive movement in vertical directions caused by varying lateral loads, live loads, and wind loads. This system found application in various industrial and residential buildings. Vertical BI systems offer flexible support in the vertical direction through a combination of metallic or air springs and complementary damping devices. Other 3-D isolation systems include rolling seal-type air springs, cable-reinforced air springs, hydraulic 3-D systems, and coned disk spring systems as shown in Figure 2.17 [143]. The benefits and challenges associated with 3-D BI systems in nuclear plants compared with horizontal isolators are discussed. They performed the linear analysis to establish the benefit of the 3-D isolator in nuclear power plants and recommended to perform the non-linear analysis in the future and model bearing in such a way that it exhibits coupling behaviour.

Liu 2023, developed an advanced technique investigating the nonlinear seismic response in complex layered sites. The 3D BI system in the innovative integrates both horizontal and vertical isolation using the principles of disc spring theory. This allows for the flexible modification of the structural stiffness and vertical bearing capacity. The outcomes demonstrate the systems' exceptional ability to isolate vibrations, making it suitable for practical use in nuclear installations located in complex-layered sites with significant levels of seismic activity. This work presents a novel 3D BI technology designed for nuclear structures. It provides precise quantitative correlations between parameters and can effectively respond to seismic inputs. The seismic study, which incorporates three-way coupling, demonstrates substantial enhancements in both horizontal and vertical seismic isolation. Reduced vertical stiffness in the 3D base isolation system results in a rocking effect. Precise control of the vertical fundamental frequency is vital for designing 3D base isolation in Nuclear Power Plants (NPPs) at complex sites. Further development of a rocking suppression system is needed for 3D base-isolated NPPs, considering complex conditions. To guide seismic design, quantitative analysis of specialized cases, such as near-field inhomogeneities



(a) Thick-rubber-layer (b) GERB system (c) cable reinforced air spring



(d) Rolling seal type air spring (e) Hydraulic three-dimensional isolation (f) Coned disk spring

Figure 2.17 Schematic representation of three-dimensional Isolators [143] and different foundations, is essential [144]. The system shows promise but requires further exploration, especially for addressing the rocking effect in complex sites. Future work should focus on developing a rocking suppression system for practical applications in nuclear power plants. A unique 3-D BI device, merging a conventional horizontal bearing with an innovative long-period vertical isolation device featuring variable stiffness (LVIVS) [145].

2.7 Economic Benefit

The cost analysis of the BI system is an essential parameter for its practical feasibility and application. The designed economic structures with seismic isolation must withstand their service life without failure at all applied loads, naturally induced loads, and beyond designed-basis loadings. It has been an area of intensive research so far. Several studies were published related to the cost appraisal and economy of the BI systems. Conceptually, cost comparisons have not measured the early design process, while specific cost appraisals were proposed [133]. The absence of comparable performance and cost data for base-isolated and fixed-base structures has further hampered the use of the analyzed base-isolation systems [146]. The analysis results show that using an appropriate isolation system can minimize the lifecycle cost by up to 20%, corresponding to a fixed base structure. It was obtained from the analysis that the initial cost of seismic isolated structures corresponds more to the fixed base structure, but when the life-cycle cost is considered, isolated base structures are more economical [147]. The LRB and high-damping natural rubber bearing were considered as seismic isolation to compare the results with a fixed base. It was observed that the initial cost is expensive for both isolators but considering the life-cycle cost then, generally, both provide an economical solution than a fixed one, but particularly LRB [148]. With ample stiffness, the rubberized mortar isolation system minimizes material loss and is adaptable to various ground motions

[149]. Unlike traditional friction pendulum systems, it is not limited by frequency content. The study addresses previous low-cost sliding isolation system limitations by using re-centering bars to mitigate residual displacement. Proper design, considering seismic demands and structure height, is essential for these bars. For a two-story masonry structure, 12.7 mm rebars showed no yielding, but design adjustments are necessary for taller buildings. Using face bricks with holes is recommended for easy re-centering rebar installation. The examination focused on a 10-story reinforced concrete residential building situated in Dhaka, with a c/c spacing of 7.62 meters in both directions [150]. The analysis involves two types of isolators: the first is 16 LRB, and the second is 9 HDRB) Considering detailing costs, the reduced reinforcement in the base-isolated building resulted in a 19.78% overall cost savings compared to the fixed base building. Deducting bearing costs, the net savings for adopting base isolators in the ten-story building amounted to almost 8%, indicating a potential net cost saving of around 10% with optimal treatment. The total capital cost reduction for nuclear reactor ranges between 40% and 50% with the implementation of seismic isolation compared to conventional reactor [151]. Table 2.1 illustrates the types of isolation systems, descriptions, and responses with their advantages and disadvantages.

Table 2.1 Advantages and Disadvantages of Seismic Base Isolation System

Type of Device	Description and Behaviour	Advantages	Disadvantages
Friction Pendulum System	Rubber pad durability ensures the durability of the isolator, Lubricants are used to ensure frictionless movements	Reduced base shear, floor acceleration, inter-story drift significantly, cost-effective, higher displacements are possible	Heating of rubber, lubricants must provide friction, unsuitable for differential foundation settlements
Variable Friction Pendulum System	Variable friction coefficient, gradually varying the roughness of the surface	Isolator displacement and base shear are within the desirable range,	Performed well only in a limited domain of time period,
Electricite-de-France Base Isolation System	Comprises neoprene pad laminates shielded by a	Cost-effective, natural time period increases	Not suitable for larger loadings, less acceleration

	lead-bronze plate		reductions compared to LRB
Core-Suspended Isolation System	Developed by a double layer of inclined rubber bearing	Elongates the natural period, imparts displacements at strong ground motion	Less practically applicable,
Resilient-Friction BI System (R-FBI)	Consist of sliding elements and a rubber core, and the sliding ring is Teflon coated	Rigid in the vertical direction, Limit the maximum sliding displacement, and the design is simple, cost-effective, and quick to acceptance, the stiffness of the rubber core restrains sliding.	Need to build block to restrict failure in case of strong ground motion
Sliding Resilient-Friction (SR-F) BI System	Two EDF-base isolators and the R-FBI base system combined to form SR-F isolation system	Reducing peak acceleration and deflection response, base displacement is in a manageable range	insensitive to a longer period of the ground acceleration
Lead Rubber Bearing (LRB)	It is made up of a hyperelastic rubber layer sandwiched between steel shim plates with the lead core at the center.	Most widely used LRB. It is useful for buildings, bridges, etc.	Properties are dependent on size and fabrication typically requiring prototype and usually production testing.
Hysteretic damping+ Elastomeric BI Bearings	-	Commonly used in bridges. It is very cost-effective also.	Not suitable for larger displacements.
Cross-linear bearings	Combination of roller-bearing rails at 90^0 to each other. Curved rails are used for pendulum bearings.	Less friction i.e. suitable for a large site requiring large displacements	No significant damping. Expensive. Durability important.
Flat slider bearing	The polished surface has lower friction material,	Restoring mechanism has not adverse impact on the peak horizontal floor acceleration.	Initial frictions are higher, depending upon surface material.
Sliding Hydromagnetic Bearing	Components are sliding bearings, permanent earth magnets, circular aluminum base plates,	Insensitive to the frequency of earthquake motions, restraint against sliding displacements beyond the plate boundaries, activated under small lateral forces, less maintenance required, cost-effective.	It cannot be used where buildings are prone to bearing upliftment or fluid leaks.

2.8 Codes used for Seismic Base Isolation

In the USA, the first seismically isolated buildings design "Tentative Isolation Design Requirements" provisions were developed by SEAONC in 1986 ("Tentative Seismic Isolation Design," 1986). Later, the provisions were revised by SEAONC seismology committee and published the amendments as Appendix 1L in SEAONC blue book 1990 ("Recommended Lateral Force Requirements and Commentary," 1990) and revised further in 1999 ("Recommended Lateral Force Requirements and Commentary," 1999). Afterward, minor revisions in Appendix 1L were done by the International Conference of Building Officials (ICBO) ("Division III—Earthquake Regulations for Seismic-Isolated Structures," 1991) and incorporated in UBC Chapter 23 as a non-necessary appendix. The SEAONC proposed two approaches; the first approach was simplified formulas analogous to Equivalent static analysis formulas recommended by UBC, and the second approach used dynamic analysis procedures, i.e., time history and response spectra analyses. The SEAONC base isolation code with the experimental result of the shake table test was compared (Chalhoub, 1990) [95]. They investigated the response of a nine-story steel frame structure inserted with sliding bearings and rubber bearings as an isolation device.

Currently, available base isolation building codes, e.g., UBC 1997, AASHTO 1999, Euro Code 8 Section 10 Part 1, EN 15129, EN 1998-1 Section 4 & 8, NTC 2008, FEMA 273, FEMA 274, FEMA 356, FEMA 450, FEMA p695, ASCE 7-05, ASCE 41-06 Clause 9, ASCE 7-16 Chapter 17, ASCE 7-22, IS 1893 (Part 6): 2022 etc. are used to perform a linear and non-linear examination for designing most of the BI structures. ISO 22762-1 is used for elastomeric bearing design and protection. The isolators must be designed in such a way that it is robust enough to provide the following functions: (a) energy dissipation (b) re-centering capability

(c) laterally restraint, i.e., sufficient elastic stiffness under non-seismic service lateral load (d) Vertical load carrying capacity (e) the life span of isolator needs to be equal or greater than the life span of the building. It is essential to use extensively detailed and well-defined structural models requiring critical computational analysis. Ramirez and Miranda [152] gave a suitable and simplified analysis of the BI structure preliminary design. The proposed analysis is established on the dynamic equilibrium of the BI system. Chalhoub [95] used 2-DoF equations and further extended them to the multi-storied structure. The equation developed by Kelly considered lumped mass m_s with stiffness k_s and damping c_s at the uppermost of the structure and at the base of the structure, it is considered a lumped mass m_b having stiffness k_b and damping c_b of the structure having a lateral displacement u_s and u_b respectively. In this cited paper, a continuum model was employed, comprising a cantilever flexure beam connected laterally to a shear beam. The essential structural parameters for the model included (a) the natural period of the structure, (b) the damping ratio, representing the overall damping of the building, and (c) the non-dimensional parameter that governs the structures shear and flexural response.

Harris [153] made the quantification of seismic performance of the building. The project aims to provide a methodology to compute the structures' performance and response reliably for use in seismic design. The comparative study of seismic design guidelines, including ASCE/SEI 7-16, EN 15129, and NTCS-17 [154]. It focuses on key sections: type of dissipation devices, general design requirements, procedure selection, seismic design action, inspection, and testing of dissipaters. The analysis highlights specific strengths: ASCE/SEI 7-16 in Procedure Selection, EN 15129 in Testing, and NTCS-17 in Inspection. The findings offer valuable insights for engineers and guideline developers globally working on structures with supplementary damping. For industrial base-isolated structures, the design of the isolator is presented by Erickson and Altoontash [155]. They have presented their study in conformity with building code provisions of IBC, ASCE-7. Villegas and Colunga [156] studied the dynamic design procedure for the structure located on the Mexican Pacific Coast. They used UBC 1997 provisions with some modifications.

Table 2.2 outlines the necessary requirements and restrictions according to various codes worldwide. It encompasses various parameters such as site class, effective damping, building height, seismic intensity, etc., essential for the effective implementation of the BI system. It provides insight into the existing seismic isolation provisions in different codes. Additionally, Table 2.3 presents equivalent linear analysis codal provisions, including design equations for structural components used internationally. Table 2.4 highlights practical applications of diverse isolation systems, offering project specifics, locations, and other relevant details.

Table 2.2 Codal limitations and recommendations of various parameters

Code	Site Class	Seismic Intensity S_a	Superstructure Height above BI interface	Effective Period T_{eff} at Maximum Displacement (D_m)	Effective Damping at Maximum Displacement (D_m)	Eccentricity limitations
IBC 2000	A,B,C or D	≤ 0.6g	≤ 4-story or 65ft. or 19812mm	$3T_{\text{fix}} - 3$sec	≤ 30%	-
ASCE 7-10 Chapter 17	A,B,C,D	≤ 0.6g	≤ 4-story or maximum height of the building 20m	≤ 3.0 sec	≤ 30%	-
ASCE 7-16 Chapter 17	A,B,C or D	≤ 0.6g	≤ 4-story or 65ft. or 19812mm but it may exceed when there is no tension or uplift on isolator	≤ 5.0 sec	≤20%	-
EC-8	A,B,C,D	≤ 0.6g	Plan size 50m, height 19.8m	$3T_{\text{fix}} - 3$sec	≤30%	-
TSDC 2016	-	< 0.6g	20m	$3T_{\text{fix}} - 3$sec	-	5%

Japanses Code	1,2	-	60m	≥2.5 sec	-	3%
NTC-08	-	≤ 0.6g	20m	$3T_{fix} - 3sec$	-	3%

Table 2.3 Equivalent Linear Analysis codal comparison of different parameters [157][158]

Structure	Sign	Algeria	Taiwan	Japan	USA	China	Italy
Superstructure	Q_S	$\frac{Q_{ISO}}{R_i}$	$\frac{Q_{ISO}}{R_i}$	Q_{ISO}	$\frac{Q_{ISO}}{R_i}$	Q_{ISO}	$\frac{Q_{ISO}}{R_i}$
	Q_j	$\frac{Q_S M_i H_i}{\sum_{j=1}^{n} M_j H_j}$	$\frac{Q_S M_i H_i}{\sum_{j=1}^{n} M_j H_j}$	$\gamma(A_i Q_\xi + Q_e)$	$\frac{Q_S M_i H_i}{\sum_{j=1}^{n} M_j H_j}$	$\frac{Q_S M_i H_i}{\sum_{j=1}^{n} M_j H_j}$	$M_j S_a(T_e, \xi_e$
substructure	Q_b	$\frac{K_e D_D}{0.8R_i}$	$\frac{K_e D_D}{0.8R_i}$	Q_{ISO}	$K_{e,max} D_D$	Q_{ISO}	Q_{ISO}
Time period	T_e	$2\pi\sqrt{\frac{M}{K_e}}$	$2\pi\sqrt{\frac{M}{K_e}}$	$2\pi\sqrt{\frac{M}{K_e}}$	$2\pi\sqrt{\frac{M}{K_{e,min}}}$	$2\pi\sqrt{\frac{M}{K_e}}$	$2\pi\sqrt{\frac{M}{K_e}}$
Isolation System	D_D	$\frac{M\sqrt{\frac{7}{2+\xi}}S_a T}{K_e}$	$\frac{g}{4\pi^2}\frac{S_{aD} T_{eD}^2}{B}$	$\frac{M F_h(\xi) Z G_S S_o(T}{K_e}$	$\frac{g}{4\pi^2}\frac{S_{D1} T_D}{B_D}$	$\frac{Q_{ISO}}{K_e}$	$\frac{M S_a(T_e, \xi_e)}{K_{e,min}}$
	D_{TD}	$(1+y_i \frac{12e}{b^2+d^2})$	$(1+ y_i \frac{12e}{b^2+d^2})$	1.1	$(1+ y_i \frac{12e}{b^2+d^2})$	$(1+ y_i \frac{12e}{b^2+d^2})$	$(1+ y_i \frac{12e}{b^2+d^2})$
	Q_{ISO}	$K_e D_D$	$K_e D_D$	$K_e D_D$	$K_{e,max} D_D$	$S_a(T_e)\beta M$	$K_{e,max} D_D$
	D_M	$1.5D_{TD}$	$1.5D_{TD}$	γD_{TD}	D_M	$\lambda_S D_{TD}$	-

Table 2.4 Useful case studies and application of Base Isolation system

Project Name	Place Country	Completion Year	Project Details	Types of Isolation device used	Remarks
County Building and salt lake city	USA	1980	A total of 447 number of lead rubber is installed.	LRB	First, building in the USA that is retrofitted using seismic isolation system.
William Clayton Building [159]	New Zealand	1981	80 columns inbuilt with rubber isolator, four-story RC building Frame with Plan size 97×40m.	Lead rubber bearing	Manufactured by Empire Rubber Mills Limited, Christchurch, NZ
The Foothill Communities Law and Justice Center	Rancho Cucamong, Los Angeles,USA	1985	4-story, 15794 m^2, 98 bearings	High Damping Natural Rubber	First building in the USA to be BI. Designed on the request of County of San Bernardino.
West Japan Postal Computer Center	Sanda, Kobe, Japan	1986	6-story, 47000 sq.m., 120 LRB, 3.9 sec. isolation period	Elastomeric rubber isolators with steel and lead dampers	-

US Court of Appeals in San Francisco [121]	California, USA	1993	Plan area 100 × 81m and total floor area 31500 m^2	Single concave sliding isolation system	It is monumental structure of historical importance which suffer severe damage during Loma Prieta 1989 earthquake.
Sabiha Gokcen Airport International Terminal	Istanbul, Turkey	2009	2 lakhs sq.m. area, Plan of building 160m×272m, four-story above basement level, 279 triple fiction pendulum	Triple Friction Pendulum Isolator	The Airport is operated by Limak Holdings in partnership with GMR infrastructure Limited and Malaysia Airports Holding Berhad.
The Great hall of Nanjing Museum [160]	China	2011	Total building area is 4830 m^2 . Total 161 lifting points means equal numbers of LRB were used.	LRB	
Tan Tzu Medical Center	Tai Chung, Taiwan	2011	17-story tower with two underground levels with 325 LRB and 88 fluid viscous dampers.	LRB and fluid viscous dampers	Designed by C.C. Hsu & Associates. The BI system was designed by KPFF consultant, led by Andrew Taylor.
Tokyo Skytree East Tower	Tokyo, Japan	2012	31-story office towers, eight-story podium with area 229,237 sq.m.	LRB	Complex was designed by Nikken Sekkei and built by Obayashi Corp.
Emergency Operation Center	California, USA	-	2-story steel braced frame,28 bearings	High Damping Natural Rubber	Bearings were provided by Bridgestone Engineered Products Company.
Institute of Histology and Embryology of Mendoza (IHEM) laboratories	Mendoza, Argentina	2014	-	LRB	Designed and constructed by Santiago Monteverdi CC SA
Apple Park	Cupertino, USA	2015	Four-story structure having ring shaped design with circumference of 1512 sq. ft	Stainless Steel saucers, Sliding Bearing	This park is designed to survive all major earthquakes. As per New York Times report the saucer system will be able to shift upto 4 feet.
Adana Integrated health Campus	Turkey	2017	Total area of construction 430,000 sqm, 1512 no. of isolator were used.	LRB	The structure was designed by HWP and constructed by Ronesans Saghk.

2.9 Innovative Base Isolation Techniques

Alongside the traditional approach, the researcher introduced novel methods, assessing their viability and practical application. Some of these methods include:

A rectangular rubber isolator is developed to mitigate the impact of seismic forces. A rubber core is wrapped with CFRP sheet and stainless steel, increasing damping in rectangular isolators and reducing seismic forces and deformation [161]. Orientation had minimal impact, emphasizing core quality. Installation in tunnel-form buildings prolonged vibration, revealing torsional first modes. Base-isolated structures showed significantly lower interstory drift in Design Basis Earthquake and Maximum Considered Earthquake scenarios, mitigating seismic impact. Zhao *et al* [162] developed a design and mechanism for an inerter-based isolation system to reduce the displacement demand of the structure during earthquakes. This isolator consists of an inerter, spring, and dashpot; it is shown to be effective in refining the seismic response of structures.

Losanno *et al* [163] have examined the performance of low-cost BI techniques for brick masonry buildings. Further, Losanno *et al* [35] has compared the recycled and natural rubber properties to use in a BI system. The newly developed flat-spring friction system for BI, described in [115], excels in withstanding higher vertical forces, ensuring durability, and adapting to variable frequencies. Employing a flat sliding bearing and a flexible-length spring made of high-quality stainless steel, the FFS determines increased isolation effectiveness with higher PGA. A new type of seismic isolation device was developed [103] termed the Iso1GOODS® curved surface slider system. It is a unidirectional BI system used for steel pallet rack structures. A new polyurethane bearing is proposed to protect the structure from hazardous seismic effects [164]. They performed experimental and analytical investigations to present the response of the bearing.

In line of innovative base isolation systems, one can find designs distinguished by unconventional shapes that integrate mechanisms combining elements from various previously mentioned isolation systems. Some examples are highlighted here. Nakamura *et al* [165] developed the core-suspended isolation (CSI) system featuring a double-layer inclined rubber bearing. Initially installed in Tokyo, Japan, the shake table test results align well with the expected behavior of the CSI system. The tilting of the rubber layer effectively controls the dynamic behavior of the structure and amplifies the natural time period of the structure. Further, Hosseini and Farsangi [166] have developed a new isolation system termed the telescopic column. In this isolation system, the structure is supported on the foundation with a pivotal connection at its mass center. Telescopic arms, designed for vertical and horizontal movement, create a pendulum-like effect, achieving seismic isolation. Energy dissipation occurs through the yielding of the steel plate in the telescopic arms. Karayel *et al* [167] developed spring tube braces for the isolation system. In this system, base-story columns are pin-connected to the upper-story, and telescopic spring braces, exhibiting symmetrical behavior, allow free lateral movement for seismic isolation. Zhou *et al* [168] explored a quasi-zero stiffness isolation system with a parallel arrangement of linear and disc springs, finding reduced amplitude response at higher damping and amplitude-dependent response for non-linear conditions. The system aims to isolate vertical vibrations. The innovative Convex Friction System (CFS) as a seismic isolation system, demonstrating a potential reduction of around 30% in structural response, particularly effective in mitigating the impact of near-fault earthquakes [169]. The installation of BI technology is not restricted to the base of the columns; now, the inter-story installation of isolators is proposed for high-rise buildings [170].

2.10 Summary

This chapter proposes a comprehensive review of the BI system, covering analyses, experiments, numerical investigations, various types, and practical applications. It offers an overview of significant seismic isolation analyses and responses, coupled with a historical evolutionary assessment of the BI system. The BI technologies are categorized based on functions and principles, facilitated by an illustrative schematic diagram. The review highlights BI types, applications, suitability, advantages, disadvantages, and various codal recommendations. While each isolator has its drawbacks and benefits, their selection depends on specific requirements. The chapter includes a comparison and discussion of their advantages and limitations. The following conclusion have been drawn after vast and comprehensive review:

- The base isolation device must possess an effective re-centering mechanism, sufficient shear resistance, suitable vertical stiffness, and the ability to dissipate the energy generated by seismic forces. Additionally, it should maintain its mechanical characteristics throughout the service life of the base isolation systems.
- The selection of the seismic isolation system type is contingent on the specific structure undergoing retrofitting, such as masonry structures, historical monuments, buildings, bridges, liquid retaining structures, etc. Additionally, the design must account for the structural implications of any long-term changes in the properties of the base isolation system.

- Concerning nuclear power plants, it is crucial to examine the impact of radiation exposure on the mechanical characteristics of isolated devices. Additionally, if radiation adversely affects and leads to the deterioration of a device, protective measures must be implemented to prevent harm to the structural components.
- The seismic response of the BI system in the context of the nuclear industry raises concerns as it overlooks the impact of vertical acceleration on the isolated structure. Recent ground motion records indicate that the vertical acceleration surpasses 1g.
- When dealing with blast loading, it is imperative to distinguish between the blast energy transmitted through air and the ground shock. Therefore, it is essential to establish a robust procedure and guidelines to validate numerical simulations by comparing them with field responses. Generating vertical and horizontal time series resulting from ground-induced shock for consistent soil characteristics proves beneficial. In scenarios involving both blast loading and seismic excitation, the structural vulnerability arising from differing story heights and blasts with varying charge weights requires evaluation.
- Researchers are currently developing isolation systems, like double and triple surface friction pendulum systems, to address diverse seismic challenges. However, the adaptive behavior of these systems needs experimental verification. Priority should be given to affordable systems, crucial for earthquake-prone areas in developing countries.
- Typically, the analysis assumes that the superstructure remains within the linear elastic range during ground motions. However, under very strong ground motions with higher Peak Ground Acceleration, it transitions into the nonlinear range. Therefore, it is essential to analyze the impact of the nonlinear characteristics of the structure.

- It is concluded from the literature that the bearing should provide adequate horizontal flexibility to extend the building's natural period and accommodate spectral demands. It must possess adequate energy dissipation capacity to restrict displacements within the prescribed limits, ensuring structural integrity. It should maintain an appropriate level of rigidity, allowing the BI building to behave comparably to a fixed-base structure under normal service loads.
- Elastomeric bearings, such as LRB, are susceptible to deterioration over a period of time, which may impair functionality. The rubber material might degrade and lose its flexibility when exposed to weathering, UV radiation, and other adverse environmental conditions. Further, research is required to create more resilient rubber polymers that can endure exposure to these elements over an extended period of time.
- Extreme temperatures could have a detrimental effect on the efficiency of the bearings because they are temperature-sensitive. Consequently, their capability to mitigate seismic forces may be influenced by alterations in their stiffness, damping, and other mechanical characteristics. Therefore, further study is needed to create more robust bearings.
- Significant deformations might take place in bearings during severe tremors, which may impair their long-term functioning. To precisely forecast how bearings will perform amid substantial deformation, research is required to create more accurate analytical and numerical models and robust testing procedures and guidelines.

Despite the maturity of base isolation techniques for real-life structures, their widespread adoption remains limited, especially in developing countries like India. The reluctance to embrace these technologies is primarily linked to perceived higher costs. Additionally, a lack of understanding of the long-term benefits of isolation and the complexity of design code documents contribute to hesitations in implementing isolation techniques. The new technique allows engineers to customize base isolation for site-specific needs. Yet, questions remain, making the development of adaptive systems and better-performing devices a key research priority with ongoing projects. The unique focus on emerging technologies and unexplored applications in seismic base isolation sets this review apart, offering valuable insights for both researchers and practitioners in the field.

2.11 Research Gap

Based on a comprehensive review of past research in the field of seismic base isolation, it was observed that several parameters require further analysis. These parameters need to be examined and proposed through numerical verification to ensure their effectiveness and accuracy. The following research gap has been observed from the comprehensive literature review:

- Literature review indicates that before numerically simulating Lead Rubber Bearing, High Damping Rubber Bearing and frame structures, accurate and precise earthquake response records must be obtained for both near-field and far-field seismic events. Additionally, material characteristics from the literature should be carefully considered to ensure realistic simulation conditions. Proper attention to these factors is essential for accurately predicting the seismic performance of structures equipped with these bearings under varying earthquake conditions.

- In Lead Rubber Bearing and High Damping Rubber Bearing, isolation reduces story drift and peak acceleration responses, protecting structural elements and non-structural components. While base displacements increase due to the system's flexibility, they remain within practical limits. LRB and HDRB must preserve mechanical characteristics over time and effectively handle self-weight and external forces to ensure durability and optimal seismic performance.

- The LRB and HDRB should be tested by incorporating them into buildings to evaluate their practical performance across various superstructural parameters. The results should then be compared with those of a fixed-base structure to gain a clearer understanding of the benefits and effectiveness of using these bearings in seismic isolation.

- A comparative study of sliding friction bearings and fixed base structure should be conducted to assess their performance. The combinations of linear and conical springs, both separately and together, should be tested to determine the most optimal configuration that significantly reduces structural responses. This approach helps identify the most effective combination for minimizing vibrations and improving stability, ensuring optimal performance in various applications while maintaining structural integrity during dynamic events such as earthquakes or other external forces.

- It was observed from the literature that before performing sliding bearing frame structure tests on a shake table, key prerequisites for dynamic characterization must be ensured. These include conducting impact hammer analysis, modal analysis in Abaqus, spring deformation curve analysis, and material testing. Proper execution and numerical verification of these steps are crucial for accurate assessment of the structure's dynamic behavior and for ensuring reliable test results.

2.12 Objective of the Research

Based on the literature review in Chapter 2 and identified research gaps, the objectives of the present study are proposed as follows:

This study aims to analyze the dynamic response of High Damping Rubber Bearing and Lead Rubber Bearing under vertical loading subjected to various near-fault ground motions, with a focus on reducing acceleration and displacement responses using Abaqus software. Finite element analysis of HDRB and LRB is necessary to evaluate their actual behavior and the performance of various components under applied loading conditions. To achieve this, the study first validates existing literature on LRB [74], then assesses HDRB of the same dimensions and specifications. Additionally, numerical analyses of both HDRB and LRB are conducted, incorporating varying coefficients for strain-energy functions to assess their effectiveness.

The study further investigates the dynamic responses of a 10-story reinforced concrete building equipped with HDRB and LRB using SAP2000. Parametric variations are performed to evaluate the effectiveness of HDRB and LRB isolators in real building structures. The structural responses are simulated under near-fault and far-fault earthquakes, matched to the IS 1893 Zone V response spectrum using SeismoMatch software.

In addition to assessing the efficiency of HDRB and LRB, the literature review highlights limited focus on combining restoring devices with sliding isolators. This study conducted experimental tests on a scaled steel moment-resisting frame with various configurations, including fixed base, sliding base, low-stiffness linear springs, high-stiffness linear springs, and conical springs. Shake table tests, compatible with the Pulse Labshop software package, were used to evaluate these configurations.

Dynamic characterization is a critical aspect of dynamic analysis. This study employs Impact Hammer testing and numerical modeling using Abaqus software to ensure model compatibility. Experimental results are compared with numerical simulation outcomes for various configurations.

The findings and recommendations aim to promote further research on sliding isolators and broaden their application in diverse structural designs. This study holds substantial practical significance, offering insights to optimize building performance under seismic conditions, enhance overall seismic resilience, and safeguard the longevity of structures and the safety of their occupants.