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Sustainable base isolation: a review of techniques, implementation, and extreme events

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Abstract. Growing concerns about seismic events enforced structural engineers and architects to embrace the hazardous effect of ground motion in design. To address this, researchers have developed various base isolation (BI) techniques. This study comprehensively reviews BI system types, techniques, and implementation. Exploring the dynamic response of three-dimensional BI devices and the mutual effects of isolation devices and soil-structure interaction during strong ground motion, the paper covers topics such as seismic isolation of nuclear power plants, cost analysis, and various optimization techniques. Furthermore, the paper investigates the behavior of isolation devices in beyond-design events, including blast and aircraft impact loading. In general, the seismic isolation and control device response is demonstrated through shaking table tests and computational analysis. The study sheds light on the functions of seismic isolation system by comparing them with fixed base structures. Additionally, the paper presents codal recommendations, recent advancements, and current practices, aligning them with historical developments and past reviews of different BI techniques, along with their advantages and disadvantages. In conclusion, the closing remarks emphasize the future research prospects in this field.

Keywords. Base isolation; aircraft impact; earthquake; optimization; cost analysis; blast loading.

1. Introduction

Among various natural disasters and undesirable shakings, earthquakes stand out as the most harmful and perilous occurrences, leading to significant loss of human lives and widespread destruction of infrastructure. Tackling this daunting challenge poses a significant hurdle for structural designers and engineers. Extensive research, analysis, and experiments have led to the development of diverse strategies aimed at mitigating the effects of ground motion on structures, thereby strengthening the seismic capacity of structures. Among the available seismic protection methods, base isolation is the predominant seismic protection technology due to its stability, application and reliability [1].

The base isolation technique is not recent; it has historical roots and was widely employed in ancient structures, including Chinese monasteries, bridges, temples, and walls. Early constructions used layers of materials, predominantly clay mixed with ashes and charcoal, allowing relative movement between the foundation and the ground during seismic activity [2]. Over the course of history, comprehensive analyses have explored into the origin, development, and application of seismic BI technology. Extensive research has been conducted on critical structures, such as hospitals, storage vessels, nuclear power plants, and fire stations, that require protection from ground motion-induced damage, particularly due to their sensitivity to vibrations. It has been observed that implementing an isolation system can enhance the seismic capacity of these structures to a considerable extent [3].

1.1 *Basic mechanism*

Base isolation is pivotal for seismic hazard mitigation, focusing on structural safety and sustainability. Among the numerous approaches, the development of base isolation techniques is notable—raising buildings from the ground with flexible foundations to minimize force and motion transmission [4]. The detailed study [5] regarding the dynamic behavior of the structures concludes that resonance significantly intensifies the probability of severe destruction, which occurs when the natural vibrating frequency of the building approaches the dominant frequency

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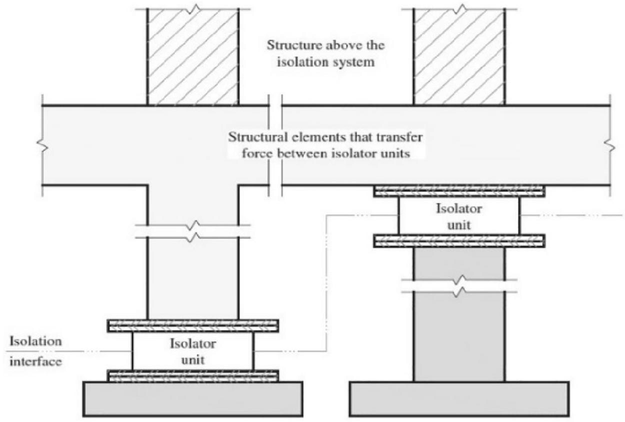


Figure 1. Base Isolation Terminology (ASCE 7-16).

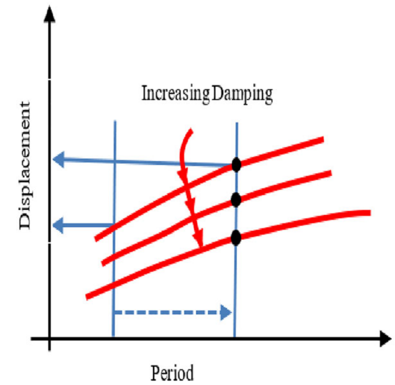


Figure 3. Displacement design response spectra [8].

of seismic excitation. The fundamental notion of base isolation entails isolating the superstructure from the harmful effects of ground motion by incorporating isolators between the superstructure and foundation, as shown in figure 1 [6, 7]. Decoupling aims to lengthen the structural period, as shown in figure 2, thereby preventing resonance with the frequencies of unwanted vibrations or earthquakes [8]. Increasing the time-period of the structure results in larger relative displacements, as depicted in figure 3. Eventually, it minimizes acceleration and lateral forces, exerting control over the structural response. Reduced seismic demand preserves superstructure elasticity, lowering the risk of damage to sensitive equipment and non-structural elements. Effective isolation devices must exhibit key characteristics, including the capability to withstand superstructure dead load, adequate lateral flexibility, accommodation of displacements, and incorporation of proper mechanisms for energy dissipation. They should also have the ability to withstand minor seismic activity while dissipating energy during high-intensity earthquakes. The material and device properties should adequately represent behavior under design conditions, consider environmental factors throughout the device lifespan, and account for aging phenomena. Extensive research over recent decades has expanded the literature on base isolation, with numerous reviews covering its development, theory, and application [9, 10].

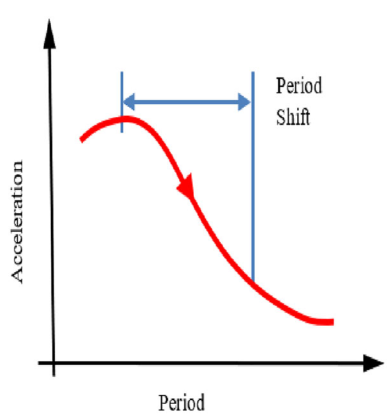


Figure 2. Time Period shift [8].

1.2 *Historical development*

Around 530 BCE, Persia used a basic sliding system for the Tomb of King Cyrus, allowing stone blocks to slide without mortar. In Corinth and Ephesus, around 540 BCE and 120 CE, monolithic columns atop rock were used to construct the Temple of Apollo and the Library of Celsus, respectively. The Obelisk of Theodosius, originally constructed in Egypt in 1450 BCE, was relocated to Constantinople and positioned in the hippodrome on a marble pedestal equipped with pivoting supports and a movable base [11]. The historical origins of the modern form of the base isolation system can be traced back to 1870, when a double concave spherical sliding-bearing base isolation system, similar to the current double concave FPS (Friction Pendulum System), was patented in San Francisco, USA [12]. The base isolation technique was first proposed in Japan in 1894 and implemented in 1934 in two bank structures using the Knee-Joint isolation mechanism below the columns [13]. In 1909, Calantarients proposed a seismic isolation technique, i.e., a sliding isolator using talc or mica layers. A 1933 building in Ljubljana, Slovenia, demonstrated early seismic isolation with metal and asphalt layers. The Pestalozzi school in Skopje, Yugoslavia, implemented base isolation in 1969 using unreinforced rubber blocks. However, these blocks lacked vertical stiffness, causing undesired vertical acceleration and a bouncing effect, rendering them unusable [14].

Over the past four decades, various seismic isolation devices, including roller bearings, elastomeric bearings, rubber bearings, sliding bearings, and frictional bearings, have been developed to control the dynamic response of structures. Rolling-type isolators employ balls or rolling rods that can crisscross on concave surfaces. The arrangement of these rolling surfaces determines the displacement-dependent restoring force [15]. The modern Friction Pendulum tackles concerns related to low-friction materials, heating effects, contact pressure, and velocity. Following this, the subsequent research introduces Double Concave Friction Pendulum and Triple Friction Pendulum bearings [4]. Elastomeric isolators, comprising rubber sheets with vulcanised reinforcement (steel or fibers), vary based on damping characteristics [16]. This type of bearing is classified as Low damping elastomer isolators are labeled LDRB [17], high damping elastomer isolators as HDRB [18], those with a lead core for increased damping as LRB, and those with rigid fiber reinforcement as FREB [19]. In recent decades, using reliable devices like elastomeric or sliding isolators, BI has gained prominence for reducing earthquake-induced losses. Numerous scholars have suggested innovative approaches to attain adaptive functionality in isolators, encompassing elastomeric and sliding mechanisms.

1.3 *Recent developments*

The escalating concerns about the recent rise in earthquake intensity have driven researchers to improve and advance the capabilities of existing seismic isolation devices while also developing new ones. Recent advancements in sustainable low-cost materials for seismic isolators, such as the Geotechnical Seismic Isolation (GSI) system that uses shredded rubber–soil mixtures, offer a cost-effective solution to reduce earthquake-induced structural response. This system enhances safety in less-developed regions and addresses the global waste tire issue, showing significant potential in mitigating seismic hazards [20]. Eco-friendly Scrap Tyre Rubber Pads (STRPs) provide a cost-effective, easily adjustable solution for shear stiffness and contribute to recycling efforts. Experimental assessments of STRP properties, crafted with thin steel shims between rubber pads and subjected to vulcanization, included axial compression tests and horizontal shear tests. The STRP isolator, crafted from radial tires, has a damping ratio of 18.48%, surpassing the 3.5% damping ratio found in natural rubber bearings. This higher damping ratio suggests the potential to eliminate additional enhancements up to a specified level [21].

An experimental study found that a thick layer of compressible limestone sand under a cantilever concrete column's foundation can act as a seismic base isolator [22]. Another smart base isolation system that adjusts its properties when triggered by an Earthquake Early Warning (EEW) signal was developed in Japan. Under normal conditions, the system is locked by shear keys, and when an earthquake is detected, a mechanical mechanism releases it [24]. Apart from these innovations, recycled rubbers are also employed as isolator materials [23]. The "composite foundation" concept impeccably integrates seismic metamaterials with a structure foundation to reduce energy transfer from seismic waves within the frequency range associated with the first vibration mode [24]. This innovative approach marks a paradigm shift in seismic protection design, particularly emphasizing S-waves and their associated high amplitudes. With the advent of new research, isolation methods, including sand layers and thermal insulation boards, have evolved for seismic protection. A recent study [15] investigates the application of thermal insulation boards for cost-effective sliding prevention. In addition, the current study introduces innovative seismic isolation systems in the section titled "Innovative Base Isolation Technique".

Base isolation, a technique designed to mitigate earthquake forces, encounters various challenges, including high costs, intricate design demands, ongoing maintenance requirements, limited applicability to specific structures, uncertainties in seismic input, sensitivity to construction quality, integration issues with existing structures, and public acceptance concerns. Despite these obstacles, base isolation remains invaluable for enhancing seismic strength, particularly in high-risk areas. Ongoing research endeavors seek to refine its effectiveness continually.

While numerous review articles on base isolation systems exist [15, 25] few probe into various aspects collectively. In this study, we investigate various aspects of base isolation, including outline commonly employed seismic isolation system, modeling techniques, numerical simulation software, retrofitting and rehabilitation of old structures, effects of soil-structure interaction, 3D isolator modeling considerations beyond design events (such as the impact of aircraft and blast loading on structures), assessments specific to nuclear power plants, cost analysis, optimization effects, and document the historical evolution of contemporary seismic BI through scaling and shake table experiment of isolated structure. The exploration of these advanced aspects is limited, as the majority of shake table tests predominantly concentrate on horizontal ground motion. The research contrasts a conventional structure with a base-isolated one to evaluate the effectiveness of the base isolation technique. This paper explores these aspects in conjunction with the advantages and disadvantages of various isolators, code recommendations, and includes relevant case studies. Furthermore, tracing its historical evolution over a century, paper evaluates recent technological advancements, including innovative materials and adaptive systems. By presenting a nuanced perspective on the strengths and limitations of the base isolation, this review contributes to the ongoing discourse in seismic engineering. The assessment ends with closing remarks and an study of potential future actions.

2. Types of seismic base isolation techniques

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. Various commonly used base isolation techniques are illustrated schematically in figure 4, and different types are described below.

2.1 *Friction pendulum system (FPS)*

In 1909, Mario Viscardini introduced a friction-based isolation device in response to the Messina earthquake. Literature [26] suggests that FPS, proposed in 1909 by Calanterients, initially involved pure sliding. He designed to address shortcomings in friction isolators, it applied a talc layer for isolation to mitigate acceleration response. These isolators offer advantages such as a frictional force directly proportional to the superstructure mass, mitigating eccentricity and torsion concerns. In contrast to rubber bearings tailored for specific seismic frequencies, friction-based isolators efficiently dissipate energy across a wide frequency spectrum, minimizing resonance. FPS bearings are frequently favored over alternative types of bearings because they offer an isolation period unaffected by the supported structures mass, have excellent dissipation and recentering capabilities, and exhibit long-lasting and durable properties. Additionally, they ensure that the maximum acceleration transmissibility aligns with the friction-induced limiting force [27]. The coefficient of friction is influenced by both ambient temperature and heating during high-velocity sliding at the isolation interface. Careful consideration is needed in designing reduced scale tests or extrapolating results to prototypes. FPS bearings exhibit significantly higher vertical stiffness compared to high shape factor elastomeric bearings, attributed to the materials including thin layer of PTFE , ductile iron, and stainless steel used to develope the FPS. The seismic properties of the isolation system are presented by the effective period of vibration T_{eff} and stiffness K_{eff}, and the

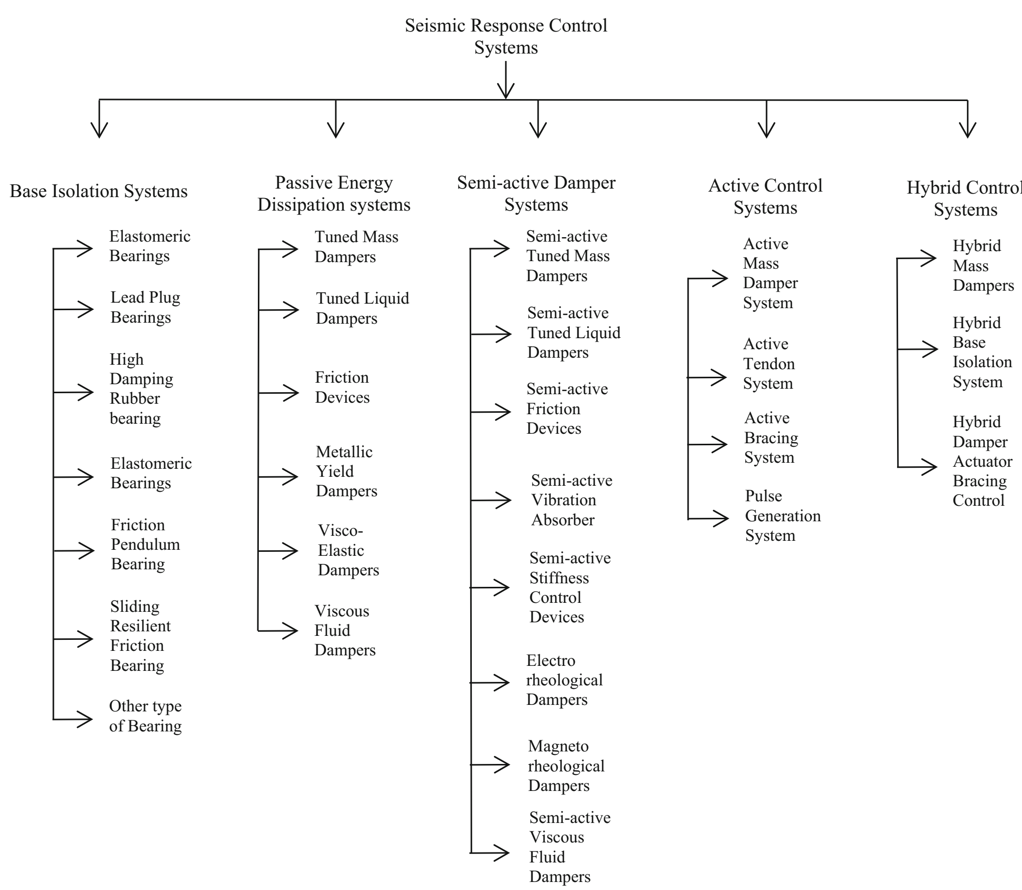


Figure 4. shows the seismic response control devices used to reduce the seismic motion.

effective damping ξ_{eff}. For the FPS isolator, if equivalent radius R and friction coefficient μ is considered, then, $T_{eff} = 2\pi\sqrt{\frac{N}{K_{eff}.g}} = 2\pi\sqrt{\frac{1}{1+\frac{\mu.R}{A}}\frac{R}{g}}$, $K_{eff} = (1 + \frac{\mu.R}{A}).\frac{N}{R}$, and $\xi_{eff} = \frac{2}{\pi}\frac{\mu}{\mu+\frac{A}{R}}$ 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 Poly-TetraFluroEthylene (PTFE), and other thermoplastics have been suggested as a bearing material [9, 28]. 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 [29]. In FPS, the natural period of the device correlates directly with the surface radius. The frictional force at the base is proportionate to the systems mass, causing the center of resistance and the center of mass of the sliding support to coincide [30]. Almazan *et al* [31] presents both analytical and experimental investigations of a frictional-control sliding base isolation structure. Introducing the concept of sliding bearings coupled with a pendulum-type reaction results in the development of the FPS, a seismic isolation device that is conceptually intriguing.

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 [32]. 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 [33]. Castaldo and Alfano [34] 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. It investigated concerns regarding device maintenance and the impact of non-negligible residual displacements on the isolator's post-earthquake service life. 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 [35]. The restoration capacity of FPS was assessed through theoretical investigations using bilinear hysteretic models and single degree of freedom systems [36]. The important parameter which affects the restoring capacity of the isolation system is the ratio of d_{max}/d_{rm}, where d_{max} is maximum displacement and d_{rm} is maximum static residual displacement. This paper concluded that if d_{max}/d_{rm} the ratio is higher, then restoring capacity increases, and if the isolation system with $d_{max}/d_{rm} > 0.5$ have tremendous restoring capacity. Thus, negligible residual displacement occurs. The BI system consists of flat sliding bearings having fluid damper or rubber bearings has enough restoring capability for $d_{max}/d_{rm} > 0.33$ [37]. Here it is important to address How's the hysteretic response looks like. And precise assessment of the maximum residual displacement of the base isolators in case of higher seismic hazards. Kim and Yun [38] and Ozbulut and Hurlebaus [39] conducted a sensitivity analysis to determine key parameters, including the natural vibration period, yielding displacement, and friction coefficient, for the precise design of the superplastic friction isolator in bridges. Despite extensive efforts to investigate velocity, vertical contact pressure, and coefficient of friction to mitigate unwanted stick-slip occurrences in FPS, uncertainties persist. The triple FPS, classified as a multi-spherical Friction Pendulum Bearing variant, has been introduced to extend the capabilities of adaptive seismic isolation systems. Despite its entirely passive nature, the TFPB showcases adaptive stiffness and adaptive damping [40]. Fenz [41] and Becker [42] have performed analytical and experimental investigation of the bi-directional response of the triple FPS. Harvey and Kelly [15] 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. However, drawbacks have been identified; while effectively reducing horizontal acceleration, the RIS transfers vertical acceleration to the superstructure, even in the absence of vertical seismic excitation. This transfer may exceed the isolators tolerance limit, potentially leading to severe building damage and undermining the intended purpose of horizontal isolation. 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 [43]. Calvi introduced a variation of VFPB utilizing materials with distinct frictional characteristics [44]. 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 [45]. VFPB offers predictable and controllable variations in stiffness and damping at manageable displacements.

The recent study proposes a cost-effective isolation system suitable for low-rise masonry structures in developing countries. Masonry buildings, widely used in developing countries, are favored for their economic advantages, ease of construction, and simplicity in repair. However, their poor seismic resistance limits their suitability for earthquake-prone regions. Zhang *et al* [46] introduced a cost-effective friction-based seismic isolation system for masonry structures aimed at enhancing their seismic resilience. The system, comprising a 50 mm thick isolation layer with low lateral stiffness sandwiched between two 4 mm thick Teflon sheets and reinforced with vertical rebars, was tested with various materials. Additionally, a study by Ali *et al* [47] assesses five low-cost, locally accessible materials for the isolation layer through analytical, experimental, and numerical analyses. Cyclic loading tests on proposed materials, between hollow concrete blocks, revealed rubberized mortar as a feasible option. Numerical studies in ABAQUS demonstrated a 40%–53% reduction in acceleration response in the isolated model compared to the fixed-base model. Bibi [48] revealed three failure types—horizontal and diagonal cracking, slippage, and spalling of the isolation layer. The isolation system experienced flexure and shear failures, with no damage to the top and bottom blocks, indicating limited harm to the isolation layer. The steel bars for re-centering remained unyielded even after severe slippage. The study involved small prototype blocks with varying isolation layer thicknesses of 50 mm, 65 mm, and 75 mm, respectively, providing insights into cracking patterns, failure modes, and isolation layer sliding. Key parameters, including stiffness degradation, displacement ductility, equivalent viscous damping, and seismic energy dissipation, were discussed based on the test results. This review examines friction-based isolation systems for their effectiveness in reducing acceleration response. Although, FPS is commonly employed as an isolation system, there is room for enhancements to enable its full integration in regions with high seismic risks, rocky terrain, and tall structures, ensuring effective recentering capabilities without the risk of uplifting and overturning. Practical implementation favors cost-effective, easy-to-install systems with re-centering capability, shear resistance, and suitable stiffness. While friction-based systems stand out as efficient, further experimental verification is needed, considering various parameters such as friction coefficient, temperature, sliding velocity, axial pressure, and exposure to different ground motions.

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 [49]. 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 [50]. The friction plate and the elastomeric bearing are provided in series for such an isolator.

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 [51, 52]. 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.

2.4 *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* [53] 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* [53] compared the SR-F isolation system with other isolation systems. Peng *et al* [54] proposed a sliding hydromagnetic bearing, which is a kind of low-friction isolator.

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 [55]. 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 [17]. 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 [26].

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 [56]. 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 [57]. 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 [58]. 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 [59]. 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 [60]. The seismic performance of a G+7, symmetrical residential building has been extensively investigated to understand the effects of seismic isolation with LRB [61]. Under El-Centro earthquake excitation, the time period extended from T=0.46 seconds to T=2.38 seconds, the base shear decreased by 4.6 in the X direction and 3.5 times in the Y direction. Displacement increased from 0.0197 meters to 0.1458 meters in the X direction and from 0.0127 meters to 0.1538 meters in the Y direction, affirming the efficacy of the seismic isolation system compared to conventional buildings. Lee *et al* [62] 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 [63] studied the effect of Lead Core Heating on the superstructure response of buildings under cyclic loading. A 20-story RC and a 3-story steel structure were earthquake-tested to evaluate the effect of isolator properties on superstructure response. Findings indicated that the effectiveness of bounding analyses in establishing a secure envelope for superstructure response is reliant on the properties of the seismic isolation bearings. The analysis of lead rubber bearings considering linear and non-linear response was done using the structural program SAP2000, OpenSees, and 3D-BASIS [64]. Top floor acceleration and Base displacement behavior from time history analyses under Kocaeli and Chi-chi earthquakes are compared. Nonlinear analyses in OpenSees exclusively model the temperature-dependent behavior of LRBs, revealing significant variations in structural response, particularly depending on earthquake intensity. Plenty of tests for rubber bearings on shake table tests for building prototype models were done by Lu *et al* [65]. Fu *et al* [66] conducted numerical modeling and shake table tests on a BI system incorporating a magnetorheological damper and elastomeric rubber bearing. They used a single-step algorithm and lead rubber bearings and verified the model experimentally on a shake table test. The prototype of the Elastomeric Polymer Bearing (EPB) investigated in this study features a cylindrical design composed of elastomeric polymer composite with a pin-ended steel core in the central hole. Vertical forces are supported by the steel core, while shear forces are borne by the EP composite.

The rolling seal-type air spring and laminated rubber bearing for three-dimensional base isolation were developed [67]. 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-storey buildings deeply. He found that HDRB is better than LRB in the instances of isolator base shear and displacement [68]. The analytical micro-modeling of LRB by using a finite element micro-model has been done [69]. Two micro-models are developed and tested under vertical static loading followed by horizontal cyclic loading to determine

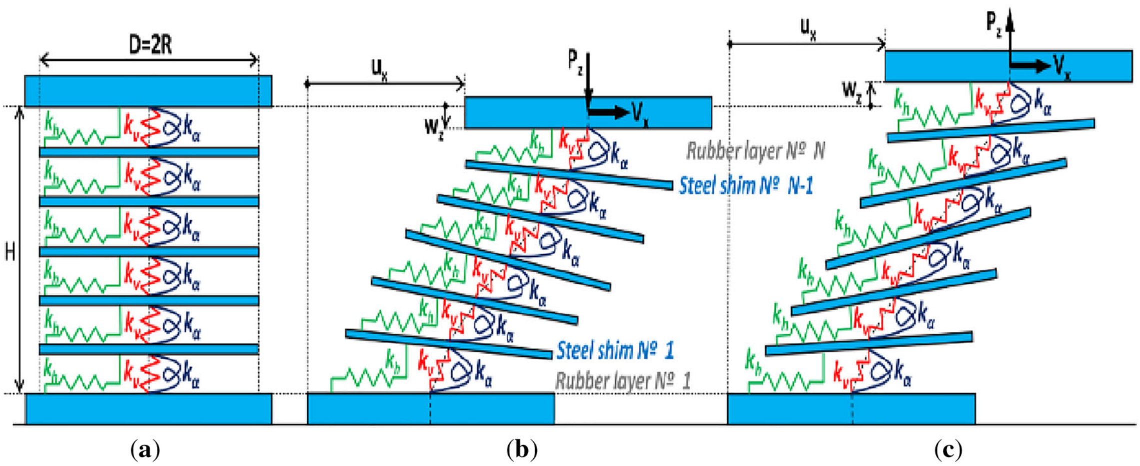


Figure 5. Schematic shape representation of multiple spring isolation model with (**a**) undeformed, (**b**) deformed in compression and (**c**) deformed in shear and tension [74].

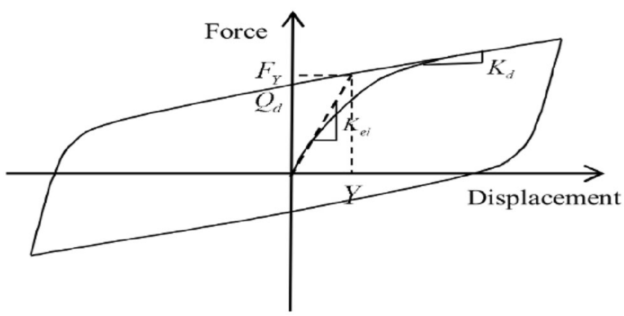


Figure 6. Shows the force–displacement curve for LRB [75].

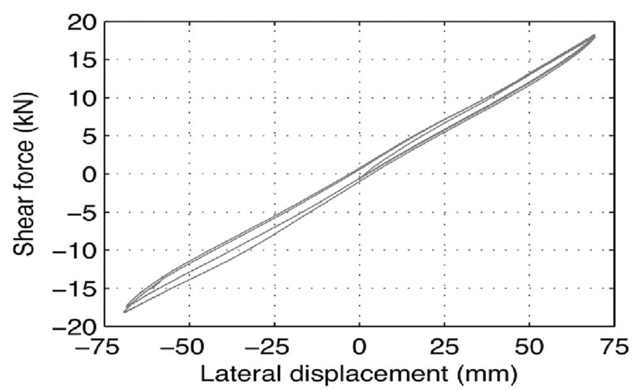


Figure 7. Lateral displacement vs shear force [25].

the impact of lead core confinement on bearing behavior. The analysis includes studying strain, stress, and plastic zone distribution within the bearing, and comparing lateral force-displacement curves with the manufacturers recommended curve. Neethu and Das [70] examined the response of soil-structure interaction on bridges deeply by inserting elastomeric bearings to cater to the effect of strong ground motion. Iizuka [71] 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 [72]. They compared the response of strain energy function's coefficients for the rubber material. Karimi and Khordachi [73] studied the behavior of LRB and laminated rubber bearing under different strong ground motions, i.e.,

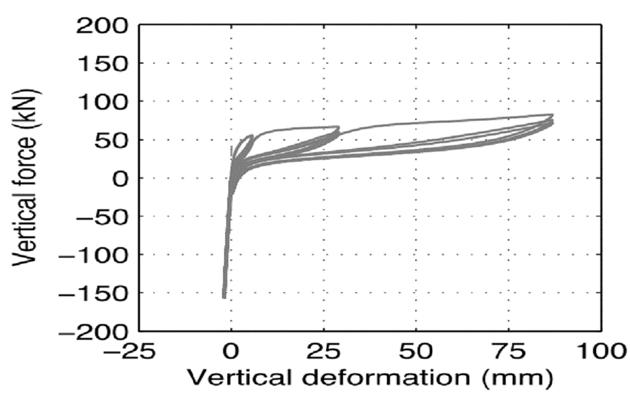


Figure 8. Vertical deformation vs vertical force [25].

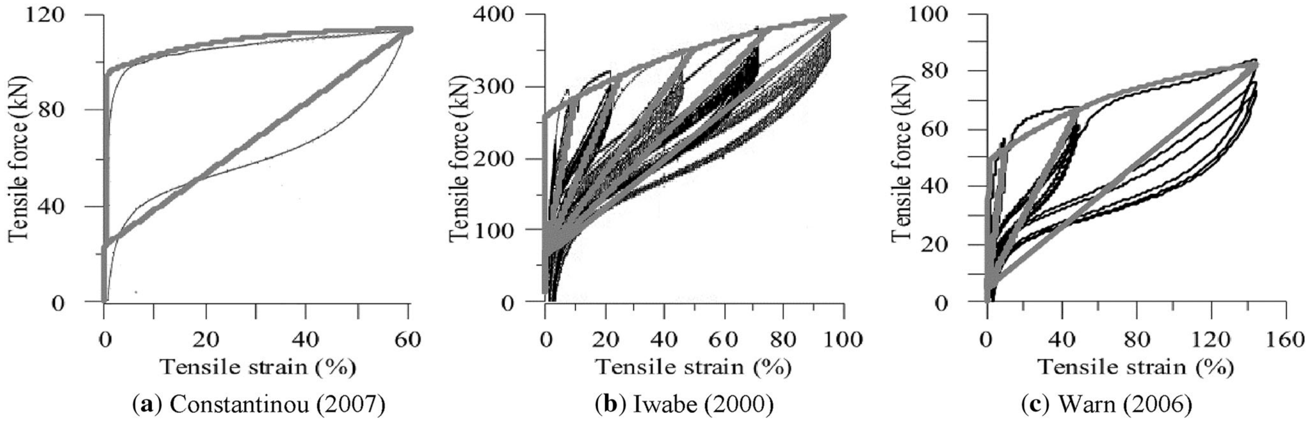


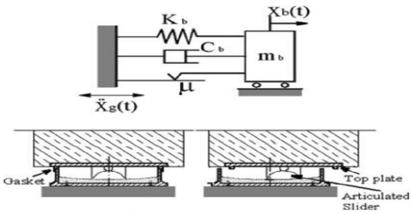
Figure 9. Comparison of experimental response with mathematical model [75].

El Centro (1940), Northridge (1994), and Kobe (1995). They performed the 3-D analysis on ABAQUS software. Maureira *et al* [74] developed a model predicting the non-linear mechanical performance of elastomeric bearings, as depicted in the schematic diagram in figure 5. The model accounts for rubber inelasticity and hardening to capture the non-linear behavior of the bearing. Figures 6, 7, and 8 illustrate the vertical and horizontal displacements, the Force-Displacement curve for LRB, and 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 [75]. The study modeled the 3-D continuum geometry of the bearing with a 2-node, 12-degree-of-freedom discrete elements. Three analyses were conducted using experimental data (figure 9) to assess the proposed mathematical models ability to simulate bearing response under cyclic tensile loading. The benefit of the LRB isolator lies in its avoidance of elevated initial friction, which can lead to high accelerations in the system. Furthermore, it eliminates the issue of variable friction coefficients at high speeds, ensuring that the accepted hysteretic behavior closely aligns with the actual behavior. Additionally, the lead core imparts elastic rigidity to the system during small-amplitude earthquakes or wind events. Existing literature records problems in BI systems subjected to rare strong ground motions, including (a) buckling or shear failure in elastomeric bearings and (b) fatigue of the displacement capability (hammering the rim) in FPS.

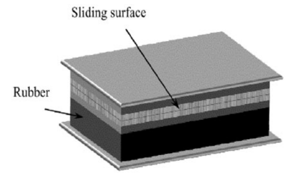
2.6 *Sliding BI systems*

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 [76] examined the uniaxial and biaxial response of the sliding BI system; the response of the sliding BI building was investigated by Calvi and Calvi [4], Calvi [44], and Calvi and Ruggiero [77] 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* [78] have evaluated experimentally the dynamic control response of the flat sliding bearing base isolation system [79]. Quaglini *et al* [80] 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 [81]. A special smart restorable sliding BI system is proposed [82]. 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.

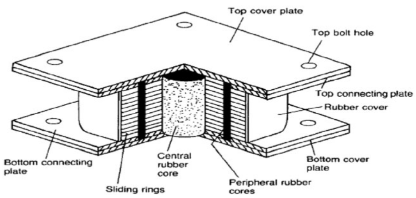
Figure with reference of Base Isolation System



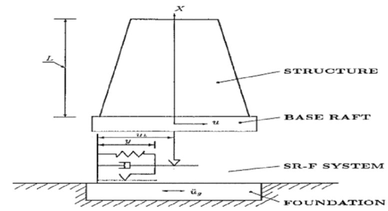
2.1 Friction Pendulum System [8].



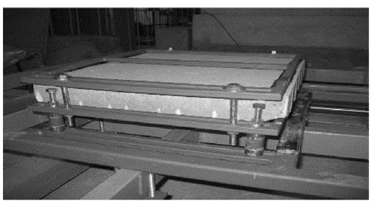
2.2 Electricite-de-France System [27].



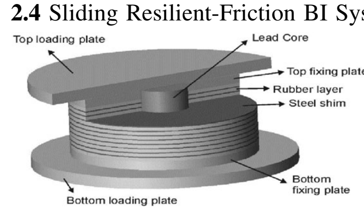
2.3 Resilient-Friction Base Isolation System [49].



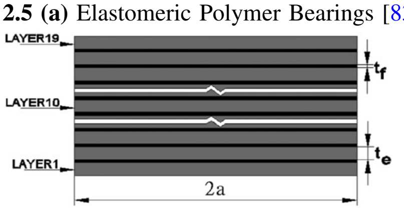
2.4 Sliding Resilient-Friction BI System [53].



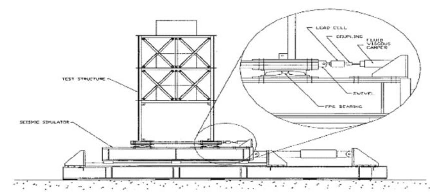
2.5 (a) Elastomeric Polymer Bearings [83].



2.5(b) Lead Rubber Bearing [69].



2.5(c) Fibre Reinforced Elastomeric Isolator [84].



2.6 Sliding Base Isolation Systems [85].

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 [86–88]. 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 [7]. Mathematical expressions and equations are also introduced to forecast the heat generation in the lead core and the subsequent decline in strength [89]. 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 [7]. The published paper [90] 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 [91]. 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 [58]. 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:

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

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

$$\bar{t} = \frac{\alpha_s t}{a^2} \quad (3)$$

where, T_L lead core temperature rise at time t, Parameter $\bar{t}$ is referred to as the 'dimensionless time'. In (1)–(3), $\sigma_{YL_0,}$ 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 [89]. 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. The equation can be precisely solved for a specific scenario where heat conduction in the steel plates and the end steel shims is disregarded. The analysis examines the heating impact on the lead core in LRB installed in bridges. The LRB specimen was anticipated to consistently replicate the performance of full-scale prototypes. In dynamic non-linear time history analysis, scaling seismic excitation is essential to align with the reduced size of the bearing prototype [92].

Later on, in Japan, a comprehensive shake table test was undertaken to assess authentic seismic damage.. Earlier, the single-storey shake table experiment was performed using a sliding isolation system [93]. The response of multi-storey building models using a shake table experiment inserted with sliding elastomeric bearing was performed [94] and with friction pendulum bearing [28]. Astroza *et al* [95] performed experiments on a full-scale five-storey 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 [94]. The three-storey reinforced concrete masonry structure was scaled by one-quarter [96]. It used a rubber elastomeric bearing isolator to reduce the response of lateral force in areas of high seismicity. Wu and Samali [97] performed a shake table analysis to validate the numerical results of the 5-storey steel frame structure inbuilt with laminated rubber bearings. They used a 3 m×3 m shake table having a maximum acceleration of ±0.9 g, 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-storey high-rise building was done in China in 2007 [65]. The shake table used for dynamic response is 4m×4m, having a maximum payload of 250KN. The frequency ranges between 0.1 Hz to 50 Hz. In vertical, longitudinal, and transverse directions, the maximum accelerations are 0.7 g, 1.2 g, and 0.8 g, respectively. Madden *et al* [85] and Patrick *et al* [98] 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 [99]. The experiment aimed to assess the damage inflicted on high-rise structural steel buildings under real ground conditions through a comprehensive full-scale shaking table test. Tagliafierro conducted a shake table analysis on the steel pallet racking structure, incorporating a seismic isolation system. 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 [100]. 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 storey drift, and more. The evaluation also encompasses the validation of diverse sliding bearings [101]. Sliding Implant-Magnetic Bearings [54] and hydro-magnetic bearings [102] 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 [100]. 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. The prototype model testing on the shake table is shown in figure 4 and full-scale shake table testing is shown in figure 5. In the full-scale shaking table tests conducted on BI structures, the experimental findings reveal significant damage to non-structural components. However, given the random nature of ground motions, the pronounced horizontal movement at the isolator level during extended periods and extreme events raises concerns in BI systems. Designing the isolator for extreme events may result in stiffness, potentially hindering satisfactory response during less intense ground motions.

3.1 *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-storey structure is analyzed, focusing on parameters like peak global drift, inter-storey 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 [103]. 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 (Pushover) [104]. 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 [105]. 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 structures failure.

4. 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* [106] 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. [51]. The behaviour of the BI structure was compared with that of the flexible and rigid superstructure by using time-history [107]. 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 storey 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 [108] 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-storey 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 storey [109]. 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

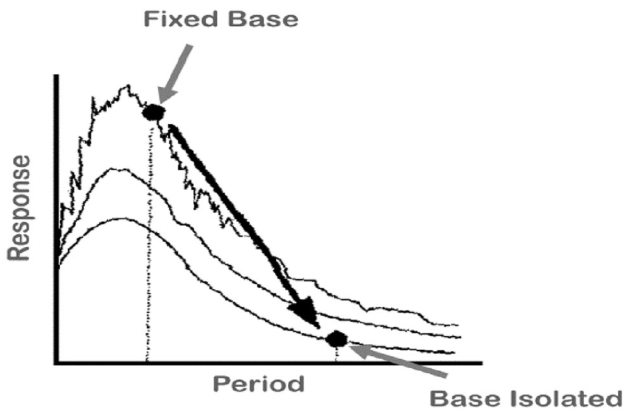


Figure 10. Response vs time period for conventional fixed base and base isolated structures.

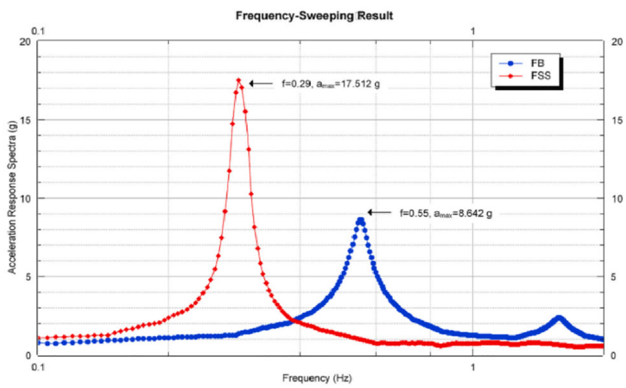


Figure 11. Acceleration response vs frequency sweeping with FB and FSS structures [112].

same. They used the National Building Code of Canada 2010 to check lateral and inter-storey drift. Dao *et al* [110] 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 [111]. It is evident from figure 10 that an increase in the time period and damping of the structure leads to a significant decrease in the structures response to ground motion. Figure 11 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 [112]. 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 0.15 g. [113]. The present section defines the benefits of seismic BI device in reducing the response of the earthquakes over conventional structures.

The limitations of the low-stiffness vertical isolation system were suggested [114]. 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 12 illustrates the limitations of BI structures, highlighting vulnerability when adjacent to multi-storey buildings with water tanks and unreinforced structures.

5. Optimization methods

Optimizing the base isolation device can significantly enhance the seismic response of the buildings superstructure. This involves selecting the most suitable seismic isolation parameters, including characteristic strength, stiffness, friction characteristics, damping ratio, time-period, and the mass of the system. These parameters aim to minimize floor acceleration responses and limit displacements, representing an essential technique for achieving the

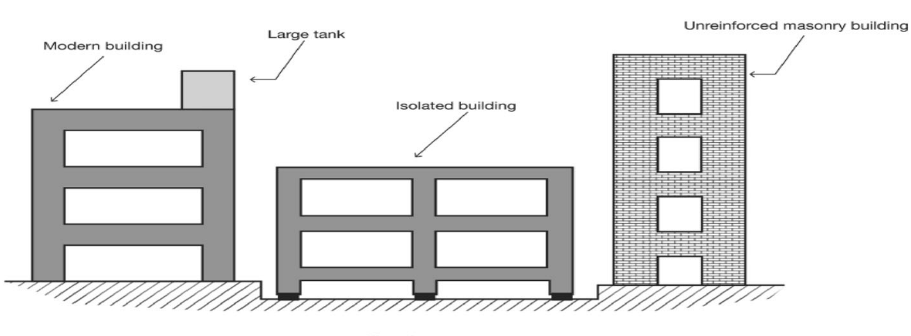


Figure 12. Limitation of Isolated building [114].

most feasible and economical solution. Furthermore, recent advancements in computational mechanics and design optimization integrity have led to a shift from earlier trial-and-error design methods to computerized dominant search algorithms. Various methods are employed to study the optimization of BI devices. The swarm intelligence algorithm method is used to optimize and compare the response of the superstructure by installing two isolators (a) Single FPS, (b) Triple FPS [115]. The study optimized friction coefficient and radius of curvature for isolators on squat and slender steel tanks to minimize base accelerations. Significant reductions in base accelerations were observed, particularly in slender tanks, with no notable impact on isolator displacement fragility curves from the tank's slenderness ratio. Harmony Search, developed by Geem [116], is a metaheuristic with design factors resembling other algorithms. These factors, inspired by natural behaviors, are adjustable during optimization. Nigdeli *et al* [117] aims to reduce the acceleration response of the BI building without surpassing isolator displacement limitations, optimal friction [118], GA (Genetic Algorithm) optimizer at near-fault ground motions for triple friction pendulum [119], a Genetic Algorithm (GA) is an optimization tool inspired by natural evolution. It selects and evolves solutions iteratively, incorporating processes like mutation and crossover. The differential evolution and particle swarm optimization methods [120] were implemented for the parametric study of the BI system. The optimum design of a single-storey BI building was examined [119] and for multi-storey buildings [121]. The aim of the investigation is to minimize the maximum floor acceleration response of the building by distributing isolators vertically. The metaheuristic search method [122] is used for the optimum design of the shear frame model having a BI system with the aim of obtaining minimum floor acceleration without surpassing the displacement limits. It used grey wolf optimization (GWO), crow search optimizer (CSA), and whale optimizer (WOA). These three bio-inspired search techniques are current additions to metaheuristic algorithms. GWO has been applied in structural optimization, but the use of WOA and CSA is limited. The Grey Wolf Optimizer (GWO), presented by Mirjalili in 2014, draws inspiration from the unique searching and hunting characteristics of grey wolves. Askarzadeh introduced the Crow Search Algorithm (CSA) in 2016, which proved highly effective as a metaheuristic algorithm encouraged by the intelligent behaviors of crows in their natural environment. The Whale Optimization Algorithm (WOA), formulated by Mirjalili and Lewis in 2016, emulates the hunting strategy of humpback whales known as air bubble behavior [122]. The Fuzzy Differential Evolution with Virtual Mutant (FDEVM) method is utilized [123]. FDEVM is a self-adaptive, parameter-free algorithm that effectively determines optimal values for dynamic parameters in seismic BI systems. This method dynamically adjusts the algorithms search behavior using a fuzzy decision-making mechanism, serving as both a self-adaptive and parameter-free approach. The results offer a viable range for adjusting seismic parameters in BI systems, demonstrating the efficacy of the FDEVM optimization method in structural dynamic analysis.

6. Application of base isolation system

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 [124]. 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 [125]. A novel seismic retrofitting method has been proposed, aiming to preserve the originality of existing structures while markedly reducing dynamic responses [126].

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* [127]. 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 [29] 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 13 [128].

In the retrofitting of historical structures, the base isolation technique emerges as a highly effective method for ensuring safety without compromising aesthetic values, architectural features, or the overall appearance of the structure. When undertaking the retrofitting of an existing

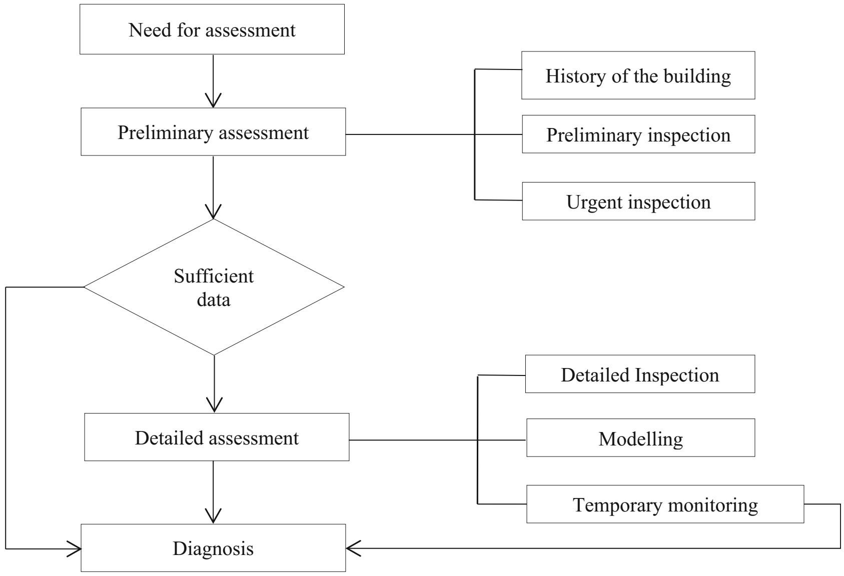


Figure 13. Approach to rehabilitation of the historical building [128].

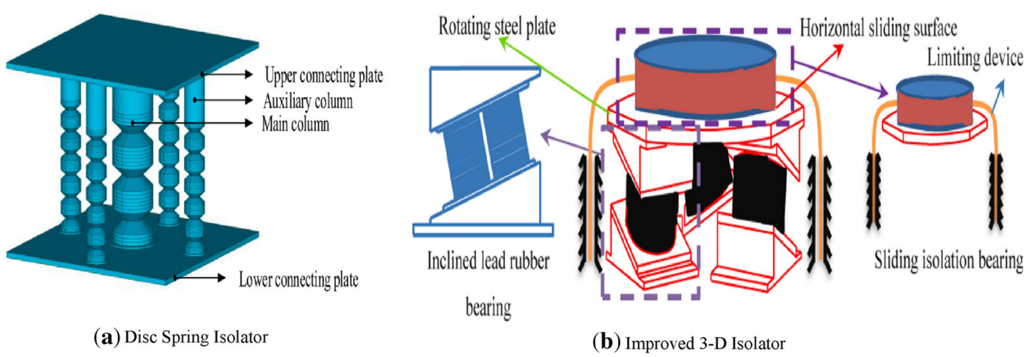


Figure 14. Diagram illustrating the enhanced design of the novel three-dimensional isolation bearing [134].

building, it becomes crucial to meticulously consider factors such as the placement of isolators, the types of isolation systems employed, dynamic properties, and the implementation of vibration tests. The selection of the seismic BI system type is contingent upon the specific nature of the structure being retrofitted, whether it be masonry structures, historical monuments, buildings, bridges, liquid retaining structures, and so forth. In the design phase, careful attention must be paid to the structural implications of long-term changes in the properties of the base isolation system. This holistic approach ensures that the retrofit not only enhances safety but also preserves the intrinsic characteristics and historical significance of the structure.

6.2 *Effect of liquid retaining structure on Isolator*

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 [129]. EPS has presented a large-scale BI storage tank (Available online: www. earthquakeprotection.com., 2019) [130]. The performance of an FE elevated liquid tank is performed [131]. 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* [132]. 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 [133]. The study [134] explores the seismic vulnerability of both fixed-base and newly designed 3-D isolated bearings as shown in figure 14 for liquid storage tanks. It investigates the probability of failure for these tanks under various limit states, discussing the annual average failure probability and design life failure probability. The findings indicate that, during a rare 9-degree earthquake, the fixed-base liquid storage tank has a 72.0% probability of fully damaged wave height and a 49.6% probability of axial stress failure. In comparison, the BI liquid storage tank exhibits significantly diminished failure probabilities for axial compressive stress, hoop stress, and liquid sloshing wave height.

6.3 *Effect of soil–structure interaction*

The impact of Soil–Structure Interaction (SSI) on the seismic response of elevated liquid storage was investigated [135]. The dynamic response of the underground liquid storage tank under SSI-induced ground motions was studied as well [136]. 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 [137]. 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 [70].

In 1978, the equivalent linearization method was used (Bielak, 1978) [138] 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 [139]. Bielak's model was expanded [140] 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 [141] for the elastic 1-DoF system. If the superstructure is treated as rigid, the results of are applicable [138].

Veletsos and Tang [142] 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 [143]. The SSI effect is categorized into Kinematic Interaction and Inertial Interaction. While kinematic interaction remains part of ongoing research, inertial interactions have been explored [144]. 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 15 illustrates the response of soft soil and rock [145]. Han and Marin [146] employed an

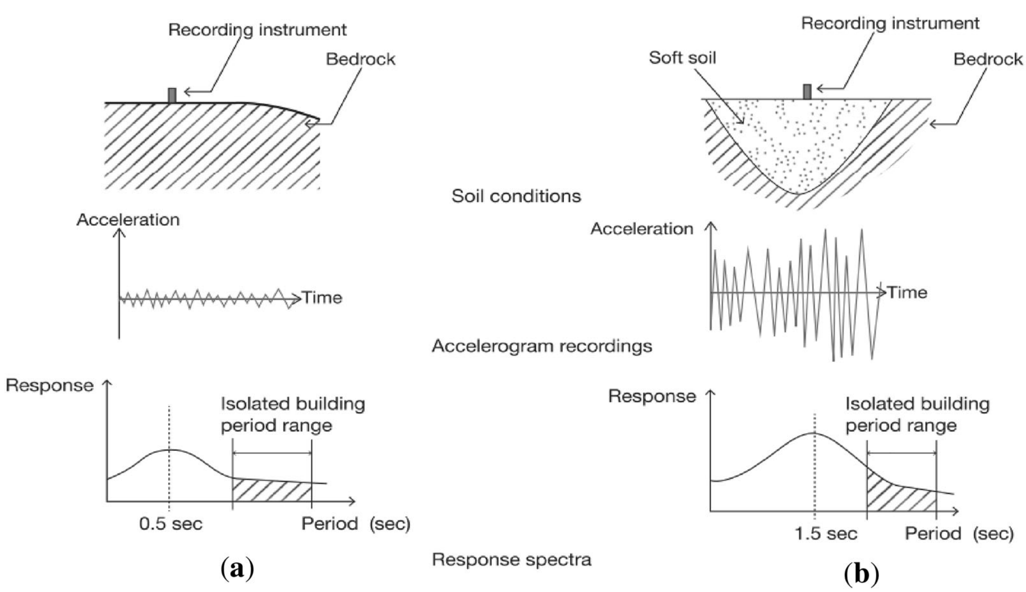


Figure 15. The effects of soft soil on earthquake shaking at (**a**) rock site and at (**b**) a soft soil site [145].

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 nonlinearity of the isolator. The SSI analysis response demonstrated a significant reduction in the horizontal movement of isolated nuclear power plants. Linear equivalent SSI analysis [147] and non-linear SSI analysis of isolated nuclear structures with rigid basemats were conducted [148]. 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 nonlinear behavior of the isolation device.

While various works in the literature address numerical simulations of the mutual role of SSI and BI systems considering the horizontal component of earthquake motions, the effects of the transverse component must be addressed for a comprehensive understanding and field response of the isolators. Numerous experts have proposed 3-D base isolation schemes for nuclear power plants, studying their dynamic behavior. However, prior studies typically assume a rigid foundation, emphasizing seismic isolation performance, neglecting the crucial aspect of SSI. To address this, a comprehensive analysis, considering SSI effects, is needed for realistic evaluations under earthquake motions. While existing studies have suggested various 3-D seismic isolation techniques, a clear quantitative association between mechanical and design parameters remains elusive. In the detailed analysis of the BI system, the effect of kinematic interaction of SSI attracts serious attention for research in the parametric analysis of the structure. The flexibility of the superstructure may become an area of interest for design engineers in the future for base isolation systems.

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-storey RC structure in Japan [149]. 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 16 [150]. 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 nonlinear analysis in the future and model bearing in such a way that it exhibits coupling behaviour.

Traditional materials and components, like rubber and springs, are popular in civil engineering due to their reliable performance and cost-effectiveness. A three-dimensional (3D) model for base-isolated structures was developed, focusing on a single degree of freedom (SDOF) model. A time history analysis was undertaken to assess the damping impact of the isolation layer on building response parameters. Notably, adjusting the thickness of the rubber layer proved effective in significantly reducing the vertical frequency [151]. The concept of application of periodic material foundation for nuclear plants in high-intensity seismic zones was encouraged [152]. The periodic material was originally developed in solid-state physics; later, it was artificially made by arranging contrasting materials in a periodic fashion [153]. These periodic materials are categorized as 1-D, 2-D, and 3-D. The experimental verification has stated that a 3-D periodic foundation is capable of protecting the superstructure from incoming hazardous seismic waves in vertical and horizontal directions and also from torsional mode. The 3-D modelling and response of laminated rubber bearings and lead rubber bearings were studied [73]. It used five-storey scaled steel frame building for analysis, which was subjected to the Northridge, El Centro, and Kobe earthquakes. The Opensees 3-D numerical simulation model was developed to examine the combined role of the BI system and Soil-Structure Interaction effects on building arrangements [154]. The analysis considered three models: fixed base, BI linear model, and BI non-linear model. It considered 240 non-linear 3-D models for numerical analysis to verify the relationship and to establish the efficiency in estimating the spectra accelerations. It derived a relationship among the elongation ratio and damping increase with the stiffness ratio by following the trend lines for different arrangements. Although the numerical simulations and response of the 3-D BI system with SSI effect are derived considering the horizontal components of seismic excitation but it needs to be done considering the simultaneous effect of horizontal and vertical elements of earthquake for field behavior simulations.

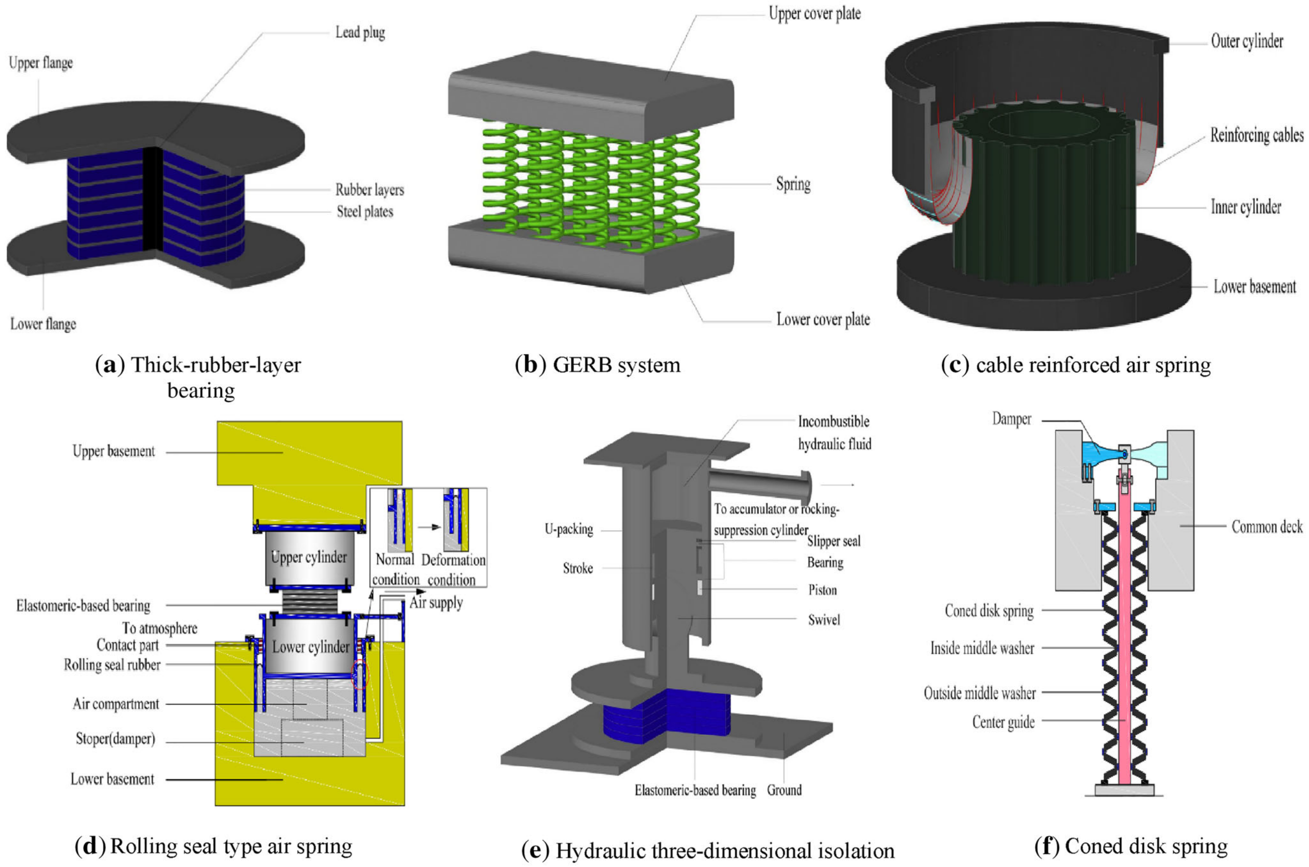


Figure 16. Schematic representation of three-dimensional Isolators [150].

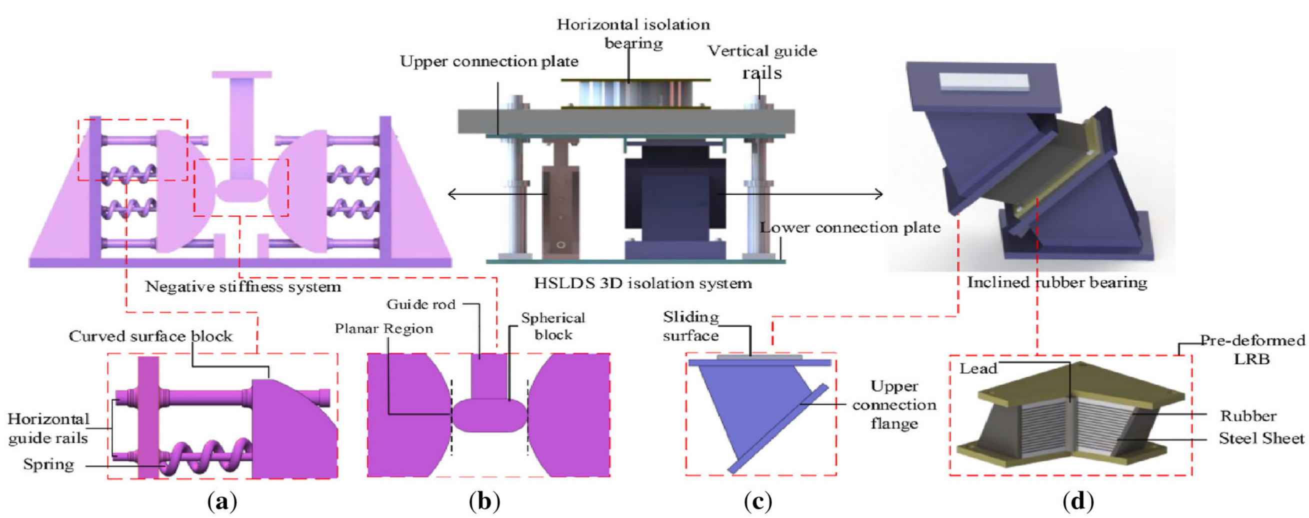


Figure 17. Three dimensional high-static-low-dynamic stiffness (HSLDS) Isolation [155].

The use of three-dimensional (3D) isolators has been constrained by the need for extended isolation periods and robust supporting capacity. The study introduces a 3D BI system with high-static-low-dynamic stiffness (HSLDS) as shown in figure 17, featuring a negative stiffness device and a pre-deformed inclined rubber bearing. A mechanical model, incorporating both negative and positive stiffness, is developed. Comparing vertical accelerations and isolator behavior confirms the effectiveness of the HSLDS isolator in reducing structural acceleration and vertical static displacement [155]. 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 and different foundations, is essential [156]. 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) [157]. The LVIVS, comprising three layers of springs with two prestressed, exhibits adaptable stiffness through displacement constraint components. Engineered for optimal performance, it offers substantial vertical stiffness under normal conditions, low stiffness for extended isolation, and increased stiffness during extreme events. The prestressed springs introduce a self-centering feature, enhancing stability and enabling a prolonged isolation period.

6.5 *Implementation of isolator in nuclear power plants*

In advocating for the implementation of 3-D base isolation in Nuclear Power Plants, many researchers and scholars have proposed and developed various 3-D base isolation methods. Additionally, they have conducted comprehensive studies on the dynamic behavior of NPPs employing 3D base isolation. Ebisawa *et al* [158] introduced a program for implementing a base isolation system for nuclear components, including a case study on the base isolation of diverse nuclear components. This technique proves to be an effective measure in nuclear power plants, ensuring safety and mitigating the risk of seismic instability. The initial successful application of a base isolator in a nuclear plant dates back to Cruas, France, where four units were operationalized in 1983. Subsequently, another two-unit nuclear power plant in Koeberg, South Africa, became operational in the 1980s [62]. The model is converted into OpenSees software to perform the seismic analysis, including the Bouc-Wen model, to calculate the effect of second hardening on floor response spectra [159]. They incorporated two distinguished material characteristics and variations in strong-quake motion. Decades ago, there was limited technical guidance and knowledge related to the implementation, investigation, and design of seismic BI systems in nuclear plants and associated financial risk. The Department of Energy and the Nuclear Regulatory Commission (NRC) in the USA have funded research projects to develop tools and guidelines for the base isolation system of nuclear power plants. With the consensus of both organizations, ASCE 4-16 and ASCE/SEI 43-19 have included a base isolation chapter. The guidelines and standards related to seismic isolated nuclear structures were published in ASCE 4-16 in 2017. It also stipulates the multi-step non-linear SSI analysis based on the base isolation design response spectrum, which considers both non-linear behaviour and SSI effects. This multi-step analysis considered both the equivalent linear method and time domain analysis. Three technical reports were also published by NRC on the analysis, design, and response of the seismic base isolation system implemented in nuclear power plants (a) NUREG/CR-7253, Technical consideration for Seismic isolation of nuclear facilities [160], (b) NUREG/CR-7254, Seismic isolation of nuclear power plants using sliding bearing [161] and (c) NUREG/CR-7255 Seismic isolation of nuclear power plants using elastomeric bearing [162]. There is also ongoing application of base-isolation in a nuclear reactor using rubber bearings in the France e.g., Jules Horowitz Reactor and International Thermonuclear Experimental Reactor. The former is basically a fusion reactor. Numerous research articles, conference papers, and technical reports authenticate the seismic isolation standards for nuclear power plants. These include: (a) The development of an enhanced base isolator to meet the specific standards and protocols of nuclear power plants. (b) The precise characterization of advanced isolated nuclear reactors, with a particular emphasis on soil-structure and fluid-structure interactions. (c) The accurate analysis of advanced isolated reactors considering both vertical and horizontal seismic intensity inputs. (d) An investigation into the influence of radiation exposure on the mechanical characteristics of bearings.

6.6 *Impact of beyond design events*

"Beyond design events" refers to scenarios that surpass the expected conditions or parameters set during the design of a base isolation system. While design events typically involve anticipated seismic forces and ground motions, situations beyond design events may exceed the expected intensity, duration, or other relevant factors. In the context of seismic isolation, it is crucial to consider and address challenges posed by events that go beyond the initially envisioned design parameters to enhance the resilience of structures against a broader range of unforeseen circumstances. The behavior of the BI structure is equally desirable to be addressed in case of non-seismic events and blast loads, i.e., beyond design basis events. Explosions to the buildings generated a significant amount of energy release for a very short duration of time in the form of waves and heat with temperatures ranging 4000 ^{0}C and pressure also rises many folds to atmospheric. Structures experienced the response of blast loading in various stages. Initially, shock waves damaged the structures façade. Then, in the next stage, it entered the structure and exerted pressure on the building components. The pressure generated due to the blasts damaged the columns and internal slabs, including occupants. During the final phase, the structure frame is loaded altogether, responding to the short-duration impulses and strong ground motion NRC. Damage is chiefly determined by the explosive charge weight and distance from the blast to the target. These factors impact the required blast-resistant features for damage mitigation. Smaller explosives with shorter standoff distances, possibly due to security breaches, can destroy load-bearing elements, leading to a progressive collapse. Larger explosives at longer distances create more uniform loading, causing both local and global damage [163]. The evaluation of the sample reactor structure resistance to a presumed threat involving the detonation of 2000 kg of TNT explosive on the surface, positioned 10 meters away from the building, includes an analysis of air- and ground-shock waves. Computational Fluid Dynamics code, Air3D, is employed to calculate the air-blast loading on the reactor building, while a rock response attenuation model is used to generate the ground-shock time series LS-DYNA is then applied for response-history analysis of both the conventional and base-isolated reactor buildings to external blast loads. The outcomes indicate that incorporating BI systems does not amplify the vulnerability of the containment vessel to air-blast loading and significantly diminishes the ground-shock response. [164]. A proposed seismic control device, comprising a tuned-mass damper and non-linear bumper, aimed to safeguard structures against blast and seismic loads. To evaluate BI structures under explosive blasts, a theoretical and empirical equations were employed for 5-Storey fixed base and isolated base structure, using Trinitrotoluene (TNT) for its common representation in blast equations. Explosives with 500 and 1,000 kg TNT charge weights simulate automotive and van delivery methods. The fixed-base structure has a fundamental natural period of 0.54 s and a damping ratio of 2%, while the BI structure is tuned to a fundamental natural period of 2.5 s and a 4% damping ratio. Blast loads are computed considering a structure width of 12 m, each story's height of 3 m, and a detonation point located 15 m away from the center of the base, as illustrated in figure 18a and b [165]. Observations indicate that, when subjected to blast loads, base isolation exhibits superior performance in comparison to fixed-base structures, as depicted in figure 18c. This is evident in the reduction of base shear and inter-story drift. However, it does not mitigate the maximum absolute acceleration of the superstructure, given the immediate and intense loading. Kangda *et al* [166] extended this work, incorporating various damping impact and blast models. Tolani *et al* [167] evaluated BI effects using a non-linear analysis method for an BI structure with different damping impacts. Further studies are required to understand how isolated structures respond to blast effects. While blast load design codes offer safe distance information, there is a lack of literature comparing these codes to the dynamic behavior of seismic BI structures. Blast distances in standards are based on general evaluations, but structural differences may lead to varying damage. Therefore, numerical simulations are essential to analyze isolated structures dynamic behavior under blast loads. The analysis revealed that these devices are less effective under mild ground motion control but significantly restrict base displacement under severe seismic excitations. The study found that, for non-uniform distributed blast loadings, base isolation ensures a uniform building response.

The study of aircraft impact on nuclear plants holds a significant place in nuclear engineering. Unlike ground motion events, the direct influence of aircraft impact energy affects the response of the superstructure. The isolation system, coupled with various aircraft loads, can cause significant horizontal deformation, posing a risk to the foundation and superstructure's constraint function and potentially leading to structural instability. The three-dimensional (3-D) model was developed to study the dynamic features of the base-isolated CPR1000 containment under the impact of various aircraft loading. Several factors contribute to the structural damage caused by aircraft impacts, including impact velocity, the angle of the aircraft, and the type of aircraft. Different aircraft impacts generate varying impact loads and energy with distinct properties and velocities. Even under similar isolation conditions, the displacement and acceleration responses of the CPR1000 containment differ due to the diverse properties resulting from various aircraft loads. Adequate stiffness can prevent severe structural damage under the influence of aircraft impact loads. The AI acts directly on the superstructure within a brief timeframe, meaning the seismic isolation system cannot influence the plastic strain distribution of the containment. As a result, there is a risk of

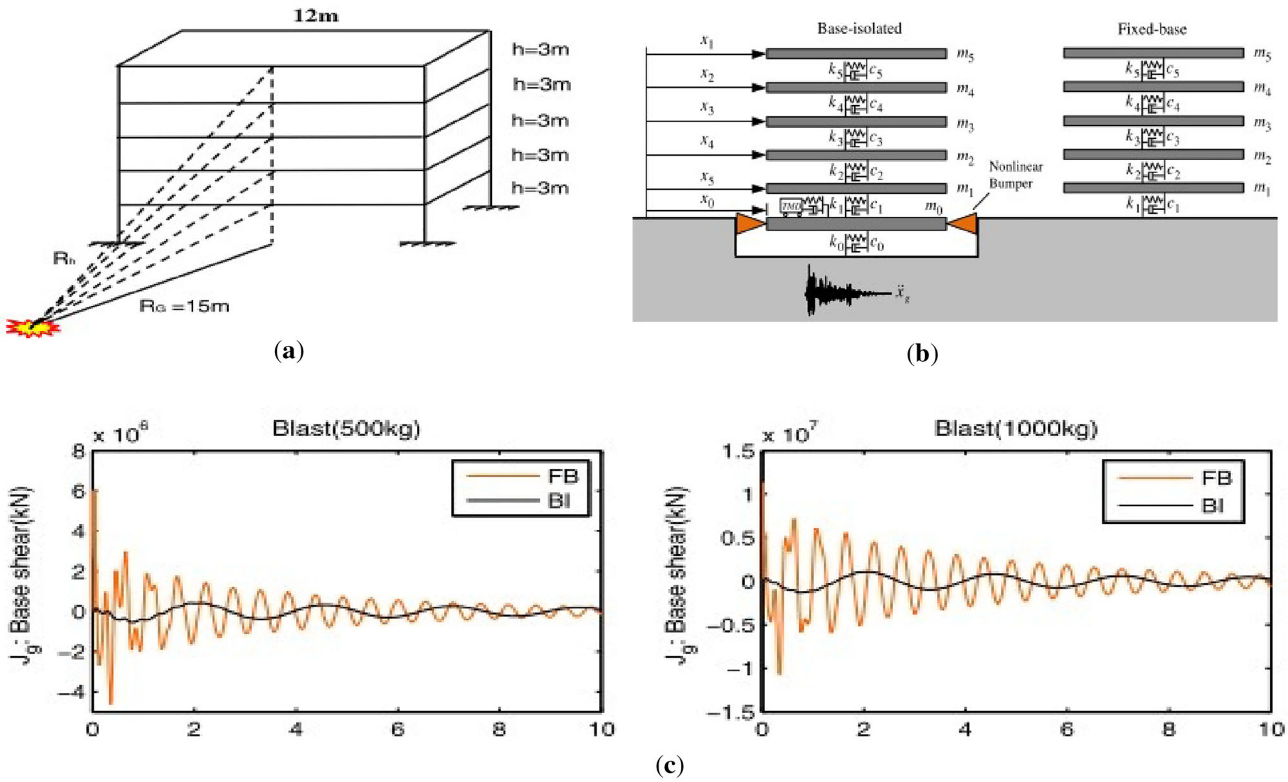


Figure 18. (**a**) Schematic of 5-story structure subjected to blast loading, (**b**) Diagram depicting a 5-story model of base-isolated and fixed-base structures, (**c**) Performance of base shear in base isolated and fixed base structure subjected to blast loading [165].

excessive displacement and acceleration responses leading to internal equipment failure. The study concludes that damping in isolation bearings could expedite the dissipation of aircraft impact energy [168]. Post blast event in a building equipped with the Blast Isolation (BI) system, there is a reduction in absolute acceleration, peak-storey displacement, and storey-drift. The study also explored energy-based equations to assess the system's hysteretic energy dissipation under blast loading. The results indicate that increased isolation damping improves structural performance, with isolators featuring higher damping exhibiting superior responses compared to those with lower damping when subjected to blast loading [169]. The sensitivity analysis was performed to examine the effectiveness of the BI structure; they also proposed an optimal BI-designed method under blast load. The eight-storey non-linear shear-type structure is subjected to blast load. Using an eight-storey non-linear shear-type structure subjected to blast loads, the research highlighted the substantial impact of base mass on the response of the BI structure [170]. The seismic response of third-generation nuclear power plants equipped with seismic isolation systems was investigated under the influence of a large commercial aircraft, specifically the Airbus A340-300. The study identified key parameters, including aircraft direction and impact force, which significantly influenced the vibration intensity of nuclear plants. Total weight and weight distribution impacted the vibration response in various regions of the plants, while horizontal stiffness affected the constraint between the superstructure and foundation. Additionally, the horizontal damping of isolation bearings played a crucial role in the energy dissipation of power plants [171]. oreover, the investigation evaluates how columns perform when isolated at the bottom or both the top and bottom under blast loads. The research employs a thorough analysis of dynamic and static coupling through numerical simulation and finite element analysis in ABAQUS. Various factors, such as blast load characteristics (explosion point height, charge weight, and standoff distance), are methodically taken into account. With a practical application in mind, the study delivers a performance assessment for columns equipped with isolators at the top or bottom, providing a reasoned evaluation of displacement and capacity-based performance under blast loads [172]. Advancing from the installation of isolators at the column top or both top and bottom, the isolated columns showed the same or even improved blast-resistance capacity when exposed to multiple blast loads.

It was concluded from the analysis that the relative displacements and shear forces of the isolated columns were lower than those of the original columns. It is observed from the literature that the three-dimensional response of the isolator for beyond-design events is very limited. So, scholars and academics may acquire an interest in this field.

It is crucial to ascertain how the building responds to the influence of noise. Buildings experience continuous stimulation from ambient noise, specifically microtremor waves near the ground surface. These waves, caused by stationary (e.g., factories) and moving sources (e.g., traffic, wind bursts), result in displacement amplitudes of 0.1μ to 1μ and velocities of 0.001 to 0.01 cm/s. In densely settled areas, microtremor amplitudes are larger during the day and smaller at night [173]. Currently, ambient vibration analyses are widely used to identify natural frequencies, vibration mode shapes, and damping parameters [174] in structures such as bridges, dams, and nuclear power plants. These analyses also contribute to refining model properties and calibrating various small amplitude excitations for different structures, including bridges, chimneys, dams, and nuclear power plants.

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 [140]. 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 [175]. The cost and estimation of seismic isolation were compared with the estimated cost of damaged structural retrofitting of the superstructure and other components. The result has shown that for a small magnitude of seismic excitation, it is uneconomical, whereas for moderate to large intensity earthquakes, it would be of great benefit. 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 [176]. 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 [177]. The sliding hydro-magnetic bearing is one of the cost-effective seismic isolation methods because it takes the benefits of the advent, an accessible and significant strength of earth's everlasting magnetic fields. It has relatively low-cost components and ease of manufacturing and installation. It is manufactured by simple welding and machining over the steel pieces, and aluminum plates are polished. It concluded results by examining the response of six-storey buildings and whether this seismic isolation system is suitable for execution in actual structures or not [178]. The assessment focused on electrical transfers at elevated hazard levels, encompassing both 220 kV and 800 kV, and incorporated the double friction pendulum base isolation system. Results from the analysis reveal a notable 30% reduction in costs when compared to structures without isolation. This underscores the economic viability of utilizing base isolation for transformers, particularly high-voltage transformers in regions with a PGA exceeding 0.3 [179]. With ample stiffness, the rubberized mortar isolation system minimizes material loss and is adaptable to various ground motions [46]. 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 [180]. 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 cost analysis of nuclear reactors integrated with Base Isolation technology is presented. Incorporating seismic isolation in the construction of advanced reactors brings substantial cost and time savings. Standardized structures and components simplify the engineering process, making regulatory reviews more efficient. Bulk ordering of identical equipment from the nuclear supply chain allows cost reductions through advanced manufacturing technologies. The total capital cost reduction for nuclear reactor ranges between 40% and 50% with the implementation of seismic isolation compared to conventional reactor [181]. Table 1 illustrates the types of isolation systems, descriptions, and responses with their advantages and disadvantages.

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

Table 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-storey 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 lead-bronze plate	Cost-effective, natural time period increases	Not suitable for larger loadings, less acceleration 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

Table 1 continued

Type of device	Description and Behaviour	Advantages	Disadvantages
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

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) [94]. They investigated the response of a nine-storey 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 and (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 [182] 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 [94] 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 [183] 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. Wen and Baifeng [184] have presented a novel way of designing base isolation systems termed the two-step design process. The first step is determining the layer, and the second is analyzing time history. Chalhoub [94] and Li and Huo [185] conducted a study on base isolation and concluded with certain criteria related to response, cost, and life span of the structure. Jain and Thakkar [186] analyzed the effect of BI structures on ten-storey, fourteen-storey, and twenty-storey flexible buildings. The reference paper considered low damping viscous damper combined with a laminated rubber-bearing BI system. They analyzed the effect of the BI system on a tall building in the time period of 1.0 sec. to 3.0 sec. it increases the primary structural elements, damping of the superstructure, and flexibility of the BI system to check the response of the tall building. The comparative study of seismic design guidelines, including ASCE/SEI 7-16, EN 15129, and NTCS-17 [187]. 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 [188]. They have presented their study in conformity with building code provisions of IBC, ASCE-7. Villegas and Colunga [189] studied the dynamic design procedure for the structure located on the Mexican Pacific Coast. They used UBC 1997 provisions with some modifications.

Table 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 3 presents equivalent linear analysis codal provisions, including design equations for structural components used internationally. Table 4 highlights practical applications of diverse isolation systems, offering project specifics, locations, and other relevant details.

8. 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 [194]. Orientation had minimal impact, emphasizing core quality. Installation in tunnel-form

Table 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	≤ 0.6 g	≤ 4-storey or 65ft. or 19812 mm	$3T_{fix} - 3$ s	≤ 30%	–
ASCE 7-10 Chapter 17	A, B, C, D	≤ 0.6 g	≤ 4-storey or maximum height of the building 20 m	≤ 3.0 s	≤ 30%	–
ASCE 7-16 Chapter 17	A, B, C or D	≤ 0.6 g	≤ 4-storey or 65ft. or 19812 mm but it may exceed when there is no tension or uplift on isolator	≤ 5.0 s	≤20%	–
EC-8	A, B, C, D	≤ 0.6 g	Plan size 50 m, height 19.8 m	$3T_{fix} - 3$ s	≤30%	–
TSDC 2016	–	< 0.6 g	20 m	$3T_{fix} - 3$ s	–	5%
Japanses Code	1, 2	–	60 m	≥2.5 s	–	3%
NTC-08	–	≤ 0.6 g	20 m	$3T_{fix} - 3$ s	–	3%

Table 3. Equivalent linear analysis codal comparison of different parameters [190, 191].

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	$\frac{K_e D_D}{0.8 R_i}$	$\frac{K_e D_D}{0.8 R_i}$	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	$\frac{M\sqrt{\frac{7}{2+\xi}} S_a T_e}{K_e}$	$\frac{g}{4\pi^2}\frac{S_{aD} T_{eD}^2}{B}$	$\frac{M F_h(\xi) Z G_S S_o(T_e)}{K_e}$	$\frac{g}{4\pi^2}\frac{S_{D1} T_D}{B_D}$	$\frac{Q_{ISO}}{K_e}$	$\frac{M S_a(T_e,\xi_e)}{K_{e,min}}$
	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	$1.5 D_{TD}$	$1.5 D_{TD}$	γD_{TD}	D_M	$\lambda_S D_{TD}$	-

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* [195] 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. Zhang *et al* [126] recommended a novel technique for seismic retrofitting in existing historical structures, prioritizing the preservation of cultural relics and aesthetic aspects. The proposed isolation system incorporates laminated rubber bearings, viscous dampers, elastic sliding bearings, and jack reaction joints, with the latter facilitating building re-centering after seismic events. This system effectively reduces structural vibration response. The underpinning layer offers translocation protection, and jack reaction joints address resetting limitations, as depicted in figure 19.

Losanno *et al* [196] have examined the performance of low-cost BI techniques for brick masonry buildings. Further, Losanno *et al* [23] 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 [112], 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. Numerical analysis on a four-storey structural model indicates a 69.4% reduction in roof acceleration amplitude during the Kobe earthquake, emphasizing the importance of the FFS isolation system. A new type of seismic isolation device was developed [100] 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 [197]. They performed experimental and analytical investigations to present the response of the bearing. The paper [198] introduces an inertial amplifier coupled base isolator (IABI) using inertial amplification. It compares the seismic performance, including story drift and base shear reduction, of IABI with conventional base isolator (CBI) and inerter-BI system.

The study concluded that the peak displacement amplitude reduces for a damping ratio of up to 20%, and for a damping ratio above this value, is almost constant. The response reduction and performance of the proposed isolator are 89.38% better than the conventional isolator and 72% superior to the inerter-based isolator.

An intelligent base isolation system is characterized by its adaptive nature, capable of dynamically decoupling the structure in real-time against various levels of excitations with differing frequencies. Li and Li [199] employed MR elastomer as a smart material to enable adaptive behavior in the BI system. In this smart system, control forces are manipulated by adjusting the lateral stiffness of the isolator. This adjustment aids in achieving a non-resonant condition by shifting the natural frequency away from dominant frequencies. Li and Li have proposed a flow chart for a smart base isolation system, as shown in figure 20.

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* [200] 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 [201] 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

Table 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 [192]	New Zealand	1981	80 columns inbuilt with rubber isolator, four-storey 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-storey, 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-storey, 47000 sq.m., 120 LRB, 3.9 s isolation period	Elastomeric rubber isolators with steel and lead dampers	–
US Court of Appeals in San Francisco [127]	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-storey 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 [193]	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-storey 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

Table 4. continued

Project name	Place country	Completion year	Project details	Types of isolation device used	Remarks
Tokyo Skytree East Tower	Tokyo, Japan	2012	31-storey office towers, eight-storey 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-storey 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-storey 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.

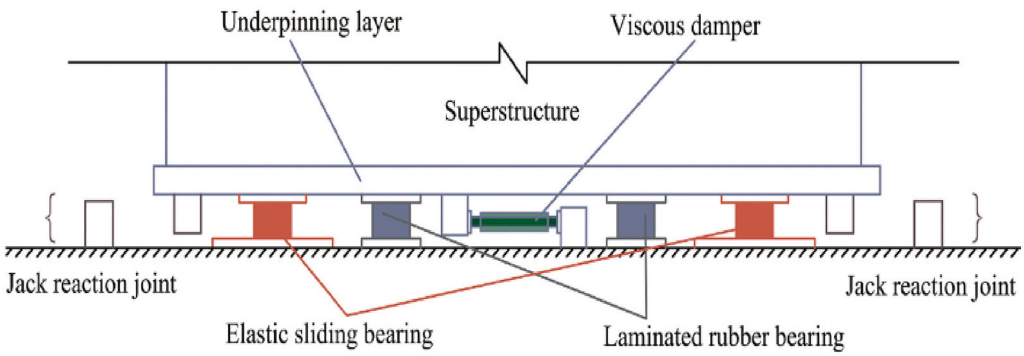


Figure 19. Schematic representation of the proposed isolation device [126].

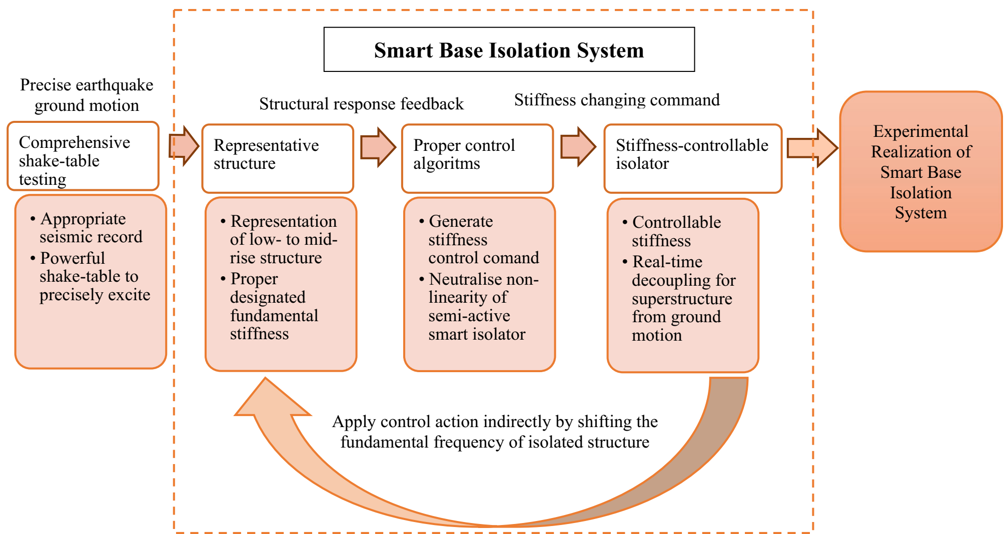


Figure 20. Fundamental setup for the smart isolation system [199]

a pendulum-like effect, achieving seismic isolation. Energy dissipation occurs through the yielding of the steel plate in the telescopic arms. Karayel *et al* [202] developed spring tube braces for the isolation system. In this system, base storey columns are pin-connected to the upper storey, and telescopic spring braces, exhibiting symmetrical behavior, allow free lateral movement for seismic isolation. Zhou *et al* [203] 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 syatem, demonstrating a potential reduction of around 30% in structural response, particularly effective in mitigating the impact of near-fault earthquakes [204]. The installation of BI technology is not restricted to the base of the columns; now, the inter-storey installation of isolators is proposed for high-rise buildings [205]. Inter-storey seismic isolation provides benefits like inertial force filtering and enhanced seismic capacity.

9. Conclusions

This paper 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 paper 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 paper includes a comparison and discussion of their advantages and limitations. Despite numerous benefits and applications, the BI system faces challenges, such as accurately calculating vertical acceleration, understanding the kinematic effect of soil-structure interaction on isolator and superstructure, and evaluating the capacity and recentering capability of the isolation device during strong ground motion. In summary, the closing remarks are as follows:

- The base isolation device must possess an effective recentering 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 1 g.
- 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 storey heights and blasts with varying charge weights requires evaluation.
- The review indicates a lack of comprehensive guidelines and code provisions for the seismic isolation design of tall structures. Addressing these concerns is crucial, especially for high-rise buildings in regions prone to high seismic activity.
- 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.

Current design methods, like Displacement Based Design, accurately predict peak displacements in base-isolated structures. However, challenges persist in reliably predicting base shear, lateral forces, and accelerations due to factors like higher modes of vibration and modeling assumptions. Defining protection factors, acceptable ductility demand, and inter-story drift levels is crucial in the design context. Improved approaches for estimating residual displacements and criteria for assessing their relevance to desired performance are needed. Recent efforts focus on developing multi-surface devices capable of adaptive behavior and optimization for different earthquake magnitudes.

Ongoing research aims to develop devices meeting diverse performance goals under varying ground motion intensities, emphasizing the crucial importance of ensuring complete 3D protection for structures.

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.

List of symbols

D_D	Design Displacement
Q_{ISO}	Shear force
Q_S	Shear force at the base of the superstructure
$\beta(\xi, T_e)$	Response reduction factor
$S_a(T_e, \xi_e)$	Spectral acceleration
K_e	Effective stiffness

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