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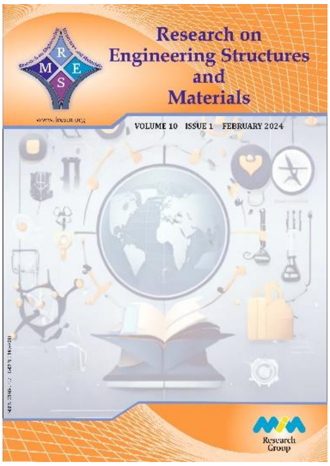

Advancements in base isolation for seismic mitigation: Perspectives on elastomeric and lead rubber bearings

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Review Article

Advancements in base isolation for seismic mitigation: Perspectives on elastomeric and lead rubber bearings

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Abstract

Base isolation represents an environmentally sustainable and highly effective technique for mitigating structural responses to strong seismic forces generated by plate boundary tectonic activities. Its primary benefits include preventing structural collapse, minimizing property damage, and safeguarding human lives during severe earthquakes. This passive, energy-efficient approach is often complemented by supplementary dampers to further reduce seismic impact. This study provides a comprehensive overview of elastomeric and lead rubber isolators, covering their theoretical, experimental, and numerical aspects. The paper examines the seismic response of structures equipped with elastomeric and lead rubber bearings, including a discussion of their pros and cons. This paper presents the comparison of fixed base and rubber isolated base in SAP 2000 to assess the effectiveness of base isolation. Additionally, it presents findings from shaking table tests, relevant building codes, and practical applications, considering the impact of events beyond initial design parameters. The review delves into the historical evolution of elastomeric and lead rubber-bearing systems, offering valuable insights into their contemporary understanding. Furthermore, the paper introduces three-dimensional isolators designed to attenuate ground motion responses in both horizontal and vertical directions. It investigates the effects of soil-structure interaction and evaluates isolator responses under blast and impact aircraft loading conditions. Notably, specific types of bearings exhibit exceptional energy dissipation capabilities during catastrophic seismic events, leading to reduced floor acceleration and inter-storey sway at critical levels. In conclusion, the study offers future recommendations and identifies potential constraints in this field.

1. Introduction

Earthquakes, ancient and unpredictable natural hazards, shake the earth beneath us, impacting structures and systems with the potential for significant loss of life and property. In seismic engineering, two vital aspects are considered as seismic loading and building resistance. Traditional seismic design aims to prevent building collapse during strong earthquakes, but it often results in damage to non-structural elements and some structural components, rendering buildings non-functional. This can be problematic, especially for critical structures such as nuclear plants, hospitals, government buildings, and other critical structures. To address the challenges posed by strong earthquakes, the concept of seismic base isolation is introduced.

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The base isolation technique involves implementing specially designed devices inserted between the superstructure and its foundation, effectively decoupling the structure from intense seismic motion. The utilisation of the seismic Base Isolation (BI) system represents an innovative approach within the realm of earthquake-resistant structural design, currently implemented across various nations [1-4]. Laminated elastomeric bearings are presently the most extensively utilised devices among the various types available. The composition comprises successive layers of rubbers and steel, where the rubber layers are subjected to vulcanization to bond with the steel layers. Including steel shim layers effectively mitigates the likelihood of bulging in the rubber layer, resulting in a notable enhancement in vertical stiffness. The presence of these layers has a slight effect on the shear stiffness. Studies shown that excessive damping at smaller, more realistic displacements may stiffen the isolation system, impacting its effectiveness and affecting internal equipment [5]. The three most prevalent kinds of laminated rubber bearings are Lead Rubber Bearings, High Damping Rubber Bearings, and Natural Rubber Bearings.

Base isolation systems are a resilient, efficient, and practical approach to safeguard structures and non-structural components against seismic risks. Nevertheless, significant shifts due to intense seismic forces can potentially result in detrimental effects on both the bearing and the overall structural integrity. The concept of decoupling involves altering the inherent vibration period of a building to a longer duration, as depicted in Fig. 1. The shown picture illustrates a decrease in spectral acceleration when the natural period shifts. This suggests that when the fundamental natural frequency does not align with the frequency of the seismic excitation, it serves as a preventive measure against catastrophic consequences. The increase in the duration of the structural time-period results in greater relative displacements, as illustrated in Fig. 2. The mitigation in inter-storey drift and floor acceleration in the superstructure is observed across all risk categories. Various isolation techniques have efficiently diminished the dynamic behaviour during low to moderate earthquakes and restrained displacement during more severe seismic events.

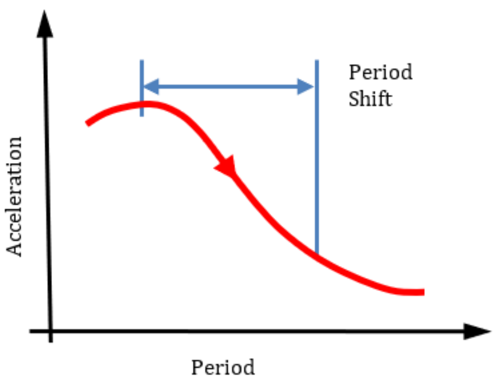

Fig. 1. Time Period shift

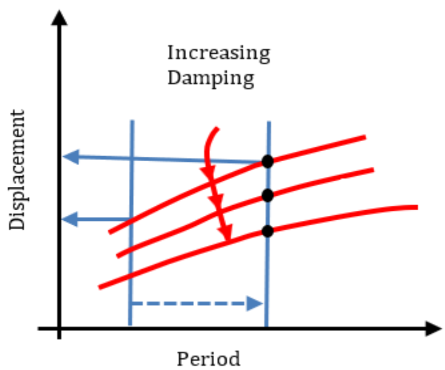

Fig. 2. Displacement design response spectra

Primarily, it is imperative to identify strategies for reducing the expenses associated with the implementation of base isolation systems to facilitate their widespread use in both retrofitting and new building endeavours [6]. Furthermore, it is imperative to conduct a comprehensive assessment to evaluate the potential ramifications of device malfunctions on the adjacent infrastructure in the event of seismic occurrences. The behaviour of structures that are equipped with foundation isolation can be divided into two different components: the performance of the bearings and the behaviour of the superstructure. In the event of a failure in one of these components, there is a potential for the complete collapse of the entire system [7]. The countries prone to severe earthquakes have adopted the technique on a large scale. Japan, USA, China, European nations, New Zealand, etc., are pioneering in developing the technique and implementing suitable isolators as a convenience. The isolator is widely applied in retrofitting old historical buildings and new constructions. Fig.3 shows the insertion of isolators in the structure between foundation and superstructure.

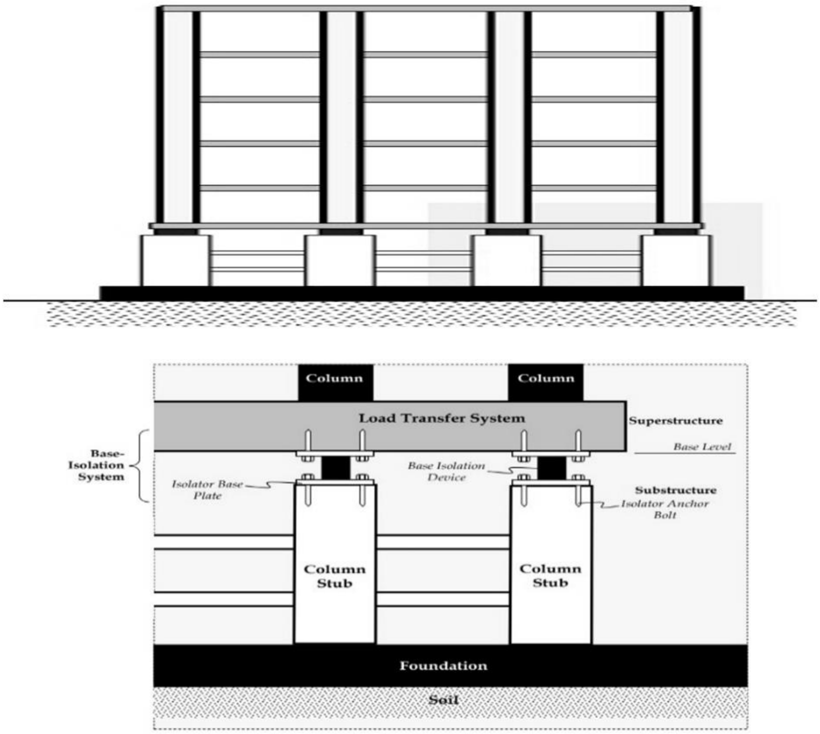

Fig. 3. Sectional representation of Base-Isolated Structure [IS 1893 Part 6]

The laminated rubber bearings are capable of sustaining high load in compression and also withstand more than one movement in shear. It is classified into three types: (i) Natural rubber bearings, which use natural rubber, which is less damping and has moderate flexibility. Therefore, it is used to withstand the effects of pre-stressing, creep, and shrinkage in bridges, and for base isolated buildings, it is combined with supplemental energy absorption devices like steel, viscous dampers, and lead [8]; (ii) High Damping Rubber Bearings (HDRB) has highly capable energy absorbing rubber material; (iii) Lead Rubber Bearings have high damping and extensively implemented in bridges and buildings to safeguard against strong ground motions. The seismic responses of fixed-base and various base isolation models for typical low- and mid-rise reinforced concrete buildings are compared [9]. This study analyses 352 cases with 11 ground motion pairs, it finds that LRB isolators are preferable for regular buildings without re-centering issues. The isolator must: (i) re-centre itself during strong earthquakes, depending on seismic intensity and duration; (ii) withstand wind forces with minimal horizontal restraint; (iii) tolerate vibrations, requiring damping to reduce relative superstructure-foundation movement; (iv) support superstructure weight for unrestricted horizontal movement; and (v) enable back-and-forth movement to keep the superstructure at rest [10-12]. Ongoing efforts in advanced isolation bearings focus on adaptive system development. The flow chart mentioned in Fig. 4 shows the development of elastomeric and lead rubber bearings.

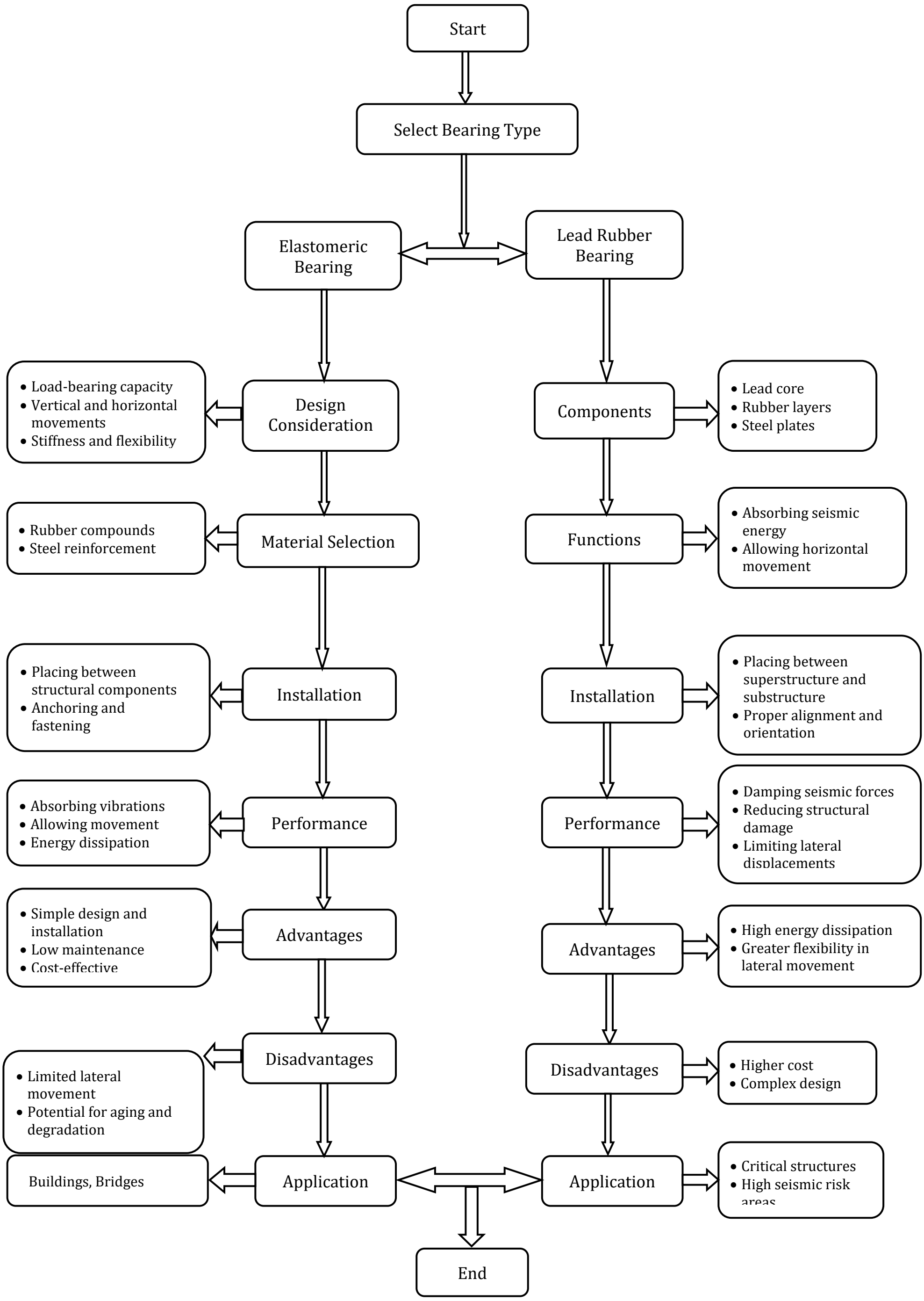

Fig. 4. Flow Chart representation of the Elastomeric Rubber Bearing and LRB

This paper presented a detailed analysis and application of lead and elastomeric rubber bearing. The elastomeric bearings are isolators comprised of a loading plate, fixing plate, alternate layers of rubber layer, and steel shim, while 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 centre. The primary quality of laminated rubber bearings is their strong vertical rigidity, which maintains structural weight while retaining horizontal flexibility. The rubber layers increase the system's horizontal flexibility, shifting the building's natural period away from the region's projected earthquakes' peak time, which reduces seismic amplifications. Moreover, the structural inter-storey drift is significantly diminished during seismic activity because displacements are centred at the level of isolation systems. Consequently, the damage in structural and non-structural elements is diminished. The steel shim plates are provided to protect rubber layers experiencing large deformations when bearings are subjected to heavy loads. These bearings are rigid in vertical directions but ductile in horizontal directions. The vertical rigidity of the interior steel plates is hundreds of times greater than the horizontal stiffness [13]. The experimental investigations were done to examine compression modulus behaviour for the rubber block attached to the rigid end of the plates [14]. There are many devices to be used as base isolation systems in buildings, but lead rubber bearings and elastomeric bearings provide convenient, inexpensive, and suitable solutions against seismic excitation. The steel plates are inserted to reduce the response of rubber bulging, i.e., to increase the vertical stiffness of the isolator [3,15]. A new type of laminated bearings recognized as fibre-reinforced elastomeric bearings (FREI) is introduced where fibre fabric is used instead of steel shims plates [16]. This paper provides a numerical and experimental investigation of isolator bearings, including an exploration of their constants and equations employed in various numerical simulations. The shake table test is used to analyse the responses and simulate the experimental results in the laboratory. In recent times, a multitude of scholars has proposed novel methodologies to achieve flexible behaviour in isolators, regardless of whether they are based on lead rubber bearing or elastomeric rubber bearing mechanisms. Elastomeric and lead-rubber bearings are extensively employed bearings in practice. During seismic occurrences, the bearings within an isolation system experience significant axial compressive loads resulting from the combined effects of gravity and overturning forces. These loads are accompanied by substantial lateral displacements occurring simultaneously. Nevertheless, research has demonstrated that the capacity of elastomeric bearings to withstand critical loads decreases as lateral displacement increases. Therefore, it is imperative to demonstrate stability at the greatest displacement when designing isolation systems consisting of these types of bearings [4]. While bearings offer numerous advantages, they also come with certain drawbacks. This study explores the impact of temperature fluctuations on the lead core in LRB and delves into the issues related to cavitation and buckling in rubber layers.

This study offers a thorough examination of lead rubber and elastomeric bearings, encompassing their interaction with foundations and superstructures, soil effects, as well as responses to blasts and aircraft impact loading. Unlike previous literature, this review integrates various aspects, including soil-structure interaction, 3-D BI system and applications in diverse fields. Additionally, it evaluates the pros and cons of these bearings and provides insights into future research directions with limitations as closing remarks. Both bearing types offer unique advantages and applications in enhancing the earthquake resistance of buildings and infrastructure. This introduction provides a glimpse into the essential characteristics and functions of lead rubber and elastomeric bearings in seismic-resistant design.

The field of seismic BI technology has witnessed notable progress in the creation of advanced and sustainable base isolation devices, which possess the ability to modify their properties in accordance with different intensities of seismic loading. The utilization of advance systems exhibits the potential to augment the overall efficacy of BI across various threat scenarios. In brief, BI techniques have made significant advancements since its inception, providing a robust approach to safeguard structures from seismic hazards. Through continuous study and invention, BI is undergoing constant development, resulting in enhanced safety and reliability of infrastructure in regions susceptible to earthquakes. The advancement in base isolation techniques has resulted in novel BI systems that showcase adaptable capabilities. The behaviour is considered adaptable when the Isolation characteristics exhibit substantial changes in response to varying loading levels. Recently, the perception of adaptive behaviour has garnered noteworthy consideration among scholars and researchers. This paper summarizes the historical developments and current understanding of adaptive BI devices in situations where active control mechanisms are not available. It was observed that adaptive devices possess a noteworthy capacity to disperse the input energy during intense seismic actions.

2. Historical Developments

The compilation of pertinent data about the numerical and practical evaluation of the chosen base isolators was sourced from credible international conferences, research papers, journal articles, and high-quality studies. The greatest emphasis was given to submissions that investigated isolation devices with adaptable characteristics. This review involves the utilisation of numerical investigations, modelling techniques, and experimental validations. In the present context, adaptive devices refer to mechanisms that exhibit distinct softening characteristics, followed by significant stiffening reactions and modifications in damping ratio as movement magnifies. Base Isolation is not a new tool; earlier in China and Italy, it was used in monasteries, bridges, etc. It was made of layered material, which allows relative movements over each other. Its history can be traced back to 1870 when Touaillon [17] proposed the idea of decoupling the superstructure and modelled seismic isolation system. The technique was implemented by Frank Wright in the Imperial Hotel, Tokyo, in 1921. His design was enormously controversial [18]. The rudimentary concept behind this method is to decouple the structure to reduce the detrimental response of the strong ground motion. In the late 1930s, the notion of a flexible first-storey was proposed [19,20]. It examined the response by reducing the lateral stiffness of columns at first-storey considering deformations concentrated at first-storey columns underground motion load. It concluded that columns at first-storey behave elastically, i.e., having low damping. Later on, in the late 1970s, the concept of a soft first-storey, which is a modified investigation of the flexible first-storey concept, was proposed. It considered that the first-storey columns yield during seismic excitation, thus controlling the displacement response and producing energy-absorption mechanisms. But these concepts failed to consider the three-dimensional effect of earthquakes and were implemented to the response of the higher storey, but potentially detrimental effects can occur at first-storey columns. Many roller bearings have been proposed, tested, and patented [21-26]. The stability of rubber bearings by theoretical approaches by considering linearity in rubber and small displacements was proposed [27-29]. The Haringx theory was applied to predict the reduction in horizontal stiffness on increasing axial loads [30]. The implementation of rubber bearings was first implemented in a school building in Skopje, Yugoslavia. It was a three-storey RC building completed in 1969 [31]. It was founded on Neoprene rubber. Since 1969, elastomers have been employed in seismic isolation, benefiting from their near incompressibility, capacity to endure substantial recoverable strains, and low shear modulus under comparatively low stress.

With the advent of new research, there has been a significant extent of improvement has been made in understanding the function and operation of rubber bearings. The application and principles of rubber bearing isolator were proposed by [32] and its design details and stability by [33,34]. The lead rubber bearing was applied first in Clayton building in 1981 [35]. The structural components consist of the superstructure, which encompasses elements above the base level, like columns, beams, walls, and roofs supported by the substructure. The substructure, located below the base level, includes foundation elements such as footings or piles that transfer loads to the ground. A base-isolation system involving isolators made of materials like rubber or steel, mitigates seismic effects by allowing independent movement between the superstructure and the substructure, absorbing, and dissipating seismic energy [11,36-37].

In the past few decades, the technique has grown significantly worldwide. Earlier, the investigations were performed based on mechanical characteristics of the bearings under large deformations in horizontal directions having constant vertical load [35,38-42]. Furthermore, many experiments were conducted to validate the results [40,41,43-45]. This analysis and experiment were limited to unidirectional only. Later, the analysis and experiment were conducted to validate the response of bearings in multi-directions. The seismic BI system in two horizontal directions is employed in buildings and bridges. Park 1986 [46] proved the significance of coupling effects under multi-axial loadings. The multi-axial response of steel dampers and HDRB was examined by Yasaka [41]. The response of Teflon bearings subjected to triaxial loadings was investigated by Mokha [47]. The multi-axial loading is applied on laminated rubber bearings to envisage the cyclic response of the bearings [48]. It studied the mechanical behaviour of laminated bearings under biaxial, triaxial, and small deformations. Fig.5 shows the optimal steps and design parameters for the advancement of a smart BI system [49]. There are various kinds of seismic BI systems developed to shield structures from intense ground quakes. However, the elastomeric bearings and LRB are commonly employed isolators. The numerical and experimental analysis of elastomeric bearings and LRB based on BI systems and their outstanding agreement with results gives imminence confidence to structural designers to implement confidently. The ongoing developments and research to protect structures from the detrimental effect of seismic excitation are important steps to ensure the seismic safety of buildings.

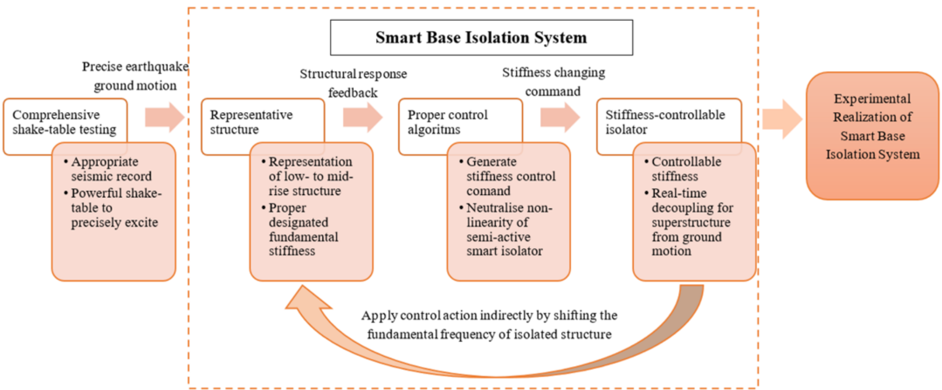

Fig. 5. Fundamental setup for the smart isolation system [49]

3. Guidelines and Development of Modern Isolators

Elastomeric materials are well-suited for use as BI systems due to their capability to endure significant retrievable strains. Rubber varieties like polychloroprene or polyisoprene, as well as rubber-like substances such as polyurethane, are potential options for rubber isolators. To augment both the bending and vertical characteristics of these isolators, a blend of rubber elastomer infused with fibres or steel is frequently employed. Tailored responsiveness to varying input levels can be attained by capitalizing on natural rubber's strain-induced crystallization feature or by utilizing elastomeric isolators with unbonded or partially bonded fibre reinforcement. Additionally, achieving desired adaptive qualities in elastomeric isolators often involves integrating supplemental dampers.

Currently, various building codes such as 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, and IS 1893 (Part 6): 2022 are utilised to conduct linear and non-linear analyses in order to design most base isolation (BI) structures. The ISO 22762-1 standard is employed in the field of elastomeric bearing design and protection. There are multiple standards available that offer guidance regarding the material qualities of bridge and structural bearings. The document EN 15129 [50] provides a comprehensive overview of the material properties associated with Anti-Seismic devices, such as rubber elastomeric isolators. The standard EN 1337-3 [51] primarily addresses the topic of elastomeric bearings, including detailed specifications about the mechanical and physical characteristics of rubber elastomeric materials. ISO 6446 [52] delineates the stipulations for elastomeric rubber bearings materials employed in bridges, whilst ASTM 4014 [53] offers standardized criteria for elastomeric materials utilised in bridge bearings. Nevertheless, the existing criteria fail to consider the potential impact of the constituents present in elastomeric rubber compounds on the characteristics of rubber constituents. Table 1 shows the comparison of different codes for linear equivalent analysis. Therefore, it is evident that additional investigation is essential in this particular domain to investigate the effect of rubber elastomer constituents on the mechanical and dynamic characteristics of the isolator.

Table 1. Equivalent Linear Analysis codal comparison of different parameters [54]

Structure	Sign	Algeria	Taiwan	Japan	USA	China	Italy
Superstr-ucture	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	$\frac{Q_S M_i H_i}{\sum_{j=1}^{n} M_j H_j}$	$\frac{Q_S M_i H_i}{\sum_{j=1}^{n} M_j H_j}$	$\gamma(A_i Q_\xi + Q_e)$	$\frac{Q_S M_i H_i}{\sum_{j=1}^{n} M_j H_j}$	$\frac{Q_S M_i H_i}{\sum_{j=1}^{n} M_j H_j}$	$M_j S_a(T_e, \xi_e)$
Substruct-ure	Q_b	$\frac{K_e D_D}{0.8R_i}$	$\frac{K_e D_D}{0.8R_i}$	Q_{ISO}	$K_{e,max} D_D$	Q_{ISO}	Q_{ISO}
Time period	T_e	$2\pi\sqrt{\frac{M}{K_e}}$	$2\pi\sqrt{\frac{M}{K_e}}$	$2\pi\sqrt{\frac{M}{K_e}}$	$2\pi\sqrt{\frac{M}{K_{e,min}}}$	$2\pi\sqrt{\frac{M}{K_e}}$	$2\pi\sqrt{\frac{M}{K_e}}$
Isolation System	D_D	$\frac{M\sqrt{\frac{7}{2+\xi} S_a T_e}}{K_e}$	$\frac{g}{4\pi^2}\frac{S_{aD} T_{el}^2}{B}$	$\frac{MF_h(\xi) Z G_S S_o (T}{K_e}$	$\frac{g}{4\pi^2}\frac{S_{D1} T_D}{B_D}$	$\frac{Q_{ISO}}{K_e}$	$\frac{MS_a(T_e, \xi_e)}{K_{e,min}}$

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	$\lambda_S D_{TD}$	-

Notations
D_D: Design Displacement
Q_{ISO}: Shear force
Q_j: Portion of Q_S that is assigned to Level i
M_i: Portion of M that is located at or assigned to Level i
M_j: Portion of M that is located at or assigned to Level j
H_i: Height above the base of Level i
H_j: Height above the base of Level j
Q_b: Minimum lateral force
S_{D1}: Design 5 percent damped spectral acceleration parameter at 1-s period
T_D: The effective period of the isolated structure at design displacement
B_D: Numerical coefficient related to the effective damping of the isolation the system at the design displacement
R_i: Reduction factor linked to the ductility of the superstructure
Q_S: Shear force at the base of the superstructure
A_i: Seismic shear force coefficient distribution
$\beta(\xi, T_e)$: Response reduction factor
$S_a(T_e, \xi_e)$: Spectral acceleration
ξ: Equivalent damping factor
λ_S: Property Modification Factor
K_e: Effective stiffness
$K_{e,max}$: Maximum effective stiffness
$K_{e,min}$: Minimum effective stiffness
D_M: Maximum design displacement
D_{TD}: Total design displacement
y_i: Distance between the centre of rigidity of the isolation system rigidity and the element of interest measured perpendicular to the direction of seismic loading under consideration
e: Actual eccentricity
b: Shortest plan dimension of the structure
d: Longest plan dimension of the structure
Z: Seismic hazard zone factor
G_S: Soil amplification factor

Rubber substances, such as polychloroprene or polyisoprene, as well as materials with rubber-like characteristics, such as polyurethane [55], may be viable options for elastomeric isolators. The incorporation of a composite material comprising of rubber elastomers, which are reinforced with steel or fibres, is a prevalent approach to improving the bending and vertical characteristics of the bearing. The attainment of adaptable behaviour at various levels of input can be accomplished by the utilization of strain-induced crystallization, a characteristic inherent to natural rubber [56], or by employing partially bonded or unbonded fibre-reinforced elastomeric isolators [57-59]. In elastomeric rubber isolators, it is a prevalent practice to achieve the needed adaptability through the incorporation of additional dampers [60.61]. Numerous studies, both numerical [61-64] and experimental [65,66], have examined the incorporation of steel dampers into elastomeric isolators. Yuan [60] introduced an innovative polyurethane elastomeric steel shim isolator attached through steel dampers designed to remain inactive during short displacements. Addressing the requirement for higher vertical capability bearings, particularly for heavyweight and larger span bridges, engineers introduced a polyurethane elastomer (PUE) material with enhanced shear performance [54]. PUE consists of both rigid and ductile sections, allowing for the adjustment of mechanical properties [67,68]. PUE bearings consist of notable vertical strength and shear deformability, capable of achieving an eventual shear strain of 300% and compressive stress exceeding 60 MPa in experiments. PUE demonstrates an energy dissipation capability of approximately 10%-14% at a shear strain of 150%. To mitigate extreme displacement during severe ground motion, the system was enhanced by integrating hysteretic dampers to reinforce the polyurethane bearing. This combination allows for the synergistic application of the bearing's high vertical strength and energy dissipation capability. The steel damper-reinforced polyurethane bearing is composed of a polyurethane bearing with four C-shaped hysteretic dampers. This configuration has been considered to attain a damping of 20% when subjected to a shear strain of around 150% [60]. The steel dampers and PUE are mounted to the upper and lower plates, correspondingly. An initial clearance is provided between the PUE and the steel ring in order to allow for unrestricted movement of the superstructure in response to mild load impacts. To mitigate the effects of frictional heating and maintain low stiffness during minor events, a circular sheet made of polytetrafluoroethylene (PTFE) is incorporated into the bottom plate of the system. This PTFE sheet serves the dual purpose of safeguarding the system from excessive heat generated by friction and ensuring its flexibility under minor disturbances. Therefore, in the case of small shifts, reactions are mostly governed directly by the PUE. However, for bigger displacements beyond the preliminary gap, the steel dampers come into play and contribute to the dissipation of the seismic energy.

An alternate methodology for the process of developing Isolators leverages a characteristic of natural rubber known as strain-induced crystallization [69]. The process of crystallization has the ability to take place in a broad range of natural rubber combinations, but the shear strain essential for crystallization (generally 100% or higher) depends on combining and filler content. The occurrence of Strain-Induced Crystallization (SIC) was readily apparent in guayule and dandelion natural rubbers following purification using acetone, crosslinking with Sulphur, and subsequent application of strain. The guayule natural rubber demonstrated a more notable strain-induced crystallization (SIC) phenomenon when exposed to substantial stretching in comparison to the Hevea natural rubber.

In contrast, dandelion natural rubber displayed a SIC behaviour similar to that of Hevea natural rubber [70]. Building upon this property, Yang [9] introduced a system called crystallizing rubber isolation (CRS). Yang [9] also conducted numerical assessments to compare the performance of CRS with that of the lead plug system, featuring bilinear hysteresis, concerning structural and equipment response. The study revealed that the structural floor acceleration results were larger for the lead plug system when considering shorter durations, which is consistent with the behaviour typically observed in bilinear systems. Nevertheless, this approach is less appropriate for safeguarding conventional machinery that possesses shorter natural durations. On the other hand, the CRS system demonstrated reduced floor acceleration responses that fell within the designated period range, so effectively safeguarding the devices. With the advent of modern research and new technology, there are many others ‘Adaptive’ seismic isolation system has been developed other than Elastomeric Rubber Bearing and LRB, which is being in practice.

4. Factors Affecting Bearing Performance

In the realm of seismic engineering, there are three critical factors that require consideration: the occurrence of cavitation and buckling in bearings, the influence of temperature on the performance of lead cores, and the interaction between soil and structure. These elements play a fundamental role in determining the efficiency of base isolation systems, and they are subjects of extensive research and enhancement in earthquake-resistant construction.

4.1. Cavitation and Buckling Phenomena in Bearings

Cavitation in rubber bearings, particularly elastomeric ones used for seismic isolation, arises from micro-cracks in the rubber volume and can result in irreparable damage [71]. It leads to material degradation, reduced bearing performance, loss of load-carrying capacity, increased vibrations and displacements, and poses a risk of failure in critical structures. To mitigate cavitation, engineers and researchers consider material selection, damping devices, optimized design, advanced analysis, and experimental testing. Cavitation damage increases with higher tensile strain amplitudes, and no additional damage occurs if the preceding maximum strain is not surpassed. Exceeding the prior maximum strain results in new cavity formation and additional damage, leading to a decrease in cavitation strength, which eventually stabilizes at a minimum value [72].

Furthermore, the study involved conducting investigations on a total of sixteen rubber bearings obtained from two different manufacturers. These bearings had comparable geometric characteristics but differed in terms of their shear moduli. The objective of the study was to gain insights into the cavitation behaviour exhibited by these bearings. The researchers conducted an investigation into the effects of cavitation on shear and axial properties. They performed post-cavitation tests to gather data and subsequently verified a tension model for elastomeric bearings using the experimental results. This model was then incorporated into software platforms such as OpenSees, ABAQUS, and LS-DYNA [73].

Low shear stiffness in bearings leads to a well-studied buckling phenomenon, with theory providing reasonably accurate design safety factors against buckling instability [74-76]. This theory, based on linear elastic analysis, is applied despite elastomers not being strictly linearly elastic. However, elastomers used in bearings typically exhibit significant linearity in shear over a wide strain range [77]. Studies by Kelly and other researchers [78-80] confirm that the linear theory, though an approximation, is generally accurate and sufficient for most design needs. The phenomenon of rubber-bearing buckling has been extensively investigated under compressive loads, yet there remains a research gap concerning buckling under tension. Experimental validation of the response of steel-reinforced bearings under high shear strain was performed [81]. They employed a non-linear analytical model depending upon the Koh-Kelly framework, corroborated by empirical findings, which encompassed elastomer non-linearity, substantial rotations, and displacements, as demonstrated by Nagarajaiah and Ferrell. The predictive behaviour of multi-layered elastomeric bearings was assessed through finite element numerical simulation using ABAQUS software [16]. Notably, the occurrence of buckling is induced by the low shear stiffness. Theoretically, buckling is rooted in linear elastic model analysis. However, the practicality deviates from this, given that elastomers exhibit non-linear behaviour, closely approximating the elastic range within a shear strain. Regarding design considerations, the linear theory proves relatively suitable and accurate. Through this analysis, it was deduced that the mechanism of an elastomeric isolator in tension, mirror its behaviour in compression. When subjected to tension, the rubber layers at the bearing's central region undergo rotations in opposing directions, engendering shear deformation due to the tensile force. Consequently, substantial displacements allow the isolator's upper portion to ascend. Owing to non-linear geometric effects inherent in the cylindrical rubber model, the compressive load leading to buckling surpasses the corresponding load in tension. In compression, the vertical load remains nearly constant, and rubber bearings deflect horizontally. In contrast, tension entails a gradual reduction in vertical load accompanied by horizontal deflection.

4.2. Impact of Temperature on Lead Core Performance

The Finite Element Analysis (FEM) was performed considering the steel, rubber, and LRB isolation, but it was limited to mechanical behaviour only [15,82]. The numerical and experimental examination was accomplished to appraise the effect of lead core heating on durability degradation. It extensively investigated the mechanical response of LRB and proposed a model based on Kalpakidis and Constantinou [83-85]. This model accounts for the effects of lead-core heating under cyclic shear loadings. The system has the ability to forecast the instantaneous temperature of the lead core and its immediate impact on the properties and strength of the bearings [86]. This model is expressed as the bi-linear hysteretic model, which is further executed and analysed in SAP2000 and 3D-BASIS computer software. Further, the results were validated by [83-85]. The bounding analysis theory is applied in the context of the lead-core rubber response of bearings to evaluate the importance of lead-core heating. In this analysis, the material characteristics variations are considered at the time of bearings fabrication. Additionally, it incorporates the changes in the mechanical behaviour of the isolators that occur during the life span of bearings due to loading history, environmental changes, and aging. It was accounted by analysis done through upper bound and lower bound properties. The scaling of lead rubber bearing was considered 3-4 times reduced-sized specimen for investigation [87]. They proposed a model that considered the rise in temperature in the lead core owing to the repeated cyclic motion of LRB, which is governed by the subsequent set of equations:

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

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

$$\bar{t} = \frac{\alpha_s t}{a^2} \tag{3}$$

where, T_L lead core temperature rises at time t, $v(t) = |du/dt|$, where u = motion of the lead-rubber bearing, Parameter $\bar{t}$ is referred to as the 'dimensionless time'. In Eq. (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 experimentally determined from the testing of lead samples [84]. The effect of lead core heating with LRB in near-fault zone is studied deeply [88], finding minimal impact from geometric parameters. Bounding analyses tend to overestimate displacements, especially with higher earthquake magnitudes and larger lead core diameters. The rise in lead core temperature decreases with increasing lead core diameter due to reduced cyclic displacement amplitudes. The post-elastic period and rubber height have negligible effects on lead core heating. Additionally, the study explores the influence of low temperatures on LRB hysteretic properties [89]. Conditioning full-scale LRBs from -20 °C to 20°C, the study applies displacement-controlled cyclic motions at frequencies of 0.1 and 0.5 Hz. Results reveal that post-yield stiffness and characteristic strength increase with decreasing temperature, with characteristic strength showing greater sensitivity to temperature variations than post-yield stiffness.

4.3. Influence of Soil-Structure Interaction

The concept of soil-structure interaction within a BI system pertains to the dynamic interplay and interaction between the foundation (structure) and the encompassing soil when exposed to external pressures, such as seismic quakes. The aforementioned interaction has the potential to exert a substantial influence on the performance of the BI system and the overall reaction of the building during seismic events. The impact of soil-structure interaction (SSI) is disregarded during isolator design, often assumed to involve a rigid base [90]. Yet, sacking SSI's influence leads to inaccurate assessments of structural response. SSI can be defined as a bidirectional interaction: the soil's behaviour influences the structure's motion, and vice versa. Evaluations of bridge seismic responses, considering elastomeric bearings and accounting for SSI, are presented [91]. In 1978, Bielak [92] employed the equivalent linearization method to scrutinize the harmonic response of a bilinear hysteretic structure resting on a viscoelastic half-space. When soil flexibility is neglected, and the BI system is assumed linear, results are deduced (78). Extending Bielak's model [93], SSI's effect on the non-linear seismic response of the BI system in simple elastic structures was explored. It was deduced that, minus SSI effects and in undamped scenarios, a harmonic motion emerges beyond the isolator's steady-state response, resulting in unbounded superstructures. Furthermore, it was found that assuming a rigid BI system aligns with the outcomes of [94] for elastic 1-DoF systems. If the superstructure's rigidity is assumed, [92] findings hold. Nevertheless, recent research proposes that under intense ground motion, non-linear effects (e.g., gapping, uplift, sliding) frequently occur near the soil-structure boundary [95]. SSI effects are categorized into two types: (a) Kinematic Interaction and (b) Inertial Interaction. While kinematic interaction remains under investigation, inertial interactions have been explored (3). Soft soil resonates more than rock, intensifying shaking and elevating the natural period at peak response to align with the range of isolated building vibration natural periods. Considering SSI's mutual influence, Han [96] adopted an iterative approach for numerically simulating base-isolated systems in nuclear power plants. The authors incorporated isolator material non-linearity. The SSI analysis outcome showcases a noteworthy reduction in horizontal displacement for isolated nuclear power plants. Linear equivalent SSI analysis [97] and non-linear SSI analysis of isolated nuclear structures with rigid basemats were conducted [98]. The reference study adhered to ASCE 4-16 for non-linear analysis, following a multi-step procedure integrating equivalent linear methods and time-domain techniques that account for both SSI effects and isolator non-linear behaviour. An array of literature explores numerical simulations concerning the interplay between SSI and BI systems, predominantly focusing on the horizontal component of seismic motion. However, addressing the effects of the transverse component is crucial for a comprehensive understanding of isolator behaviour and field response.

5. Experimental Modelling of Elastomeric and Lead Rubber Bearings

Over the course of more than three decades, a significant amount of shaking table testing has been conducted on buildings equipped with base isolation systems. This testing has occurred simultaneously with the advancement of isolation devices designed for use in large-scale structures and the global development and refinement of base isolation practices. The initial tests were primarily focused on validating various isolation devices and establishing the feasibility of the concept, but they lacked rigorous criteria for measuring the responses of buildings. The development of elastomeric bearings has outpaced the progress of friction-based sliding systems. Shake table experiments were performed on several of the original systems at the Earthquake Engineering Research

Centre (EERC) located at the University of California. The systems comprised elastomeric bearings with low damping, elastomeric rubber bearings with steel dampers [99], and elastomeric rubber bearings with improved damping through a friction fail-safe mechanism. The lead-rubber bearing (LRB), which originated in New Zealand [100], was subjected to shake table testing at EERC for evaluation purposes [101]. The evaluation of systems was conducted on a 5-storey frame assembly, which allowed for the examination of responses in higher modes and the assessment of the efficacy of different techniques to implement seismic isolation. Numerous studies have frequently shown that isolation systems characterised by elevated levels of damping, particularly nonlinear damping, have proven to be successful in managing isolator displacements. However, this approach has also been found to lead to amplified floor accelerations and heightened high-frequency responses. The effect of tension on rubber bearings was investigated by experimental analysis [102]. It considered sixteen rubber bearings to perform experiments, including lead-plug rubber bearings, natural rubber bearings, and high-damping rubber bearings. It evaluated the characteristics and factors involved in the performance of rubber bearings, including tensile properties, compression, and shear response. The shake table is used for experimental testing of the bearing.

A comprehensive shake table test was conducted in Japan to evaluate the extent of seismic damage in a realistic manner [103]. The experiment involved the evaluation of multi-storey building models using shake tables and sliding elastomeric bearings [104]. Astroza [105] conducted an experiment on a whole five-storey reinforced concrete (RC) building using the NEES-UCSD shaking table. The study focused on analysing the building's structural reactions, non-structural components, and dynamic interactions under different ground motions. The specimens used in this study were subjected to various conditions, such as forced vibration, impact-free vibration, and ambient vibration while being supported by fixed and isolated bases. These conditions were compared to the SEAONC Tentative Code of 1986 [104]. The investigation encompassed a total of eight distinct ground motion records. A three-storey reinforced concrete masonry building was employed in high seismicity zones, utilising a rubber elastomeric bearing isolator to mitigate lateral force responses. This structure was built at a one-quarter scale [106]. In their study, Wu and Samali (2002) [107] conducted a shake table analysis to verify the accuracy of their numerical findings pertaining to a 5-storey steel frame building that was outfitted with laminated rubber bearings. A 3m×3m shaking table was employed in the study, with a maximum acceleration of ±0.9g, a load capacity of up to 10 tonnes, and a maximum stroke of ±100mm. The frequency of the input waveform spanned from 0.1 to 50 Hz, while the time axis was scaled down to one-third of its original size. In 2007, a study was conducted in China to analyse a high-rise building model consisting of 30 storeys. The analysis was performed on a shake table of 4m4m, with a maximum payload capacity of 250 KN [108]. The frequencies observed in the study spanned from 0.1 Hz to 50 Hz, while the maximum accelerations recorded were 0.7g in the vertical direction, 1.2g in the longitudinal direction, and 0.8g in the transverse direction.

The adaptability of a base isolation system was investigated by Madden [109] and Patrick [110] through the implementation of laboratory experiments with scale-model building structures. Over the years, as time has advanced, researchers have consistently introduced fresh ideas and innovations in the field of base isolation. These concepts have been validated through successful shake table testing. The dynamic properties were assessed by means of the autoregressive with exogenous term (ARX) approach and the frequency response function (FRF) curve-fitting method [111], based on floor acceleration measurements. This research aimed to detect structural damage in high-rise steel buildings under realistic ground conditions using full-scale shaking table tests. In their study, Tagliafierro [112] performed a shaking table analysis on a steel pallet racking structure, which incorporated a seismic isolation device. The base isolation system underwent 3-D shaking table testing at the E-defence facility, also known as the Hyogo Earthquake Engineering Research Centre, located in Japan. The testing was conducted on a 15m×20m platform with a load-bearing capacity of 12000 metric tonnes, specifically designed for tiny full-scale buildings. At maximum payloads, the system exhibited horizontal accelerations above 0.9 times the acceleration due to gravity (0.9g) and vertical accelerations of 1.5 times the acceleration due to gravity (1.5g). The experiment conducted at E-Defence [113] involved subjecting a steel frame building with five storeys to seismic shaking. The latest shake table experiment conducted at E-defence examined the performance of lead rubber bearings and the realistic reaction of a full-scale isolated structure. This experiment yielded valuable insights into various aspects, such as base shear, floor acceleration, and maximum storey drift. The comprehensive shaking table experiments conducted on BI structures unveiled significant impairment to non-structural elements. Nevertheless, unpredictable ground motions and significant horizontal displacements at the isolator level for extended durations and during extreme occurrences have generated apprehension inside base isolation (BI) systems. The design of isolators for extreme events may lead to stiffness that exhibits insufficient responsiveness to lower ground vibrations.

6. Numerical Modelling of Elastomeric and Lead Rubber Bearings

Implementing numerical modelling techniques performs a vital task in comprehending and enhancing the capability of elastomeric rubber bearings and LRB within structural solutions. The procedure encompasses several steps, including the definition of geometric and material properties, the selection of suitable constitutive models, the application of boundary conditions and loadings, the execution of finite element analysis (FEA), the incorporation of contact and friction modelling, the integration of damping mechanisms, the performance of non-linear analysis, the validation and calibration of the model, the execution of sensitivity analysis and optimisation, and the interpretation of the obtained results. Numerical simulations offer valuable insights into the functioning of isolation devices across diverse situations, facilitating design improvements and bolstering seismic resilience.

6.1. Material Properties used for Numerical Simulations and Analysis

The behaviour of rubber is like homogenous, isotropic, hyper elastic, and incompressible solids. The elastic characteristics of rubber in terms of potential strain energy function U in terms of Green's deviatoric strain invariants are as follows:

$$U = f(I_1, I_2, I_3) \tag{4}$$

I_1, I_2, I_3 are first, second and third deviatoric strain invariant of the green deformation tensor in terms of $\lambda_1, \lambda_2, \lambda_3$.

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \tag{5}$$

$$I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2 \tag{6}$$

$$I_3 = \lambda_1^2\lambda_2^2\lambda_3^2 \tag{7}$$

The design and modelling of hyper-elastic materials hinge on the careful selection of an appropriate strain-energy function W, as well as the precise determination of material constants. The choice of a particular model is contingent upon the inherent material properties. The equations presented herein illustrate various models, along with their respective material constants and model parameters utilized in numerical simulations. These values are crucial for numerical analysis of the rubber hyper elastic properties.

6.1.1. Aruda-Boyce strain energy potential model [114-117]

$$U = \mu\left\{\frac{1}{2}(\bar{I}_1 - 3) + \frac{1}{20\lambda_m^2}(\bar{I}_1^2 - 9) + \frac{11}{1050\lambda_m^4}(\bar{I}_1^3 - 27) + \frac{19}{7000\lambda_m^6}(\bar{I}_1^4 - 81) + \frac{519}{673750\lambda_m^8}(\bar{I}_1^5 - 243)\right\} + \frac{1}{D}\left(\frac{J_{el}^2 - 1}{2} - lnJ_{el}\right) \quad (8)$$

Table 2. Coefficients for Model calculated by ABAQUS®

Mu	Mu_0	Lamda_M	D	R^2
0.4283	0.4462	3.9142	$1.712e^{-3}$	0.9902

6.1.2. Marlow Model

The strain energy function for the Marlow form are as follows [114]:

$$U = U_{dev}(\bar{I}_1) + U_{vol}(J_{el}) \quad (9)$$

U_{dev} is a deviatoric part of strain energy per unit volume and U_{vol} is volumetric part

6.1.3. Ogden Model

The potential strain energy function for the Ogden model are as follows [114]:

$$U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}\left(\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3\right) + \sum_{i=1}^{N} \frac{1}{D_i}(J^{el} - 1)^{2i} \quad (10)$$

Table 3. Coefficients for Model calculated by ABAQUS®

Mu_I	Alpha_I	D_I	R^2
0.4451	-0.2241	$1.824e^{-3}$	0.9896

6.1.4. Mooney-Rivlin Model

The potential strain energy Mooney-Rivlin model are as follows [114,118-119]:

$$U = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) + \frac{1}{D_1}(J^{el} - 1)^2 \quad (11)$$

Table 4. Coefficients for Model calculated by ABAQUS®

$\boldsymbol{C_{10}}$(MPa)	$\boldsymbol{C_{01}}$(MPa)	$\boldsymbol{D_1}$	$\boldsymbol{R^2}$
0.3339	$-3.37e^{-4}$	$1.5828e^{-3}$	0.9881

6.1.5. Neo-Hookean Model

The potential strain energy function for Neo-Hookean Model are as follows [114]:

$$U = C_{10}(\bar{I}_1 - 3) + \frac{1}{D_1}(J^{el} - 1)^2 \quad (12)$$

Table 5. Coefficients for Model calculated by ABAQUS®

$\boldsymbol{C_{10}}$(MPa)	$\boldsymbol{D_1}$	$\boldsymbol{R^2}$
0.2587	$1.5828e^{-3}$	0.9710

6.1.6. Yeoh Model

The potential strain energy function for Yeoh Model are as follows [114]:

$$U = C_{10}(\bar{I}_1 - 3) + C_{20}(\bar{I}_1 - 3)^2 + C_{30}(\bar{I}_1 - 3)^3 + \frac{1}{D_1}(J^{el} - 1)^2 + \frac{1}{D_2}(J^{el} - 1)^4 + \frac{1}{D_3}(J^{el} - 1)^6 \quad (13)$$

For N=3, the equation can be written as:

$$U = \sum_{i=1}^{3} C_{10}(\bar{I}_1 - 3)^i + \sum_{i=1}^{3} \frac{1}{D_i}(J^{el} - 1)^{2i} \quad (14)$$

Table 6. Coefficients for Model calculated by ABAQUS®

C_{10}(MPa)	C_{20}(MPa)	C_{30}(MPa)	D_1	D_2	D_3	R^2
0.2019	4.43e^{-5}	1.29e^{-4}	2.183e^{-3}	8.68e^{-5}	-1.794e^{-5}	0.9962

6.1.7. Van der Waals model [114]

The potential strain energy equation for Van der Waals Model are as follows:

$$U = \mu\left\{-(\lambda_m^2 - 3)[\ln(1-\eta) + \eta] - \frac{2}{3}a\left(\frac{\tilde{I} - 3}{2}\right)^{\frac{3}{2}}\right\} + \frac{1}{D}\left(\frac{J_{el}^2 - 1}{2} - \ln J_{el}\right) \quad (15)$$

Where, $\tilde{I} = (1-\beta)\bar{I}_1 + \beta\bar{I}_2$ and $\eta = \sqrt{\frac{\tilde{I}-3}{\lambda_m^2 - 3}}$, λ_m= locking stretch, a= global interaction β= invariant mixture parameter, μ= shear modulus.

6.1.8. Polynomial Model

The potential strain energy function of Polynomial model are as follows:

$$U = \sum_{i+j=1}^{N} C_{ij}(\bar{I}_1 - 3)^i(\bar{I}_2 - 3)^j + \sum_{i=1}^{N} \frac{1}{D_i}(J^{el} - 1)^{2i} \quad (16)$$

Where C_{ij} and D_i are temperature dependent parameter

6.1.9. Reduced Polynomial Model

The model is the same as the Polynomial Model by omitting the second deviatoric invariant of the Cauchy Green tensor. The potential strain energy functions are as follows:

$$U = \sum_{i=1}^{N} C_{i0}(\bar{I}_1 - 3)^i + \sum_{i=1}^{N} \frac{1}{D_i}(J^{el} - 1)^{2i} \quad (17)$$

C_{i0}, D_i are material constant, N= material constant (positive numbers N=1,2,3)

μ, λ_m and D are temperature-dependent parameters D $= \frac{2}{K}$; and $\bar{I}_1 = \bar{\lambda}_1^2 + \bar{\lambda}_2^2 + \bar{\lambda}_3^2$ and $\bar{I}_2 = \bar{\lambda}_1^{(-2)} + \bar{\lambda}_2^{(-2)} + \bar{\lambda}_3^{(-2)}$, where $\bar{\lambda}_i = J^{-\frac{1}{3}}\lambda_i$; J= Jacobean determinant where $J = \lambda_1\lambda_2\lambda_3$, J^{el} is the elastic volume ratio, and K is the bulk modulus. The μ_i and α_i are constants that depend upon shear behaviour and D_i is compressibility.

6.1.10. Numerical Analysis of Bearings

Numerical modelling of rubber bearings and LRBs provides valuable insights into their behaviour under dynamic loading conditions and aids in the development of more effective and reliable seismic isolation systems. The finite element micro-modelling of lead rubber bearings was performed in ADINA software [82]. The micromodels give more detailed and accurate results of stress, strain, and strength of LRBs. The modelling and analysis of low-damping rubber bearings and LRB inserted into BI structures presented for design basis earthquakes (DBE). Earlier, although numerous experiments were performed to evaluate the effectiveness of elastomeric bearings and LRB, but very few of them were evaluated numerically. However, with the recent developments in software, the results were verified experimentally and numerically to justify the effectiveness of bearings. The size and the dimensions of its different parts are shown in Table 7 for Elastomeric rubber bearings and in Table 8 for lead rubber bearings. The finite element model of passive control lead rubber and elastomeric bearings is presented [15]. The numerical modelling and analysis using the stiffness matrix of laminated rubber bearings were performed to evaluate the behaviour of columns by Haringx's theory, which considered two independent variables, i.e., rotation angle and lateral displacement [120].

Table 7. Comparison of elastomeric rubber bearing

Proposed by	Outer Diameter (d_o)mm	Lead Core Diameter	Thickness of single Rubber Pads (t_r)	Total Number of Rubber pads	Thickness of steel shims	Total number of steel pads	Horizontal Stiffness (KN/mm)	Displacement $\triangle_{max}$(mm) at lateral Force (KN)
Basshofi et al. 2019 [121]	350	60	7	15	0.5	14	0.49	90mm at 50KN
Robinson and Tucker (1980) [35]	600	105	-	-	5	8	1.7±0.1 (without lead plug)	45mm at 160KN
Kalpakidis and Constantinou [84]	1000	200	6.7	30	4.8	29	-	400mm at 1200KN
Weisman and Warn(2012) [4]	152	30	3	20	3	19	-	70mm at 18 KN

Table 8. Comparison of lead rubber bearing

Proposed by	Basshofi 2019[121]	Robinson and Tucker [35] (1980)	Kalpakidis and Constantinou [87]	Weisman and Warn(2012)[4]	Doudoumis 2005	Kanbir [122]
Outer Diameter (d_o)mm	350	600	1000	152	601	520
Lead Core Diameter(mm)	60	105	200	30	116.8	75
Thickness of single Rubber Pads (t_r)(mm)	7	-	6.7	3	9.5	14.4
Total Number of Rubber pads(mm)	15	-	30	20	11	18
Thickness of steel shims (mm)	0.5	5	4.8	3	3.0	2.0
Total number of steel pads (mm)	14	8	29	19	10	17
Displacement $\triangle_{max}$(mm) at lateral Force (KN)	90mm at 50KN	45mm at 160KN	400mm at 1200KN	70mm at 18 KN	152.4mm at 260KN	-

To assess the effectiveness of elastomeric bearings, a comparison between fixed base and rubber-isolated base structures has been conducted using SAP 2000. The analysis considered a linear elastic structure—a 10-story RC residential building located in Dhaka [95]. The center-to-center spacing is 7.62 meters in both directions. The given data includes the following: characteristic strength of 28 MPa, yield stress of 414 MPa, a live load of 2.4 KPa, a dead load (excluding self-weight) of 4.8 KPa, slab thickness of 150 mm, exterior corner dimensions of 750 mm × 750 mm, exterior middle column dimensions of 950 mm × 950 mm, interior column dimensions of 1000 mm × 1000 mm, and various beam sizes, including 525 mm × 825 mm, 600 mm × 900 mm, and 550 mm × 900 mm. Additionally, grade beams of 300 mm × 375 mm each are considered. There are two types of isolators used in this analysis: the first is LRB, and the second one is HDRB. The dimensions and properties of different isolators are as mentioned. The plan dimension of the lead rubber bearing is 800 mm, the layer thickness is 10 mm, the number of layers is 16, the lead core size is 150 mm, and the total height of the bearing is 240 mm. The horizontal effective stiffness for LRB is 2306.5 kN/m. The plan dimension of HDRB is 950 mm, the layer thickness 10 mm, the number of layers is 16, the lead core size is 175 mm, and the total height of the bearing is 240 mm. The horizontal effective stiffness for HDRB is 5186.92 kN/m. The horizontal stiffness for the total isolation system is 83586.28 kN/m. The results are presented for both fixed base and isolated base structures. Fig. 6 illustrates the schematic representation of the building in Mode 1 for the fixed base, while Fig. 7 depicts the schematic representation of the isolated base structure in the same mode. Further details are provided in Table 9. The pushover analysis is conducted to generate the capacity curve of the building, both with isolator and without isolator as shown in Fig. 8.

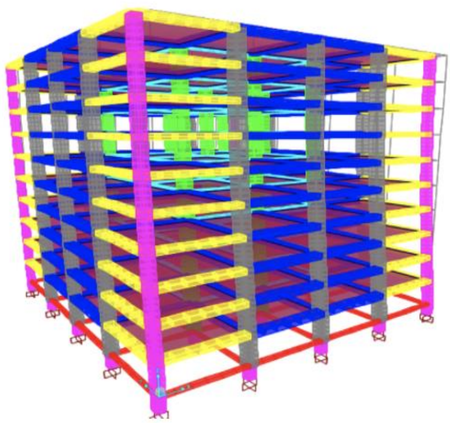

Fig. 6. Response of Fixed Base structure in Mode 1

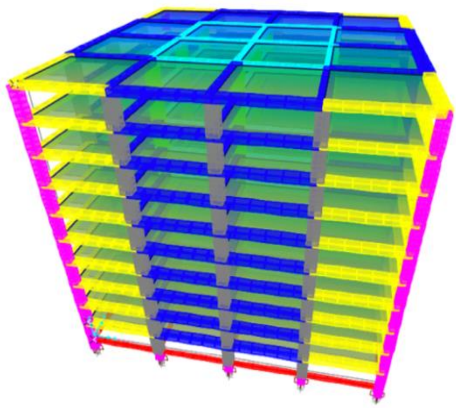

Fig. 7. Response of Isolated Base structure in Mode 1

Table 9. Modal Responses of fixed-base and isolated-base structures in SAP 2000

Mode	Fixed Base				Isolated Base			
	Time Period(s)	Cumulative Mass Participation Ratio			Time Period(s)	Cumulative Mass Participation Ratio		
		X	Y	RZ		X	Y	RZ
Mode 1	1.107558	0.24341	0.58255	0	2.702076	0.01856	0.95672	0
Mode 2	1.107558	0.82596	0.82596	0	2.702076	0.97528	0.97528	0
Mode 3	1.000222	0.82596	0.82596	0.82689	2.485254	0.97528	0.97528	0.99527
Mode 4	0.343231	0.83508	0.91326	0.82689	0.712116	0.9882	0.9882	0.99527
Mode 5	0.343231	0.92238	0.92238	0.82689	0.712116	0.99889	0.99889	0.99527

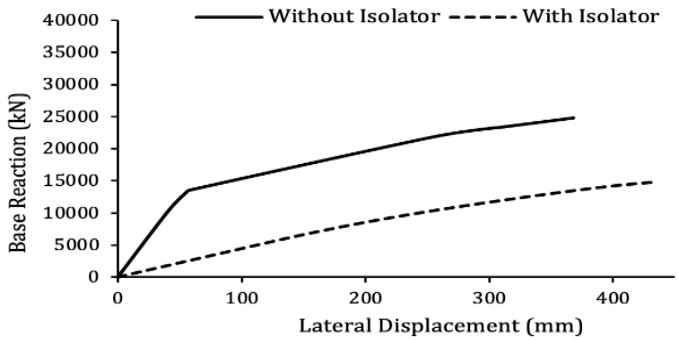

Fig. 8. Pushover curve for RC frame building

7. Enhancing Seismic Mitigation with 3-D Base Isolation Systems

While conventional base isolation effectively reduces the horizontal response of buildings to seismic forces, it falls short in addressing the transmission of vertical seismic components to the superstructure. This has led researchers to explore three-dimensional base isolation systems that account for both horizontal and vertical ground motion. In 1986, Kajima Corporation took the initiative to develop a three-dimensional laminated rubber-bearing seismic isolation system, showcasing its application in a two-storey RC structure in Japan [123]. The USA's nuclear industry also examined this approach later. Several novel 3D systems have emerged, going beyond mere design parameter adjustments. One such system is the GERB system, featuring helical springs that offer flexibility in both horizontal and vertical directions. Notably, the vertical frequency is three to five times that of the horizontal direction. This design aims to prevent excessive vertical movement caused by varying lateral loads, live loads, and wind loads. GERB has found applications in diverse industrial and residential buildings. Vertical base isolation systems provide adaptable support in the vertical direction through a grouping of metallic or air springs along with complementary damping mechanisms. Other 3D isolation systems include Rolling Seal-type air springs, Cable-reinforced air springs, Hydraulic 3D systems, and Coned Disk Spring systems.

A study was conducted involving the development and investigation of a three-dimensional (3-D) model for BI structures, employing a single degree of freedom (DOF) model [124]. Through time history analysis, the damping influence of the isolation layer on building response characteristics was examined. The thickness of the rubber layer played a significant role in notably decreasing the vertical frequency. An assessment of the advantages and challenges associated with 3-D isolation systems in nuclear facilities was performed in comparison to horizontal isolators [125]. Linear analysis was carried out to establish the merit of 3-D isolators in nuclear power plants, with a recommendation for future non-linear analysis and modelling of bearings to capture coupling behaviour. The notion of implementing periodic material foundations for nuclear plants located in high-intensity seismic zones was endorsed [126,127]. Periodic materials, originating from solid-state physics, have been artificially engineered by arranging contrasting materials in a periodic manner. These materials are categorized as 1-D, 2-D, and 3-D. Experimental verification has confirmed the efficacy of a 3-D periodic foundation in safeguarding superstructures from incoming hazardous seismic waves in both vertical and horizontal orientations, as well as torsional modes. The study further delved into the three-dimensional modelling and response of laminated rubber bearings and LRB [128]. This analysis utilized a five-storey scaled steel frame structure subjected to Northridge, El Centro, and Kobe earthquakes. Employing the Opensees 3-D numerical simulation model, an examination was conducted into the combined influence of the BI and SSI effects on various building arrangements [129]. Three models were considered: fixed base, linear BI model, and non-linear BI model. The analysis encompassed 240 non-linear 3-D models for numerical assessment, aiming to establish the correlation and efficiency in predicting spectral accelerations. Notably, a relationship was established between the elongation ratio and damping enhancement concerning the stiffness ratio through the observation of distinct trends across different arrangements. While the numerical simulations and responses of the 3-D BI system with SSI effects have been derived considering the horizontal aspects of seismic excitation, further investigations are warranted to encompass the synchronised impact of both horizontal and vertical earthquake components for comprehensive field response simulations.

8. Seismic Base Isolation in the Nuclear Structures

The utility of this technique is not just confined solely to building structures; it extends to nuclear power plants as well. In 2000, Ebisawa et al. [130] introduced a program for applying base isolation systems to nuclear components, presenting a case study demonstrating its viability. This technique can be effectively harnessed within nuclear power plants to bolster safety measures and mitigate the potential for seismic vulnerabilities. The inaugural successful integration of a base isolator into a nuclear facility can be traced to Cruas, France, where four operational units were established in 1983. Furthermore, during the 1980s, an additional two-unit nuclear power plant in Koeberg, South Africa, was brought into operation [131]. To facilitate seismic analysis, including the incorporation of the Bouc-Wen model to assess the impact of second hardening on floor response spectra, the model was adapted into the OpenSees software platform [132]. This endeavour accounted for two distinct material characteristics and variations in robust earthquake motion.

In the past, limited technical guidance and knowledge existed regarding the implementation, examination, and design of BI systems for nuclear plants, coupled with associated financial risks. In response, the Department of Energy and the Nuclear Regulatory Commission (NRC) in the USA initiated research projects to advance tools and procedures for implementing BI systems in nuclear power plants. Through mutual consensus, ASCE 4-16 and ASCE/SEI 43-19 have now incorporated a base isolation chapter. The comprehensive guidelines and standards pertaining to seismic isolation of nuclear structures were published within ASCE 4-16 in 2017. This publication advocates a multi-step nonlinear soil-structure interaction (SSI) analysis based on the base isolation design response spectrum, encompassing both nonlinear behaviour and SSI effects. The multi-step approach integrates equivalent-linear methods and time domain analysis. The NRC has also issued three technical reports concerning the analysis, design, and response of seismic base isolation systems in nuclear power plants: (a) NUREG/CR-7253, "Technical Considerations for Seismic Isolation of Nuclear Facilities" [133], (b) NUREG/CR-7254, "Seismic Isolation of Nuclear Power Plants Using Sliding Bearings" [134], and (c) NUREG/CR-7255, "Seismic Isolation of Nuclear Power Plants Using Elastomeric Bearings" [135]. Ongoing applications of base isolation include nuclear reactors in France, such as the Jules Horowitz Reactor and the International Thermonuclear Experimental Reactor. The former is a fusion reactor. A wealth of research articles, conference papers, and technical reports substantiate the efficacy of seismic isolation standards for nuclear power plants. However, certain gaps necessitate thorough addressing: (a) Developing an enhanced base isolator that aligns with nuclear power plant standards and requirements, accompanied by specific guidelines and protocols. (b) Precisely characterizing advanced isolated nuclear reactors, with a distinct focus on soil-structure interaction and fluid-structure interactions. (c) Conducting meticulous analysis and estimation of advanced isolated reactors, encompassing both vertical and horizontal seismic intensity inputs at the point of action. (d) Investigating the impact of radiation exposure from nuclear facilities on the mechanical properties of bearings.

9. Impact and Consequences of Beyond Design Events

It is essential to consider the performance of isolated structures not only during seismic events but also when subjected to non-seismic events and blast loads, which can exceed the design basis. Explosive incidents directed at buildings release substantial energy rapidly, resulting in waves and extreme heat reaching temperatures around 4000°C, along with a significant increase in pressure well beyond atmospheric levels. The impact of blast loads on structures unfolds in distinct phases: firstly, shock waves cause damage to the building's exterior, followed by penetration into the interior, exerting pressure on various building elements. The columns and internal slabs, along with occupants, were adversely affected by the pressure resulting from the detonations.

In the subsequent phase, the structure's framework encountered substantial loading, responding to the intense ground motion and short-duration impulses, as documented by the NRC [136]. Evaluations of both conventional nuclear plants and those equipped with a base isolation (BI) system were conducted in the context of blast loading, encompassing ground shock-induced blasts and air blasts [137]. The employment of LS-DYNA facilitated response history analyses for these scenarios, revealing a significant reduction in ground shock response when BI systems were integrated. A study investigated the performance and response of base-isolated buildings utilizing elastomeric isolators when subjected to blast loads while maintaining robust seismic protection [138]. This research involved numerical simulations of five-storey structures, considering fixed base, base-isolated, and isolated base configurations alongside supplementary passive control devices. These control mechanisms included tuned-mass dampers and non-linear bumpers.

A three-dimensional (3-D) model was developed to examine the dynamic features of the BI CPR1000 containment system exposed to several aircraft-induced loads [139]. The extent of structural damage was influenced by factors like impact velocity, aircraft angle, and aircraft type. Varied aircraft impacts produced distinct impact loads and energy. Notably, even under similar isolation conditions, the CPR1000 containment's displacement and acceleration responses differed due to the varying properties introduced by diverse aircraft loads. Structures with appropriately high stiffness experienced minimal damage under aircraft impact loads. The impact's brief duration meant that artificial intelligence (AI) directly affected the superstructure. Consequently, the BI system held limited effects over the plastic strain dispersal within the containment. The potential for extreme displacement and acceleration responses leading to internal equipment failure existed. It was concluded that introducing damping into isolation bearings could expedite the dissipation of aircraft impact energy. A post-blast scenario demonstrated that structures employing the BI system exhibited reduced absolute acceleration, peak-storey displacement, and storey drift [140,141].

10. Pros and Cons of Bearings

Elastomeric rubber bearings and LRB are types of base isolation (BI) devices that effectively mitigate the impact of seismic shaking on structures, providing notable benefits in terms of performance and structural safeguarding. These devices absorb and dissipate seismic energy, thereby isolating the structure from ground motion during earthquakes. As a result, the stresses and vibrations transmitted to the building are significantly reduced. These cost-effective solutions are applicable to structures of varying sizes and can be easily implemented in both new and retrofit building projects, leading to reduced construction timelines. Due to their well-established reliability backed by comprehensive research and a demonstrated history of excellent seismic performance spanning several decades, these structures require less maintenance, ultimately resulting in reduced long-term construction expenses.

Elastomeric rubber bearings have certain limitations, including their ability to support vertical loads, susceptibility to potential creep and degradation over time, sensitivity to temperature fluctuations, and restricted displacement capacity. These limitations can pose challenges in structures subjected to significant vertical loads and during highly intense seismic events. Regular maintenance and replacement may also become necessary. On the other hand, the use of Lead Rubber Bearings raises environmental and health concerns due to the toxic nature of lead. Additionally, these bearings primarily rely on friction to dissipate energy, which can potentially limit their effectiveness when compared to alternative systems. The manufacturing and installation costs of these systems can be higher, and their performance in severe earthquake events may not be optimal. Careful design and installation are crucial, as improper implementation can compromise their effectiveness.

Over a century ago, the earliest known use of current seismic isolation methods was documented. However, comprehensive studies and significant applications of these techniques have only recently begun. Consequently, numerous investigations have been conducted by academicians, leading to the development of numerous methodologies. The review of elastomeric bearings has so far only been done in a very restricted way in multiple studies. The eccentricity in the isolated structure is the distance amid the centre of mass and the center of stiffness. If eccentricity exists in isolated structures, then chances of torsional coupling are possible [142]. It was concluded that if the isolator has an eccentricity of small or zero ($e_b/L < 0.2$), then corner-displacements magnification $\overline{U}_{cb}$ is small ($\overline{U}_{cb} < 1.3$), despite the superstructure having a large eccentricity ($e_b/L < 0.4$). Therefore, it is concluded that superstructure eccentricity has less effect. It has been concluded [143] that increasing e_b/L leads to an increase in Torque Amplifications. The non-linear behaviour of torsionally coupled BI buildings subjected to random earthquakes having different parameters was investigated [144]. He concluded that if isolator eccentricity increases, then the effectiveness of the base isolator decreases while reducing the torsional response of the superstructure [145]. The two horizontal components of earthquakes are investigated to evaluate the influence of torsion on the seismic response of the structures. To evaluate the response, the parameters are varied, e.g., the ratio of eccentricity to a radius of gyration, mass, and stiffness with height, number of storeys, etc. Torsional irregularities in base-isolated systems, stemming from architectural and functional changes, need careful consideration during design. While base isolators reduce seismic demands, the alignment of the isolator rigidity centre and superstructure mass centre is crucial to minimize torsional effects on seismic response. It was concluded from the study that LRB isolators display greater sensitivity to torsional effects when compared to other isolators [146]. Models of LRB isolators featuring 10% and 20% eccentricities indicate average displacements that are 11% and 14% higher, respectively, than those observed in models without eccentricity. In contrast, FPS isolators show a disparity of less than 5%. The influence of eccentricities on rubber-isolated structures is contingent upon the torsional frequency of the isolation system.

The selection of an appropriate isolation system to protect a structure involves consideration of various factors. These factors include the seismic risk magnitude of the area, the expected displacement capacity, concerns related to uplift, the long-term performance, durability, and maintenance requirements, as well as the cost implications.

The primary function of BI systems is to offer a mechanism capable of fulfilling various performance objectives during different seismic events, thereby ensuring the protection of both the structural and non-structural elements, even under highly intense seismic conditions. Several experimental studies and numerical simulations have been conducted on various kinds of BI systems that demonstrate seismic features. Additional investigation is required to (i) collect three-dimensional response data for buildings employing contemporary isolation systems, (ii) evaluate the precision of current analytical and numerical models in forecasting demands on primary, secondary, and non-structural systems, and (iii) advance our comprehension of the seismic susceptibility of secondary and non-structural systems across diverse scenarios. This study has the potential to uncover constraints in traditional isolation techniques employed to defend these systems, hence motivating the investigation of new strategies to attain total three-dimensional safety.

11. Conclusions

This study provides an overview of significant research on seismic elastomeric and lead rubber bearings, both in terms of numerical and experimental techniques, while conducting a historical evaluation of isolation approaches. Additionally, it categorizes useful strategies based on their underlying mechanisms and contrasts their benefits and drawbacks. While these bearings are effective in reducing ground-shaking forces, existing research has also identified limitations that must be addressed to ensure their optimal performance. The following highlights the closing remarks:

- It is essential to validate the assumptions made in the fabrication, manufacturing, and material properties of the LRBs. It gives a satisfactory understanding of mechanical behaviour, and allows the identification of critical areas, thus significantly contributing to the improvements in their designs.
- It is concluded from the literature that the bearing should provide adequate horizontal flexibility to extend the building's natural period and accommodate spectral demands. It must possess adequate energy dissipation capacity to restrict displacements within the prescribed limits, ensuring structural integrity. It should maintain an appropriate level of rigidity, allowing the BI building to behave comparably to a fixed-base structure under normal service loads.
- Elastomeric bearings, such as LRBs, are susceptible to deterioration over a period of time, which may impair functionality. The rubber material might degrade and lose its flexibility when exposed to weathering, UV radiation, and other adverse environmental conditions. Further, research is required to create more resilient rubber polymers that can endure exposure to these elements over an extended period of time.
- Extreme temperatures could have a detrimental effect on the efficiency of the bearings because they are temperature-sensitive. Consequently, their capability to mitigate seismic forces may be influenced by alterations in their stiffness, damping, and other mechanical characteristics. Therefore, further study is needed to create more robust bearings.
- Significant deformations might take place in bearings during severe tremors, which may impair their long-term functioning. To precisely forecast how bearings will perform amid substantial deformation, research is required to create more accurate analytical and numerical models and robust testing procedures and guidelines.
- As a consequence of their propensity for compression set, these bearings may begin to lose their elasticity and become less capable to withstand seismic stresses. This is especially problematic for structures that experience low-frequency vibrations.

Further study is required to create materials that are more durable and capable of withstanding compression sets.

- These bearings must be installed and maintained appropriately in order to function at their best. However, installation and maintenance can be difficult and call for specialized expertise and tools. Better maintenance and installation methods that are affordable and simple to use need to be developed through investigation.
- If the ratio of eccentricity to the radius of gyration increases, then modal energy and input energy are reduced. The reduced stiffness of the structure along the height does not influence the energy reduction.
- It is proved from triaxial loading analysis that the coupling effect cannot be neglected. Therefore, to manufacture an accurate base-isolated model with HDRB or natural rubber bearings with rational and economical design, proper material characteristics and coupling effects must be considered.
- It was observed from the literatures that an increase in the number of rubber layers enhances the horizontal flexibility of the isolator; thus, the vibration period of the structure increases, leading to a significant reduction in seismic amplification. During the period of seismic activity, the inter-storey drifts are reduced significantly as displacements are concentrated at the isolator level. Thus, it leads to minimizing damages in structural and non-structural components of the structure.
- An increase in the number of rubber layers improves the isolator's horizontal flexibility; as a result, the vibration period of the structure lengthens, resulting in a considerable decrease in seismic amplification. As displacements are localised at the isolator level during a seismic event, inter-storey drifts are greatly reduced. As a result, it helps to reduce impairment to both structural and non-structural elements of the structure.

There are several challenges associated with elastomeric and LRB that must be addressed to optimize their performance in mitigating seismic forces. Through the resolution of these challenges, researchers have the potential to enhance the overall efficacy and reliability of bearings, thereby leading to the creation of structures that are more resilient and less prone to risks in earthquake-prone areas. The field of base isolation systems has witnessed significant progress in the development and investigation of adaptive properties, specifically in relation to elastomeric and lead rubber bearings. Certain types of building infrastructure devices have demonstrated a significant capability to disperse the input energy in the event of dangerous seismic occurrences. These devices have proven to be beneficial for structures that house delicate equipment situated in regions prone to prolonged seismic activity. Nevertheless, it was observed from the review that certain categories of isolation devices may prove to be more advantageous when subjected to ground motions of low to moderate intensity.

There is a need for ongoing evaluation of the BI system to ensure that it fulfils all the requirements necessary for its application in these domains. Certain deliberated selections are presently limited to investigation only and potentially not deemed practical or economically viable for large-scale use at present. Hence, it is recommended that future research endeavours explore cost-effective and pragmatic approaches for implementing these solutions in real-world architectural structures and across a wide range of applications. It is suggested that a comprehensive investigation be undertaken, encompassing numerical simulations and experimental analyses, to explore a wider range of isolation systems that demonstrate seismic isolation properties. This investigation should also consider multifaceted ground motions with varying intensities and diverse properties.

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