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Engineering Adaptability: Evolution of Seismic Isolation Systems for Enhanced Resilience.

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ABSTRACT

The resilience of infrastructure in earthquake-prone regions is critical for mitigating the impact of seismic events. Traditional seismic design approaches have limitations in handling the dynamic nature of earthquakes, prompting the development of advanced seismic isolation systems. This review paper explores the evolution of seismic isolation technologies, focusing on their adaptability and enhanced performance. We examine innovative systems such as friction pendulum bearings, elastomeric isolators, and magnetorheological dampers, highlighting their principles, mechanisms, and effectiveness. Additionally, the integration of smart materials like shape memory alloys and magnetorheological elastomers is discussed for their role in adaptive response to seismic activity. By synthesizing recent research and advancements, this paper provides a comprehensive overview of adaptive seismic isolation systems, emphasizing their potential to significantly improve infrastructure resilience and safety. The findings underscore the importance of continued innovation in seismic engineering to develop systems that not only withstand but dynamically respond to seismic forces, ensuring robust protection for structures and their occupants.

Key word: Adaptive behavior, Friction pendulum bearings, Elastomeric isolators Shape memory alloys, Magnetorheological elastomers, Earthquake resilience.

1. Introduction

In regions prone to seismic activity, the resilience of infrastructure against earthquakes is paramount. Traditional seismic design approaches often relied on rigid structural elements, which, while effective to some extent, presented limitations in their ability to withstand the dynamic and unpredictable nature of seismic events. Recognizing these limitations, engineers and researchers have embarked on a transformative journey to develop seismic isolation systems that possess not only robustness but also adaptability. The concept of adaptability in seismic isolation systems signifies a departure from static, one-size-fits-all solutions towards dynamic, responsive mechanisms capable of adjusting to varying levels of seismic intensity. This evolution has been driven by a combination of factors, including advancements in materials science, computational modelling, and a deeper understanding of seismic phenomena. The introduction of innovative seismic isolation technologies, such as friction pendulum bearings, elastomeric isolators, and magnetorheological dampers, has ushered in a new era of seismic engineering. These systems leverage the principles of friction, elasticity, and magneto rheology to dissipate seismic energy, thereby protecting structures from damage and ensuring occupant safety. Through a critical examination of recent research findings, this review paper aims to shed light on the principles underpinning these seismic isolation systems, their performance characteristics, and their potential applications in enhancing infrastructure resilience. By synthesizing insights from diverse disciplines, ranging from structural engineering to materials science, this paper seeks to provide a comprehensive understanding of the evolution of seismic isolation systems and their role in fortifying infrastructure against seismic hazards .Overall, this review paper serves as a guide to navigating the complex landscape of seismic engineering, offering valuable insights into the development of adaptive seismic isolation systems and their implications for the future of resilient infrastructure..

2. Base Isolation of Adaptive Devices.

2.1 Sliding isolation with adaptive behaviour

Friction pendulum bearings utilize sliders resting on a curved surface, typically made of either stainless steel or PTFE, known for its low coefficient of friction [1]. Recent research highlights concern regarding the susceptibility of these bearings to strong, long-period near-field earthquakes, particularly when the event period aligns closely with the isolation system's period [2]. To accommodate larger displacements and mitigate excessive responses, engineers have resorted to enlarging isolators, albeit at increased costs [3]. Recognizing the limitations of conventional friction pendulum bearings, engineers have pursued innovative approaches that integrate adaptability into sliding isolators. These advancements include multi-spherical sliding bearings [4], sliding isolators featuring variable friction, and sliding isolators with adjustable curvature.

2.1.1 Multi-Spherical Sliding Bearing

Zayas et al. introduced the single friction pendulum (SFP) isolators, which feature a bilinear hysteresis loop. These isolators are suitable for moderate seismic events but are less effective during severe earthquakes [5]. To address this limitation, the double friction pendulum (DFP) system was developed, offering twice the displacement capacity of SFPs and reducing heating effects. Further advancements led to the creation of triple friction pendulum (TFP) bearings, which enhance adaptability by providing smoother transitions between stiffness regimes and increased displacement capacity in a more compact design. TFPs include four spherical sliding surfaces, creating three distinct pendulum mechanisms [5]. Various configurations of modified SFPs, DFPs, and TFPs have been explored both theoretically and experimentally, demonstrating adaptive behavior when properly configured. However, TFP systems exhibit more complex hysteresis behavior, with up to five different stiffness regimes depending on the combination of sliding surfaces. Figure 1 shows the cross-section and typical force-displacement relationship of a TFP system. The force-displacement behavior is based on assumptions such as ($R1 = R4$) being significantly larger than ($R2 = R3$), as detailed in references [4]. The friction coefficient of the sliding materials varies with factors like sliding velocity, temperature at the sliding surface, and axial pressure, typically ranging from 2% to 12%, depending on the application and materials used [6]. Sodha et al. [7] conducted a numerical study to analyze the seismic response, including base shear, roof absolute acceleration, and bearing displacement. Their findings highlighted the highly adaptive nature of quadruple friction pendulums (QFPs) across different earthquake intensities. Additionally, a comparative analysis was performed to evaluate the responses of SFP, TFP, and QFP systems, all designed with identical effective damping and displacement capacities to ensure consistent energy dissipation per cycle. The implementation of QFPs resulted in significant reductions in top-floor acceleration by approximately 58% and 17% compared to SFP and TFP systems, respectively. Moreover, the base shear in the QFP system decreased by about 18% and 14% relative to the SFP and TFP systems, respectively [7].

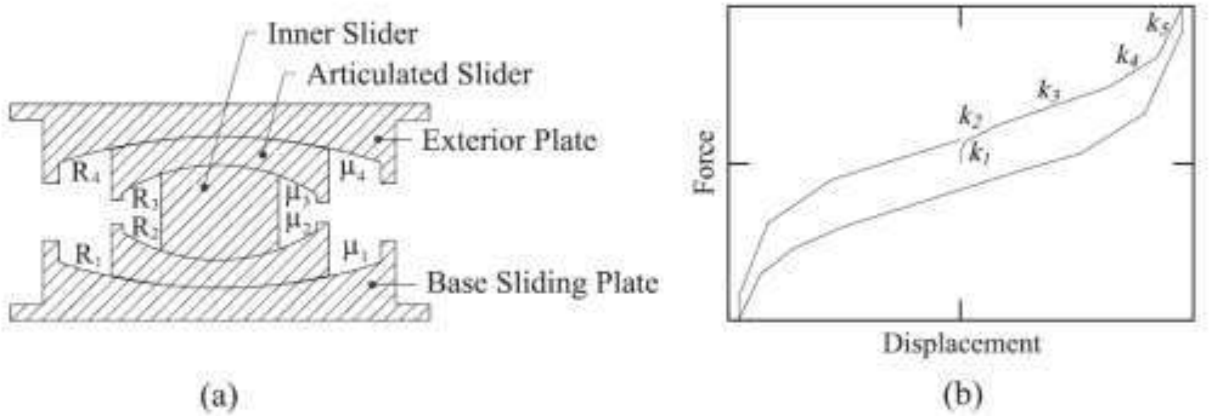

Figure 1: (a) Cross section and (b) typical force–displacement relationship of TFP

2.1.2 Sliding isolator with variable friction (SIVF)

Kelly [8] initially proposed the concept of sliding isolator with variable friction (SIVF), which was further explored by Panchal and Jangid [9] as a means to regulate isolator displacement during severe events. In such isolators, the friction coefficient on the sliding surface is assumed to change gradually with increasing displacement. This friction variation can be achieved by altering surface roughness or employing materials with different frictional properties [7]. Calvi et al. conducted a numerical investigation into the performance of three device types (BowTie, BowC, and SFP) with identical target displacement. Their study revealed that the BowTie and BowC SIVF devices exhibited approximately 40% and 30% higher equivalent viscous damping, respectively, compared to 20% in SFPs. This increased energy dissipation led to reduced average force demand and lower maximum structure acceleration. research approach for studying the factors contributing to non-acceptance of indoor residual spraying (IRS) in Mangochi district can involve a combination of qualitative and quantitative methods. This mixed-methods approach allows for a comprehensive understanding of the various factors at play.

2.2 Elastomeric isolation with adaptive behavior

Base isolators composed of elastomers offer an ideal solution owing to their capacity to withstand significant recoverable strains. Materials such as rubber (polyisoprene or polychloroprene) or those exhibiting rubber-like characteristics, such as polyurethane, are commonly employed [11]. To improve vertical and bending properties, elastomers are often reinforced with steel or Fibers. Adaptive behaviour across various input levels can be achieved through strategies such as utilizing natural rubber's strain induced crystallization property or incorporating unbonded or partially bonded Fiber-reinforced elastomeric isolators (FREIs) [10].

2.2.1 Sliding isolator with variable friction (SIVF)

The use of fiber reinforcement in elastomeric isolators aims to reduce both production and installation costs associated with steel-reinforced elastomeric isolators (SREIs), making them a more cost-effective option for widespread use, particularly in developing countries. Fiber-reinforced elastomeric isolators (FREIs) can be installed either bonded or unbonded between upper and lower supports. In an unbonded configuration, FREIs reinforced with flexible fibers exhibit a unique rollover deformation pattern when subjected to horizontal displacement [13]. The force-displacement behavior of an unbonded FREI (UFREI, shown in Fig. 2) features distinct softening and stiffening phases due to this rollover effect. Initially, at low displacements, the lateral stiffness is high and nearly linear. As the displacement increases, the horizontal surfaces lose contact with the supports and begin to rotate, increasing lateral flexibility (Fig. 2b). This rotation continues until the originally vertical faces of the bearing rotate 90 degrees and make full contact with the supports, resulting in a complete rollover (Fig. 2c). Beyond this point, any further displacement leads to a stiffening lateral response, which acts as a self-restraint mechanism to prevent excessive displacements [13].

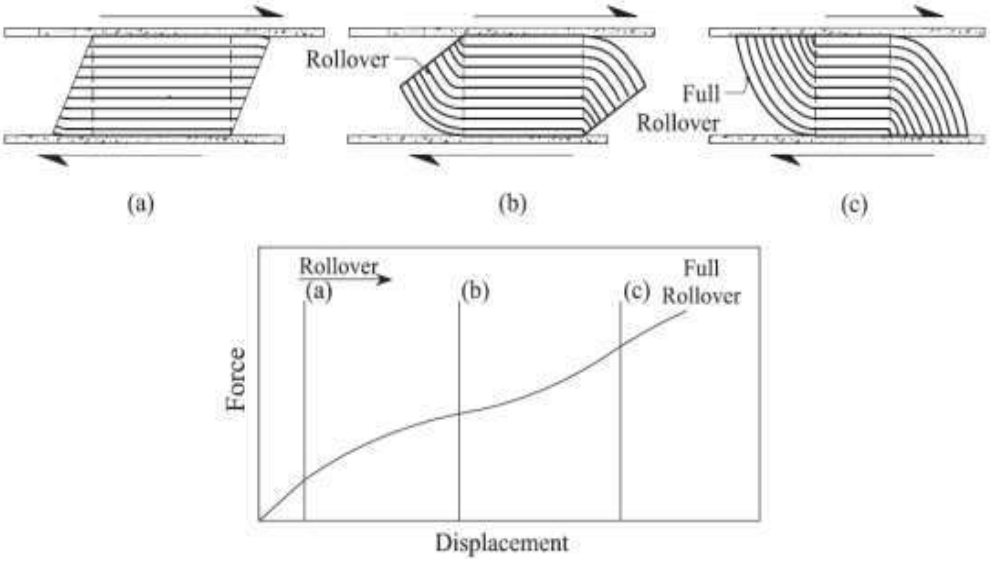

Figure 2 Typical force–displacement relationship of an UFREI.

Experimental and numerical studies have investigated methods to modify the hysteresis behavior of unbonded fiber-reinforced elastomeric isolators (UFREIs). One technique involves adding holes to the UFREIs to reduce the horizontal response while improving energy dissipation [14]. Another method uses modified support geometry (MSG) [15], which changes the shape of hysteresis loops by altering the surrounding support conditions. The goal of MSG is to either accelerate or delay the stiffening phase of UFREIs without affecting the softening phase [21]. Figure 3 demonstrates the concept of MSG, showing its capability to either hasten (A-MSG) or delay (D-MSG) full rollover, along with normalized hysteresis loops at different MSG levels. Additionally, a partially bonded FREI system was proposed [15] to address potential issues with UFREIs, such as sliding and residual displacement, susceptibility to overturning, and the expectation of high vertical accelerations [14]. This hybrid approach, which involves partially bonding the device, maintains its adaptive characteristics while addressing these concerns [15].

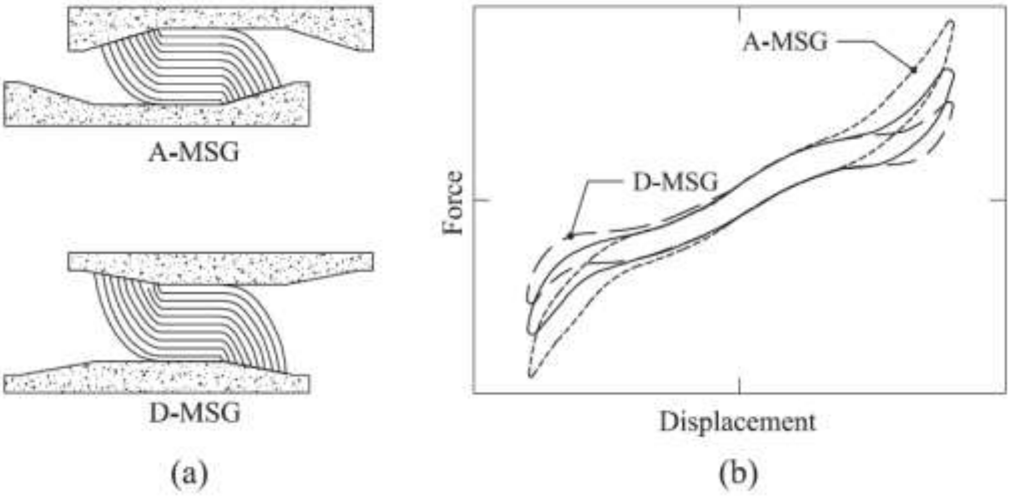

Fig. 3. (a) MSG that accelerates full rollover and delays full rollover and (b) typical force–displacement relationship of different levels of MSG

2.2.2 Elastomeric bearing with steel dampers

The integration of steel dampers into elastomeric isolators has been extensively examined through both numerical and experimental studies. Yuan et al. [10] introduced a design for polyurethane elastomeric isolators reinforced with steel dampers, where the dampers remain inactive during minor displacements. To enhance shear performance, a polyurethane elastomer (PUE) material was employed, featuring both hard and soft segments, which allow for the mechanical properties to be adjusted by altering the proportions of these segments [11]. PUE bearings exhibit high vertical strength and significant shear deformability, with experimental results indicating an ultimate shear strain of 300% and compressive stress exceeding 60 MPa [11]. The energy dissipation capacity of PUE is around 10%-14% at a shear strain of 150% [11]. To mitigate excessive displacement during severe earthquakes, hysteretic dampers were incorporated into the system to bolster the polyurethane bearing, merging the advantages of high vertical strength and energy dissipation capacity [10]. The steel damper reinforced polyurethane bearing (SDRPB) includes a polyurethane bearing and four C-shaped hysteretic dampers, achieving a damping ratio of 20% at a shear strain of approximately 150% [10]. Figure 4 illustrates the configuration and typical hysteresis response of SDRPB in cyclic shear testing. The PUE and steel dampers are attached to the top and bottom plates, respectively, with an initial gap between the PUE and steel ring allowing free movement of the superstructure under minor loads. A circular polytetrafluoroethylene (PTFE) sheet embedded in the bottom plate protects the PUE from frictional heating and ensures low stiffness during minor events. Consequently, the response at small displacements is controlled by PUE alone, while at larger displacements, where the PUE displacement exceeds the initial gap, the steel dampers activate, assisting in seismic energy dissipation.

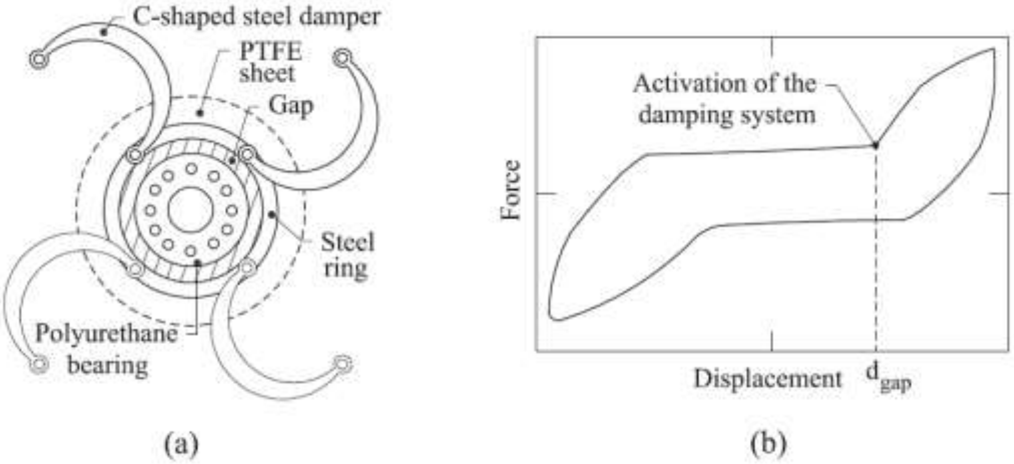

Fig. 4. (a) Plan view of a SDRPB and (b) typical force–displacement relationship of SDRPB in the cyclic shear tests.

2.2.3 Rubber isolators with strain-induced crystallization

An alternative approach to isolation system design capitalizes on a natural rubber property known as strain-induced crystallization. While crystallization occurs in most natural rubber compounds, the shear strain level required for this phenomenon (typically 100% or higher) varies depending on compounding and filler content.

Figure 5 illustrates the typical lateral force-displacement response of a CRS in cyclic shear testing. CRS is engineered to exhibit linear behaviour during low-level events, transitioning to linear or slightly nonlinear behaviour at moderate displacements. At larger displacements, as natural rubber begins to crystallize, CRS demonstrates nonlinear behaviour and stiffens accordingly.

The efficacy of CRS was compared to that of the single friction pendulum (SFP) and lead plug system (LPS) with bilinear hysteresis in terms of structural and equipment performance by Yang et al. [12]. Results indicated that SFP and LPS yielded higher floor acceleration responses at shorter periods, as expected from bilinear systems. However, for typical equipment with shorter natural periods, this heightened response is undesirable. In contrast, CRS exhibited a lower floor acceleration response within the period range crucial for equipment protection.

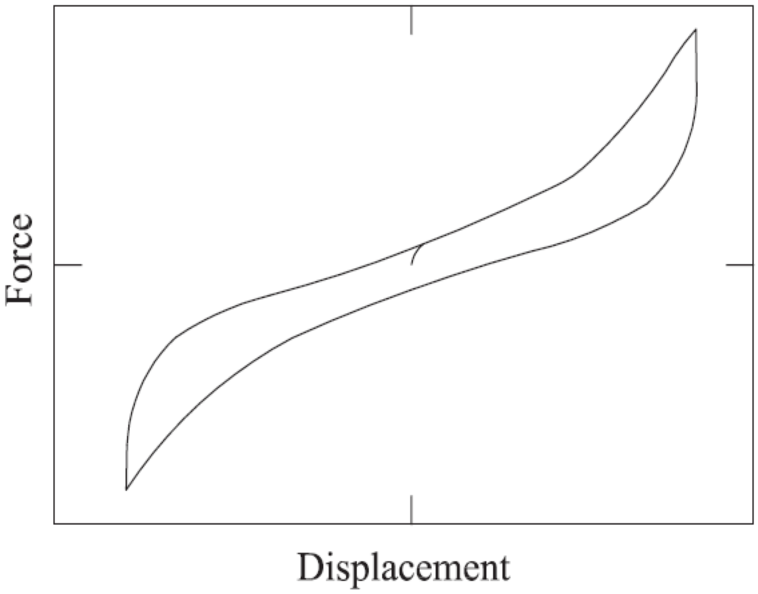

Fig.5. Typical Force-displacement relationship of CRS in the cyclic shear tests

2.3 Isolators involving magnetic fields.

Smart materials like magnetorheological (MR) dampers and magnetorheological elastomers (MRE) can mitigate structural vibrations by altering stiffness and damping properties when exposed to an external magnetic field [16]. Recent research endeavors have focused on developing adaptable isolator solutions, often semi-active, leveraging magnetic fields. Villaverde [17] introduced a sliding hydromagnetic bearing that demonstrated adaptive energy dissipation and deflection control by creating a magnetic field in the surrounding space. This device consists of a steel tube containing a low-viscosity fluid, with magnets affixed around the tube and the edge of the bottom plates, as depicted in Fig. 6a. Movement of the tubes on the aluminum plate generates a varying intensity magnetic field in the surrounding space. When facing the same poles, the permanent magnets repel each other, serving as a restoring force. A typical force-displacement relationship for hydromagnetic bearings is illustrated in Fig. 6b. Experimental and numerical modelling investigations have assessed the performance of hydromagnetic bearings as seismic protection systems. Results indicated reasonable mitigation of floor acceleration and interstory drift of superstructures during far-field earthquakes (15–30%) compared to near-field earthquake ground motions (10–15%) [18]. However, these bearings were ineffective in reducing vertical floor accelerations, and it's worth noting that they may not be suitable for structures prone to uplift [17].

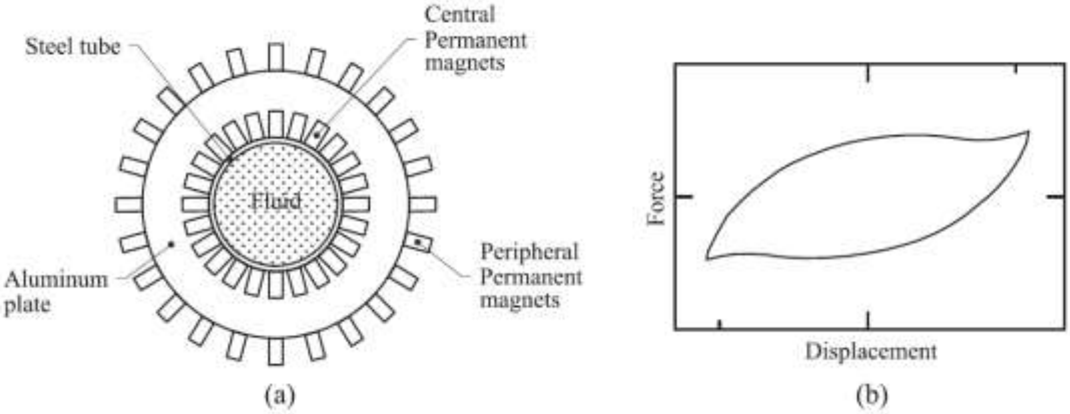

Fig.6. Hydromagnetic bearing (a) plan view and (b) typical force–displacement relationship.

Hybrid base isolation incorporating magnetorheological dampers has garnered significant interest for enhancing the performance of base isolation systems against both short- and long-period ground motions [8]. A numerical investigation by Rabie and Chae [20] demonstrated that a base-isolated structure equipped with a MR damper could achieve high performance levels across both long- and short-period earthquake ground motions. This was achieved by maximizing damping of the isolation system during long-period ground motions while minimizing it during short-period events. However, integrating MR fluids into base isolation systems presents challenges for commercial viability due to sealing issues [16] and complexity of implementation, which impact cost, reliability, and sustainability.

In recent years, a novel form of adaptive base isolation system utilizing magnetorheological elastomers (MRE) has emerged, resembling rubber but with the capability to adjust shear modulus and damping in real-time through a magnetic field. MREs consist of polarizable particles dispersed within a polymer medium. Li et al. [21] introduced MRE isolators, where MRE layers are sandwiched between thin steel sheets to enhance vertical loading capacity, akin to SREIs and FREIs. An external electromagnetic coil was positioned adjacent to the laminations to generate a controllable magnetic field (refer to Fig. 7). Tariq et al. [22] evaluated the efficacy of MRE base isolation against both near- and far-field earthquakes. Their findings indicated reduced structural responses in MRE base-isolated structures, with a more pronounced reduction observed in near-field earthquake scenarios compared to far-field events for the considered earthquake cases. The shear modulus of MREs under a magnetic field can vary from approximately 50% to over 300% [23], while the damping ratio ranges from around 10% to 30%, contingent upon the rubber matrix type, properties of iron particles, and magnetic field strength [23].

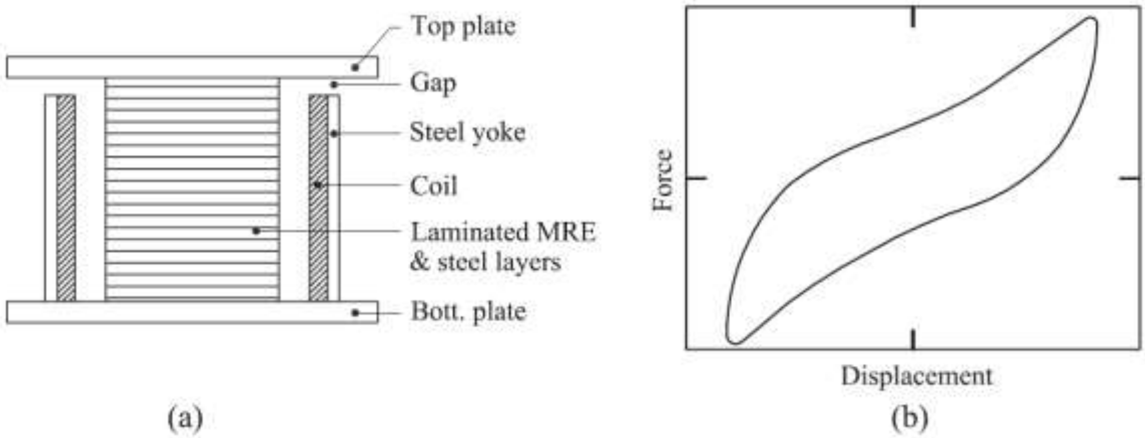

Fig.7. (a) Cross-section and (b) typical force–displacement relationship of MRE

2.4 Hybrid isolation system using shape memory alloy cables/wires.

Shape memory alloy (SMA) materials offer potential for creating effective base isolators by providing additional energy dissipation and re-centering capacity through the superelastic effect and substantial recoverable strain capability [24]. Notably, SMA materials, such as Ni-Ti, Cu-Al-Zn, etc., exhibit significantly larger recoverable elongation (up to 10%) compared to stainless steel (0.2%) while maintaining comparable corrosion resistance [26]. These unique properties stem from a reversible transition between austenite and martensite phases, unlike the irreversible process in steel alloys. This transition can be induced thermally or by stress. SMA materials are predominantly in the austenite phase at higher temperatures and lower stress levels, whereas martensite becomes stable at lower temperatures and higher stress levels. During loading, stress-induced martensite formation occurs, while in the unloading phase, a reverse transition at lower stress levels leads to super elastic behavior [27].

2.4.1 Elastomeric-based isolation system with SMA

In recent developments, a combination of various isolator types (elastomeric and sliding) with SMA wires/cables has emerged to enhance the adaptability of primary devices. Research efforts have focused on investigating the behavior of natural rubber bearings (NRBs), high-damping rubber bearings (HDRBs), and lead-plug rubber bearings (LRBs) when integrated with SMA wires for bridge applications [28-29]. Fig.8 illustrates two configurations and hysteresis curves of HDRB with SMA wires, providing a visual representation of the concept [29]. In this configuration, SMA wires within the isolation system serve as a rigid connection between the pier and deck during low seismic events. However, under extreme excitations, the system enhances energy dissipation and restricts displacement due to the hardening phase of SMA wires. Conceptually, the specimen featuring SMA wires/cables functions as a bi-linear isolation device at very low displacements. As the SMA wires/cables engage, a hardening effect becomes evident. Additionally, the area enclosed within the hysteresis loops increases, aiding in displacement control during larger events.

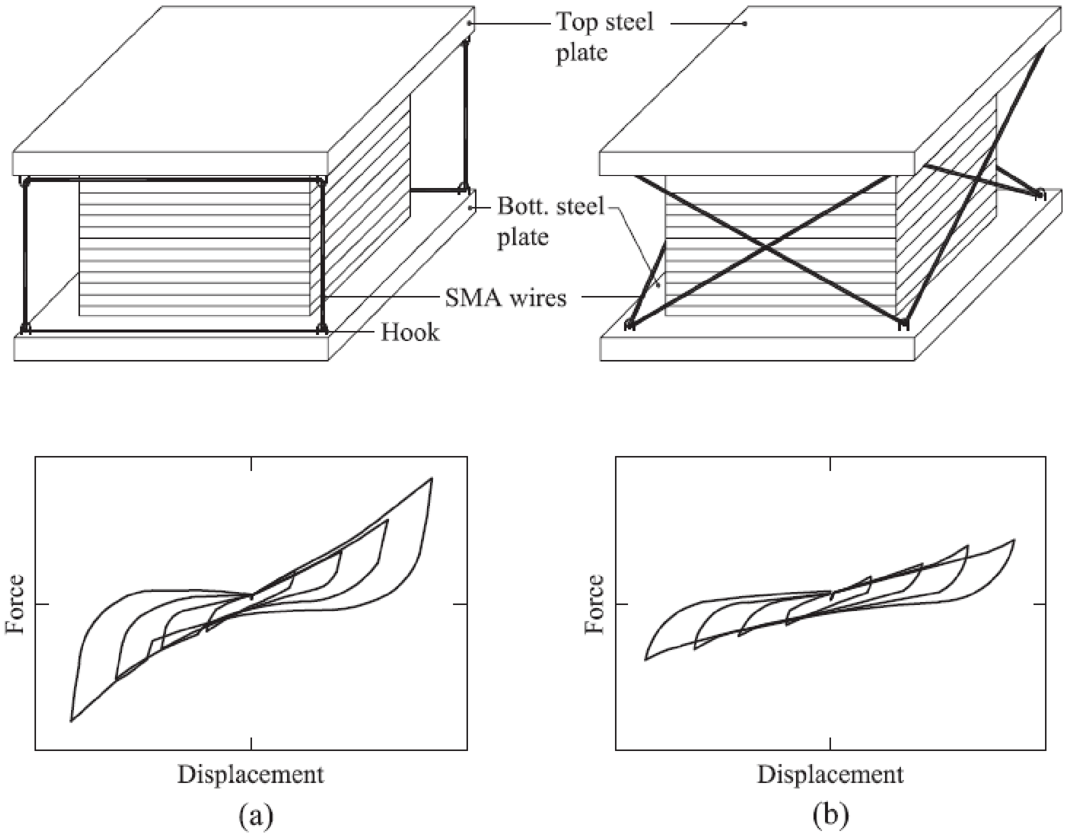

Fig.8. Configuration and typical force–displacement relationship of HDRB (a) with straight SMA wires and (b) with cross SMA wires

The sensitivity analysis performed to assess the efficacy of LRB-SMA under near-field earthquake events demonstrated that the system effectively mitigated the seismic response of highway bridges [30]. Furthermore, SMA wires have been integrated with MRE isolators to attenuate vibrations of the primary system by leveraging the sharp modulus changes inherent in SMA wires [31]. Fig. 9 displays the configuration and hysteresis curves of UFREI-SMA, illustrating the integration of SMA wires with the isolator system**.**

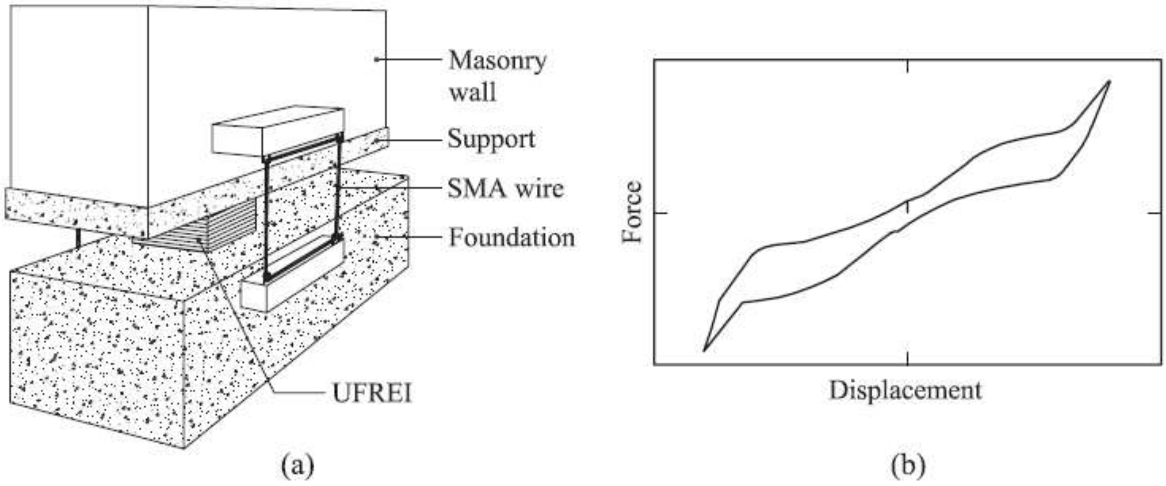

Fig.9. (a) Configuration and (b) typical force–displacement relationship of the UFREI-SMA

2.2.1 Sliding-based isolation system with SMA

The utilization of SMA materials has aso been explored in friction-based sliding isolators [24,25]. A hybrid isolation system combining friction-based isolators with SMA was devised to mitigate base displacement demand through supplementary stiffening and energy dissipation [24]. Peng et al. [25] proposed the integration of SMA cables with the DFP system. Experimental and numerical investigations were conducted, revealing multistage stiffness and energy dissipation characteristics of the device, indicating its adaptability to varying earthquake intensities. Fig. 10 illustrates a schematic of the hysteretic behaviors of the DFP, SMA cables, and the composite system. Initially, the specimen displayed a bi-linear behavior at lower displacements. As horizontal displacement exceeded the initial gap, the SMA cables gradually tightened, leading to increased stiffness and energy dissipation in the isolator.

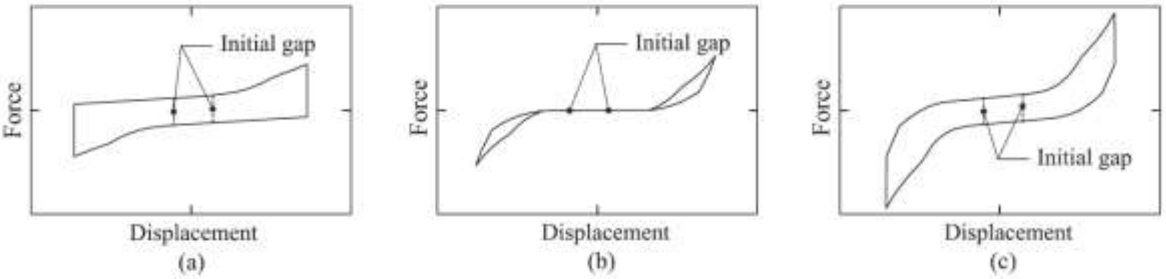

Fig. 10. Typical force–displacement relationship of (a) DFP, (b) SMA cables, and (c) DFP-SMA device.

3. Innovations in Adaptive Base Isolation Systems

The review paper explores various types of adaptive seismic isolation devices designed to enhance the resilience and safety of structures during earthquakes. Among these devices, sliding isolation systems have seen significant advancements. Multi-spherical sliding bearings, such as single friction pendulum (SFP), double friction pendulum (DFP), and triple friction pendulum (TFP) bearings, have been developed to improve displacement capacity and adaptability. The TFP bearings, in particular, offer smoother transitions between stiffness regimes and increased displacement capacity within a smaller plan size, featuring up to five different stiffness regimes.

Sliding isolators with variable friction (SIVF) represent another innovative approach. These devices adjust the friction coefficient on the sliding surface gradually with increasing displacement, achieved by altering surface roughness or using different frictional materials. Types like BowTie and BowC SIVF devices exhibit higher equivalent viscous damping compared to standard SFPs, leading to reduced force demand and lower maximum structure acceleration.

Elastomeric isolation devices have also been enhanced for adaptive behavior. Unbonded fiber-reinforced elastomeric isolators (UFREIs) offer a cost-effective alternative to steel-reinforced isolators, featuring a distinctive rollover deformation pattern under horizontal displacement. Techniques like introducing holes or modifying support geometry adjust the hysteresis behavior, providing both softening and stiffening regimes. Additionally, elastomeric bearings with steel dampers combine polyurethane elastomer bearings with steel dampers, which remain inactive during low displacements but enhance energy dissipation during larger displacements. Rubber isolators utilizing strain-induced crystallization exhibit nonlinear behavior and increased stiffness at higher displacements, providing lower floor acceleration response beneficial for equipment protection.

Magnetic field-influenced isolators, such as magnetorheological (MR) dampers and magnetorheological elastomers (MRE), alter stiffness and damping properties in response to a magnetic field, enhancing adaptability. Applications include sliding hydromagnetic bearings and MRE layers with controllable magnetic fields, reducing structural responses during earthquakes.

Hybrid isolation systems incorporating shape memory alloy (SMA) cables or wires combine the benefits of different isolation types with the unique properties of SMAs. Elastomeric-based systems with SMA wires enhance energy dissipation and re-centering capacity under extreme excitations. Sliding-based systems with SMA materials, like SMA cables integrated with DFP systems, provide multistage stiffness and adaptability to varying earthquake intensities.

These adaptive devices represent significant advancements in seismic isolation technology, aimed at improving the resilience and safety of infrastructure against seismic events.

4. CONCLUSION

This review paper has comprehensively examined the evolution and advancements in seismic isolation systems, emphasizing their adaptability to enhance resilience against varying earthquake intensities. Traditional systems, such as single friction pendulum (SFP) bearings, have been foundational in providing basic seismic protection but often fall short during severe seismic events. The development of multi-spherical sliding bearings, including double and triple friction pendulum systems, represents a significant leap in displacement capacity and energy dissipation efficiency. These systems demonstrate a marked improvement in adaptability through multiple stiffness regimes and enhanced damping characteristics. Further innovations, such as sliding isolators with variable friction and adjustable curvature, offer additional layers of adaptability, crucial for mitigating responses during strong, long-period near-field earthquakes. Elastomeric isolation systems, including unbonded fiber-reinforced elastomeric isolators (UFREIs) and steel damper-reinforced polyurethane bearings (SDRPBs), have been tailored to provide cost-effective solutions with improved vertical and horizontal performance, crucial for broad implementation in diverse geographical regions.

Moreover, the integration of smart materials like magnetorheological (MR) elastomers and shape memory alloys (SMAs) into isolation systems has paved the way for real-time adaptability. These materials' unique properties enable dynamic adjustment of stiffness and damping, enhancing the overall performance of seismic isolation systems under varying seismic demands. The collective advancements in these adaptive isolation technologies signify a paradigm shift towards more resilient structural designs capable of withstanding the complexities of seismic activity. Continued research and development in this field will undoubtedly lead to even more sophisticated solutions, ensuring better protection of infrastructure and human lives in earthquake-prone regions.

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