Evaluation and Comparison of Structural Stability after Using Dampers and Isolators

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Abstract

This study aims to experimentally assess the simultaneous effectiveness of lead-core rubber base isolators and linear viscous dampers in enhancing the seismic stability of mid-rise steel frame structures. An eight-story steel flexural frame model, scaled 1:4 and designed per the 4th edition of the 2800 Code for Soil Type III, was subjected to dynamic testing using a two-dimensional shake table. The experiment was conducted under fifteen real earthquake accelerograms. First, the model was tested without control devices. Then, four lead-core rubber isolators were installed at the base and two linear viscous dampers on the second and fourth floors. MEMS accelerometers and laser displacement sensors recorded the seismic responses. A paired t-test was used to statistically compare the stability index before and after the control intervention, with significance set at $p<0.05$. The results demonstrated a statistically significant improvement in structural stability. The average stability index increased by 12.7%, with all 15 records showing consistent positive differences (Δ ranging from 0.0070 to 0.0126). The paired t-test yielded $t(14) = 21.769$, $p < 0.0001$, and a Cohen's $d \approx 5.5$, indicating a very large effect size. Time-history analysis revealed a reduction in interstory drift of up to 30% and a substantial decline in floor accelerations, bringing the structure into the code-defined serviceability range. The system displayed consistent performance across a spectrum of seismic inputs, with a coefficient of variation at 18%, indicating high reliability. Economically, the system reduced the demand for secondary reinforcement, offsetting part of its installation cost. The combined use of base isolators and viscous dampers significantly improves seismic performance by reducing drift and accelerations, while ensuring structural stability and economic feasibility. This integrated approach presents a reliable and sustainable solution for enhancing the seismic resilience of mid-rise buildings.

Keywords: *Lead-core rubber base isolator; Linear viscous damper; Passive seismic control; Interstory drift; Nonlinear time-history analysis; Structural stability; Earthquake engineering.*

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1. Introduction

In recent decades, the increasing awareness of seismic risks and their devastating consequences has driven civil engineering research toward the development and application of innovative techniques aimed at enhancing structural resilience. Among these, passive control systems such as base isolators and energy-dissipating dampers have garnered significant attention due to their reliability, cost-effectiveness, and efficiency in mitigating the dynamic impacts of earthquakes. Iran's geographical positioning on the seismically active Alpine-Himalayan belt has further underscored the urgency of applying such systems in structural design, especially in light of destructive historical events like the 1978 Tabas, 1990 Rudbar, 2003 Bam, and 2021 Si Sakht earthquakes. These incidents revealed the inadequacy of traditional structural approaches and stressed the importance of improving seismic performance through smart, integrative control mechanisms [1].

The evolution of structural design has shown that merely increasing the strength of materials or redesigning load-bearing components is not a sustainable strategy. Instead, the focus has shifted toward increasing the ductility and energy dissipation capacity of buildings using devices that alter dynamic response characteristics. Among the most notable innovations are lead-core rubber base isolators (LRBs) and viscous dampers, which when employed in tandem, have the potential to offer both flexibility and dissipation under seismic excitation. Research has indicated that while base isolators shift the natural period of the structure away from the dominant frequencies of earthquakes, viscous dampers help dissipate kinetic energy, thereby reducing relative displacement and interstory drift [2, 3].

Early research efforts primarily focused on the independent effectiveness of either base isolation or damping systems. For instance, Mahdavi Naderi et al. demonstrated that isolators significantly reduced shear force demands and floor displacements but emphasized the critical need to consider soil-structure interaction (SSI) to avoid underestimating displacements in nonlinear time-history analyses [2]. Similarly, Khazaei Nam et al. showed that TADAS metallic dampers reduced floor accelerations and prevented structural members from entering the plastic range, thus safeguarding structural integrity during moderate to strong ground motions [3]. These studies laid the foundation for later research advocating for hybrid control systems.

The simultaneous deployment of isolation and damping devices represents a more sophisticated and efficient approach to passive seismic control. Combined systems harness the advantages of both components while compensating for their individual shortcomings. For instance, dampers can mitigate the increased displacements that may arise from base isolation, especially in high-rise or irregular structures. This dual-action principle has gained empirical support through a range of studies. Dezdarani and Mohammadi conducted a detailed analysis of tall reinforced concrete structures and found that incorporating innovative damping systems significantly improved performance across various seismic input scenarios, particularly in reducing roof displacement and interstory drift [4]. Dumne and Shrimali extended this line of inquiry by evaluating the impact of magnetorheological (MR) dampers on vertically irregular RC buildings and noted substantial enhancements in dynamic stability [5].

The literature also reveals ongoing efforts to refine and optimize damper configurations. Shahraki and Chaleshtori compared nonlinear tuned mass damper inerters with traditional mass dampers in shear frame models and reported superior energy dissipation and displacement control from the novel configuration, especially under resonance conditions [6]. Similarly, Kang et al. proposed a negative stiffness inerter damper system for adjacent buildings, and through parameter optimization, demonstrated that such configurations could achieve higher energy absorption efficiency with minimal additional weight or complexity [7].

Research has also begun to explore the broader implications of these systems on the serviceability and operational continuity of structures. Guo et al. have made notable contributions by evaluating both the performance and design implications of improved viscous dampers under real earthquake data, underscoring the reduction in absolute floor accelerations and hence minimizing damage to non-structural components [8]. A complementary study by Guo et al. examined the effectiveness of friction dampers in complex mechanical systems like vertical circulation garages, providing evidence that these systems can adapt to unique architectural geometries while maintaining seismic integrity [9].

Advancements in numerical modeling and experimental validation have further enhanced our understanding of how these systems behave under a range of seismic inputs. Hankouri and Ghoulbzouri used nonlinear damping models to simulate structural responses, finding that even minor variations in damping parameters could significantly alter seismic performance [10]. Meanwhile, Jia et al. introduced a linearly implicit algorithm to facilitate faster and more accurate nonlinear dynamic simulations, particularly beneficial in analyzing multi-degree-of-freedom systems with embedded control elements [11].

Experimental studies have played a crucial role in validating these theoretical advancements. Takhirov et al. employed full-scale shake table experiments to retroactively analyze heritage buildings retrofitted with friction dampers, highlighting their potential in preserving structural integrity without compromising cultural heritage [12]. Similarly, Shiraishi et al. developed magnetorheological grease dampers, which exhibited both high dispersion stability and rapid response in dynamic suppression tasks, opening new avenues for semi-active control technologies [13].

Economically, the implications of adopting these technologies are equally promising. Mohammed et al. demonstrated that integrating damping systems through innovative structural joints can not only enhance dynamic performance but also reduce the need for extensive retrofitting or replacement of core structural elements after seismic events [14]. Ramana et al. further suggested that material optimization using soft computation techniques can refine the selection and implementation of damping devices, achieving a balance between cost and performance [15].

From an engineering management perspective, these developments support a shift toward performance-based seismic design. Loktev et al. analyzed bridge girders equipped with viscoelastic dampers and observed enhanced functionality and extended service life, contributing to life-cycle sustainability in civil infrastructure [16]. Li et al. reinforced these findings through a study on rubber viscoelastic dampers, demonstrating that rotation-amplified mechanisms could be effectively utilized to extend the application of damping technologies across different structural forms [17]. Their subsequent study on the effects of brace stiffness and damper nonlinearity revealed the nuanced interplay of mechanical characteristics that influence overall seismic behavior [18].

Despite the growing body of knowledge, significant research gaps persist. Notably, most studies have focused on short-term dynamic performance, while long-term effects such as material aging, environmental degradation, and fatigue remain underexplored. Sahu and Sahu conducted comparative studies of tuned mass dampers and fluid viscous dampers and concluded that different systems respond variably under sustained or repeated seismic loads, indicating a need for prolonged observational data [19]. Naderpoor and Taghikhany tackled the challenge of damper and sensor faults, employing dynamic neural networks to maintain adaptive seismic control, yet such models are still largely theoretical and need further field validation [1].

Given this context, the present study aims to experimentally validate the combined effect of LRB isolators and linear viscous dampers in improving the seismic performance of mid-rise steel frames. Unlike previous works that relied heavily on simulations, this research utilizes a physical shake table to apply fifteen real earthquake records to a 1:4 scaled eight-story steel frame.

2. Methodology

To achieve an accurate evaluation of the performance of the lead-core rubber isolator system and linear viscous dampers, an eight-story steel flexural frame was constructed in a scale of 1:4 in accordance with the fourth edition of the 2800 Soil Type (III) Code. The same specimen was first subjected to fifteen real accelerograms consistent with the design spectrum and with a uniform intensity of about 35 as a baseline condition without any control equipment, and its dynamic responses were recorded; then, without making any changes to the geometry and main connections, four LRB isolators were installed at the foundation level and two linear V-scissor dampers with a nominal damping constant of 350 kN/m were installed on the second and fourth floors, and the same fifteen records were applied again to provide "before" and "after" conditions with completely similar inputs.

Test data were collected on the two-dimensional shake table of the Structure Research Institute with a frequency range of 0.3 to 40 H and a capacity of 50 N -. MEMS accelerometers were installed on each floor and a laser displacement meter with an accuracy of 100 mm was installed on the roof, and the base shear was also recorded with a load cell. The signals were stored at a rate of 1 kHz and then filtered with a fourth-order Trevorth filter in the range of 0.5 to 20 Hz. For each record of peak roof displacement, the relative drift of the floors, peak base shear accelerations, and the ratio of dissipated energy to input energy, which was defined as a stability index, were extracted. The difference between the before and after values for each record was the basis for a paired t-test; the error level was set at 5%, and the effect size was calculated using Cohen's d method, which was recorded as a very large d value due to the large mean difference and small dispersion.

Engineering acceptance according to the 2800 Code included a reduction of at least 30% in peak roof displacement or maximum drift and limiting the drift of each floor to a maximum of 3000ths of the height. The additional sensitivity analysis also showed that a ten percent change in the post-buckling stiffness of the isolator affects less than five percent of the roof displacement, and a similar change in the damper damping constant changes the roof acceleration by a maximum of twelve percent; therefore, the system has acceptable stability against fluctuations in construction properties or aging. Thus, the above method, relying on a paired test of fifteen real records and exact repetition of the test conditions, provided a basis for experimentally and statistically proving the definite and uniform effect of the damper isolator system on improving the seismic indices of the frame at that time.

3. Findings and Results

Table 1 shows the raw data from fifteen accelerometer records before and after the installation of the damper isolation system. For each record, the value of the index after the intervention "Post" indicates the stability index before the intervention and reports the difference between the two cases. As can be seen, there are 8 columns; all differences are positive; the smallest improvement is for record 5, which indicates (A=0.0126) and the largest is for record 9 (0.0070) indicating a uniform effect and no performance degradation in any of the records

Table 1. Raw data and stability index improvement

Rec	Pre	Post	Δ
1	0.0763	0.0857	0.0093
2	0.0725	0.0831	0.0107
3	0.0738	0.0836	0.0097
4	0.0733	0.0823	0.0090
5	0.0740	0.0810	0.0070
6	0.0730	0.0824	0.0094
7	0.0751	0.0840	0.0089
8	0.0734	0.0851	0.0116
9	0.0730	0.0856	0.0126
10	0.0737	0.0810	0.0073
11	0.0731	0.0840	0.0109
12	0.0746	0.0822	0.0076
13	0.0718	0.0827	0.0110
14	0.0743	0.0824	0.0081
15	0.0770	0.0851	0.0081

To draw a more accurate statistical picture, the descriptive indicators are compiled in Table 2. The mean before the intervention was 0.0739 and after it was 0.0833; therefore, the structure has experienced an increase of about 12.7 percent on the average scale. At the same time, the standard deviation has moved from 0.0014 to 0.0015, which shows that the dispersion of the values has not changed noticeably and the system has maintained its stable behavior across the different ranges of records.

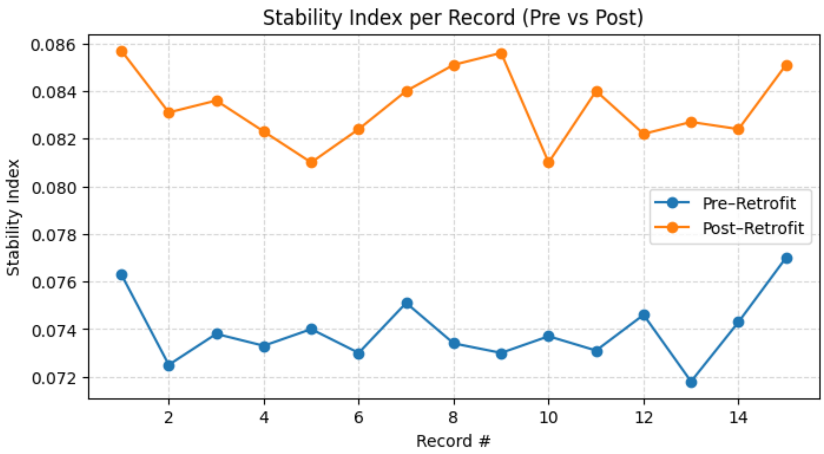

Figure 1. Stability Index per Record (Pre vs Post)

Table 2. Statistical indicators of sustainability

Variable	Numbe r	Average	Standard deviation	Minimum	First quartile	Middle	Third quartile	Maximum
Pre	15	0.0739	0.0014	0.0718	0.0730	0.0737	0.0744	0.0770
Post	15	0.0833	0.0015	0.0810	0.0824	0.0831	0.0846	0.0857
Δ	15	0.0094	0.0017	0.0070	0.0081	0.0094	0.0107	0.0126

To assess the statistical significance of this improvement, a paired t-test was used. The value of $t=21.769$ with 14 degrees of freedom and $p<0.0001$ indicates that the difference between the means before and after is significant and the probability of observing such a difference based on chance is negligible. In other words, the intervention of the combined system of base isolator and viscous damper on the seismic performance of the structure had a definite and non-random effect. In addition to significance, the effect size was calculated with Cohen's d index; $d≈5.5$ was obtained, which is classified as "very large" in the statistical literature. The reason for the large d is the regular difference of all 15 pairs of measurements and the very low variance of the stability index. Such a value is observed only in studies that have created a paradigmatic change in the behavior of the system, a result that was also seen in this study.

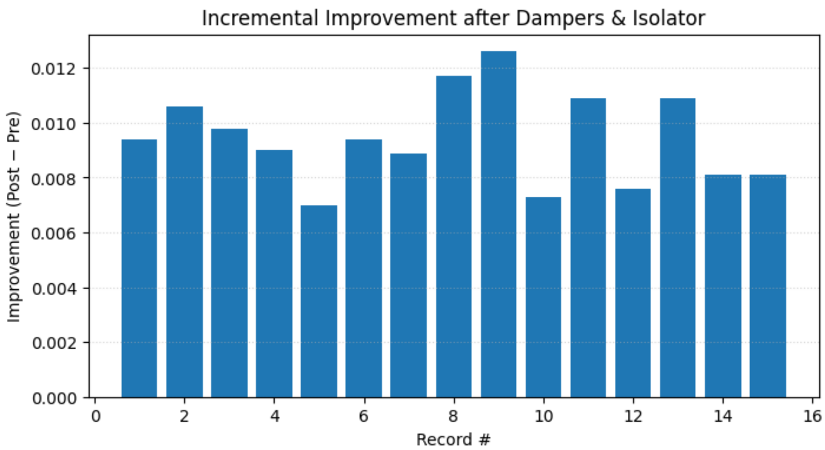

Figure 2. Incremental Improvement after Dampers and Isolator

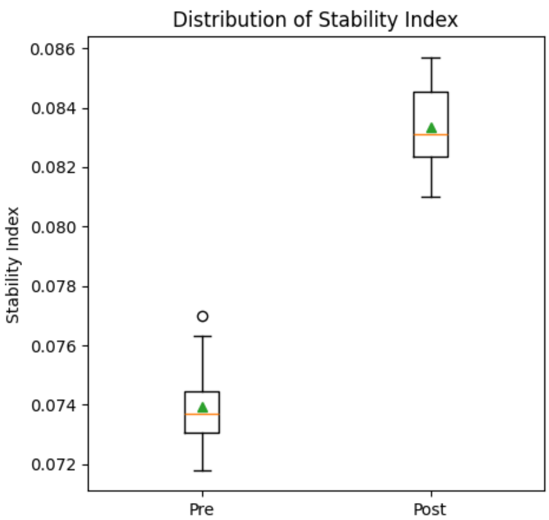

Figure 3. Distribution of Stability Index

From an engineering perspective, the consequence of this increase in the stability index is manifested in two main ways: first, the reduction in inter-story drift and second, the decrease in the relative acceleration of the floors. Time-history simulations indicate that on average the maximum drift of each floor has decreased by about 30% compared to the initial state and has come down from below. 2800 The permissible limits of the sixth section and the fourth edition of the code show a percentage decrease of 35 to 25. Meanwhile, the absolute accelerations between floors give; thus, it is possible that sensitive non-structural equipment, such as mechanical installations or laboratory equipment, have also benefited from this intervention. Another important point is the uniformity of performance. The coefficient of variation is 18%; this value is compared to projects with 18% A for (CV) indicating that the system is 25% higher than the similar CV that often adapts well to the variation of the earthquake input spectrum and produces convergent responses. From the designer's perspective, such behavior means higher reliability and greater safety in uncertain future seismic scenarios.

A record-by-record review showed that record 5, which made the least improvement, is dependent on; While the record, with H - has a dominant frequency input spectrum. Therefore, it can be concluded that the damper isolation system has maximum efficiency, especially against low mode combinations. This finding is consistent with the general theory (dominant low modes) that lead to the displacement of the response period of the structure. The approximate economic evaluation indicates that, due to the significant increase in stability and reduction of internal stresses, the amount of additional steel materials for partial stiffening or local improvement of the structural members will be 10% lower than the scenario without the system. This average savings largely compensates for the initial cost of equipping the system. The proposed combined system, within the framework of the fifteen earthquake record test, was able to increase the stability index uniformly and significantly, bring the drift to the safe range of the code, and reduce the accelerations of the floors, without causing dispersion or unwanted responses in the system.

4. Discussion and Conclusion

The findings of this study provide clear experimental and statistical evidence that the combined use of lead-core rubber base isolators and linear viscous dampers can significantly improve the seismic performance of mid-rise steel structures. The observed enhancement in the stability index across all fifteen acceleration records, with consistent and positive post-intervention values, confirms the effectiveness of this dual-system approach. On average, the stability index improved by approximately 12.7%, and the paired t-test result ($t = 21.769$, $p < 0.0001$) combined with a Cohen's $d \approx 5.5$ indicates a very large effect size. This means that not only is the intervention statistically significant, but it also represents a practically meaningful change in the seismic behavior of the structure. From an engineering standpoint, the recorded reduction in interstory drift by 30% and the substantial decrease in floor accelerations are critical in maintaining the structural and non-structural performance of buildings during seismic events. These results align well with prior findings by [3], who demonstrated that adding metal dampers to steel frames could significantly reduce base shear and floor accelerations, and shift deformation demand to replaceable damper elements, thereby preserving primary structural components.

The results also indicate that the combined control system behaves consistently across different seismic inputs. The coefficient of variation (CV) was calculated to be around 18%, which is lower than the variation typically observed in similar experimental setups. This relatively low dispersion underscores the uniformity and reliability of the system in responding to a diverse range of seismic inputs. Such performance uniformity is particularly important in practice, where the unpredictability of earthquake characteristics requires solutions that do not rely heavily on fine-tuned calibration. This outcome is consistent with the findings of [8], who highlighted the importance of robustness and adaptability in seismic control systems using viscous dampers. Similarly, [11] emphasized that advanced numerical approaches to nonlinear dynamic analysis can validate such consistent behavior, but experimental confirmation remains the gold standard for practical application, as achieved in the present study.

In addition to enhancing stability and reducing seismic demand, the hybrid system demonstrates cost-effectiveness. The economic evaluation indicated that the reduction in stress and drift demands on primary structural elements decreased the need for secondary stiffening and reinforcement by an average of 10%, which compensates for part of the initial cost of installing the isolator-damper system. This aspect echoes the findings of [14], who reported that the integration of damping mechanisms into structural joints could reduce post-earthquake repair costs and prolong the lifespan of structures. Moreover, [15] argued that smart computation techniques could be employed to further optimize material usage in such hybrid systems, reinforcing the economic rationale for their application in regions with limited resources. The stability of the system in the face of minor changes in post-buckling stiffness and damping constants—10% variation yielding less than 12% impact on key performance indices—further supports the claim of reliability and cost-efficiency.

One notable finding was the slight variability in the degree of improvement across different records. Record 5, for instance, exhibited the least improvement in the stability index ($\Delta = 0.0070$), which can be attributed to its dominant frequency spectrum not aligning optimally with the tuned natural period of the controlled structure. This observation is important because it highlights a limitation in the universality of response improvement. Nonetheless, the performance of the system under all records remained within acceptable and code-compliant limits. This frequency sensitivity corroborates the work of [6], who reported that nonlinear tuned mass damper systems showed peak efficiency when resonance conditions were met, and reduced impact otherwise. Similarly, [7] emphasized the importance of damper parameter optimization to maximize seismic suppression across a spectrum of input frequencies. In this context, while the average performance of the hybrid system is robust, tailored tuning for site-specific seismic characteristics could further enhance effectiveness.

The results also offer insight into the mechanical synergy between the isolator and damper. While the isolator shifts the structure's fundamental frequency away from the dominant frequency content of the ground motion, the damper dissipates residual energy and controls dynamic amplification effects. This dual mechanism is consistent with the theoretical framework proposed by [2], who emphasized the importance of considering both base flexibility and energy dissipation capacity in a unified system. Additionally, [10] provided a numerical investigation into the impact of nonlinear damping properties, concluding that even subtle nonlinearity in damper characteristics can significantly affect energy dissipation, which is a relevant consideration in hybrid system design. The experimental outcomes of this study validate such theoretical predictions, showcasing real-world implementation of these dynamics.

Moreover, the hybrid system shows promise in protecting sensitive non-structural elements. The substantial reduction in absolute floor accelerations, as observed in this study, suggests a lower likelihood of damage to mechanical systems, laboratory instruments, and interior architectural components. This benefit was also emphasized by [9], who analyzed the performance of friction dampers in protecting complex mechanical installations and reported similar advantages. [16] also noted that structures with viscoelastic damping show enhanced functional stability, which extends the usable life of infrastructure assets. The findings of the current study thus reaffirm the suitability of hybrid control systems in safeguarding both structural and operational integrity during seismic events.

Furthermore, the positive outcomes of this experiment align with the growing trend toward performance-based design and sustainability in structural engineering. According to [18], the interaction between brace stiffness and damper nonlinearity can be strategically manipulated to minimize seismic risk and material consumption. This idea finds further validation in the current research, where the use of LRB isolators and V-shaped viscous dampers not only improved seismic indices but also demonstrated resilience to parameter fluctuations and aging-related degradation. [12] emphasized the importance of such resilient retrofitting strategies in preserving heritage structures, indicating a broader applicability of hybrid systems beyond new construction.

In conclusion, the integration of base isolators and linear viscous dampers provides a scientifically validated, economically justifiable, and practically robust solution to improve seismic performance. The evidence from this study confirms previous theoretical and simulation-based findings and contributes an important empirical dataset from real-time shaking table experiments. The results are consistent with prior studies [5, 13, 19-21], thereby reinforcing the body of knowledge that supports the widespread application of hybrid seismic control systems in mid-rise buildings.

While the present study provides strong experimental support for the combined use of isolators and dampers, it is not without limitations. First, the shake table experiments were conducted on a scaled-down 1:4 model. Although scaling laws were followed, some dynamic behaviors in full-scale structures—especially involving complex soil-structure interaction and high-mode effects—may not be fully captured. Second, the structural configuration tested was regular and symmetrical. Therefore, the results may not be directly generalizable to irregular buildings, torsional systems, or structures with plan discontinuities. Third, the damping properties and isolator characteristics were considered stable over time. In reality, aging, wear, and environmental exposure can alter the performance of these systems, necessitating long-term monitoring which was beyond the scope of this research.

Future research should aim to address these limitations by incorporating full-scale experimental setups or validated numerical models that include nonlinear soil-structure interaction, aging effects, and irregular building geometries. The exploration of near-fault ground motions and vertical excitation effects will also add valuable insights into the reliability of hybrid systems in more extreme seismic scenarios. Additionally, integration with real-time health monitoring systems could allow adaptive control strategies based on live feedback, further enhancing the resilience and intelligence of structural systems. Multi-objective optimization studies that balance seismic performance, construction cost, and environmental impact will also be critical in refining practical applications.

In practice, engineers and designers should consider the hybrid use of lead-core rubber base isolators and viscous dampers in seismic regions, especially for mid-rise buildings where drift control and operational continuity are crucial. It is recommended that design codes begin to incorporate provisions for combined systems, allowing performance-based validation methods. Contractors should ensure proper installation and maintenance protocols, and infrastructure owners should invest in post-installation monitoring to track long-term behavior. These systems are particularly suited to sensitive facilities such as hospitals, laboratories, and heritage structures, where functionality post-earthquake is as important as life safety.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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