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Evaluation the Seismic Behavior of Irregular Moment Resisting Steel Frame with Combination System of Base Isolator and Friction Damper

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ABSTRACT

The seismic behavior of irregular steel frames with rigid contact members, incorporating the combined effects of seismic isolators and friction dampers, was comprehensively analyzed in this study. To evaluate the dynamic response under seismic loading, 3, 7, and 12-story irregular steel frames were subjected to time history analysis using the ground motion from the Tabas earthquake. This approach allowed for a detailed assessment of various damping configurations, including frames with only friction dampers, frames with seismic isolators, and those integrating both systems. The results revealed that friction dampers alone reduced base shear by 10%, 25%, and 35% for the 3, 7, and 12-story frames, respectively. Seismic isolators provided even greater reductions, achieving 20%, 35%, and 45% decreases for the same frames. Most notably, the combined use of dampers and isolators resulted in the highest reductions, lowering base shear by 30%, 45%, and 55%, respectively. These findings highlight the critical role of hybrid damping systems in improving the seismic resilience of irregular steel frames, especially as the frame height increases, where enhanced ductility significantly influences overall structural performance.

1. INTRODUCTION

Earthquakes pose a critical threat to human life and infrastructure, necessitating robust and scalable design methodologies, particularly in seismically active regions. With increasing urbanization and the complexity of modern architectural designs, the necessity for advanced seismic mitigation technologies has taken center stage. Effective earthquake-resistant systems not only aim to ensure structural integrity but also ensure operational continuity for critical infrastructure following seismic activity [1, 2].

Seismic design philosophy has undergone significant developments over the last decades, evolving from traditional strength-based design schemes to more comprehensive performance-based schemes of design. The new concepts aim not only at structural integrity but also at avoiding long-term loss of function and ensuring post-event functionality [3]. Prominent innovations include energy dissipation technologies such as friction dampers and seismic base isolators, which are used to reduce structural responses and seismic forces by modifying the dynamic characteristics of buildings. Importantly, the application of lead-core rubber isolators (LRBs) and friction dampers has been found to offer notable benefits of base shear reduction and overall enhancement of structural stability [4]. Apart from these, steel structures, being ductile and simple to build, exhibit good seismic behavior and possess scrap value when they are destroyed, thus are economical options [5].

Despite proven efficacy of LRBs and friction dampers in seismic mitigation, their joint usage is not as researched, particularly in the event of irregular buildings whose seismic response is inherently complex. Stiffness, geometric, or mass irregularities yield unevenly distributed forces sideways, localized damage, and higher vulnerability during earthquakes. These effects become further intertwined in multi-story building configurations, whose higher-mode vibration and structural coupling get proportionally boosted, potentially contaminating overall stability [6, 7].

Though plenty of research has focused on the isolation use of friction dampers and base isolators in standard frames, thorough examinations of their interaction phenomena in irregular frames are sparse [6, 8, 9]. Previous studies disregard the interactive dynamic behavior of these systems, particularly in non-uniform height structures and complex geometric configurations. This discrepancy is important, as non-standard frames are widely employed in contemporary architectural designs, where preservation of structural stability during earthquakes is vital [10].

Earlier studies have proven the effectiveness of friction dampers in reducing interstory drifts and energy demands in regular and irregular frames [6, 8, 9]. They have, for instance, been shown to reduce base shear by up to 40% in regular frames and by the same amount in irregular structures under certain conditions [11, 12]. Similarly, it has been demonstrated that LRBs can efficiently minimize base shear and protect both structural and non-structural components by decoupling the superstructure from the ground motion and hence reducing transmitted forces [10]. In addition, recent studies identify the crucial role played by interconnections in determining the overall rigidity and seismic response of moment-resisting frame buildings.

As the increasing dominance of irregular high-rise structures in seismically active regions, particularly in densely populated cities, demands urgent attention, there is a need for novel seismic control systems that would effectively address these special requirements. As resilience and post-event performance issues are more relevant than ever, the applicability of this research to current practice is very high [13].

The aim of this study is to evaluate the combined effect of lead-core rubber isolators and friction dampers on seismic performance of irregular steel moment-resisting frames (MRFs). Specifically, the research aims to identify their influence on critical response parameters like:

- Lateral displacement at the top level
- Base shear reduction
- Total energy dissipation

The primary purpose of this paper is to provide a comprehensive understanding of the synergistic effect of friction dampers and LRBs on the enhancement of the seismic performance of irregular steel frames. By comparing the structural response of frames under various configurations (bare frame, damper alone, isolator alone, and combined systems), the research seeks to make meaningful contributions to the design and optimization of hybrid seismic control strategies for irregular structures, prioritizing the improvement of resilience and minimization of long-term damage in seismic areas [4, 14, 15].

2. METHODOLOGY

The objective of this research is to comprehensively assess the seismic performance of irregular steel moment-resisting frames of varying heights, specifically 3-story (short), 7-story (medium), and 12-story (tall) structures. These frames exhibit two primary types of irregularities: geometric height irregularities and stiffness height irregularities, which reflect the complex architectural and structural features often encountered in modern high-rise buildings.

In the first phase of the study, the frames were analyzed without any supplemental damping or isolation systems, serving as the baseline configuration. In subsequent phases, the seismic response of these frames was evaluated with the addition of friction dampers and lead-core rubber isolators, first separately and then in combination, to capture the distinct and synergistic effects of these energy dissipation devices. This multi-stage approach provides a detailed understanding of the individual and combined influence of these passive control systems on key response parameters, including top story displacement, interstory drift, and base shear.

The analyses were conducted using advanced nonlinear time history simulations in SAP2000, a widely recognized structural analysis platform known for its robust capabilities in capturing complex inelastic behavior under realistic seismic loading condition [16].

2.1 Frame configurations and structural irregularities

The frame models were configured as three-span, multi-story moment-resisting frames in which every span was 5 meters long with a story height of 3 meters normally as shown in Figure 1, as is routinely practiced in mid- to high-rise construction [17]. The above configuration accommodates the height-dependent seismic behavior of irregular frames, including higher-mode response, complex patterns of vibration, and stress concentration concentrated at regions [18].

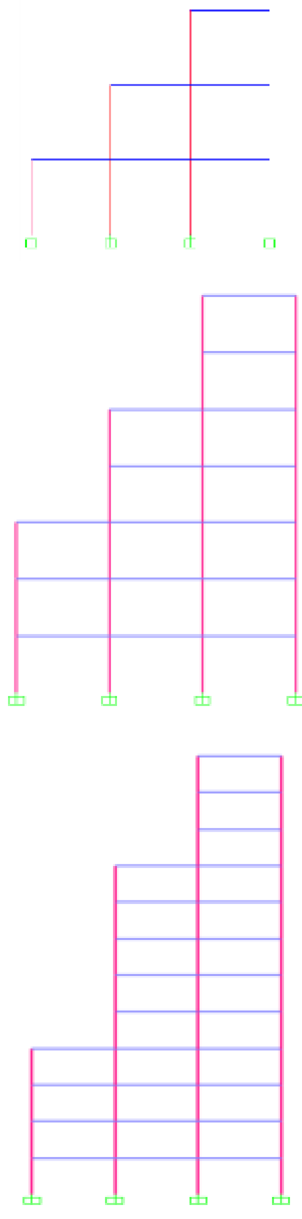

Figure 1. Irregular steel frames of 3, 7, and 12 stories

Geometric Irregularities: Geometric irregularities were obtained by modifying the height and mass distribution in the frames, simulating actual architectural plans with setbacks, vertical offsets, and asymmetrical arrangements. The 7-story and 12-story frames included abrupt changes in cross-sectional size and column heights, demonstrating typical irregularities in modern high-rise buildings with open ground floors, podium levels, or vertically offset floor plates. These irregularities have a significant influence on the dynamic response by increasing torsional modes, increasing inter-story drift, and concentrating seismic demands in localized areas and leading to localized yielding and potential collapse of the structure

Stiffness Irregularities: Stiffness irregularities were introduced by altering the lateral stiffness of different stories, simulating the impact of open floors, reduced bracing, and modifying the structural configurations. These alterations depict extreme variations in lateral stiffness present in real structures, where lower stories have reduced stiffness due to large open areas, and higher stories may have reduced mass and stiffness due to smaller floor plates. They have a far-reaching impact on the distribution of seismic forces, inducing soft-story mechanisms and higher-mode effects that increase the likelihood of localized damage and structural instability [19].

2.2 Material properties and nonlinear behavior

The frame members were modeled employing high-strength, ductile material properties typical of contemporary seismic frames. The steel was modeled with a yield strength of 350 MPa and elastic modulus of 200 GPa, which are typical grades used in the construction of high-rise buildings nowadays [20]. The material model employed bilinear elastoplastic behavior to model the entire range of yielding, plastic deformation, and strain hardening. It entailed the application of the Bauschinger effect, the reason behind reduced yield strength when loading in reverse direction, a factor that profoundly influenced the whole ductility as well as the energy absorption behavior of the frame. The steel further received a density of 7850 kg/m³ and Poisson's ratio of 0.3 in order to attain accurate mass calculations and inertia. These characteristics were designed specifically to replicate the real high cyclic loading behavior of structural steel in real-world situations, including significant events such as local buckling, flange and web yielding, and strain hardening.

2.3 Boundary conditions and foundation modeling

In order to model realistic foundation behavior, the frames were modeled with fixed base conditions that restrict translational and rotational movements at the support level. This is an assumption that models the stiffening effect of reinforced concrete footings or deep foundations, which has a great influence on the total lateral stiffness and natural frequencies of the structure [21]. But it also possesses some disadvantage in that it excludes the potential effect of soil-structure interaction (SSI) that has potential to change the seismic response in flexible or soft ground. Such a limitation can be avoided by future research utilizing more advanced models of foundations, like pile-soil-structure interaction (PSSI) and soil impedance effects, to model the whole range of soil-structure interactions.

2.4 Gravity and seismic loading conditions

The frames were subjected to comprehensive loading conditions, including both gravity loads (dead and live loads) and dynamic seismic loads. The gravity loads included the self-weight of the structural steel members, floor slabs, and additional superimposed dead loads, reflecting typical building occupancy classifications such as office, residential, and commercial uses [22]. Seismic loading was applied using the Tabas earthquake ground motion record, characterized by high peak ground acceleration (PGA > 0.6g) and long-duration, high-frequency content. This record was selected to impose severe demands on both the primary structural elements and the seismic control devices, providing a rigorous test for the hybrid control system. The ground motion was scaled to match the design spectra for each building height, ensuring accurate representation of the seismic hazard [23]. In order to perform the analysis, the time history dynamic analysis method is used. In this regard, the Tabas earthquake record, whose acceleration-time curve is shown in Figure 2, is used.

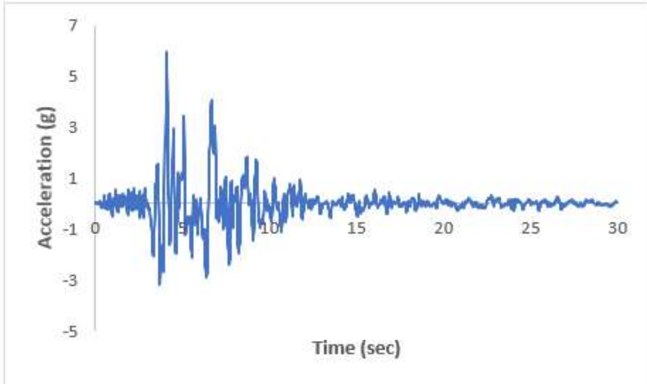

Figure 2. Acceleration-time curve of the Tabas earthquake for the purpose of performing dynamic analysis of the time history of the frames

2.5 Modeling of friction dampers and lead-core rubber isolators in SAP2000

Friction dampers were incorporated into the frame models as nonlinear link elements, strategically placed at critical beam-to-column connections to effectively control inter-story drift and dissipate seismic energy through controlled sliding. These elements were characterized by a set of precise mechanical properties designed to capture their distinctive bilinear hysteretic behavior [24].

The slip load, also known as the yield threshold, represents the force required to initiate sliding and was calibrated based on expected peak story shears. This threshold typically ranged from 10 kN to 50 kN, varying according to the frame height and the anticipated seismic demand [25]. The energy dissipation efficiency of the dampers was governed by the friction coefficient, which generally fell within the range of 0.3 to 0.6, depending on the materials used at the sliding interfaces.

Additionally, a post-yield stiffness component, typically defined as 2% to 5% of the initial stiffness, was included to provide residual resistance once sliding begins, ensuring structural stability under repeated cyclic loading [26]. To further enhance performance, viscous damping characteristics were incorporated, capturing rate-dependent effects that are particularly effective in reducing peak accelerations and controlling higher-mode vibrations, thereby improving overall structural resilience under seismic excitation as shown in Figure 3(A) [26].

Lead-core rubber isolators were incorporated at the base of the frames as nonlinear spring elements, specifically designed to decouple the superstructure from ground motion, thereby significantly reducing the forces transmitted to the structure during seismic events. These isolators were characterized by a set of well-defined mechanical properties that capture their complex bilinear hysteretic behavior as shown in Figure 3(B), which is crucial for effective energy dissipation and lateral stability [27].

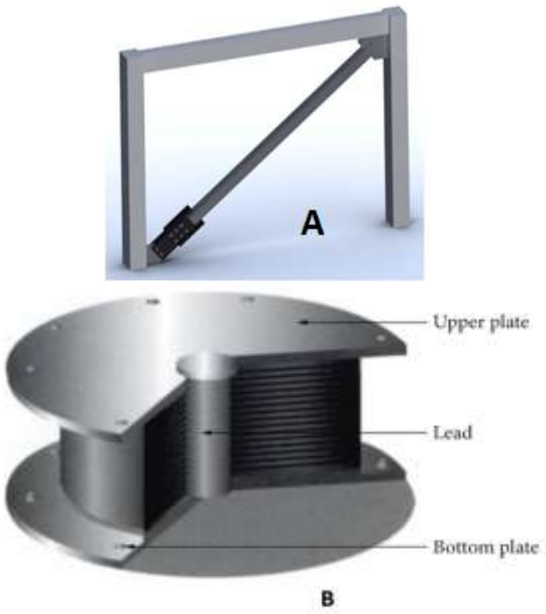

Figure 3. Friction damper and Lead Rubber Bearing (LRB) isolator

The initial stiffness of these isolators is deliberately set high, typically ranging from 100 kN/mm to 300 kN/mm, to provide the necessary lateral stability under service loads and prevent excessive displacements during minor seismic events [28]. Upon yielding of the lead core, the post-yield stiffness is substantially reduced to approximately 10% to 20% of the initial stiffness, allowing the isolator to accommodate large displacements while maintaining overall stability.

The yield strength of the isolators, which governs the transition from elastic to inelastic behavior, is calibrated based on the expected base shear and typically ranges from 50 kN to 200 kN, depending on the mass and seismic demand of the structure. Additionally, the damping ratio of these isolators is set between 15% and 25% of critical, reflecting their inherent high-energy absorption capability, which is essential for effectively reducing structural responses during strong ground motion [29].

To accurately capture the significant energy absorption provided by the yielding lead core, the hysteretic behavior of these isolators was modeled with pronounced, stable hysteresis loops, ensuring reliable performance under repeated cyclic loading [29]. This combination of high initial stiffness, reduced post-yield stiffness, substantial yield strength, and robust hysteretic behavior makes lead-core rubber isolators highly effective in enhancing the seismic resilience of high-rise structures.

3. FINDINGS

This section presents the numerical results of nonlinear time history analysis performed on irregular steel moment-resisting frames (MRFs) under seismic loading conditions. The results are focused on seismic response of three building configurations 3, 7, and 12 story irregular frames and subjected to the Tabas earthquake record. Each setup was tested under four seismic control conditions: (1) bare frame (no damping or isolation), (2) frame with friction dampers but no base isolation, (3) frame with base isolation but no friction dampers, and (4) hybrid system with both base isolators and friction dampers.

Major response parameters studied include top-story horizontal displacement, base shear, and total energy absorption. The objective of the comparative study is to quantify quantitatively the relative performance of each control strategy and determine the synergistic advantages of the hybrid system. The results are compared graphically in the form of time-history plots and cumulative energy curves for each building height, providing an integrated picture of how different damping mechanisms influence seismic performance for different structural configurations.

Figure 4 presents the time history of top-story lateral displacement for a 3-story irregular steel moment-resisting frame (MRF) subjected to seismic loading, comparing four structural configurations: a bare frame, a frame with friction dampers, a frame with base isolation, and a hybrid system incorporating both dampers and isolators. The bare frame exhibited the largest peak displacements and sustained oscillations, particularly between 5 and 10 seconds, indicating a lack of sufficient damping and heightened sensitivity to seismic excitation due to geometric irregularity. Introducing friction dampers moderately reduced displacement amplitudes; however, the structure continued to oscillate at high frequencies, suggesting that dampers alone offered limited displacement control. In contrast, the base-isolated frame displayed a longer-period response and smoother displacement curve, effectively shifting the structural response away from the dominant frequencies of the ground motion. Although its peak displacement was not significantly lower than the damped frame, the isolation system clearly altered the dynamic characteristics of the structure. The most favorable performance was observed in the hybrid configuration, which exhibited the lowest displacement amplitudes, rapid decay of vibrations, and minimal residual displacement. This result underscores the complementary benefits of combining dampers and isolators where isolation extends the natural period of the structure and dampers dissipate energy resulting in a synergistic effect that significantly enhances seismic performance.

Figure 5 illustrates the base shear response over time for a 3-story irregular steel moment-resisting frame subjected to seismic excitation, evaluated under four control configurations: a bare frame, a frame with friction dampers, a frame with base isolation, and a hybrid system combining both dampers and isolators. The bare frame (blue curve) records the highest base shear amplitudes, exceeding ±300 N, indicating that the structure fully transmits ground motion forces without any mitigation, which is typical for short, stiff frames lacking energy dissipation or decoupling mechanisms. With the addition of friction dampers (orange curve), there is a moderate reduction in peak base shear; however, significant oscillations persist, suggesting that while dampers help dissipate energy, they do not significantly decouple the structural response from the input motion. The isolated frame (gray curve) demonstrates a more substantial decline in peak shear values, reflecting the effectiveness of base isolation in elongating the structural period and reducing ground force transmission. The most favorable response is observed in the hybrid configuration (yellow curve), which achieves the lowest base shear peaks and the fastest decay of oscillations.

This synergy arises from the isolator reducing the fundamental frequency interaction with the ground motion and the damper enhancing energy dissipation. Overall, the hybrid system provides the most efficient seismic mitigation by limiting both the magnitude and duration of base shear, thereby enhancing the structural performance of low-rise irregular frames under earthquake loading.

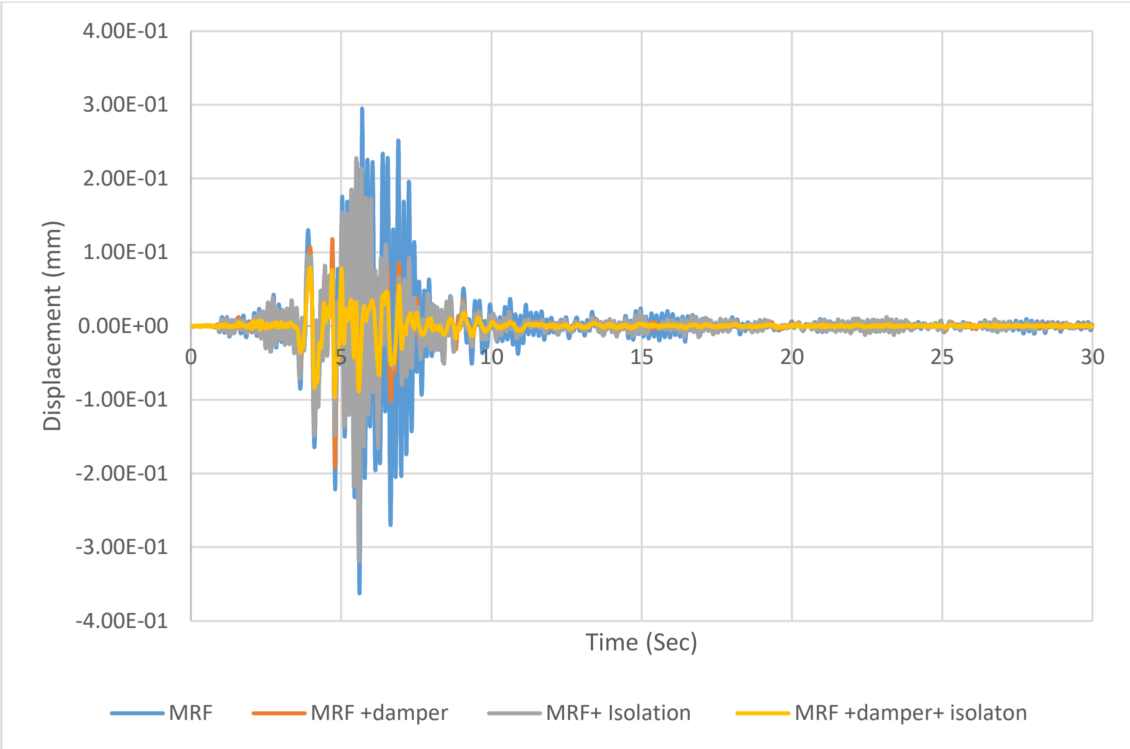

Figure 4. Comparison of lateral displacement changes for a 3-story frame under earthquake action 1: Frame without damper and isolator 2: Frame with damper 3: Frame with isolator 4: Frame with damper and isolator

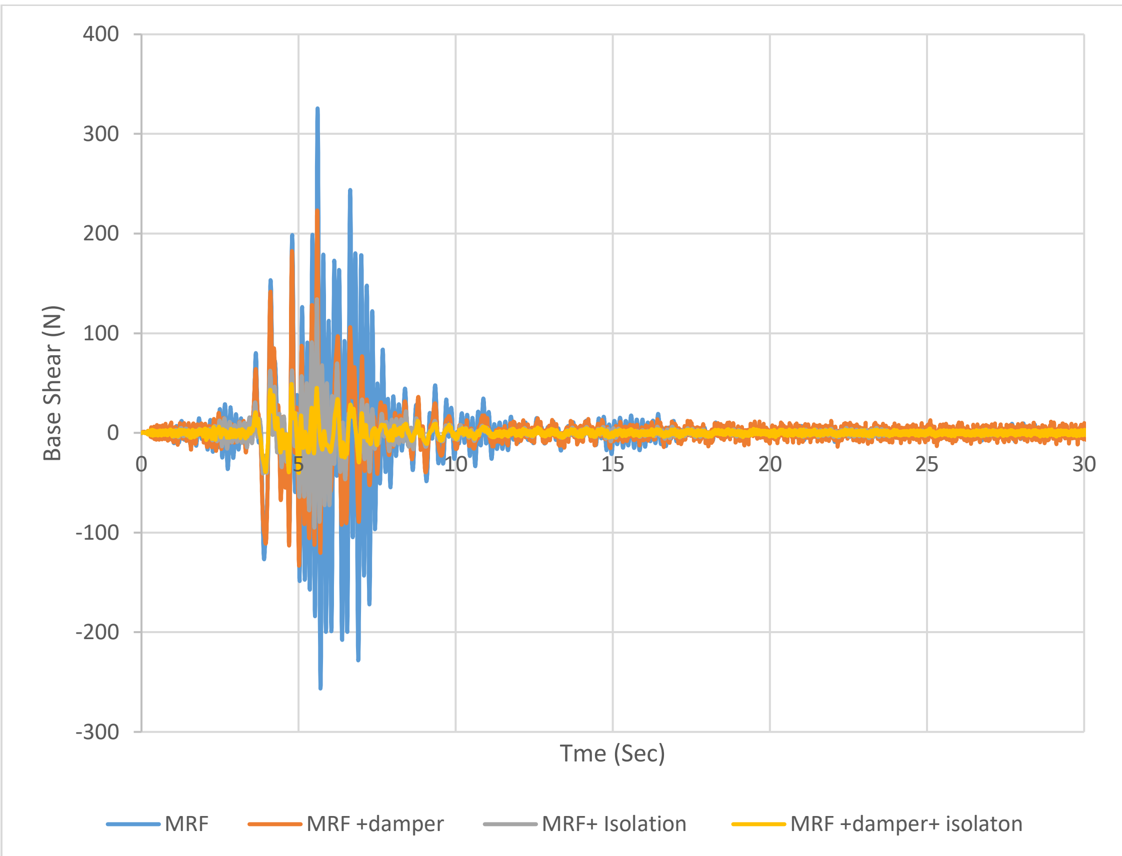

Figure 5. Comparison of base shear changes for a 3-story frame under earthquake action 1: Frame without damper and isolator 2: Frame with damper 3: Frame with isolator 4: Frame with damper and isolator

Figure 6 presents a comparison of cumulative energy absorption in a 3-story irregular steel MRF subjected to seismic excitation, under four structural configurations: a conventional MRF without any control devices, MRF with a friction damper, MRF with a base isolation system, and MRF with a combined damper–isolation system. The plot shows a clear divergence in the energy curves beginning around 10 seconds, coinciding with the arrival of peak ground acceleration in the Tabas earthquake record. The bare MRF accumulates the highest total energy, exceeding 11,000 J, which reflects the full extent of seismic energy being absorbed by the structural members, primarily in the form of plastic deformation and internal stresses. When a friction damper is introduced, the energy curve shifts downward, indicating that part of the input energy is dissipated through the damper mechanism, resulting in a lower total accumulation (~9,500 J). The base isolation system further improves energy management, reducing the energy demand on the superstructure to approximately 8,200 J. This result is attributed to the isolator's ability to decouple the building from the high-frequency components of the ground motion, thus softening the seismic input. The most favorable energy profile belongs to the combined damper–isolator system, which consistently shows the lowest total energy, leveling off around 7,000 J. This hybrid approach benefits from both period elongation (due to isolation) and direct energy dissipation (via friction damping), resulting in a more controlled and attenuated structural response. The gradual slope and earlier stabilization of the curve further emphasize the efficiency of this configuration in reducing dynamic energy accumulation. Overall, the results underscore the effectiveness of integrated seismic control strategies in minimizing energy demand and enhancing structural resilience in low-rise, irregular frames.

Figure 7 displays the time history of top-story lateral displacement for a 7-story irregular steel moment-resisting frame subjected to seismic loading under four configurations: the bare frame, the frame with friction dampers, the frame with base isolation, and the hybrid frame with both dampers and isolators. The bare frame (blue curve) exhibits the largest displacement amplitude, with sharp, high-frequency oscillations reaching nearly ±5 units, indicating significant vulnerability due to the structure's height and irregularity. The frame equipped with friction dampers (orange curve) shows a moderate reduction in displacement amplitude compared to the bare frame; however, the oscillations remain frequent and relatively prolonged, suggesting limited control over the structural response. The base-isolated frame (gray curve) demonstrates a clear transformation in dynamic behavior, characterized by a longer response period and smoother displacement curve. Although displacement amplitudes are still notable, the motion decays earlier, and the frequency content shifts away from that of the input ground motion. The most effective performance is observed in the hybrid configuration (yellow curve), where both the peak displacement and oscillation duration are minimized. This system combines the benefits of base isolation, which lengthens the natural period, with the enhanced energy dissipation offered by friction dampers. The result is a significantly improved control of seismic response, both in amplitude and stability, making the hybrid system particularly advantageous for mid-rise irregular structures.

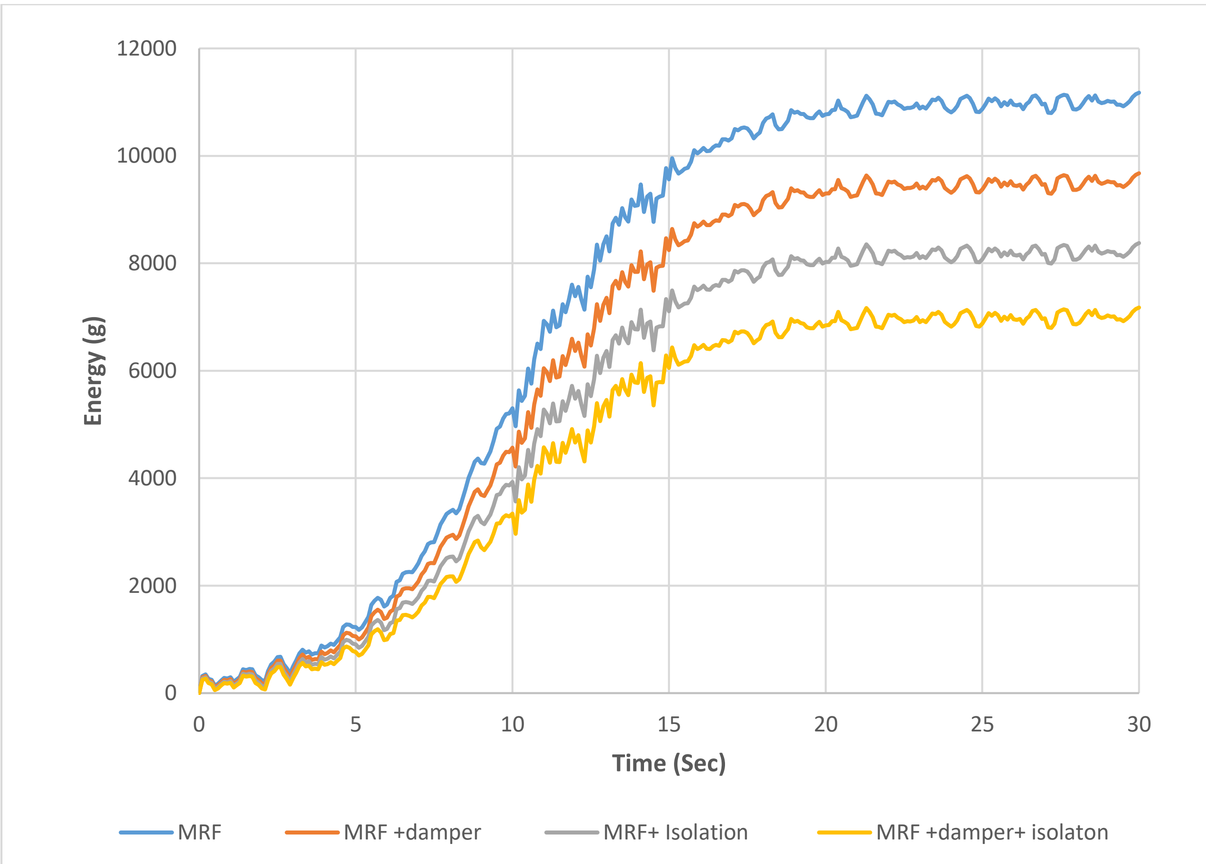

Figure 6. Comparison of energy changes for a 3-story frame under earthquake effects

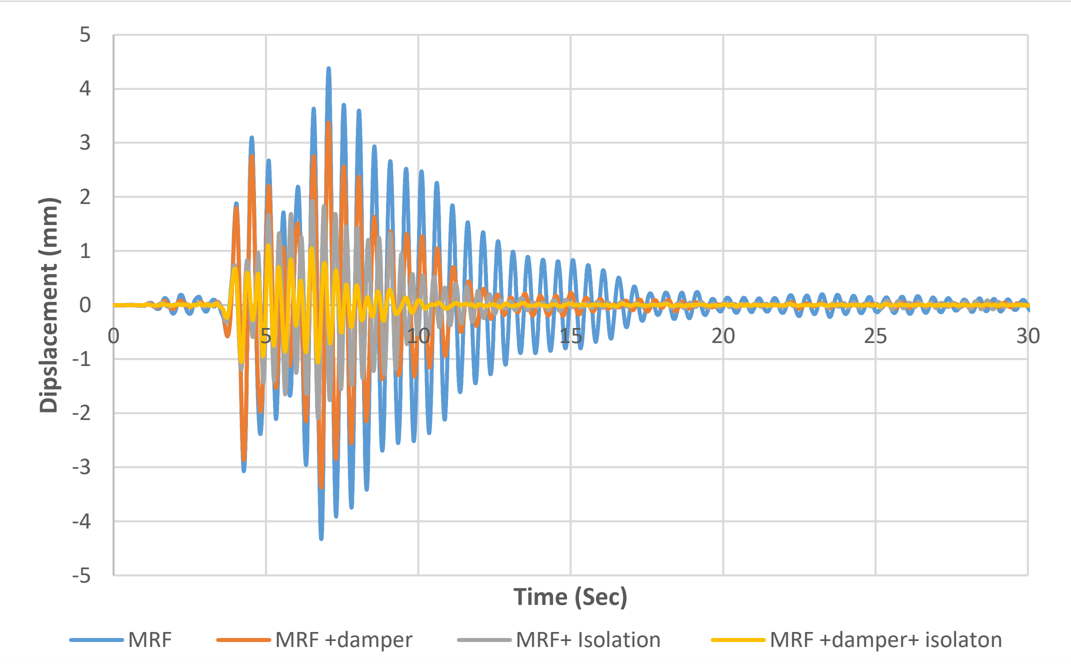

Figure 7. Comparison of lateral displacement changes for a 7-story frame under earthquake action 1: Frame without damper and isolator 2: Frame with damper 3: Frame with isolator 4: Frame with damper and isolator

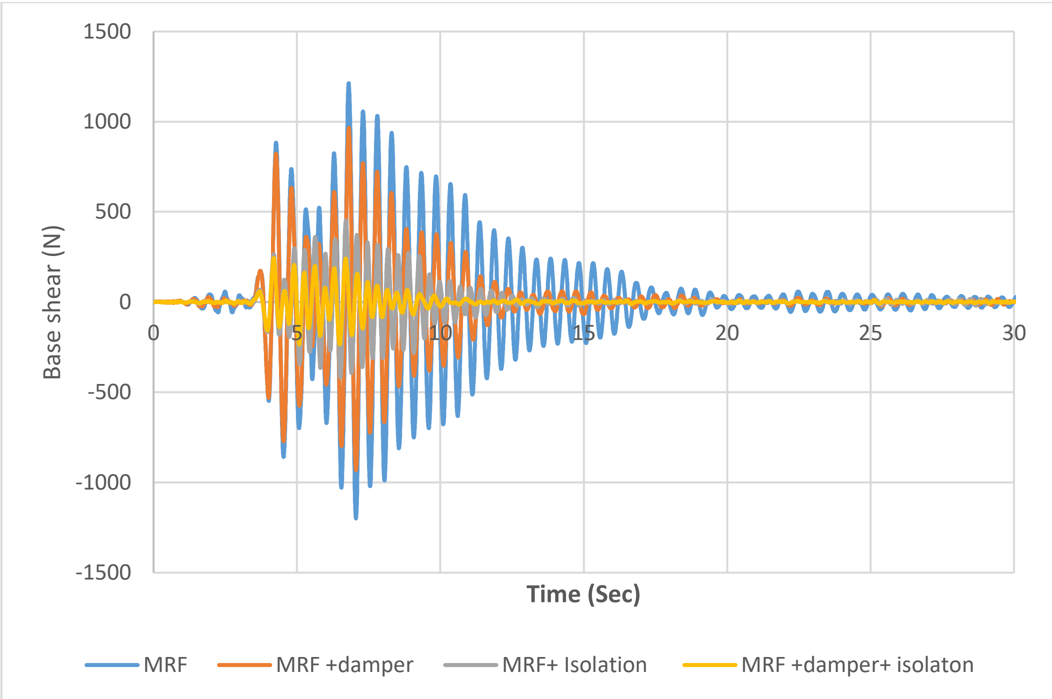

Figure 8. Comparison of base shear changes for a 7-story frame under earthquake action 1: Frame without damper and isolator 2: Frame with damper 3: Frame with isolator 4: Frame with damper and isolator

Figure 8 presents the time-history response of base shear for a 7-story irregular steel moment-resisting frame subjected to seismic loading under four different structural control configurations: a bare frame, a frame with friction dampers, a frame with base isolation, and a hybrid frame utilizing both dampers and isolators. The bare frame (blue curve) experiences the highest peak base shear forces, reaching values exceeding ±1200 N, accompanied by prolonged and high-frequency oscillations. This indicates a complete transfer of ground motion forces into the structure, typical of mid-rise irregular frames lacking energy dissipation or flexibility at the base, thereby increasing the risk of structural overstress. Incorporating friction dampers (orange curve) results in a moderate reduction in peak shear and a slight smoothing of the response, as the dampers dissipate part of the seismic energy. However, this setup does not significantly alter the force transmission path or response frequency. The base-isolated configuration (gray curve) exhibits a more noticeable reduction in both peak shear magnitude and oscillation intensity. This improvement is attributed to the isolator's ability to decouple the structure from the ground motion and shift the system's natural period, thus reducing resonance and force transfer. The hybrid configuration (yellow curve) demonstrates the best performance, combining the isolator's flexibility with the damper's energy dissipation. It results in the lowest base shear values and the fastest decay of oscillations, confirming its effectiveness in mitigating both the amplitude and duration of seismic forces. This dual mitigation approach makes the hybrid system particularly effective for mid-rise irregular structures where multiple vibration modes and force accumulation are critical design concerns.

Figure 9 compares the cumulative energy response of a 7-story irregular steel frame subjected to seismic loading for four configurations: a conventional moment-resisting frame (MRF) without control systems, an MRF with a friction damper, an MRF with base isolation, and an MRF with both damper and base isolator. The bare frame (MRF) exhibits the highest energy accumulation, reaching over 17,000 joules by the end of the earthquake duration. This steep and sustained increase reflects the intense vibrational energy absorbed directly by the structural members, primarily through inelastic deformation and stress concentration, typical of irregular mid-rise buildings lacking supplemental damping.

When a friction damper is introduced, total energy absorption decreases significantly to around 14,000 joules, illustrating the effectiveness of passive energy dissipation mechanisms in reducing internal demands. The curve is less steep than the bare frame, and its slope diminishes earlier, suggesting faster stabilization of the frame response.

In the case of base isolation, the energy profile shows further improvement, with a total energy accumulation of near 12,500 joules. The isolator effectively decouples the superstructure from seismic ground motion, delaying and diffusing input energy and thereby reducing stress transfer and plastic demand on the upper structure.

The combined system (MRF + Damper + Base Isolation) delivers the most efficient performance, as indicated by the lowest total energy accumulation, leveling off below 11,000 joules. This configuration demonstrates a synergistic behavior where the isolator limits energy transfer into the structure and the damper dissipates the remaining energy efficiently. The energy curve in this case rises more gradually and stabilizes more quickly than in all other configurations, clearly reflecting enhanced damping and reduced dynamic demand.

In summary, the use of a hybrid damper–isolation system in a 7-story irregular frame results in the most significant improvement in seismic energy performance, validating the dual strategy of period elongation and frictional dissipation as an effective mitigation approach for mid-rise structures.

Figure 10 illustrates the top-story lateral displacement response of a 12-story irregular steel moment-resisting frame under seismic loading for four structural configurations: the bare frame, the frame with friction dampers, the frame with base isolation, and the hybrid frame integrating both systems. The bare frame (blue curve) exhibits the largest displacement amplitudes, reaching nearly ±8 mm, with high-frequency oscillations and prolonged vibration duration, clearly reflecting the vulnerability of tall, irregular structures without any control mechanisms. The introduction of friction dampers (orange curve) leads to a moderate reduction in peak displacement and a slight improvement in decay rate; however, the overall vibration pattern remains within the structure's original frequency range, limiting its effectiveness. The base-isolated frame (gray curve) shows a longer-period and smoother response with lower displacement amplitudes, around ±6 mm, indicating a shift in dynamic characteristics due to the isolator's ability to decouple the superstructure from ground motion. Notably, the hybrid system (yellow curve) provides the most favorable performance, with the smallest displacement amplitude (under ±5 mm) and the fastest decay of oscillations. This configuration effectively combines the period lengthening benefits of isolation with the energy dissipation capacity of damping, resulting in a controlled, stable seismic response. Overall, the hybrid system demonstrates superior efficiency in minimizing lateral displacements and vibration duration, making it an optimal solution for enhancing the seismic resilience of high-rise irregular frames.

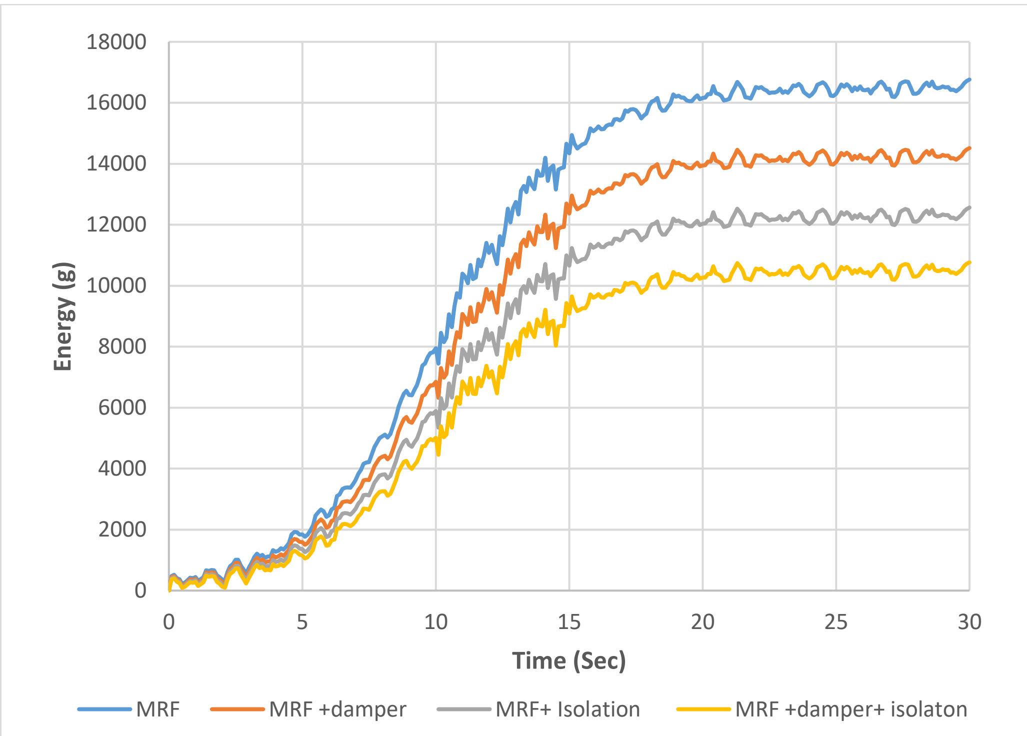

Figure 9. Comparison of energy changes for a 7-story frame under earthquake effects

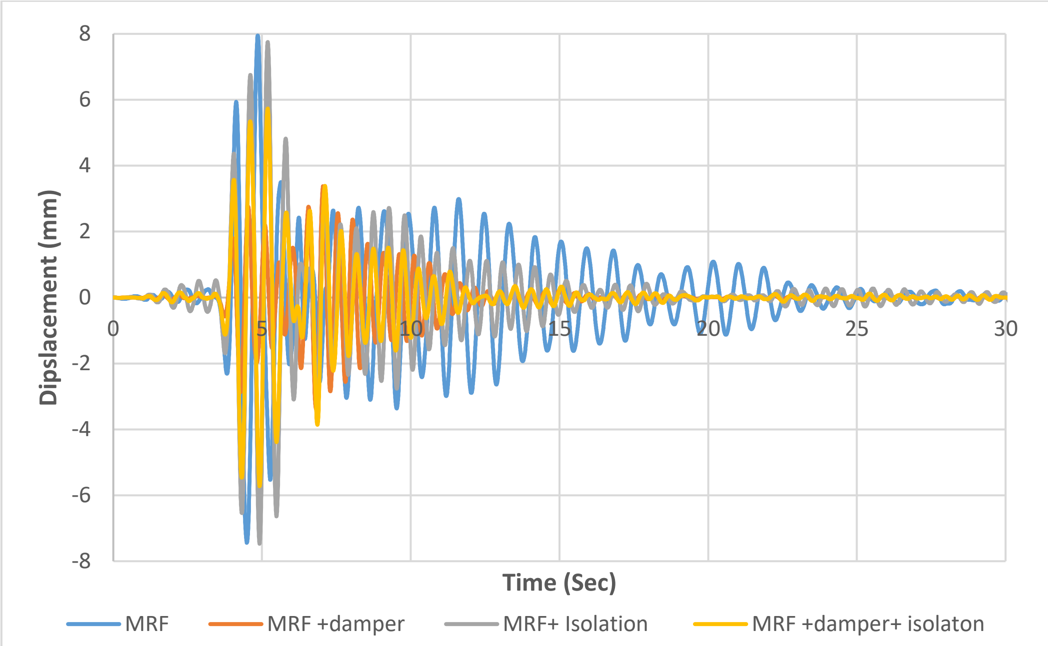

Figure 10. Comparison of lateral displacement changes for a 12-story frame under earthquake action 1: Frame without damper and isolator 2: Frame with damper 3: Frame with isolator 4: Frame with damper and isolator

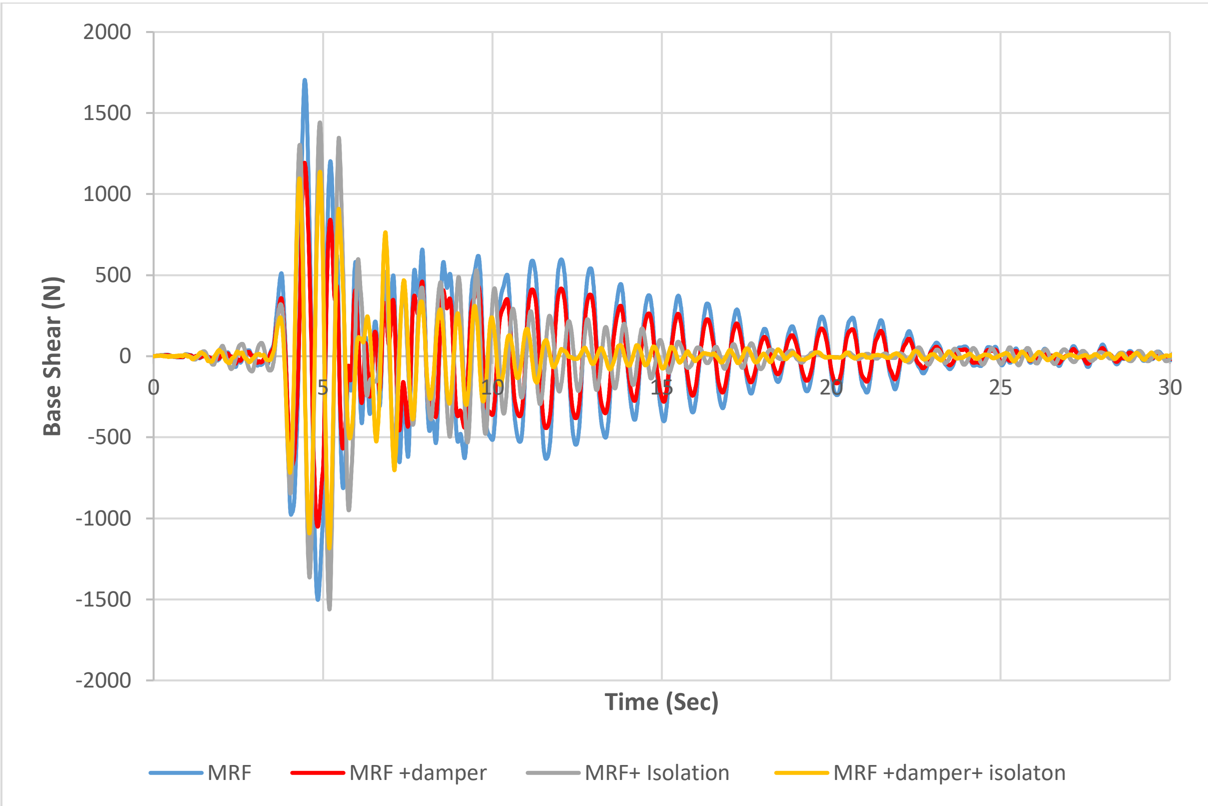

Figure 11. Comparison of base shear changes for a 12-story frame under earthquake action 1: Frame without damper and isolator 2: Frame with damper 3: Frame with isolator 4: Frame with damper and isolator

Figure 11 illustrates the base shear time-history response of a 12-story irregular steel moment-resisting frame under seismic loading for four structural configurations: a conventional bare frame, a frame with friction dampers, a frame with base isolation, and a hybrid system integrating both dampers and isolators. The bare frame (blue curve) exhibits the highest base shear amplitudes, exceeding ±1500 N, with intense and prolonged oscillations throughout the seismic duration. This indicates a full and unmitigated transfer of seismic forces from the ground into the structure, a critical issue in tall, irregular buildings where dynamic amplification and higher-mode participation are significant. Incorporating friction dampers (red curve) leads to a notable reduction in peak base shear, lowering it to around ±1000 N. While the overall oscillatory nature remains, the damping action contributes to a smoother decay and reduced duration, confirming the damper's ability to dissipate energy and limit structural force demands. The isolated frame (gray curve) exhibits an even further reduction in peak base shear (approximately ±750 N), coupled with a noticeable change in response frequency and quicker attenuation of vibrations. This reflects the isolator's role in elongating the structure's fundamental period and filtering high-frequency ground motion. The most favorable outcome is seen in the hybrid system (yellow curve), where the combination of base isolation and damping yields the lowest base shear amplitudes generally within ±600 N and the most rapid stabilization of response. The dual mechanism of shifting dynamic characteristics and dissipating residual energy proves highly effective in controlling seismic demands in high-rise irregular frames. Overall, this hybrid approach significantly enhances seismic performance by minimizing both the amplitude and duration of base shear forces, thereby improving the structure's resilience and reducing the risk of damage.

Figure 12 illustrates the variation of cumulative seismic energy absorption in a 12-story irregular steel moment-resisting frame subjected to earthquake excitation, evaluated under four structural configurations: the bare MRF without any control devices, the MRF equipped with a friction damper, the MRF equipped with a base isolator, and the MRF with a combined damper and base isolator system. As expected, the bare frame (MRF) absorbs the highest amount of seismic energy, exceeding 36,000 tons, which reflects a substantial accumulation of vibrational energy in the structure. This energy, primarily absorbed through inelastic deformation, indicates a high potential for internal damage and reduced post-earthquake functionality.

In the damper-only configuration, the cumulative energy decreases notably, leveling around 25,000 tons. The inclusion of a friction damper facilitates energy dissipation through controlled sliding and mechanical friction, reducing the demand on structural components. Although effective, the response still reflects elevated energy intake, which is characteristic of taller structures with multiple vibration modes and complex dynamic behavior.

The base isolator-only system results in a further improvement, with total energy absorption reduced to below 20,000 tons. The isolator shifts the system's natural frequency and decouples the superstructure from abrupt ground accelerations, thereby mitigating the intensity of energy transferred to the upper structure. This effect is particularly beneficial in high-rise frames, where base flexibility aids in limiting resonance amplification.

The hybrid system combining both damper and isolator offers the most efficient performance, with energy absorption stabilized just above 15,000 tons. This dual mechanism enhances seismic performance by both delaying and softening ground motion input (via the isolator) and dissipating the induced structural vibrations (via the damper). The energy curve of this configuration rises more gradually and reaches a lower final value than any other, indicating a well-controlled seismic response and minimized internal energy demands.

In conclusion, Figure 12 clearly demonstrates that the combined use of a friction damper and a base isolator in a tall, irregular frame significantly enhances seismic energy management and reduces the risk of structural and non-structural damage. This hybrid strategy is particularly well-suited for high-rise structures where large displacements and force amplification are critical concerns.

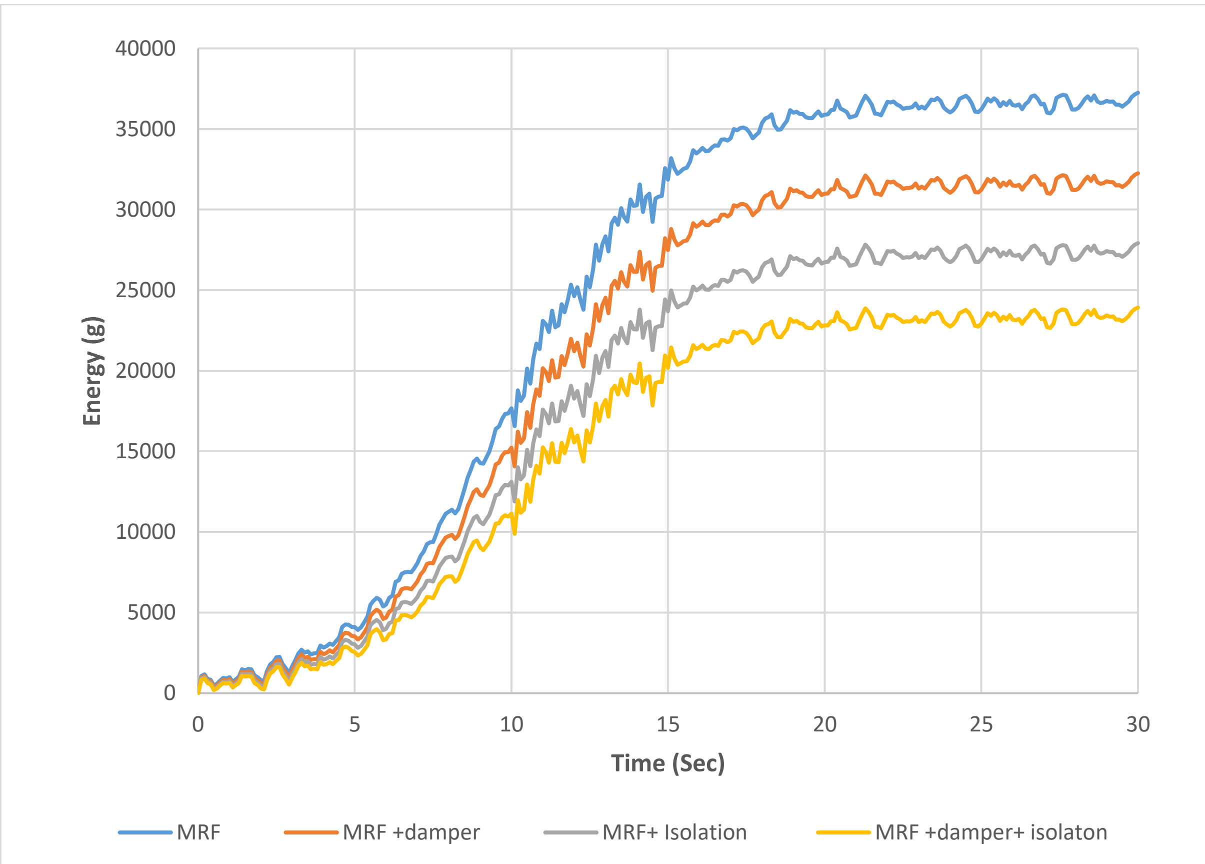

Figure 12. Comparison of energy changes for a 12-story frame under earthquake effects

4. CONCLUSION

The seismic behavior of irregular steel frames with rigid contact members, integrating the combined effects of seismic isolators and friction dampers, was thoroughly investigated in this study. The analysis focused on three frame configurations 3, 7, and 12 stories under the dynamic loading conditions of the Tabas earthquake. This approach enabled a comprehensive assessment of different damping strategies, including the use of friction dampers alone, seismic isolators alone, and a hybrid combination of both systems.

The results demonstrated that friction dampers alone provided moderate reductions in base shear, achieving 10%, 25%, and 35% decreases for the 3, 7, and 12-story frames, respectively. This indicates that while friction dampers are effective at dissipating internal energy, their isolated use may not sufficiently control overall displacement in mid- and high-rise structures, where lateral flexibility becomes a more significant factor. In contrast, frames equipped solely with seismic isolators exhibited superior base shear reductions of 20%, 35%, and 45% for the 3, 7, and 12-story configurations, respectively. This enhanced performance is largely attributed to the isolators' ability to extend the natural period of the structure, significantly reducing the transmission of ground motion to the superstructure.

Most notably, the combination of seismic isolators and friction dampers consistently yielded the largest performance benefits, reducing base shear by 30%, 45%, and 55% for the 3, 7, and 12-story buildings, respectively. This synergy lies in the fact that these two systems are complementary: isolators effectively reduce base input energy while dampers control internal vibrations and deformations, resulting in an optimized and efficient energy dissipation mechanism.

From the engineering perspective, these findings underscore the substantial relevance of hybrid damping systems towards enhancing the seismic robustness of irregular steel frames. The effectiveness of such systems is more accentuated with taller frames, where greater ductility and energy-absorbing potential are crucial for maintaining structural stability. Since the demand for innovative, non-conventional architectural structures continues to grow, hybrid control schemes offer an effective and practical approach to ensuring structural performance and safety under harsh seismic excitations.

However, several areas warrant further investigation. Future work could explore the impact of varying mass and stiffness irregularities on the performance of hybrid systems, including the influence of non-structural components and vertical irregularities. Additionally, studies should consider the effects of soil-structure interactions, which can significantly alter the effectiveness of base isolation systems. Optimization of damper and isolator placement within irregular frames also remains a critical area for maximizing system efficiency. Finally, long-term performance assessments, including material aging and cumulative seismic damage, would provide valuable insights for the lifecycle design of resilient structures.

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NOMENCLATURE

A	Cross-sectional area (m^2)
D	Displacement (m)
E	Modulus of elasticity (GPa)
F	Force (kN)
h	Story height (m)
I	Moment of inertia (m^4)
k	Stiffness (kN/m)
Ki	Initial stiffness (kN/m)
Kp	post-yield stiffness (kN/m)
M	Mass (kg)
P	Axial load (kN)
R	Response reduction factor
T	Fundamental period (s)
V	Shear force (kN)
ω	Natural frequency (rad/s)
ξ	Damping ratio (%)
Δ	Displacement (m)
σ	Stress (MPa)
τ	Shear stress (MPa)
ρ	Density (kg/m^3)
μ	Friction coefficient
PGA	Peak Ground Acceleration (g)
PGD	Peak Ground Displacement (m)
MRF	Moment-Resisting Frame
LRB	Lead-Rubber Bearing