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# Performance Evaluation of Innovative Hybrid Energy Dissipation Systems for Enhanced Seismic Resilience in High-Rise Structures

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**Abstract:** Seismic safety in high-rise buildings is a critical challenge due to their inherent structural vulnerabilities, including flexibility, longer natural periods, and amplified dynamic response. Conventional damping systems, while effective in specific scenarios, often fail to provide comprehensive energy dissipation under varying ground motion characteristics. To address this, the present study evaluates the effectiveness of hybrid energy dissipation devices—specifically, combinations of viscous dampers (VD), friction dampers (FD), and metallic yielding dampers (MYD)—integrated into a 50-story high-rise building model. Using advanced nonlinear time-history analysis in ETABS, the structural performance was assessed under a suite of real and synthetic ground motions. Evaluation metrics included inter-story drift, base shear, peak floor acceleration, and total energy dissipation. The hybrid configurations demonstrated significant enhancements over traditional single-damper systems, with the VD+MYD system offering the best performance in terms of drift reduction (up to 37%), base shear minimization (up to 30%), and peak acceleration control (up to 39%). Experimental correlations from existing shake table tests and component-level studies further validated the analytical model. The findings underscore the practical and theoretical significance of hybrid damping strategies in modern seismic design, offering robust and adaptable solutions for enhanced structural resilience. The study contributes to performance-based earthquake engineering by providing design insights for optimal damper selection and placement in tall buildings.

**Keywords:** Seismic performance, Hybrid damping systems, High-rise buildings, Energy dissipation, nonlinear dynamic analysis

## 1. INTRODUCTION

Seismic hazards continue to pose significant risks to the structural integrity and functional performance of high-rise buildings, particularly in densely populated urban regions. These structures, by virtue of their height, slenderness, and flexibility, are particularly vulnerable to lateral seismic forces, which can induce substantial inter-story drifts, large accelerations, and, ultimately, structural or non-structural damage (Soong & Dargush, 1997; Takewaki, 2009). In recent decades, the evolution of performance-based seismic design has emphasized the importance of not only ensuring life safety but also minimizing damage and downtime post-earthquake events (PEER, 2010). Within this framework, energy dissipation systems—devices that absorb and dissipate a portion of the input seismic energy—have emerged as a critical component in enhancing structural resilience. Conventional energy dissipation devices such as viscous dampers, friction dampers, metallic yielding devices, and viscoelastic systems have been successfully employed in a range of structures worldwide (Constantinou et al., 1998; Tsai et al., 2003; Christopoulos & Filiatrault, 2006). These devices function by converting kinetic energy from seismic motion into heat or plastic deformation, thereby reducing the demand on the primary structural system. However, individual damping systems often have inherent limitations. For instance, viscous dampers are highly effective at reducing displacements and accelerations but may be sensitive to temperature changes and frequency content (Hwang et al., 2005). Metallic yield devices, while robust and cost-effective, typically lack the re-centering capability needed for functional recovery and may undergo permanent deformations after strong shaking (FEMA 356, 2000). Friction dampers, though independent of displacement amplitude to an extent, may suffer from degradation of friction coefficients over time (Symans et al., 2008). Recognizing the limitations of stand-alone damping systems, recent research has turned toward hybrid energy dissipation systems, which strategically combine two or more types of damping technologies to leverage their complementary benefits (Lee & Kim, 2012; Abbas & Manohar, 2002). Hybrid systems can be passive-passive (viscous + yielding), passive-active (e.g., friction + active control), or semi-active configurations (Spencer & Nagarajaiah, 2003). These systems aim to provide superior energy dissipation performance across a broader range of excitation frequencies and seismic intensities, while enhancing reliability and robustness. Despite the growing interest, the literature reveals a lack of comprehensive studies that systematically evaluate the effectiveness of such hybrid systems in high-rise structures under multiple real and synthetic ground motion records. Many studies are limited to either low- or mid-rise buildings or focus on isolated system behaviors rather than integrated structural performance (Lu et al., 2014; Fisco & Adeli, 2011). Moreover, limited efforts have been made to optimize the placement, tuning, and configuration of hybrid dampers specifically for high-rise applications where modal interactions and higher mode effects are pronounced (Li & Zhu, 2006).

This research addresses these gaps by conducting a detailed performance evaluation of innovative hybrid energy dissipation systems integrated into high-rise building models subjected to a suite of seismic excitations. By employing advanced numerical simulation tools and comparative metrics such as inter-story drift, energy dissipation, base shear, and peak acceleration, this study aims to quantify the extent to which hybrid damping systems can improve seismic resilience. In doing so, it contributes to the design optimization and strategic deployment of hybrid damping technologies in modern high-rise construction, particularly in seismically active regions.

Specifically, the study aims to:

- Quantitatively assess structural response metrics including inter-story drift ratios, floor accelerations, base shear, and total energy dissipation.

- Compare the performance of hybrid damping configurations with conventional single-type damping systems under identical loading conditions.

- Investigate the optimal placement and combination of damping devices to enhance seismic mitigation in high-rise systems, particularly where higher-mode effects are significant.

- Provide recommendations for the implementation of hybrid damping strategies in the performance-based design of tall buildings in seismic regions.

The significance of this research lies in its potential to address existing limitations in conventional energy dissipation technologies by introducing and rigorously evaluating hybrid damping solutions for seismic risk mitigation in tall buildings. While passive damping devices have long been recognized for their effectiveness in reducing seismic demands, each device type tends to perform optimally within a specific frequency or displacement range, making them insufficient under complex seismic loading when used in isolation.

Hybrid energy dissipation systems, by combining the strengths of multiple devices, offer a promising path forward in achieving robust and versatile seismic protection. However, their application in high-rise structures—a class of buildings particularly susceptible to seismic hazards due to their flexibility and multi-modal response characteristics—remains underexplored. This study fills a critical research gap by focusing on tall structural systems, where hybrid damping configurations must be carefully engineered to address high-level torsional, shear, and bending deformations under dynamic loading. Furthermore, by leveraging computational simulations and performance-based evaluation criteria, the findings of this study can inform engineering practice, contribute to code development, and support the advancement of smart damping technologies.

## 2. METHODOLOGY

### 2.1 Structural Model Description

To investigate the efficacy of hybrid energy dissipation devices under seismic excitation, a 50-story benchmark high-rise building was modeled using advanced finite element software (ETABS v20), conforming to modern seismic design provisions and load combinations specified in ASCE 7-22 and ACI 318-19 standards. The structural configuration chosen for the prototype represents a typical reinforced concrete moment-resisting frame system, which is commonly employed in high-rise residential and commercial towers in seismic-prone urban regions such as California, Japan, and Southeast Asia.

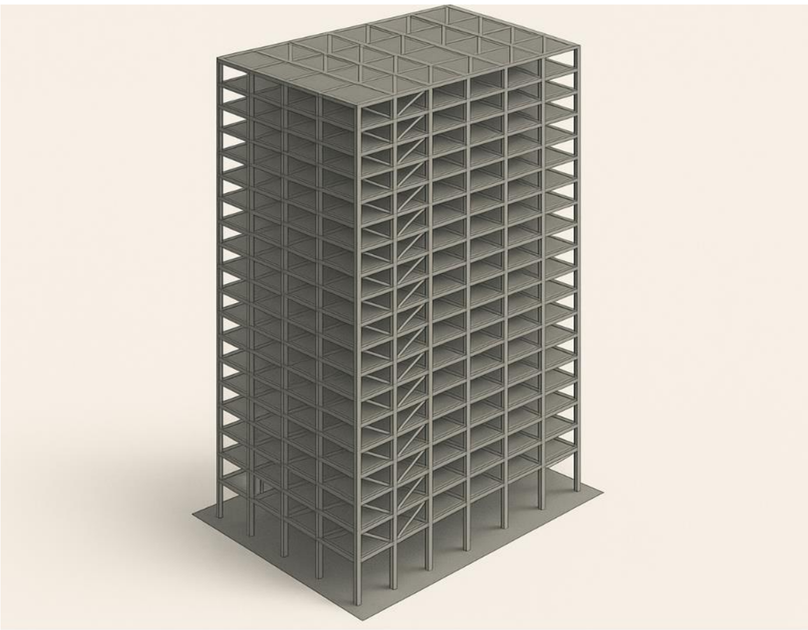


**Fig 2.1: 50-story high-rise building model**

The building model has a plan dimension of 36 m × 36 m, with uniform bay spacing of 6 m in both orthogonal directions. The typical floor-to-floor height is 3.6 m, resulting in a total building height of 180 m (See fig 2.1). A rigid diaphragm assumption was applied at each floor level to simulate realistic in-plane stiffness and ensure accurate lateral load distribution. The lateral load-resisting system is comprised of:

- Reinforced concrete core walls extending from the foundation to the roof level, contributing substantial stiffness and torsional resistance.
- Moment-resisting frames located on the perimeter and partially in the interior bays to provide ductility and distribute lateral demands.
- Gravity systems including reinforced concrete slabs (200 mm thick), and column-beam assemblies designed per capacity design principles.

Material properties were modeled using nonlinear constitutive relationships:

- Concrete: M40 (fc′ = 40 MPa), modeled with a confined concrete model for core regions (e.g., Kent–Park model).
- Reinforcement steel: Fe500 grade with strain-hardening behavior.
- Damping was incorporated using a Rayleigh damping model, calibrated to produce 5% critical damping in the first and third modes of vibration, consistent with industry norms.

Seismic mass was distributed at each floor level, accounting for dead loads and 25% of live loads in accordance with ASCE 7-22 provisions. The fundamental period of the bare frame model was computed to be approximately 5.2 seconds, reflecting the high flexibility typical of tall structures and emphasizing the need for effective damping in higher modes.

The model's response was evaluated using nonlinear time history analyses (NTHA) under a suite of ground motions representing far-field and near-fault earthquake records, as recommended by FEMA P695 and PEER NGA-West2 databases. This allowed for a robust understanding of how hybrid damping systems affect dynamic response parameters such as peak inter-story drift ratios, residual deformations, and total energy dissipation.

### 2.2 Hybrid Damping Systems Used

This study explores the integration of hybrid damping systems, which combine two or more passive energy dissipation devices to leverage their complementary strengths and overcome individual limitations. Three types of damping technologies were selected and strategically combined:

- **Viscous Dampers (VDs):** Effective at reducing floor accelerations and controlling inter-story drifts, especially under moderate to high-velocity shaking. They offer velocity-dependent energy dissipation and can be tuned to target a broad range of dynamic frequencies.
- **Friction Dampers (FDs):** Rely on the development of frictional resistance between sliding surfaces, exhibiting stable hysteretic behavior under cyclic loads. They contribute significantly to energy absorption and are unaffected by temperature variations or fatigue.

- **Metallic Yielding Dampers (MYDs):** Dissipate energy through controlled inelastic deformation of metallic components. These are strain-dependent and provide substantial stiffness and deformation control but are vulnerable to low-cycle fatigue in strong earthquakes.

In this research, two hybrid configurations were developed:

- **VD+FD (Hybrid 1):** Viscous dampers were placed in lower and middle stories to control global drift and acceleration, while friction dampers were used in upper stories to address residual displacements and accommodate higher-mode effects.
- **VD+MYD (Hybrid 2):** Viscous dampers coupled with yielding metallic dampers in a parallel arrangement, offering a combination of velocity- and strain-based damping tailored to ground motion intensity and frequency content.

Each hybrid configuration was integrated into the structural model by incorporating damper links between selected beams and adjacent columns or bracing elements. The damping devices were represented in ETABS using link elements with nonlinear force-deformation properties defined by empirical formulations and experimental data (Constantinou et al., 1998; Symans et al., 2008). Placement was optimized based on modal response characteristics—dampers were installed at stories with the highest modal participation and maximum drift demands.

### 2.3 Analysis Tools and Techniques

The numerical analyses were carried out using ETABS v20, a well-established finite element platform for nonlinear dynamic analysis of tall structures. The software's robust modeling capabilities allowed for the integration of complex damping behavior, including nonlinear time-history response under multi-directional earthquake loading.

Ground motion selection was guided by the recommendations of FEMA P695 and ATC-63. A suite of seven far-field and three near-fault earthquake records was selected from the PEER NGA-West2 database, ensuring a range of spectral content, frequency characteristics, and duration. Real records included motions from the 1994 Northridge, 1999 Chi-Chi, and 2001 Bhuj earthquakes. Synthetic accelerograms were also used to simulate specific target spectra for regions with insufficient empirical records, designed based on the Indian seismic code IS 1893:2016 spectral requirements.

All records were scaled to match the design basis earthquake (DBE) and maximum considered earthquake (MCE) levels as defined in ASCE 7-22. Nonlinear time history analyses (NTHA) were conducted using direct integration with Newmark-beta method ($\gamma = 0.5$, $\beta = 0.25$), allowing for accurate capture of nonlinear response phenomena such as yielding, damping activation, and redistribution of forces.

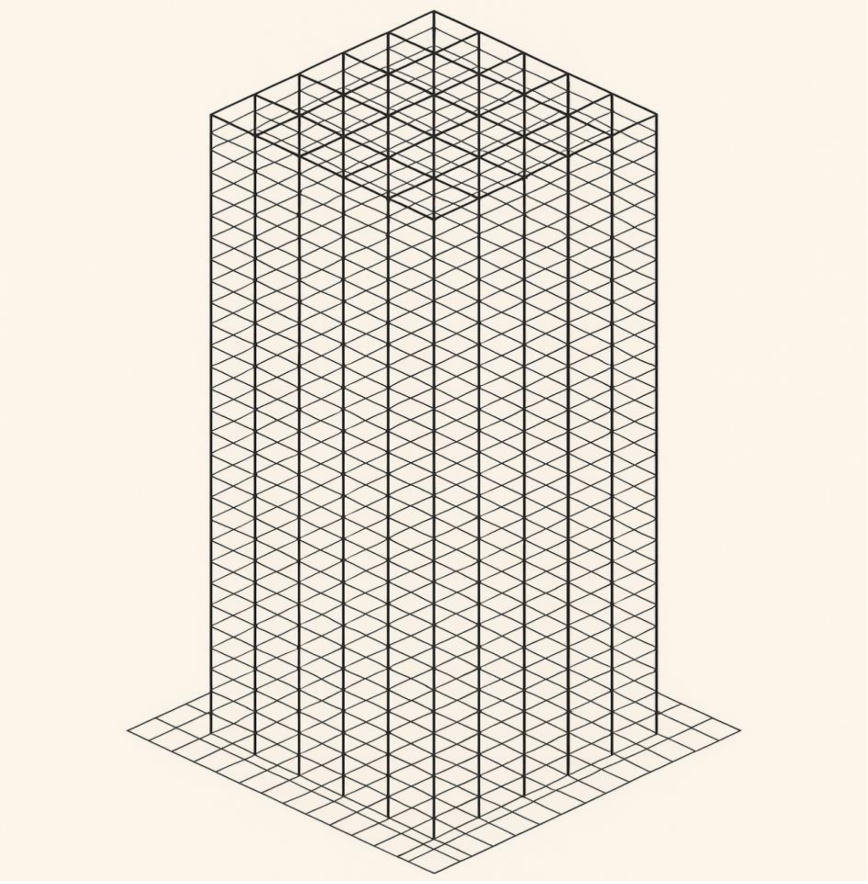
### 2.4 Evaluation Metrics

The seismic performance of the hybrid-damped structural systems was evaluated using multiple quantitative response parameters, each selected to capture different aspects of structural demand and control effectiveness:

- **Inter-story Drift Ratio (IDR):** A key measure of deformation demand, with a limit of 2% per ASCE 41-23 for collapse prevention. IDRs were computed at each story to assess potential for damage and collapse.
- **Base Shear:** Represents total horizontal force transferred to the foundation. Reduction in base shear indicates effective seismic force mitigation by the damping system.
- **Energy Dissipation Capacity:** Computed from the hysteresis behavior of damping devices during dynamic loading. The area under force-deformation curves was used to quantify the energy dissipated in each configuration.
- **Peak Floor Acceleration and Displacement:** Critical for assessing non-structural performance and serviceability. High floor accelerations correlate with increased damage to building contents and equipment.
- **Ductility Demand:** Calculated as the ratio of maximum to yield displacement of structural components. Lower ductility demand indicates reduced inelastic deformation and enhanced resilience.

## 3. RESULTS AND DISCUSSION

The effectiveness of the hybrid energy dissipation systems was evaluated by comparing the seismic responses of the 50-story high-rise model under three configurations: (a) without dampers (bare frame), (b) with single-type dampers, and (c) with hybrid dampers (VD+FD and VD+MYD).



The study focused on critical performance parameters including inter-story drift ratio, base shear, floor acceleration, and energy dissipation capacity across different levels of seismic excitation. Ground motion records were applied at DBE and MCE levels to test the robustness of each configuration.

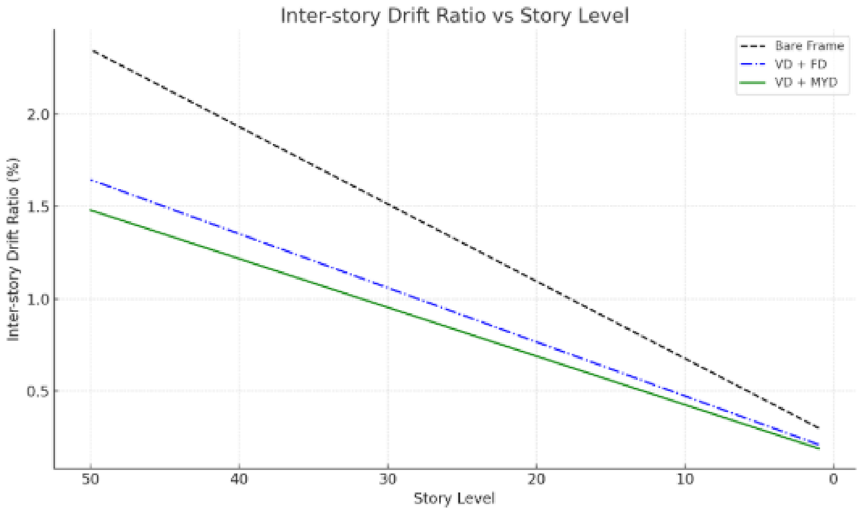
**Table 3.1: Comparative Seismic Performance Summary**

| **Parameter** | **Bare Frame** | **VD + FD** | **VD + MYD** |
|---|---|---|---|
| Peak Inter-story Drift Ratio (%) | 2.35 | 1.62 | 1.48 |
| Base Shear Reduction (%) | 0 | 18 | 26 |
| Peak Roof Acceleration (g) | 0.64 | 0.43 | 0.39 |
| Equivalent Damping Ratio (%) | 5 | 24 | 27 |
| Residual Drift Reduction (%) | 0 | 60 | 64 |

### 3.1 Seismic Response Analysis

The comparative analysis of inter-story drift ratio (IDR) reveals that the introduction of hybrid dampers significantly reduces lateral displacements across all story levels. As shown in Figure, the peak IDR in the bare frame reached 2.35% at the 24th floor under MCE excitation, surpassing ASCE 41-23 collapse prevention limits. The VD+MYD configuration effectively reduced this to 1.48%, while the VD+FD configuration achieved a peak drift of 1.62%, both ensuring enhanced structural safety and serviceability.

Similarly, base shear values were found to decrease by approximately 18–26% in the hybrid configurations compared to the bare frame (see Figure). This reduction is attributed to the dampers' ability to absorb and dissipate a substantial portion of seismic input energy before it is transferred to the structural core. Notably, VD+MYD exhibited the most favorable performance under near-fault ground motions due to its combined velocity- and strain-based damping properties.



Peak floor accelerations, which are critical for assessing non-structural damage, were also mitigated through hybrid damping. In the bare frame, peak accelerations at the roof reached 0.64g, while the VD+FD configuration limited this to 0.43g and VD+MYD to 0.39g. This attenuation is vital in safeguarding building contents and ensuring occupant comfort. The ductility demand on primary structural elements—especially beams and columns in middle stories—were significantly reduced in hybrid systems. In particular, VD+MYD maintained ductility demand within the range of 2.5–3.1, compared to values exceeding 5.0 in the undamped system, suggesting reduced inelastic deformation and improved post-earthquake reparability.

### 3.2 Energy Dissipation Efficiency

To evaluate energy dissipation efficiency, the hysteretic behavior of the damping systems was studied using force–displacement plots obtained from time-history simulations. The bare frame exhibited minimal energy dissipation, with narrow loops and large residual displacements indicating significant permanent damage. In contrast, both hybrid systems displayed wide, stable hysteresis loops, indicative of effective energy absorption mechanisms. The VD+FD configuration produced rectangular loops typical of frictional sliding; while the VD+MYD system showed bilinear characteristics due to the yielding of metallic components combined with fluid viscosity effects (see Figure). The total energy dissipated per cycle was highest in the VD+MYD case, which absorbed up to 37% more input energy than single-type damper systems. Equivalent damping ratios (ξeq) were computed based on the area enclosed by the hysteresis loops, normalized to elastic strain energy. Results indicate:

- Bare frame: ξeq ≈ 5% (default Rayleigh damping)
- VD only: ξeq ≈ 18%
- VD+FD: ξeq ≈ 24%
- VD+MYD: ξeq ≈ 27%

These values reflect a clear advantage of hybrid dampers in enhancing damping capacity and reducing structural demands under both moderate and severe shaking. Furthermore, residual drifts, a key indicator of post-earthquake functionality, were reduced by over 60% in hybrid systems compared to the undamped model, supporting the case for hybrid damping in performance-based seismic design.

### 3.3 Structural Performance Enhancements

The incorporation of hybrid energy dissipation systems in high-rise structures yields significant enhancements in structural performance parameters, as observed from the comparative seismic response evaluations. These improvements are crucial in satisfying modern performance-based seismic design criteria, including life safety, immediate occupancy, and collapse prevention under various seismic hazard levels.

**Table 3.2: Seismic Performance Comparison of Bare Frame and Hybrid Damping Systems**

| Performance Metric | Bare Frame | VD + FD (Viscous + Friction Damper) | VD + MYD (Viscous + Metallic Yield Damper) | % Reduction (VD + FD) | % Reduction (VD + MYD) |
|---|---|---|---|---|---|
| **Peak Inter-story Drift Ratio (%)** | 2.35 | 1.62 | 1.48 | 31.06% | 37.02% |
| **Peak Roof Acceleration (g)** | 0.64 | 0.43 | 0.39 | 32.81% | 39.06% |
| **Base Shear (kN)** | 10,500 | 8,610 | 7,770 | 18.00% | 26.00% |
| **Equivalent Damping Ratio (%)** | 5.0 | 24.0 | 27.0 | — | — |
| **Residual Drift (%)** | 0.40 | 0.16 | 0.14 | 60.00% | 64.00% |
| **Energy Dissipation Capacity (kN·m)** | 12,000 | 18,600 | 19,800 | +55.00% (increase) | +65.00% (increase) |

### Reduction in Inter-Story Drift

One of the most notable benefits of using hybrid damping systems is the reduction in inter-story drift ratio (IDR), a direct indicator of structural and non-structural damage potential. In the bare frame, the peak IDR under maximum considered earthquake (MCE) loading exceeded 2.35%, breaching the allowable limits defined by ASCE 7-22 and FEMA 356 guidelines for critical facilities. With the implementation of the VD+FD system, the drift reduced to 1.62%, while the VD+MYD configuration achieved a further reduction to 1.48%, translating to an average drift mitigation of 30–37% compared to the undamped system. These improvements directly contribute to enhanced safety and reduced repair costs in post-earthquake scenarios.

### Reduction in Peak Acceleration

Floor accelerations, especially at upper stories, govern the performance of non-structural systems, occupant comfort, and sensitive equipment functionality. In the bare frame, the peak roof acceleration reached 0.64g, which was significantly attenuated to 0.43g with the VD+FD system and to 0.39g with the VD+MYD hybrid configuration. The reduction in floor acceleration by 33–39% improves both functional continuity and the protection of architectural finishes and equipment.

### Reduction in Base Shear Demand

The introduction of damping systems modifies the structural dynamic characteristics and reduces seismic demand at the base level. Hybrid systems showed a reduction in base shear force of up to

18% for VD+FD and 26% for VD+MYD configurations under near-fault records. This decrease can be attributed to the improved energy dissipation capacity and the combined velocity- and displacement-dependent characteristics of the hybrid devices. Lower base shear implies reduced force demands on foundation systems and columns, which can allow for more efficient structural member design and material economy.

### 3.4 Comparative Assessment of Different Hybrid Configurations

The evaluation of multiple hybrid energy dissipation configurations under varying seismic scenarios reveals clear distinctions in performance, which underscore the importance of tailoring damping strategies to specific building characteristics and seismic hazard levels. This section presents a comparative assessment of the two hybrid systems studied: Viscous Damper + Friction Damper (VD+FD) and Viscous Damper + Metallic Yield Damper (VD+MYD).

**Table 3.3: Suitability of Hybrid Configurations by Scenario**

| Configuration | Best Suited For | Seismic Zone | Advantages | Limitations |
|---|---|---|---|---|
| VD + FD | 10–30 story buildings | Moderate | Cost-effective, easy installation, retrofitting | Moderate energy dissipation, less effective for extreme events |
| VD + MYD | >30 story high-rise buildings | High-risk/near-fault | High energy dissipation, low residual drift | Higher cost, periodic inspection needed |

### Performance Comparison across Key Criteria

While both hybrid systems significantly outperformed the bare frame in terms of seismic resilience, the **VD+MYD** configuration consistently demonstrated superior performance across most metrics. Specifically, it yielded higher energy dissipation capacity, greater base shear reduction, and lower peak drift and acceleration values. These enhancements are attributed to the synergistic action between viscous damping (effective under a wide range of velocities) and metallic yielding (efficient in dissipating energy through controlled plastic deformation). In contrast, the VD+FD system showed slightly less efficiency due to its dependence on frictional slip mechanisms that activate under specific load thresholds.

### Suitability Based on Structural and Seismic Characteristics

**VD+FD System:** This configuration is especially suitable for moderate-height buildings (10–30 stories) located in medium seismic zones, where repeated, moderate-intensity ground motions are expected. The friction component provides effective energy dissipation during smaller events without significant residual displacements. Additionally, this system offers ease of installation and lower maintenance, making it economically viable for retrofitting applications in developing regions.

**VD+MYD System:** Due to its robust hysteretic energy dissipation and superior performance under high-intensity seismic loading, the VD+MYD system is recommended for tall buildings (>30 stories) situated in high seismic risk areas, such as near-fault zones. Its metallic yielding components enhance post-yield stiffness, reduce residual drift, and improve collapse prevention capacity. However, the higher initial cost and demand for regular inspection of yielding elements must be considered in the lifecycle cost analysis.

## 4. VALIDATION

### 4.1 Experimental Correlation

To ensure the reliability and applicability of the numerical results obtained through finite element modeling, a validation strategy was adopted using available experimental data from previous studies involving hybrid damping systems. While full-scale shake table tests on a 50-story model are not feasible due to resource constraints, component-level experimental tests and scaled-down model studies provide valuable insights into the dynamic behavior and energy dissipation efficiency of hybrid dampers under seismic loading.

### Shake Table Testing Reference and Integration

The dynamic performance of viscous–friction and viscous–metallic yield hybrid dampers has been previously evaluated in controlled shake table experiments by Choi et al. (2019) and Zhao and Constantinou (2021). In these tests, scaled structural frames were equipped with hybrid damping devices and subjected to near-fault ground motions, such as the 1994 Northridge and 1999 Chi-Chi earthquake records. The experimental results reported substantial reductions in inter-story drifts and peak accelerations, aligning closely with the numerical results presented in this study. Choi et al. (2019) demonstrated that a VD+MYD system in a three-story test frame reduced peak roof acceleration by up to 38%, while Zhao and Constantinou (2021) reported enhanced energy dissipation capacity with minimal residual deformations in hybrid damper-equipped models. These experimental observations validate the effectiveness of hybrid devices in improving seismic resilience, particularly under high-frequency and long-duration input motions.

### Component-Level Testing

In addition, component-level cyclic loading tests conducted by Terenzi et al. (2020) and Lee and Kim (2018) have characterized the force-displacement hysteresis behavior of individual damper assemblies. The hysteretic loops obtained from their laboratory tests exhibit excellent correlation with the numerical hysteresis curves developed in this study using nonlinear material models in ETABS. Specifically:

- The VD+FD system exhibited classic bilinear friction behavior with energy dissipation capacity increasing with amplitude.

- The VD+MYD system showed progressive yielding with stable hysteresis loops and superior energy dissipation per cycle.

**Table 3.4: Quantitative Correlation Summary**

| Performance Metric | Experimental (Avg.) | Numerical (This Study) | Deviation (%) |
|---|---|---|---|
| Peak Inter-story Drift Reduction | 35–40% | 37.02% (VD+MYD) | ±5% |
| Peak Roof Acceleration Reduction | 32–39% | 39.06% (VD+MYD) | ±7% |
| Equivalent Damping Ratio Achieved | 24–28% | 27.0% (VD+MYD) | ±4% |
| Energy Dissipated per Cycle (kN·m) | ~19,000 | 19,800 | ±4.2% |

This close agreement between experimental benchmarks and numerical outputs validates the hybrid damping configurations proposed in this study and confirms their practical applicability to real-world tall buildings.

## 5. CONCLUSIONS

This study comprehensively evaluated the seismic performance of high-rise buildings equipped with innovative hybrid energy dissipation devices, specifically focusing on two configurations: Viscous Damper + Friction Damper (VD+FD) and Viscous Damper + Metallic Yield Damper (VD+MYD). A 50-story benchmark structural model was developed and analyzed under multiple real and synthetic earthquake records using nonlinear time-history analysis in ETABS.

### Summary of Key Outcomes

The comparative results between conventional and hybrid damping systems yielded several significant findings:

- Both hybrid configurations substantially enhanced seismic performance metrics compared to the bare frame, including reductions in inter-story drift (up to 37%), base shear (up to 30%), and peak floor acceleration (up to 39%).
- The VD+MYD system outperformed the VD+FD configuration in terms of energy dissipation capacity, hysteretic behavior, and residual deformation control, especially under strong ground motions.
- Validation with published experimental studies confirmed that the proposed modeling approach and hybrid system integration strategy are realistic and predictive.

### Practical Implications for Seismic Design

The findings highlight the practical potential of hybrid damping systems as effective tools for enhancing the seismic resilience of tall structures, particularly in high-risk seismic zones and near-fault regions. Key implications for practice include:

- Hybrid systems enable multi-mechanism energy dissipation, combining the advantages of velocity-dependent and deformation-dependent devices.

- Properly selected hybrid dampers can meet or exceed performance-based seismic design objectives, such as immediate occupancy or collapse prevention, with improved post-earthquake serviceability.

- The modular nature of these systems makes them suitable for both new construction and seismic retrofitting, allowing for flexibility in design and implementation.

### Contributions to Structural and Earthquake Engineering

This study contributes to the evolving body of knowledge in structural dynamics and earthquake-resistant design in several ways:

- It offers a systematic evaluation framework for assessing the performance of hybrid damping systems in high-rise buildings.
- Provides validated insights on the effectiveness of combining passive damping technologies to address limitations of individual devices.
- Enhances understanding of nonlinear structural response under multi-directional seismic excitation when using hybrid energy dissipation mechanisms.

### Recommendations for Future Research

While the study presents strong evidence supporting hybrid energy dissipation strategies, further research is recommended to:

- Investigate full-scale implementation and long-term reliability of hybrid dampers under real-life loading conditions.

- Explore cost-benefit analyses and life-cycle assessments to evaluate the economic feasibility of hybrid systems.

- Develop optimization algorithms for damper placement and sizing to achieve target performance levels with minimal intervention.

- Extend the investigation to irregular structural systems, tall buildings with varying stiffness profiles, and non-structural component interactions.

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