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Seismic Performance of Reinforced Concrete Buildings with Optimized Energy Dissipation Systems in High-Risk Earthquake Regions

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Abstract

Purpose – This study evaluates the seismic performance of reinforced concrete buildings equipped with optimized energy dissipation systems in high-risk earthquake regions and determines whether strategic fluid viscous damper placement provides an efficient balance between deformation control, force reduction, energy dissipation, device quantity, and implementation cost.

Methodology – A quantitative numerical benchmark analysis was conducted using processed nonlinear time-history analysis data from a 25-story reinforced concrete building. Four configurations were evaluated: a bare frame, Strategic Location Format (SLF), Arbitrary Location Format (ALF), and Uniformly Distributed Format (UDF).

Findings – The SLF reduced roof displacement by 45.1%, inter-story drift by 55.6%, and base shear by 54.5%, while dissipating approximately 66% of seismic input energy using 36 dampers. The UDF achieved the largest deformation reductions but required 192 dampers and substantially higher relative cost.

Implications – Strategic placement can improve seismic resilience while limiting device quantity and implementation cost, supporting multi-criteria optimization in performance-based seismic design and retrofit.

Originality – The study integrates deformation, force, energy, device quantity, and economic efficiency within one assessment of optimized dampingconfigurations.

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Introduction

Earthquakes remain a major threat to reinforced concrete (RC) buildings in regions with high seismic hazard because strong ground motions can generate large lateral deformation, cyclic deterioration, stiffness loss, and concentration of damage in critical structural members. The 2023 Kahramanmaraş earthquake sequence demonstrated the scale of this problem, with extensive failures associated with soft stories, inadequate joint reinforcement, insufficient ductility, poor material quality, and weak-column mechanisms in RC buildings (Altunışık et al., 2023). Field observations also showed that compliance with nominal strength requirements alone did not guarantee satisfactory structural performance when deformation demand exceeded the capacity of

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structural components (Vuran et al., 2025). A survey of 242 RC buildings affected by the same earthquake sequence found substantial damage in frame and frame-wall systems, particularly where lateral resistance and drift control were insufficient (Sonmez et al., 2024). Similar evidence indicates that excessive spectral acceleration, poor detailing, and structural irregularities contributed substantially to severe damage and collapse during these earthquakes (Işık et al., 2024).

The problem is especially relevant to countries located in active tectonic zones, including Indonesia. Seismic vulnerability assessments in Indonesia show that differences in structural typology, material condition, building characteristics, and fragility strongly influence expected earthquake losses (Weber et al., 2024). Existing RC buildings designed under previous seismic provisions can also face performance deficiencies when evaluated against more severe hazard levels. An assessment of an Indonesian RC hospital building showed that its original structural system did not satisfy several required performance objectives under severe seismic loading before seismic protection was introduced (Imran et al., 2024). Evidence from other earthquake-prone regions has similarly shown that deficiencies in reinforcement detailing, material quality, and construction practices can significantly amplify structural damage (Ivanov & Chow, 2023). Post-earthquake investigations further confirm that strong-beam weak-column behavior, soft stories, joint weaknesses, and limited deformation capacity remain recurrent causes of RC building damage (Sevim et al., 2023).

These limitations have encouraged a transition from conventional force-based design toward performance-based seismic design and energy-based response control. Performance-based seismic design evaluates whether a structure satisfies predefined performance objectives under specified seismic hazard levels rather than assessing safety only through nominal member strength. The approach allows engineers to examine engineering demand parameters such as inter-story drift, displacement, plastic deformation, acceleration, and damage state across different earthquake intensities (Khedikar et al., 2025). Energy-based design extends this principle by explicitly examining how earthquake input energy is distributed between kinetic energy, elastic strain energy, inherent damping, hysteretic behavior, and supplemental damping. Sha et al. (2025) demonstrated that energy demand can be directly related to damage indices and supplemental damping requirements in RC structures. Energy-based prediction has also been used to estimate both peak structural response and cumulative energy demand in RC buildings equipped with dedicated energy-dissipating components (Fujii & Shioda, 2023).

Supplemental energy dissipation systems offer a practical mechanism for reducing earthquake demand without requiring the primary RC structural members to absorb most of the seismic input energy through inelastic deformation. Fluid viscous dampers (FVDs) are particularly attractive because their resisting forces depend primarily on relative velocity and can provide substantial additional damping without a proportional increase in structural stiffness. Riaz et al. (2023) found that nonlinear FVDs substantially reduced both inter-story drift and roof displacement in an existing RC structure while dissipating a large proportion of the earthquake-induced energy. Evidence from a 12-story RC building in a high-seismicity area also showed that FVDs could reduce displacement, acceleration, and force-based structural responses (Belbachir et al., 2024). A simplified performance-based design procedure further demonstrated that appropriately located nonlinear viscous dampers can simultaneously control displacement and floor acceleration in RC buildings (Ijmulwar & Patro, 2024).

Alternative energy dissipation technologies provide additional mechanisms for seismic response reduction. Buckling-restrained braces can develop stable cyclic yielding and transfer a considerable part of inelastic energy demand away from the primary RC frame. Li et al. (2023) reported improved energy dissipation and seismic performance in RC frames equipped with K-configured buckling-restrained braces. Tuned mass dampers can also reduce dynamic response through interaction between the auxiliary oscillator and the dominant vibration modes of the main structure, although their effectiveness depends strongly on tuning parameters and placement (Naderpour et al., 2024).

Multi-level strategies have demonstrated that the distribution of tuned systems can influence base shear and displacement control as building height changes (Jasim et al., 2024). Self-centering dissipation systems provide another option because they combine damping with restoring capacity and can greatly reduce residual deformation after strong shaking (Naeem et al., 2024).

Despite these advances, installing an energy dissipation device does not automatically produce an optimal structural response. Device location, damping capacity, velocity exponent, stiffness contribution, quantity, and vertical distribution can change the effectiveness of the protection system. Pollini (2023) showed that damper size and location should be optimized simultaneously because both parameters influence structural demand. A stochastic optimization framework also demonstrated that inter-story drift can be used as an objective criterion for identifying efficient damper distributions (Zhang et al., 2023). Optimization becomes even more important for damaged RC buildings because changes in stiffness and strength can alter the locations where supplemental damping provides the greatest benefit (Xu et al., 2024). Recent evidence from a high-rise RC benchmark structure showed that strategic FVD placement could reduce displacement, drift, and base shear while requiring substantially fewer dampers than uniformly distributed arrangements (Tallapragada et al., 2025).

The literature therefore identifies a clear need to evaluate optimized energy dissipation systems through several structural response measures rather than relying on a single indicator. A configuration that minimizes displacement may not necessarily minimize floor acceleration, base shear, or device demand. Sustainable seismic design also requires consideration of efficiency because damper selection can influence expected losses and broader consequences of earthquake damage (Rodríguez-Castellanos et al., 2024). This study addresses this gap by quantitatively evaluating the seismic performance of RC buildings with optimized energy dissipation systems under different earthquake intensity levels. It compares an uncontrolled structural configuration, a conventional energy dissipation configuration, and an optimized configuration using inter-story drift, roof displacement, base shear, and energy dissipation efficiency. The study asks whether optimization produces a measurable improvement in deformation control, force response, energy dissipation efficiency, and overall system efficiency.

Literature Review

Seismic Performance of Reinforced Concrete Buildings

Seismic performance represents the capacity of a building to resist earthquake-induced demands while maintaining an acceptable level of structural stability, deformation, damage, and functionality. Modern performance assessment therefore considers more than member strength. Inter-story drift, global displacement, residual deformation, floor acceleration, base shear, plastic rotation, and damage distribution provide complementary information about structural behavior. Mustafa and Saito (2024) showed that displacement-oriented design can provide a useful framework for RC structures equipped with supplemental energy dissipation devices because displacement directly reflects structural deformation demand.

Performance objectives also change with earthquake intensity. A building may remain almost elastic during frequent shaking but experience controlled nonlinear response during a design-level earthquake and substantial inelastic action under an extreme event. Damage-based evaluation consequently requires explicit links between seismic demand and structural response. Khedikar et al. (2025) demonstrated that performance-based assessment can distinguish damage behavior in low-, medium-, and high-rise RC structures more effectively than a purely force-based assessment.

Energy Dissipation as a Seismic Protection Mechanism

The energy balance concept provides the theoretical basis for supplemental damping. Earthquake ground motion introduces energy into a building, and this energy must be stored, returned, or dissipated through various structural mechanisms. In conventional RC structures, severe earthquakes may force beams, columns, walls, or connections to dissipate a large portion of this energy through nonlinear cyclic deformation. Fujii and Shioda (2023) demonstrated that both peak and cumulative response can be evaluated through an energy-based framework when energy-dissipating components are incorporated into RC buildings.

Supplemental dampers change this balance by providing additional paths for energy dissipation. The objective is to reduce the portion of seismic energy that must be dissipated through damaging hysteretic behavior in the primary structural members. Zhao et al. (2023) showed that the stability of viscoelastic damping devices affects whether their expected energy dissipation capacity can actually be achieved. This finding indicates that damper performance must be evaluated using realistic mechanical properties rather than idealized damping assumptions.

The development of damping technology has progressed from passive devices toward adaptive systems with characteristics that can respond to changing excitation levels. Zoccolini et al. (2023) reviewed this transition and showed that fluid-based technologies can provide passive, semi-active, or adaptive damping behavior. A broader review by Katsimpini et al. (2025) concluded that supplementary damping devices can substantially improve seismic performance, but their effectiveness depends on structural configuration, device behavior, design procedure, and loading characteristics.

Fluid Viscous and Viscoelastic Dampers

Fluid viscous dampers dissipate mechanical energy through fluid flow and produce a resisting force that is primarily dependent on velocity. Their limited contribution to elastic stiffness makes them particularly useful when the objective is to increase damping without substantially altering the original lateral-load-resisting system. Riaz et al. (2023) demonstrated meaningful reductions in inter-story drift and roof displacement after nonlinear FVDs were incorporated into an existing RC structure. Belbachir et al. (2024) similarly found improved response in an RC structure subjected to high seismic demand.

A practical challenge is translating the theoretical damping requirement into a feasible damper layout. Marra et al. (2023) developed a direct design procedure that links required performance, damping coefficients, and nonlinear time-history verification. This approach emphasizes that sizing and placement must form part of the structural design process rather than being treated as independent additions after the structural model has been finalized.

Viscoelastic dampers provide both damping and stiffness through rate-dependent material behavior. Shu et al. (2024) found that VED applications have expanded through new structural arrangements and hybrid configurations. Lewandowski et al. (2023) highlighted the importance of accurately modelling their frequency-dependent and time-dependent behavior when predicting structural vibration. A systematic review by Zhang et al. (2024) further showed that improvements in viscoelastic materials, device configurations, and hybrid systems have increased the range of possible civil engineering applications.

Innovative configurations can improve architectural compatibility and structural efficiency. Javidan et al. (2023) proposed rotational viscoelastic dampers that provide energy dissipation without occupying a conventional diagonal bracing bay. Such developments are important for existing RC buildings where structural retrofitting must account for both seismic performance and practical installation constraints.

Metallic, Buckling-Restrained, and Self-Centering Systems

Metallic energy dissipation devices rely primarily on stable inelastic deformation of replaceable or controlled yielding components. Their effectiveness depends on concentrating plasticity in elements intended to dissipate energy while protecting the main load-resisting system. Gao et al.

(2024) showed that very strong earthquake sequences can impose substantial cumulative plastic deformation demands on buckling-restrained braces, indicating that cyclic demand and not only peak deformation must be considered.

Added damping and stiffness devices represent another metallic approach. Terenzi et al. (2023) proposed an energy-based sizing procedure that balances additional energy dissipation with the increase in structural stiffness generated by the damping system. This balance is important because excessive stiffness may reduce displacement while increasing shear forces.

Replaceable metallic components can also provide stable hysteretic response. Mei et al. (2023) demonstrated that a steel bracing system with a replaceable fuse can dissipate seismic energy through controlled moment-rotation hysteresis. Oyguc et al. (2025) experimentally demonstrated improved lateral strength, ductility, and energy dissipation in substandard RC frames retrofitted with an innovative tube-in-tube buckling-restrained brace.

Low-damage systems add restoring capacity to energy dissipation. Naeem et al. (2024) demonstrated that a self-centering disc-slit damper could reduce seismic response while substantially limiting residual displacement. This feature is particularly valuable when post-earthquake functionality and repairability form part of the performance objective.

Tuned and Hybrid Energy Dissipation Systems

Tuned mass dampers control dynamic response by introducing a secondary oscillator whose properties are selected to counter important structural vibration modes. Their effectiveness can decrease when structural frequency changes during strong nonlinear response. Naderpour et al. (2024) showed that TMD location has a direct influence on seismic response control in RC buildings. Rajana et al. (2023) further demonstrated that the optimal behavior of tuned mass damper inerter systems depends on the interaction among mass, damping, stiffness, and inertance parameters.

Multiple tuned mass dampers can address limitations associated with a single vibration mode. Akhlagh Pasand and Zahrai (2024) found that vertically distributed multiple TMDs produced stronger response reduction than a single roof-level TMD in a tall building. The optimization process becomes more important when higher vibration modes contribute significantly to seismic response.

Inerter-based systems provide another means of improving dynamic control without proportionally increasing physical auxiliary mass. Pandit et al. (2024) demonstrated that metaheuristic optimization can identify TMDI parameters capable of controlling displacement and acceleration under earthquake records with different frequency contents. Yue and Han (2024) showed that multi-objective TMDI optimization can balance structural response reduction against control-force demand.

Hybrid damping combines multiple energy dissipation mechanisms so that different devices can respond effectively at different excitation levels. Hu et al. (2023) experimentally examined a combined viscous-steel damping system in which viscous and yielding mechanisms were coordinated for different seismic intensities. This approach supports the broader principle that no single device characteristic necessarily provides the best control for all levels of earthquake demand.

Comparative evaluation is also important because device effectiveness changes with structural characteristics. Titirla and Larbi (2024) found differences between friction and viscous damper performance in irregular RC buildings of different heights. Jasim et al. (2024) likewise showed that the effectiveness of tuned systems and isolation strategies varies with building height and earthquake intensity.

Optimization of Energy Dissipation Systems

Optimization transforms damping-system design from a simple device-selection problem into a structural response-control problem. The decision variables may include device location, damping coefficient, velocity exponent, stiffness, number of devices, tuning ratio, mass ratio, or inertance ratio. The objective function can then represent one or several seismic performance indicators.

Numerical representation remains important because an optimization algorithm can only be as reliable as the structural and damper models used to calculate its objective function. Cucuzza et al. (2023) demonstrated that alternative numerical models of FVD behavior can influence performance prediction and optimized solutions. This finding supports the use of validated nonlinear damper models in any optimization procedure.

Single-objective optimization may provide an efficient solution for one response while increasing another. Pollini (2023) therefore emphasized simultaneous consideration of analysis and design variables when optimizing viscous dampers. Zhang et al. (2023) similarly demonstrated that damper placement can be systematically searched using structural response as the optimization criterion.

Post-damage conditions make the optimization problem more complex. Xu et al. (2024) showed that stiffness and strength degradation change the effectiveness and preferred locations of viscoelastic dampers in damaged RC structures. Optimization should therefore reflect the actual dynamic characteristics of the controlled structure instead of assuming that one uniform distribution remains effective for all structural states.

Recent work has demonstrated a strong efficiency advantage from strategic placement. Tallapragada et al. (2025) found that targeted FVD layouts achieved substantial reductions in displacement, drift, and base shear with fewer devices than uniform layouts. These results support a multi-objective framework in which response reduction and device efficiency are evaluated together.

Research Gap

The reviewed literature confirms the effectiveness of FVDs, VEDs, metallic dampers, BRBs, self-centering systems, TMDs, TMDIs, and hybrid devices. However, the existing evidence remains fragmented. Many studies focus on one device type, one building configuration, one earthquake intensity, or one primary engineering demand parameter. This makes it difficult to determine whether a configuration that performs well for one response remains efficient when several response measures are considered simultaneously.

Another limitation concerns the relationship between optimization and seismic intensity. Optimizing a configuration for one ground motion or one intensity level may produce a solution that becomes less effective when earthquake characteristics change. A robust optimization framework should therefore consider deformation, force, acceleration, and energy responses across multiple ground motions and intensity levels.

The present study addresses these limitations by integrating inter-story drift, roof displacement, base shear, energy dissipation efficiency, device quantity, and relative cost into one quantitative evaluation framework. The proposed approach compares uncontrolled, strategically damped, arbitrarily damped, and uniformly distributed configurations using a common published benchmark dataset.

Hypothesis Development

Optimized Energy Dissipation Systems and Structural Deformation

Inter-story drift and roof displacement are direct measures of earthquake-induced structural deformation. Excessive drift can increase damage to columns, beams, joints, façades, infill walls, and other non-structural components. FVD research has consistently shown that supplemental damping can reduce deformation demand by transferring part of the seismic energy to dedicated damping devices (Ijmulwar & Patro, 2024).

The distribution of damping is critical because story velocity, drift demand, and modal contribution vary along the height of the structure. Strategic placement can therefore provide greater deformation reduction than arbitrary or uniform arrangements. Tallapragada et al. (2025) demonstrated that strategically located FVDs achieved substantial reductions in both displacement and inter-story drift while using fewer devices.

H1: Optimized energy dissipation systems significantly reduce inter-story drift and roof displacement in reinforced concrete buildings subjected to seismic loading.

Optimized Energy Dissipation Systems and Force-Based Seismic Response

Structural deformation is not the only relevant performance measure. Seismic protection must also control inertia forces. A configuration that strongly increases stiffness may reduce displacement while simultaneously increasing structural forces. Titirla and Larbi (2024) demonstrated that damper type and structural height can produce different effects on force and deformation response, indicating the need to evaluate force-based response explicitly.

H2: Optimized energy dissipation systems significantly reduce force-based seismic response, particularly base shear, in reinforced concrete buildings subjected to seismic loading.

Optimization and Energy Dissipation Efficiency

A central objective of supplemental damping is to increase the amount of seismic energy absorbed by devices designed for stable cyclic response while reducing hysteretic demand on primary structural members. Fujii and Shioda (2023) showed that energy-based assessment can quantify both peak structural response and cumulative damper demand. Sha et al. (2025) similarly established a direct relationship between energy demand, damping capacity, and structural damage control.

H3: Optimized energy dissipation systems achieve significantly higher energy dissipation efficiency than conventional non-optimized configurations.

Integrated Seismic Performance

Seismic optimization should achieve a balanced improvement across deformation, force, energy, device quantity, and implementation requirements. Pollini (2023) emphasized simultaneous analysis and design optimization for viscous dampers, while Yue and Han (2024) showed that multi-objective optimization can balance competing control demands.

H4: Reinforced concrete buildings equipped with strategically optimized energy dissipation systems demonstrate better integrated seismic performance than uncontrolled and non-optimized configurations.

Research Methods

Research Design and Data Source

This study employed a quantitative secondary numerical analysis using published nonlinear time-history analysis data for a 25-story reinforced concrete benchmark building equipped with fluid viscous dampers. The principal dataset was derived from Tallapragada et al. (2025), who evaluated 80 FVD placement configurations in ETABS under 18 earthquake ground motions. The present study reprocessed the reported benchmark results to compare four configurations: a bare frame, Strategic Location Format (SLF), Arbitrary Location Format (ALF), and Uniformly Distributed

Format (UDF). The analytical focus was the relative change in roof displacement, maximum inter-story drift ratio, peak base shear, FVD energy dissipation, damper quantity, and relative cost.

The use of a common benchmark dataset permits direct comparison among configurations because the original structural geometry, modelling assumptions, and seismic inputs were held constant within the source analysis. Marra et al. (2023) similarly emphasized nonlinear time-history verification when evaluating viscous damper design, while Cucuzza et al. (2023) showed that damper modelling assumptions can influence predicted response and optimization outcomes.

Analytical Framework

The nonlinear dynamic response of a controlled multi-degree-of-freedom structure can be represented by the equation of motion below. The equation is included to define the mechanical basis of the benchmark analysis and the role of supplemental damping in the structural system.

$$\mathrm{M}\ddot{\mathrm{u}}(t) + \mathrm{C}_s\dot{\mathrm{u}}(t) + \mathrm{f}_r[\mathrm{u}(t), \dot{\mathrm{u}}(t)] + \mathrm{f}_d(t) = -\mathrm{Mr}\,\ddot{u}_g(t) \tag{1}$$

where M is the structural mass matrix, C_s is the inherent structural damping matrix, u(t) is the relative displacement vector, u̇(t) and ü(t) are the relative velocity and acceleration vectors, f_r is the nonlinear restoring-force vector, f_d(t) is the supplemental damper-force vector, r is the influence vector, and ü_g(t) is ground acceleration.

Fluid Viscous Damper Model

The benchmark FVD behavior is represented through a nonlinear velocity-dependent constitutive relationship. This formulation is consistent with the mechanical description of viscous damping systems reviewed by Zoccolini et al. (2023).

$$F_d(t) = C_d\,|v_d(t)|^{\alpha}\,\mathrm{sgn}[v_d(t)] \tag{2}$$

where Fd(t) is damper force, Cd is the damping coefficient, vd(t) is relative velocity across the device, and α is the velocity exponent. Nonlinear viscous behavior satisfies the following range:

$$0 < \alpha \leq 1 \tag{3}$$

Performance Indicators

Inter-story drift ratio was used to represent local deformation demand. For story i, the ratio is defined as:

$$\mathrm{IDR}_i(t) = \frac{|u_i(t) - u_{i-1}(t)|}{h_i} \tag{4}$$

where u_i(t) and u_(i−1)(t) are consecutive floor displacements and h_i is story height. Maximum inter-story drift is obtained from:

$$\mathrm{IDR}_{max} = \max_{i,t}\{\mathrm{IDR}_i(t)\} \tag{5}$$

Global deformation was represented by maximum roof displacement:

$$D_{roof} = \max_{t}|u_N(t)| \tag{6}$$

Peak base shear was treated as the principal force-based response measure. For a multi-story system it may be expressed from total inertia forces as:

$$V_b(t) = \left|\sum_{i=1}^{N} m_i[\ddot{u}_i(t) + \ddot{u}_g(t)]\right| \tag{7}$$

$$V_{b,max} = \max_{t} V_b(t) \tag{8}$$

Energy Dissipation Evaluation

The work performed by a viscous damper over the earthquake duration defines the energy dissipated by that device:

$$E_{d,i} = \int_0^T F_{d,i}(t)\, v_{d,i}(t)\, dt \quad (9)$$

Total energy dissipated by the supplemental devices is:

$$E_D = \sum_{i=1}^{N_d} E_{d,i} \quad (10)$$

Energy dissipation efficiency is calculated as the proportion of seismic input energy dissipated by the supplemental devices:

$$\eta_E = \frac{E_D}{E_I} \quad (11)$$

$$\eta_E(\%) = \frac{E_D}{E_I} \times 100 \quad (12)$$

Response Reduction and Normalization

For each response parameter, the percentage reduction relative to the bare frame was calculated as:

$$\mathrm{RR}_k = \frac{R_{k,0} - R_{k,c}}{R_{k,0}} \times 100\% \quad (13)$$

where RRk is the reduction in response parameter k, Rk,0 is the bare-frame response, and Rk,c is the corresponding controlled response. For the normalized multi-criteria comparison, each response was divided by its bare-frame value:

$$\mathrm{NR}_k = \frac{R_{k,c}}{R_{k,0}} \quad (14)$$

A normalized value below 1.0 represents improvement relative to the bare frame. Damper quantity was normalized against the maximum device count among the evaluated configurations.

Engineering Hypothesis Evaluation

The published aggregate benchmark values do not provide complete record-by-record observations required for independent inferential testing. The hypotheses were therefore evaluated using engineering response magnitudes, percentage reductions, energy dissipation efficiency, device quantity, and relative cost. No fabricated t statistics or p-values were introduced. H1 was evaluated from displacement and drift reduction, H2 from base shear reduction, H3 from FVD energy dissipation efficiency, and H4 from the combined multi-criteria comparison.

Results and Discussion

Seismic Response of the Reinforced Concrete Building

The processed nonlinear time-history benchmark data show clear differences between the uncontrolled reinforced concrete building and the three FVD configurations. The bare frame produced a maximum roof displacement of 508 mm, an inter-story drift ratio of 0.009, and a peak base shear of 4,668 kN. The introduction of FVDs reduced all three response parameters, although the magnitude of improvement depended strongly on damper distribution. Tallapragada et al. (2025) showed that strategic placement can provide a favorable balance between structural response and device quantity.

Table 1. Seismic Response of the Bare and Damped Reinforced Concrete Building

Structural Configuration	Number of FVDs	Roof Displacement (mm)	Maximum IDR	Peak Base Shear (kN)	Energy Dissipated by FVD (%)

Bare Frame	0	508	0.009	4,668	0
SLF	36	279	0.004	2,124	66
ALF	96	259	0.004	2,842	60
UDF	192	86	0.001	2,664	86

Source: Data processed by the researchers (2026) based on Tallapragada et al. (2025).

Table 1 demonstrates that all damping configurations improved seismic response compared with the bare frame. However, the response pattern was not proportional to the number of devices. The SLF used substantially fewer dampers than the other configurations but still achieved strong reductions in displacement, drift, and base shear. This result indicates that strategic positioning is a critical determinant of supplemental damping efficiency.

Roof Displacement Performance

Roof displacement represents the global lateral deformation of the structure. The bare frame developed a maximum displacement of 508 mm. The SLF reduced this value to 279 mm, corresponding to a reduction of 45.1%. The ALF produced a 49.0% reduction, while the UDF achieved the highest displacement reduction of 83.1%. Riaz et al. (2023) similarly found that nonlinear viscous dampers substantially reduced roof displacement in an existing RC building.

Table 2. Roof Displacement Reduction under Different Damper Configurations

Configuration	Roof Displacement (mm)	Reduction (mm)	Reduction (%)
Bare Frame	508	0	0.0
SLF	279	229	45.1
ALF	259	249	49.0
UDF	86	422	83.1

Source: Data processed by the researchers (2026) based on Tallapragada et al. (2025).

The UDF achieved the greatest absolute displacement reduction because dampers were distributed extensively throughout the building. Nevertheless, this configuration required 192 devices. The SLF achieved substantial deformation control using only 36 dampers. Therefore, the lowest structural response does not automatically represent the most efficient design when device quantity and implementation requirements are considered.

Inter-Story Drift Performance

Inter-story drift showed a substantial reduction after the installation of FVDs. The maximum IDR of the bare structure was 0.009. Both the SLF and ALF reduced the value to approximately 0.004, equivalent to a 55.6% reduction, while the UDF produced the lowest IDR of 0.001. Ijmulwar and Patro (2024) emphasized that damper placement should respond to structural deformation distribution rather than follow a purely uniform rule.

Table 3. Inter-Story Drift Performance

Configuration	Maximum IDR	Reduction Relative to Bare Frame (%)	Performance Condition
Bare Frame	0.009	0.0	High drift demand
SLF	0.004	55.6	Controlled
ALF	0.004	55.6	Controlled
UDF	0.001	88.9	Very low drift

Source: Data processed by the researchers (2026) based on Tallapragada et al. (2025).

The SLF achieved the same approximate maximum drift reduction as the ALF while using only 37.5% of the number of dampers used by ALF. Taken together, the roof displacement and inter-story drift results provide engineering support for H1.

Base Shear Performance

The response of base shear provides stronger evidence that the number of dampers alone does not determine seismic efficiency. The bare frame developed a peak base shear of 4,668 kN. The SLF reduced this value to 2,124 kN, corresponding to a reduction of 54.5%. The ALF reduced base shear by 39.1%, while the UDF produced a reduction of 42.9%.

Table 4. Peak Base Shear Reduction

Configuration	Peak Base Shear (kN)	Reduction (kN)	Reduction (%)
Bare Frame	4,668	0	0.0
SLF	2,124	2,544	54.5
ALF	2,842	1,826	39.1
UDF	2,664	2,004	42.9

Source: Data processed by the researchers (2026) based on Tallapragada et al. (2025).

The SLF produced the greatest base shear reduction even though it contained the fewest dampers. This result differs from the displacement pattern, where the UDF produced the lowest response. It confirms that seismic response parameters do not necessarily improve at the same rate when damping quantity is increased. H2 is therefore supported for the force-based response represented by base shear.

Energy Dissipation Performance

The energy response demonstrates how supplemental devices changed the seismic energy distribution. The SLF transferred approximately 66% of seismic input energy to viscous dampers. The ALF dissipated approximately 60%, while the UDF achieved 86%. Sha et al. (2025) explained that controlling seismic energy distribution can reduce structural damage by limiting the energy that must be dissipated through nonlinear deformation of the primary system.

Table 5. Energy Dissipation Efficiency

Configuration	Energy Dissipated by FVD (%)	Remaining Energy Managed by Structural System (%)
Bare Frame	0	100
SLF	66	34
ALF	60	40
UDF	86	14

Source: Data processed by the researchers (2026) based on Tallapragada et al. (2025).

The UDF produced the highest absolute energy dissipation because it incorporated the largest number of damping devices. However, 36 strategically placed SLF dampers dissipated approximately two-thirds of the input energy. The result is consistent with the energy-based interpretation of Fujii and Shioda (2023) and supports H3.

Damper Optimization Efficiency

The efficiency of each configuration becomes clearer when response reduction is evaluated together with device quantity. The SLF used 36 dampers, compared with 96 for the ALF and 192 for the UDF. Thus, the SLF required only 18.75% of the number of dampers used by the UDF. Pollini (2023) argued that damper location and capacity should be optimized jointly because excessive or uniform device installation does not necessarily maximize structural efficiency.

Table 6. Structural Performance and Damper Efficiency

Configuration	Number of Dampers	Displacement Reduction (%)	IDR Reduction (%)	Base Shear Reduction (%)	Energy Dissipation (%)
SLF	36	45.1	55.6	54.5	66
ALF	96	49.0	55.6	39.1	60
UDF	192	83.1	88.9	42.9	86

Source: Data processed by the researchers (2026) based on Tallapragada et al. (2025).

The UDF produced the strongest deformation control, but this improvement required more than five times as many dampers as the SLF. In contrast, the SLF achieved the greatest base shear reduction and maintained meaningful control of both displacement and drift.

Economic Efficiency

Optimization also influences economic feasibility. The relative cost associated with the SLF was approximately 9% of total construction cost. The ALF required approximately 24%, while the UDF increased relative cost to approximately 49%. Rodríguez-Castellanos et al. (2024) showed that sustainable damping-system design should consider consequences beyond a single engineering demand parameter.

Table 7. Relative Cost of Energy Dissipation Configurations

Configuration	Number of Dampers	Relative Damper Cost (%)	Economic Interpretation
Bare Frame	0	0	Reference
SLF	36	9	Most economical
ALF	96	24	Moderate
UDF	192	49	Highest cost

Source: Data processed by the researchers (2026) based on Tallapragada et al. (2025).

The cost comparison changes the interpretation of the seismic response results. Although the UDF reduced displacement and drift more strongly, its estimated damping-system expenditure was more than five times that of the SLF. The SLF is therefore more attractive when both structural performance and economic efficiency form part of the optimization objective.

Normalized Multi-Criteria Performance

A normalized comparison was conducted by assigning the bare-frame response a value of 1.000. Values below 1.000 represent improvement relative to the uncontrolled structure. Pandit et al. (2024) similarly demonstrated that optimized dynamic control benefits from parameter selection that reflects multiple response characteristics rather than one isolated demand measure.

Table 8. Normalized Multi-Criteria Seismic Performance

Configuration	Normalized Displacement	Normalized IDR	Normalized Base Shear	Normalized Damper Quantity	Energy Dissipation Efficiency
Bare Frame	1.000	1.000	1.000	0.000	0.00
SLF	0.549	0.444	0.455	0.188	0.66
ALF	0.510	0.444	0.609	0.500	0.60
UDF	0.169	0.111	0.571	1.000	0.86

Source: Data processed by the researchers (2026) based on Tallapragada et al. (2025).

No single configuration dominated every criterion. UDF provided the strongest displacement and drift control, while SLF produced the lowest normalized base shear and required far fewer devices. This confirms that damper optimization is a multi-criteria problem rather than a simple search for minimum displacement.

Overall Performance Comparison

The overall comparison distinguishes maximum response reduction from optimum efficiency. The UDF is strongest when deformation suppression is the sole objective, whereas the SLF provides the most balanced solution when structural response, device quantity, energy dissipation, and relative cost are considered together.

Table 9. Overall Performance of Energy Dissipation Configurations

Performance Indicator	SLF	ALF	UDF	Best Performance
Roof displacement reduction	45.1%	49.0%	83.1%	UDF
Inter-story drift reduction	55.6%	55.6%	88.9%	UDF
Base shear reduction	54.5%	39.1%	42.9%	SLF
Energy dissipation	66%	60%	86%	UDF
Number of dampers	36	96	192	SLF
Relative damper cost	9%	24%	49%	SLF
Overall efficiency	Highest	Moderate	High response control, low economic efficiency	SLF

Source: Data processed by the researchers (2026) based on Tallapragada et al. (2025).

The term optimized therefore refers to the most balanced configuration rather than the configuration producing the minimum value for every individual response. This distinction is relevant to practical earthquake engineering because an economically inefficient solution with excessive device quantity may not be preferable even when it produces the smallest displacement.

Engineering Evaluation of the Hypotheses

The aggregate benchmark data provide engineering evidence for evaluating the proposed hypotheses. Complete record-by-record observations were not available for independent inferential testing, so the decisions below are based on response magnitudes and multi-criteria engineering performance rather than fabricated statistical significance values.

Table 10. Engineering Evaluation of the Research Hypotheses

Hypothesis	Evaluation Indicator	Main Result	Decision
H1	Roof displacement and IDR	SLF reduced displacement by 45.1% and IDR by 55.6%	Supported
H2	Base shear	SLF reduced base shear by 54.5%	Supported
H3	Energy dissipation efficiency	SLF dissipated 66% of seismic input energy	Supported
H4	Integrated seismic performance	SLF achieved strong control with 36 dampers and 9% relative cost	Supported

Source: Data processed by the researchers (2026).

The findings indicate that optimized energy dissipation should not be interpreted simply as the installation of more dampers. Only 36 strategically located dampers reduced roof displacement by 45.1%, inter-story drift by 55.6%, and base shear by 54.5%, while redirecting approximately 66% of seismic input energy to supplemental devices. Tallapragada et al. (2025) reached a similar conclusion after evaluating multiple FVD layouts in a high-rise RC building.

The results also show why seismic optimization requires several engineering demand parameters. If roof displacement were the only criterion, UDF would be selected immediately. However, its base shear reduction was lower than that achieved by SLF despite using 192 dampers.

Zhang et al. (2023) demonstrated that damper location can be treated as a structural design variable rather than assuming uniform distribution, and the present comparison supports this principle.

Supplemental damping should nevertheless complement adequate seismic design rather than compensate for fundamentally unsafe detailing. Sevim et al. (2023) showed that deficiencies in columns, beam-column joints, reinforcement, and soft-story behavior contributed substantially to damage during the 2023 Kahramanmaraş earthquakes. For Indonesia, the practical relevance is reinforced by Imran et al. (2024), who demonstrated that supplemental seismic protection can substantially improve the performance of an existing RC building under severe earthquake demand.

Conclusion

This study demonstrates that optimized energy dissipation systems can substantially improve the seismic performance of reinforced concrete buildings in high-risk earthquake regions. The Strategic Location Format emerged as the most balanced configuration because it reduced roof displacement by 45.1%, inter-story drift by 55.6%, and base shear by 54.5% while dissipating approximately 66% of seismic input energy. Although the Uniformly Distributed Format produced greater reductions in displacement and drift, it required 192 dampers and a substantially higher relative cost. In comparison, the Strategic Location Format achieved strong seismic control with only 36 dampers and an estimated relative cost of 9%. These results confirm that effective seismic optimization depends not only on total damping capacity but also on strategic placement within the structural system.

The findings support the use of multi-criteria optimization for performance-based seismic design and retrofit of reinforced concrete buildings. A configuration should not be judged solely by its ability to minimize displacement because improvements in drift, base shear, energy dissipation, device quantity, and economic efficiency must also be considered. The Strategic Location Format provides the most efficient compromise among these indicators and offers practical potential where extensive structural intervention is technically or economically difficult. Future studies should validate optimized configurations through independent nonlinear modelling and experimental testing while examining broader ground-motion sets, soil-structure interaction, residual displacement, lifecycle cost, and long-term damper performance.

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Conflict of Interest

The authors declare that they have no known financial, professional, institutional, or personal conflicts of interest related to this manuscript.

Statement on the Use of Artificial Intelligence

The authors used Claude AI and ChatGPT for language refinement, grammatical improvement, and assistance in improving the clarity and readability of the manuscript. All AI-assisted output was reviewed and verified by the authors, who take full responsibility for the originality, accuracy, citation verification, research ethics, and final content of the manuscript.

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