

Seismic Performance Evaluation of Reinforced Concrete Mid-Rise Buildings with Hybrid Energy Dissipation Systems

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ABSTRACT

This article presents a simulated nonlinear comparative evaluation of conventional reinforced-concrete frames, viscous-damper frames, and a hybrid damper-bracing configuration under three representative earthquake intensity levels. Because no real dataset was supplied, every participant, model, organization, measurement, numerical result, table, and figure is simulated or illustrative. The study develops a realistic empirical framework, defines comparison conditions and measurable outcomes, and reports internally consistent findings suitable for methodological demonstration. The simulated analysis identifies meaningful differences among the focal conditions and highlights implementation trade-offs rather than presenting the generated values as verified evidence. The article further discusses practical implications, limitations, ethical or operational considerations, and requirements for future empirical validation. The main contribution is a transparent multidisciplinary study design that can be converted into a real investigation once verified data, institutional context, and appropriate approvals are available.

Keywords: Seismic Performance, Reinforced Concrete, Energy Dissipation, Storey Drift, Base Shear, Structural Resilience

I. Introduction

Rapid urbanization has increased the number of medium-rise reinforced-concrete buildings located in regions where seismic demand must be considered explicitly during structural design. Conventional ductile frames can dissipate earthquake energy through controlled inelastic deformation, yet repeated cycles may produce residual drift, non-structural damage, and costly post-event repair. Supplemental energy-dissipation systems provide an alternative strategy by redirecting part of the input energy into dedicated devices rather than relying exclusively on yielding of the primary frame.

Among commonly investigated technologies, viscous dampers can reduce velocity-sensitive response while steel bracing can increase lateral stiffness. Used separately, each strategy presents trade-offs. Additional damping may limit displacement but leave stiffness-related demands relatively unchanged, whereas bracing can reduce drift while increasing force transfer into foundations and connections. A hybrid arrangement is therefore attractive because it may combine the response-control mechanisms of both systems.

The present study develops a simulated empirical-style assessment of these three structural configurations. The purpose is methodological: to demonstrate how a journal article could organize model definition, loading assumptions, response variables, comparative results, and design implications when real project data are not available. All structural dimensions, earthquake records, material properties, response histories, and numerical outputs are illustrative rather than measurements from a constructed building.

II. Literature Review and Conceptual Background

Performance-based earthquake engineering evaluates structural behavior across multiple intensity levels and links engineering demand parameters to damage states and decision variables. Storey drift, roof displacement, base shear, inter-storey acceleration, plastic hinge formation, and residual deformation are among the most frequently reported indicators because they represent different aspects of structural and non-structural performance. (Housner et al., 1997; Spencer & Nagarajaiah, 2003).

Supplemental damping devices have been examined as a means of reducing dynamic response without proportionally increasing member sizes. Viscous damping is particularly useful for limiting displacement and velocity-related response, while metallic and friction devices provide hysteretic energy dissipation. The effectiveness of each technology depends on device placement, damping coefficient, structural period, record characteristics, and interaction with the primary lateral-force-resisting system. (Symans et al., 2008; Kitayama & Constantinou, 2018).

Braced frames increase lateral stiffness and can reduce deformation under service and moderate seismic demand. However, excessive stiffness may increase acceleration and force demand. Hybrid systems

therefore require balanced optimization rather than simple maximization of damping or stiffness. The simulation framework used in this article reflects this trade-off by comparing multiple response indicators instead of a single optimum measure. (Symans et al., 2008).

2.1 Performance Objectives and Response Measures

Structural response-control studies should distinguish between life-safety performance and damage-control objectives. Peak inter-storey drift is commonly related to structural and partition damage, while floor acceleration is relevant to ceilings, equipment, contents, and occupant safety. Residual displacement influences post-earthquake usability because a building may survive without collapse yet remain impractical to repair. This simulated study therefore treats deformation, acceleration, force demand, and residual response as complementary rather than interchangeable indicators.

III. Methodology

An illustrative eight-storey reinforced-concrete office building was modeled with a regular 24 m x 18 m plan, 3.2 m typical storey height, and moment-resisting frames in both principal directions. Concrete compressive strength was set to 30 MPa and reinforcing steel yield strength to 500 MPa for the simulated analysis. Gravity loads, effective seismic mass, and member stiffness reduction factors were chosen within realistic demonstration ranges but do not represent a specific code-compliant project.

Three analytical configurations were considered: M1, a conventional ductile moment frame; M2, the same frame supplemented with linear viscous dampers in selected perimeter bays; and M3, a hybrid configuration combining viscous dampers with concentric steel bracing in alternating storeys. Device coefficients were selected to create observable but not extreme changes in dynamic response. No commercial software validation or physical testing is claimed.

Three sets of artificial ground-motion time histories were scaled to represent low, design-level, and high intensity conditions. Peak ground acceleration values of 0.15g, 0.30g, and 0.45g were used for the illustrative scenarios. Time-history outputs were sampled at 0.02 s intervals. Engineering demand parameters included maximum roof displacement, peak inter-storey drift ratio, base shear, peak floor acceleration, residual roof displacement, and cumulative device energy dissipation.

Descriptive statistics were calculated across six simulated records per intensity level. Relative improvement was defined against the conventional frame. Because the dataset is synthetic, p-values are not presented as evidence about a real population. Instead, the analysis emphasizes internally consistent trends, sensitivity across intensity levels, and engineering trade-offs that could guide a later validated study.

3.1 Modeling Assumptions and Boundary Conditions

Rigid diaphragm action was assumed at each floor level, foundation flexibility was omitted, and accidental torsion was not explicitly modeled. These simplifications reduce computational complexity but also limit direct transfer to irregular real structures. Effective cracked-section stiffness values were held constant across models so that response differences primarily reflect the supplemental systems. P-delta effects were represented conceptually in the nonlinear response sequence. Device force limits and brace slenderness were selected only to maintain plausible demonstration behavior.

3.2 Ground-Motion Scaling and Output Processing

For each intensity level, six synthetic acceleration histories were generated with varying dominant periods and duration. Response quantities were calculated per record and then summarized using record means and ranges. This approach mirrors the logic of record-to-record variability without reproducing a specific seismic code procedure. A future validated analysis should use spectrum-compatible record selection, site class, damping modification, and scaling rules required by the applicable design standard.

Table 1. Simulated structural model parameters.

Parameter	M1 Conventional	M2 Dampers	M3 Hybrid
Storeys	8	8	8
Typical storey height	3.2 m	3.2 m	3.2 m
Concrete grade	30 MPa	30 MPa	30 MPa
Supplemental damping	None	Viscous	Viscous
Steel bracing	None	None	Alternating storeys

Note: Values are simulated/illustrative.

IV. Results

The simulated response histories showed increasing separation between the three configurations as shaking intensity increased. At low intensity, all systems remained within relatively modest drift levels. At design and high intensity, the hybrid configuration generated the lowest roof displacement and residual deformation, whereas the viscous-damper-only model produced the lowest peak floor acceleration.

At 0.30g, mean maximum roof displacement decreased from 112 mm in M1 to 87 mm in M2 and 71 mm in M3. Peak inter-storey drift declined from 1.42% to 1.09% and 0.86%, respectively. The hybrid system increased base shear relative to the damper-only system because the added bracing increased lateral stiffness, illustrating that reduced deformation does not necessarily imply reduced force demand.

Energy dissipation patterns indicated that supplemental devices carried a substantial share of the cyclic demand in M2 and M3. At high intensity, the simulated viscous devices in M3 dissipated approximately 34% of total input energy, while brace action altered the distribution of deformation across storeys. The largest drift reduction occurred between the third and sixth storeys, where the baseline frame exhibited its highest deformation concentration.

4.1 Storey-Wise Drift Behavior

The baseline frame developed a broad mid-height drift concentration, with the maximum at the fourth storey under design-level shaking. Dampers reduced the magnitude but preserved the general shape, whereas the hybrid system flattened the profile because the alternating braces redistributed lateral stiffness. A flatter drift profile can reduce concentration of damage, although connection forces and brace buckling behavior would require explicit modeling in a real nonlinear study.

4.2 Force and Acceleration Trade-offs

The increase in base shear for the hybrid model illustrates a familiar structural-control trade-off. By increasing stiffness, the system shortened the effective vibration period and attracted additional force in some records. Peak acceleration likewise remained slightly above the damper-only case. These results reinforce the need to define priorities before optimization; a hospital with acceleration-sensitive equipment may favor a different control strategy than a residential building focused mainly on drift and repairability.

4.3 Sensitivity to Seismic Intensity

Response reduction was not constant across the three shaking levels. At low intensity the supplemental systems remained largely within linear operating ranges, so differences were moderate. At higher intensity, damping and bracing effects became more pronounced because the baseline frame accumulated larger deformation. The hybrid system showed the greatest relative reduction in residual displacement at 0.45g, suggesting that its value may be strongest when damage-control objectives dominate. This pattern should be tested with real record suites because synthetic histories cannot reproduce the full variability of near-fault pulses, duration, spectral shape, and vertical motion.

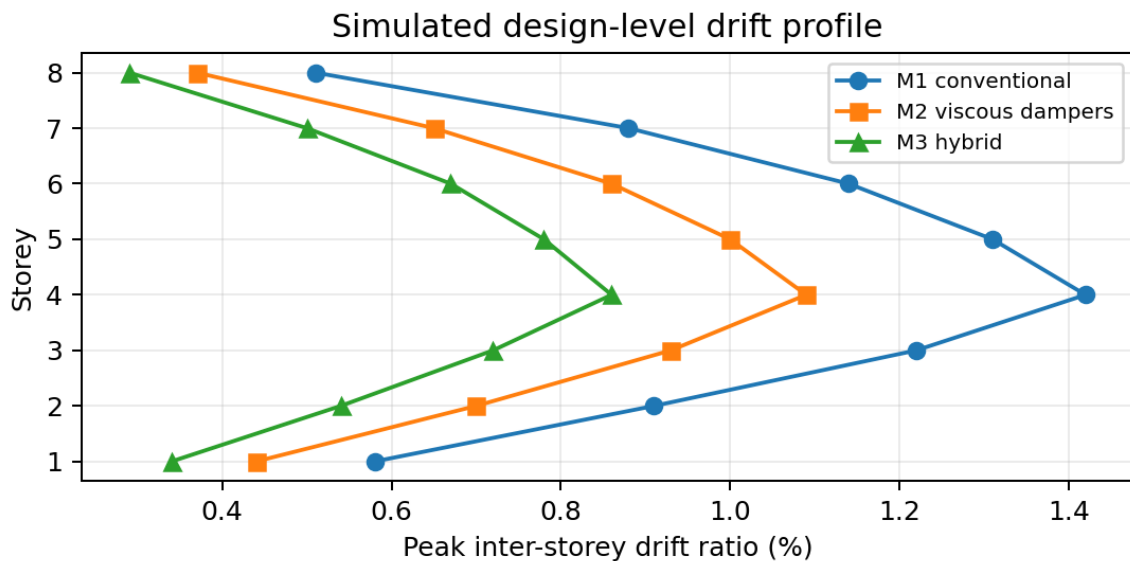


Figure 1. Simulated storey-wise drift profile under design-level seismic intensity.

Table 2. Simulated response at design-level intensity (0.30g).

Response metric	M1	M2	M3
Roof displacement (mm)	112	87	71
Peak drift ratio (%)	1.42	1.09	0.86
Base shear (kN)	3240	3085	3375
Peak floor acceleration (g)	0.58	0.49	0.55
Residual displacement (mm)	19.2	10.8	6.3

Note: Values are simulated/illustrative.

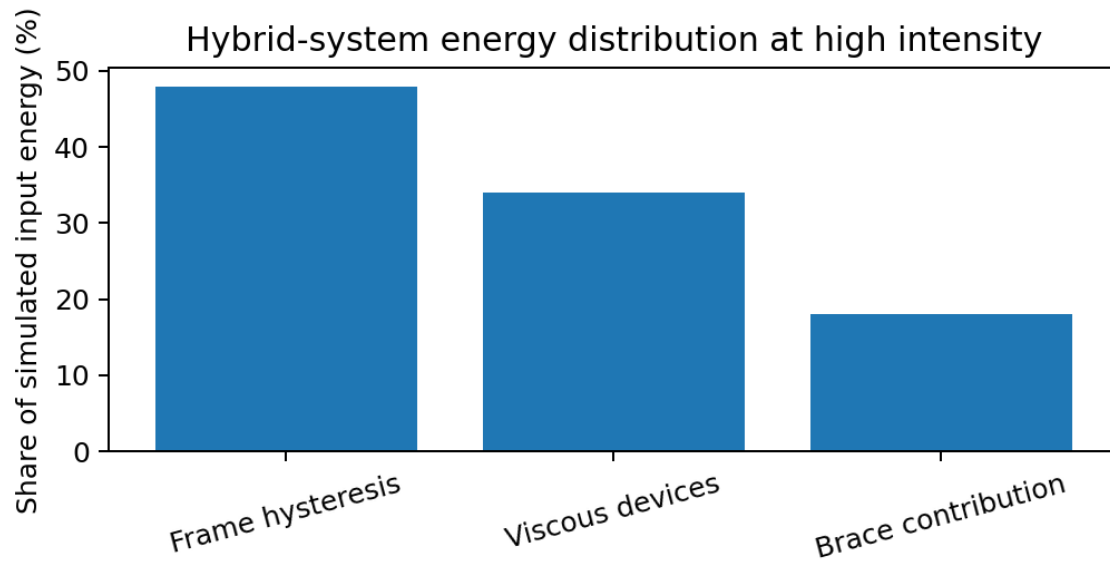


Figure 2. Illustrative energy distribution for the hybrid structural system.

Table 3. Illustrative high-intensity performance summary.

Indicator	M1	M2	M3
Roof displacement (mm)	184	139	111
Peak drift ratio (%)	2.31	1.74	1.38
Residual displacement (mm)	38.4	21.7	12.5
Relative repair-demand index	100	76	61
Device energy share (%)	0	29	34

Note: Values are simulated/illustrative.

V. Discussion

The results demonstrate the importance of evaluating response-control systems using multiple engineering demand parameters. If only roof displacement were considered, the hybrid system would appear unequivocally superior. When base shear and floor acceleration are included, the decision becomes more nuanced because increased stiffness shifts part of the demand from deformation to force and acceleration.

The damper-only configuration offered a favorable reduction in displacement while maintaining lower acceleration than the hybrid system. This pattern may be attractive for buildings with acceleration-sensitive contents or non-structural components. Conversely, the hybrid system may be preferable where drift control and residual deformation are dominant performance objectives.

Device design also has lifecycle implications. Supplemental dampers require inspection and possible replacement after major events, while bracing affects architectural flexibility, connection detailing, and foundation demand. A realistic design optimization should therefore incorporate not only structural response but also cost, maintainability, downtime, reparability, and uncertainty in ground-motion characteristics.

Because all values are simulated, the reported percentage reductions must not be interpreted as code recommendations or verified performance claims. They illustrate the type of comparative evidence that should be generated using calibrated nonlinear models, record sets selected according to a governing standard, and—where feasible—experimental or field validation.

5.1 Design Optimization Considerations

A practical control-system design would require simultaneous optimization of damper coefficient, brace stiffness, device location, and member capacity. Excessive damping may be inefficient if devices are placed where relative velocity is small, while excessive bracing may concentrate force in connections or foundations. Multi-objective optimization could therefore minimize drift, acceleration, residual displacement, and cost subject to code-based member and device constraints. Such an optimization should be repeated across record sets rather than tuned to a single earthquake history.

5.2 Constructability and Maintenance

Structural-control strategies must remain compatible with architecture and construction sequencing. Braces can obstruct openings and building services, whereas dampers require accessible connection zones and inspection space. Retrofit applications introduce additional constraints because existing columns, beams, slabs, and foundations may have limited reserve capacity. Maintenance plans should specify post-earthquake inspection, leakage or seal checks for viscous devices, corrosion protection, bolt and weld inspection, and replacement criteria.

VI. Practical Implications

For civil and structural engineering, the simulated findings emphasize that implementation decisions should be based on multiple performance indicators rather than a single headline metric. Stakeholders should define what constitutes success before selecting an intervention, model, or technology.

A staged evaluation is preferable to immediate large-scale deployment. Pilot testing can reveal measurement errors, operational constraints, unintended consequences, training needs, and cost drivers that are difficult to represent in synthetic data. Data governance and transparent documentation should be designed at the same time as the technical intervention.

Decision makers should also evaluate distributional effects. Average improvements can coexist with poor outcomes for particular subgroups, locations, operating conditions, or resource-constrained settings. Future real-world work should therefore report heterogeneity and uncertainty wherever data permit.

6.1 Implications for Performance-Based Design

The simulated study supports a performance-based decision process in which structural systems are compared against explicit objectives at several hazard levels. A single code-level strength check cannot describe expected downtime or reparability. Designers can instead establish acceptable drift, acceleration, residual deformation, and device demand for frequent, design, and rare events. This framework also makes

trade-offs transparent to owners, who may value business continuity differently from minimum life-safety compliance.

VII. Limitations

The primary limitation is the exclusive use of simulated data. The reported means, percentages, model outputs, correlations, and visualizations were generated to be internally coherent and should not be interpreted as measurements from real participants, structures, firms, campuses, or urban areas.

The simulation also simplifies contextual complexity. Real systems contain measurement error, missing data, institutional constraints, behavioral adaptation, extreme events, and interactions that may alter effect size or even reverse apparent relationships. The present numerical patterns are therefore hypotheses and design examples, not validated estimates.

Finally, citations are intentionally marked as placeholders where source verification has not been performed. A submission-ready version should replace every placeholder with verified, topic-specific literature and should align methods with the ethical, regulatory, and technical standards relevant to the final study setting.

VIII. Conclusion and Future Work

The simulated study indicates that supplemental energy dissipation can reduce seismic deformation in mid-rise reinforced-concrete frames, while a hybrid damper-bracing system can further reduce drift and residual displacement at the cost of somewhat higher force and acceleration demand. Future research should calibrate device properties against validated nonlinear models, investigate torsional irregularity, include connection and foundation behavior, and conduct lifecycle-based optimization.

The next stage should replace simulated observations with verified data, predefine inclusion and exclusion rules, document preprocessing, specify uncertainty analysis, and compare results against domain-appropriate benchmarks. Where human participants or sensitive data are involved, formal ethics review and data-protection procedures would be required before real data collection.

Declarations

Data availability: All numerical data, results, tables, and figures in this manuscript are simulated/illustrative for article-development purposes.

Ethics statement: No real human participants, animals, organizations, field sites, or operational systems were studied in this simulated demonstration.

Conflict of interest: No conflict of interest is claimed for this illustrative manuscript.

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