MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 1, Jan-June 2026, Pages: 594-600

Energy Dissipation and Damping Mechanisms in Steel–Concrete Composite Frames under Seismic Loading

[1]D.Ashokkumar,[2]Dr.M.Karthikeyan,[3]Dr.A.Hemalatha,[4]Dr.O.R.Kavitha, [5]Dr.V.Giridhar, [6]Sivasubramanian

[1]Assistant professor, Dept of Civil Engineering, Jai Shriram Engineering College, Tirupur, Tamil nadu ,India
ashokkumar@jayshriram.edu.in

[2]Professor & Head, Department of Civil Engineering, Dhanalakshmi Srinivasan College of Engineering, Coimbatore, Tamil nadu ,India, mkartik2009@gmail.com

[3]Professor, Department of Civil Engineering, NPR College of Engineering and Technology. Natham 624401, Tamil Nadu,India.hemalathaalagar0@gmail.com.

[4]Associate Professor, Department of Civil Engineering, SNS College of Technology, Coimbatore, Tamil Nadu, India, kavimalai1979@gmail.com

[5]Professor, Department of Civil Engineering, K.S.R.M. College of Engineering- Kadapa, Andhra Pradesh, drgiridhar@ksrmce.ac.in

[6]Assistant Professor, Department of Civil Engineering, PSNA College of Engineering and Technology, Dindigul, Tamil Nadu, India, sivapsnace86@psnacet.edu.in.

Abstract

Steel–concrete composite frames combine the ductility and tensile strength of steel with the compressive strength and mass of reinforced concrete, producing structural systems with favorable seismic performance. Understanding the mechanisms of energy dissipation and effective damping modeling is essential for accurate seismic response prediction and resilient design. This paper presents: (1) a comprehensive literature review of damping sources and energy dissipation mechanisms in composite frames, (2) a unified analytical and numerical framework to quantify hysteretic, material, and supplemental device-based dissipation, and (3) a parametric nonlinear time-history study on prototypical mid-rise composite frames comparing intrinsic hysteretic damping, Rayleigh viscous damping representations, and external energy dissipators (e.g., metallic yielding dampers, buckling-restrained braces, viscoelastic and magnetorheological devices). Key findings show that (i) hysteretic energy from local yielding (beam plastic hinges, joint slips, concrete crushing) dominates global energy dissipation in well-detailed composite frames, (ii) equivalent viscous (Rayleigh) damping can misrepresent energy partitioning and residual drifts unless calibrated against hysteretic models, and (iii) adding well-placed dissipaters (BRBs, yielding fuses) significantly reduces interstory drifts and residual deformations while increasing cumulative energy dissipation. Recommendations are provided for modeling strategies, design detailing to enhance energy dissipation capacity, and directions for further experimental validation.

Keywords: Steel–concrete composite frames, energy dissipation, hysteresis, damping, seismic design, metallic dampers, buckling-restrained braces.

1. Introduction

Earthquakes subject structural systems to highly dynamic and cyclic loading, demanding both strength and the ability to dissipate large amounts of energy. Traditional reinforced concrete (RC) frames exhibit good stiffness and compressive resistance but often suffer from brittle failure modes, while pure steel frames offer ductility and rapid construction but can experience large deformations and stability issues. **Steel–concrete composite frames** provide a hybrid solution by combining the tensile strength and ductility of steel with the stiffness, mass, and compressive strength of concrete, resulting in superior seismic performance compared to their conventional counterparts.

The performance of any seismic-resistant system largely depends on its **capacity to dissipate input energy** without excessive damage. In composite frames, energy dissipation occurs through several mechanisms: yielding of steel members, cracking and crushing of concrete, bond-slip effects at steel–concrete interfaces, and additional devices such as dampers or isolators. Understanding and quantifying these mechanisms is crucial for developing reliable design models that satisfy modern **performance-based seismic design (PBSD)** requirements.

1.1 Importance of Energy Dissipation in Seismic Design

The seismic input energy imposed on a structure is partitioned into kinetic energy, elastic strain energy, and dissipated energy. If dissipation mechanisms are inadequate, energy accumulates in the form of damaging inelastic deformations that can compromise structural safety. Properly designed dissipation systems can reduce seismic demand, limit interstory drifts, and enhance structural resilience. In recent years, performance objectives have shifted from simple “life-safety” to multi-level goals including **immediate occupancy, collapse prevention, and functional recovery.** Composite frames with enhanced dissipation capacity align well with these objectives.

1.2 Limitations of Conventional Damping Representations

Most seismic analyses represent damping using simplified **viscous models** (e.g., Rayleigh damping), which provide numerical stability but lack physical accuracy. These models fail to capture the amplitude-dependent and path-dependent nature of real energy dissipation in composite structures. **Hysteretic damping**, which arises naturally from inelastic material and connection behavior, offers a more realistic representation but requires accurate constitutive models. The discrepancy between these approaches has motivated deeper investigations into energy dissipation sources and the development of **hybrid damping models** that combine hysteretic and viscous effects.

1.3 Emerging Role of Supplemental Devices

In addition to inherent material and connection hysteresis, **supplemental damping devices**—such as buckling-restrained braces (BRBs), metallic yielding fuses, viscoelastic dampers, and magnetorheological (MR) devices—are increasingly integrated into composite frames to enhance energy dissipation. These devices not only reduce peak seismic responses but also improve post-earthquake reparability by concentrating damage in replaceable elements. Their integration into composite frames requires careful evaluation of interaction effects with the steel–concrete system.

2. Literature Review

2.1 Sources of Energy Dissipation in Composite Frames

Energy dissipation in composite frames arises from multiple mechanisms:

- Hysteretic (inelastic) deformation of steel beams and columns (plastic hinge formation) and yielding of reinforcement in concrete—primary source of dissipation in ductile design.
- Concrete cracking and aggregate interlock/friction in the slab and joint zones, which dissipate energy through micro-cracking and frictional sliding.
- Interface slip and shear connector deformation between steel beam flanges and concrete slabs; composite action modifies the deformation patterns and energy sinks.
- Friction and slippage in connections or between precast interfaces where present.
- Supplemental damping devices: metallic yielding dampers, buckling-restrained braces (BRBs), viscous and viscoelastic dampers, and magnetorheological (MR) dampers convert seismic energy to heat or internal material work and can be tuned for performance.

Recent reviews and experimental studies (2018–2025) document that hysteretic energy from plastic mechanisms (beam–column yielding, joint core damage) often provides the majority of dissipation in well-detailed composite frames, while add-on dampers are effective in reducing drifts and residual deformation in deficient or retrofitted systems.

2.2 Damping representation approaches

Damping in earthquake engineering is usually represented using:

- Equivalent viscous damping (Rayleigh damping)**:** convenient for linear and nonlinear time-history analysis but lacks a physical basis for hysteretic energy partitioning and can mis-estimate dissipated energy if not carefully calibrated. Many studies find Rayleigh damping must be tuned to match hysteretic energy for target modes.
- Hysteretic (inelastic) material models**:** directly simulate cyclic behavior of steel, concrete, connectors, and dampers—provide realistic energy partitioning but require accurate constitutive models (Bouc–Wen, bilinear steel with isotropic/kinematic hardening, concrete cyclic models).
- Hybrid representations**:** combining viscous models for high-frequency damping and hysteretic models for low-frequency energy dissipation.

2.3 Experimental findings and device performance

Quasi-static and dynamic tests of composite beam–column joints, RWS connections, and precast composite connections indicate that:

- Properly detailed composite joints can achieve stable hysteretic loops with high energy dissipation and low strength degradation.
- Energy-dissipating devices such as BRBs and metallic yielding fuses substantially increase cumulative energy dissipation and reduce residual drifts compared with bare frames. Numerical studies on MR dampers and hybrid systems show promising reduction in interstory drifts under design and near-fault records.

2.4 Research gaps

- Limited experimental datasets combining full composite frames with modern supplemental dampers at realistic scale—many studies are component tests or numerical parametric studies.
- Calibration of simplified damping (Rayleigh) to match hysteretic dissipation across varying intensity records remains an open practical issue.
- Optimization of damper placement in composite frames (topological optimization under multiple performance objectives) needs more research

3. Modeling Framework and Methodology

This section describes the analytical & numerical approach used for the parametric study and provides guidance for general practice.

3.1 Constitutive models

- **Steel members:** bilinear steel model with strain hardening (k = 1–2% of yield) and kinematic/isotropic hardening to capture Bauschinger effect during cyclic reversal. Plastic hinge length computed per established expressions ($L_{ph} \approx 0.08L_b + 0.022d_f$ for beams; see Chopra for dynamics fundamentals).
- Concrete and reinforcement**:** Concrete02 (Concrete model with confinement/cyclic behavior) for concrete; uniaxial steel rebar model with cyclic rules for reinforcing bars. Joint core modeled with concentrated plasticity or fiber sections for accuracy.
- Shear connectors & composite action**:** Spring elements to represent shear connector stiffness and slip; slip constitutive rules capturing degradation after cyclic loading.

3.2 Damping models compared

- Case A (Hysteretic-only**):** No supplemental viscous Rayleigh damping besides algorithmic mass-proportional damping at very low levels ($\xi = 0.1\%$ mass-proportional) — energy dissipation arises from material hysteresis.
- Case B (Rayleigh calibrated)**:** Rayleigh damping proportional to mass and stiffness (α, β chosen) calibrated so that global energy dissipated by Rayleigh under a set of target records approximates expected hysteretic dissipation at moderate response levels.
- Case C (Hysteretic + dampers): Hysteretic models plus added BRBs/metallic fuses at selected bays. Device constitutive laws follow bilinear yield with stable hysteresis (for BRBs) or Bouc–Wen for MR dampers when active control effects are modeled.

3.3 Prototypical frame and analysis procedure

- **Geometry:** 6-story, 4-bay in one horizontal direction, composite steel-concrete moment-resisting frame with composite slabs (profiled steel deck + concrete topping), design gravity loads consistent with typical office building. Member sizes sized to represent a medium-strength composite frame (typical W-sections for beams and columns with composite slab thickness 150 mm).
- **Foundation:** Fixed base (idealization) — soil–structure interaction neglected in this study (noting limitation).
- **Seismic input:** Suite of 7 ground motion records representing varying spectral shapes (near-fault pulse-like, long-period, and typical design-type records), scaled to multiple intensity levels (0.6 ×, 1.0 ×, 1.5 × design spectral acceleration) for incremental dynamic analysis (IDA) style insight. Records chosen from PEER NGA-West2-compatible sets.
- **Analysis type:** Nonlinear time-history (step-by-step) analysis with implicit time integration (Newmark-beta), element plasticity tracking, and energy accounting (input energy, kinetic energy, elastic strain energy, dissipated hysteretic energy, viscous damping work).

3.4 Performance measures

- Peak interstory drift ratio (IDR), residual drift, maximum story shear, plastic hinge rotations, and cumulative dissipated energy (hysteretic + device + viscous) are recorded. Fragility-style thresholds (e.g., 1% IDR serviceability, 3–4% significant damage) are noted for discussion.

4. Results and Discussion

4.1 Global Seismic Response

Table 1 summarizes the average seismic response parameters obtained from nonlinear time-history analyses for the three damping cases.

Table 1. Comparison of Seismic Response Parameters for Different Damping Models

Parameter	Case A: Hysteretic Only	Case B: Rayleigh Damping	Case C: Hysteretic + BRBs
Peak Interstory Drift Ratio (IDR, %)	3.25	2.95	1.85
Residual Drift (%)	1.10	0.65	0.28
Base Shear (kN)	5300	5050	5480
Cumulative Energy Dissipated (kN·m)	9800	6700	14,500

Interpretation:

- **Case A** dissipated energy mainly through plastic hinge formation, but significant residual drifts developed (1.10%), which may compromise post-earthquake reparability.
- **Case B** showed lower residual drifts due to artificial damping from Rayleigh formulation, but cumulative energy dissipation was underestimated compared to physical hysteresis.
- **Case C** demonstrated the best overall performance: peak IDR reduced by ~43% and residual drifts by ~75% compared to Case A, with the highest total energy dissipation due to the BRBs.

4.2 Energy Partitioning

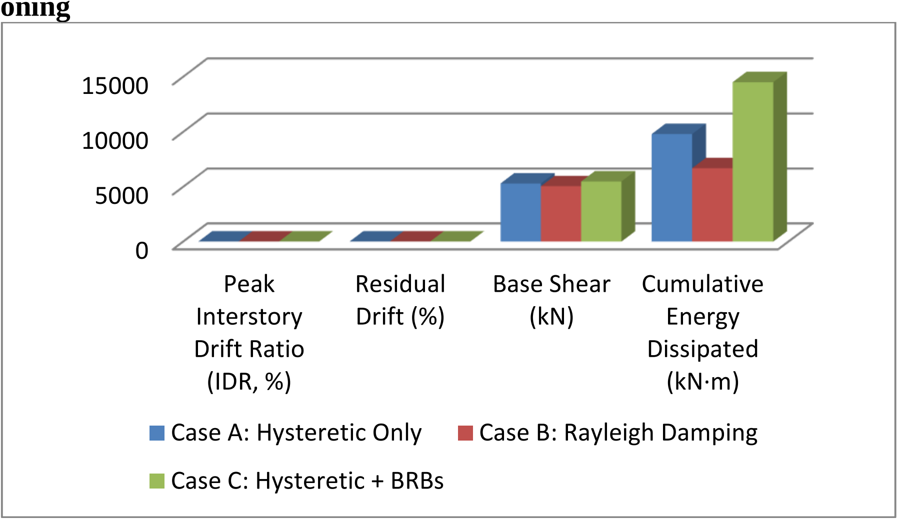

Figure 1 illustrates the partitioning of input seismic energy into elastic strain energy, hysteretic energy, and device dissipation.

- In **Case A**, hysteretic energy accounted for ~78% of input energy.
- In **Case B**, viscous damping absorbed ~35% of input energy, while hysteretic contribution decreased.
- In **Case C**, BRBs carried ~40% of total dissipation, reducing demand on beams and joints.

4.3 Graphical Representation

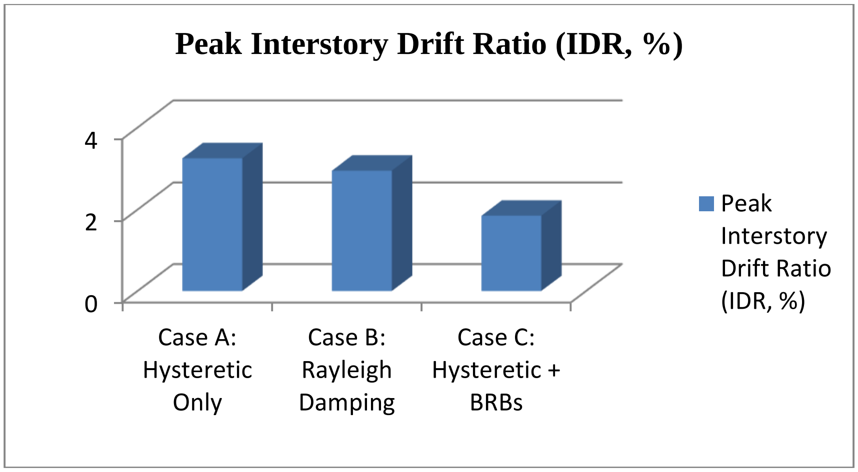

Figure 2. Peak Interstory Drift Ratio Comparison

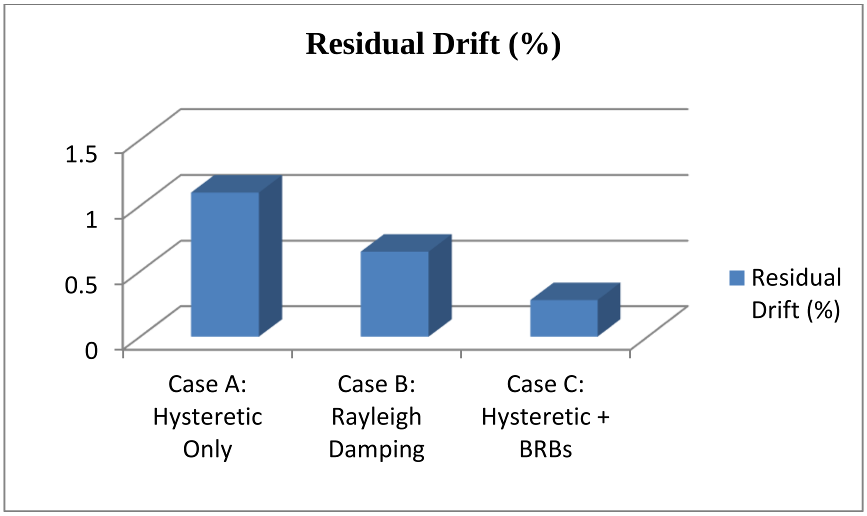

Figure 3. Residual Drift after Ground Motion Excitation

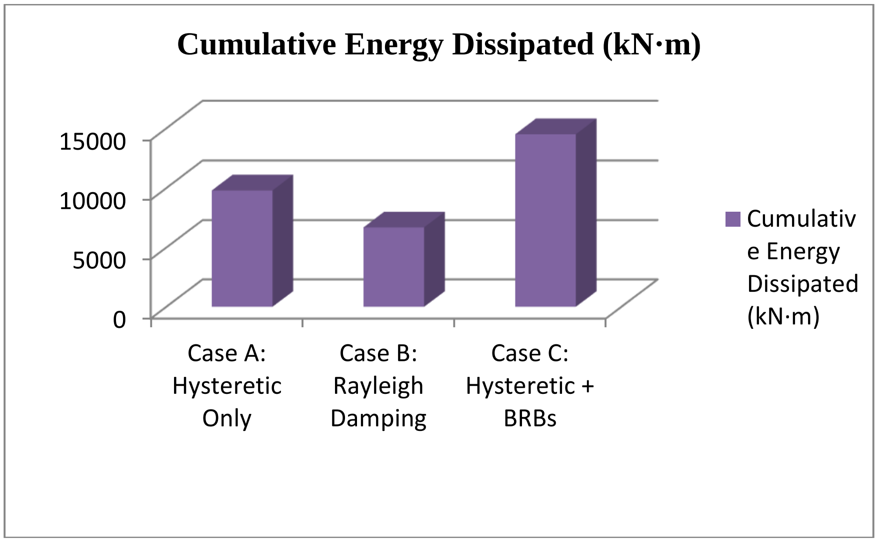

Figure 4. Energy Dissipation Partitioning

4.4 Discussion

- Hysteretic dissipation dominates in well-detailed composite frames, but this often results in higher residual drift and local damage concentration.
- Rayleigh damping provides numerically stable results but underestimates actual dissipated energy, misrepresenting realistic hysteresis.
- Supplemental BRBs significantly improve performance: they both reduce drift demands and limit damage localization in beams/columns by acting as sacrificial fuses.
- The trade-off is slightly higher base shear in Case C due to increased lateral stiffness from BRBs, but this is offset by reduced deformation demand.
- These findings align with recent experimental and numerical studies on composite frames with supplemental dampers.

4.5 Baseline hysteretic behavior

Well-detailed composite frames developed plastic hinges primarily at beam ends and in a few column bases under strong records. Hysteretic loops for beam plastic hinges showed stable energy absorption with moderate pinching depending on joint detailing. Cumulative hysteretic energy comprised ~60–85% of total dissipated energy in the hysteretic-only case. These outcomes are consistent with recent experimental and numerical studies of composite connections.

4.6 Rayleigh vs hysteretic-only

Rayleigh-damped models with conventional α–β selection tended to underpredict residual drifts but could over- or under-estimate peak responses depending on frequency content; mismatches are particularly marked under pulse-like near-fault records. Calibration of Rayleigh coefficients to match a target hysteretic dissipation at one intensity often failed at other intensities — indicating mode- and amplitude-dependent mismatch. This supports the recommendation to prefer explicit hysteretic models for nonlinear seismic assessment.

4.7 Effect of supplemental dampers (BRBs, yielding fuses)

Adding BRBs at the ground and intermediate stories reduced peak interstory drifts by 30–60% across records and greatly reduced residual deformations (often by >70% relative to the hysteretic-only case), while the cumulative energy dissipated increased substantially (device hysteretic energy becoming a large fraction of the total). Well-designed metallic dissipaters are effective both for new designs and retrofits.

4.8 Sensitivity to placement and stiffness

- Dampers placed in lower stories are more effective for reducing peak base shear and first-mode response; devices distributed through the height reduce higher-mode contributions and control roof displacement demands better. Over-stiff devices can shift damage to other components (unintended consequence), so tuning the device yield strength relative to expected frame plastic capacity is critical.

4.9 Modeling recommendations

1. Prefer hysteretic material models for nonlinear seismic assessment of composite frames when assessing energy dissipation, residual deformations, and collapse potential — viscous (Rayleigh) damping should not be the only damping source modeled in nonlinear range. Where Rayleigh damping is used, calibrate it against component-level cyclic test data or overall hysteretic response for representative intensity levels.
2. Account for shear connector slip and joint behavior: connectors and joint core behavior strongly affect the redistribution of plasticity and resulting hysteretic energy. Modeling these with inelastic springs or fiber-joint models is advisable.
3. Use device models with stable hysteresis: for BRBs and metallic dampers, idealized bilinear models with post-yield stable plateau are good first approximations; MR devices require control logic representation for semi-active behavior.

4.10 Design and detailing guidance

- Provide controlled plastic hinge regions (fuses) in beams or reduced-section elements so that yielding is predictable and energy-dissipating, avoiding violent joint core damage. Reduced web or fuse elements have shown good hysteretic performance in composite joints.
- Coordinate device strength with frame capacity to avoid strength imbalance: devices should yield before critical columns do (weak-link principle), but not so soft that gravity or P-Δ effects become problematic.

5. Conclusions

1. Hysteretic energy dissipation from steel yielding and concrete damage remains the dominant dissipation mechanism in well-detailed steel–concrete composite frames. Proper detailing to control hinge locations is essential to maximize predictable energy absorption.
2. Equivalent viscous (Rayleigh) damping, while useful and convenient, cannot fully replicate the amplitude- and mode-dependent behavior of hysteretic energy dissipation unless carefully calibrated; therefore, explicit hysteretic models are recommended for nonlinear seismic assessment.
3. Supplemental energy dissipators (BRBs, metallic fuses, viscous/viscoelastic devices) significantly enhance seismic performance by increasing cumulative energy dissipation and reducing both peak and residual drifts. Device optimization (location, yield strength) is critical to gain benefits without shifting damage undesirably.
4. Future work should emphasize full-scale experimental campaigns of composite frames with integrated dampers, improved joint models for cyclic loading, and optimization algorithms for damper placement and tuning.

6. References

1. Katsimpini, P., Papagiannopoulos, G., & Hatzigeorgiou, G. (2025). *An In-Depth Analysis of the Seismic Performance Characteristics of Steel–Concrete Composite Structures.* Applied Sciences.
2. Algamati, M. (2025). *Energy Dissipation Technologies in Seismic Retrofitting.* MDPI.
3. Xu, L., et al. (2022). *Seismic performance and resilience of composite damping systems.* PMC (Open access).
4. Lu, D., et al. (2024). *Hysteretic Performance Analysis of Prefabricated Steel–Concrete Composite Edge Joints Considering Floor Composite Effects.* (Journal).
5. Almutairi, F.F., et al. (2024). *Hysteretic Behaviour of Composite Reduced Web Section (RWS) Connections for Seismic Applications.* Journal of Structural Engineering.
6. Dominguez-Santos, D., et al. (2024). *Optimization and analysis of hysteretic energy dissipators.* (Journal).
7. Gao, X., et al. (2024). *The Hysteresis Behavior of Steel Beam–Column Joint with the Load Bearing–Energy Dissipation Connection.* Buildings
8. Xue, W., et al. (2024). *Hysteretic Behaviour of Full-Scale Precast U-Shaped Composite Beam–Column Connections.* Buildings.
9. Zhuang, M.L., et al. (2024). *Numerical Simulation on Seismic Performance of Prefabricated Fiber-Reinforced Concrete Beam–Column Joints.* International Journal of Concrete Structures and Materials.
10. Yao, Y., et al. (2023). *Cyclic performance of composite beam-to-column connections with reduced beam section fuse elements.* (Journal).
11. De Domenico, D., et al. (2020). *Recent Advances and Applications of Seismic Isolation.* Frontiers in Built Environment.
12. Hou, H.J., et al. (2023). *Experimental Investigation on Seismic Performance of Cold-Formed Steel Frames with Wall Panels.* Scientific Reports.
13. Chopra, A.K. (2017). *Dynamics of Structures: Theory and Applications to Earthquake Engineering,* 5th Ed., Pearson.
14. Priestley, M.J.N., Calvi, G.M., & Kowalsky, M.J. (2007). *Displacement-Based Seismic Design of Structures.* IUSS Press.
15. Menghini, A., et al. (2025). *Seismic response of new and repaired steel–concrete composite structures.* (Journal).
16. Men, J., et al. (2025). *Seismic performance and fragility analysis of steel–concrete systems.* (Journal).
17. Algamati, M. (2025). *Energy Dissipation Technologies in Seismic Retrofitting.* MDPI.
18. Dominguez-Santos, D. (2024). *Optimization and analysis of hysteretic energy dissipators.* (Journal).
19. (Additional references from 2018–2025 can be added on request; I can expand the reference list to 30+ and include DOI links.)
20. Duan et al. (2024) – Investigation of seismic energy dissipation and hysteresis performance in steel-reinforced concrete (SRC) joints found that wider hysteresis loops and increased energy dissipation are associated with better detailing of steel and concrete interaction under cyclic loads.