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Effect of Structural Damping Characteristics on the Dynamic Behaviour of Framed Structures: A Comprehensive Review

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Abstract - Structural damping significantly influences the dynamic behaviour and response control of framed structures subjected to seismic, wind, and service loads. This comprehensive review examines damping characteristics, sources, modelling techniques, and their impact on key dynamic response parameters. Early foundational studies established mathematical formulations and experimental identification methods, forming the theoretical backbone of structural damping research. However, their validation in complex multi-storey framed systems under realistic loading conditions remains limited. Research on composite, viscous, hysteretic, and viscoelastic damping has advanced understanding of energy dissipation at material and component levels, yet full-scale structural integration is still inadequate. Comparative assessments of Rayleigh, viscous, and hysteretic damping models reveal analytical capabilities but insufficient experimental correlation for practical design implementation. Supplemental damping devices demonstrate substantial effectiveness in mitigating structural vibrations and seismic responses. Nevertheless, optimization of damper placement, hybridization strategies, durability, and lifecycle cost performance requires further investigation. Emerging technologies such as motion amplification and smart control systems necessitate standardized analytical frameworks and codified design guidelines. Overall, the review identifies critical research gaps and outlines future directions for improving damping modelling and performance-based seismic design of framed structures.

Keywords: Structural damping, Dynamic behaviour, Framed structures, Vibration control, Damping characteristics, Damping Modelling Techniques, Energy Dissipation Mechanisms

1. INTRODUCTION

Structural damping plays a critical role in governing the dynamic behaviour of framed structures subjected to seismic, wind, and other dynamic loads. It represents the inherent ability of a structure to dissipate vibrational energy, thereby reducing response amplitudes such as displacement and acceleration. Additional viscous dampers influence the seismic response of steel frame structures, showing that increased damping significantly reduces displacement and base shear under seismic excitation by enhancing energy dissipation. It emphasizes the engineering importance of optimal damper placement for dynamic mitigation [1]. Modal damping ratios evolve during construction phases of RC frames, showing low modal damping but significant changes in natural frequencies and mode shapes. The introduction contextualizes dynamic behaviour of frames during construction, where damping characteristics vary with stage and influence vibrations. It highlights the importance of time-varying dynamic properties [2].

Damping ratios and dynamic performance in frames with motion amplification devices, emphasizing how damping influences dynamic characteristics. The introduction describes the need to quantify damping effects for enhanced prediction of response parameters. It situates damping research within advanced control device integration studies[3].

2. FUNDAMENTAL CONCEPTS OF STRUCTURAL DAMPING

The mathematical models and experimental approaches for material and structural damping in vibrations, presenting key measures and techniques used in dynamic analysis. It highlights the foundational models used to represent energy dissipation in materials. The work remains a cornerstone for understanding structural damping behavior[4]. The underlying physical and mathematical concepts of damping in structures, where damping is presented as an energy dissipation phenomenon essential to dynamic response. Damping must be appropriately modelled for accurate dynamic analysis[5]. Material damping in dynamic analysis, stressing that physical material properties and structural configuration influence energy dissipation. The introduction highlights how damping must be included in numerical dynamic models for realistic structural response. This underscores the physical basis for structural

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damping in dynamic behaviour studies[6]. Though focused on composite beams, structural damping mechanisms are accounted for in analytical models for vibration and sound response, highlighting shear-layer damping contributions as fundamental damping components. It reinforces that damping is integral to dynamic structural behaviour[7].

3. SOURCES AND MECHANISMS OF DAMPING IN FRAMED STRUCTURES

Seismic energy dissipation in multi-storey framed structures with friction, viscoelastic, and hybrid dampers, demonstrating how different mechanisms contribute to response reduction. It highlights that damper type, location, and configuration significantly alter damping performance. These findings illustrate practical sources of added structural damping during earthquakes[8].

Damping performance of frame structures equipped with viscoelastic dampers, showing how viscoelastic material properties and support conditions govern energy dissipation under dynamic loading. It identifies that configuration and damper parameters significantly influence damping effectiveness. This clarifies material and mechanical sources of structural damping[9].Viscoelastic dampers emphasizes that structural damping mechanisms stem from velocity-dependent deformation in VE materials, whose loss factor and electrodynamic properties determine energy dissipation. Importance of material selection and damper design. Viscoelastic mechanisms thus provide a key source of added damping in frames[10]. Although focusing on damping models, insight into underlying viscous and hysteretic damping mechanisms, clarifying how each relates to structural energy dissipation in dynamic systems and why model interpretation matters for system identification. It thus informs understanding of inherent damping sources[11].

4. TYPES OF DAMPING MODELS USED IN STRUCTURAL ANALYSIS

A refined mathematical approach for Rayleigh-type viscous damping that avoids unrealistic damping forces in inelastic dynamic analysis by adjusting the damping matrix assembly. The model improves prediction of structural response under seismic loads compared to conventional Rayleigh damping. It demonstrates the significance of proper damping representation in dynamic modelling[12]. A complex mode superposition method is developed for non-classically damped systems, incorporating frequency-dependent hysteretic loss factors. This mathematical model captures non-proportional damping effects and provides more accurate time-domain dynamic responses for hybrid structures. It bridges gap between classical proportional damping and complex hysteretic representations[13].

Mathematically analyses viscous versus hysteretic damping models, showing how each represents structural energy dissipation differently in dynamic equations. The authors highlight the assumptions and limitations of each model in structural dynamics. Choosing between models impacts simulated responses and design predictions[14].

Develops a complex inverse eigen sensitivity method for identifying damping matrices from measured system dynamics data. The mathematical model correlates analytical mass, stiffness, and damping matrices with complex modal properties, enabling more precise damping modelling. It underscores mathematical techniques for realistic damping representation[15].. Compares proportional damping representations including Rayleigh and Caughey models, highlighting how series expansions allow mathematical specification of multiple modal damping ratios. The paper explains limits of each approach for multi-degree-of-freedom systems. Mathematical modelling choices thus affect modal damping and response prediction[16].

An iterative finite element method for evaluating nonlinear material damping using mathematical modelling of internal damping characteristics. The method refines the structural dynamic model for material-dependent damping behaviour, demonstrating how numerical methods improve representation over simple linear models[17].

A damping matrix identification method that uses experimental modal data to calibrate mathematical damping models in finite element structural dynamics. This enhances accuracy of damping representation in dynamic simulations. The approach highlights the integration of mathematical modeling with real-world data[18].

5. INFLUENCE OF DAMPING ON DYNAMIC RESPONSE PARAMETERS

Material damping influences dynamic stress responses in concrete-filled steel tubular columns under seismic/harmonic loading. Damping (hysteretic and viscous) is shown to modify loss factor and peak response magnitudes, highlighting stress dependent damping effects[19].

Analyses the effect of damping on plate dynamic stability. Damping alters the stability regions and phase-space behaviour's, with detailed analyses using phase portraits and Poincare maps to illustrate the response differences[20].

Increasing damping coefficients in Rayleigh beam models reduces amplitude responses to moving masses. Bridges analytical methods with numerical outcomes, clarifying how damping parameters influence dynamic amplitudes[21]. The importance of material damping (via Rayleigh models) in accurate seismic dynamic analyses. It proposes damping formulation improvements for enhanced structural safety and response prediction[22].

Demonstrates that stochastic perturbations can manifest as increased effective damping in linear oscillators, altering mean dynamic responses and frequency content significantly[23].

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Evaluates the influence of Rayleigh damping parameters on explicit and implicit dynamic analyses of large structural systems, showing how such parameters affect predicted response characteristics[24].
Damping significantly affects dynamic stress intensity factors (DSIFs) in functionally graded materials and that neglecting damping leads to large errors in dynamic fracture predictions[25].
Comprehensive review of hydrodynamic damping on blade-like structures detailing quantitative identification methods and core damping parameters that modify dynamic responses[26]]. Early analysis showing that uncertainties in damping affect transient and steady-state responses of structural systems under dynamic loads like wind and seismic forces, underscoring the sensitivity of response to damping variation[27].
Structural damping using viscoelastic materials significantly modifies stiffness and energy dissipation in framed systems. The review synthesizes rheological modelling approaches and parameter identification techniques for dynamic analysis. It concludes that viscoelastic layers enhance vibration attenuation and improve structural response under dynamic loads[28].
Evaluates passive damping devices installed in steel braced frames for seismic energy absorption. It compares friction, metallic, and viscous dampers in terms of performance, constructability, and retrofit efficiency. Proper damper selection depends on structural configuration and cost–benefit considerations[29]. Discusses different damping devices for vibration mitigation in framed buildings. It summarizes the working mechanisms of metallic, friction, viscoelastic, and fluid viscous dampers. The paper concludes that supplemental damping systems effectively reduce displacement, acceleration, and failure risk in tall frames[30].

6. CONSOLIDATED FINDINGS AND KNOWLEDGE GAPS

Table 1 Fundamental Concepts of Structural Damping

Year	Author(s)	Study Focus	Fundamental Damping Concept	Structural Damping Knowledge
1973	Bert, C. W.	Mathematical & experimental review of material damping	Energy dissipation theory; damping measurement methods	Foundational work defining physical and mathematical basis of structural damping.
2005	Li, Z., & Crocker, M. J.	Damping in sandwich composite structures	Shear-layer and viscoelastic damping mechanisms	Extended damping fundamentals to composite and layered structural systems.
2008	Tian, M.	Dynamic behaviour of RC frames during construction	Time-varying modal damping	Introduced stage-dependent damping and evolving dynamic properties in frames.
2011	Puthanpurayil, A. M., Dhakal, R. P., & Carr, A. J.	Review of in-structure damping models	Analytical & experimental damping modelling	Key synthesis of modelling techniques for structural dynamic simulations.
2020	Barabash, M., Pisarevskyi, B., & Bashynskyi, Y.	Material damping in numerical structural analysis	Material property based damping	Linked physical damping properties with computational dynamic modelling.
2024	Lan, X., Zhang, L., Sun, B., & Pan, W.	Steel frames with additional viscous dampers	Supplemental viscous damping	Experimental validation of passive damping effectiveness in seismic control.

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2025	Gao, W.	Frames with motion amplification devices	Control-device induced damping	Demonstrated that integrating motion amplification devices (MADs) with damping systems significantly improves vibration control

Despite extensive research on structural damping, several gaps remain. Early foundational studies established mathematical and experimental damping concepts but lacked validation in complex framed structural systems under realistic loading. Composite and viscoelastic damping research focused largely on material and component levels, with limited integration into full-scale frame behaviour. Time-varying damping during construction has been identified, yet comprehensive predictive models accounting for evolving stiffness, mass, and damping simultaneously are still scarce. Comparative evaluations of damping models (viscous, hysteretic, Rayleigh) often remain analytical, with insufficient experimental correlation in multi-storey frames. Recent device-based studies validate supplemental damping effectiveness, but optimization of damper placement, hybridization, and life-cycle performance is not fully explored. Furthermore, emerging control technologies such as motion amplification devices require standardized modelling frameworks and design guidelines for reliable implementation in seismic design practice.

Table 2 Sources and Mechanisms of Damping in Framed Structures

Year	Author(s)	Structural System	Source of Damping Identified	Mechanism of Energy Dissipation	Findings
2004	Marko, J., Thambiratnam, D., & Perera, N.	Multi-storey framed buildings under seismic loads	Friction, viscoelastic & hybrid dampers	Sliding friction, material deformation & combined mechanisms	Demonstrated that different supplemental damping devices significantly reduce seismic response; damper type, placement, and configuration control effectiveness.
2009	Lin, R. M., & Zhu, J.	General structural dynamic systems / framed applications	Viscous & hysteretic inherent damping	Velocity dependent viscous forces & hysteresis loop energy loss	Clarified theoretical relationship between viscous and hysteretic damping; emphasized correct model interpretation for accurate system identification.
2020	Zhang, M., & Pang, H.	Frame structures with viscoelastic dampers	Viscoelastic material damping	Shear deformation & rate-dependent stress–strain behaviour	Showed damping effectiveness depends on viscoelastic properties, damper configuration, and support conditions influencing structural response.

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2024	Zhang, H., Li, A., Su, Y., Xu, G., & Sha, B.	Civil engineering framed structures with VE dampers	Engineered viscoelastic damping systems	Velocity dependent deformation governed by loss factor & elastodynamic properties	Provided systematic review of VE damper materials, construction, and applications; highlighted material selection and design as key damping source

Although significant progress has been made in identifying damping sources in framed structures, gaps remain in integrating multiple damping mechanisms within unified analytical frameworks. Existing studies largely examine friction, viscous, or viscoelastic dampers independently, with limited research on hybrid interaction effects under real seismic loading. Theoretical relationships between viscous and hysteretic damping are well established, yet their simultaneous calibration in practical structural systems is insufficient. Material-level viscoelastic investigations emphasize rheological properties, but large-scale frame implementation and long-term performance validation remain underexplored.

Table 3 Types of Damping Models in Structural Analysis

Year	Author(s)	Damping Model Type	Analytical Approach	Key Features of the Model	Comparative Findings
1994	Lin, R. M., Lim, M. K., & Du, H.	Damping matrix identification models	Complex modal parameter identification	Correlates damping matrices with measured modal data using inverse techniques.	Provided early mathematical framework for identifying system damping matrices from experimental dynamics.
1999	Gounaris, G. D., & Beskos, D. E.	Nonlinear material damping (FE-based)	Iterative finite element modelling	Evaluates internal material damping using nonlinear numerical analysis.	Demonstrated improved damping representation over simplified linear models.
2015	Sana, V.	Proportional damping models (Rayleigh & Caughey)	Series expansion of damping matrix	Allows specification of modal damping ratios in MDOF systems.	Highlighted advantages and limits of proportional damping formulations.
2017	Pradhan, S., et al.	Experimentally calibrated damping matrices	Modal testing + FE model updating	Uses experimental vibration data to calibrate damping matrices.	Showed integration of analytical modelling with real structural response data.
2019	Zareian, F., & Medina, R. A.	Refined Rayleigh viscous damping	Modified damping matrix assembly	Avoids spurious damping forces in inelastic seismic analysis.	Improved prediction accuracy over conventional Rayleigh damping.

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2022	Liu, Q., Wang, Y., Sun, P., & Wang, D.	Viscous vs. hysteretic damping models	Comparative mathematical formulation	Examines energy dissipation representation in dynamic equations.	Demonstrated that model choice significantly alters simulated structural response.
2024	Sun, P., Yan, Y., & Yang, H.	Non-classical hysteretic damping	Complex mode superposition method	Incorporates frequency dependent loss factors & nonproportional damping.	Bridges gap between classical viscous and advanced hysteretic damping modelling.

Despite advancements in damping modelling, gaps persist in developing unified frameworks that accurately capture nonlinear, non-proportional, and frequency-dependent damping simultaneously. Most proportional models (Rayleigh, Caughey) remain limited for complex multi-degree and inelastic structural systems. Although experimental calibration and inverse identification techniques improve realism, their application to large-scale framed structures is still scarce. Comparative studies highlight differences between viscous and hysteretic models, yet practical guidelines for model selection in design practice are inadequate. Furthermore, integration of advanced non-classical damping models into standard finite element software and seismic codes remains limited.

Table 4 Influence of Damping on Dynamic Response Parameters

Year	Author(s)	Structural / Mechanical System	Damping Type / Parameter Studied	Dynamic Response Parameter Influenced	Key Comparative Findings
1988	Kareem, A., & Sun, W.-J.	Structures under wind & seismic loads	Uncertain structural damping	Transient & steady-state responses	Demonstrated that uncertainty in damping significantly alters predicted dynamic response, highlighting sensitivity of response to damping variability.
2012	Wang, Y. F., & Li, X. R.	Concrete filled steel tubular columns	Material (hysteretic viscous) damping	Dynamic stress & peak response	Showed damping modifies loss factor and reduces peak stress responses under seismic/harmonic loading.
2016	Chowdhury, R., et al.	Stochastic oscillators	Effective stochastic damping /	Mean response & frequency content	Identified that stochastic perturbations increase effective damping, altering vibration magnitude and spectral characteristics.
2016	Ghajar, R., & Peyman, S.	Functionally graded materials	Material damping	Dynamic stress intensity factors (DSIFs)	Found damping significantly affects fracture response; neglecting damping leads to large prediction errors.

2019	Borkowski, Ł. P.	Structural plates	Viscous damping	Stability regions nonlinear response	Demonstrated damping shifts dynamic stability boundaries and phasespace trajectories.
2020	Barabash, M., et al.	General structural systems	Material damping	Seismic response prediction	Showed realistic damping inclusion improves accuracy of structural dynamic simulations.
2023	Famuagun, K. S.	Rayleigh beams with moving masses	Rayleigh damping coefficients	Vibration amplitude	Increasing damping coefficients reduces displacement amplitudes under moving loads.
2023	Lewandowski, R., et al.	Frames & plates with VE dampers	Viscoelastic damping	Stiffness, vibration attenuation	VE damping enhances energy dissipation and reduces dynamic structural response.
2023	Titirla, M. D.	Steel braced frames	Passive supplemental damping	Seismic displacement & acceleration	Different damper types provide varying
					response reduction efficiencies.
2024	Chen, Y., et al.	Large structural systems	Rayleigh damping parameters	Numerical dynamic response accuracy	Response predictions vary significantly with damping parameter selection in explicit vs implicit analysis.
2025	Zeng, Y., et al.	Blade-like marine structures	Hydrodynamic damping	Fluid-structure vibration response	Hydrodynamic damping parameters strongly modify vibration amplitudes and frequencies.
2025	There, A. A., & Dahake, H. B.	Framed buildings with dampers	Metallic, friction, viscous damping	Displacement, acceleration, failure risk	Supplemental damping devices significantly improve vibration control and seismic safety.

The reviewed studies collectively confirm that structural and material damping significantly influences dynamic response parameters across diverse structural and mechanical systems. However, most investigations are system-specific—focusing on beams, plates, marine blades, or braced frames—limiting generalized understanding for multi-storey framed buildings under combined hazards. Considerable variation exists in damping modelling approaches (viscous, Rayleigh, stochastic, hydrodynamic, viscoelastic), yet no unified comparative framework evaluates their relative effectiveness on common response indices. Uncertainty in damping parameters has been highlighted, but probabilistic calibration with real structural monitoring data remains insufficient. Many works emphasize response reduction (displacement, stress, vibration amplitude) without linking damping selection to design optimization or performance-based seismic criteria. Interaction of material damping with supplemental damping devices is rarely studied in integrated structural systems. Numerical sensitivity to Rayleigh damping coefficients is noted, yet standardized selection guidelines for nonlinear time-history analysis are lacking. Limited research addresses damping effects under multi-hazard loading (wind–seismic–moving loads combined). Scale effects and damping behaviour in tall or irregular framed structures remain underexplored. Hence, a comprehensive, comparative, and experimentally validated framework for damping characterization in complex framed systems is still needed.

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7. CONCLUSION

Structural damping research has progressed substantially from foundational mathematical formulations to advanced device based energy dissipation technologies. Early studies built strong theoretical and experimental bases; however, their direct validation in complex multi-storey framed structures under realistic seismic and wind loading remains limited. Investigations on composite and viscoelastic damping have enriched understanding at material and component scales, yet system-level integration into full structural frames is still insufficient. Similarly, recognition of time-varying damping during construction has opened new research directions, but predictive models capturing simultaneous evolution of stiffness, mass, and damping are scarce.

. Comparative evaluations of viscous, hysteretic, and Rayleigh damping models highlight analytical strengths but lack robust experimental correlation for practical design adoption. Supplemental damping devices have proven highly effective in response mitigation; nevertheless, optimal damper placement, hybrid combinations, durability, and life-cycle cost performance require deeper exploration. Emerging technologies such as motion amplification and smart control systems Future research should therefore focus on developing unified analytical and numerical frameworks capable of simulating nonlinear, non-proportional, and frequency dependent damping in integrated structural systems. Large-scale experimental validation, real-time hybrid simulation, and field monitoring of damped framed buildings are essential to bridge theory–practice gaps. Additionally, integration of advanced damping models into mainstream finite element platforms and seismic design codes will be crucial. A performance-based, standardized approach linking damping characteristics with global structural dynamic behaviour represents the most critical future scope for resilient structural design

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