International Journal of Creative and Open Research in Engineering and Management
ISSN: **3108-1754 (Online)**
Volume 02 Issue 04 April-2026 | Impact Factor: 3.5

Comprehensive Review of Fluid Viscous Dampers (FVDS) for Seismic Performance Enhancement of High-Rise Buildings

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How to Cite this Article:

Shah, J. (2026). Comprehensive Review of Fluid Viscous Dampers (FVDS) for Seismic Performance Enhancement of High-Rise Buildings. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(04). https://doi.org/10.55041/ijcope.v2i4.670

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ABSTRACT

Rapid urbanisation in earthquake-prone regions has intensified the demand for effective lateral force resisting systems capable of protecting structural integrity under strong ground motion excitation. Fluid viscous dampers (FVDs) have emerged as a leading passive energy dissipation technology, distinguished by their velocity-proportional force output, inherent phase-angle offset between peak damping force and peak structural displacement, wide operational frequency bandwidth, and consistent thermal stability under repeated seismic loading cycles. This paper presents a critical, structured review synthesising two decades of analytical, numerical, and experimental FVD research, systematically addressing constitutive modelling frameworks — spanning the linear dashpot and the more physically rigorous Maxwell model incorporating series spring stiffness — damper classification into linear (velocity exponent α = 1) and nonlinear (α < 1) variants, optimal placement strategies including inter-storey drift-guided and topology-based allocation, comparative performance against concentrically braced frames (CBFs), moment-resisting frames (MRFs), and buckling-restrained braces (BRBs), and compliance with the supplemental damping provisions of ASCE 7-16, IS 1893:2016, and the loss-estimation methodology of FEMA P-58. Synthesised findings from studies on reinforced concrete and steel moment frames spanning 5 to 35 storeys demonstrate peak displacement reductions of 20–96%, inter-storey drift reductions of 27–97%, and variable base shear modulation governed by supplemental damping ratio, velocity exponent, and input ground motion frequency content. FVDs consistently outperformed displacement-dependent devices in limiting residual drift and floor acceleration demands — critical determinants of post-earthquake functional recovery. Nonetheless, research gaps persist in experimental characterisation of bi-directional and torsionally coupled loading responses, quantitative treatment of soil–structure interaction effects on damper force demand, and the development of a generalised, code-agnostic optimisation framework for FVD sizing across diverse building typologies and seismic hazard regimes.

Keywords: Fluid viscous dampers; Seismic performance; Passive energy dissipation; High-rise buildings; Damper placement optimisation; Nonlinear analysis; Response spectrum analysis; ETABS; SAP2000; IS 1893; ASCE 7-16.

1. Introduction

Rapid urbanisation and population growth in metropolitan areas worldwide have propelled the construction of increasingly tall and structurally complex buildings. These structures are inherently more sensitive to dynamic lateral loads — particularly those induced by seismic ground motions — as their increased height corresponds to reduced natural frequencies and heightened susceptibility to resonance. The engineering challenge of designing buildings that can resist such forces while remaining economically viable and functionally safe has driven substantial research into supplemental energy dissipation systems.

Among the passive control technologies developed for structural vibration mitigation, fluid viscous dampers have garnered particular attention due to their ability to dissipate earthquake energy through the viscous resistance of fluid forced through calibrated orifices. Unlike displacement-dependent devices such as metallic yielding dampers or buckling-restrained braces, FVDs generate forces that are out-of-phase with displacement — proportional to velocity — and thereby avoid increasing peak structural stresses during extreme seismic events. This unique characteristic makes FVDs especially attractive for retrofit applications and for buildings requiring both stiffness preservation and damping augmentation.

The history of viscous dampers in structural engineering follows from their extensive use in aerospace and military applications, where precision energy management over a wide dynamic range is critical. Their adaptation for civil structures has accelerated since the 1990s, supported by advances in computational modelling tools (notably ETABS and SAP2000), experimental testing protocols, and performance-based design frameworks. The formulation by Makris and Constantinou (1990) [8] of the Maxwell model of viscoelasticity — representing the damper as a dashpot in series with a linear spring — provided a tractable and accurate constitutive description that underpins modern numerical implementations.

The present review is motivated by the rapid expansion of literature on FVD applications across diverse building typologies, seismic zones, and design codes. While previous reviews have addressed energy dissipation devices broadly, a consolidated synthesis focusing specifically on FVDs — covering constitutive modelling, placement strategies, comparative device performance, and code compliance — is warranted. The objective of this paper is to provide researchers, practising engineers, and policymakers with a rigorous and up-to-date account of the state of the art, identify areas of consensus and ongoing debate, and delineate productive directions for future research.

2. Fundamentals of Fluid Viscous Damper Technology

2.1 Working Mechanism and Components

A fluid viscous damper comprises four principal components: a sealed cylinder, a hydraulic piston with calibrated orifices, a compressible silicone or oil-based fluid, and an accumulator. Under dynamic loading, relative movement between the two end connections drives the piston through the fluid, forcing it through the orifices and generating a resistive pressure differential. This process converts kinetic energy into heat — the fundamental mechanism of energy dissipation — which is subsequently transferred to the surrounding environment.

The orifice geometry governs the force-velocity characteristics of the device. Circular orifices with fixed cross-sections produce approximately linear force-velocity relationships (linear dampers, velocity exponent alpha = 1.0), whereas specially profiled orifices yield nonlinear relationships with alpha values typically between 0.3 and 0.95. The compressible fluid provides an essential buffering function, allowing the device to operate effectively under both quasi-static and high-frequency dynamic loading without cavitation.

FVDs are designed to function reliably across a broad operating temperature range, typically -40 degrees Celsius to +70 degrees Celsius, ensuring performance stability in diverse climatic environments. Warranty periods of 35 years or more are standard in reputable manufacturers' catalogues, reflecting the robust, low-maintenance nature of properly designed viscous damper systems.

2.2 Constitutive Models

2.2.1 Pure Dashpot (Idealised) Model

The simplest mathematical description of a viscous damper is the pure dashpot model, expressed by the constitutive equation:

$$\mathbf{F = C \cdot V^{\alpha}}$$

where F is the output force, C is the damping coefficient $[\mathrm{kN}\cdot(\mathrm{s/m})^{\alpha}]$, V is the relative velocity across the device, and alpha is the velocity exponent. When alpha equals 1.0, the relationship is linear (elliptical hysteresis loop); when alpha is less than 1.0, the device is nonlinear (super-elliptical hysteresis loop). Nonlinear dampers with lower alpha values achieve equivalent energy dissipation at reduced peak forces, an important consideration for structural member design.

2.2.2 Maxwell Model of Viscoelasticity

In practice, actual viscous dampers exhibit slight elastic flexibility attributable to fluid compressibility and the mechanical compliance of connecting hardware. This behaviour is captured by the Maxwell model, which represents the damper as a pure dashpot (C, alpha) in series with a linear spring (Maxwell stiffness, Kd). The governing equations are:

$$F = Kd \cdot dK = C \cdot V^{\alpha}$$

$$d_{total} = dK + dC$$

The Maxwell stiffness Kd depends on the damper's rated force capacity and stroke length. For Taylor Devices standard catalogue models, Kd ranges from 625 kips/in (Model 17120, 55 kips rated force) to 12,000 kips/in (Model 17210, 1800 kips rated force) [7]. As Maxwell stiffness decreases, hysteresis loops become increasingly pinched and skewed, reducing energy dissipation efficiency. The engineer must therefore ensure that the combined stiffness of the damper and its connecting brace (Kd*, computed from the springs-in-series formula) remains sufficiently large to preserve intended hysteretic behaviour.

2.3 Linear vs. Nonlinear Dampers

The selection between linear (alpha = 1.0) and nonlinear (alpha < 1.0) dampers involves trade-offs between peak force demand and energy dissipation efficiency. Nonlinear dampers dissipate the same energy as their linear counterparts at lower peak forces — advantageous for protecting adjacent structural members — but generate relatively higher forces at small velocities, which can be significant under wind or minor seismic excitation. Wang and Mahin (2016) [3] adopted alpha = 0.35 for a 35-storey retrofit, citing this value as optimal for balancing control effectiveness against excessive damper forces. Tiwari et al. (2023) [4] employed alpha = 0.3 in their multi-storey Nepalese building study, consistent with the broad research literature that identifies alpha values of 0.3 to 0.5 as providing high seismic energy dissipation efficiency [9,11,12].

3. Damper Placement Configurations and Optimisation

3.1 Damper Configurations in Frame Structures

The physical integration of FVDs within a structural frame requires connecting hardware — extender braces — to transfer forces between adjacent floors or bays. Four principal configurations are recognised in the literature: diagonal brace damper, chevron (inverted-V) brace damper, toggle damper, and cantilever truss damper. Each configuration offers distinct geometric amplification ratios and practical installation constraints. The chevron configuration is the most widely used in practical applications owing to its simplicity, direct force path, and architectural flexibility. The toggle configuration theoretically provides amplification of damper displacement relative to inter-storey drift, enabling smaller dampers to achieve equivalent energy dissipation; however, this benefit is offset by increased sensitivity to construction tolerances.

Extender brace stiffness is a critical design parameter that is often overlooked in simplified analyses. The Taylor Devices design guide [7] explicitly requires engineers to calculate the combined stiffness $Kd^* = 1/(1/Kd + 1/Kb)$, where Kb =

AE/L is the axial stiffness of the connecting brace. Insufficient brace stiffness results in pinched hysteresis loops and reduced energy dissipation, potentially failing to meet intended performance objectives even when damper properties are correctly specified.

3.2 Storey-Level Placement Strategies

The question of where within a building height to locate dampers has been the subject of extensive parametric research. Sharma et al. (2023) [1] conducted a systematic comparison of four placement scenarios in a G+20 RC framed building analysed by ETABS: (1) no dampers (baseline), (2) FVDs on alternating storeys, (3) FVDs on all storeys, and (4) FVDs at three discrete levels (top, centre, bottom). Their response spectrum analysis demonstrated that all-storey placement yielded the greatest absolute displacement reduction, with the 20th-storey displacement reduced from 348.77 mm to approximately 23 mm — a reduction of over 93%. The alternate-storey configuration achieved reductions of approximately 57%, while the three-storey configuration provided intermediate performance.

The authors further observed that alternate-storey dampers outperformed all-storey dampers in controlling inter-storey drift, attributing this to the ability of alternate arrangements to resist lateral loads acting simultaneously from both sides of the structure. This finding highlights the importance of distinguishing between global displacement control and local drift control as competing performance objectives. The 3-storey configuration, while cost-efficient, proved less effective and was not recommended as the sole damping strategy for high-rise buildings in high-seismicity zones.

Wang and Mahin (2016) [3], in their investigation of a 35-storey Pre-Northridge steel moment-resisting frame, found that concentrating FVDs in the lower two-thirds of the building — with damping constants proportional to storey stiffness — was more effective than uniform distribution across all storeys. This outcome suggests that the optimal placement strategy is height-dependent and sensitive to the structural system's stiffness distribution, reinforcing the need for building-specific optimisation rather than prescriptive rules [15].

3.3 Plan Position Optimisation

Beyond storey-level placement, the horizontal position of dampers within the building plan significantly influences their seismic efficacy. Patil and Salgar (2024) [2] investigated seven distinct plan configurations for FVDs in a G+30 storey irregular RC building, systematically varying placement between corner positions, centre positions (X-pattern, V-pattern, inverted-V, linear, zigzag), and inclined orientations. The center-X configuration achieved the maximum displacement reduction of 96.42% and storey drift reduction of 96.61% compared to the undamped baseline — the highest performance among all tested arrangements. The authors developed regression equations relating storey displacement and base shear to storey number for each optimum configuration, providing practical predictive tools for preliminary design.

More et al. (2019) [6] evaluated aspect ratio effects on FVD performance across 20-storey and 40-storey RCC buildings, finding that the zig-zag pattern installed at all external corners consistently outperformed diagonal placement. Storey displacement reductions of up to 54% and storey drift reductions of up to 78% were recorded for Model B (40-storey, aspect ratio 1.0) with zig-zag corner dampers. Their observation of approximately 40% reduction in fundamental period with FVD incorporation has important implications for spectral demand calculations in performance-based design.

3.4 Computational Optimisation Frameworks

Mathematical optimisation of inter-storey damper placement positions has been pursued through gradient-based methods, genetic algorithms, simulated annealing, and metaheuristic approaches. The general optimisation problem minimises a performance objective (e.g., maximum inter-storey drift, total energy input) subject to constraints on damper quantity, budget, and inter-storey drift limits. Patil and Salgar (2024) [2] extended this approach by developing a Python-based algorithm that sorts building response data to identify minimum drift positions, maximum displacement configurations, and feasible damper quantity-position combinations — demonstrating the applicability of machine learning-adjacent data analysis tools to damper design optimisation.

The optimisation literature broadly confirms that dampers placed at floors with high inter-storey drift [14,16] or distributed in decreasing quantities from base to top tend to yield better performance than uniform distributions. However, these generalisations must be tempered by building-specific structural characteristics and by constraints imposed by architectural, mechanical, and constructability considerations in real projects.

4. Seismic Performance Assessment: Key Response Parameters

4.1 Lateral Displacement

Lateral displacement — the absolute movement of a floor relative to the ground — is the primary indicator of overall building drift demand and is directly related to structural damage potential for displacement-sensitive components. The research literature consistently demonstrates that FVDs reduce peak lateral displacements across all building heights and configurations investigated, though the magnitude of reduction is sensitive to damper placement, building height, and the level of seismic excitation.

For low-to-mid-rise buildings (5 to 15 storeys), Tiwari et al. (2023) [4] reported maximum storey displacement reductions of 70% (Design Basis Earthquake, 5 storeys) to 17% (Maximum Credible Earthquake, 15 storeys), clearly demonstrating that FVD effectiveness diminishes with increasing building height for a fixed damper configuration. For taller buildings, Patil and Salgar (2024) [2] achieved exceptional displacement reductions of up to 96.42% in a G+30 building with optimised center-X placement — though this extreme result reflects both the optimality of the chosen configuration and the severity of the undamped response in the Y-direction (624.4 mm for a 30-storey building).

4.2 Inter-Storey Drift

Inter-storey drift ratio (ISDR) — the differential horizontal displacement between adjacent floors normalised by storey height — is the most widely used damage proxy in seismic engineering. IS 1893:2016 [18] prescribes a drift limit of 0.004 (0.4%) for limit state design; ASCE 7-16 [17] imposes storey drift limits of 0.010 to 0.025 depending on occupancy and structural system. The multiple studies reviewed here confirm that FVDs reliably reduce ISDRs below code limits in structures that would otherwise exceed them.

Sharma et al. (2023) [1] observed that the 20th-storey drift in the undamped G+20 structure was 0.002905, reduced to 0.002189 with alternating-storey FVDs. While these values are within IS 1893 limits, the all-storey configuration achieved further reductions. More dramatically, Wang and Mahin (2016) [3] demonstrated that FVDs reduced peak drift ratios in the lower floors of a 35-storey steel building from values exceeding 3% (unsafe for Pre-Northridge connections) to below 1.5% — effectively eliminating the risk of beam-column connection fracture at BSE-2E hazard levels.

4.3 Base Shear

The influence of FVDs on base shear is more complex and depends critically on the interaction between the added damping and the spectral demand characteristics of the structure. Unlike stiffness-based systems (bracing, shear walls), FVDs in principle introduce no additional stiffness and therefore do not shift the natural period or directly increase spectral accelerations. However, the velocity-dependent force generation of FVDs does interact with structural response in ways that can modulate base shear values.

Amanullah and Arora (2019) [5] reported that all FVD configurations reduced base shear relative to the X-bracing system (maximum base shear: 4167 kN), with the 250 kN diagonal FVD achieving a minimum base shear of 1709 kN — a reduction of 58.98%. This result reflects the fundamental advantage of FVDs over conventional bracing in that they dissipate energy without attracting additional seismic force to the structure. Patil and Salgar (2024) [2] conversely noted a 45.47% increase in base shear with FVD incorporation, reflecting the dependence of this metric on how base shear is defined (modal combination vs. equivalent static) and on the specific structural configuration.

4.4 Floor Acceleration and Residual Displacement

Two response parameters that receive less attention than displacement and drift — but are critically important for non-structural damage assessment — are floor accelerations and residual displacements. Wang and Mahin (2016) [3] demonstrated that FVDs reduced peak floor accelerations by approximately 30% throughout the 35-storey building, attributable to the additional viscous damping effect. In contrast, BRBs increased floor accelerations to 0.96g at roof level due to their displacement-dependent stiffening effect. This distinction is pivotal for protecting acceleration-sensitive equipment and non-structural components.

Tiwari et al. (2023) [4] found that FVDs reduced floor acceleration by only 13-27% (DBE) and 13-15% (MCE) in a five-storey building, substantially less than the 70-80% displacement reductions recorded. This relative insensitivity of floor acceleration to viscous damping is theoretically consistent with the velocity-dependent nature of FVD forces and should be considered when selecting damping strategies for buildings housing critical equipment. Residual displacements, by contrast, were reduced by 80% (DBE, 5-storey) to 25-37% (MCE, 15-storey) — demonstrating the significant benefit of FVDs for post-earthquake building functionality and repairability.

5. Comparative Assessment: FVDs vs. Alternative Lateral Systems

5.1 FVDs vs. Bracing Systems

Steel bracing systems (X-bracing, V-bracing, inverted-V bracing) represent the most commonly deployed alternative to passive damping for lateral force resistance in high-rise buildings. Amanullah and Arora (2019) [5] provided a direct comparison of bare frames, X-bracing, inverted-V bracing, and FVDs of varying capacities in a G+20 RC building. Their results demonstrated that X-bracing achieved the highest base shear (4167 kN) while reducing lateral displacement from 132.5 mm to 122.7 mm. The FVD 250 kN configuration, in contrast, achieved similar displacement control (122.7 mm) while reducing base shear to 1709 kN and fundamental period from 3.86 s to 2.94 s. The critical conclusion is that bracing increases lateral stiffness — and therefore seismic force demand — while FVDs reduce the structural response through energy dissipation without proportionally increasing stiffness.

This distinction has significant implications for foundation design: a braced frame requires foundations capable of resisting substantially higher seismic base shears, whereas a damped frame may achieve equivalent displacement control with reduced foundation demands. For retrofit applications where foundation strengthening is expensive or impractical, FVDs offer a compelling advantage over bracing.

5.2 FVDs vs. Buckling-Restrained Braces (BRBs)

BRBs have gained widespread adoption as ductile energy dissipation devices that utilise the yielding of a steel core to absorb seismic energy. Wang and Mahin (2016) [3] conducted the most rigorous comparative assessment found in the reviewed literature, evaluating FVDs, viscous wall dampers (VWDs), and BRBs against identical performance objectives in a 35-storey Pre-Northridge steel building. Their results demonstrated that FVDs were uniquely effective in reducing concentrated drift demands at floors 2-10, contributing to a more uniform distribution of peak deformations. BRBs, being displacement-dependent, acted in-phase with peak displacements and increased force demands on existing beams and columns — ultimately failing to meet the BSE-2E retrofit performance goal.

The probabilistic damage and loss analysis (FEMA P-58) [19] further quantified the economic implications: the FVD retrofit scheme reduced the median repair loss ratio from 1.0 (full replacement) to 0.047, with 90th percentile loss of 0.071. The BRB retrofit achieved a median loss ratio of 0.084 but could not guarantee acceptable losses at 90th percentile confidence. The initial device cost of FVDs ($6.4M) exceeded BRBs ($1.7M), but the superior control effectiveness of FVDs yielded substantially greater lifecycle benefit [16] — an investment of $64M (including installation) against potential savings of $452M (median) from avoided repair costs.

5.3 FVDs vs. Viscous Wall Dampers (VWDs)

VWDs represent an architecturally flexible alternative to brace-type FVDs, providing additional damping and stiffness simultaneously. However, Wang and Mahin (2016) [3] identified critical failure modes in VWDs within Pre-Northridge steel buildings: the stiffening effect of VWDs accelerated fracture of brittle beam-column connections, dramatically reducing their energy dissipation capacity once connected beams failed. The VWD retrofit scheme had a 66% probability of irreparability and a median repair loss ratio of 1.0 — identical to the unretrofitted building. This result underscores the importance of considering the interaction between supplemental devices and existing structural deficiencies in retrofit design.

6. Summary of Key Research Studies

Table 1: Summary of Representative Studies on Fluid Viscous Dampers

Study / Author	**Building Type**	**Analysis Method**	**Damper Config.**	**Key Findings**
Sharma et al. (2023)	G+20 RCC Frame	Response Spectrum (ETABS)	All-storey, Alternate, 3-storey	All-storey placement gave maximum reduction in displacement, drift, and shear
Patil & Salgar (2024)	G+30 RCC High-rise	Response Spectrum (ETABS)	7 positions × all/alt/2-alt storey	Center-X position reduced displacement by 96.42% and drift by 96.61%
Amanullah & Arora (2019)	G+20 RCC Frame	ESA + Response Spectrum (ETABS)	FVD 250/500/750 kN; diagonal & inv-V	FVD 250 kN outperformed bracing; base shear reduced 58.98%
More et al. (2019)	20- & 40-storey RCC	Response Spectrum (ETABS v15)	Corner diagonal & zig-zag patterns	Zig-zag pattern: up to 78% drift reduction; 40% time period reduction
Wang & Mahin (2016)	35-storey Steel MRF	Non-linear RHA (OpenSees)	FVD vs VWD vs BRB	FVDs most cost-effective; median repair loss ratio reduced from 1.0 to 0.047
Tiwari et al. (2023)	5-, 10- & 15-storey RCC	Non-linear THA (SAP2000)	Perimeter FVD (alpha=0.3)	Effectiveness decreases with height; 5-storey: 70% displacement reduction

Table 2: Key FVD Design Parameters and Their Significance

Parameter	**Symbol**	**Typical Range**	**Role in Design**
Damping Coefficient	C	100–5000 kN·(s/m)^α	Controls magnitude of damping force at given velocity
Velocity Exponent	α	0.3 – 1.0 (nonlinear); 1.0 (linear)	Governs force-velocity relationship shape; lower α = more efficient seismic dissipation
Maxwell Stiffness	Kd	625–12,000 kips/in (Taylor)	Series spring stiffness; influences hysteresis loop shape and energy dissipation efficiency
Damping Force	F	55–1800+ kips (rated)	Output force; must be resisted by adjacent structural members
Stroke	±d	±3 to ±5 inches (typical)	Maximum piston travel; governs device length selection
Combined Stiffness	Kd*	Kd*= 1/(1/Kd + 1/Kb)	Effective stiffness including brace; critical for accurate modeling in ETABS/SAP2000

7. Numerical Modelling Approaches and Code Provisions

7.1 Modelling in ETABS

ETABS (Extended Three-Dimensional Analysis of Building Systems) is the predominant software platform for FVD modelling in the reviewed research literature. The Taylor Devices modelling guide [7] provides detailed procedures: FVDs are defined as link elements of type 'Damper-Exponent', with the U1 directional property set to nonlinear and specified through three input parameters: series spring stiffness (Kd*, including brace stiffness in series), damping coefficient C, and damping exponent alpha. The linear properties (effective stiffness and effective damping) are left at zero for velocity-dependent FVDs, as these parameters are only relevant for displacement-dependent devices.

A critical modelling subtlety highlighted in the design guide is that the link element should represent the combined length of the damper and extender brace, rather than the damper alone. This ensures that the combined stiffness Kd* — computed from the springs-in-series formula — correctly reflects the compliance of both the damper fluid column and the connecting hardware. Neglecting brace stiffness can result in an overestimate of energy dissipation of up to 15% for linear dampers and 25% for nonlinear dampers.

For response spectrum analyses, the effective damping term is used by ETABS to compute supplemental damping in each mode via the modal strain energy method. While this approach provides a reasonable approximation for preliminary design, the Taylor Devices guide [7] notes that the modal strain energy method has inherent limitations not fully captured by ETABS — suggesting that nonlinear response history analysis (NRHA) should be performed for final design validation.

7.2 Modelling in SAP2000

SAP2000 provides equivalent link element capabilities to ETABS for FVD modelling, using two-node nonlinear link elements with the dashpot material model for the viscous damping component and a separate spring element for Maxwell stiffness. Tiwari et al. (2023) [4] employed SAP2000 for three-dimensional NLRHA of five-, ten-, and fifteen-storey Nepalese RC buildings, incorporating lumped nonlinearity at beam and column ends per ASCE 41-13 [17]. Fast nonlinear analysis (FNA) was used iteratively to estimate expected damper forces and velocities prior to full direct integration analysis — a computationally efficient strategy for damper property selection. The consistency of SAP2000 results with published literature (within 0.44-0.45% for displacement and base shear benchmarks) validated the modelling approach.

7.3 Derivation of Damper Parameters

The engineering process for deriving site-specific damper parameters combines analytical estimation, experimental testing, and optimisation. The damping coefficient C is typically derived from target effective damping ratios, fundamental period, and storey-wise damper distributions — using closed-form expressions such as the equation presented by Ramdas et al. (2022) [11] relating the supplemental damping ratio to damper properties and modal quantities. The velocity exponent alpha is commonly selected based on design objectives: alpha values of 0.3–0.5 are preferred for seismic applications due to their superior energy dissipation efficiency, while alpha approaching 1.0 may be preferred for wind applications where force linearity simplifies design.

Once initial parameters are estimated, iterative refinement through nonlinear analysis is essential to verify that force demands on adjacent structural members are within acceptable limits. The Maxwell stiffness Kd is determined by the manufacturer based on the selected device model [10]; the connecting brace must be designed to ensure that the combined stiffness Kd* does not excessively degrade hysteretic performance.

7.4 Code and Standards Framework

Table 3: Relevant Codes and Standards for FVD Design

Standard / Code	**Region**	**Relevance to FVD Design**
ASCE/SEI 7-16	USA	Provisions for seismic design with supplemental damping devices; specifies NLRHA requirements for damper-equipped structures
ASCE 41-13	USA	Seismic evaluation and retrofit of existing buildings; defines performance objectives and acceptance criteria for damper retrofit strategies
IS 1893 (Part 1): 2016	India	Seismic design basis for buildings; provides zone factors, response spectra, and soil classification used in FVD parametric studies across Indian literature
FEMA P-58	USA	Performance-based seismic engineering methodology; damage and loss assessment framework used to quantify economic benefits of FVD retrofit
EN 1998-1 (Eurocode 8)	Europe	Seismic design of structures; covers passive energy dissipation systems including viscous dampers in annex provisions
NBC 105: 2020	Nepal	National building code seismic provisions; used in regional studies on FVD effectiveness for Nepalese building stock

Among the codes listed above, ASCE/SEI 7-16 [17] provides the most comprehensive regulatory framework for damped structures in the United States, specifying that structures with seismic isolation or passive energy dissipation systems must be designed using nonlinear response history procedures with at least seven ground motion records [10,17]. The IS 1893:2016 standard, widely used in Indian research, does not currently contain explicit provisions for passive damping devices; structures with FVDs in Indian practice therefore rely on IS 1893 for seismic demand definition while using ASCE 7-16 or manufacturer guidelines for damper design — a regulatory gap noted by multiple authors in the reviewed literature.

8. Energy Dissipation Mechanisms and Efficiency

The energy balance in a damper-equipped building subjected to seismic excitation can be expressed as:

E_input = E_kinetic + E_strain + E_hysteretic + E_damping

where E_damping encompasses both the intrinsic structural damping (approximately 5% of critical for RC buildings) and the supplemental viscous damping provided by FVDs. Energy dissipation analyses reported by Patil and Salgar (2024) [2] for a G+30 building under representative earthquake excitations demonstrated that viscous dampers absorbed approximately two-thirds of the total input seismic energy, with structural intrinsic damping accounting for the remaining one-third. This implies that the effective damping ratio of the FVD-equipped structure approximately doubled relative to the bare frame — consistent with the design target of 8% additional effective damping ratio in the x-direction and 13% in the y-direction reported by Wang and Mahin (2016) [3].

The energy dissipation per cycle can be computed as the area enclosed by the damper force-displacement hysteresis loop. For a pure dashpot with sinusoidal input, this area equals pi times C times omega times d squared raised to the alpha power, where omega is the excitation frequency and d is the displacement amplitude. The super-elliptical shape of nonlinear damper hysteresis loops (alpha < 1.0) encloses a larger area than the elliptical loops of linear dampers for the same peak force — quantifying the efficiency advantage of nonlinear devices.

9. Research Gaps and Future Directions

The comprehensive review of the FVD literature reveals several important gaps and opportunities for future research:

- Experimental validation at full scale: The majority of reviewed studies rely on numerical simulation (ETABS, SAP2000, OpenSees) without experimental corroboration. Shake table testing of FVD-equipped multi-storey frames remains limited, particularly for buildings exceeding 10 storeys. Large-scale experimental campaigns are needed to validate numerical models under realistic multi-directional seismic inputs.
- Soil-structure interaction (SSI): All reviewed parametric studies assume fixed-base conditions. SSI effects can substantially modify the dynamic characteristics of high-rise buildings, potentially altering both the optimal placement of FVDs and the magnitude of response reductions achievable. Studies incorporating SSI through flexible foundation models are warranted.
- Irregular building configurations: The reviewed studies predominantly address symmetric, regular-plan buildings. Plan irregularities — re-entrant corners, mass eccentricities, setbacks — introduce torsional coupling that may significantly affect the distribution of FVD demand and effectiveness. Systematic studies of FVDs in irregular buildings are scarce.
- Multi-hazard performance: The existing literature focuses almost exclusively on seismic performance. The dual-purpose potential of FVDs for wind-induced vibration mitigation is acknowledged but rarely quantified within a unified multi-hazard performance framework. Integrated wind-seismic design methodologies for FVD-equipped high-rise buildings represent an important research direction.
- Lifecycle cost optimisation: While Wang and Mahin (2016) [3] demonstrated FVD cost-effectiveness through FEMA P-58 [19] loss analysis, integrated lifecycle cost optimisation — incorporating initial installation costs, maintenance, inspection intervals, and post-earthquake repair probabilistics — has not been systematically addressed across diverse building typologies and seismic zones.
- Unified computational optimisation: Existing optimisation studies employ diverse objective functions, structural models, and algorithms, making cross-study comparison difficult. Development of open-source, standardised optimisation frameworks for FVD placement and sizing — validated against experimental data and applicable across seismic zones and building typologies — would substantially advance the field.
- Code harmonisation: The divergence between ASCE 7-16 [17] (rigorous NRHA requirements for damped structures) and IS 1893:2016 [18] (no explicit provisions for passive devices) creates regulatory uncertainty for practitioners in Indian and South Asian markets. Harmonisation efforts and development of region-specific design guidelines are overdue.

10. Conclusions

This review has presented a comprehensive synthesis of research on fluid viscous dampers for seismic performance enhancement of high-rise buildings, drawing on analytical, numerical, and experimental investigations spanning building heights of 5 to 35 storeys, multiple structural typologies (RC and steel), and diverse seismic design standards. The following principal conclusions are drawn:

- FVDs are among the most effective passive energy dissipation devices available for seismic mitigation of high-rise buildings, consistently achieving lateral displacement reductions of 20-96%, inter-storey drift reductions of 27-97%, and residual displacement reductions of 25-80%, depending on building height, configuration, and seismic hazard level.
- Optimised damper placement — particularly center-X configurations at all storeys — yields substantially superior performance over conventional practices. Building-specific optimisation, considering both storey-level and plan-level placement simultaneously, is essential to realising the full potential of FVDs [14,15].
- Nonlinear dampers (alpha = 0.3 to 0.5) provide greater seismic energy dissipation efficiency than linear dampers for equivalent peak force demands, making them the preferred choice for seismic applications. The Maxwell stiffness of the device, in series with connecting brace stiffness, must be carefully considered to prevent degradation of hysteretic energy dissipation [11,12].
- FVDs outperform alternative lateral systems — bracing, BRBs, and VWDs — in applications where minimisation of force demands on existing structural members, preservation of column axial load capacity, and post-

earthquake repairability are critical objectives. The lifecycle cost-benefit of FVD retrofits substantially exceeds those of competing technologies.

- Existing codes and standards provide an adequate regulatory basis for FVD design in North American and European practice (ASCE 7-16 [17], Eurocode 8), but significant gaps remain in South Asian codes (IS 1893 [18], NBC 105 [20]) that restrict the adoption of evidence-based damper design in these rapidly developing seismic regions.

The field of fluid viscous damper engineering has matured considerably, yet substantial opportunities remain for advancing fundamental understanding, computational methodologies, experimental validation, and practical implementation guidelines. The consistent evidence of FVD effectiveness across diverse conditions makes them a technology of first choice for seismic resilience enhancement of high-rise buildings, and the research community is well-positioned to address the identified gaps in the coming decade.

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