



REVIEW ARTICLE

SEISMIC BEHAVIOUR OF HIGH-RISE BUILDINGS EQUIPPED WITH FLUID
VISCOUS DAMPERS: A REVIEW

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ABSTRACT

Earthquakes pose a significant threat to structural integrity and human safety, necessitating effective seismic mitigation strategies. This review paper explores the effectiveness of Fluid Viscous Dampers (FVDs) in mitigating seismic responses in high-rise structures. FVDs, as passive energy dissipation devices, enhance structural resilience by reducing inter-story drift, base shear, and overall structural accelerations without significantly altering stiffness. The study compares FVDs with alternative damping systems, including Tuned Mass Dampers (TMDs), Hysteretic Dampers (HDs), Friction Dampers (FDs), and Lead Rubber Bearings (LRBs), highlighting the superior adaptability and efficiency of FVDs in high-rise applications. Placement strategies for FVDs, their integration with other damping systems, and their effectiveness under varying seismic intensities are examined. Findings indicate that uniform distribution across all stories ensures balanced energy dissipation, while targeted placement at lower levels enhances efficiency in specific structural configurations. Also, hybrid approaches, such as combining FVDs with BRBs or base isolation, show promising outcomes in optimizing seismic resilience. The review suggests the importance of further research into computational optimization and practical implementation, torsional irregularities, uniform load distribution in high-rise structures on FVD performance particularly in developing regions like Nigeria, where seismic risks are evolving.

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1.0 Introduction

Natural disasters are unexpected events that occur in nature and have been a part of human history since the beginning of life on Earth. Among the various natural disasters experienced, earthquakes are considered one of the most devastating. Its impact on human lives and property depends largely on their magnitude, often resulting in significant harm and destruction. (Oluwafemi et al., 2018). An earthquake is a sudden and rapid shaking of the ground caused by the release of energy stored in the Earth's crust. The energy released is typically as a result of the movement of tectonic plates, volcanic activity, or human activities such as mining or reservoir-induced seismicity. Earthquakes are usually characterised by their magnitude, intensity, and the damage they cause to the environment and human structures (USGS, 2023).

The significant socioeconomic impacts of earthquakes on structures cannot be entirely eliminated, but they can be greatly reduced by adopting appropriate structural design strategies. In recent years, the use of innovative supplementary devices in both newly constructed and existing buildings has emerged as an effective and economical approach. Gupta et al., (2024); Hussain et al., (2024) and Hamza et al., (2024) have highlighted the success of these devices in minimizing the forces and deformations experienced by structural components. This is accomplished by altering the dynamic characteristics of the system, thereby applying the principles of structural response control and energy dissipation through advanced technologies. Among these, the passive control method remains the oldest and most widely used technique for structural response management, with extensive research conducted in this area. A common approach in much of the literature involves integrating discrete components, known as dampers, into the structural framework. These dampers, known for their low maintenance requirements and independence from external power sources, are strategically placed within the

framing system to link various elements and provide additional damping, effectively dissipating seismic energy (Hejazi et al., 2024).

1.1 Seismic Activity in Nigeria

Osagie, (2008) as cited in Umasabor & Alutu (2021), gave very descriptive and well-detailed information on various earth tremors that have occurred in Nigeria from 1923 to 1990. The earth tremors included Warri town in 1923, Ohafia in 1933, Yola in 1984, Jere town of Kaduna state in 1990, Osererun hills in Gombe council area of Gombe state and Amauze Ede-Obela in Edema council area of Anambra state both in 1988. Also, an earth tremor occurred in Abeokuta in 1986 and Ibadan in 1990. Osagie, (2008) as cited in Umasabor and Alutu (2021), queried the age-long belief that Nigeria was a seismic haven due to the series of earth tremors experienced in the country. He warned that these incidences of earth tremors could be a build-up to a major earthquake in future.

Furthermore, Oluwafemi et al., (2018) projected that Nigeria could encounter earthquakes with magnitudes reaching 7.0 between 2025 and 2026, and 7.1 by 2028, with a probability of 36.79%. On the Earthquake Magnitude Scale, magnitudes between 5.5 and 6.0 can cause slight damage, 6.1 to 6.9 may result in significant damage, 7.0 to 7.9 represents a major earthquake, and 8.0 or higher can cause severe devastation near the epicentre (Muanya, 2021). Despite being classified as a region of low seismic activity, Nigeria faces a growing risk of a major earthquake in its southwestern region. The National Building Code 2006, section 8.8.13 also made provisions for earthquake lateral forces in buildings. Therefore, structural engineers in Nigeria should ensure the inclusion of earthquake lateral forces in their designs for structures in seismic active areas in Nigeria to mitigate its effects on its integrity (Umasabor & Alutu, 2021).

Due to seismic activity and strong winds, high-rise buildings require meticulous design to balance stiffness and strength. Traditionally, buildings are stiffened with braced frame and rigid frame system to reduce their dynamic response. However, this approach increases the seismic base shear experienced by the structure which can result to increased structural damage and higher foundation stress. Additionally, incorporating supplementary damping into the design allows for reduced flexural stiffness, which minimises seismic base shear while effectively managing the building's response to wind forces (Qadri and Kacker, 2022).

The seismic response of high-rise buildings in Nigeria has become an increasingly critical issue due to the country's growing urbanization and the rise in high-rise constructions. Although Nigeria is not traditionally considered a high-seismic-risk zone, certain regions, particularly in the southern and central parts of the country, have shown susceptibility to low-to-moderate seismic activity, driven by tectonic activity along the boundary of the West African Rift System. The absence of robust earthquake-resistant measures in the design and construction of many high-rise buildings raises significant concerns about the safety of these structures during seismic events. This review explores existing research on the seismic response of high-rise building structures, with a particular focus on the introduction of FVDs as an energy dissipation system to mitigate seismic impacts on such structures.

2. Mechanisms of Vibrations in High-Rise Buildings

High-rise buildings are increasingly susceptible to vibrations due to their height, flexibility, and exposure to dynamic forces such as wind, seismic activity, and human-induced movements. Understanding how vibrations act on high-rise buildings is critical for ensuring structural integrity, occupant comfort, and overall building performance (Zhao et al., 2022). This section explores the mechanisms of vibrations in high-rise buildings, their effects, and recent research on mitigation strategies.

Vibrations in high-rise buildings originate from both external and internal sources. Wind-induced vibrations are among the most significant concerns, particularly for slender and super-tall structures. Wind creates pressure differentials on the building surfaces, leading to oscillatory motion. When vortex shedding occurs at the building's natural frequency, it can lead to resonance, amplifying structural displacement and acceleration (Zhang et al., 2021).

Seismic activity also plays a crucial role in high-rise building vibrations. Earthquake-induced ground motions introduce lateral forces, causing base shear, inter-story drift, and sway motions that impact the building's stability (Li & Sun, 2023). The dynamic response of a high-rise structure to an earthquake depends on its natural period, stiffness, and damping characteristics. Inadequate damping can result in excessive displacement, which may lead to structural damage or collapse (Jiang et al., 2023).

Human-induced vibrations, such as those caused by occupants movement, elevators, and mechanical equipment, also contribute to structural motion. In office and residential high-rises, floor vibrations can be problematic, affecting user comfort and potentially interfering with sensitive equipment. Wang *et al.*, (2021) found that perceptible floor vibrations in commercial buildings can be effectively controlled using structural modifications and damping systems.

2.1 Effects and Mitigation of Vibrations on High-Rise Buildings

Excessive vibrations can lead to structural fatigue, serviceability issues, and occupant discomfort. Structural fatigue occurs when repeated dynamic loads cause microcracks and material degradation over time, compromising the integrity of load-bearing components (Chen & Yang, 2023). Serviceability issues, including excessive lateral sway and floor accelerations, may render a building unsuitable for occupancy, particularly in cases where vibrations exceed human comfort thresholds (Kwok *et al.*, 2020). Studies indicate that lateral accelerations above 0.1 m/s^2 can cause discomfort for occupants, necessitating effective vibration control measures (Lin *et al.*, 2021).

To counteract the adverse effects of vibrations, various damping technologies have been developed. Passive damping systems such as TMDs and FVDs are widely used to absorb and dissipate vibrational energy, reducing overall motion (Cui *et al.*, 2022). Active and semi-active damping systems, which utilize sensors and adaptive controls, further enhance the dynamic response of buildings by adjusting damping forces in real time (Jiang *et al.*, 2023).

Aerodynamic modifications, including tapered building shapes and perforated facades, have also been shown to minimize wind-induced vibrations by disrupting vortex shedding patterns (Zhang *et al.*, 2021). A case study on two skyscrapers Shanghai Tower and Taipei 101 demonstrated the effectiveness of these combined strategies in mitigating vibrations and enhancing structural resilience (Wu *et al.*, 2020).

3. Fluid Viscous Damper

FVDs as shown in Figure 1, are passive energy dissipation devices designed to control vibrations in structures and mechanical systems. While these dampers have been widely used in the military and aerospace industries for many years, they are now increasingly applied in buildings to mitigate vibrations caused by wind and earthquakes. One of their most notable advantages is their ability to simultaneously reduce both stress and deflection in structures subjected to transient loads. This capability arises because the damping force is solely dependent on velocity, meaning the response remains out of phase with structural stresses due to flexing. Since FVDs rely on velocity for energy dissipation, they are highly effective in minimizing building vibrations. Additionally, FVDs are frequency-independent devices that function without a stiffness component (Varun & Sureshchandra, 2020).

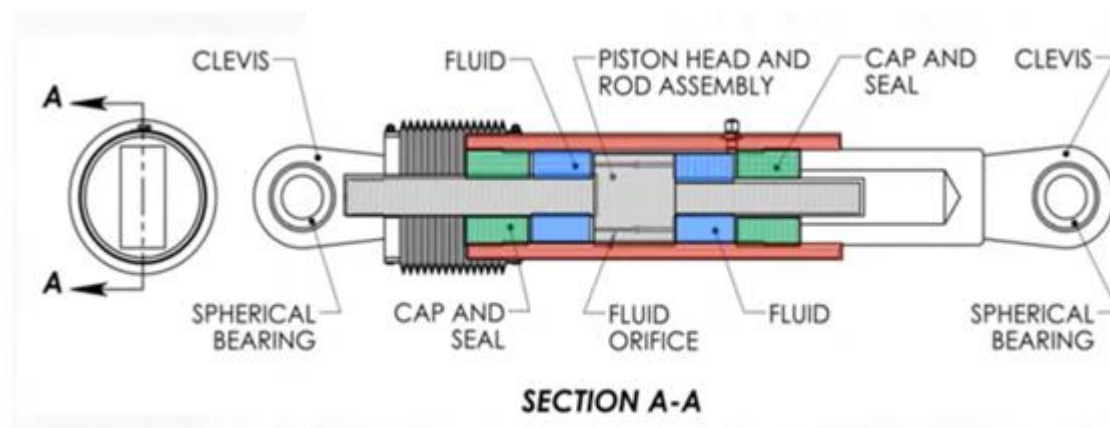


Figure 1: Fluid Viscous Dampers (Gupta, 2024).

Figure 1 illustrates the damper in its mid-stroke position. The main pressure chamber, known as the cylinder, is completely filled with fluid and includes the volumes on both sides of the piston. The piston head is connected to the piston rod, and a clevis is attached to the left-hand side of the rod to connect with the structure. During dynamic loading, the piston rod, piston head, and clevis move together as a single unit while the other components remain stationary. The cylinder contains a compressible, viscous silicone oil that is heat stable, non-toxic, non-flammable, and environmentally friendly.

3.1 Damping Characteristics

The operation of a FVD occurs when the structure moves, generating a resisting force without adding stiffness or carrying any load. However, stiffness can be incorporated into the dampers if required. In FVDs, pressure develops as the piston moves back and forth. A custom-designed orifice within the piston creates an optimized relationship that regulates this pressure based on velocity. The resisting force increases as velocity rises, ensuring effective vibration control (Varun & Sureshchandra, 2020).

This relationship is represented by an Equation 1.

$$FD = C_D |\dot{u}|^\alpha \text{sgn}(\dot{u}) \quad 1$$

where C_D represents the damping coefficient, expressed in terms of force per velocity raised to the power of α is the damping exponent, typically ranging between 0.35 and 1.0 for seismic applications; \dot{u} denotes the relative velocity between the two ends of the damper; and $\text{sgn}()$ is the signum function.

For $\alpha=1.0$, Equation 1 simplifies to:

$$FD = C_D \dot{u} \quad 2$$

which describes the linear force-velocity behaviour of a linear FVD. Hence, the value of α determines the extent of non-linearity in FVDs.

The value of α plays a crucial role in determining the magnitude of the damping force. When α is equal to 1, the damper behaves as a linear damper, meaning the damping force is directly proportional to velocity. In practical applications, α values greater than 1 are not commonly used. The damping coefficient typically ranges from 0.2 to 2.0 (Liu et al., 2021), depending on the specific application, though in some cases, it falls within 0.3 to 1.0. For modern seismic-resistant structures, an α value between 0.3 and 0.5 is commonly applied.

3.2 Mechanical Behaviour of an FVD

The mechanical behaviour of an FVD can be represented mathematically using the Maxwell model as shown in figure 2, which consists of a damper and an equivalent spring with stiffness K_D . Another schematic illustrates that a spring with stiffness K_b represents the brace, while a spring with stiffness K_d accounts for the inherent stiffness of the FVD. In the Maxwell model, the damper and brace are arranged in series (Mokhtari & Naderpour, 2022).

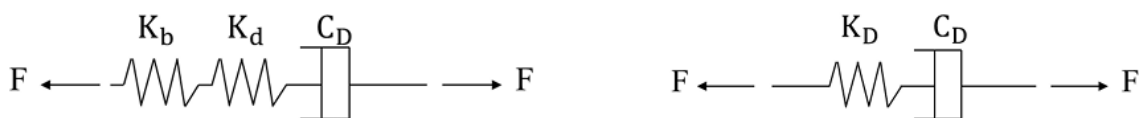


Figure 2: (a) Mechanical FVD- Brace System; (b) Maxwell model

3.3 Equation of Motion for Fluid Viscous Dampers

(FVDs are velocity-dependent damping devices that dissipate energy through fluid resistance. The equation of motion for a system with an FVD is derived using Newton's Second Law of Motion and the dynamic equilibrium of a damped single-degree-of-freedom (SDOF) system as shown in figure 3.

$$M\ddot{u}(t) + C_D |\dot{u}|^\alpha \text{sgn}(\dot{u}) + Ku(t) = -M\ddot{u}_g(t) \quad 3$$

where: M = Mass of the structure, $\ddot{u}(t)$ = Acceleration of the structure, $u(t)$ = Displacement of the structure relative to the ground, $C_D |\dot{u}|^\alpha \text{sgn}(\dot{u})$ = Damping force, K = Structural Stiffness, $\ddot{u}_g(t)$ = Ground acceleration (earthquake input)

3.4 FVDs Design

The primary function of FVDs is to convert kinetic energy into heat through the movement of a piston within a cylinder filled with a viscous fluid. The damping force generated by an FVD is typically proportional to the velocity of motion, following a nonlinear or linear damping law (Li et al., 2022). The design of an FVD involves

selecting the appropriate fluid, cylinder, piston, and seals to ensure optimal energy dissipation and durability. Recent studies have explored the impact of piston configurations and orifice designs on damper efficiency, leading to improvements in force-displacement behavior and response time (Wu et al., 2021; Hejazi et al., 2024b; Wang et al., 2025).

3.5 FVDs Design Considerations

Several factors must be considered in the design of FVDs to achieve optimal performance:

- i. **Fluid Selection:** The choice of fluid affects viscosity stability, temperature resistance, and damping efficiency. Silicone-based and oil-based fluids are commonly used due to their consistent rheological properties under varying temperature conditions (Zhao & Wang, 2021).
- ii. **Damping Coefficient:** The damping coefficient is a crucial parameter that determines the effectiveness of energy dissipation. It is influenced by the damper's geometry, fluid viscosity, and operating conditions (Jiang et al., 2023).
- iii. **Structural Integration:** The placement of FVDs within a building significantly impacts their performance. Strategic positioning in structural braces, shear walls, or between floors can enhance damping effectiveness and reduce inter-story drift (Cui & Zhang, 2022).
- iv. **Temperature Effects:** High-rise buildings experience temperature fluctuations that can affect the viscosity of the damper fluid. Thermal stability must be considered to ensure consistent damping performance across different environmental conditions (Lin et al., 2021).
- v. **Maintenance and Longevity:** The long-term performance of FVDs depends on material durability and the ability to withstand repeated dynamic loads. Advances in seal technology and corrosion-resistant materials have contributed to improved lifespan and reliability (Wang et al., 2021).

4. Other Dampers for Dissipating Energy in High-Rise Building During Earthquake

This section explores various damping systems beyond fluid viscous dampers, examining their mechanisms, structural applications, and effectiveness in enhancing the seismic performance of high-rise buildings. Also, comparative analysis summarizing the key advantages, disadvantages, and application scenarios of each damping system is presented in Table 1.

4.1 Tuned Mass Dampers (TMDs)

Tuned Mass Dampers (TMDs) have gained significant attention as an effective tool for mitigating structural vibrations caused by dynamic forces such as seismic and wind loads. Their application ranges across various types of structures, including high-rise buildings, bridges, and towers. Recent advancements have focused on enhancing TMD designs to address challenges posed by nonlinear behaviors, complex building geometries, and soil-structure interaction (SSI) effects (Hosseini et al., 2022).

Kim and Kang (2021) investigated the application of semi-active TMDs (SATMDs) in tilted high-rise buildings, a structural form prone to lateral displacement even under self-weight. Their study employed magnetorheological (MR) dampers integrated into a SATMD system on a 100-story tilted building subjected to seismic excitations. The control strategy utilized a fuzzy inference system controller (FISC), optimized using an evolutionary multi objective optimization technique. Results demonstrated that the SATMD outperformed conventional passive TMDs, achieving similar control performance with less than 30% of the mass quantity.

TMDs and FVDs both improve seismic response by reducing vibrations, but they operate differently. TMDs consist of a pendulum or spring-mass system that oscillates out of phase with the building's motion, counteracting seismic forces through resonance tuning. On the other hand, FVDs use a viscous fluid to resist motion, providing velocity-dependent damping that dissipates seismic energy smoothly. While both reduce inter-story drifts and structural accelerations, TMDs are most effective in high-rise buildings and for wind-induced vibrations, whereas FVDs work across a broader range of structures and seismic frequencies. TMDs require precise tuning to match the building's natural frequency, whereas FVDs are self-adaptive to different seismic intensities (Desai, 2021). Tuned Mass Damper is shown in figure 3.

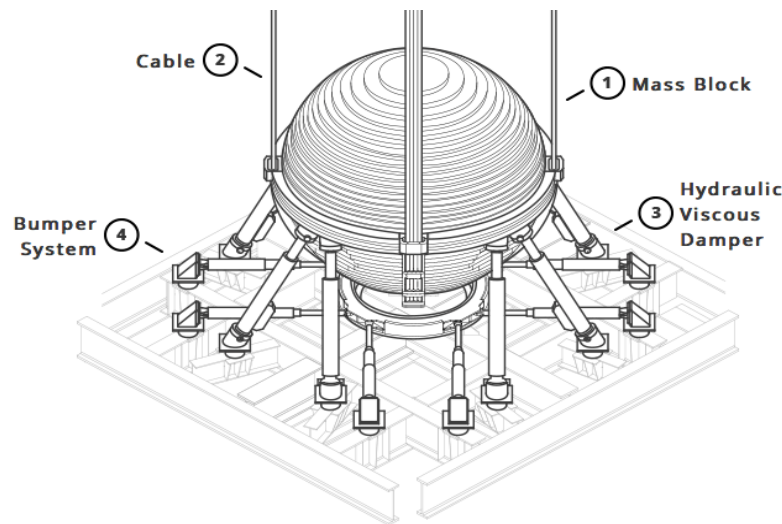


Figure 3: Tuned Mass Damper: (Qamaruddin, 2016).

4.2 Hysteretic Dampers

Hysteretic dampers (HDs) as shown in Figure 4, are integral components of modern seismic protection systems, designed to dissipate energy and enhance the structural safety of buildings during seismic events. Traditional bilinear hysteretic dampers (BHDs) have been widely employed to increase the effective stiffness and damping of buildings, ensuring structural safety during severe seismic events. However, as Gandelli *et al.*, (2021) highlight, BHDs primarily operate within their elastic regime during minor earthquakes, providing minimal damping and resulting in high peak floor accelerations (PFAs) that can damage non-structural components (NSCs) like electric systems and false ceilings. To address these limitations, a novel adaptive hysteretic damper (AHD) capable of modulating its damping and stiffness based on earthquake intensity, significantly enhancing NSC protection during minor earthquakes without compromising safety during severe events.

The evolution of vibration control technologies has led to the emergence of inerter-based vibration absorbers (IVAs), such as tuned-mass-damper-inerters (TMDIs). Patsialis *et al.*, (2023) explored the application of TMDIs in multi-storey hysteretic buildings under seismic excitation, presenting a bi-objective design framework that balances structural drift/acceleration suppression and control forces. Through nonlinear response-history analyses, the study demonstrated the effectiveness of IVAs in optimizing vibration suppression, particularly when considering the nonlinear behaviour of structures. This optimization process offers a promising alternative to traditional HDs, particularly for complex multi-storey designs.

Hysteretic dampers and FVDs both enhance seismic performance by dissipating energy, but they do so differently. Hysteretic dampers (such as steel or lead dampers) dissipate energy through inelastic deformation, meaning they absorb seismic forces by yielding and undergoing plastic deformation. In contrast, FVDs use a viscous fluid to resist motion, providing velocity-dependent damping without permanent deformation. Both reduce inter-story drifts and vibrations, but hysteretic dampers rely on material yielding, making them effective for low-to-moderate seismic events, whereas FVDs offer adaptive damping, making them more effective for high-frequency and varying-intensity earthquakes. While hysteretic dampers may require replacement after large earthquakes due to material fatigue, FVDs generally require less maintenance (Katsimpini *et al.*, 2025).



Figure 4: Hysteretic Dampers (Qamaruddin, 2016).

4.3 Friction Dampers

Friction dampers (Figure 5) are energy dissipation devices widely utilized in buildings to mitigate the effects of dynamic forces such as seismic and wind loads. These dampers dissipate energy through material yielding or inelastic deformation, making them effective and reliable in enhancing structural resilience. Studies have demonstrated their significant role in reducing vibrations and improving the safety of structures. For instance, Xu *et al.*, (2021) investigated triple friction pendulum bearings, which incorporate hysteretic damping mechanisms, and found them effective in balancing seismic isolation and wind-induced accelerations in high-rise buildings. Similarly, Guo *et al.*, (2022) proposed a rotational friction negative stiffness damper (RFNSD), which combines rotational friction with hysteretic properties, to improve the seismic performance of twin-tower structures, highlighting the value of hybrid damping systems.

Further advancements include integrating hysteretic dampers into multi-functional systems like two-level friction dampers and friction-type multiple tuned mass dampers (FT-MTMDs) Lin *et al.*, (2024) demonstrated the effectiveness of FT-MTMDs in reducing seismic and wind vibrations by leveraging hysteretic energy dissipation across multiple frequency ranges. Additionally, Tadas *et al.*, (2024) evaluated the performance of hysteretic dampers in irregular buildings, showing their ability to reduce inter-story drift and floor accelerations, even in asymmetrical structures. However, the performance of these dampers can be affected by site-specific factors such as SSI. Etedal *et al.*, (2023) found that while hysteretic dampers significantly reduce seismic responses, their efficiency diminishes on soft soils or near fault lines, emphasizing the importance of probabilistic and site-specific design considerations.

Friction dampers and FVDs both improve seismic resilience by dissipating energy, but they differ in their mechanisms. Friction dampers use sliding surfaces with a predetermined slip force to convert seismic energy into heat through friction, providing stable energy dissipation once sliding begins. In contrast, FVDs use a viscous fluid to resist motion, offering velocity-dependent damping that smoothly absorbs seismic energy. While both reduce inter-story drifts and vibrations, friction dampers provide constant resistance once activated, whereas FVDs offer adaptive damping based on movement speed. Friction dampers are more cost-effective and require minimal maintenance, but FVDs offer better performance in high-frequency seismic events (Almajhali *et al.*, 2024).

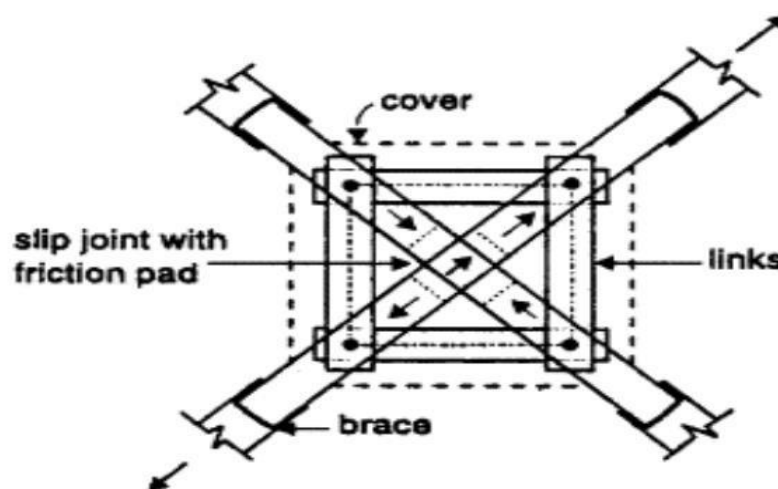


Figure 5: Friction Damper (Qamaruddin, 2016).

4.4 Lead Rubber Bearings (LRBs)

Lead Rubber Bearings (LRBs) are among the most effective base isolators used to enhance structural resilience during seismic events. LRBs consist of alternating layers of rubber and steel plates with a central lead core, where the rubber provides flexibility, the steel offers vertical stiffness, and the lead core dissipates seismic energy through hysteresis, significantly reducing structural acceleration and displacement (Rong, 2020). They are commonly used in low to mid-rise buildings to improve seismic resilience by introducing an isolation layer at the foundation level, reducing the impact of seismic forces (Faqiri *et al.*, 2023). In high-rise and twin-tower structures, LRBs work effectively in conjunction with RFNSDs to mitigate dynamic responses and structural damage, as demonstrated in the research by Guo *et al.*, (2022). Comparative studies, such as Patel *et al.*, (2024), show that LRBs outperform High Damping Rubber Bearings (HDRBs) in seismic response reduction, with a maximum acceleration reduction of 68.42% during strong earthquakes. Furthermore, LRBs are increasingly integrated into composite buildings, where their effectiveness in reducing seismic forces surpasses that of

fixed-base reinforced concrete (RC) structures (Darwish & Bhandari, 2022). Optimizing LRB parameters is crucial for maximizing their performance, as highlighted by Rong (2020), who identified the optimal yield shear coefficient range of 0.10 to 0.14 and a pre-yield to post-yield stiffness ratio between 16 and 35 to enhance energy dissipation.

LRBs and FVDs are two widely used seismic mitigation devices, each with distinct mechanisms and applications. LRBs function as base isolation systems, providing flexibility at the base of a structure to reduce transmitted seismic forces (Chen *et al.*, 2022). They dissipate energy through the plastic deformation of the lead core while allowing lateral movement, thereby reducing acceleration and structural damage. In contrast, FVDs operate by dissipating seismic energy through fluid movement within a cylinder, effectively controlling inter-story drifts and reducing structural response without altering the building's fundamental period (Sharma *et al.*, 2023).

The primary advantage of LRBs is their ability to significantly reduce base shear and prevent damage to superstructures by isolating seismic energy (Hu *et al.*, 2023). However, their effectiveness is limited for taller buildings, where flexibility at the base may not be sufficient to control upper-story accelerations. Additionally, LRBs require a substantial footprint and are more suitable for low- to mid-rise structures with strong foundations. On the other hand, FVDs are highly versatile and can be installed at multiple levels, making them effective in high-rise buildings where inter-story drifts need to be minimized (Khan, 2023). Unlike LRBs, FVDs do not significantly alter the building's stiffness, allowing them to be integrated into existing structures without major modifications (Kiral & Tonyali, 2025). Lead rubber bearings is shown figure 6:

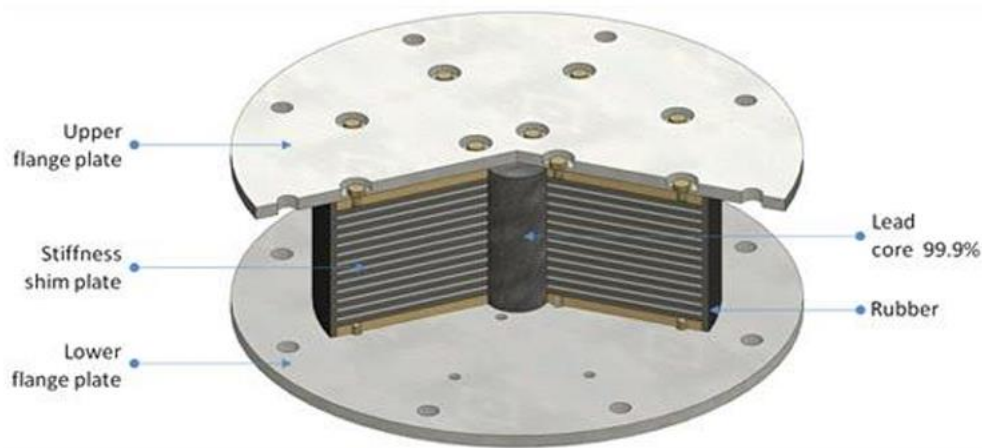


Figure 6: Lead Rubber Bearings (Qamaruddin, 2016).

Table I: A comparative analysis table summarizing key advantages, disadvantages, and application scenarios of each damping system

S/N	Authors	Damping Device	Key Advantage(s)	Key Disadvantage(s)	Application Scenario(s)
I	Rong (2020); Faqiri <i>et al.</i> , (2023); Guo <i>et al.</i> , (2022); Patel <i>et al.</i> , (2024); Darwish & Bhandari (2022)	Lead Rubber Bearings (LRBs)	<ul style="list-style-type: none">- Significant reduction in base shear and structural damage.- Effective seismic isolation for low-to-mid-rise buildings.- Energy dissipation through hysteresis of the lead core.	<ul style="list-style-type: none">- Less effective for high-rise structures due to excessive flexibility at the base.- Requires a larger foundation footprint.	<ul style="list-style-type: none">- Used in low-to-mid-rise buildings to isolate seismic forces.- Integrated with Rotational Friction Negative Stiffness Dampers (RFNSDs) for twin-tower structures.- Common in composite buildings for enhanced seismic resilience.

S/N	Authors	Damping Device	Key Advantage(s)	Key Disadvantage(s)	Application Scenario(s)
2	Xu et al., (2021); Guo et al., (2022); Lin et al., (2024); Tadas & Sanghai (2024); Etedali et al., (2023)	Friction Dampers (FDs)	<ul style="list-style-type: none">- Stable energy dissipation through friction.- Cost-effective and low maintenance.- Efficient in reducing vibrations and structural drift.	<ul style="list-style-type: none">- Performance can be affected by site-specific factors (e.g., soil-structure interaction).- May require additional mechanisms to optimize damping force.	<ul style="list-style-type: none">- Used in high-rise and irregular structures for vibration control.- Applied in hybrid damping systems like RFNSDs and FT-MTMDs.- Effective in regions with frequent moderate earthquakes.
3	Gandelli et al., (2021); Patsialis et al., (2023); Katsimpini et al., (2025)	Hysteretic Dampers (HDs)	<ul style="list-style-type: none">- Effective for energy dissipation through inelastic deformation.- Increases damping and stiffness, improving seismic performance.	<ul style="list-style-type: none">- Limited effectiveness for minor earthquakes (low energy dissipation).- Material fatigue may require post-earthquake replacement.	<ul style="list-style-type: none">- Common in multi-story structures to reduce inter-story drifts.- Integrated with inerter-based vibration absorbers (IVAs) for complex buildings.- Used in buildings located in high seismic regions.
4	Hosseini et al., (2022); Kim & Kang (2021); Desai (2021)	Tuned Mass Dampers (TMDs)	<ul style="list-style-type: none">- Highly effective in reducing vibrations, especially wind-induced.- Can significantly decrease lateral displacement in high-rise buildings.	<ul style="list-style-type: none">- Requires precise tuning to the structure's natural frequency.- Performance decreases if detuning occurs due to structural changes.	<ul style="list-style-type: none">- Ideal for tall buildings, bridges, and towers.- Applied in tilted high-rise structures for displacement control.- Used in cases where wind-induced vibrations dominate.
5	Sharma et al., (2023); Kiral & Tonyali (2025)	Fluid Viscous Dampers (FVDs)	<ul style="list-style-type: none">- Adaptive damping across various seismic frequencies.- Effective in reducing inter-story drifts and structural accelerations.- Can be integrated into existing structures with minimal modification.	<ul style="list-style-type: none">- Higher initial cost compared to friction dampers.- Long-term performance may degrade under sustained loading.	<ul style="list-style-type: none">- Common in high-rise buildings to reduce seismic and wind loads.- Used in retrofitting older structures for improved seismic resilience.- Applied in critical infrastructure (e.g., hospitals, bridges).

5. Review Analysis

5.1 Effectiveness of FVDs in improving Seismic Response

The various studies collectively highlight the effectiveness of FVDs in improving seismic response by significantly reducing displacement, drift, base shear, and bending moments. Hu et al., (2020); Belbachir et al., (2023), and Tiwari et al., (2023) agree on the positive impact of FVDs on structural stability during seismic events. The findings of these authors collectively demonstrate the effectiveness of FVDs in improving seismic response by reducing displacement, drift, base shear, and bending moments. Tamang & Sharma, (2021); and Hatipoglu & Duzgun, (2023) acknowledge the significant impact of FVDs on structural stability during seismic events. However, limitations in scope, such as specific building types, configurations, and regional biases, necessitate further research for broader applicability. The studies differ in their focus on structural types, with some emphasizing low-rise buildings (Belbachir et al., 2023) and others on high-rise structures (Hamza et al., 2024). The methodologies also vary, with some authors using steel strip dampers (Zhai et al., 2021) and others employing non-linear viscous dampers (Riaz et al., 2023). Additionally, the scope of effects examined, such as plastic deformation (Hu et al., 2020) versus energy dissipation (Zhai et al., 2021), highlights the diverse approaches to evaluating FVDs performance.

In a multi-degree of freedom (MDOF) system incorporating FVDs, the damping coefficient can be determined following the procedure outlined in the flowchart of figure. 7. This flowchart, which focuses on the first vibration mode, presents an equation for the effective damping ratio contributed by the FVDs in a building structure, as derived by Seleemah and Constantinou (1997) and Soong and Constantinou (1994) as cited in Mokhtari & Naderpour, (2022). Study by Ras & Boumechra (2016) suggests that distributing the damping coefficient values uniformly across all stories is a practical approach. Their study also found that dampers are more effective on the lower floors compared to the upper ones.

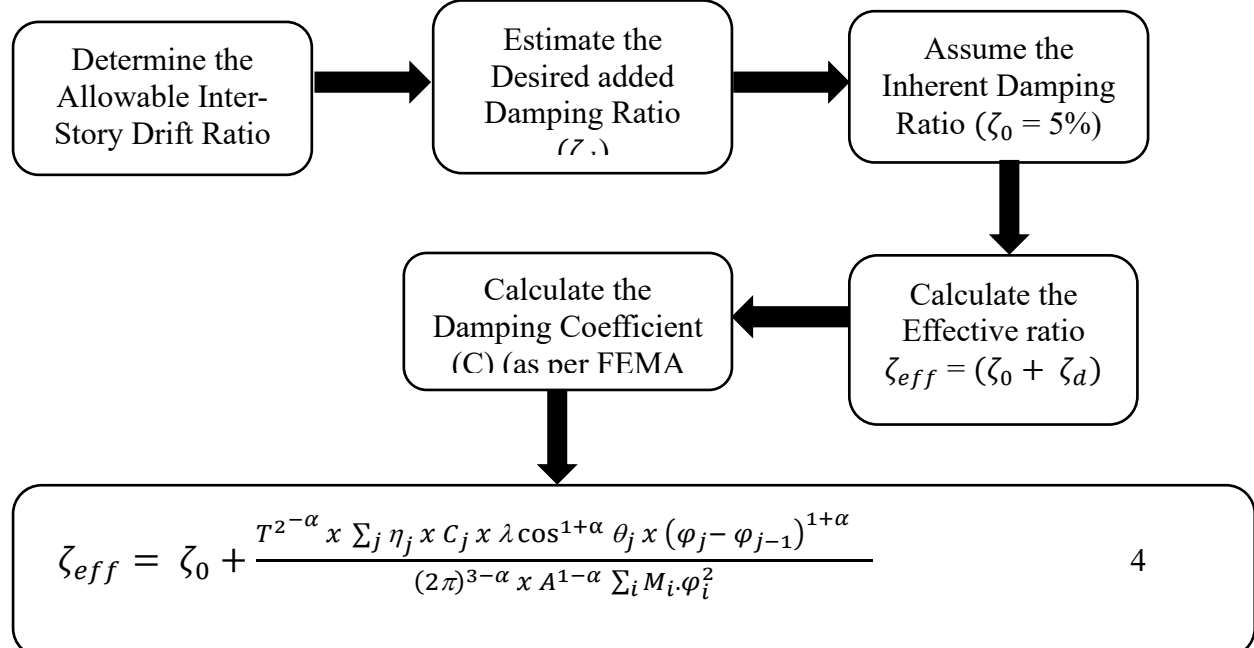


Figure 7: Flowchart of the calculating the damping coefficient of an MDOF system with FVDs (Mokhtari & Naderpour, 2022).

where: T is the natural period of the first vibration mode, C_j is the damping coefficient of the FVDs at the j^{th} story, η_j is the number of identical FVDs with the same C_j in each story, φ_j and φ_{j-1} are the first modal displacements of the j^{th} and $j - 1^{th}$ stories, respectively, θ_j is the inclination angle of the FVDs at the j^{th} story, A is the amplitude of the roof response corresponding to φ_j , normalized to a unit value at the roof, M_i is the mass of the i^{th} floor, λ is a factor that can be determined using a specific Equation 5.

$$\lambda = 2^{2+\alpha} \frac{\Gamma^2(1+0.5\alpha)}{\Gamma(2+\alpha)} \quad 5$$

where Γ is the gamma function.

5.2 Placement of seismic dampers in reducing seismic responses

The placement of FVDs in high-rise buildings is a crucial factor in optimizing seismic performance. Various methods have been explored to determine the most efficient arrangement of FVDs for minimizing earthquake-induced vibrations. Sharma *et al.*, (2023) analyzed three placement scenarios in a G+20 structure and concluded that placing dampers on all stories significantly reduces displacement, drift, and shear forces. Similarly, Jigar *et al.*, (2018) found that placing FVDs at the lower stories leads to greater reductions in displacement and drift, while distributing dampers across all stories effectively minimizes base shear. However, alternative approaches have also been investigated, including concentrated placement at external corners (Mujeeb *et al.*, 2019), uniform distribution (Martinez-Paneda & Elghazouli, 2021), and optimized placement using algorithms (Nguyen-Thai *et al.*, 2024).

As supported by Sharma *et al.*, (2023) and Martinez-Paneda & Elghazouli (2021), uniform placement of FVDs across all stories ensures balanced energy dissipation and effective structural resilience under seismic and wind conditions. However, this method can be costly and requires precise tuning to avoid excessive base shear. On the other hand, lower-story placement, as suggested by Jigar *et al.*, (2018), is more effective in reducing drift and displacement but may not adequately control upper-story accelerations. Concentrated placement at external corners, as recommended by Mujeeb *et al.*, (2019), enhances lateral stability but may be less effective in structures with irregular geometries.

Algorithm-based optimization, as explored by Nguyen-Thai *et al.*, (2024), has emerged as a promising approach, effectively minimizing inter-story drift and floor accelerations. Nevertheless, the scalability of such methods to taller and more complex structures remains a challenge. Similarly, Patel & Agrawal (2020) demonstrated that FVDs significantly reduce seismic response in structures with different bay sizes, but their study was limited to specific configurations, indicating the need for broader parametric research. While various placement methods have been studied, the most widely used and effective approach appears to be the uniform distribution of FVDs across all stories, as it ensures overall seismic resilience and minimizes base shear. Figure 8 and 9 shows how FVDs are placed in high rise building.

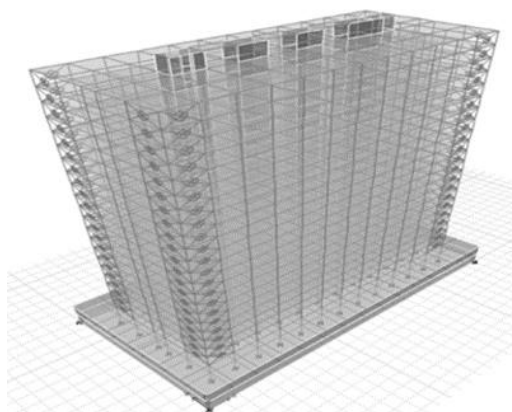


Figure 8a: Model with FVD for all storeys at Exterior Corners.

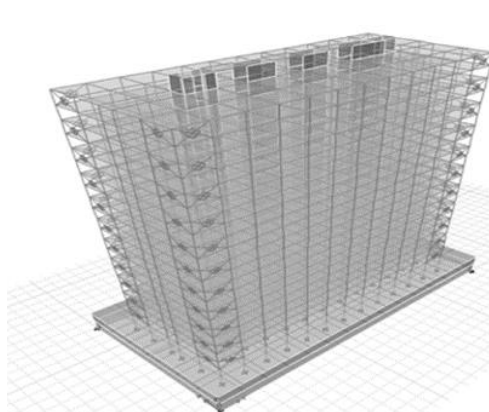


Figure 8b: Model with FVD alternate for all storeys at Exterior Corners (Giwa & Oyelade, 2024).

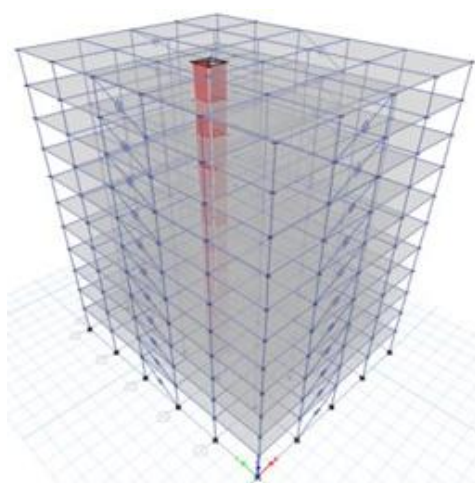
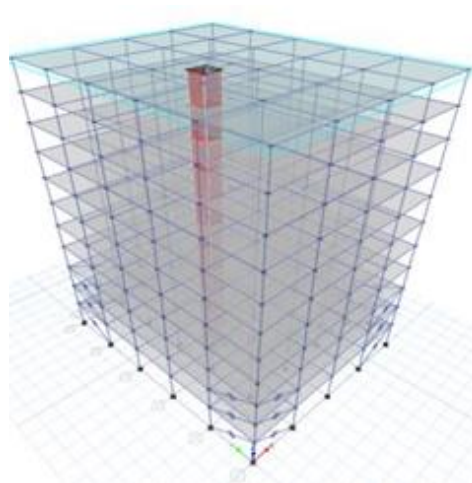


Figure 9a: Model with FVD at central in the storeys. **Figure 7b:** Model with FVD at bottom 3 storeys (Mujeeb *et al.*, 2019)



5.3 Combining FVDs with different damper systems to improve energy dissipation

Alhamdany & Dilsiz (2025) and Thakur & Tiwary (2023) studied the integration of FVDs with other systems. Additionally, the applicability of findings varies, with some studies focusing on specific regions, building types, or seismic zones, as highlighted by Mahakalka *et al.*, (2023) and Benita & Hemalatha (2017). Several studies, such as Du *et al.*, (2020) and Thakur & Tiwary (2023), indicate that combining FVDs with other retrofitting systems (e.g., BRBs, base isolation) offers superior seismic performance. This approach leverages the benefits of different damping mechanisms to achieve enhanced energy dissipation and structural stability. According to Alhamdany & Dilsiz (2025), the choice between FVDs and shear walls depends on project goals, economic considerations, and focus areas. FVDs are effective in reducing vibrations and structural displacements, making them suitable for projects prioritizing occupant safety. Shear walls, on the other hand, improve lateral stiffness and stability, offering durable solutions for resource-limited projects.

6. Major Findings

- i. FVDs significantly reduce inter-story drift, structural accelerations, and base shear forces in high-rise buildings.
- ii. One of the key advantages of FVDs over the others is that it can be integrated into existing structures with minimal modification.
- iii. FVDs are more effective on the lower floors compared to the upper ones.
- iv. Effective placement appears to be the uniform distribution of FVDs across all stories.
- v. There is limited or no studies on torsional irregularities of buildings with FVDs

7. Conclusion

This review has examined the seismic behavior of high-rise buildings equipped with FVDs, evaluating their effectiveness in mitigating earthquake-induced structural responses. The study highlighted the significance of structural response control and energy dissipation technologies in enhancing the resilience of high-rise buildings, particularly in regions susceptible to seismic activity. Various seismic mitigation techniques, including TMDs, hysteretic dampers, friction dampers, and LRBs, were compared with FVDs in terms of energy dissipation capacity, cost-effectiveness, and application scenarios and found out that FVDs were more superior.

Findings indicate that FVDs offer substantial benefits in reducing inter-story drift, structural accelerations, and base shear forces. Unlike traditional stiffening methods that increase seismic base shear, FVDs provide adaptive damping without significantly altering the structural stiffness, making them highly effective for high-rise buildings. However, the computational and hardware requirements for optimizing FVD placement and integration remain a key challenge. While uniform distribution across all stories ensures balanced energy dissipation, targeted placement at lower stories or external corners has been found to enhance efficiency in some structural configurations.

Recent advancements in combining FVDs with other damping systems, such as BRBs and base isolation, suggest that hybrid approaches can further enhance seismic resilience. The integration of FVDs with emerging structural control technologies, including artificial intelligence-based optimization methods, represents a promising area for future research. Additionally, the practical implementation of FVDs in developing regions, including Nigeria, requires further studies on economic feasibility and structural adaptability.

Finally, the review highlights the importance of FVDs in mitigating lateral forces, but their role in counteracting torsional irregularities, uniform load distribution in high-rise structures is essential especially in regions with varying soil conditions like Nigeria requires further research.

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