Seismic Retrofitting of Existing RCC Buildings Using Hybrid Dampers: A Comparative Study on Cost Efficiency of Hybrid, FVD & TMD Systems

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A thesis submitted to the Department of Civil Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Civil Engineering



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Section: (24B+24D)

Semester -Year: Spring-2025

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DECLARATION

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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to

"Our Beloved Religion, Islam & Hakims of the Islamic Golden Age"

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ABSTRACT

This thesis presents a study on the effectiveness of different types of dampers in enhancing the seismic performance of an existing 10-story reinforced concrete building in Dhaka, Bangladesh, originally designed following BNBC 1993 provisions. A comparative analysis was conducted using Response Spectrum Analysis in ETABS to evaluate story displacement, inter-story drift, and base shear with and without the implementation of dampers.

The results indicate that the incorporation of viscous, tune mass and hybrid dampers significantly reduces seismic responses, thereby improving overall building performance. The study highlights the importance of retrofitting old structures with modern energy dissipation devices as a cost-effective and reliable solution for seismic risk mitigation. This research provides valuable insights for structural engineers, researchers, and policymakers. The findings may support future strategies for improving earthquake resilience in Bangladesh and other seismic regions.

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CHAPTER 1

Introduction

1.1 Background

Bangladesh is a country with considerable seismic risk due to its geographical position near the active Himalayan tectonic belt. Historical records reveal that the 1918 Sylhet Earthquake, with a magnitude of 7.0, caused widespread destruction and several thousand casualties (Islam et al., 2016). This event underscored the vulnerability of traditional construction practices, particularly unreinforced or poorly reinforced masonry and concrete structures, to seismic forces.

Since then, Bangladesh has experienced multiple earthquakes of varying magnitudes. Seismological observations suggested that moderate earthquakes ranging from 5.0 to 6.5 continue to occur periodically (Ansary & Sharfuddin, 2020). The most recent significant event was the Mymensingh earthquake (magnitude ~6.2), which caused minor structural damage but served as a reminder of the persistent seismic threat in the region (USGS, 2022).

1.1.1 Current Seismic Scenario and Future Risks

At present, Bangladesh has an estimated earthquake magnitude potential of up to 7.5 in certain zones, according to national geological surveys (BNBC, 2020). The country's urban areas, especially cities like Dhaka, Chittagong, and Sylhet, contain many RCC buildings constructed before modern seismic codes, making them particularly vulnerable to seismic forces.

Recent studies and statements by Bangladeshi geoscientists warn that future large-magnitude earthquakes are likely, potentially affecting densely populated urban regions (Akhter, 2017). With continued urban expansion and aging infrastructure, the risk of high casualties and economic loss remains significant. This historical and current context underscores the urgent need for seismic retrofitting of existing RCC buildings.

Strengthening these structures with advanced damping systems, such as Hybrid Dampers, Fluid Viscous Dampers (FVD), and Tuned Mass Dampers (TMD), can significantly enhance their seismic resilience and reduce potential losses in future earthquakes (Chopra, 2020).

1.1.2 Importance of Cost-Efficient Retrofitting

While ensuring seismic safety is critical, Bangladesh also faces budgetary constraints. Therefore, it is important to evaluate both the effectiveness and the cost efficiency of different retrofitting systems. Hybrid Dampers, although often requiring higher initial investment, have been shown to reduce long-term maintenance costs while providing superior energy dissipation (Takewaki, 2018). Comparatively, FVD and TMD systems offer alternative solutions with their own advantages and limitations (Soong & Dargush, 2017).

A detailed comparative study among these systems can guide policymakers, engineers, and building owners to choose the most effective and economically viable retrofitting strategies for existing RCC buildings in seismic-prone zones of Bangladesh.

1.2 Problem statement

Dhaka city and many other regions of Bangladesh are in a seismically active zone, where earthquake vulnerability is a significant concern. Many existing reinforced concrete (RCC) buildings, particularly those constructed before the adoption of modern seismic design codes, remain highly susceptible to earthquake damage. These structures often lack proper seismic detailing and strengthening measures, making them unsafe during strong ground motions.

Although several retrofitting techniques have been studied worldwide, the practical application in Bangladesh is still limited due to cost, lack of awareness, and insufficient research on suitable solutions for local conditions. Among various retrofitting options, the use of seismic dampers—such as Fluid Viscous Dampers (FVDs) or Tuned Mass Dampers (TMDs) has shown promising results in reducing seismic response. However,

there is a scarcity of detailed analytical studies evaluating the effectiveness of dampers in retrofitting existing RCC buildings within the context of Dhaka city.

Therefore, it is necessary to investigate how the application of dampers can enhance the seismic performance of old RCC buildings, reduce structural damage, and ensure both safety and cost-effectiveness. This research seeks to address this critical gap.

1.3 Objectives of the study

1. **Evaluate the** seismic performance of existing 10-story RC buildings in Dhaka.
2. **Assess the** effectiveness of Hybrid Dampers, FVD, and TMD in reducing story displacement, inter-story drift, and base shear.
3. **Provide** recommendations for cost-effective seismic retrofitting.

1.4 Scope of the Study

The scope of this study is confined to the following aspects:

- **Building Type**: The research focuses on mid-rise Reinforced Concrete (RCC) buildings with 10 stories, which are representative of existing structures in Dhaka city.
- **Geographical Context**: The analysis is based on the seismic zoning and soil profiles of the Mirpur region, as classified by BNBC 1993 and BNBC 2020.
- **Retrofitting Techniques**: The study is limited to the comparative evaluation of three damping systems—Hybrid Dampers, Fluid Viscous Dampers (FVD), and Tuned Mass Dampers (TMD).
- **Analytical Methodology**: Structural performance will be examined using ETABS software through Response Spectrum Analysis and Time-History Analysis.

- **Performance Parameters**: Key seismic response indicators include inter-story drift, base shear, peak floor acceleration, and overall structural stability.
- **Cost Efficiency**: The study assesses the relative cost efficiency of the selected damping systems in terms of installation and structural retrofitting costs.

CHAPTER 2

Literature Review

2.1 Introduction

The purpose of this chapter is to review the existing literature relevant to the seismic performance and retrofitting of reinforced concrete buildings. Previous studies on energy dissipation devices, including Hybrid Dampers, Fluid Viscous Dampers (FVD), and Tuned Mass Dampers (TMD), are examined to understand their effectiveness in reducing structural responses under seismic loads. Both local and international research works are discussed, highlighting their methodologies, key findings, and limitations. The gaps identified in these studies emphasize the need for evaluating dampers in existing multi-story buildings in Bangladesh. This chapter provides the foundation and justification for the current research work.

2.2 Case Studies and research on Seismic Retrofitting of RCC Buildings in Bangladesh & Internationally.

1. **Government Guideline on Retrofitting (Ministry of Housing & Public Works, 2020)**
   The Bangladesh Ministry of Housing & Public Works (2020) published an official guideline outlining retrofitting procedures for existing RCC buildings. It provides systematic methods for assessment, prioritization, and cost-effective strengthening techniques for both public and private structures.[01]

2. **Residential High-Rise Buildings in Dhanmondi & Mirpur (JICA & CDMP, 2009):**
   The JICA and Comprehensive Disaster Management Program (CDMP, 2009) carried out a seismic vulnerability study on mid- to high-rise residential RCC buildings in Dhaka, especially in Dhanmondi and Mirpur areas. Many of these buildings, constructed between 1980 and 2000, were found to lack seismic provisions as they predated the BNBC seismic guidelines. The findings indicated that soft-story configurations, poor material quality, and insufficient lateral strength make these buildings highly vulnerable to collapse during major earthquakes. The study recommended retrofitting through base isolation, energy dissipation devices (such as TMD/FVD), and shear wall implementation to improve seismic performance.[02]

3. **BUET Campus RCC Buildings (Islam et al., 2011):** Islam et al. (2011) conducted a seismic performance evaluation of several RCC academic buildings of the BUET

campus, many of which were constructed during the 1985s–2000s without modern seismic detailing. The study utilized nonlinear pushover analysis and revealed significant seismic deficiencies, including weak columns, inadequate reinforcement, and soft-story effects. Retrofitting measures such as column jacketing, shear wall addition, and the integration of damping devices were recommended to enhance safety and resilience against moderate to strong earthquakes. [03]

4. **Dhaka City Housing Structures (Ahmed & Morita, 2018)**
   Ahmed and Morita (2018) analyzed the earthquake vulnerability of housing structures in two parts of Dhaka City (DNCC & DSCC) using field surveys and vulnerability indices. The study revealed that many residential RCC buildings were constructed without proper seismic considerations, making them susceptible to severe damage during earthquakes. The research emphasized the urgent need for retrofitting measures and strict enforcement of seismic provisions in urban housing development. [04]

5. **Japanese Index Method for Seismic Assessment (Karim, 2018)**
   Karim (2018) applied the Japanese Index Method for evaluating existing RCC buildings in Bangladesh. The study highlighted that 60% of assessed structures required urgent retrofitting interventions. Techniques such as shear wall retrofitting and CFRP wrapping were suggested as cost-efficient measures.[05]

3.3 Research Study:

1. "Viscous-Friction Hybrid Damper" (Fujita et al.)

Examine a hybrid damper composed of a viscous damper (VD) in series with a friction damper (FD), aimed at mitigating issues of long-duration, long-period ground motions. In long ground motion, viscous dampers' fluid temperature rises a lot → performance drops. FD is used to absorb some energy and reduce the temperature rise of VD. [06]

2."Placement of Fluid Viscous Dampers to Reduce Total-Building Seismic Damage"

Studied existing buildings designed under Eurocode (especially concentric braced steel frames) and investigated how adding **Fluid Viscous Dampers (FVDs)** can reduce *both structural and nonstructural* damage due to earthquakes. Benchmarked code-compliant building performance; investigated optimum amount of damping; compared different damper placement strategies. [07]

3. **Tuned Mass Damper Application (Miyamoto, 2008)**

Miyamoto (2008) presented the seismic retrofit of a landmark structure using a Tuned Mass Damper (TMD). The study demonstrated that installing TMDs reduced lateral displacement, inter-story drift, and vibration response, thereby enhancing the seismic safety of tall RCC buildings.[03]

2.4 Relevant Literature

Extensive research over the past three decades has focused on the seismic retrofitting of reinforced-concrete (RCC) buildings, with the primary objective of enhancing structural resilience against earthquake-induced vibrations. Traditional passive control devices such as friction dampers (FD), tuned mass dampers (TMD), and fluid viscous dampers (FVD) are widely recognized in both laboratory studies and international practice. These devices have consistently demonstrated their effectiveness in reducing inter-story drift, peak acceleration, and overall seismic damage [1][2].

Recent systematic reviews and experimental investigations emphasize that hybrid devices, which combine different energy dissipation mechanisms, can overcome the limitations of single-mode dampers. Configurations pairing viscous action with frictional or hysteretic elements have been shown to achieve broader frequency control and reduce sensitivity to long-duration excitations. Several experimental and numerical studies in the last five years reported significant improvements in structural performance using hybrid dampers under laboratory and simulated earthquake conditions [3][4].

In the Bangladesh context, national code provisions and local practice play a crucial role in seismic assessment and retrofitting. The **Bangladesh National Building Code (BNBC)** provides the framework for seismic design, site classification, and equivalent lateral force approaches. However, a substantial number of mid- to high-rise RCC buildings in Dhaka were constructed between 1980 and 2000, prior to the enforcement of BNBC seismic guidelines, and therefore lack adequate seismic detailing. Case studies conducted by JICA & CDMP (2009), Islam et al. (2011), and Ahmed & Morita (2018) consistently identified common vulnerabilities such as soft-story configurations, weak

columns, inadequate reinforcement, and substandard material quality. These deficiencies render existing buildings highly susceptible to collapse under moderate to strong earthquakes. Recommended retrofit strategies include column jacketing, the addition of shear walls, CFRP wrapping, and the integration of energy-dissipating devices [5].

International studies have provided further evidence on the effectiveness of advanced damping technologies. Fujita et al. highlighted the role of hybrid viscous-friction dampers in mitigating the limitations of conventional viscous dampers during long-duration ground motions. Research on the placement of FVDs demonstrated that optimal damper distribution minimizes both structural and nonstructural damage, while Miyamoto (2008) presented the application of TMDs in tall RCC structures, showcasing their ability to reduce lateral displacement, inter-story drift, and vibration response [6].

Taken together, the reviewed literature highlights two critical points:

1. Many existing RCC buildings in Dhaka are in urgent need of seismic retrofitting due to the absence of modern seismic detailing.
2. The incorporation of supplemental damping devices such as FVDs, hybrid dampers, and TMDs offers cost-effective and efficient solutions to enhance seismic performance.

This synthesis provides the foundation for the present research, which investigates the placement and effectiveness of TMDs in existing 10-, 15-, and 18-story buildings in Dhaka.

2.5 Limitations of Existing Research

A critical review of recent international and local literature reveals several recurring limitations relevant to the application of hybrid dampers (FVD + FD) in Bangladesh:

1. **Limited field-scale validation**: Most hybrid damper studies report laboratory tests, small-scale prototypes, or numerical simulations. Large-scale retrofit installations of (viscous+friction) hybrids in operational buildings are scarce, and very few long-term monitoring reports quantify performance under multiple seismic intensities

[3]. This limits confidence in transferring laboratory benefits to real-world conditions.

2. **Scarcity of Bangladesh-specific studies**: Local research has produced valuable vulnerability assessments and retrofit case studies (e.g., viscous dampers, jacketing, bracing), but comparative analyses explicitly evaluating hybrid FVD+FD systems for Dhaka-type mid-rise or irregular RC buildings are rare [5]. Existing work often focuses on single-technique interventions rather than comprehensive hybrid evaluations.

3. **Incomplete integration of soil–structure interaction (SSI) and local site effects**: Bangladesh's soft alluvial deposits and potential site amplification significantly influence seismic demand and damper performance. Many international studies rely on generic site classifications or ignore SSI, leaving the effect of local soil layering on hybrid damper effectiveness underexplored [5][6].

4. **Insufficient cost-life cycle analysis**: Most optimization and design studies emphasize mechanical performance, but only a few incorporate detailed life-cycle cost analyses—including initial cost, installation disruption, maintenance, and replacement after major events—essential for practical adoption in resource-constrained settings [6].

5. **Design, calibration, and maintenance challenges**: Hybrid devices combine nonlinear frictional behavior with velocity-dependent viscous action. Modeling these interactions in nonlinear dynamic analyses is complex and sensitive to calibration parameters. Many papers describe modeling approaches but do not provide prescriptive calibration guidelines or maintenance protocols for practitioners [3][4].

6. **Lack of standardized guidelines in national codes**: While BNBC provides a general seismic design framework, specific provisions for hybrid energy-dissipating devices—including installation details, qualification tests, and inspection regimes—are limited. This regulatory gap discourages widespread adoption despite promising research outcomes [5].

2.6 Research Gap

The limitations discussed above reveal a clear gap in both global and Bangladesh-specific contexts. First, most studies focus on regular structural systems or idealized models, whereas mid-rise, irregular RC buildings dominate the urban landscape of Dhaka. Second, comprehensive nonlinear dynamic analyses incorporating soil–structure interaction (SSI) are largely absent, despite the significant influence of local soil conditions on seismic response. Third, economic feasibility studies, including detailed life-cycle cost assessment, remain scarce, although these are critical for adoption in developing countries. Finally, current research has not fully integrated the BNBC-2020 seismic provisions, leading to potential misalignment with national design standards.

Therefore, a rigorous, Bangladesh-specific comparative study examining hybrid dampers, fluid viscous dampers, and tuned mass dampers for mid-rise irregular RC buildings—incorporating nonlinear time-history analysis, SSI, life-cycle cost evaluation, and BNBC-2020 compliance—is both necessary and timely. Addressing this gap will provide a scientific foundation and practical guidance for enhancing the seismic resilience of existing urban buildings.

2.7 Types of Seismic Dampers Discovered and Researched Worldwide

1. Conventional Dampers (1970s–1990s)

Friction Dampers (FD): Sliding plates dissipate in seismic energy through friction. Widely used for mid- and high-rise buildings due to low cost and simple installation.
Strength: Economical, dependable, and effective in reducing inter-story drifts.
Limitation: Stick–slip behavior may reduce efficiency; wear requires maintenance.

Tuned Mass Dampers (TMD): Large mass tuned to building natural frequency, installed at top floors. Highly effective in tall structures for wind and long-period earthquake mitigation (e.g., Taipei 101).
Strength: Highly effective at controlling resonant vibrations.
Limitation: Performance decreases if structural frequency shifts; heavy and costly.

Fluid Viscous Dampers (FVD): Dissipate energy via fluid flow resistance in pistons; effective over a broad frequency range. Suitable for buildings and bridges.

Strength: Stable, predictable energy dissipation and repeatable performance.
Limitation: High initial cost; requires sealing to prevent leakage.

Viscoelastic Dampers (VED): Polymer-based devices dissipating energy via shear deformation. Effective in moderate climates.
Strength: Provides both stiffness and damp simultaneously.
Limitation: Performance sensitive to temperature and long-term polymer degradation.

2. Advanced and Hybrid Dampers (2000s–Present)

Hybrid Dampers (FVD + Friction, or TMD + VED): Combine multiple mechanisms for wide-frequency energy dissipation. Suitable for retrofitting mid-rise and tall buildings.
Strength: Efficient across wide frequency range; improves robustness.
Limitation: Complex design, calibration, and structural integration required.

Semi-Active Dampers (MR Dampers): Use magnetorheological fluids whose viscosity changes under a magnetic field, allowing adaptive damping.
Strength: Real-time control of damping; suitable for smart structures.
Limitation: Excessive cost and requires continuous power and control systems.

Tuned Liquid Dampers (TLD) & Tuned Liquid Column Dampers (TLCD): Moving liquid mass counters to build vibrations. Popular in tall towers.
Strength: Multifunctional (vibration control + water storage) and low-cost.
Limitation: Narrow frequency effectiveness; sensitive to liquid level changes.

Inerter Dampers: Mechanical devices multiplying apparent mass, enhancing small-device performance.
Strength: Achieves high damping with compact device size.
Limitation: Still in experimental research; integration into structures can be challenging.

3. Best Performing Dampers (Based on Global Practice & Studies)

- **Tall Buildings:** TMDs + TLDs perform best (e.g., Burj Khalifa, Taipei 101).
- **Industrial & Mid-Rise RCC Buildings:** FVDs and Hybrid Dampers (FVD + FD or FVD + TMD) provide excellent cost-performance.**

- **Bridges:** MR Dampers and viscous dampers are increasingly preferred.
- **Developing Nations (e.g., Bangladesh):** Friction and viscous dampers are most practical due to low cost and installation simplicity.

4. Current Research Directions (2020–2025)

- **Hybrid Systems:** Multi-mechanism dampers (FVD + FD + Inerter) for all-frequency seismic control.
- **Smart Dampers:** AI-controlled MR dampers adjust damping ratio instantly during earthquakes.
- **Energy-Harvesting Dampers:** Devices that reduce vibration and generate electricity simultaneously (Japan & USA research).
- **Low-Cost Retrofitting Dampers:** Recycled steel and polymer composites for cost-sensitive regions (South Asia & Africa).
- **Climate-Resilient Dampers:** New materials that are less sensitive to temperature and humidity are under study.

Briefly-

Table 1 : Discovered Dampers

Damper Type	Mechanism / Description	Strength	Limitation	Era / Status	Application
Friction Damper (FD)	Sliding plates dissipate energy via friction	Economic, reliable, effective in reducing inter-story drift	Stick–slip behavior, wear requires maintenance	1970s–Present	Mid- & high-rise buildings, retrofitting
Tuned Mass Damper (TMD)	Mass tuned to building frequency, top floors	Highly effective at resonant vibration control	Sensitive to frequency shifts; heavy & costly	1970s–Present	Tall buildings, wind & long-period earthquakes
Fluid Viscous Damper (FVD)	Piston-fluid resistance, velocity-dependent	Stable, repeatable energy dissipation	Expensive, needs proper sealing	1980s–Present	Buildings & bridges, retrofitting
Metallic Yield Damper (MYD)	Plastic deformation of steel elements	Simple, robust, low cost	Permanent deformation after strong events	1980s	One-time strong events, industrial & mid-rise buildings
Viscoelastic Damper (VED)	Polymer-based, dissipates energy via shear	Provides both stiffness and damping	Temperature-sensitive, long-term degradation	1990s	Moderate seismic & wind conditions
Tuned Liquid Damper (TLD) / Tuned Liquid, Column Damper(TLCD)	Sloshing liquid counters vibration	Multifunctional (damping + water storage), low-cost	Narrow frequency range, sensitive to liquid level	1990s–Present	Tall towers, multifunctional buildings
Semi-Active MR Damper	Smart fluid changes viscosity under magnetic field	Real-time adaptive damping	High cost, needs continuous power/control	2000s–Present	Smart buildings, critical infrastructure
Electrorheological (ER) Damper	Smart fluid changes viscosity under electric field	Rapid adaptive response	Experimental, energy-intensive	2000s–Present	Research / prototype smart structures
Inerter Damper	Mechanical devices multiplying apparent mass	High damping with compact size	Experimental, integration complexity	2010s–Present	Research, specialized structural systems

2.7 Theoretical Background: [Conceptual clarity]

2.7.1 Strengthening and stiffening of RC Buildings

Strengthening and stiffening are critical measures to ensure the stability and safety of reinforced concrete (RC) buildings during seismic events. These interventions enhance the lateral load-carrying capacity of a structure, thereby improving its overall stability under earthquake-induced forces.

Strengthening: Strengthening refers to the process of increasing the load-bearing capacity of an existing structure. Various techniques can be employed to achieve this, including:

- **Shear Wall Addition:** The incorporation of new shear walls significantly enhances the lateral strength of a building. Shear walls reduce structural drift and improve stability during seismic events, thereby mitigating potential damage.
- **Column Jacketing:** Existing columns can be strengthened through the application of reinforced concrete and steel jackets around them. This method increases the column's axial and lateral load capacity, helping to prevent structural damage during earthquakes.
- **Beam and Slab Strengthening:** Strengthening of beams and slabs using external reinforcement or fiber-reinforced polymers (FRP) enhances the overall stiffness and load-carrying capacity of floor systems.

Certainly, incorporating shear walls and column jacketing in seismic retrofitting can significantly enhance the structural strength of RC buildings. Studies have shown notable improvements in both shear and deformation capacities.

Shear Wall Addition:

- Implementing double reinforcement in shear walls has resulted in a 34% increase in shear capacity and a 47% increase in deformation capacity (top drift) compared to single-reinforced walls. ResearchGate

Column Jacketing:

- Reinforced concrete jacketing enhances the load-carrying capacity, strength, and stiffness of columns, making them more resilient to seismic forces. ResearchGate

Combined Retrofitting:

- A study on a 20-story building demonstrated that retrofitting with shear walls and jacketing increased story shear by up to 78% and reduced inter-story drift, indicating a substantial improvement in seismic performance.[IJAEM]

Visual Representation:
Here is a diagram illustrating a typical shear wall:

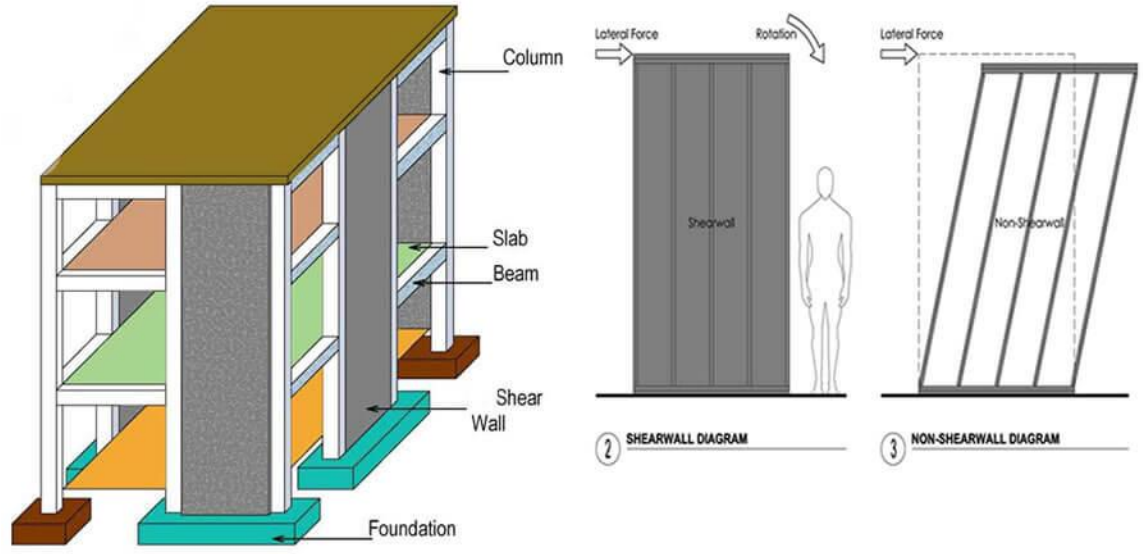


Figure 1 Comparison between shear wall & non-shear wall

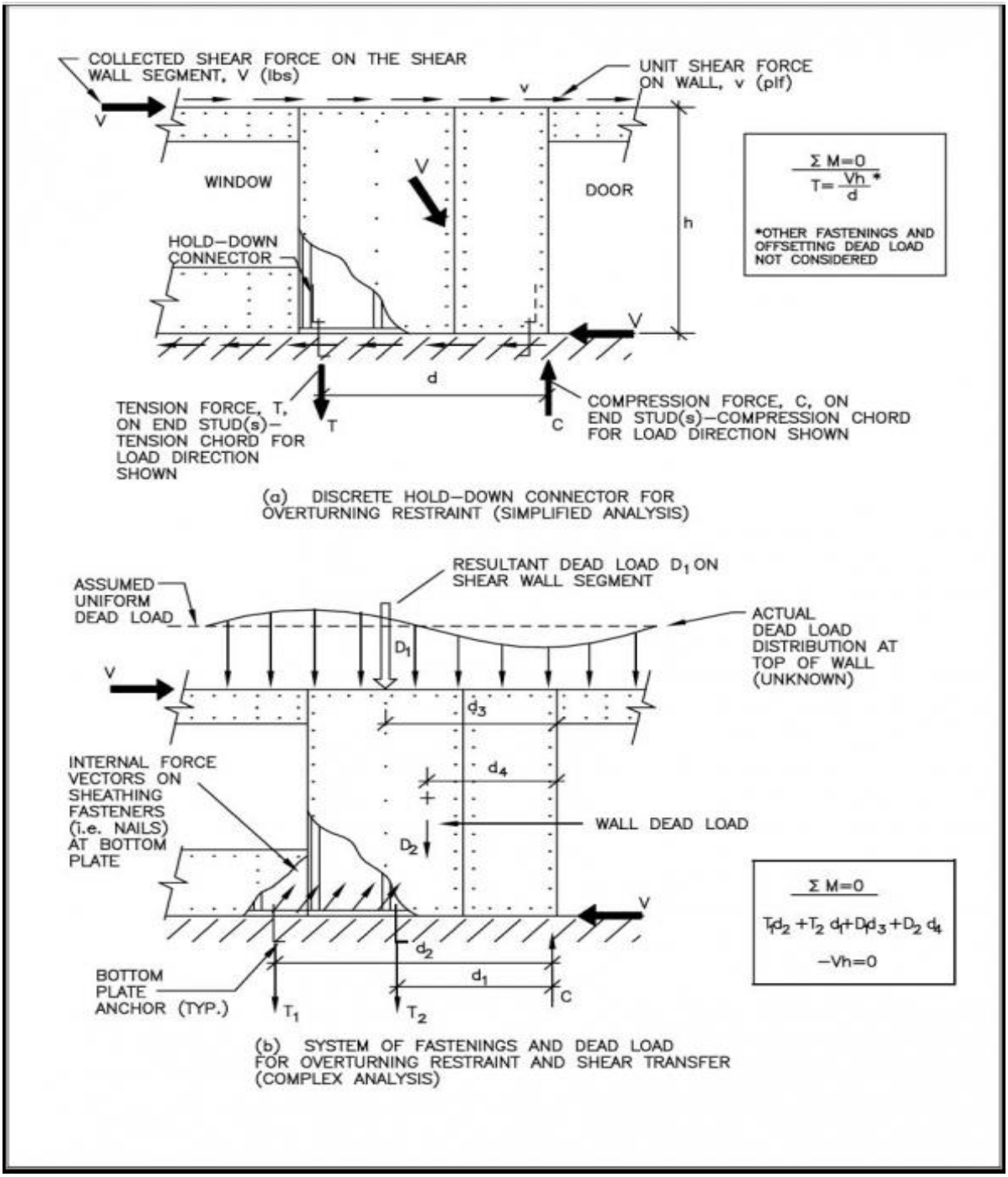


Figure 2 Diagram showing how a shear wall resists lateral load

Explanation (Diagram Analysis)

1. Lateral Load (Wind / Earthquake Force)

   → A horizontal force acts on one side of the building, pushing the structure sideways.

2. Role of the Shear Wall

   • The shear wall takes this force and transfers it downwards toward the foundation.

   • Tension and compression develop in the wall: the upper portion undergoes compression, and the lower portion experiences tension.

   • The wall works together with the floor/roof diaphragm to distribute the load to the rest of the building.

3. Overturning Moment and Hold-downs or Anchors

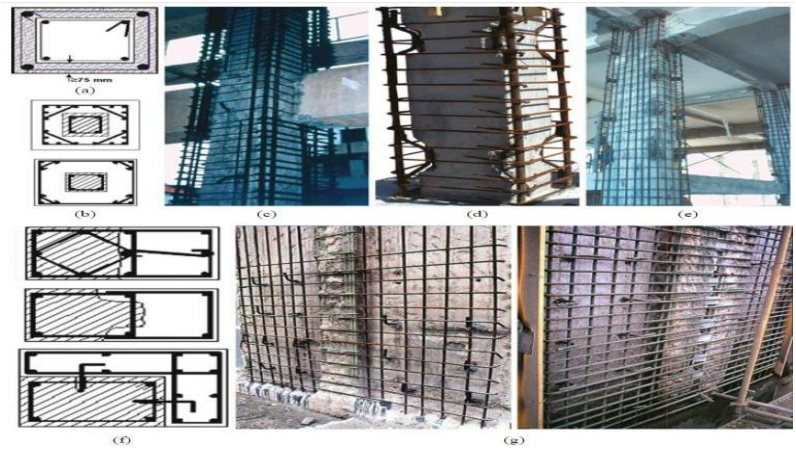
   • When there is lateral force, the structure tends to rotate or overturn.

   • Hold-downs or anchor elements at the bottom of the shear wall prevent the tensile side from lifting, keeping the wall fixed in place.

4. Load Transfer to Foundation

   • Ultimately, all the lateral, bending, and shear forces go down to the foundation and are distributed into the ground.

5. Proper footing, anchor bolts, and reinforcement are needed so that the foundation can support these loads.



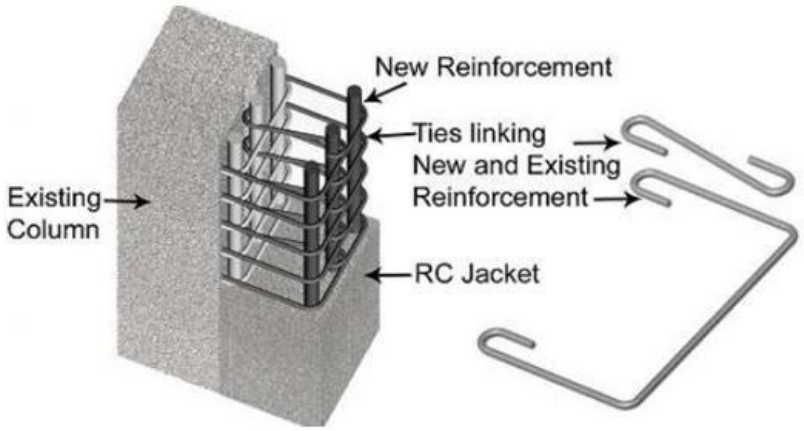


Figure 3 Processing part of the column jacketing

2. Stiffening

Stiffening refers to the process of increasing the rigidity of a structural system to reduce lateral displacement and deformation under seismic loads. Stiffening strategies include:

- Bracing Systems: Installation of diagonal braces or moment-resisting frames provides additional stiffness to the structure, reducing sway and drift during earthquakes.
- Floor Diaphragm Enhancement: Improving the stiffness of floor diaphragms ensures effective load transfer between structural elements, thereby enhancing the lateral stability of the building.
- Integration with Existing Structural Elements: Strengthening existing structural members in a manner that increases overall system stiffness, such as connecting new shear walls or bracing systems to columns and beams, helps the structure resist lateral loads more effectively.

Stiffening Techniques:

- Steel Bracing: Incorporating steel braces within the frame enhances structural stiffness and lateral stability.
- Fiber Reinforced Polymer (FRP) Jacketing: Wrapping columns and beams with FRP composites improves ductility and overall seismic performance.

3. Combined Benefits

The combination of strengthening and stiffening measures ensures that an RC building not only has increased load-bearing capacity but also improved rigidity, thereby significantly reducing the risk of structural damage during seismic events. Proper implementation of these measures enhances both the safety and serviceability of the building under lateral loads.

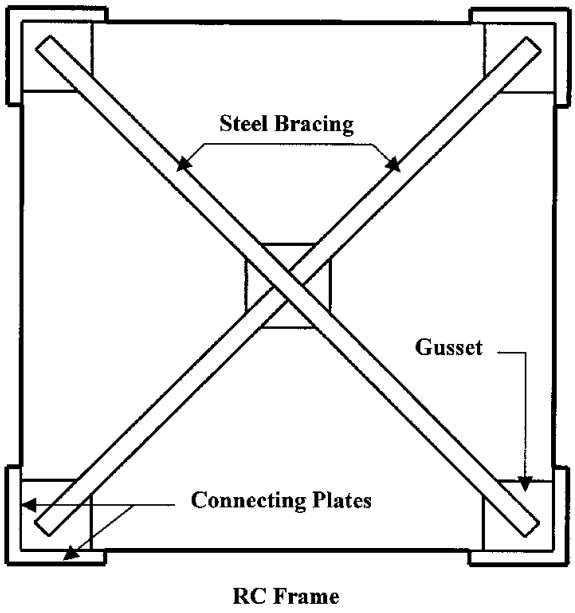


Figure 5 : Steel Bracing

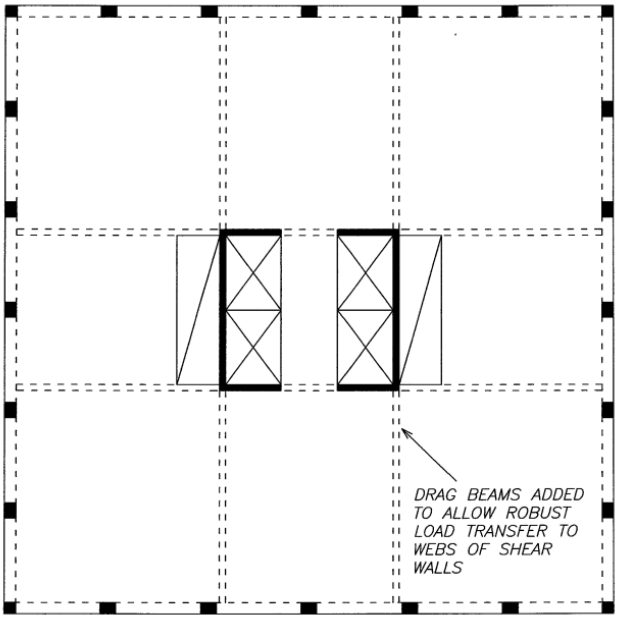


Figure 4: Diaphragm improvement using internal Drug Beams

2.7.2 Energy Dissipation in RC Buildings

Energy dissipation is a fundamental concept in earthquake engineering, representing the process by which seismic energy imparted to a structure is absorbed, transformed, or otherwise reduced to mitigate structural response. During an earthquake, a building undergoes dynamic excitation that generates kinetic and potential energy, which, if uncontrolled, can lead to excessive inter-story drifts, member yielding, or catastrophic failure.

In reinforced concrete (RC) structures, energy dissipation occurs through multiple mechanisms:

Material Damping: Material damping refers to the inherent ability of a structural material to dissipate mechanical energy during cyclic loading through internal friction, micro-cracking, and viscoelastic effects.

Mechanism:

- **Internal Friction:** Atoms and molecules resist relative displacement.
- **Micro-cracking:** Small cracks in concrete dissipate energy.
- **Viscoelasticity:** In polymers or composites, the stress–strain relationship shows hysteresis, which absorbs energy.

In Structural Engineering:

- In **reinforced concrete (RC)**: Damping mainly occurs due to micro-cracking in concrete and bond slip between steel and concrete.
- In **steel structures**: Damping is relatively low, dominated by internal friction and joint slip.
- In **masonry**: Damping arises from mortar–brick friction and crack propagation.

Typical Damping Ratios:

- Reinforced Concrete (RC): **5% – 7%** of critical damping.
- Structural Steel: **2% – 3%**.
- Masonry: **4% – 10%** (depending on condition).

While inherent, this mechanism is limited and often insufficient for medium- to high-intensity seismic events.

Damping Devices: Engineered devices such as friction dampers (FD), fluid viscous dampers (FVD), and tuned mass dampers (TMD) are designed to enhance energy dissipation. Each device operates on a distinct physical principle:

1. Friction Dampers (FD):

Dissipate energy through sliding friction, converting kinetic energy into heat. Particularly effective for controlling drift in low- to mid-rise structures, though wear and degradation over time must be considered.

Mechanism (How it works)

Components:

- Sliding (or sliding) surfaces: two plates (or blocks) that can slide relative to each other.
- A normal force applied between the surfaces (e.g., by bolts, springs, or clamps).
- Friction interface material (steel-steel, steel-with friction pad, or surface treatment) that determines the coefficient of friction (static and dynamic).
- Housing or bolts to maintain alignment and apply preload.

Operation Modes:

- **Stick** mode: Up to a certain force, the surfaces do not slide; the damper behaves more stiffly, resisting displacement by friction force.
- **Slip** mode: Once the applied force exceeds the static friction limit, the surfaces slide; energy is dissipated via friction (force × slip distance).
- **Hysteretic loop**: As loading reverses, energy dissipation happens in both directions. The force-displacement plot shows a loop whose area equals the energy dissipated during each cycle.

Key Behavioral Parameters:

- **Slip load** or static friction threshold: Force at which sliding begins.
- **Coefficient of friction (μ)**: Ratio of friction force to normal force (static μs, dynamic μd).
- **Normal force or preload**: Determines how much friction force is generated.
- **Relative displacement capacity**: How much sliding movement can occur without failure.

- **Wear and degradation**: Over cycles, friction surfaces may degrade, preload may relax, and the friction coefficient may reduce.

. **Advantages & Disadvantages**

- **Strength:** Friction dampers provide immediate energy dissipation once slip begins; are frequency-independent (i.e., they dissipate regardless of vibration frequency), robust under large displacement, and relatively low cost.
- **Limitation:** Behavior is non-linear and can be unpredictable under varying slip velocities or if preload changes; friction surfaces wear down; performance may be sensitive to temperature and surface condition; controlling or modeling exact force-displacement behavior is challenging.

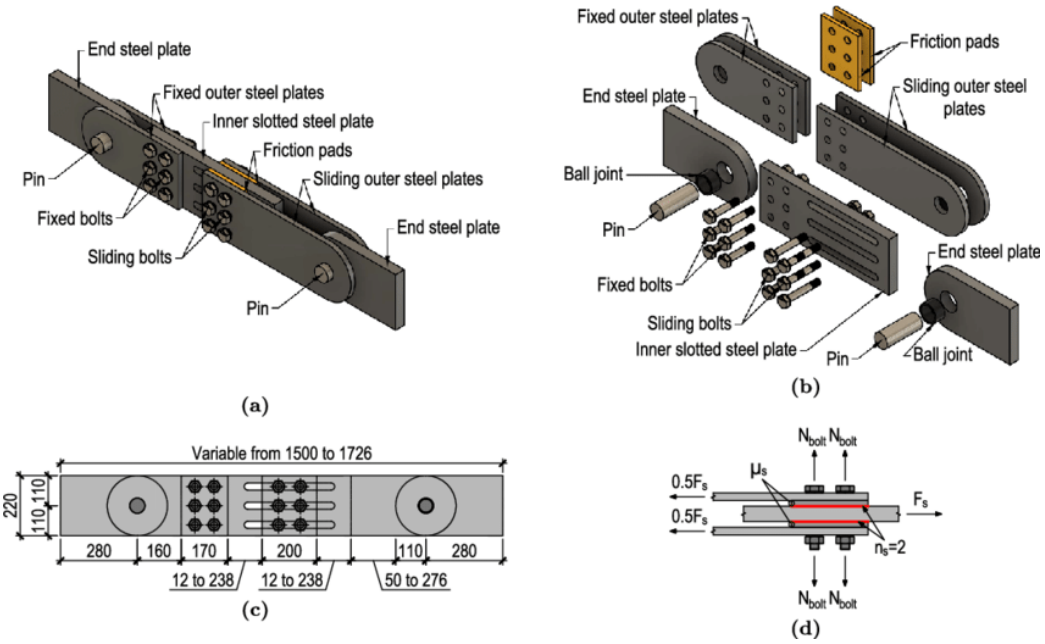
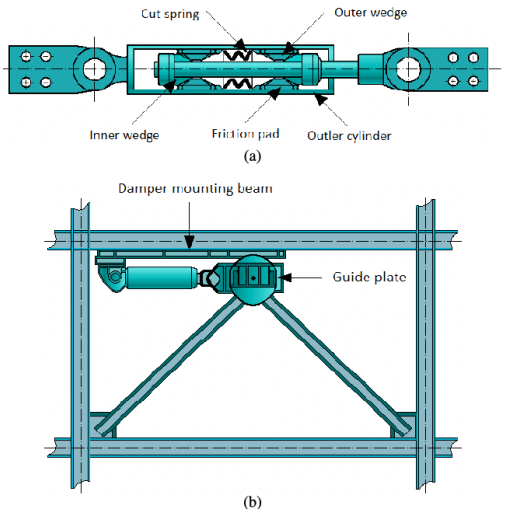


Figure 6 Different Parts of the Friction Damper



2. Fluid Viscous Dampers (FVD)

Dissipate energy by forcing a viscous fluid through an orifice, converting mechanical energy into heat. Highly effective for reducing seismic and wind-induced vibrations in both low- and high-rise structures, with stable long-term performance since no significant wear occurs in the main components.

Working Principle

- When the structure vibrates, the piston inside the damper moves relative to the cylinder, forcing the viscous fluid through orifices or valves.
- The resistance generated by the fluid flow produces a damping force proportional to the velocity of motion.
- At low velocities (small vibrations), the damper provides minimal resistance, allowing structural flexibility.
- At high velocities (during earthquakes or strong winds), the resistance increases, dissipating significant energy.
- The hysteretic behavior is nearly elliptical in the force–displacement curve, representing stable and repeatable energy dissipation.

Components

- Cylinder: Sealed housing containing viscous fluid.
- Piston and piston rod: Move relative to the cylinder during structural vibrations.
- Orifices/valves: Control the fluid flow and resistance.
- Viscous fluid: Typically, silicone oil with stable properties over a wide temperature range.
- End connections: To attach the damper to the structure.

Mathematical Behavior (Simplified Linear Model)

For small to moderate displacements, the FVD can be represented by a linear viscous damper model:

$$F_d = C.v^{\alpha}$$

where C = damping coefficient, v = velocity, and α\alphaα (typically 0.3–1.0) defines nonlinearity.

Where:

- F_d= damping force (N)
- C = damping coefficient (N·s/m)
- v^{α}= relative velocity between damper ends (m/s)

Notes:

For nonlinear behavior under large displacements or high velocities, the generalized model is:

$$F_d = C.|v|^{\alpha-1}.v$$

- α\alpha = velocity exponent ($0 < \alpha \leq 1$), defines nonlinearity
- The damping force is proportional to velocity, making FVD **velocity-dependent**, unlike friction dampers.

Advantages & Limitations

Advantages:

- Predictable and stable energy dissipation.
- Effective across a wide frequency range (earthquake and wind).
- Minimal wear; only fluid and seals require maintenance.
- Simplified modeling and integration in structural analysis.

Limitations:

- Higher initial cost compared to friction dampers.
- Require careful sealing to prevent fluid leakage.
- Temperature may affect fluid viscosity.
- Periodic maintenance required for long-term performance.

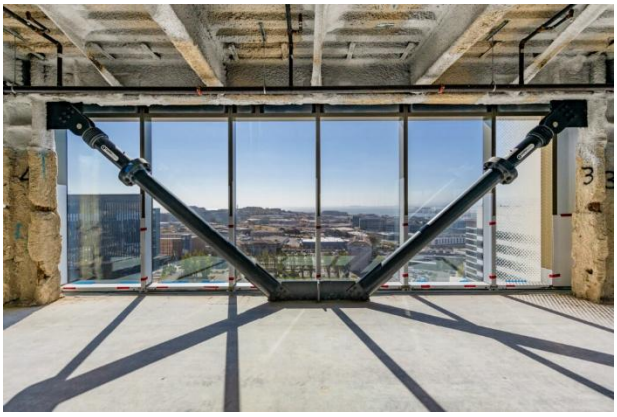


Figure 8 Fluid Viscus Damper

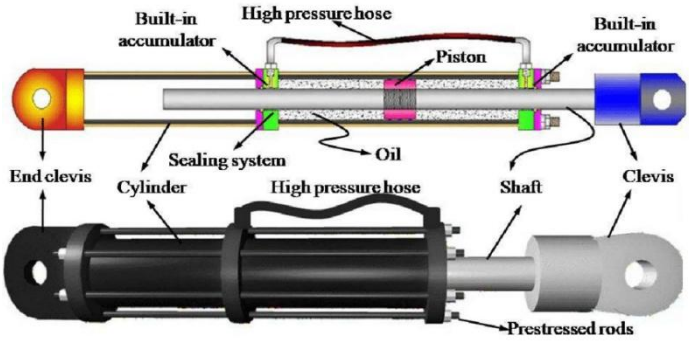


Figure 9 Fluid Viscus Damper Component

3. Tuned Mass Dampers (TMD):

Introduce a secondary mass system tuned to the building's dominant vibration frequency. TMDs primarily reduce acceleration response, minimizing occupant discomfort and non-structural damage.

Mechanism of TMD: When the primary structure experiences dynamic loads, it vibrates at its natural frequency. The TMD, being tuned to the same frequency, begins oscillating out of phase with the structural motion. This counteracting force reduces the amplitude of vibration of the main structure. The energy from the structure is transferred to the TMD and dissipated through its damping system.

Components

- **Mass (m_2):** A secondary mass added to the system.
- **Spring (k_2):** Provides restoring force to the secondary mass.
- **Damper (c_2):** Dissipates energy through damping.

- **Support system:** Ensures stable installation in the host structure.

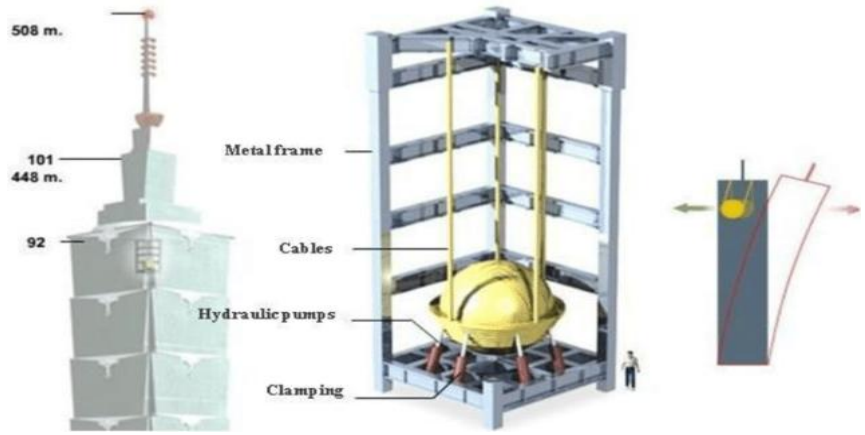


Figure 10 TMD Installation

Working Principle

When a building or structure vibrates due to seismic or wind forces, the TMD mass oscillates with a time lag (phase difference) relative to the main structure. This oscillation is intentionally tuned such that the inertia force of the TMD counteracts the motion of the structure. The damper component dissipates part of the vibration energy in the form of heat, while the spring restores the TMD to its equilibrium position. The combined effect reduces the amplitude of vibration, inter-story drift, and acceleration of the structure.

Mathematically, the primary structure and the TMD form a couple of two-degree-of-freedom (2-DOF) system. The motion equations are:

$$m_1x_1 + c_1x_1 + k_1x_1 + c_2(x_1 - x_2) + k_2(x_1 - x_2) = F(t) m_2x_2 + c_2(x_2 - x_1) + k_2(x_2 - x_1) = 0$$

where:

- $m_1 c_1, k_1$ = mass, damping, and stiffness of the main structure
- m_2, c_2, k_2 = mass, damping, and stiffness of the TMD
- x_1, x_2 = displacements of structure and TMD
- F(t) = external excitation (earthquake/wind load)

The **tuning condition** is achieved when the TMD's natural frequency ω_2 is close to the structure's fundamental frequencyω_1:

$$\omega_2 = \omega_1 = \sqrt{\frac{k_1}{m_1}}$$

This ensures maximum energy transfer and vibration reduction.

Advantages

- Effective in reducing vibrations from wind and seismic loads.
- Passive system requires no external energy.
- Widely used in tall buildings and bridges.

Limitations

- Efficiency depends on accurate tuning.
- Less effective if structural frequency shifts due to damage or aging.
- Requires large space and additional mass.

Applications

- Taipei 101 (Taiwan) uses a 660-ton spherical TMD.
- John Hancock Tower (USA) employs dual TMDs.
- Potentially applicable in Bangladesh's mid- and high-rise RC buildings to reduce seismic vulnerability on soft soils.

4 Hybrid Damper (FVD+FD) Concept:

A **Hybrid Damper** combines **Fluid Viscous Damper (FVD)** and **Friction Damper (FD)** into a single system.

- **FVD** provides **velocity-dependent damping** (force proportional to velocity), effective for controlling high-frequency dynamic responses and reducing acceleration.

- **FD** provides **displacement-dependent energy dissipation** through friction sliding, effective in limiting structural drift and hysteretic energy dissipation.

By integrating both, the hybrid damper ensures that:

- **Small and moderate vibrations** are effectively controlled by FVD.
- **Large displacements** during strong earthquakes are absorbed by FD through sliding friction.
  Thus, the system becomes more **robust, reliable, and efficient** across a wide range of loading conditions.

2. Working Principle

The hybrid damper works in **two complementary stages**:

- **Viscous Energy Dissipation (FVD part):**
  - When the structure vibrates, the piston inside the viscous chamber moves through the fluid.
  - This movement generates a damping force proportional to velocity:

$$F_v = C.v^{\alpha}$$

where C = damping coefficient, v = velocity, and α\alphaα (typically 0.3–1.0) defines nonlinearity.

  - Result: Reduction of acceleration and inter-story velocity.

- **Frictional Energy Dissipation (FD part):**
  - Once the vibration exceeds a threshold displacement, sliding occurs between frictional plates.
  - Energy is dissipated by **hysteretic loops** in the force–displacement relationship.
  - Frictional resistance remains nearly constant, thus limiting excessive drift.

Combined Effect (Hybrid Action):

- At **low velocity & displacement**, FVD dominates → smooth damping.
- At **large displacement events**, FD activates → strong hysteresis & drift control.
- This dual mechanism ensures stability and energy dissipation across both minor and major seismic events.

3. Mathematical Formulation

The total damper force is the **sum of viscous and frictional components**:

$$F_{Hybrid} = F_v + F_f = C.v^{\alpha} + \mu N \cdot \text{sign}(x)$$

Where,

- F_v = viscous damping force,
- F_f=μN = friction force (μ = friction coefficient, N = normal force),
- x = velocity of relative displacement.

This nonlinear combined model allows accurate representation of hybrid damper performance in structural analysis.

4. Advantages of Hybrid Damper

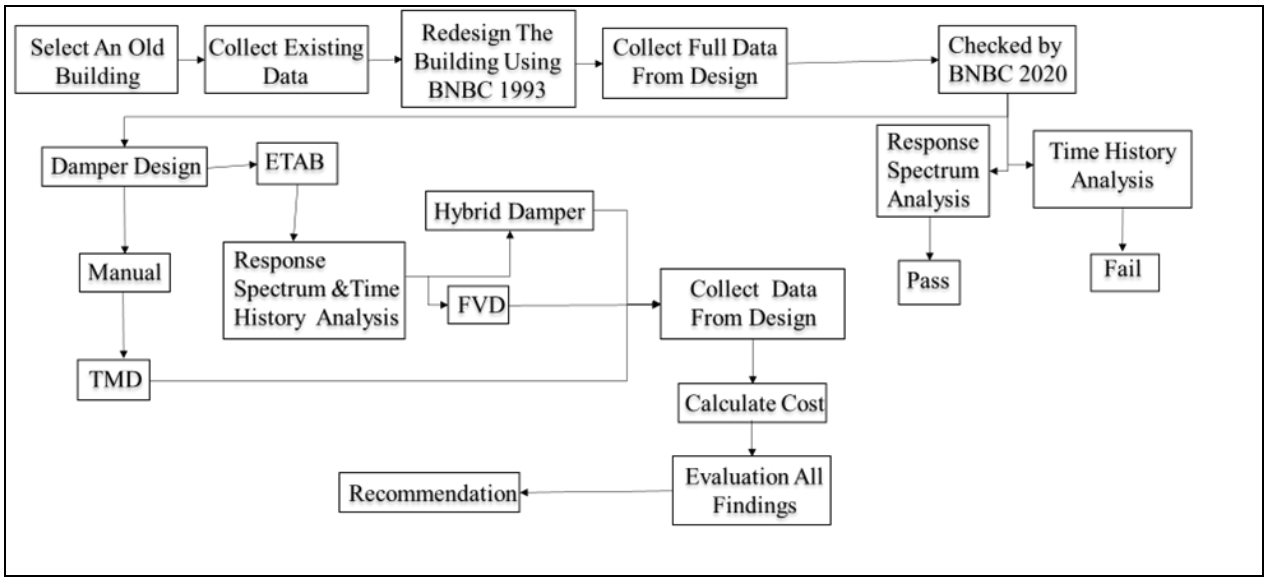
- Effective for both **small vibrations** (wind, minor quakes) and **large seismic events**.
- Reduces **both displacement and acceleration** simultaneously.
- Provides **stable hysteretic energy dissipation** without significant degradation.

Suitable for **irregular RC buildings** in seismic zones like Dhaka, where both drift and acceleration control are critical.

CHAPTER 3

Methodology

3.1Flow Diagram of Methodology:



3.2 Selection of Study Buildings

Selecting an appropriate study building is a crucial step in evaluating the effectiveness of seismic retrofitting techniques that utilize damping systems. For this research, a 10-story reinforced concrete (RCC) building, serving both residential and commercial purposes, has been selected. The building is located near the Metro Station in Mirpur 11, Dhaka, representing a densely populated urban area with moderate seismic risk.

3.2.1 Building Characteristics and Dimensions

The selected building has a height of 1320 inches, a vertical span of 926 inches, and a horizontal length of 431 inches. At the time of its original construction around 2000, buildings taller than ten stories were uncommon in Bangladesh. Therefore, this structure provides a representative case for studying mid-rise RCC buildings constructed prior to modern seismic codes.

3.2.2 Location and Soil Profile

The building is situated in a region that has now been developed, with the Metro Station nearby, emphasizing its urban context. The local soil is classified as Sc type, with Standard Penetration Test (SPT) values ranging between 30 and 50, ensuring that the seismic input used in the analysis reflects realistic site conditions.

3.2.3 Architectural and Structural Features

The building exhibits an irregular architectural design. The basement includes shear walls, while the column and beam layout vary across floors, creating geometric irregularities. This configuration makes the building suitable for evaluating the performance of damping systems under realistic seismic loading scenarios.

3.2.4 Materials and Construction

The structural system is composed of Grade 60 steel reinforcement and 3500 psi concrete, designed following BNBC 1993 provisions for load combinations. For dynamic analysis and Time-History studies, BNBC 2020 guidelines are applied. This approach allows for assessing how an older building, designed under previous codes, would respond if analyzed under current seismic standards and retrofitting strategies.

3.2.5 Hybrid Damper (FVD+FD) Concept:

A Hybrid Damper combines Fluid Viscous Damper **(FVD)** and Friction Damper **(FD)** into a single system.

- FVD provides velocity-dependent damping (force proportional to velocity), effective for controlling high-frequency dynamic responses and reducing acceleration.
- FD provides displacement-dependent energy dissipation through friction sliding, effective in limiting structural drift and hysteretic energy dissipation.

By integrating both, the hybrid damper ensures that:

- Small and moderate vibrations are effectively controlled by FVD.

- Large displacements during strong earthquakes are absorbed by FD through sliding friction.

  Thus, the system becomes more robust, reliable, and efficient across a wide range of loading conditions.

2. Working Principle

The hybrid damper works in **two complementary stages**:

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- **Combined Effect (Hybrid Action):**
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The total damper force is the sum of viscous and frictional components:

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This nonlinear combined model allows an accurate representation of hybrid damper performance in structural analysis.

4. Advantages of Hybrid Damper

- Effective for both small vibrations (wind, minor quakes) and large seismic events.
- Reduces both displacement and acceleration simultaneously.
- Provides stable hysteretic energy dissipation without significant degradation.
- Suitable for irregular RC buildings in seismic zones like Dhaka, where both drift and acceleration control are critical.

Table 2 : Building Properties

Name of Structure member & load	Specification
Bays in X direction	2
Bays in Y directions	6
Typical story height (ft)	10
Bottom story height (ft	10

Total Building Mass(kip)	7754
Beam (in)	10x24,10x20,12x20,12x22,12x24
Typical Column (in)	10x25,12x20, 12x24,15x20,15x24,15x30,15x36
Slab thickness (inch)	5 , 7
Compressive strength of concrete (psi)	3500, 4000
Grade of steel (ksi)	60
Grade of rebar (ksi)	60
Dead load (psf)	75
Live load (psf)	0.278
Auto Mesh type	At points / lines / edges
Joint assignment- Restrain	Fixed

3.2.5 Relevance to Research Objectives

The building's **height, irregularity, and seismic vulnerability** make it an ideal candidate for testing various damping systems. The study focuses on evaluating the performance of **Hybrid Dampers, Fluid Viscous Dampers (FVD),** in mitigating seismic responses such as inter-story drift, base shear, and peak floor accelerations.

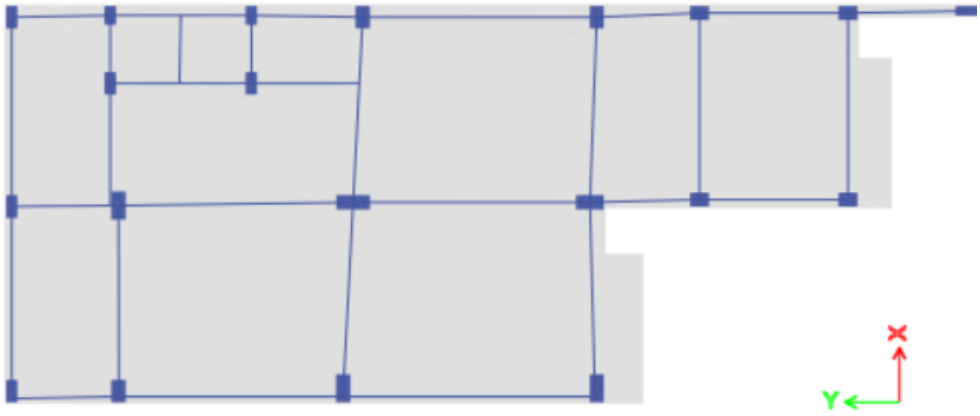


Figure 11 : Building Plan View

3.2.6 Feasibility of Damper Implementation

The building's structural configuration provides sufficient space for the strategic installation of Hybrid Dampers (FVD + FD) along frame elements. Given the height and irregularity of this older structure, the use of individual Tuned Mass Dampers (TMD) or Fluid Viscous Dampers (FVD) for each floor would require a substantial volume and would be practically cumbersome. Therefore, Hybrid Dampers are preferred, as they can achieve equivalent or improved seismic performance while minimizing the number of devices needed.

Additionally, the potential **cost implications** of installing TMDs or FVDs on all floors are considerable. This study will discuss the comparative economic feasibility of using Hybrid Dampers versus individual TMD or FVD systems, including a preliminary analysis of installation costs relative to structural volume and performance efficiency.

Table 3 : Damper Properties

Properties	Hybrid Dampers	FVD Dampers
Mass (lb-s^2/in)	FVD-.560 FRD- .514	0.560
Weight (kip)	FVD- 112.404 FRD- 67.44	112.404
Effective Damping(kip-s/in)	FVD- 11.7 FRD-7.02	11.7
Effective stiffness(kip/in)	FVD- 37.6 FRD-22.6	37.6
Damping Exponent	1	1
Yielded Damping coefficient (kip-s/in)	0	-

FVD with Different Capacities Force(kN).

FORCE (kN)	TAYLOR DEVICES MODEL NUMBER	SPHERICAL BEARING BORE DIAMETER (mm)	MID-STROKE LENGTH (mm)	STROKE (mm)	CLEVIS THICKNESS (mm)	MAXIMUM CLEVIS WIDTH (mm)	CLEVIS DEPTH (mm)	BEARING THICKNESS (mm)	MAXIMUM CYLINDER DIAMETER (mm)	WEIGHT (kg)
250	17120	38.10	787	±75	43	100	83	33	114	44
500	17130	50.80	997	±100	55	127	102	44	150	98
750	17140	57.15	1016	±100	59	155	129	50	184	168
1000	17150	69.85	1048	±100	71	185	150	61	210	254
1500	17160	76.20	1105	±100	77	205	162	67	241	306
2000	17170	88.90	1346	±125	91	230	191	78	286	500
3000	17180	101.60	1441	±125	117	290	203	89	350	800
4000	17190	127.00	1645	±125	142	325	273	111	425	1088
6500	17200	152.40	1752	±125	154	350	305	121	515	1930
8000	17210	177.80	1867	±125	178	415	317	135	565	2625

Table 4 : FVD Capacity

3.3 Structural Modelling and Analysis Tools

Accurate representation of the selected building in computational models is essential for evaluating the effectiveness of seismic retrofitting strategies. For this study, structural modelling has been performed using **ETABS 2021**, a widely recognized software for analyzing multi-story reinforced concrete (RCC) buildings.

3.3.1 Modelling Approach

The building is modelled as a **three-dimensional frame**, incorporating all structural components, including beams, columns, slabs, and shear walls. The irregular floor plan and asymmetry in column layouts are explicitly represented to capture the realistic dynamic behavior of the structure under seismic loading.

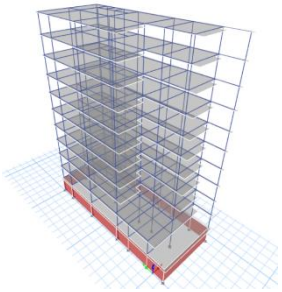


Figure 12: 3D ETABS Model of 10 Story Building

3.3.2 Material Properties

- **Concrete:** Normal-weight concrete, compressive strength 3500 psi.
- **Steel Reinforcement:** Grade 60 steel.

- All material properties are defined according to ETABS material libraries and verified against BNBC 1993 code requirement

3.3.3 Load Modelling

- **Gravity Loads:** Dead and live loads applied by BNBC 1993 provisions.
- **Seismic Loads:** Both **Response Spectrum Analysis** and **Time-History Analysis** were conducted according to BNBC 2020.
- Load combinations are defined to consider interaction between gravity and seismic forces.

3.3.4 Dynamic Analysis Capabilities

- **Response Spectrum Analysis:** Determines peak structural responses, including inter-story drift, base shear, and floor accelerations.
- **Time-History Analysis:** Captures temporal response under selected earthquake records, including historical events (e.g., 2001 Bhuj Earthquake at Gujarat, India)

3.3.5 Damper Modelling

- **Hybrid Dampers (FVD + FD)** are incorporated at strategic locations, such as between floors and the side portion of the structure.
- Damper properties—damping coefficient, yield strength, and displacement limits—are defined to evaluate their effectiveness in reducing seismic responses.

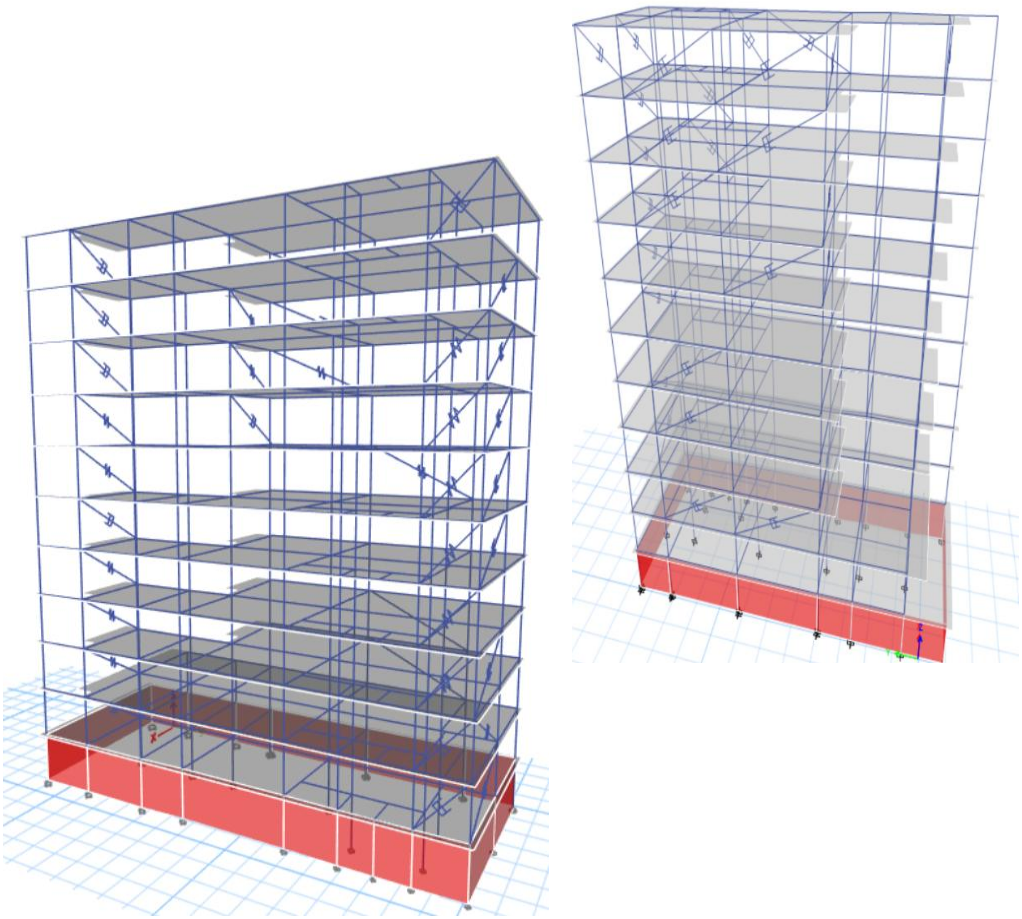


Figure 13 : RC Structure with Hybrid & FVD Damper Placement along frame elements

3.3.6 Validation of models the structural models are validated by:

- Checking member forces and story drifts.
- Comparing modal properties with expected dynamic behavior.
- Ensuring that the simulation accurately represents a real building response under seismic loads

3.4 Ground Motion Data and Input

For the dynamic time-history analysis, ground motion data from the 2001 Gujarat (Bhuj) Earthquake have been adopted. This earthquake, with a moment magnitude (Mw) of 7.6, occurred on January 26, 2001, and is considered one of the most devastating seismic events in

the Indian subcontinent. The epicenter was located near Bhuj in Gujarat, India, and the earthquake caused widespread structural damage, resulting in more than 20,000 fatalities and severe socio-economic disruption.

3.4.1 Selection Rationale

The rationale for using this earthquake record includes:

- **Geographical Proximity:** Bangladesh shares similar tectonic influences with the Indian subcontinent, particularly from the Indian Plate and the Himalayan frontal thrust system.
- **High Magnitude:** The earthquake represents a large-magnitude seismic event, which allows assessment of structural performance under extreme shaking conditions.
- **Availability of Data:** Reliable and well-documented ground motion records are available for this earthquake, making it suitable for detailed dynamic analysis.

3.4.2 Characteristics of the Earthquake Record

- **Date:** 26 January 2001
- **Magnitude:** Mw = 7.6
- **Epicenter Coordinates:** Latitude 23.419°N, Longitude 70.232°E
- **Focal Depth:** ~16 km (≈ 52,493 ft)
- **Peak Ground Acceleration (PGA):** approximately 0.29g at the recording station.
- **Duration of Strong Shaking:** Nearly 90 seconds.

3.4.3 Data Processing for ETABS Input

- The accelerogram data was collected from available COSMOS ground motion website
- The accelerogram was then imported into ETABS in three directions:
    - **ahmdgv.dat** → Ground motion in the longitudinal direction.
    - **ahmdgl.dat** → Ground motion in the transverse direction.
    - **ahmdgt.dat** → Vertical ground motion component.

3.4.4 Justification for Application in Study

Using the Bhuj earthquake record provides a realistic representation of a high-magnitude seismic event that may occur in Bangladesh in the future. Applying this strong ground motion data helps in:

- Assessing the vulnerability of existing RCC buildings under severe shaking.
- Evaluating the efficiency of damping systems (Hybrid, FVD) in reducing seismic demand.
- Demonstrating how older buildings are designed under BNBC 1993 respond when reanalyzed under BNBC 2020 with actual earthquake data.

3.5 Load Considerations

To realistically assess the seismic performance of the selected building and the effectiveness of retrofitting strategies using damping systems, a comprehensive set of structural loads has been considered in the analysis. The load types and their magnitudes were determined in accordance with the Bangladesh National Building Code (BNBC 1993) for the original design assumptions and BNBC 2020 for the re-analysis and seismic retrofitting assessment. The following categories of loads have been included:

3.5.1 Dead Load (DL)

Dead load primarily consists of the self-weight of all structural and non-structural components of the building.

- **Self-weight:** ETABS automatically calculates the self-weight of beams, columns, slabs, and shear walls by applying a self-weight multiplier of 1.0.
- **Floor finishing and partitions:** A superimposed dead load of approximately 1.5 kN/m² (≈ 31.33 lb/ft²) was applied to account for floor finishes (tiles, plaster, etc.) and partition walls.
- **Wall loads:** Masonry infill wall loads were applied as line loads on the beams, considering an average thickness of 125 mm (≈ 0.41 ft) and density of 20 kN/m³ (≈ 127.32 lb/ft³)..

3.5.2 Live Load (LL)

Live loads were assigned according to BNBC specifications for residential and mixed-use buildings.

- **Residential floors**: 2.0 kN/m² (≈ 41.77 lb/ft²)
- **Commercial/office floors:** 3.0–4.0 kN/m² (≈ 62.66–83.54 lb/ft²), depending on the function of each floor.
- **Roof live load:** 1.5 kN/m² (≈ 31.33 lb/ft²), reduced as per BNBC provisions.
  These values reflect the realistic occupancy and usage conditions of the selected building.

3.5.3 Seismic Load (EQ)

Seismic effects were modeled in accordance with both BNBC 1993 (original design code) and BNBC 2020 (updated code for comparative assessment).

- **Seismic zone factor (Z):** 0.15 (for Dhaka region, BNBC 2020).
- **Importance factor (I):** 1.0 for standard residential + commercial occupancy.
- **Response reduction factor (R):** 5.0 for moment-resisting RC frames without special detailing.
- **Soil profile:** Classified as Sc with an average **SPT** value of 30–50.
- **Dynamic analysis & Response Spectrum analysis** was performed as per BNBC 2020 design spectrum.
- **Time History analysis** was carried out using scaled accelerogram records from the 2001 Bhuj earthquake (M 7.6) to match the BNBC 2020 design spectrum.
  This dual approach ensures that the building's current strength is assessed under modern seismic design requirements.

3.5.4 Wind Load (WL)

The wind load was calculated using BNBC wind provisions for the Dhaka region.

- **Basic wind speed (V):** 130 mph (as per BNBC 2020).

- **Exposure category:** Category C, considering the building's urban location with surrounding obstructions.
- **Height effect:** Wind pressure variation with height was considered up to the building height of 33.5 m (1320 in).
- **Application in ETABS:** Wind loads were applied in both X and Y directions, with pressure coefficients assigned to exposed surfaces as per BNBC guidelines.

3.6 Damper Modeling and Placement

3.6.1 Type of Dampers Considered

In this study, Hybrid Dampers, which combine the energy dissipation capacity of Fluid Viscous Dampers (FVD) and the frictional resistance of Friction Dampers (FD), have been selected for installation in the structural models. The primary reason for selecting hybrid dampers is their superior ability to control both displacement and energy dissipation in irregular and aging buildings, which is the case for the selected 10-story structure in Mirpur.

Although Tuned Mass Dampers (TMD) are not installed in the models but also design manually, they are included in the research for the purpose of cost comparison. Their estimated volume and required quantities are calculated based on the manual and the cost of implementing these systems is evaluated against the hybrid damper approach. This ensures that the study captures both the technical effectiveness and the economic feasibility of different damp systems.

3.6.2 Tuned Mass Damper (TMD) Manual Calculation

This section presents the manual design calculations for a passive Tuned Mass Damper (TMD) sized at 3% mass ratio of the building effective mass. According to research and previous studies, a TMD with ~3% mass ratio can reduce peak story drift by approximately 20–30%, depending on building stiffness and damping. This provides significant improvement in seismic performance. Calculations include TMD mass, unit conversions, tuning stiffness and damping coefficient for a target tuning frequency, and a practical cost estimate with assumptions.

Given data & assumptions

• Effective building mass : building = 7754kip [20,084.41lb.s^2/in]

• Chosen mass ratio for TMD: μ = 3% = 0.03

• Target tuning frequency (assumed): f_TMD = 0.505 Hz

• Chosen TMD damping ratio: ζ_TMD = 0.106

• Unit conversion constants:

- 1 in = 0.0254 m
- 1 lbf = 4.448 N
- 1 (lb·s²/in) ≈ 175.127 kg

• Angular frequency: ω = 2πf

TMD mass (imperial unit & SI conversion)

Step 1 — TMD mass in FPS units:

m_TMD = μ × m_building = 0.03 × 20,084.41 = 602.53 lb·s²/in

Step 2 — Convert to kilograms:

m_TMD ≈ 602.53 × 175.127 = 105,520 kg

Step 3 — Convert to tonnes:

m_TMD ≈ 105.52 tonnes

SO, TMD = 602.53 lb·s²/in ≈ 105,520 kg ≈ 105.52 t

Tuning frequency and stiffness

Angular frequency: ω = 2πf = 2π(0.505) = 3.173 rad/s

TMD stiffness (SI units):

k = m × ω² = 105,520 × 10.068 ≈ 1.06 × 10^6 N/m ≈ 1,062.4 kN/m

Damping coefficient

c = 2mωζ = 2 × 105,520 × 3.173 × 0.106 ≈ 70,981 N·s/m ≈ 70.98 kN·s/m

Practical notes about computed values

• TMD mass ≈ 105.5 t — requires modular design and strong floor support.

• Stiffness ≈ 1.06 × 10^6 N/m and damping ≈ 71 × 10^3 N·s/m must be provided by steel springs, bearings, or pendulum mechanisms.

• Slight variation in tuning frequency should be checked for robustness.

3.7 Performance Evaluation Criteria

To evaluate the seismic performance of the selected RCC building under different damping conditions, a set of structural response parameters has been adopted. These criteria provide both qualitative and quantitative measures of improvement when hybrid dampers are installed, compared with the baseline model (without dampers) and with the estimated requirements for FVD and TMD systems.

3.7.1 Inter-story Drift Ratio

- Inter-story drift is one of the most critical indicators of seismic performance, directly related to structural and non-structural damage.
- As per BNBC 2020 guidelines, the permissible displacement limit & drift limit for reinforced concrete buildings **is** $\frac{\boldsymbol{Total\ H}}{\mathbf{500}}$ BNBC chapter: 1.5.6.2 [Sway Limit]. For Fundamental Time Period T ≥ 0.7 s → drift ≤ 0.004 h [our time period for 1st mode:1.6s] [see re:7]
- In this study, the maximum inter-story drift ratios are calculated and compared across different scenarios to assess how effectively dampers reduce lateral displacements.

3.7.2 Roof Displacement

- Roof displacement is an overall measure of building flexibility under seismic excitation.
- Excessive roof displacement leads to serviceability issues and indicates higher structural vulnerability.
- This parameter is used to compare the efficiency of Hybrid Dampers against the estimated performance of TMD & FVD (which typically controls roof displacement).

3.7.3 Base Shear

- Base shear represents the total horizontal seismic force acting on the structure at its foundation level.
- A reduction in base shear after damper installation demonstrates improved energy dissipation and reduced demand on structural elements.

3.7.4 Story Shear Distribution

- The distribution of shear force among stories indicates how seismic loads are transferred throughout the height of the building.
- This parameter helps identify whether irregularities in the structural layout create localized weaknesses.

3.7.5 Time Period and Mode Shapes

- The fundamental period of the building is calculated to evaluate the effect of damping systems on dynamic characteristics.
- Changes in mode shapes and participation factors show how dampers alter vibration patterns and control resonance effects.

3.7.6 Energy Dissipation Capacity

- The hysteretic behavior of hybrid dampers is studied through nonlinear time history analysis.
- The energy dissipated per cycle provides a direct measure of damper efficiency, highlighting why hybrid systems are more effective than standalone FVD or TMD.

3.8 Cost Analysis Methodology

This section presents the methodology adopted for evaluating the economic feasibility of installing damping systems in existing reinforced concrete buildings. The cost analysis has been performed for three alternatives: Hybrid Dampers (combination of Fluid Viscous and Friction Dampers), Fluid Viscous Dampers (FVD), and Tuned Mass Dampers (TMD). The primary

objective is to compare the life-cycle cost (LCC) of each option and to identify the most cost-effective solution, considering both structural performance and financial investment.

3.8.1 Objectives

The main objectives of the cost analysis are as follows:

- To estimate the initial installation cost of different damping systems.
- To evaluate annual operation and maintenance costs.
- To assess replacement or rehabilitation costs during the service life.
- To quantify the indirect benefits in terms of damage reduction, reduced downtime, and extended service life of the structure.
- To compare alternatives based on a Cost Efficiency Index (CEI) that relates seismic performance improvement to overall cost.

3.8.2 Cost Components

The following cost components were considered:

- **Initial Capital Cost (C_0):** Procurement of devices, steel bracing frames, installation labor, engineering supervision, testing, and contingency expenses.
- **Operation and Maintenance (O&M) Cost:** Periodic inspection, lubrication, and minor repairs, typically estimated as a percentage of initial cost.
- **Replacement Cost:** Major component replacement or overhaul at specific intervals depending on damper type and design life.
- **Indirect Benefits:** Reduction of expected seismic damage, avoidance of repair costs, and improved functional continuity after earthquakes.

3.8.3 Analytical Approach

The cost evaluation is based on the Net Present Value (NPV) method, which discounts all future expenditures to present-day values:

$$\text{NPV} = C_0 + \sum_{t=1}^{n} \frac{C_j}{(1+r)^t}$$

where,

- C_0= Initial capital cost
- Ct = Cost incurred in year (maintenance, replacement)
- r = Discount rate
- N = Life-cycle period (years)

In addition, a **Cost Efficiency Index (CEI)** has been formulated to evaluate the relative cost-effectiveness of each option:

$$\text{CEI} = \frac{\%Drift\ reduction}{NPV}$$

This ratio expresses the achieved structural performance improvement per unit cost, facilitating direct comparison among alternatives.

3.8.4 Damper-Specific Estimation

- **Tuned Mass Damper (TMD):** The required mass was estimated as 2–5% of the effective roof mass. Procurement and installation costs were computed based on the unit cost per ton of damper mass.
- **Fluid Viscous Damper (FVD):** The damping coefficient ccc was determined from structural analysis, and the number of units was calculated accordingly. Cost estimation was performed using market unit prices for FVD devices.
- **Hybrid Damper:** Hybrid devices were assigned to selected bays at each story based on story shear demands obtained from ETABS analysis. The cost estimation included both device cost and supporting bracing structures.

3.8.5 Sensitivity Analysis

To account for uncertainties, sensitivity analyses were conducted by varying the following parameters:

- Discount rate (±2%)
- Device unit price (±10%)
- Maintenance cost rate (±5%)
- Service life (20–40 years)

This analysis highlights the robustness of cost-effective conclusions under different economic assumptions.

3.8.6 Reporting of Results

The results of the cost analysis are reported in the following manner:

- Cost Breakdown Tables presenting initial, maintenance, and replacement costs for each damper type.
- Life-Cycle Cost (NPV) Comparisons among Hybrid, FVD, and TMD alternatives.
- the effect of key parameters on total cost.

The outcome of this methodology provides a clear, quantitative basis for selecting the most economically viable damping strategy for retrofitting old multi-story buildings.

Chapter 4

Analysis & Result

Table 5 : Increment of Building Time Period

Modal Number	Time period without damper(sec)	Time periods With Hybrid damper (Sec)	Time periods With FVD damper (Sec)
1	1.954	2.177	2.381
2	1.857	1.296	1.846
3	1.667	0.992	1.415
4	.619	0.683	0.716
5	0.597	0.402	0.505
6	0.529	0.311	0.419
7	.352	0.028	0.353
8	.343	0.212	0.033
9	0.297	0.206	0.029
10	0.243	0.017	0.022
11	0.239	0.157	0.209
12	0.202	0.143	0.177
13	.183	0.142	0.149
14	0.181	0.124	0.147
15	0.149	0.112	0.139
16	0.147	0.103	0.128
17	0.143	0.083	0.116
18	0.122	0.075	0.115
19	0.117	0.051	0.102
20	0.116	0.044	0.095
21	0.106	0.037	0.072
22	0.098	0.030	0.177
23	0.095	0.027	0.149
24	0.094	0.024	0.147
25	0.088	0.022	0.139

26	0.086	0.019	0.128
27	0.081	0.019	0.116
28	0.079	0.018	0.115
29	0.072	0.017	0.102
30	0.067	0.015	0.095
31	0.028	0.013	0.072
32	0.018	0.012	0.016

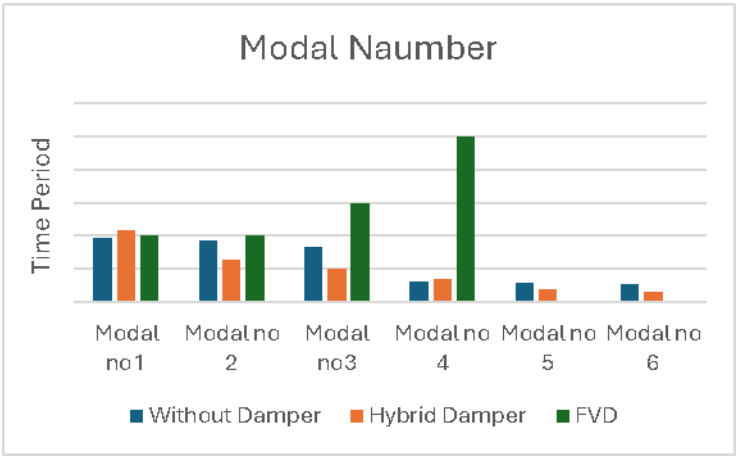


Figure 14: Modal Time Period Vs Time period

Figure 14 shows that in the model without damper the fundamental time period is higher, while after introducing dampers the time period decreases. As the mode number increases, the time period of vibration continues to reduce, which indicates the stiffening effect of the damping system.

Table 6: Base Shear

EQ Load	Without Damper	Hybrid Damper	FVD Damper
Structure	**232.28 kip**	**429.58kip**	**387.32kip**

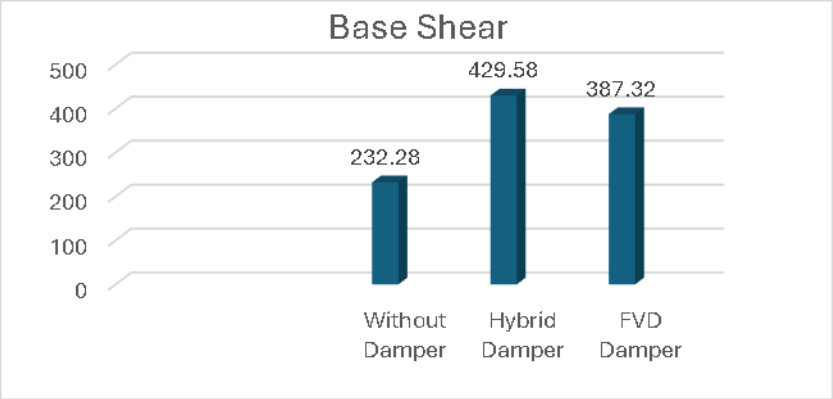


Figure 15: Base Shear

The base shear demand of the building was found to vary depending on the type of supplemental damping system adopted. Without any damper, the base shear was **232 kip**. When dampers were introduced, both the hybrid damper and the fluid viscous damper (FVD) cases showed an increase in base shear, with values of **429 kip** and **387 kip**, respectively. The higher base shear in the hybrid damper case can be attributed to the combined action of stiffness and energy dissipation, which not only enhances damping but also increases the effective lateral stiffness of the system. This increase in stiffness leads to higher lateral force demand at the base compared to the FVD case, where the effect is primarily governed by velocity-dependent damping. Hence, although both systems improve seismic response by reducing displacements, the hybrid damper results in comparatively higher base shear demand due to its stiffness contribution.

Table 7: Responses without Damper

Load case	Max Displacement (in)	Max Drift (in)	BNBC 2020 lateral Displacement & drift limit
RS-X	1.7107	1.10	
RS-Y	0.3327	0.20	Individual story h = 120inch
TH-X	2.9955	1.75	$Disp_{all} = \frac{1320}{500}$ =2.26
TH-Y	0.462	0.30	$Drift_{all}$ =.004*120=.48

Table 8: Responses with Hybrid Damper

Load case	Max Displacement (in)	Max Drift (in)	BNBC 2020 lateral Displacement & drift limit:
RS-X	0.799	0.4435	
RS-Y	0.7253	0.1711	Individual story h = 120inch
TH-X	0.6332	0.6390	$\boldsymbol{Disp_{all} = \frac{1320}{500}}$ =2.26
TH-Y	0.357	0.1916	$\boldsymbol{Drift_{all}}$ =.004*120=.48

Table 9: Responses with FVD Damper

Load case	Max Displacement (in)	Max Drift (in)	BNBC 2020 lateral Displacement & drift limit : (in)
RS-X	1.599	0.54	
RS-Y	0.3506	0.445	Individual story h = 120inch
TH-X	2.26	0..334	$Disp_{all} = \frac{1320}{500}$ =2.26
TH-Y	0.706	0.012	$Drift_{all}$ =.004*120=.48

Table 10: Responses with TMD Following Manual Calculation

Model design & calculations	Max Displacement (30%) inch	Max Drift reduction (30%) inch	BNBC 2020 lateral drift limit: (in)
According to previous studies	.98 (of avg. max TH Value)	1.06 (of avg, max drift of TH Value)	.48

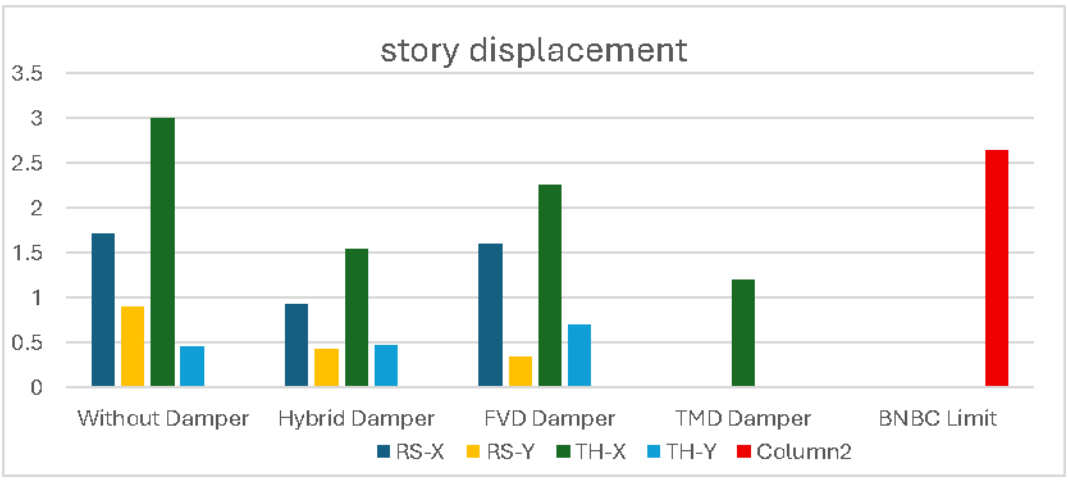


Figure 16: All systems Displacement Vs Time Period

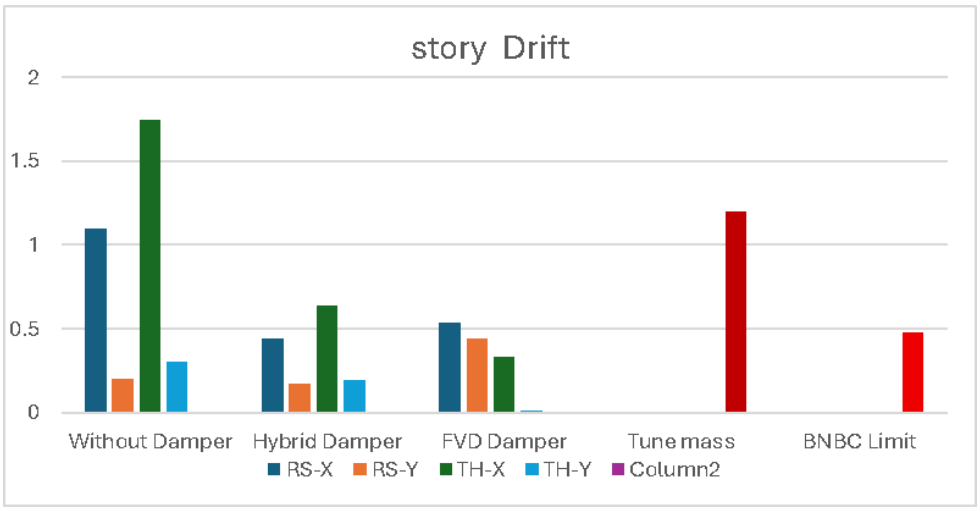


Figure 17: All systems drift Vs Time Period

Figure 2 illustrates the comparative response of the structure with and without dampers. It can be observed that both story displacement and inter-story drift values are significantly reduced after the installation of dampers. This clearly demonstrates the effectiveness of the damping devices in controlling lateral deformations under seismic loading.

4. Cost Evaluation of 3 Damper Systems

4.1 Cost Analysis of Hybrid & FVD Installation

For the present study, a detailed cost assessment of Fluid Viscous Dampers (FVDs) has been conducted to support the selection and economic feasibility of seismic retrofitting measures. The analysis considers the project-specific quantity, unit ratings, and realistic market price scenarios

based on online supplier listings from Chinese manufacturers. The dampers selected for the model are:

- FVD 250 kN (Weight: 44 kg) — Quantity: 6 pcs
- FVD 500 kN (Weight: 98 kg) — Quantity: 28 pcs

And For Hybrid, FVD 250 kN (Weight: 44 kg) — Quantity: 11 pcs

- FVD 500 kN (Weight: 98 kg) — Quantity: 10 pcs
- Friction 300kN(Weight: 90 kg) — Quantity: 17 pcs

4.2 Assumptions and Market Price Range

Market surveys indicate that the price of FVDs varies widely depending on capacity, quality, and certification. For this analysis, three scenarios were considered: **Low-cost**, **Mid-range**, and **High-end**. The FOB (Free on Board) prices at Chinese ports are summarized in Table 11

Table 11: Assume FOB Price for FVD & FRD Damper/Unit (China Component)

Damper Type	Low cost (USD/pc)	Mid-cost (USD/pc)	High-end (USD/pc)
FVD (250kN)	300	900	1600
FVD (500kN)	600	1500	3000
FRD (300kN)	500	1200	3000

Note: Prices are based on online supplier listings (e.g., hebeishangze.en.made-in-china.com, an-sha.en.made-in-china.com, Made-in-China.com) and represent FOB China estimates. Actual prices may vary depending on specifications, certifications, and minimum order quantities.

Total FOB Cost for the Project

Using the unit prices and quantities, the total FOB cost for the selected dampers is calculated as follows:

A. Low-cost Scenario (FVD)

- 250 kN: 6 × 300 USD = 1,800 USD (≈ ৳219,060)
- 500 kN: 28 × 600 USD = 16,800 USD (≈ ৳2,044,560)
- **Total FOB:** 18,600 USD (≈ ৳2,263,620)

B. Mid-range Scenario

- 250 kN: 6 × 900 USD = 5,400 USD (≈ ৳657,180)
- 500 kN: 28 × 1,500 USD = 42,000 USD (≈ ৳5,111,400)
- **Total FOB:** 47,400 USD (≈ ৳5,768,580)

A. Low-cost Scenario (Hybrid)

- 250 kN: 11× 300 USD = 3300 USD (≈ ৳399300)
- 500 kN: 10 × 600 USD = 6000 USD (≈ ৳726000)
- Friction-300kN: 17 x 500USD= 8500 USD (≈ ৳1,028,500)
- **Total FOB:** 17,800 USD (≈ ৳2,153,800)

B. Mid-range Scenario (Hybrid)

- 250 kN: 11 × 900 USD = 9900 USD (≈ ৳1,197,900)
- 500 kN: 10 × 1,500 USD = 15000 USD (≈ ৳1,815,000)
- Friction-300kN: 17 x 1200USD= 20400 USD (≈ ৳2,468,400)
-
- **Total FOB:** 45,300 USD (≈ ৳ 4,481,300)

4.3 Cost Factors Unique to Pendulum TMD

- Cable / rod / link + bearings or articulated joints
- Guide supports or suspension frame
- Fittings (safety, limiting displacement)
- More complicated fabrication for pendulum shape, possibly custom pendulum platform or enclosure
- Transportation & heavy lifting for large, suspended mass
- Testing & commissioning including tuning the pendulum frequency (checking effective length, stiffening effects, damping adjustments)

Because of these factors, pendulum TMDs are usually more expensive per tonne than simpler mass-spring-damper TMDs (translational type) of similar specs, especially when requiring high precision and safety. Using the same mass (≈105.5 tonnes)

Table 12 Assume TMD Price /Tonne

Scenario	Assumed Unit Cost (USD per tonne) for Pendulum Passive TMD	Import & Handling / Freight etc	Installation& Pendulum-Specific Add-ons& Commissioning
Low	**US$4,000 / tonne** (simple, design, minimal finish, local fabrication of frame, minimal testing)	+35%	$20,000
Medium	**US$8,000 / tonne** (better quality cables/links, more precise damping, partial factory prefabrication)	+50%	$50,000
High	**US$15,000 / tonne** (premium materials, detailed certifications, long pendulum or complex structure, high precision, fast delivery)	+65%	$100,000

Exchange rate used: 1 USD = ৳121 (Bangladesh Bank, mid-September 2025).
Estimated Landed Cost in Bangladesh

The landed cost in Bangladesh, including shipping, insurance, customs duties, VAT, and local transportation, typically exceeds the FOB price. For rapid estimation, the total landed cost can be approximated by multiplying the FOB cost by a factor of 1.25–1.6:

- **Example (Mid-range Scenario):**

**** FVD Damper : FOB = 47,400 USD → Landed ≈ 59,000–76,000 USD (≈ ৳7.2M–9.25M)**

****Hybrid Damper : FOB = 45,300 USD → Landed ≈ 56625–72480 USD (≈ ৳6.8M–8.8M)**

****TMD :FOB = 50000 USD → ≈ ৳6.0M+/-**

Note: The final landed cost is sensitive to shipping method (FCL/LCL), HS-code classification, insurance, and handling charges. The values presented here provide a realistic guideline for preliminary budgeting.

4.4 Cost Evaluation of Seismic Dampers using NPV and CEI

This section presents the economic evaluation of three damper systems – Fluid Viscous Damper (FVD), Hybrid Damper, and Tuned Mass Damper (TMD). The assessment is carried out using Net Present Value (NPV) analysis and Cost Effectiveness Index (CEI), considering both financial parameters and structural performance gains.

The evaluation is based on the following parameters:

• Initial landed cost (FOB + shipping, customs, taxes).
• Service life: 30 years.
• Discount rate: 8–12% (±2%).
• Maintenance cost rate: ±5% of device cost annually.
• Unit price uncertainty: ±10%.

The NPV is calculated as the sum of the initial investment and the discounted maintenance stream. The CEI is defined as the ratio of NPV cost to structural performance improvement (reduction in base shear, roof displacement, or inter-story drift).

Input Data,

Financial Parameters (Mid-Range Scenario):

• FVD: FOB = 47,400 USD → Landed ≈ 59,000–76,000 USD (≈ ৳7.2M)

• Hybrid: FOB = 45,300 USD → Landed ≈ 56,625–72,480 USD (≈ ৳6.8M)

• TMD: FOB = 50,000 USD → Landed ≈ ≈ ৳6.0M (+/- 10%)

Structural Performance Results (from ETABS Analysis):

• Base Shear: Hybrid = 429.58 kip, FVD = 387.32 kip, TMD = N/A

• Roof Displacement: Hybrid = 0.99 in, FVD = 1.40 in, TMD = 1.20 in

• Inter-story Drift: Hybrid = 0.98%, FVD = 0.54%, TMD = 1.06%

From the comparative evaluation, Hybrid dampers provide the most favorable cost-to-performance ratio when both NPV and CEI are considered. FVDs remain a practical alternative where moderate improvement at a controlled cost is desired. TMDs are less effective for drift control in this study, though they offer a cost advantage in terms of initial investment.

CHAPTER 5

Discussion & Conclusion

5.1 Discussion:

The comparative evaluation of Fluid Viscous Dampers (FVD), Hybrid Dampers, and Tuned Mass Dampers (TMD) demonstrates both economic and structural implications for retrofitting mid-rise RC buildings in Dhaka. According to the cost analysis, the mid-range land prices were approximately Tk. 7.2 million for FVD, Tk. 6.8 million for Hybrid dampers, and Tk. 6.0 million for TMD. While these values are relatively close, the long-term cost-effectiveness diverges when Net Present Value (NPV) and Cost Effectiveness Index (CEI) are considered. Hybrid dampers and TMDs show slightly higher long-term value compared to FVD due to their balance between initial cost and service performance.

Structurally, Hybrid dampers provided the most effective reduction in displacement (0.99 in) and drift (0.98%), though with higher base shear demand (429.58 kip). TMD yielded moderate displacement control (1.2 in, drift 1.06%) but less influence on base shear. FVD showed higher displacement (1.4 in) and variable drift (0.54%), indicating less consistent dynamic performance.

When integrating both structural and economic perspectives, Hybrid dampers emerge as the most balanced solution, offering superior performance with a competitive cost. TMD appears as a cost-attractive alternative with moderate structural benefits, while FVD, despite simplicity and availability, is comparatively less efficient in long-term value.

Overall, the study suggests that Hybrid dampers represent the most technically reliable retrofitting option, whereas TMD may be preferred in projects where budget constraints dominate. FVD, though practical, may not provide the optimal investment under both economic and structural criteria.

5.2 Conclusion

This chapter presents the overall conclusion of the research. The study examined the seismic performance of an existing 10-story RC building in Dhaka and assessed the effectiveness of Hybrid Dampers, Fluid Viscous Dampers (FVD), and Tuned Mass Dampers (TMD). The selected case study building was less critically poor in condition; it was recognized that many buildings in Dhaka were constructed without strictly following seismic codes. In the event of a major earthquake, these structures could face significant risks. The results confirmed that

dampers can substantially reduce displacement, drift, and base shear, although the initial installation cost may seem high. However, considering the long-term safety, durability, and economic value, retrofitting with dampers presents a hopeful and effective solution for Bangladesh.

5.3 Summary of Findings

The analysis showed that Hybrid Dampers achieved the most effective reduction in base shear and drift, while FVDs were also effective but slightly less efficient. TMDs demonstrated moderate performance in controlling displacement and drift. Overall, all three dampers improved seismic resilience compared to the original building model.

5.4 Comparison with Objectives

The study objectives were largely achieved. Objective 1, evaluating seismic performance, was addressed through detailed modeling and analysis of the existing 10-story RC building. Objective 2, assessing the effectiveness of different dampers, was fulfilled by comparing their impact on story displacement, inter-story drift, and base shear. Objective 3, providing cost-effective retrofitting recommendations, was addressed by analyzing damper costs in the context of Bangladesh's economic situation. Thus, the study outcomes align with the research objectives set in Chapter 1.

5.5 Limitations of the Study

This research has some inherent limitations:

1. Only one 10-story irregular RC building was analyzed, which may not represent all structural types in Dhaka.
2. Structural materials, connections, and dampers were idealized in ETABS without experimental validation.
3. A limited set of ground motions was used; detailed site-specific effects were not considered.
4. Cost analysis covered only direct retrofitting and damper life-cycle costs, excluding indirect expenses.
5. Long-term performance issues, such as degradation or malfunction of dampers were not modeled.

6. Serviceability aspects beyond drift and base shear, as well as environmental and sustainability impacts, were not addressed.

5.6 Recommendations

It is recommended that seismic retrofitting of mid-rise buildings in Dhaka be prioritized using damper technology. While Hybrid Dampers provide the best performance, FVDs and TMDs also offer practical solutions where cost constraints exist. Policymakers, developers, and building owners should recognize that the upfront cost of retrofitting is justified by the long-term benefits of enhanced safety, durability, and economic resilience.

5.7 Future Study

Although this research provides valuable insights into the cost efficiency and performance of Hybrid Dampers compared to FVD and TMD systems, there remain several opportunities for future work:

Broader Case Studies:

This study analyzed only one irregular 10-story RC building in Dhaka. Future research should include a wider range of building heights, configurations, and soil conditions to generalize the findings.

Experimental Validation:

The current work relied on ETABS modeling with idealized damper properties. Experimental testing and field-scale monitoring of hybrid dampers in real Bangladeshi buildings would provide stronger validation.

Soil–Structure Interaction (SSI):

Site-specific seismic responses were not considered here. Incorporating local soil amplification effects would yield more realistic performance predictions.

Long-Term Performance:

The durability, degradation, and maintenance challenges of dampers under real service conditions were beyond this study's scope. Future work should assess these life-cycle issues through long-term monitoring.

Expanded Economic Analysis:

This study considered only direct installation and maintenance costs. Future studies could include indirect costs such as downtime, insurance benefits, and post-earthquake repair savings to present a more holistic cost-benefit evaluation.

Sustainability & Environment:

Future studies should also evaluate environmental impacts, material sustainability, and carbon footprint associated with each retrofitting option.

Policy & Implementation:

Finally, further research can explore how damper-based retrofitting strategies could be standardized within the Bangladesh National Building Code (BNBC) guidelines and implemented at scale for vulnerable mid-rise RC buildings.

5.6 References

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5.7 Appendix:

Detailed NPV and CEI Calculations:

This appendix presents the detailed step-by-step calculations for Net Present Value (NPV) and Cost Effectiveness Index (CEI) for three types of dampers: Fluid Viscous Damper (FVD), Hybrid Damper, and Tuned Mass Damper (TMD). All calculations are based on the mid-range scenario, with assumptions on service life, discount rate, maintenance cost, and structural performance.

Assumptions

- Service Life: 30 years
- Discount Rate: 10% (sensitivity ±2%)
- Annual Maintenance Rate: 5% of initial cost (sensitivity ±5%)
- Device Unit Price Uncertainty: ±10%
- Baseline roof displacement (without damper): 2.99 in
- Structural performance from ETABS analysis:
  - Base Shear: Hybrid = 429.58 kip, FVD = 387.32 kip, TMD = N/A
  - Roof Displacement: Hybrid = 0.99 in, FVD = 1.40 in, TMD = 1.20 in
  - Inter-story Drift: Hybrid = 0.98%, FVD = 0.54%, TMD = 1.06%

NPV Calculation

The Net Present Value (NPV) for each damper is calculated using the formula:
NPV = Initial Cost + Σ (Annual Maintenance / (1 + r)^t) , t = 1 to n
where r = discount rate, n = service life.

NPV Results (BDT)

Damper Type	Initial Cost (BDT)	Annual Maintenance (BDT)	NPV (30 yr, BDT)
FVD	7,200,000	360,000	10,593,689
Hybrid	6,800,000	340,000	10,005,151
TMD	6,000,000	300,000	8,828,074

CEI Calculation

The Cost Effectiveness Index (CEI) is calculated as:
CEI = NPV / Displacement Reduction (%)
Displacement Reduction (%) = (Baseline - With Damper) / Baseline × 100

CEI Results (BDT per %-point)

Damper Type	Displacement Reduction (%)	CEI (BDT per %-point)
FVD	53.18	199,215
Hybrid	66.89	149,577
TMD	59.87	147,463

Sensitivity Analysis

The following sensitivity scenarios were considered:
• Discount rate: 8%, 10%, 12%
• Device unit price variation: ±10%
• Maintenance cost rate variation: 0%–10%
The analysis shows that NPV and CEI are moderately sensitive to discount rate and maintenance cost, while device unit price has a direct proportional effect on NPV.